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Ambient Temperature Ultrasonic Bonding of Si-Dice Using Sn-3.5wt.%Ag

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Ultrasonic bonding of Si-dice to type FR-4 printed circuit boards (PCB) with Sn-3.5wt.%Ag solder at ambient temperature was investigated. The under-bump metallization (UBM) on the Si-dice comprised Cu/Ni/Al from top to bottom with thicknesses of 0.4 μm, 0.4 μm, and 0.3 μm, respectively. The pads on the PCBs consisted of Au/Ni/Cu with thicknesses of 0.05/5/18 μm, sequentially from top to bottom. Solder was supplied as Sn-3.5wt.%Ag foil rolled to 100 μm thickness, and inserted in the joints. The ultrasonic bonding time was varied from 0.5 s to 3.0 s, and the ultrasonic power was 1400 W. The experimental results showed that reliable joints could be produced between the Si-dice and the PCBs with Sn-3.5wt.%Ag solder. The joint breaking force of "Si-die/solder/FR-4" increased with bonding times up to 2.5 s with a maximum value of 65 N. A bonding time of 3.0 s proved to be excessive, and resulted in cracks along the intermetallic compound between the UBM and solder, which caused a decrease in the bond strength. The intermetallic compound produced by ultrasonic bonding between the UBM and solder was confirmed to be $(Cu, Ni)_6Sn_5$.

Key words: Ultrasonic bonding, lead free solder, Sn-3.5wt.%Ag, joint reliability, intermetallic compound

INTRODUCTION

Among various Pb-free solders, Sn-3.5wt.%Ag (hereafter denoted Sn-3.5Ag) is a leading candidate for the electronics industry with applications to automotive circuits, computer motherboards, and other high reliability components. It is also considered to be a possible candidate for bump material on Si-dice in microelectronic packaging. Sn-3.5Ag has comparable wettability to Sn-3.5%Ag-0.7%Cu and shows reliable thermo-mechanical properties.[1]

For flip chip circuit assembly, bonding processes including thermal compression, thermosonic, and ultrasonic bonding have been introduced.[2–4] The thermal compression (TC) process is performed at high temperature with added pressure to bond chips. For example, in the case of a Sn-plated Cu bumps, a TC bonding temperature of 300°C with bonding force of 24.5 N for 10 s has been used.[2] However, the TC process carries a risk of thermal damage to both the chip and the PCB.[3] Furthermore, the bonding time must be longer than with other processes because the TC bond is generated through diffusion.[4] Meanwhile, thermosonic (TS) bonding is carried out at a chip temperature between 70°C and 150°C with ultrasonic power and pressure. This process operates at lower temperature and pressure than TC bonding. Additionally, the bonding time is shorter than that of TC.[5] However, the TS process still needs pre-heating for bonding.

Ultrasonic (US) bonding, however, is performed with the components initially at ambient (room)

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temperature, using only pressure and ultrasonic vibration. Thus, US bonding could minimize thermal damage to the chip and PCB substrate, and minimize overgrowth of intermetallic compounds (IMCs) compared to the TC and the TS processes. In addition the processing time could be shorter than those of TC or TS processes. If it were confirmed to be feasible, US bonding has a further advantage in that it is a fluxless assembly process[6–8] compared to reflow soldering, due to the removal of oxides and other contaminants from the metal surfaces by vibration.[9,10]

Related to the US bonding process, Au-wire bonding at ambient temperature has also been reported.[11] Flip chip packaging with solder bumps using pre-heated US bonding was also studied,[12] but reports of successful US bonding of multi-contact assemblies at ambient temperature are very rare.

This is a basic feasibility study of US bonding of Si-dice to PCBs at room temperature, which could be applied to flip chip bonding or to die bonding. For this work, rolled solder foil was used instead of solder bumps to evaluate the feasibility.

EXPERIMENTAL

Si-dice of 10 mm × 10 mm in size and PCBs of 10 mm × 15 mm were prepared for use as bonding samples. The under bump metallization (UBM) on the Si-dice consisted of Cu/Ni/Al with the thicknesses of 0.4/0.4/0.3 μm, sequentially from top to bottom. The UBM layers were deposited by electron-gun evaporator. The pads on the PCB substrate comprised 0.05 μm thickness of Au, 5 μm of Ni, and 18 μm of Cu, sequentially from top to bottom of the metallization. The metal layers of the pads were deposited by electroplating. The pads on the PCB were 300 μm in diameter and laid out in a 10 grid × 10 grid with a pitch of 800 μm. For simplicity in this basic study, the Si-dice were not patterned. Sn-3.5Ag solder was rolled to foil of 100 μm thickness and cut to the size of 10 mm × 10 mm. The sandwich system of "Si-die/rolled solder/FR4" was bonded by the US process at room temperature, that is, the process bonded the grid of 100 pads simultaneously.

Figure 1 presents a schematic of the US bonder and the bonding specimens for these experiments. The bonding parameters of US frequency, pressure and US power were fixed as 20 kHz, 23 N/cm^2 and 1400 W, respectively. Thus, in this study the bonding time was the main variable, and its effect on joint breaking force and other characteristics was examined. The US bonding time was varied in the range from 0.5 s to 3.0 s. In order to estimate the temperature profile in the joint during US bonding, a K-type thermocouple was placed between the Si-die and the PCB. Hotplate (HP) soldering at 250°C for 2.5 s was also performed as a reference process to compare with the US-bonding at ambient temperature.

Bond length was measured from the cross-sections of the joints using SEM and an image analysis program named "Image-Pro". Bonded length ratio (BR) was calculated by averaging the values from 10 measurements on 10 different pads. In order to analyze the IMC, the specimens after shear testing were etched in a solution of 10% HCl and 90% methanol. The composition of the IMC between Sn-3.5Ag solder and pad was analyzed by energy dispersive spectroscopy (EDS).

The joint breaking force was measured by a micro-shear tester (see Fig. 2). The shearing speed of the tip was 200 μm/s, and the gap between the tip and the PCB was 100 μm. The shear test was performed on 20 specimens for each bonding condition, and the average value from them was taken as the joint breaking force. Fracture surfaces of the shear tested specimens were analyzed using SEM and EDS.

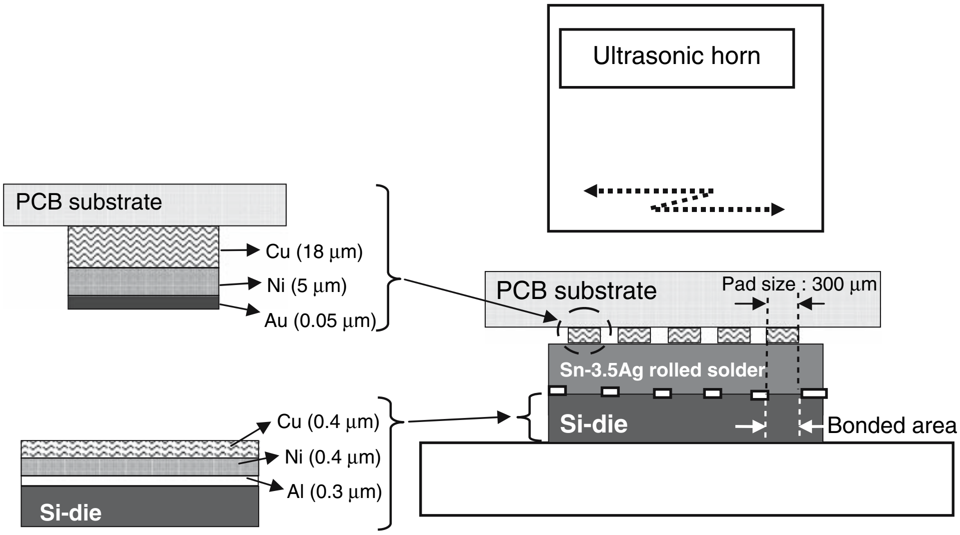

Fig. 1. Schematic diagram of the specimen arrangement for bonding.

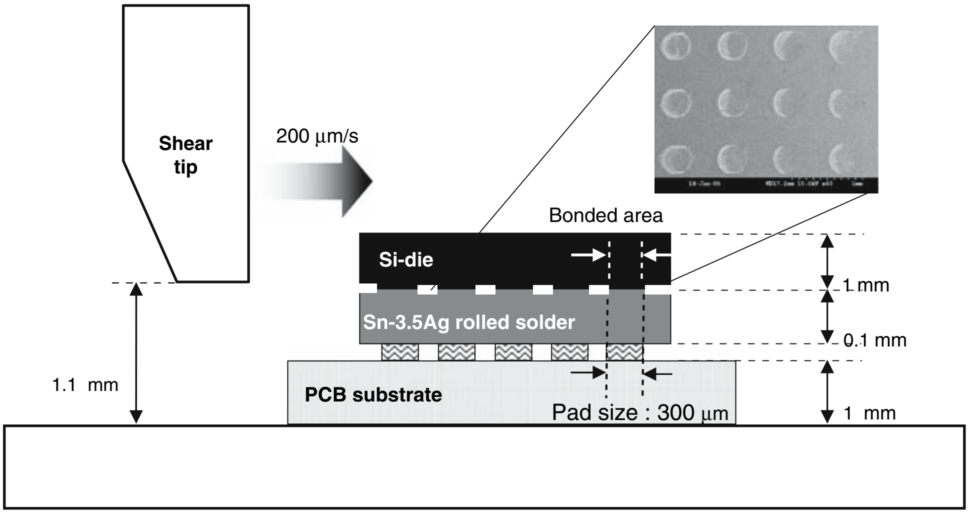

Fig. 2. Schematic diagram of shear testing.

RESULTS AND DISCUSSION

US Bonding at Ambient Temperature

Figure 3 shows cross sections of the “Si-die/Sn3.5Ag/PCB pads” sandwich system bonded by US at ambient temperature with different bonding times. Apparently, a metallurgical bond developed between 1.0 s and 3.0 s although some defects were observed along the bonding interfaces. Especially, the result from 2.5 s of US showed good bonding without defects, which was comparable to the joints made by HP soldering. Thus, US bonding at ambient temperature showed promise of being a feasible method to bond successfully without serious damage to Si-dice or joint interface.

Bonded length ratios between the Si-die and Sn-3.5Ag solder were measured, and the results are presented in Fig. 4. The bonded length ratio, BR(%), was calculated as $b/L \times 100$ (%), where b indicates bonded length and L is the pad diameter. In the “Si-die/Sn3.5Ag/PCB pads” sandwich system, both sides of the sandwich “Si-die/solder” and “PCB pads/solder” were bonded well without serious problem. However, in this study investigation was focused on the “Si-die/solder” interface. During shear testing, the fractures mostly occurred along the “Si-die/solder” interface, thus the “Si-die/solder” interface behaviour was understood to be more critical for joint reliability.

At 1.0 s of US bonding time the BR was 37%, and at 1.5 s it increased to 42.7%. At 2.5 s of bonding time, the BR reached 100%, and the joints showed a sound interface without any defects. This is comparable to the result from the HP soldering at 250°C

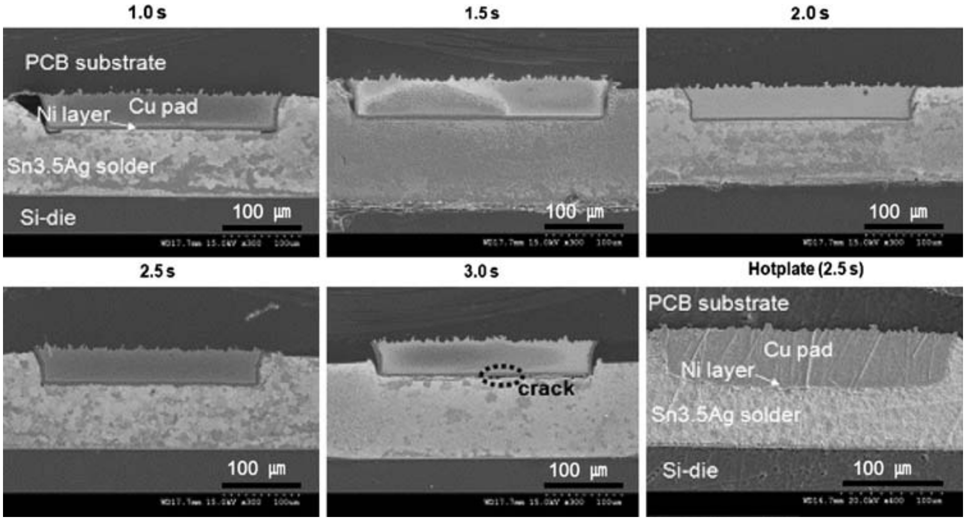

Fig. 3. Joints made by US soldering at various bonding times, compared to HP (hotplate soldering) (US frequency: 20 kHz, US power: 1400 W, HP temp.: 250°C).

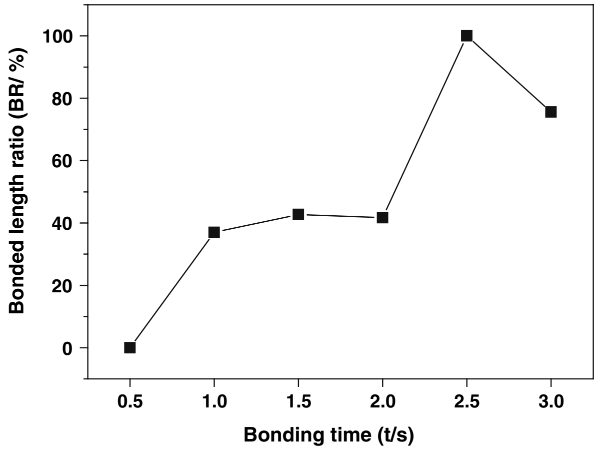

Fig. 4. Bonded length ratio between Si-die and Sn-3.5Ag solder (US frequency: 20 kHz, US power: 1400 W).

for 2.5 s which presented a good interface as well without cracks in the joints. With increasing US bonding time further to 3.0 s, cracks were generated in the joint so that the effective BR decreased to 75.6%. The reason was observed to be the fracture of the IMC, which was evidently caused by the mechanical fatigue from the continued US vibration after reaching the fully bonded condition.

Bonding interface appearance at higher magnification, typical cracks and IMCs between Si-dice and solder are illustrated in Fig. 5. The bonding interfaces at 1.0 s appeared relatively rough, and at 1.5 s became flatter. It appeared that the bonding interfaces were flattened by abrasion due to horizontal vibration during ultrasonic application.

The IMC observed between the Si-die and Sn-3.5Ag solder at 2.5 s of US bonding time was analyzed as 48.10 at.% Cu, 9.44 at.% Ni, and 42.46 at.% Sn, and it was estimated as (Cu, Ni)$_6$Sn$_5$. IMC from the HP soldering was also (Cu, Ni)$_6$Sn$_5$ which comprised 40.71 at.% of Cu, 18.82 at.% Ni, and 40.47 at.% Sn. Thus, it is evident that the IMC produced in solid state by US bonding is almost the same as the IMC by HP soldering which involved melting of the solder. In Fig. 5, the cracking is shown which occurred along the brittle IMC of (Cu, Ni)$_6$Sn$_5$ in case of excessive bonding time of 3 s.

Microstructure of US Bonded Joints

Figure 6 shows the comparison of microstructures between Sn-3.5Ag solder joints bonded by US and HP. The two microstructures were similar, and they consisted of a β-Sn matrix with fine particles dispersed in orderly networks, the well known characteristics of Ag$_3$Sn.[13]

Temperature profiles during US bonding of Sn3.5Ag were measured, and these are presented in Fig. 7. The US was applied to the specimen for the specified bonding time, and then stopped allowing natural cooling. The temperature profiles show a rapid increase up to the peak temperature and slow cooling. The peak temperature increased with bonding time. Specifically, at 0.5 s of bonding time, the peak temperature was 32°C, and it reached 80°C at 3.0 s. This peak bonding temperature is well below the melting point of Sn-3.5Ag, 221°C. In a previous study of Al-wire bonding, the peak temperature during US bonding was reported as approximately 180°C[14] which is much lower than the melting temperature of aluminium, 660°C, and thus consistent with the present result.

US bonding is defined as a solid state bonding process without melting.[15] In solid phase bonding, the metallurgical union of the components occurs by solid state diffusion, which may also result in IMC growth.[16] During the thermal aging of a solder joint, for example at 155°C, interfacial IMC will typically

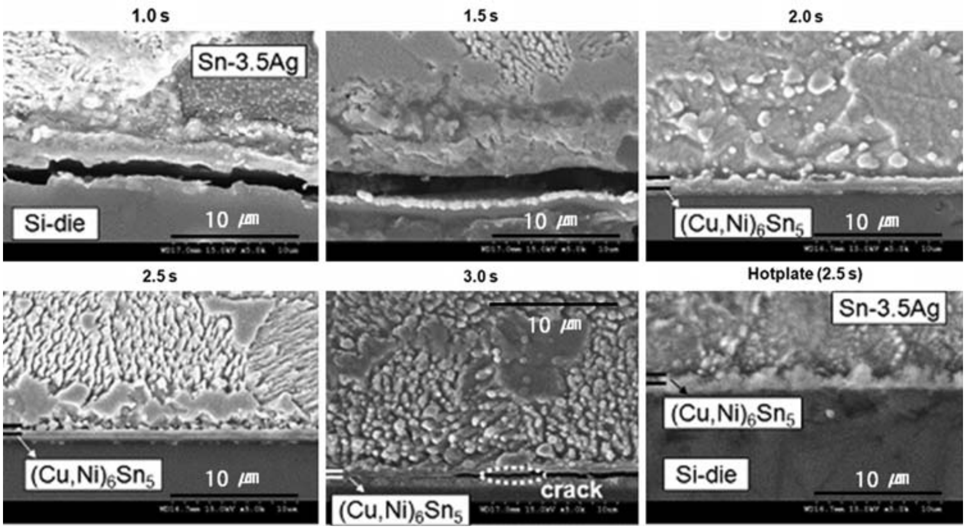

Fig. 5. IMCs between Sn-3.5Ag and Si-dice at various US bonding times and HP (US frequency: 20 kHz, power 1400 W).

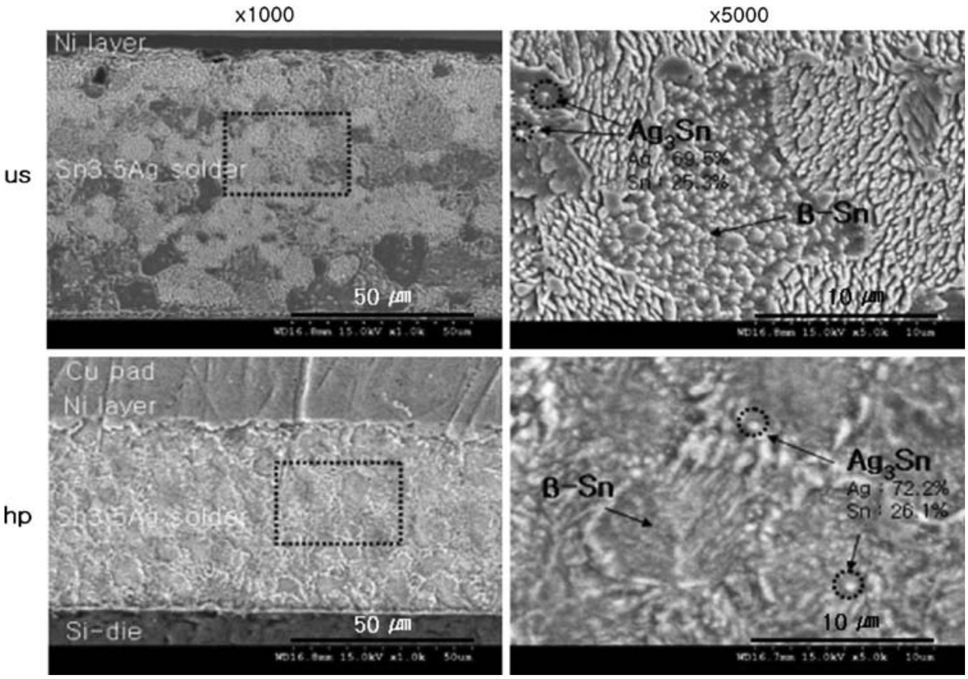

Fig. 6. Sn-3.5Ag solder bulk structures formed by US and HP soldering (US Frequency: 20 kHz, US power: 1400 W, bonding time: 2.5 s, HP temp.: 250°C).

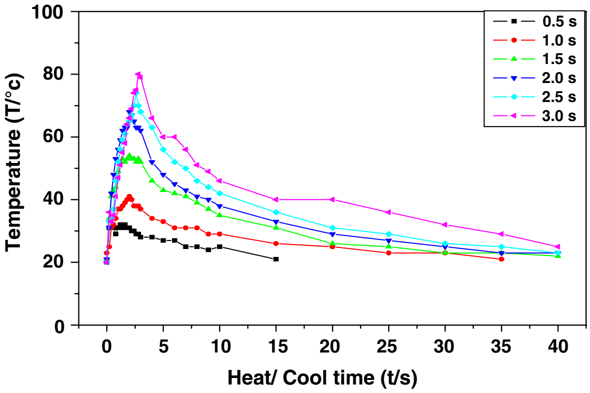

Fig. 7. Interfacial temperature profiles during the US bonding (US frequency: 20 kHz, US power: 1400 W).

grow in the solid state between solder and pad.[17] Thus, the IMC can be produced without melting of solder. In this experiment the temperature measurement was not expected to be perfect, since heat loss could occur through the solder and PCB into air. According to a study of the surface temperature measurement for a cellular plastic, the highest heat loss was found to be 36.1°C.[18] Although that experiment was not identical to the present one, it was taken as an example to guess the heat loss. Thus, in Fig. 7 real bonding temperature could be a little higher than our measurement, but was definitely well below solder melting temperature.

The thickness of the IMC layer between the Sn-3.5Ag and the Si-die after US bonding was evaluated. At 1.0 s of bonding time, the thickness of IMC was 0.63 μm, and at 2.5 s it increased to 0.78 μm. The latter value is much thinner, i.e. as much as 40% less, than that produced by HP soldering, 1.27 μm. The thicker IMC in the HP soldering clearly reflects the higher bonding temperature of 250°C compared to the peak temperature of 74°C in US bonding. In addition, during US bonding, the horizontal vibration at the faying surfaces results in rather flat and self-limiting growth of the IMC layer.

Joint Breaking Force and Failure Analysis

Figure 8 presents joint breaking forces (bonding strength) of the US bonded joints versus bonding time. At 0.5 s the bonding time was too short to get a bonded joint. With increasing bonding time to 2.0 s, the joint breaking forces increased to 49 N, and at 2.5 s it reached the maximum value of 65 N. However, at excessive bonding time of 3.0 s, it decreased drastically to 34 N. The reason for drastic decrease was found to be cracks produced in the interfacial IMC (see Fig. 5).

A similar trend of bond strength with US bonding time was previously reported for gold wire ball bonding on Al pads, where the substrate temperature was 34°C, and US frequency, 100 kHz.[19] In that study, the shear strength of the bonded Au balls increased with US bonding time up to the optimal time of 12 ms, and over 12 ms the strength decreased. An analogous study was also reported by Jeng and Horng[20] for wedge bonding of Al wire.

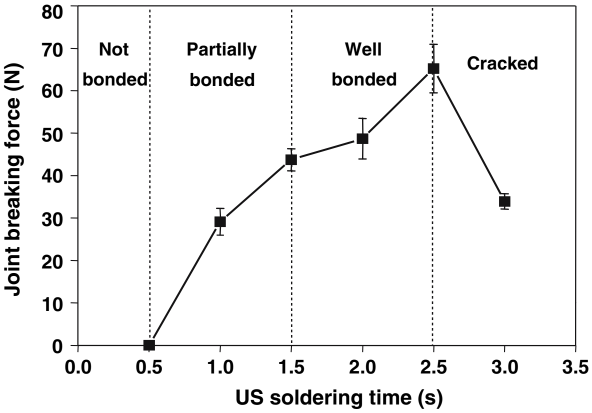

Fig. 8. Joint breaking forces between "Si-die/Sn-3.5Ag solder" by US soldering.

These results tend to confirm that an optimal bonding time for US is important to avoid interfacial cracking and strength decrease.

The bonded length ratio, BR, which has close relationship with bonding time, is an important influence on the joint breaking force. With increase of the US time to 1.0 s and 2.5 s, the BR increased to 37% and 100%, and the strength also improved to 29 N and 65 N, respectively. At US bonding time of 3.0 s, the BR decreased to 75.6%, and the strength decreased to 34 N as well. However, the BR did not correspond completely to the breaking force since the strength can be also affected by other metallurgical factors such as the extent of IMC growth.[21] In a case of flip chip bonding, it was reported that the bond shear strength increased with IMC thickness up to 1 μm.[21] In this study the joint breaking force also increased with IMC thickness up to 0.78 μm at 2.5 s, and hence the breaking force was affected by IMC thickness as well as the BR.

The fracture surfaces of the Si-dice after shear test are illustrated in Fig. 9. At higher magnification, the fracture surfaces consisted of two kinds of areas, "A" (white) and "B" (dark grey). The results of the chemical analysis by EDS confirmed that area "A" comprised 94.44 at.% Sn, 2.43 at.% Ag, 3.13 at.% Cu, which indicates the "A" was mostly Sn3.5Ag solder. Meanwhile, the area "B" revealed 72.03 at.% Cu, 27.97 at.% Ni, which are the components of two thin UBM layers. Therefore, the area "A" was produced by ductile fracture along the solder, and the area B resulted from brittle fracture through the UBM. The bonding time of 2.5 s which gave the maximum joint breaking force showed almost entirely ductile fracture along the solder.

Based on the footprints in Fig. 9 (see lower magnification), a mechanism of the bonding sequence in this process has been formulated (see Fig. 10). Specifically, at the beginning of US application (Fig. 10a) the rolled Sn-3.5Ag solder has some roughness resulting from the rolling process, and the projecting asperities start to bond with the UBM on the Si-die. The contact area between solder and the UBM becomes softened due to the US energy.[22] The bonded area propagates from the outside edge towards the centre of each bond pad as result of bonding pressure, as outlined by Mindlin's theory[23] (see Fig. 10b). Growth of the interfacial IMC is evidently promoted by US-enhanced diffusion. At the optimal bonding time of 2.5s, the whole area between solder and the Si-die becomes bonded (Fig. 10c), which leads to drastic reduction in the relative motion at the interface. The inability of the interface to absorb US energy by slip once it is fully bonded results in a major increase in the alternating stress amplitude in the interface region.[20] The continued application of vibratory motion, therefore, causes the bond to fail by fatigue, and results in cracks along the IMC (Fig. 10d). Similar bonding mechanisms have been reported for thermosonic wire ball bonding by the authors,[24] and for wire wedge bonding during US by Harman and Albers.[25]

CONCLUSIONS

The feasibility of US bonding at room temperature was investigated in a basic study for flip chip packaging application. Si-dice and PCB substrates were bonded without heating by US using a Sn-3.5Ag solder interlayer. As a reference joint to compare with US, hotplate soldering at 250°C for

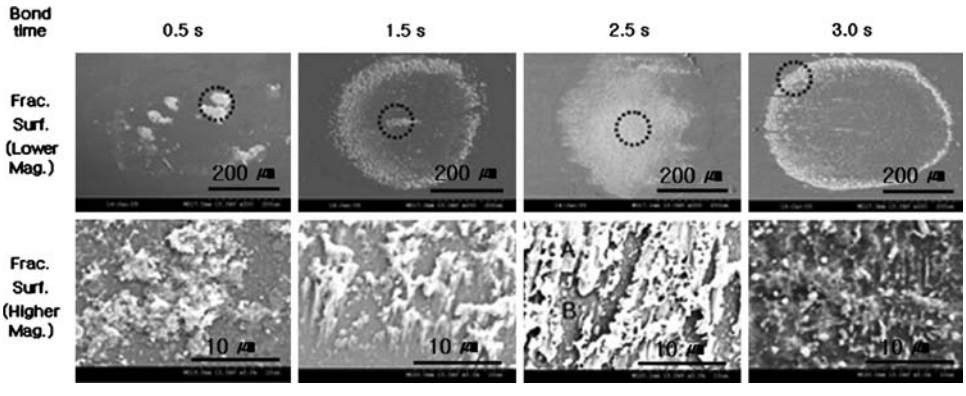

Fig. 9. Shear test fracture surfaces of Si-dice at various US soldering times (US frequency: 20 kHz, US power: 1400 W).

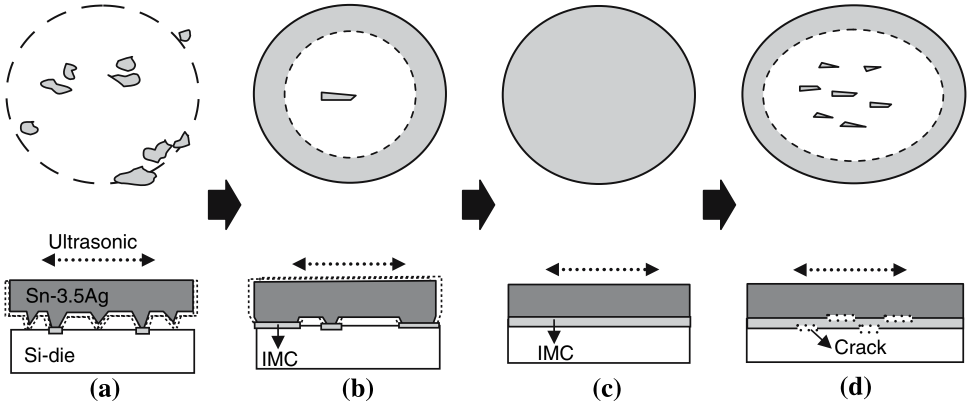

Fig. 10. Schematic mechanism of the US soldering (top view and cross-sections of interface).

2.5 s was also performed. The main results can be summarized as follows.

(1) US bonding of "Si-die/Sn-3.5Ag/FR-4" was achieved at ambient temperature, and the bonding length ratio increased with bonding time up to 2.5 s, and at the optimal time of 2.5 s the bonding length ratio reached 100%.
(2) The IMC produced by US between the solder and the UBM on Si-die was $(Cu, Ni)_6Sn_5$, and this is similar to what is normally seen in the general reflow process with melted solder. The thickness of the IMC produced by US bonding at 2.5 s became 0.78 μm, which is around 40% less than that of the hotplate soldering.
(3) The joint breaking force of US bonded joint increased with bonding time and reached to a maximum value of 65 N at 2.5 s. However, at the excessive bonding time of 3.0 s, the joint breaking force decreased to 34 N due to cracks generated along the interfaces.
(4) The specimens with maximum strength of 65 N showed mostly ductile fracture along the solder. On the other hand, the ones with excessive bonding time of 3.0 s revealed mostly brittle fracture along between the IMC and the UBM.

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