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Observations on HRTEM features of thermosonic flip chip bonding interface

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Abstract

The bonding interface features in thermosonic flip chip (FC) bonding are of interest to researchers in microelectronics packaging. In this study, a die with Al pads and eight gold bumps was bonded to a silver-coated pad on our lab test bench. The interface of the sample was analysed by using a high-resolution transmission electron microscope (HRTEM). For FC bonding parameters (e.g. ultrasonic power 2 W, bonding time 350 ms, heating temperature 150 °C, and bonding force 3.2 N), the thickness of atom diffusion at the Au–Ag interface is about 200 nm and that at the Au–Al interface is about 500 nm. In addition, ultrasonic vibration of FC bonding leads to the growth of the dislocation density in bonded materials and the formation of a cluster of dislocations at the interface. Therefore, short circuit diffusion plays a major rule during ultrasonic bonding when the temperature rise is relatively low. These observations will be helpful for further analysis.

Keywords: Thermosonic flip chip; Atom diffusion; Dislocations

1. Introduction

Thermosonic flip chip technology has unique advantages and is increasingly used in low pin counts such as smart cards, LED and surface acoustic wave (SAW) filters in telecommunication applications [1,2]. This packaging technology is promising because it is clean, lead-free, adhesive-free and solder-less for area array interconnection. By using this technology, a snap and simple assembly process can be achieved to reduce bonding temperature, pressure and time [3,4]. As thermosonic bonding provides strong metallurgical joining, it is considered to be more reliable than conductive adhesive bonding and comparable to solder interconnection [5,6].

To enhance thermosonic bond development, an improved understanding was investigated at the bond interface. By using scanning electron microscope (SEM), lift-off characteristics of interfaces in an ultrsonic flip chip simulating a torus with an unbonded central region was observed [7–9]. However, the features at flip chip bonding vertical section interfaces tested by scanning EDS of SEM cannot exactly show the diffusion at the interfaces [10].

In this work, the interface features at vertical section of the FC bonding were detected by the HRTEM. Based on the images obtained, the atom diffusion of ultrasonic FC bonding interface was then analysed. Finally, the explanation about the effect of ultrasonic vibration on the FC bonding was given.

2. Experimental

A thermosonic FC bonding test bed was built by using a T/S-2100 ultrasonic wire bonder and a U3000 ultrasonic wedge bonder. The parameters of the bed are as follows: ultrasonic frequency 60 kHz, ultrasonic power 0–5 W, bonding time 20–500 ms, bonding force 0.30–12 N. The test vehicle of the bed is shown in Fig. 1. The figure shows that a 1 mm × 1 mm die with eight Au bumps, which were formed on Al pads of the die by using a ball bonder, was bonded to an Ag-coated pad on a copper substrate. The diameter of the bumps is about 80 μm.

Since standard samples of the TEM are required to be thin discs with 3 mm in diameter, the following steps were used in order to meet the requirement.

First, a bonded die was filled with silver-loaded epoxy (Epotech H20E). The next step was to cure the epoxy at 100 °C for approximately 1 h, and grind to 2.5 mm diameter, then put into 3.0 mm diameter and 8 mm length copper pipe that have been filled with an epoxy, cure the epoxy again.

Second, the 3 mm discs with 0.5 mm thick were formed by using model 850 wire saw. Then these samples were thinned by both mechanical and ion-sputter thinning methods. Thus, vertical section of flip chip bonding interface was produced.

The samples were observed in the high resolution TEM (F30) with a line scanning EDS (energy dispersive X-ray spectroscopy) at 300 kV.

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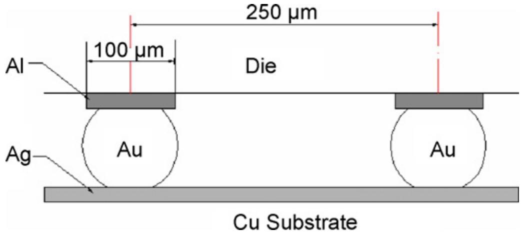

Fig. 1. 8-I/O assembly test vehicle.

3. Results and discussion

3.1. Atom diffusion

Fig. 2 shows a scaning transmition eletronic microscope (STEM) image and the EDS scanning results at the Au–Ag interface when ultrasonic power is 2 W, bonding time is 350 ms, heating temperature is 150 °C, and bonding force is 3.2 N. The thickness of atom diffusion at the Au–Ag interface was about 200 nm. The Au–Ag alloy is of unlimited solid-solution according to Au–Ag phase diagram (see Fig. 3) shows that the Au–Ag interface is also of solid solution.

Fig. 5 shows the scanning results of EDS for the Au–Al interface. The thickness of atom diffusion at the Au–Al interface was about 500 nm. According to the Au–Al phase diagram (see Fig. 6), the intermetallic compounds of Au–Al (e.g. Au_4Al, Au_2Al, AuAl, $AuAl_2$, and Au_5Al_3) may be formed. The mesophase features of the Au–Al bonding interface tested by STEM are shown in Fig. 5. Furthermore, in terms of EDS-testing results of the Au–Al interface in Table 1). The HRTEM image (see Fig. 4, there must be an intermetallic compound that mainly consists of Au_4Al. Thus, the features of the Au–Al interface tested by TEM in Fig. 7 is much different from that in Fig. 4 because of the intermetallic compound.

Pre-diffusion of the Au–Al interface formed by using an Au-ball bonder took place before flip chip bonding. Therefore, the thickness of atom diffusion at the Au–Al interface is thicker than that at the Au–Ag interface.

3.2. Activation of dislocation

For 1.75 W ultrasonic power in flip chip bonder, vibration velocity at the end of bonding tool measured by using PSV-400-M2 laser vibrometer was shown in Fig. 8 . When vibration becomes stable, the peak value of the vibration velocity is $V = 1.3\ m\ s^{-1}$. The ultrasonic vibration is sinusoid. Fig. 9 shows the result of fast fourier transform (FFT) from Fig. 8. It can be found that the resonance frequency is $f = 62.73$ kHz. Thus, the

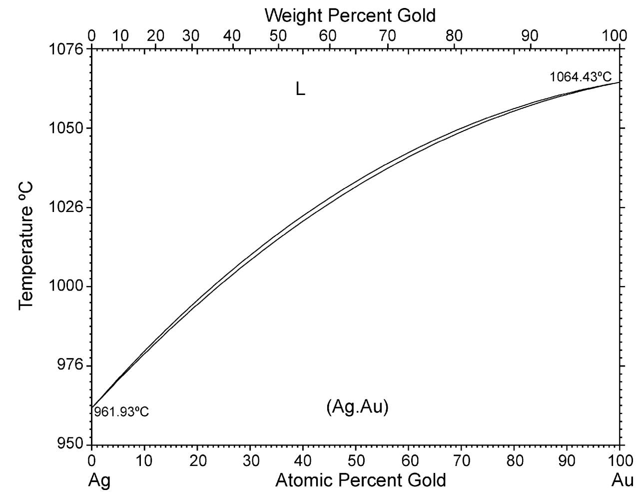

Fig. 3. Au–Ag phase diagram.

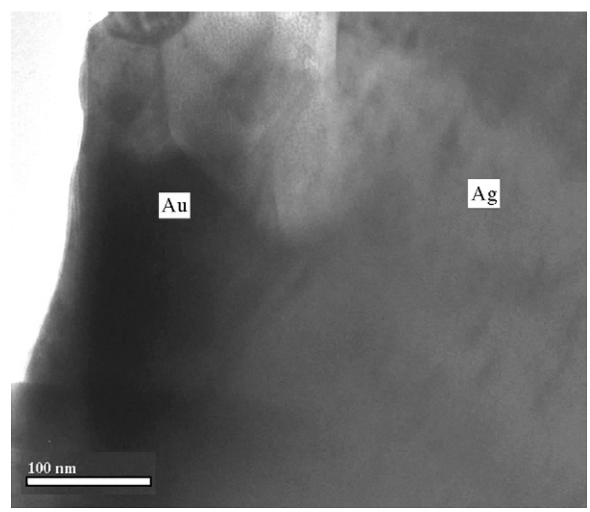

Fig. 4. TEM vertical section image of Au–Ag interface.

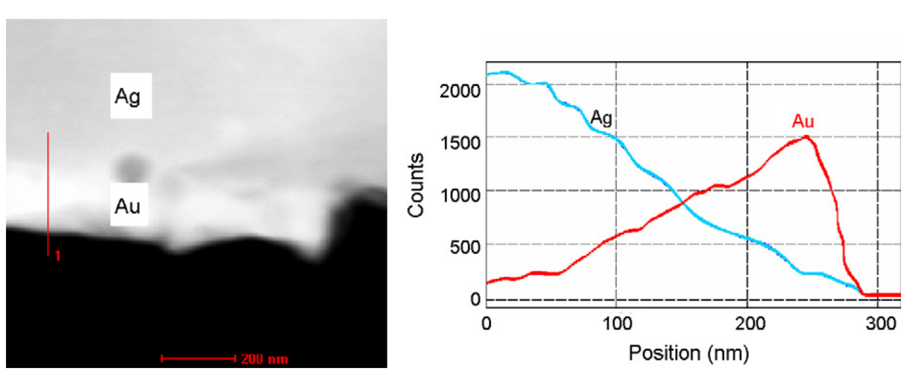

Fig. 2. STEM image and scanning results of EDS on vertical section of the Au–Ag interface.

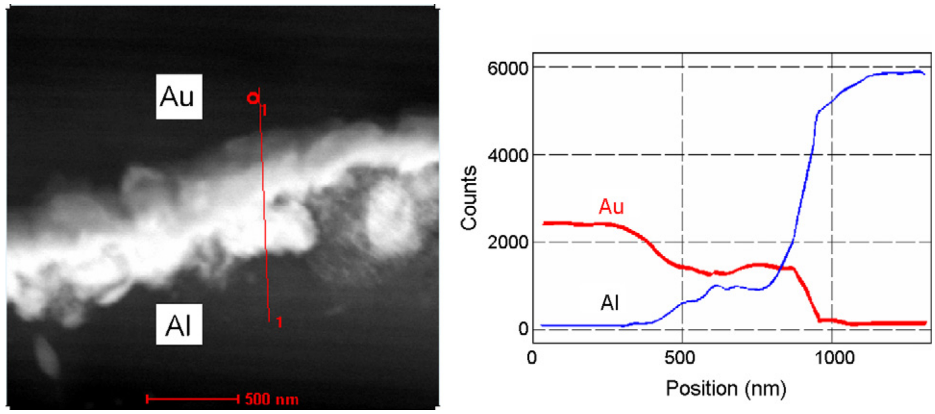

Fig. 5. STEM image and scanning results of EDS on vertical section of the Au–Al interface.

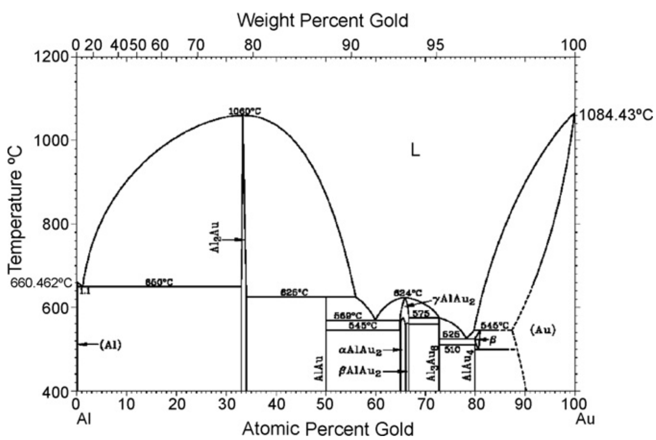

Fig. 6. Au–Al phase diagram.

Table 1
EDS–test results at atom diffusion point

Element	At.%	Wt.%
Al	20.23	4.42
Au	79.77	95.58

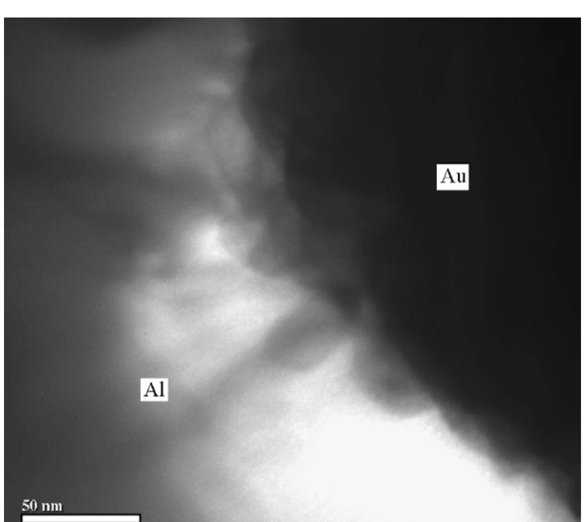

Fig. 7. TEM image of the Au–Al interface.

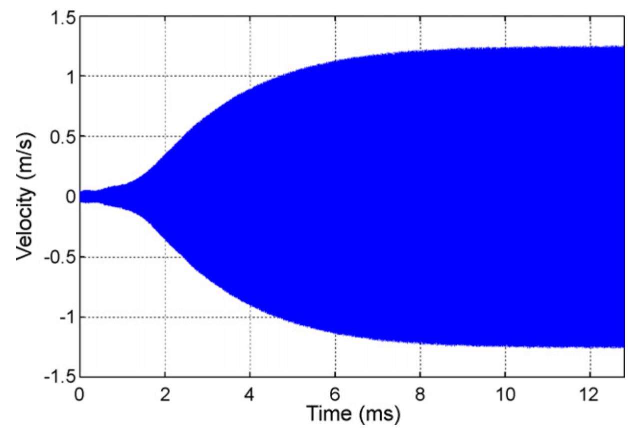

Fig. 8. Result of vibration velocity at the end of bonding tool.

angle frequency ω can be calculated as

$$\omega = 2\pi f = 2 \times 3.14 \times 62.73 \times 10^3 \approx 3.94 \times 10^5.$$

The peak value of the vibration acceleration is

$$a = V\omega = 1.3 \times 3.94 \times 10^5 = 5.122 \times 10^5\ \mathrm{m\,s^{-2}}.$$

Because the acceleration of ultrasonic vibration was about 51,220 times as that of the gravity, there is a strong mechanical effect on the interface during bonding process. Thus, much more dislocations of metal crystal lattice were activated.

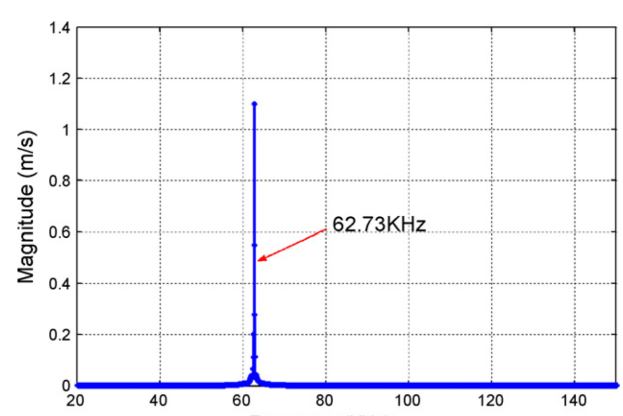

Fig. 9. FFT of vibration velocity.

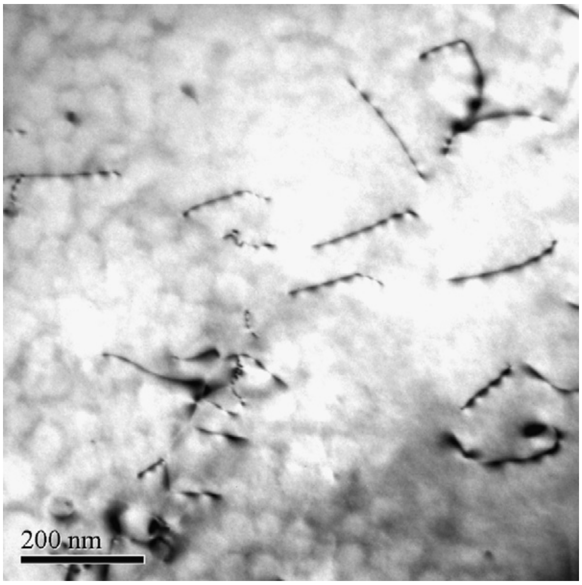

Fig. 10. TEM image of dislocation structure of aluminum without the ultrasonic treatment.

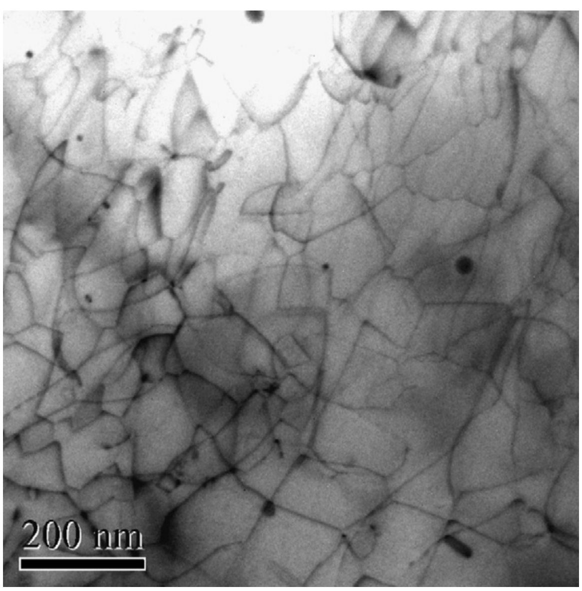

Fig. 11. TEM image of high-density dislocation lines of aluminum after the ultrasonic treatment.

Without ultrasonic treatment, the typical dislocation structure of annealed aluminum is shown in Fig. 10. The figure shows that there are only a few of dislocations. However, ultrasonic vibration in the FC bonding leads to the growth of the dislocation density in bonded materials and the formation of a cluster of dislocations at the interface (see Fig. 11).

The interfacial temperature rise during ultrasonic bonding is about 20–30 °C, which was measured by Harman [11] and Schwizer et al. [12] with a microsensor. According to diffusion theory, the diffusion coefficient along dislocation in solid materials at relatively low temperature is larger than that along crystal lattice (body diffusion). Dislocation diffusion belongs to short-circuit diffusion, which is much faster than body diffusion. Thus, short circuit diffusion plays a major rule during ultrasonic bonding processes. Therefore, by using ultrasonic energy, the atom diffusion of bonding interfaces is much easily formed.

4. Conclusions

For the given bonding parameters, the thickness of atom diffusion at the Au–Ag interface was about 200 nm. However, the thickness of atom diffusion at the Au–Al interface was about 500 nm and there is an intermetallic compound (e.g. Au_4Al). By ultrasonic vibration during ultrasonic bonding process, much more dislocations at metal crystal lattice are activated and the short circuit diffusion takes place. These observations would be helpful for further research about thermosonic FC bonding.

Acknowledgments

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