Chip to Chip Bonding Using Cu Bumps Capped with Thin Sn Layers and the Effect of Microstructure on the Shear Strength of Joints

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Chip to chip bonding techniques using Cu bumps capped with thin solder layers have been frequently applied to 3D chip stacking technology. We studied the effect of joint microstructure on shear strength. Joints were formed by joining Sn/Cu bumps on a Si die and Sn/Cu layers on another Si die at 245–330°C using a thermo-compression bonder. Three different types of microstructures were fabricated in the joints by controlling the bonding temperature and time, (1) a Sn-rich phase with a Cu₆Sn₅ phase at the Cu interfaces, (2) a Cu₆Sn₅ phase in the interior with a Cu₃Sn phase at the Cu interfaces, and (3) one single Cu₃Sn phase throughout the whole joint. The joint having a single Cu₃Sn phase had the highest shear strength. Specimens were aged up to 2000 h at 150°C and 180°C. During aging, the microstructures of all joints were transformed in a single Cu₃Sn phase. The shear strength of the joints was very sensitive to the formation of Cu₃Sn and microvoids. Microvoids formed in the solder joints with a Cu₆Sn₅ phase with and without a Sn-rich phase during aging and decreased the shear strength of the joints. Conversely, aging did not induce the formation of microvoids in the joints which originally had only a Cu₃Sn phase and the shear strength was not decreased.

Key words: Sn/Cu bumps, thin capping layer, joint microstructure, shear test, aging treatment

INTRODUCTION

Recently, 3D integration technology using chip stacking has been of interest since it provides size and weight reduction, high density, high speed, high performance, and low power consumption.^{1–5} Also, 3D integration technology makes it possible to stack heterogeneous systems.^{4–6}

A wire-bonding method has been widely used to interconnect stacked chips. This method has several disadvantages such as long connection length, deterioration of high frequency characteristics, and limited connection between chips.^{4,7–9} To overcome these wiring connection problems, 3D chip stacking

technology using a through Si via (TSV) has received increased attention. For vertical interconnection between chips, Cu to Cu bonding with a thin solder capping layer has been adapted for 3D chip stacking.^{3,4,8–13} During bonding, various microstructures, consisting of Sn, Cu₆Sn₅, or Cu₃Sn phases, can be formed in the solder joints depending on the bonding conditions due to the use of a thin Sn solder capping layer.^{3,4,6,9–12} The microstructure of the solder joints is believed to have a significant influence on the reliability. In this study, we controlled the microstructure of the solder joints by changing the Sn thickness and the bonding conditions, characterized the microstructure change of the solder joints during aging, and investigated the effect of microstructure on the shear strength of the solder joints. We used relatively large Sn/Cu bumps

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(100 $\mu\text{m} \times 100 \mu\text{m}$), the size of which is similar to that in Ref. 8, to study the effect of microstructure of the solder joints. Also, pure Sn solder, instead of Sn-Ag solder, was used as a capping layer to reduce the complexity of the microstructure.

EXPERIMENTAL PROCEDURE

Ti (50 nm), Cu (1 μm), Au (50 nm), and Ti (50 nm) thin films were sequentially deposited on oxidized Si substrates for under bump metallization (UBM) using a DC magnetron sputtering system. A thick photoresist (20 μm) was formed on the UBM and was then patterned by photolithography to form square-shaped openings of 100 $\mu\text{m} \times 100 \mu\text{m}$ for bump formation. Cu bumps were formed by electroplating after the top Ti layer was removed. Thin Sn capping layers were then formed on Cu bumps by electroplating. The height of the Cu bumps was 10 μm , and the thickness of the thin Sn layer was about 1 μm or 2 μm . Cu pads were also fabricated by electroplating Sn (1 μm or 2 μm) and Cu (10 μm). The basic process flow is presented in Fig. 1.

Solder joints were formed by joining the Sn/Cu bumps and Sn/Cu pads at 245–330°C for 10–150 s under 60 MPa using a thermo-compression bonder. To reduce the influence of surface roughness, the bonding temperature was higher than the melting temperature of Sn in all specimens. The bonded specimens were aged up to 2000 h in an oven at 150°C or 180°C. The shear strength of the solder joints was measured by shearing the test dies.^{9,14} The microstructures of the solder joints before and after aging were analyzed using scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS).

RESULTS

Microstructural Characterization of the Joints

Solder joints having various microstructures were fabricated by controlling bonding conditions. The results are shown in Fig. 2. These back-scattered electron (BSE) images clearly show three different types of microstructure in the solder joints. Type I microstructure, which consisted of a Sn-rich phase in the center region and a $\text{Cu}_6\text{Sn}_5(\eta)$ intermetallic (IMC) phase in both Cu interfaces (Fig. 2a), was obtained by bonding Sn (2 μm)/Cu bumps with Sn (2 μm)/Cu pads at 245°C for 10 s. In Fig. 2a, the Sn phase was selectively etched with a dilute HCl solution to characterize the microstructure. Type II microstructure, which consisted of Cu_6Sn_5 in the interior with Cu_3Sn at both Cu interfaces (Fig. 2b), was obtained by bonding Sn (1 μm)/Cu bumps with Sn (1 μm)/Cu pad at 270°C for 90 s. Type III microstructure, which consisted of a single $\text{Cu}_3\text{Sn}(\epsilon)$ phase (Fig. 2c), was obtained by bonding Sn (1 μm)/Cu bumps with a Sn (1 μm)/Cu pad at 330°C for

Fig. 1. Schematic diagram showing (a) Sn/Cu bumps and (b) the bonding process.

150 s. Microvoids were not observed at the interfaces of any specimens in the as-bonded condition.

Microstructural Change During Aging

The microstructural changes of the joints of three different microstructures during aging at 150°C are shown in Figs. 3, 4, and 5. In Fig. 3, a Type I microstructure, originally having Sn-rich and Cu_6Sn_5 phases, became a Type II microstructure (Cu_6Sn_5 phase in the center region and Cu_3Sn phase at both Cu interfaces) after aging for 100 h. As aging continued, it completely transformed to a single Cu_3Sn phase microstructure. Since the Sn phase was transformed to Cu_6Sn_5 then to Cu_3Sn during aging, the total IMC thickness in the solder joints increased. The microstructural change of the Type II specimen, which consisted of Cu_6Sn_5 and Cu_3Sn phases, with aging is presented in Fig. 4. After 100 h aging, as seen in Fig. 4b, the Cu_6Sn_5 phase was transformed into Cu_3Sn phase. The microstructure of the solder joints remained unchanged with further aging. A Type III microstructure of solder joints, which consisted of a single

Fig. 2. SEM images showing the cross-sections of the solder joints of the Sn/Cu bumps-Sn/Cu pads before aging. (a) Sn-Rich/ Cu_6Sn_5 (Type I) by bonding at 245°C for 10 s, (b) $\text{Cu}_6\text{Sn}_5/\text{Cu}_3\text{Sn}$ (Type II) by bonding at 270°C for 90 s, and (c) Cu_3Sn (Type III) phases by bonding at 330°C for 150 s.

Fig. 3. BSE images showing the cross-sections of the solder joints of the Sn-rich/ Cu_6Sn_5 phase after aging at 150°C for (a) 100 h, (b) 300 h, (c) 500 h, (d) 1000 h, (e) 1500 h, and (f) 2000 h.

Fig. 4. BSE images showing the cross-sections of the solder joints of the $\text{Cu}_6\text{Sn}_5/\text{Cu}_3\text{Sn}$ phase after aging at 150°C for (a) 100 h, (b) 300 h, (c) 500 h, (d) 1000 h, (e) 1500 h, and (f) 2000 h.

Fig. 5. The BSE images showing the cross-sections of the solder joints of the Cu_3Sn phase after aging at 150°C for (a) 100 h, (b) 300 h, (c) 500 h, (d) 1000 h, (e) 1500 h, and (f) 2000 h.

Fig. 6. The BSE images showing the cross-sections of the solder joints of the Sn-rich/ Cu_6Sn_5 phase after aging at 180°C for (a) 100 h, (b) 300 h, (c) 500 h, (d) 1000 h, (e) 1500 h, and (f) 2000 h.

Cu_3Sn phase, did not change with aging treatment, as shown in Fig. 5.

Figures 6, 7, and 8 show the microstructural changes of the solder joints during aging at 180°C . In Fig. 6, Type I microstructure (Fig. 2a) changed to Type II microstructure after aging for 100 h, then to Type III microstructure after aging for 300 h. After aging for 100 h, the thickness of the Cu_3Sn IMC layer of the 180°C -aged specimen was thicker than that of the 150°C -aged specimen, as compared in Figs. 3a and 6a. In the specimens having Type II microstructure, the transformation to a single

Cu_3Sn phase was completed when the specimens were aged for 100 h, as shown in Fig. 7a. These microstructural changes at 180°C were similar to those at 150°C ; however, the transformation rate was faster at 180°C . The microstructure of Type III solder joints did not change after aging, as shown in Fig. 9. This observation is consistent with the previous sample (Fig. 5) aged at 150°C .

Total thickness of the solder joints is presented as a function of aging time in Fig. 9. The total thickness of the solder joints increased with the formation of Cu_3Sn since the Cu layer was consumed in

Fig. 7. BSE images showing the cross-sections of the solder joints of the $\text{Cu}_6\text{Sn}_5/\text{Cu}_3\text{Sn}$ phase after aging at 180°C for (a) 100 h, (b) 300 h, (c) 500 h, (d) 1000 h, (e) 1500 h, and (f) 2000 h.

Fig. 8. BSE images showing the cross-sections of the solder joints of the Cu_3Sn phase after aging at 180°C for (a) 100 h, (b) 300 h, (c) 500 h, (d) 1000 h, (e) 1500 h, and (f) 2000 h.

the reaction of Cu with Sn and Cu_6Sn_5 for the formation of Cu_3Sn . The specimens having a Type I microstructure had thicker solder joints due to thick Sn layers ($2\text{ }\mu\text{m}$) after aging. Since specimens having only a Cu_3Sn phase did not undergo a microstructural change, the joint thickness of the Cu_3Sn specimen was constant before and after aging.

Microvoids were observed in the Cu_3Sn layer and at the interface between the Cu_3Sn layer and Cu layer after aging. The number of microvoids increased with aging, as shown in Figs. 3, 4, 6, and 7. Some microvoids were connected along the Cu interfaces. For the specimens having only a

Cu_3Sn phase originally, microvoids were not visible in the solder joints even though the aging time increased, as shown in Figs. 5 and 8. Figure 10 summarizes microvoid fraction to IMC area of the joints. The specimens having a Type I microstructure had a larger void fraction than that of a Type II microstructure after aging at both 150°C and 180°C .

Shear Strength of the Solder Joints and the Fracture Mode

Shear tests were performed with specimens of three different microstructures before and after

Fig. 9. IMC growth during aging at (a) 150°C and (b) 180°C.

Fig. 10. Microvoid fraction as a function of aging time at (a) 150°C and (b) 180°C.

aging. Figure 11 summarizes the change in shear strength of solder joints with aging time at 150°C and 180°C in the three specimens. Before aging, all specimens had a relatively high strength, suggesting complete bonding throughout the joints.⁹ The shear strength of Sn/ Cu_6Sn_5 specimens was lowest among the three specimens. The solder joint consisting of only Cu_3Sn phase (Type III microstructure) showed the highest shear strength. In Fig. 11a, b, the shear strength of the joints for the specimens with an initial Type I microstructure or Type II microstructure increased rapidly with aging, reached a peak, decreased, and then remained constant. The Sn and Cu_6Sn_5 specimens (Type I microstructure) had the highest shear strength after aging for 500 h, but Cu_6Sn_5 and Cu_3Sn specimens (Type II microstructure) had the highest shear strength after aging for 100 h. The shear strength of solder joints was the highest when all phases transformed into a single Cu_3Sn phase. Shear strength of Cu_3Sn specimens

(Type III microstructure) was maximum before aging, slightly decreased with aging, and then was almost constant with further aging, as shown in Fig. 11c. When the specimens (Type I microstructure and Type II microstructure) were aged at 180°C, the shear strength reached a maximum after a shorter aging time.

The fracture modes of solder joints with different aging times were observed by SEM after shear testing. Cohesive fractures in the Sn, Cu_6Sn_5 , or Cu_3Sn layers and interfacial fractures which occurred in the Sn/ Cu_6Sn_5 , $\text{Cu}_6\text{Sn}_5/\text{Cu}_3\text{Sn}$, or $\text{Cu}_3\text{Sn}/\text{Cu}$ interfaces were observed. The fracture mode of solder joints can be divided into 12 types, as shown in Fig. 12. The Sn cohesive fracture is a ductile shear fracture, which is evident in the magnified image of Sn cohesive failure (Fig. 13).

Fracture mode changes during aging are summarized in Figs. 14, 15, and 16. The fracture mode was almost the same in the two different aging

Fig. 11. Shear strength of (a) Sn-Rich/Cu₆Sn₅ (Type I), (b) Cu₆Sn₅/Cu₃Sn (Type II), and (c) Cu₃Sn (Type III) phase specimens as a function of aging time.

conditions (150°C and 180°C) for the specimens which had the same original microstructure (compare (a) and (b) in Figs. 14, 15 and 16). Figure 14 shows the ratio of fracture modes of Sn and Cu₆Sn₅ specimens (Type I microstructure) with aging time. Before aging, mode A (the Sn cohesive fracture) was the main fracture mode of the solder joints, as shown in Fig. 13. In some cases, fracture at Sn/Cu₆Sn₅ interfaces (mode B) was partially observed in the fractured surface. After 100 h aging treatment, the fracture mode changed from modes A and B to modes C and D. Mode C is interfacial fracture between Cu₃Sn and Cu₆Sn₅, and mode D is a mixture of mode C and Cu₆Sn₅ cohesion fracture. After aging for 500 h, the fracture mode changed to interfacial fracture between Cu₃Sn and Cu (mode F) or mixed fracture (mode E) of mode F and Cu₃Sn cohesive fracture. As aging continued, Cu₃Sn/Cu interfacial fracture became dominant. In the case of Type II microstructure, the main fracture modes of solder joints were modes C and D before aging and modes E and F after aging, as shown in Fig. 15.

Figure 16 shows the ratio of fracture modes in the specimen having a single Cu₃Sn phase (Type III microstructure) with aging time. Cohesive failure was the main fracture mode, and interfacial failure between Cu₃Sn and Cu occurred in some specimens after prolonged aging.

DISCUSSION

Our results show that various microstructures can be obtained by controlling the bonding temperature and time. When Sn became liquid and is in contact with Cu, the Cu dissolves into the Sn. During cooling, a Cu₆Sn₅ phase forms first in the Cu surface because the activation energy of the Cu₆Sn₅ phase is lower than that of Cu₃Sn IMC.^{9-11,14} Typically, a Type I microstructure (Sn + Cu₆Sn₅) is observed in the solder joints. When the liquid Sn is reacted with Cu at high temperature for a long time, Cu₃Sn begins to form.^{10,12,15} When a thin Sn layer was reacted with Cu at high temperature for a long time, the thin Sn layer was

	Bump side	Pad side	Fracture Path
Mode A	Sn-rich phase 20 μm	Sn-rich phase 20 μm	Sn cohesive failure
Mode B	Sn-rich phase Cu ₆ Sn ₅ phase 20 μm	Sn-rich phase Cu ₆ Sn ₅ phase 20 μm	Sn/ Cu ₆ Sn ₅ interfacial failure + Sn cohesive failure
Mode C	Cu ₃ Sn phase Cu ₆ Sn ₅ phase 20 μm	Cu ₆ Sn ₅ phase Cu ₃ Sn phase 20 μm	Cu ₃ Sn/ Cu ₆ Sn ₅ interfacial failure
Mode D	Cu ₆ Sn ₅ phase 20 μm	Cu ₆ Sn ₅ phase Cu ₃ Sn phase 20 μm	Cu ₃ Sn/ Cu ₆ Sn ₅ interfacial failure + Cu ₆ Sn ₅ cohesive failure
Mode E	Cu ₃ Sn phase 20 μm	Cu ₃ Sn phase Cu-rich phase 20 μm	Cu ₃ Sn/Cu interfacial failure + Cu ₃ Sn cohesive failure
Mode F	Cu-rich phase Cu ₃ Sn phase 20 μm	Cu ₃ Sn phase Cu-rich phase 20 μm	Cu ₃ Sn/Cu interfacial failure
Mode G	Cu ₃ Sn phase 20 μm	Cu ₃ Sn phase 20 μm	Cohesive failure in the Cu ₃ Sn

Fig. 12. SEM images of the fracture modes of the Sn/Cu joints after shear testing.

totally consumed by the reaction; consequently, a Type II microstructure (Cu₆Sn₅ + Cu₃Sn) and a Type III microstructure (Cu₃Sn) can be formed in the joints.

During aging, a Cu₃Sn phase formed at the interface between Cu and Cu₆Sn₅ through the interdiffusion of Cu and Sn atoms.^{9,10,12} Type I microstructure (Sn + Cu₆Sn₅) or Type II microstructure (Cu₆Sn₅ + Cu₃Sn) tended to transform to a Type III microstructure (Cu₃Sn), and the Cu₃Sn phase became the dominant phase with aging in

all specimens. Such growth requires the supply of Cu atoms from the Cu/Cu₆Sn₅ interface and the diffusion of Cu atoms to the Cu₆Sn₅/Sn interface to react with Sn. Hence, the release of Cu atoms or the reaction of Cu with Sn can be rate-limiting.¹⁶ When the Type I specimens were aged for 100 h, the Cu₃Sn IMC thickness of the specimens aged at 180°C was greater than that of the specimens aged at 150°C because diffusion is fast at high temperature, as can be seen by comparing Figs. 3a and 6a.

In solid state diffusion, interdiffusion occurs between Sn and Cu. Unequal flux of the atomic species causes vacancy formation in the interfaces. These vacancies attract each other, resulting in the formation of microvoids.⁹ The microvoids are caused by the fast migration of Cu atoms into the Sn solder

Fig. 13. SEM image of Sn cohesive failure.

since each of the Cu and Sn atomic forms move with a different velocity.^{9,10}

In Type I and Type II specimens, the solder joints did not consist of a single Cu_3Sn phase during bonding due to the low bonding temperature and short bonding time. After aging, Type I specimens ($\text{Sn} + \text{Cu}_6\text{Sn}_5$) have many more microvoids than Type II specimens ($\text{Cu}_6\text{Sn}_5 + \text{Cu}_3\text{Sn}$) since Type I specimens require more interdiffusion between Sn and Cu to be transformed into Cu_3Sn than do Type II specimens. In Type III specimens, voids did not form in the solder joints during bonding due to liquid phase reaction between Sn and Cu. Voids can occur in the as-bonded condition due to oxidation and roughness of the bonding surface.^{12,13,17} However, voids were not observed in this experiment since melted Sn easily filled the gaps. Also, aging did not induce void formation since the solder joints completely transformed to the Cu_3Sn phase during liquid phase bonding. As shown in Fig. 9, the total IMC thickness of aged Type II specimens was thicker than that of aged Type III specimens even though the Sn capping layer thickness was the same. Numerous microvoids formed in the IMC

Fig. 14. The ratio of the fracture modes of $\text{Sn}/\text{Cu}_6\text{Sn}_5$ specimens as a function of aging time at (a) 150°C and (b) 180°C.

Fig. 15. The ratio of the fracture modes of $\text{Cu}_6\text{Sn}_5/\text{Cu}_3\text{Sn}$ specimens as a function of aging time at (a) 150°C and (b) 180°C.

Fig. 16. The ratio of the fracture modes of Cu_3Sn specimens as a function of aging time at (a) 150°C and (b) 180°C.

layer of Type II specimens, contributing to an increased thickness of the IMC layer.

Insufficient bonding was not observed in the Type I specimens ($\text{Sn} + \text{Cu}_6\text{Sn}_5$).^{6,17} As such, fracture was more prone to occur in the Sn layer (Sn cohesive fracture) since Sn is softer than the Cu_6Sn_5 phase.^{9,18,19} The shear strength of Type I specimens ($\text{Sn} + \text{Cu}_6\text{Sn}_5$) was the lowest due to Sn cohesive fracture. In Type III specimens (Cu_3Sn), the shear strength was the highest because failure mainly occurred in the Cu_3Sn layer, which is harder than the Sn-rich phase.¹⁹ As aging time increased, all phases of solder joints transformed into the Cu_3Sn phase. Also, the shear strength of the solder joints was the highest at the moment where the microstructure of the solder joints transformed into a single Cu_3Sn phase. When the specimens were aged at 180°C, the shear strength of the solder joints rapidly reached maximum values at a shorter aging time due to faster diffusion at high temperature. In the case of Type I and Type II specimens, the shear strength decreased during further aging after all phases of the solder joints were completely transformed into the Cu_3Sn phase. The number of

microvoids forming along the interface between the Cu_3Sn layer and the Cu layer increased as aging time continued. Fracture tends to follow the Cu/ Cu_3Sn interface where many microvoids exist^{9,14} since this interface is the weakest region. The shear strength of Type III specimens remained almost constant with aging since the microstructure (Cu_3Sn only) did not change and microvoids did not form during aging. Occasional $\text{Cu}_3\text{Sn}/\text{Cu}$ interfacial fracture was observed after prolonged aging, indicating that the interface between Cu_3Sn and Cu became weaker during aging in the Type III specimens. This fracture mode change from cohesive Cu_3Sn fracture (mode G) to interfacial fracture (mode E) reflects a small decrease in the shear strength, as shown in Fig. 16. The formation of microvoids has a significant influence on the reliability of solder joints. Our results suggest that shear strength is very sensitive to microstructure. Tanida et al.¹² also reported that a joint composed of a single Cu_3Sn layer had a greater strength than multi-layered IMC joints. They also suggested the feasibility of a post-aging process in order to transform IMC. However, a post-aging process should be carefully controlled since solid-state diffusion during aging induces the formation of voids during transformation, which degrades the joint strength.

CONCLUSIONS

The shear strength of the joints formed between the Cu bump with thin Sn capping layers and a Cu pad with thin Sn layers was investigated. Three different microstructures were obtained in the solder joints by controlling bonding conditions. The microstructure and the fracture mode of the solder joints were characterized before and after aging treatment. The main conclusions are summarized as follows:

- (1) Before aging, Type I microstructures ($\text{Sn} + \text{Cu}_6\text{Sn}_5$) were observed in the solder joints by joining at 245°C for 10 s. Type II microstructures ($\text{Cu}_6\text{Sn}_5 + \text{Cu}_3\text{Sn}$) were observed in the solder joints by joining at 270°C for 90 s. Type III microstructures (Cu_3Sn) were formed in the solder joints by joining at 330°C for 150 s.
- (2) Type I ($\text{Sn} + \text{Cu}_6\text{Sn}_5$) or Type II ($\text{Cu}_6\text{Sn}_5 + \text{Cu}_3\text{Sn}$) phases in the solder joints transformed to the single Cu_3Sn phase during aging.
- (3) Microvoids in Type I ($\text{Sn} + \text{Cu}_6\text{Sn}_5$) and Type II ($\text{Cu}_6\text{Sn}_5 + \text{Cu}_3\text{Sn}$) specimens were observed with aging, but microvoids were not observed during aging in the solder joints having only a Cu_3Sn phase.
- (4) The solder joints which consisted of Type I microstructure after bonding have the highest shear strength.
- (5) After aging, the fracture mode was interface failure between IMC and the Cu layer, which originated from interfacial weakness due to the development of microvoids.

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