Bonding of copper to silicon chips using vapor-deposited tin film

T Fujimoto\(^1\), S Fukumoto\(^1\), T Miyazaki\(^1\), Y Kashiba\(^2\),
K Shiotani\(^1\) and K Fujimoto\(^1\)

\(^1\)Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
\(^2\)Mitsubishi Electric Corporation, 8-1-1 Tsukaguchihonmachi, Amagasaki, Hyogo 661-8661, Japan

E-mail: takashi@mapse.eng.osaka-u.ac.jp

Abstract. A bonding process between a Cu plate and a Si chip using a vapor-deposited tin film has been developed. The microstructures of the bond interface and the reliability during thermal cyclic tests were investigated. Intermetallic compounds (IMCs) of Cu\(_3\)Sn and/or Au-Cu-Sn were formed at the bond interface. The stress concentration initiated fracture in the IMC layer at the corners of the bond area and the initial cracks in the IMC layer propagated through the Al layer in the metallized layer on the Si chip. Joints using a deposited tin film showed much longer lifetime than solder joints.

1. Introduction

Nowadays, power devices are widely used as key technologies for energy saving. It has been expected that Al lead wires on Si chips will be replaced by Cu to deal with high current, which makes power devices operate at high temperatures of nearly 473 K \([1–3]\). The Cu lead is usually soldered to Si chips. However, it is difficult to secure the reliability of the joint when a solder is used at near its melting point. In order to obtain a reliable high-temperature joint, it could be favorable to form an intermetallic compound (IMC) layer at the bond interface. Since the electrical resistivity of an IMC such as Cu\(_6\)Sn\(_5\) or Cu\(_3\)Sn is smaller than that of Pb-5Sn solder, which is a typical high-temperature solder \([4, 5]\), joints whose interlayer consists of an IMC could also improve the energy efficiency of the power electronic system. The solid-liquid interdiffusion (SLID) process has been applied for mechanical and electrical interconnects \([6–8]\).

The SLID bonding process is illustrated in Figure 1. The process can be divided into four stages: (i) A low melting point metal is inserted between the base metals. (ii) Heat treatment under appropriate pressure is carried out, and the insert metal becomes liquid. (iii) Solid-liquid interdiffusion occurs between the base metals and the liquid phase. (iv) Further interdiffusion results in complete vanishing of the liquid phase to leave an IMC layer at the bond interface. By using the SLID process, high melting point compounds are formed. For example, in the case of using Sn films to bond Cu, the bonding temperature is approximately 573 K, which is higher than the melting temperature of Sn (505 K). The melting temperature of the obtained bond layer of Cu\(_6\)Sn\(_5\) (688 K) or Cu\(_3\)Sn (949 K) was higher than that of Sn \([9, 10]\).
Generally, an IMC is known to be hard and have a small coefficient of thermal expansion. In the case of an IMC formed between a Cu lead and Si chip, high thermal stress due to the different coefficients of thermal expansion of the materials will be induced between the Si chip and Cu. However, there are few studies of the reliability of such joints. The aim of this study is to investigate the microstructures of the bond interface and the reliability during thermal cyclic tests.

2. Experimental procedures

The materials used were oxygen-free Cu plates (4×4×0.2 mm³) and Si chips (14.8×7.7×0.255 mm³). The Cu plates were polished with emery paper of #4000. They were then pickled in a 5% HCl solution, and rinsed in ethanol. One of the surfaces of the Si chip had a metallization layer. The layer consisted of Al/Ni/Au in order from the surface of Si. Figure 2 shows the designs of the faying surfaces. The faying surface of the Cu plate was coated with Sn by vapor deposition. The thickness of Sn film was 4 μm. Either Sn alone or Sn and Cu were coated on the metallization layer on the Si chip. The Cu plates were bonded to the Si chips in a nitrogen atmosphere at 573 K under a pressure of 10 MPa. The bonding times were varied from 300 to 3000 s. Some bare Cu plates were soldered to the Si chips with Sn-5Sb to obtain the reference data. The microstructures at the bond interface were observed by scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDX). X-ray diffraction (XRD) analysis was carried out to identify the IMC layer. The hardness of each layer
Figure 3. Micro-focus XRD pattern on the faying surface of Cu plate with a deposited Sn layer. The sample was heated to 573 K.

3. Results and discussion

3.1. Microstructures of bond interface

It has been reported that Sn immediately reacts with Cu to form a Cu₆Sn₅ compound on deposition of a Sn-Cu composite [11]. The copper plate with the Sn film was heat treated at 573 K for 0 s to confirm the existence of Sn. Figure 3 shows the XRD pattern taken from the heat-treated Cu plate with the deposited Sn layer. In the case of heating to 573 K, Cu, Sn, Cu₆Sn₅, and Cu₃Sn phases were identified. Therefore, it is considered that liquid Sn remains at the bond interface at the beginning of bonding.

Figure 4 shows typical cross-sectional SEM images of bond interfaces in the case of using the design-A faying interface. In this case, the liquid Sn reacted with the Cu plate and with the Au layer in the metallized layer on the Si chip, and two interlayers were formed. By EDX and XRD analysis, Cu₃Sn and Au-Cu-Sn IMC were detected. The Cu₃Sn was thinner than the Au-Cu-Sn IMC for a bond time of 300 s. It is believed that the Au-Cu-Sn IMC layer includes phases such as Cu₆Sn₅ and AuSn₂. The boundary between the Cu₃Sn layer and Au-Cu-Sn IMC layer is ragged. With increasing bonding time, the Cu₃Sn phase increased while the Au-Cu-Sn intermetallic phase decreased. Since the initial Sn layer had already been consumed at a bonding time of 300 s, Cu diffused through the Cu₃Sn layer from the Cu plate and reacted with the Cu₆Sn₅ phase in the Au-Cu-Sn IMC layer to grow Cu₃Sn.

Figure 5 shows typical cross-sectional SEM images of bond interfaces in the case of using the design-B. In this case, an intermediate layer of Cu₃Sn was formed between the Cu plate and the deposited Cu layer, and there was no Au-Cu-Sn IMC found as was the case when using design-A. Since the deposited Sn layer lay next to the deposited Cu layer, the molten Sn probably reacted with...
Figure 4. Cross-sectional SEM images of bond interface using design-A. Bonding time was: (a) 300 s, (b) 1200 s, and (c) 3000 s.

Figure 5. Cross-sectional SEM images of bond interface using design-B. Bonding time was: (a) 300 s, (b) 3000 s.
Table 1. Hardness of each layer in bond interface.

| Layer               | Hardness (GPa) |
|---------------------|----------------|
| Cu                  | 1.94           |
| Cu₃Sn               | 6.54           |
| Au-Cu-Sn IMC        | 8.71           |
| Al                  | 1.56           |
| Si                  | 14.3           |

| Bonding conditions | Cycle number |
|--------------------|--------------|
|                    | 0    | 1000 | 3000 |
| (a) Design-A       | 1200 s |       |      |
| (b) Design-B       | 3000 s |       |      |
| (c) Sn-5Sb solder  |       |       |      |

Figure 6. SAT images at the bond interface between Cu plate and Si chip.

that layer first and foremost but very little with the Au layer. Even if the bonding time increased, there was no appreciable change of phase in the bond layer.

The hardness of each layer in the bond interface is shown in Table 1. The hardness was the highest for the Au-Cu-Sn IMC layer and the lowest for the Al layer. It is generally known that Cu₃Sn and Cu₆Sn₅ show similar hardnesses [12, 13]. As mentioned above, the Au-Cu-Sn IMC layer includes Cu₆Sn₅ and other unidentified phases. Therefore, the unidentified phases are probably harder than Cu₆Sn₅.
3.2. Reliability during thermal cyclic tests

The SAT images at the bond interface between Cu plate and Si chip before (0 cycle) and after the thermal cyclic test (1000, 3000 cycles) are shown in Figure 6. The samples in Figure 6(a) and 6(b) correspond to those in Figure 4(b) and 5(b), respectively. The bright region presents the fracture part at the bond area. Initiation of cracks occurred at the corners of the bond area where stress is concentrated for all samples. In the case of the solder joints, almost the whole interface fractured even after 1000 cycles (Figure 6(c)). On the other hand, the joints whose interlayer consists of an IMC showed longer lifetimes than the solder joints (Figures 6(a) and 6(b)), but there was no obvious differences in reliability between using the design-A and using the design-B.

Figures 7 and 8 show the crack propagation path at the bond interface between the Cu plate and Si chip during temperature cyclic tests. In the case of joints whose interlayer consists of Cu$_3$Sn and Au-Cu-Sn IMC, the crack passed through not only through the IMC layer but also the Al layer. The cracks in the IMC layer were observed only at the corner of the bond area and the Al layer was almost

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**Figure 7.** Crack propagation path at the bond interface between Cu plate and Si chip by temperature cyclic test. Cycle number is 3000. Bonding was carried out with design-A faying surface for 3000 s.

**Figure 8.** Crack propagation path at the bond interface between Cu plate and Si chip by temperature cyclic test. Cycle number is 3000. Bonding was carried out with Sn-5Sb solder paste for 300 s.
fractured completely. Therefore, initiation of cracks occurred in the IMC layer and the cracks propagated through the Al layer. Similar fractures were found in the case of joints with design-B whose interlayer consists of Cu_{3}Sn and Cu. On the other hand, in the case of solder joints, an overall fracture occurred in the solder layer. As mentioned in the last section, the bond layer consists of a hard IMC layer and a soft metallized layer. Hence, it is considered that initiation of cracks first occurred at the corner of the hard and brittle IMC layer where stress is concentrated, and the cracks propagated through the soft Al layer.

4. Conclusions
A bonding process of a Cu plate and Si chip using a vapor-deposited tin film has been developed. Cu_{3}Sn and/or Au-Cu-Sn IMC were formed at the bond interface. The Au-Cu-Sn IMC layer consists of several phases. Inserting a Cu layer between the vapor-deposited Sn layer and the Au layer of the Si chip prevents formation of Au-Cu-Sn IMC. In the thermal cyclic test, the joints using the deposited tin film showed much longer lifetime than solder joints. In the case of joints whose interlayer consists of IMCs, cracks occurred in the IMC layer of the joint and propagated through the Al layer in the metallized layer of the Si chip.

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