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The law of ultrasonic energy conversion in thermosonic flip chip bonding interfaces

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ABSTRACT

In this paper, the vibration characteristics during the flip chip (FC) bonding process were observed by using a laser Doppler vibrometer (LDV), and the atom diffusion features in vertical section of the FC bonding interfaces were inspected by using a high resolution transmission electron microscope (HRTEM). Results show that the vibration velocity of a die was about 500 mm/s during the traditional FC bonding process, and that of a substrate was only about 180 mm/s. It led to the difference of atom diffusion in the FC interfaces. For the given variables, the thickness of atom diffusion at an up-interface (i.e. Au/Al interface) of the FC bonding was about 500 nm where was an inter-metallic compound (i.e. $AuAl_2$), and that of atom diffusion at a down-interface (i.e. Au/Ag interface) was about 200 nm. Furthermore, the law of ultrasonic energy conversion was found that the ratio of the up-interface to the down-interface in the FC bonding was statistically about 2.21:1. According to this principle, different bonding processes are suggested to improve the performance of two interfaces. The experimental evaluation confirms the effectiveness of the suggested processes on minimizing the inter-metallic compound layer and equilibrating the thickness of atom diffusion at two interfaces.

1. Introduction

In recent years, ultrasonic flip chip technology is increasingly used in low pin counts applications in microelectronics packaging [1], while the principle and mechanism of ultrasonic bonding has not been understood very well. Many investigators have tried to find key factors.

Ultrasonic vibration generates more dislocations during the FC bonding process, the atomic diffusion can be activated more easily along the dislocation lines which perform the fast diffusion channels, thus the processes of ultrasonic bonding was enhanced and is different from melting mechanism of reflow soldering [2,3]. And atom diffusion at interface of ultrasonic bonding was tested about 100–300 nm by using the HRTEM [4,5], which is helpful for further analysis. Bonding strength of the FC bonding can be evaluated by using with the Dage 4000 bonding tester, for example, the shear force of bonding interface with 80-micron-diameter was about 65 g [6].

The acceleration of ultrasonic vibration at bonding tool of ultrasonic bonding was tested by using the laser Doppler vibrometer (LDV) which provided an important means for observing ultrasonic movement, was about 18,800 times as acceleration of gravity [7]. Furthermore, the "stall" of the velocity of ultrasonic vibration during bonding process was acquired, and was noticed that the bonding strength formed in the bonding interface [8–10].

In this paper, the features of up/down-interfaces in the FC bonding were further researched. Based on the detected pictures, the energy conversion and optimizing processes of the FC bonding was discussed.

2. Experimental

2.1. The test vehicle

The test vehicle of the FC bonding process is shown in Fig. 1, which is the traditional bonding approach. A FC die with eight gold (Au) bumps which had been formed onto aluminum (Al) pads of the die by using ball bonder was bonded onto a silver (Ag) coated pad on lab test substrate. The diameter of bumps is about 80 μm. Each pad is 100 μm square. Ultrasonic frequency is 60 kHz. Ultrasonic energy was transmitted from the Au/Al interface (up-interface) to the Au/Ag interface (down-interface, i.e. connecting interface in the FC bonding). Laser beam was accurately focused on the flank of the die or the substrate by using the PSV-400-M2 LDV, then the vibration velocity of the die and the substrate in bonding process were tested respectively.

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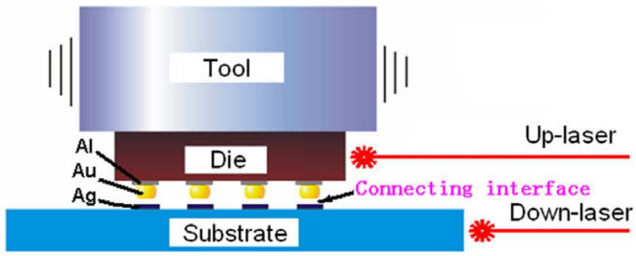

Fig. 1. The traditional pattern of the FC and vibration testing of LDV.

2.2. The specimens of HRTEM and test

The specimens of vertical section in the FC bonding interfaces were prepared by punching, grinding and ion-sputter thinning. The specimens were detected in HRTEM (F30) with a line scanning EDS (energy dispersive X-ray spectroscopy) at 300 kV.

3. Results and discussion

3.1. Dynamics characteristics

The time depended velocity of the die and the substrate were measured, as shown in Fig. 2, and time depended amplitude of vibration velocity were calculated, as shown in Fig. 3. Figs. 2 and 3 show that: at the initial stage (about 0–5 ms), the die and the substrate vibrate at the same velocity; after the initial stage, the velocity of the substrate is less than the die. When ultrasonic vibration transmitted from the die to the substrate (see Fig. 4), the up-interface of FC was vibrated along with the die and the down-interface of FC was vibrated along with the substrate. It indicated that the ultrasonic energy of the down-interface was decreased, and mostly the ultrasonic energy was transformed in the up-interface or Au-ball. Thus it likely led to the difference of microstructure at the up and down bonding interfaces.

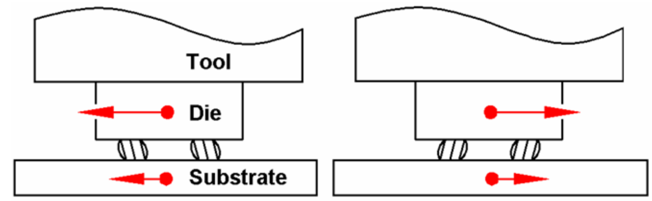

Fig. 4. Vibration illustration of interfaces.

3.2. Diffusions in the up and down-Interfaces

For the traditional pattern of the FC bonding under the given variables (i.e. ultrasonic power is 2 W, time is 120 ms, and force is 3.2 N), the FC bonding strength was about 60 g/bump by using the die shear testing with Dage 4000 bonding tester. The diffusing performance of the up-interface in the FC bonding is evaluated in Fig. 5a, where the scanning transmission electronic microscope (STEM) image and the scanning result cross the Au/Al interface from EDS-test are presented. The thickness of atomic diffusion at the bonded Au/Al interface was about 500 nm. According to Au/Al phase diagram (Fig. 6), the inter-metallic compounds (Au_4Al, Au_2Al, AuAl, $AuAl_2$, and Au_5Al_3) may be formed. From the meso-phase features at the Au/Al bonding interface and its EDS-testing results (see Table 1), this diffusion layer is likely an inter-metallic compound (mostly $AuAl_2$). The inter-metallic compounds are not good for strong bond due to its brittleness and are lower conductivity [11–13]. Thus these inter-metallic compounds should be minimized.

Similarly, the performance of the down-interface is evaluated in Fig. 5b. The thickness of Au/Ag atomic diffusion was about 200 nm. According to Au–Ag phase diagram (Fig. 7), Au and Ag is an unlimited solid-solution alloys, and Fig. 5b shows also that the interface

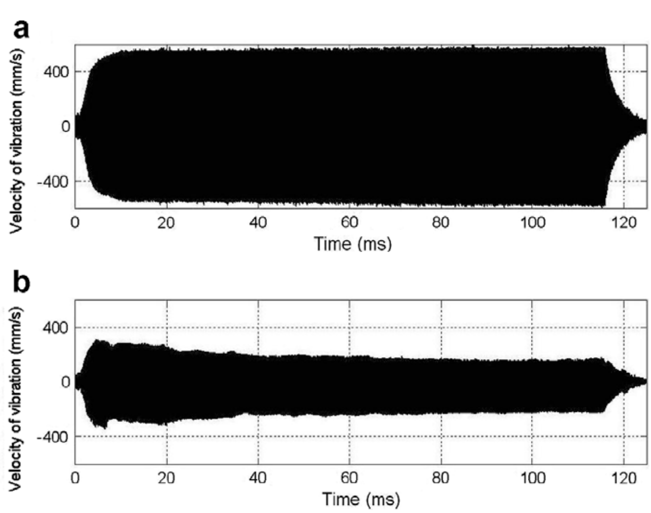

Fig. 2. Vibration velocity of the die measured by the LDV from (a), lower vibration velocity of the substrate measured by the LDV from (b).

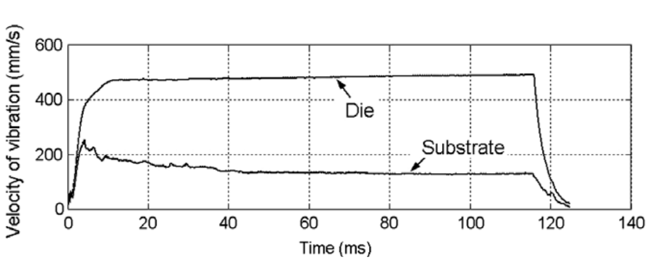

Fig. 3. The amplitude of vibration velocity at die and the substrate during bonding.

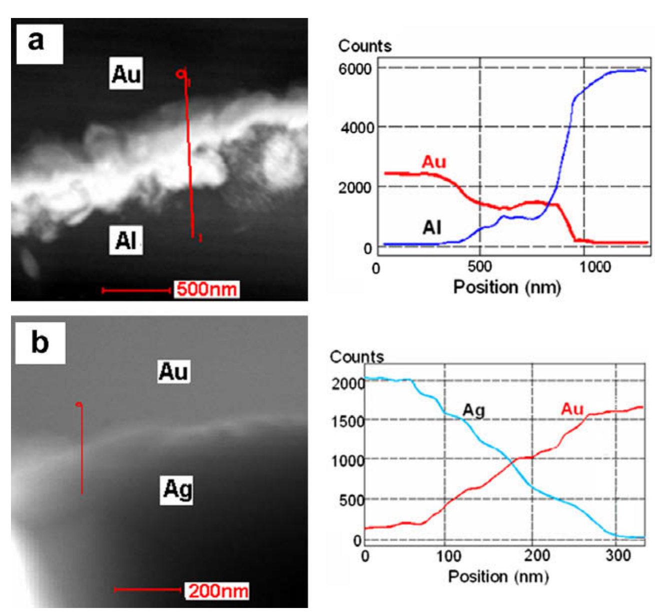

Fig. 5. STEM image and scanning EDS-testing result of the up-interface (i.e. Au/Al interface) for the traditional pattern from (a), that of the down-interface (i.e. Au/Ag interface) from (b).

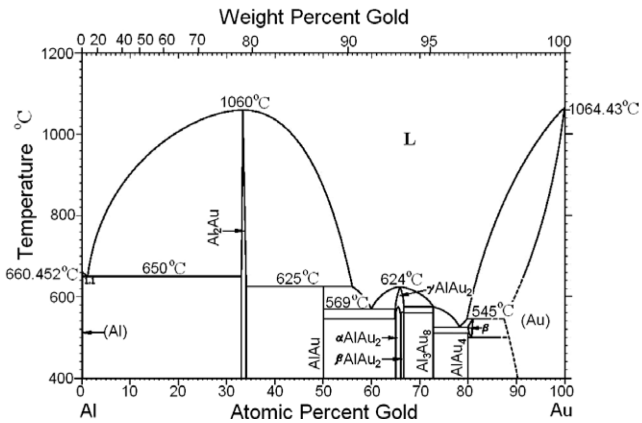

Fig. 6. Au–Al phase diagram.

Table 1
Results of EDS-test at Au/Al interface.

Element	Atom percent (%)	Weight percent (%)
Al	65.951	20.969
Au	34.048	79.030

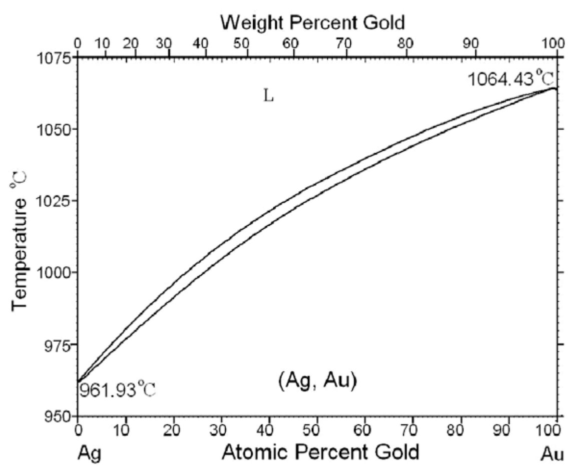

Fig. 7. Au–Ag phase diagram.

of Au/Ag bonding is a solid-solution structure. The thickness of Au/Al atom diffusion at up-interface is much thicker than that of the Au–Ag interface.

Line scanning samples of EDS-test at the up and down-interfaces of the FC bonding are shown in the Fig. 8. The ratio of ultrasonic energy conversion from the up-interface to the down-interface of the FC bonding can be statistically represented as below:

$$T_1 : T_2 = \left(\sum_{k=1}^{k=N} T_{1(k)}/N\right) : \left(\sum_{k=1}^{k=N} T_{2(k)}/N\right) \approx 2.21 : 1 \quad (1)$$

where T_1 is the average thickness of the up-interface, and T_2 is the average thickness of the down-interface.

3.3. Suggested FC processes

To reduce the inter-metallic compound of the Au–Al interface, based on above principle, a different bonding process is suggested as shown in Fig. 9. The ultrasonic energy will reach the connecting

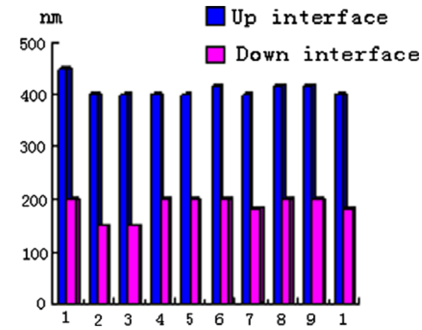

Fig. 8. Histogram of the thickness of atom diffusion.

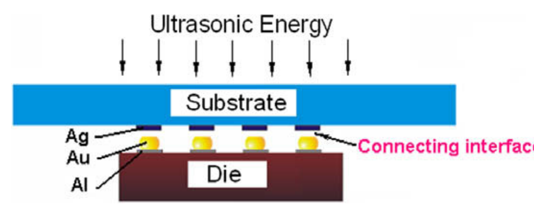

Fig. 9. A suggested pattern of the FC bonding.

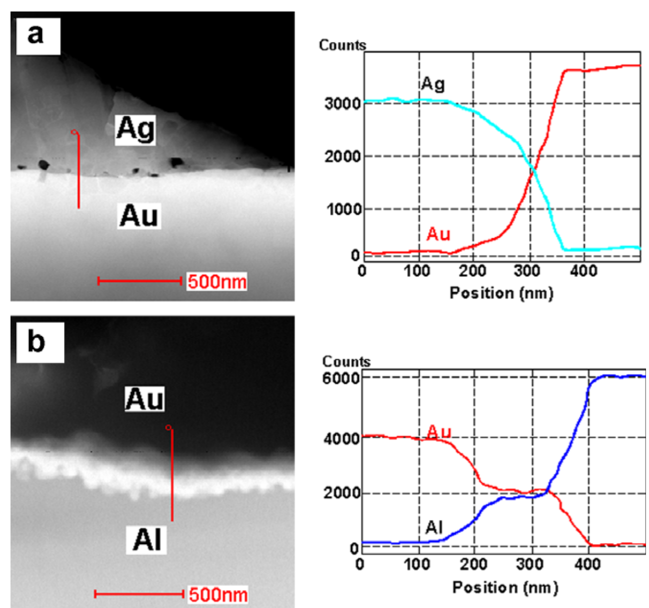

Fig. 10. STEM image and scanning EDS-testing result of the up-interface (i.e. Au/Ag interface) for the suggested pattern from (a), that of the down-interface (i.e. Au/Al interface) from (b).

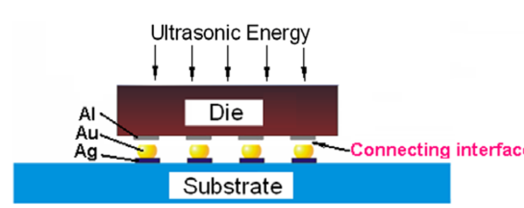

Fig. 11. Another suggested pattern of the FC bonding.

interface first instead of the Au–Al interface in the traditional approach. Results of STEM of the suggested approach are evaluated

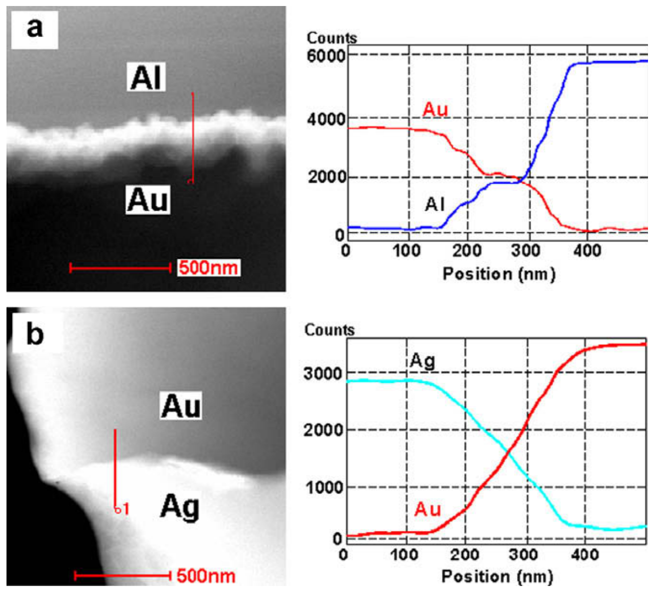

Fig. 12. STEM image and scanning EDS-testing result of the up-interface (i.e. Au/Al interface) for another suggested pattern from (a), that of the down-interface (i.e. Au/Ag interface) from (b).

in Fig. 10. The thickness of Au/Ag atomic diffusion at the connecting interface is about 220 nm from Fig. 10a, and the thickness of Au/Al atomic diffusion at the down-interface is only about 260 nm from Fig. 10b. The thickness of atom diffusion at up-interface and down-interface was balanced approximately, and the inter-metallic compound layer at the Au/Al interface has been improved to be only half of that at the traditional bonding approach.

Another approach is suggested as shown in Fig. 11. Similarly, the ultrasonic energy will reach the connecting interface first too, and results of STEM at up and down-interface are evaluated in Fig. 12. Fig. 12 shows that both atom diffusions at up and down-interfaces were about 200 nm, thus the performance of the FC bonding interfaces has been optimized accordingly.

The FC bonding strength of the suggested FC processes was about 80 g/bump by using the die shear testing with Dage 4000 bonding tester, and was increased by the optimized path of ultrasonic energy transmitting.

4. Conclusion

Ultrasonic vibration of the up-interface along the transmitting path of ultrasonic energy was bigger than that of the down-interface, thus led to the difference of atom diffusion at the up/down-interface in the FC bonding.

Based on the experimental statistics, the ratio of the ultrasonic energy conversion was obtained about 2.21:1 from the up-interface to the down-interface. According to the principle, two new approaches were suggested, and the suggested processes of the FC bonding can improve the bonding performance greatly.

Acknowledgments

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