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Characteristics of Thermosonic Anisotropic Conductive Adhesives (ACFs) Flip-Chip Bonding

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In recent years, Anisotropic Conductive Films (ACFs) have been widely used in microelectronic packaging applications due to their potential advantages, which include low processing temperatures, high-resolution capabilities, and compatibility for nonsolderable materials. In this study, we investigated a novel, thermosonic ACF flip-chip bonding process using ultrasonic vibration. The thermosonic ACF flip-chip bonding was characterized in terms of adhesion strength and electrical property in comparison with conventional thermo-compression ACF bonding. ACF has a nickel particle with a 4-μm diameter, and its recommended thermo-compression bonding conditions were 453 K for bonding temperature and 10 s for bonding time. The investigated thermosonic flip-chip bonding conditions were 433 K and 453 K for bonding temperature and 0.5 s and 1 s for bonding time at each temperature, respectively. In addition, a cross-section of the ACF joint was observed using scanning electron microscopy. As a result, the developed thermosonic flip-chip bonding process showed good electrical and mechanical characteristics, as compared with those of the conventional thermo-compression bonding process. In the future, we expect that a thermosonic flip-chip bonding method with ACFs can be effectively applied to reduce the bonding temperature and time.
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1. Introduction

Anisotropic conductive films (ACFs) have been used in a wide range of applications for their versatile properties, such as thermal stability, mechanical response, electrical resistance, and adhesive characteristics. The high interconnection reliability and fine pitch capability of ACFs have rapidly progressed since the early 1980s as LCD technologies.[1)] ACFs are polymeric composites of polymer matrices and electrically conductive fillers. Polymer matrices have excellent mechanical properties due to their adhesive characteristics and dielectric properties. The conductive fillers in ACFs provide unidirectional electrical conductivity on the Z-axis, which is produced by mechanically squeezed conductive fillers between component electrodes and the corresponding pads on the substrate.[1,2)] ACFs offer a large set of potential advantages over conventional solder, including low processing temperature, high-resolution capability for fine pitch interconnection and greater compatibility with non-solderable materials for flip-chip packaging applications.[3–5)] For flip-chip bonding with ACFs, the thermo-compression (TC) bonding process is commonly used, as shown in Fig. 1. The TC bonding technique uses a combination of temperature and pressure to form interconnections. However, the TC bonding process often poses problems such as large thermal deformations of the assembly, cost and long process time; therefore it is necessary to find another method to reduce the bonding temperature, time, and pressure.

Thermosonic (TS) bonding replaces a part of the thermal bonding energy with ultrasonic energy. This substitution allows metal-to-metal interconnections to be made within seconds, at temperatures below 423 K and at pitches less than 30 μm. Due to its low processing temperature, simplicity, and fast processing time, the TS bonding process is widely used in microelectronic packaging technologies.[6–8)]

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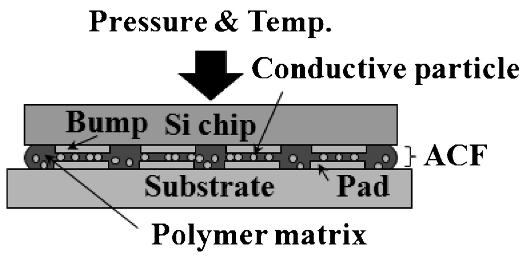

Fig. 1 Schematic diagram of typical thermo-compression (TC) ACF flip-chip bonding.

In previous work,[9)] ACF chip-on-glass (COG) bonding using thermosonic energy has been introduced. After the humidity storage test (333 K, 90%RH, 100 h) and thermal shock storage test (243 K, 1 h ↔ 353 K, 1 h, 10 Cycles), it can be known that the bonding temperature and bonding time could be reduced from 483 K to 472 K and from 3 s to 1 s, respectively, comparing with TC bonding conditions.

In this study, a novel TS ACF flip-chip bonding process using ultrasonic vibration was investigated. Horizontal ultrasonic vibration was used for flip-chip bonding, and the mechanical and electrical properties were investigated in comparison with those of conventional TC ACF bonding.

2. Experimental

2.1 Materials

Figure 2 shows a configuration of a silicon (Si) chip and a Si substrate. For the fabrication of the Si chip and substrate, a silicon dioxide (SiO_2) layer 500 nm in thickness was formed on an Si wafer, and then a titanium (Ti) layer 50 nm in thickness and a copper (Cu) layer 300 nm in thickness were subsequently sputtered on the SiO_2 layer. Another layer of SiO_2 500 nm thickness was then deposited on the Cu layer and patterned by photolithography. A Ti layer 50 nm in thickness and a Cu layer 500 nm in thickness were sub-

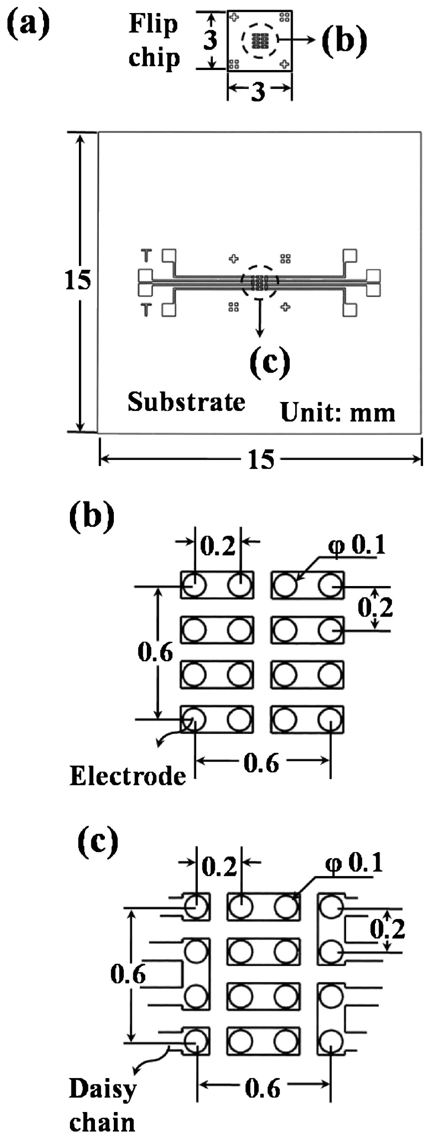

Fig. 2 Configuration of (a) the flip-chip and substrate and the electrode pattern of (b) the flip-chip and (c) substrate.

sequently sputtered on the SiO_2 layer. After the photolithography process, Cu bumps were electroplated on the sputtered Cu layer. The Ti and Cu layers were then selectively etched for the patterning of the daisy-chain structure after another photolithography process. The Si chip and substrate dimensions were $3 \times 3 \times 0.67\,mm^3$ and $15 \times 15 \times 0.67\,mm^3$ with 16 Cu bumps, respectively. The bump dimension was 100 µm in diameter and 12 µm in thickness, and the bump pitch was 200 µm. The ACF was an epoxy-based adhesive film 25 µm in thickness, and it contained Ni particles 4 µm in diameter as a conductive filler (Model: CP9731N, Sony Chemical Co., Japan). The recommended curing conditions of the ACF were 453 K for bonding temperature, 10 s for bonding time, and 6 MPa for bonding pressure. Table 1 shows the specifications of the ACF.

2.2 Differential scanning calorimetry (DSC) analysis

We used differential scanning calorimetry (DSC, Q100, TA instrument, US) to investigate the curing behavior of the ACF used in this study. The curing degree of the epoxy resin during the processing cycle was measured using the DSC in

Table 1 ACF specifications.

Items		Content
ACF	Color	Gray
	Thickness	25 µm
	Adhesive	Thermo setting resin
	Conductive Particle	Ni
Base Film	Color	White
	Thickness	50 µm

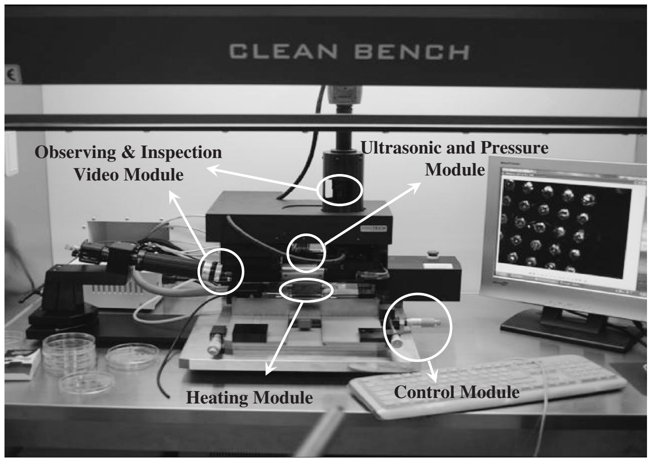

Fig. 3 Experimental setup for the TS ACF flip-chip bonding test.

dynamic heating mode. The dynamic mode measurements were obtained at various temperatures from room temperature to 573 K at a heating rate of 20 K/min. The measurements were taken with samples enclosed in an aluminum DSC pan in a nitrogen gas environment.

2.3 Thermosonic ACF flip-chip bonding test

TS ACF flip-chip bonding was carried out using an ultrasonic bonder (Model: Fineplacer-LAMDA, FINETECH Co., Germany), as shown in Fig. 3. Figure 4 shows the TS ACF flip-chip bonding process. The Si chip and substrate were carefully cleaned using an organic solvent before the bonding process in order to remove any contaminants. The ACF was then cut to the correct size to cover the bonding area and was pre-bonded to the substrate using a light pressure of 0.5 MPa and a low temperature of 343 K for a short period of time. Next, the Si chip was mounted and reflowed with the temperature profile and ultrasonic vibration. Table 2 shows the experimental conditions for the TC and TS ACF bonding tests. After completing the bonding test, the assembly was mounted in cold epoxy and mechanically polished for microstructural observation. The assembly was then die-sheared using a bonding tester (PTR-1000, Rhesca Co.) with a 50-Kgf load cell. The probe width and gap were 10 mm and 12 µm, respectively. The shear rate was 0.8 mm/s (JESD22-B117A). The total electrical resistance of the assembly was evaluated using a daisy-chain structure.

3. Results and Discussion

3.1 Thermal characteristics of ACF

The curing behavior of ACF was investigated using

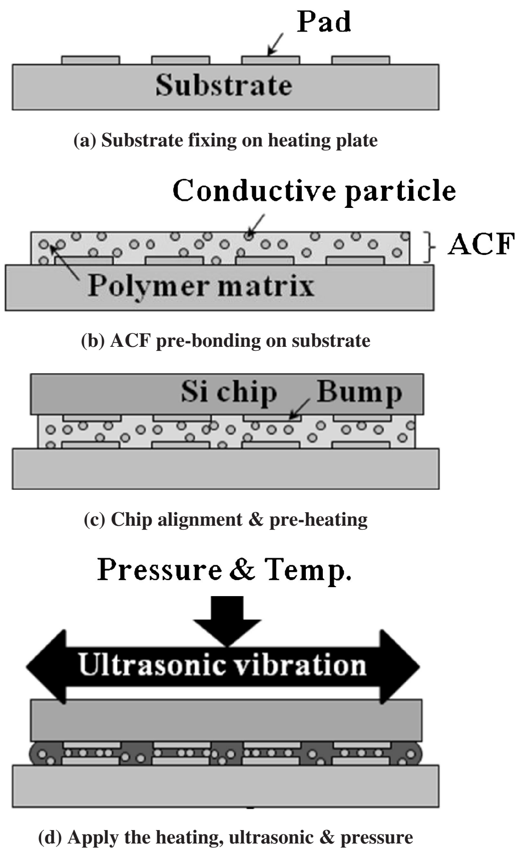

Fig. 4 TS ACF flip-chip bonding process.

Table 2 ACF flip-chip bonding conditions.

Thermo-compression Bonding (TCB)				
Temp. (K)	453			
Bonding Time (s)	10			
Pressure (MPa)	6			
Thermosonic Bonding				
	TSB-1	TSB-2	TSB-3	TSB-4
Temp. (K)	453		433	
Ultrasonic Time (s)	1	0.5	1	0.5
Pressure (MPa)	6			

dynamic mode DSC. Figure 5 shows the results of the DSC scan at a heating rate of 20 K/min. The onset of curing occurred at about 380 K, and the peak temperature of the epoxy resin was 409 K. The curing kinetic of the epoxy was investigated using a dynamic heating model. As dynamic heating model, Kissinger[10] and the Flynn-Wall-Ozawa[11,12] model were used. Assuming that the extent of the reaction, α, is proportional to the heat generated during the reaction, the reaction rate can be expressed as a function of conversion and temperature:

$$\frac{d\alpha}{dt} = K(T)f(\alpha) \tag{1}$$

where $d\alpha/dt$ is the reaction rate and $f(\alpha)$ is a function of the conversion. $K(T)$ is the reaction rate constant.

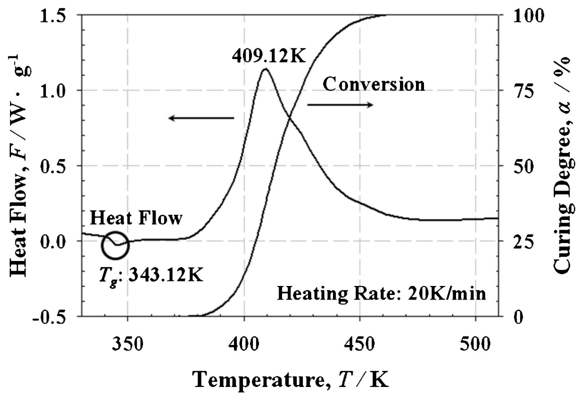

Fig. 5 DSC results at a heating rate of 20 K/min.

In TS ACF bonding, ACF can be rapidly heated using ultrasonic vibration. The main component of the ACF polymer is a viscoelastic material, which exhibits behavior somewhere in between that of purely viscous and purely elastic materials. Viscoelastic material, including polymers, is largely deformed when it approaches the glass transition temperature (T_g). At this temperature, the chains of the polymer relax, and its complex modulus, which is composed of the storage and loss moduli, decreases.[13,14] The complex modulus represents the stiffness of a viscoeleastic material and is proportional to the energy stored during a loading cycle, representing the elastic portion. The loss modulus represents the viscous portion and is defined as being proportional to the energy dissipated during one loading cycle. For example, the loss modulus represents energy lost as heat and is a measure of the vibration energy converted during vibration that cannot be recovered. Therefore, it is expected that viscoelastic material may generate a large amount of heat by ultrasonic vibration energy.[15]

3.2 Thermosonic ACF flip-chip bonding characteristics

To investigate the effect of ultrasonic vibration energy on TS ACF bonding characteristics, TS ACF flip-chip bonding was conducted using ultrasonic vibration, varying process-related parameters such as bonding temperature and ultrasonic time. Figure 6 shows the cross-sectional SEM micrograph of the flip-chip assembly bonded by the conventional TC ACF bonding process. Bonding conditions were 453 K for bonding temperature, 10 s for bonding time and 6 MPa for bonding pressure. Conductive particles were trapped and squeezed between the chip and substrate bump, and they formed a good electrical conduction path by their physical/mechanical contacts. The squeezed particle size was about 3 µm in height.

EDS analysis confirmed that the squeezed particle was composed of Ni. Figure 7 and Figure 8 show the cross-sectional SEM micrographs of a flip-chip assembly bonded by ultrasonic vibration energy. All TS flip-chip assemblies also formed good electrical conduction paths by the intimate contact between the chip and substrate bump. We observed that the conductive particle penetrated both the upper and lower Cu bumps, and the squeezed particle size was less than 3.5 µm. It is thought that this penetration is caused by ultrasonic vibration with cyclic displacement. Therefore,

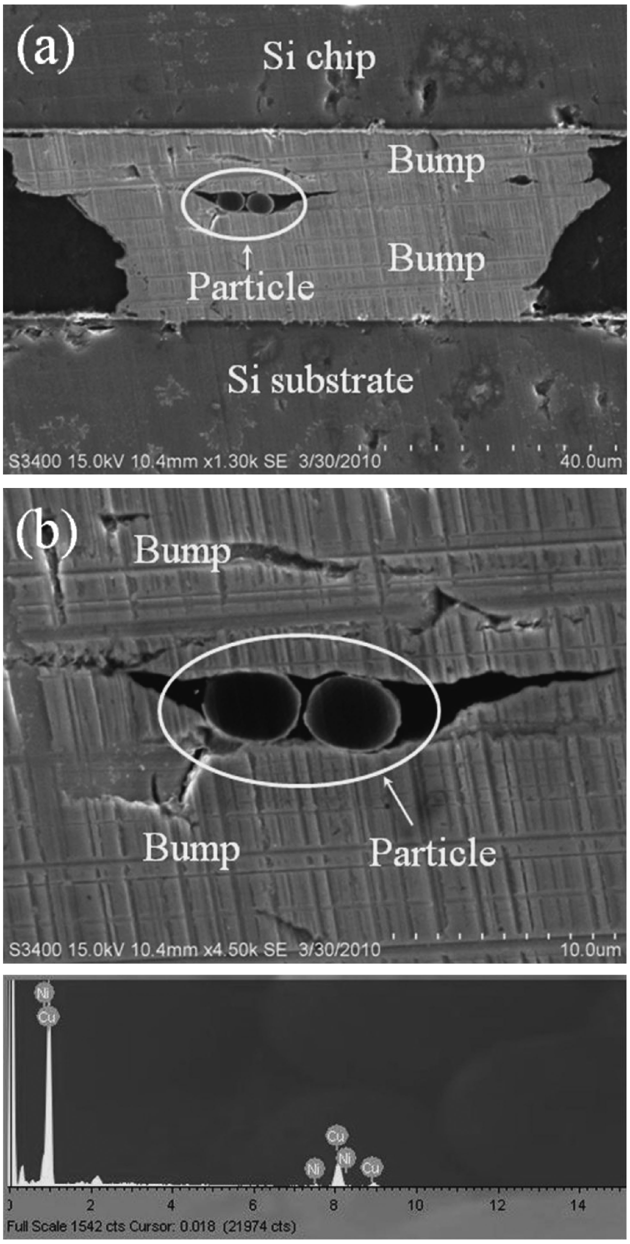

Fig. 6 SEM-EDS analysis of the flip-chip assembly bonded by the conventional TC ACF bonding process (TCB). (a) SEM micrograph and (b) EDS analysis.

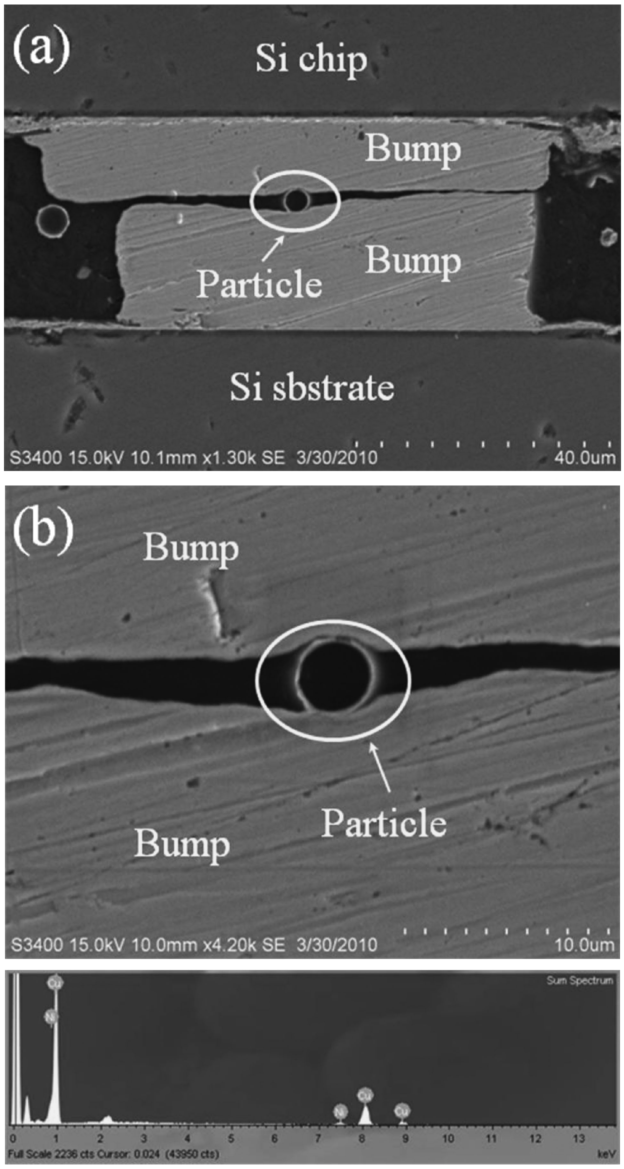

Fig. 7 SEM-EDS analysis of the TS flip-chip assembly with 0.5 s (TSB-2) for bonding time at 453 K for bonding temperature. (a) SEM micrograph and (b) EDS analysis.

good electrical characteristics were expected for the TS ACF flip-chip assembly due to the intimate contact involved.

Figure 9 and Figure 10 show the fracture surfaces after a die shear test with TC and TS bonding assemblies, respectively. A fracture initially occurred near the interface between the Si chip and the ACF, and it propagated along their interface. As shown in Fig. 9(b) and Fig. 10(b), the trace of fractured Cu bumps on the Si chip is shown on the Cu bumps of the Si substrate. TS bonding assemblies showed a greater amount of these traces, when compared to TC bonding assemblies, possibly because the amount of deformation of the Si chip side bump during TS bonding was larger than that of the TC bonding assembly; this difference was due to the ultrasonic vibration energy used in the TS procedure. Moreover, its stiffness was weakened by the ultrasonic vibration, and it resulted in the fracture at the Si chip bump.

Figure 11 shows the die-shear strength results. Although TS flip-chip bonding showed a somewhat lower shear strength, the maximum difference between TC and TS shear strengths was small. The shear strength was 65 N for TC bonding and ranged from 57.5 N (TSB-4) to 61.9 N (TSB-1) for TS bonding. The adhesive joint strength was influenced significantly by bonding conditions, such as temperature, time, and pressure. To achieve good joint strength properties, an adhesive bonding strength should be confirmed through proper ACF curing. As shown in Fig. 11, the bonding temperature and time decreased to 433 K and 0.5 s, respectively; therefore, ACF was sufficiently cured by the additional heat generation, which resulted from the cyclic ultrasonic vibration used in the TS process.

Figure 12 shows the total electrical resistance of the FC assembly bonded by the TC and TS bonding processes. The

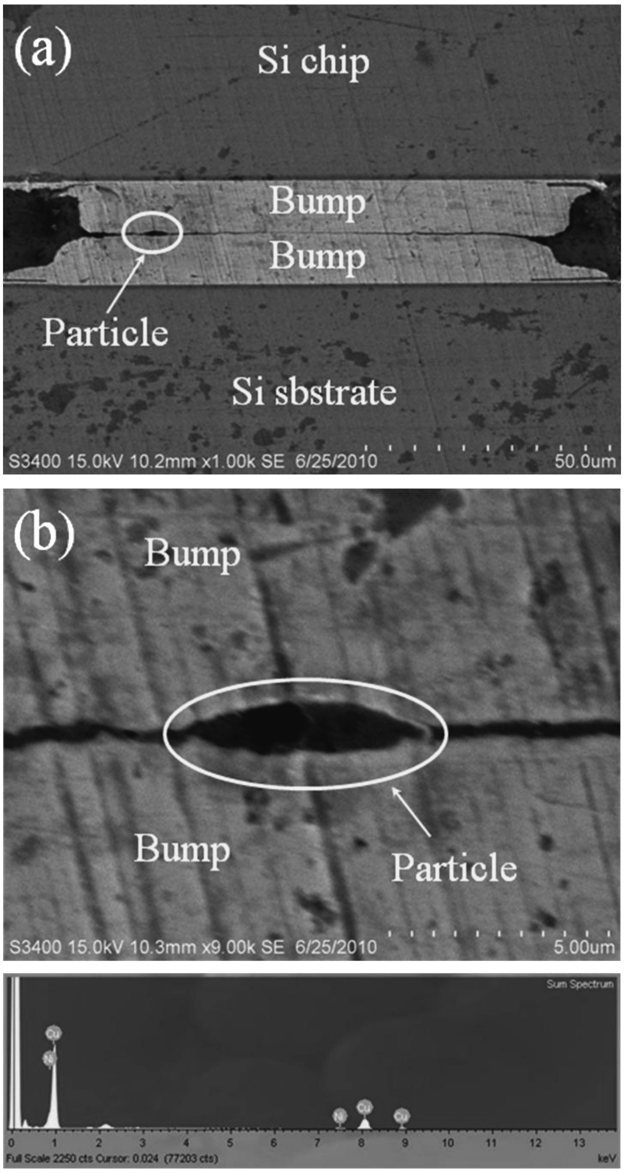

Fig. 8 SEM-EDS analysis of the TS flip-chip assembly with 0.5 s (TSB-4) for bonding time at 433 K for bonding temperature. (a) SEM micrograph and (b) EDS analysis.

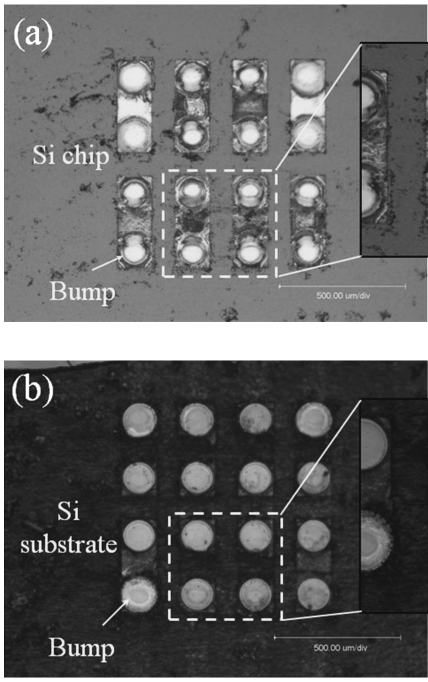

Fig. 9 Fracture surfaces of (a) a chip and (b) substrate after TC ACF flip-chip bonding (TCB).

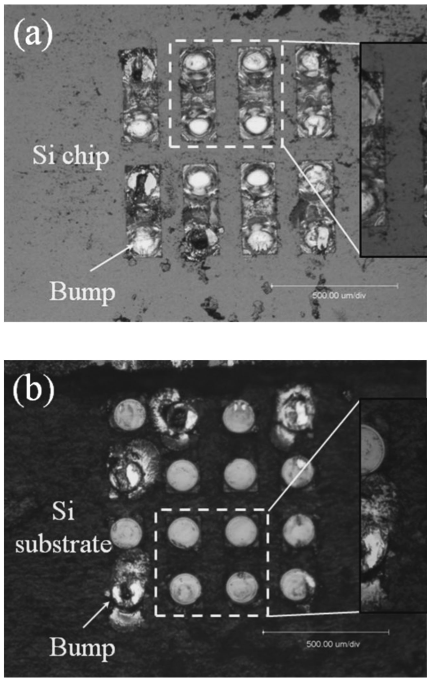

Fig. 10 Fracture surfaces of (a) a chip and (b) substrate after TS ACF flip-chip bonding with a 433 K bonding temperature and a 0.5 s bonding time (TSB-4).

electrical resistance characteristics of each process were obtained from an average of five different FC assemblies. The electrical resistance of the TC ACF flip-chip assembly was 31.3 Ω, which was much higher than that of the TS ACF flip-chip assembly. TSB-1, one of the TS ACF flip-chip bonding assemblies with a bonding time of 1 s at a bonding temperature of 453 K, showed much lower electrical resistance (about 11.7 Ω) than other TS bonding assemblies (14.8 Ω for TSB-2, 14.4 Ω for TSB-3 and 36.4 Ω for TSB-4). It is thought that higher bonding temperature results in higher curing extent for the binder, the binder hence becomes stiffer with higher modulus.[16] Therefore, the squeezed conductive particles could be maintained intimate mechanical contact condition and electrical resistance decreased with increasing of bonding temperature. Additionally, the electrical characteristics improved with an increased bonding time at the same bonding temperature.

4. Conclusion

We investigated a novel thermosonic (TS) ACF flip-chip bonding process using ultrasonic vibration. We also evaluated the mechanical and electrical characteristics of the TS flip-chip assembly. Due to the cyclic ultrasonic vibration, a good electrical conduction path was formed by the intimate contact between the chip and substrate bump in all TS flip-

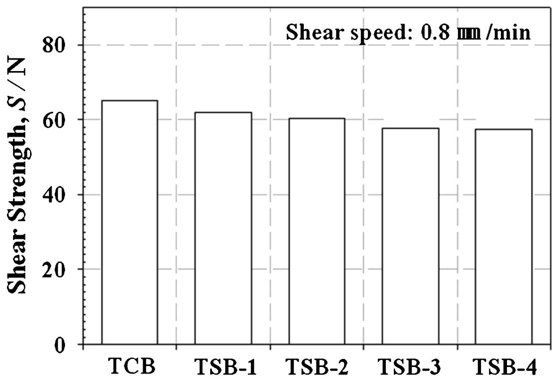

Fig. 11 Shear strengths of TC and TS ACF flip-chip assemblies.

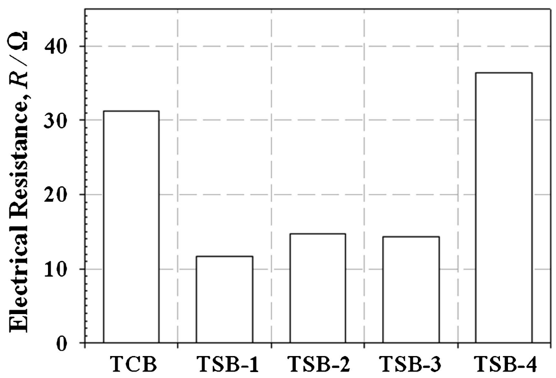

Fig. 12 Total daisy-chain electrical resistances of TC and TS ACF flip-chip assemblies.

chip assemblies. The TS assemblies showed good electrical characteristics, as compared with thermo-compression (TC) flip-chip assemblies. In addition, the shear strength of TS bonding in this study was just as high as that of TC bonding. As a result, the TS ACF flip-chip bonding method can be effectively applied to reduce both bonding temperature and time. The ACF ultrasonic process needs to be developed to further enhance the conversion capacity of the ultrasonic dissipation energy into heat.

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