Gold to gold thermosonic bonding
Characterization of bonding parameters

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Abstract

The aim of this study is to characterize a die attach method suitable for harsh environment as well as high reliability applications. Au-Au thermosonic bonding was selected. Due to high melting temperature of gold, this technique suited well for high temperature applications. In addition, thermosonic bonding introduces ultrasonic energy to soften the material joint and enhance the bonding at the metallic interface. This allows reducing the bond temperature and force. Initial characterization focuses on the effects of bonding parameters – ultrasonic energy, bond force and bond temperature – to relative bond strength. Bonded components were subjected to die shear test to measure bond strength. Cross section and SEM were used to inspect the bond interface and Au-bump deformation. Thermal shock cycling (TSC) test performed from -20 to 200^{o}C was carried out to examine bond reliability. Experiment results were compared to thermocompression bonding to evaluate the improvement of thermosonic bonding. Initial experiments showed that we obtained successful bonding at temperatures as low as 50^{o}C. Maximum shear strength measured was around 400 g/bump. TSC significantly reduced bond strength, but high shear force remained after TSC ranging from 82 to 140 g/bump. Therefore, thermosonic bonding offers high reliability, low temperature and low force process.

Key words: thermosonic bonding, thermocompression, gold stud bump, high temperature application, high reliability, low temperature bonding

I. Introduction

Flip chip interconnection is an attractive technique due to its advantages in electronic component packaging: high I/O interconnection, low resistance and inductance and high reliability compared to traditional wire bonding. Currently, there are many flip chip techniques, such as solder joining, adhesive bonding and direct metal bonding.

Solder joining offers high reliability, but the process is complex. In addition, due to low melting temperature of solder, this technique is not suitable for high temperature applications. Adhesive bonding offers low temperature process and high interconnection density, but low conductivity, as well as limited high-temperature stability.

Direct metal bonding solves the problems of solder joining and adhesive bonding, offers high conductivity and high reliability interconnects and high-temperature stability. Mainly technologies for direct metal bonding are SLID (Solid Liquid Interdiffusion), thermocompression and thermosonic bonding.

Although SLID bonding offers reliable interconnect with demonstrated bond strength up to 60 MPa at room temperature and high temperature stability up to above 350^{o}C, the process requires high bonding temperature and time [1]. Thermosonic and thermocompression can solve this problem. However, these techniques imply application of significant bonding force. In a previous study, Au-Au thermocompression has been investigated [2]. The major findings from that study, was the existence of a threshold temperature of 150^{o}C and a threshold bond force of 30 g/bump required to obtain reliable bonded interconnects.

Thermosonic bonding introduces ultrasonic energy to soften the material joint and promote metallic joining the interface [3]. This allows reducing assembly temperature and force compared to thermocompression bonding. Low temperature bonding is important for materials undergoing phase transitions. Examples are piezoelectric or ferromagnetic materials, as well as polymer materials. In addition, ultrasonic vibration of chip in bonding process removes residue and breaks metal oxidation surfaces. This allows increasing the number of possible material choices, and also increases bond strength.

In this study, we characterized Au-Au thermosonic bonding. The effects of bond parameters ultrasonic energy, bond force and bond temperature to relative bond strength were investigated. Bond components were subjected to die shear test to examine bond strength. Cross section and SEM were used to inspect bond interface and Au-Au bump deformation. Thermal shock cycling was carried out to evaluate bond reliability.

II. Experimental method

1. Samples preparation

Silicon dies were bonded to silicon substrates. Both the dies and substrates were sputter coated with gold thin film layer. Specifications of dies and substrates are given in Table 1. The dies and substrates were not patterned, since this study only focuses on mechanical properties of the joints created during bonding.

Table 1: Die and substrate specifications

	Wafer material	Dimensions [mm^2]	Gold layer thickness [nm]
Die	Si	4×4	300
Substrate	Si	7×7	300

Gold bump were deposited on substrates using Delvotec 5610 ball Wire Bonder with standard gold wire (Diameter 25 µm) using bond parameters earlier optimized by L.Pettrica et al. [4]. The number of bumps per die was 16. The bump diameter ranges from 85 to 95 µm, as measured by microscopy.

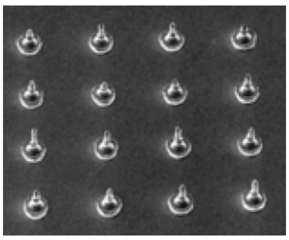


Figure 1: Gold stud bump matrix

2. Bonding parameters:

In this study, characterization was mainly focused on ultrasonic energy, bond force and bond temperature. Bond force ranges from 20 to 80 g/bump, bond temperature ranges from 500 to 2000 mW/bump and bond temperature ranges from 50 to 200^{o}C. The details of the bond parameters are given in Table 2.

3. Thermosonic bonding

Figure 2 illustrates the flip chip thermosonic bonding system. The ultrasound generator has a frequency of 60 kHz and maximum power of 40 W. The bonding tool-tip is a flat tool with vacuum suction.

Table 2: Details of bond parameters

Temperature [^{o}C]	Bonding force [g/bump]	Ultrasonic power [mW/bump]
50	20, 50	1000
	50	1500
100	20, 80,50	500
	20, 50	750
	20,35,50,65,80	1000
	20, 50, 80	1500
	20,35,50,65,80	2000
150	20, 50	1000
	50	1500
200	20, 50	1000
	50	1500

In a previous study, Taizo et al. [5] showed that to contribute to a good bond in thermosonic bonding, the ultrasonic time should be longer than 300 ms. In our study, the duration of ultrasonic pulse was set to 500 ms. The bond time was set at 1000 ms and the delay time of ultrasonic energy was 100 ms.

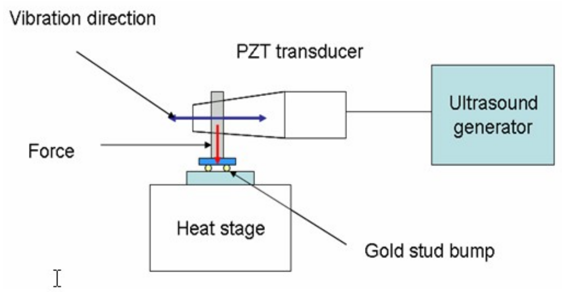


Figure 2: Thermosonic flip chip systems configuration

When ultrasound generator generate ultrasonic power of P1 (considered as ultrasonic bond power), it is transferred to the bonding tool-tip through the transducer. This energy caused the vibration of tool with power of P2. Due to friction force, the vibration energy of the tool propagated to the chip and materials joint. This makes the chip vibrate and softens the materials joint to form the bond. The propagation diagram of ultrasonic energy is shown in Figure 3

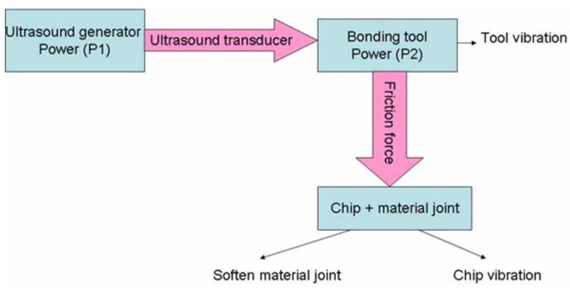


Figure 3: Ultrasonic energy propagation diagram

4. Shear strength measurement:

The bond strength was evaluated using Delvotec 5600 die shear tester. Optical microscope and SEM were used to inspect the fracture surface of the joints.

5. Cross section:

The bonded samples were cross sectioned for inspection of Au bump deformation and bond interface. Cross section was performed by molding and polishing with 1 µm paper. The bond contact area was estimated by microscopy measurement of the corresponding diameter.

6. Thermal shock cycling (TSC) test:

Based on the characterization results of die shear strength in section III.1, the parameter set of interest for TSC were selected as shown in Table 3.

Table 3: Set of parameters for TSC

Temperature [^{o}C]	Bonding force [g/bump]	Ultrasonic power [mW/bump]
100	50	1000
		1500
		2000
50	50	1500
150		
200		

There were at least eight samples for each set prior and after test. A Heraeus HT 7012 S2 dual-chamber thermal shock oven was used to carried out the TSC from -20 to 200^{o}C. The cycle parameters and profile are given in Table 4 and Figure 4.

Table 4: Cycles parameters

Number of cycles : 200 and 1000 cycles			
Temperature		Cycle time : 13 min	
Min [^{o}C]	Max [^{o}C]	Dwell time at high temperature	Dwell time at low temperature
-20	200	6.5 min	6.5 min

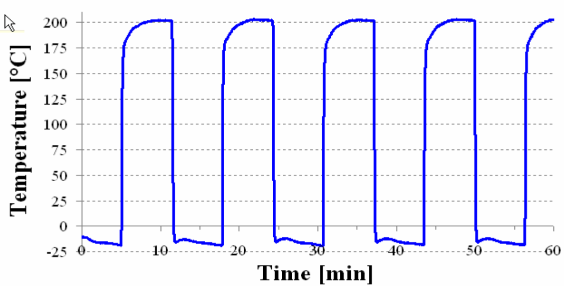


Figure 4: Thermal shock cycling profile

To examine where the samples start failing, two batches of samples were tested, at 200 and 1000 cycles. The shear strength measurement and the cross sections were performed to examine the bond strength and deformation of the bond interface after TSC test.

III. Results

1. Die shear test results:

The relationship between ultrasonic power and relative bond strength for bonding performed at 100^{o}C is shown in Figure 5. Successful bonding was obtained when the ultrasonic power was above 750 mW/bump. When the ultrasonic power increased, the bond strength increased. However, for high ultrasonic power, the shear force stabilized or decreased. The value of ultrasonic power where this occurs depends on the bond force.

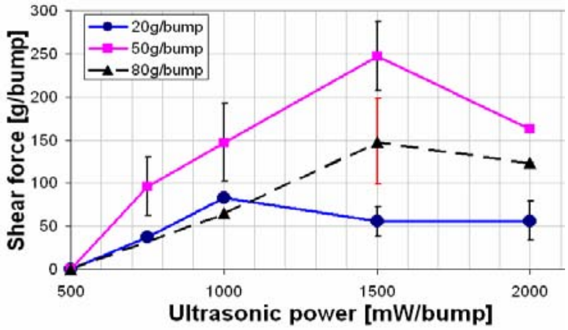


Figure 5: Die shear strength versus ultrasonic power at the bond temperature of 100^{o}C. Typical standard is indicated in the figure.

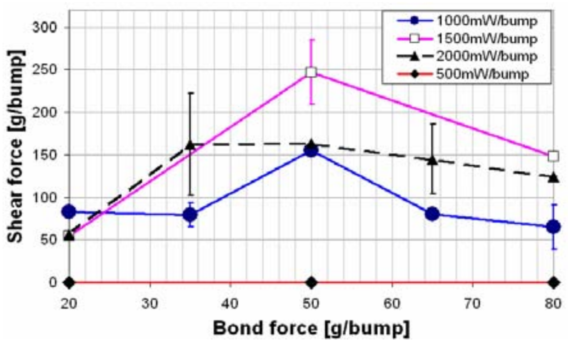


Figure 6: Die shear strength versus bond force at the bond temperature of 100^{o}C. Typical standard is indicated in the figure.

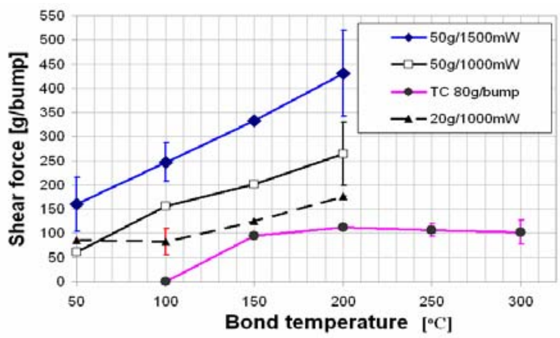


Figure 7: Die shear strength versus bond temperature of thermosonic bonding compared to thermocompression (no ultrasound power) bonding. Typical standard is indicated in the figure.

Figure 6 shows the relationship between the measured bond strength versus the bond force. However, for high bond force, the shear force stabilized or decreased.

The effect of bond temperature is presented in Figure 7. It can be observed that the bond strength of thermosonic bonding increases monotonically with the increasing bond temperature. When using ultrasonic bond force of 20 and 50 g/bump, we obtained successful bonding for as low temperatures as 50°C. With thermocompression bonding (without ultrasonic energy), successful bonding was only obtained above 150°C.

2. Contact area

Contact area was estimated from cross sections, by measuring height and contact diameter; assuming that the gold volume is constant.

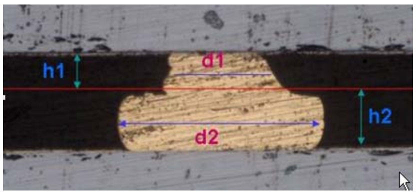


Figure 8: cross section parameters

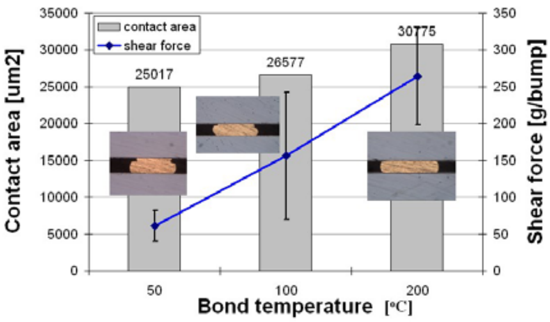


Figure 9: Contact area versus bond temperature at the bond force of 50 g/bump and ultrasonic power of 1000 mW/bump

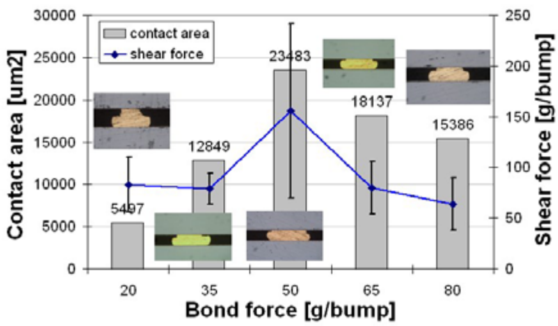


Figure 10: Contact area versus bonding force at the bond temperature of 100°C and ultrasonic power of 1000 mW/bump

Equation 1: Gold volume of bump

$$V = h1 \times \pi \left(\frac{d1}{2}\right)^2 + h2 \times \pi \left(\frac{d2}{2}\right)^2$$

Equation 2: Contact area

$$A = \pi \left(\frac{d1}{2}\right)^2$$

3. Thermal shock cycling test results

Figure 11 and Figure 12 show that after TSC test, the measured shear force of the bonded samples is reduced. The standard deviation of the shear force also reduces. Only small degradation was found between 200 and 1000 thermal shock cycles. We found smaller dependence on ultrasonic power and bond temperature of the bond strength after TSC than prior to TSC.

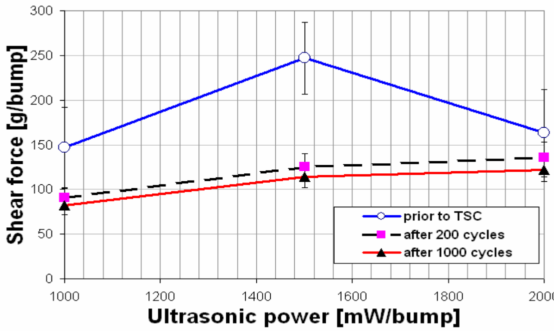


Figure 11: Die shears strength prior and after thermal shock cycling – bond temperature of 100°C and bond force of 50 g/bump

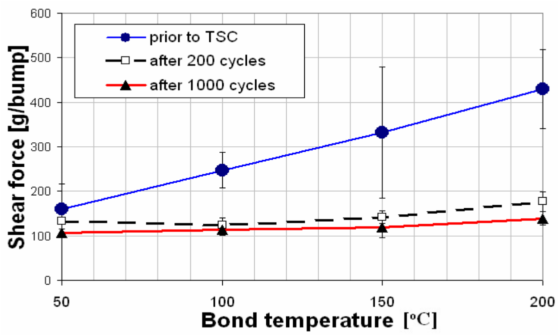
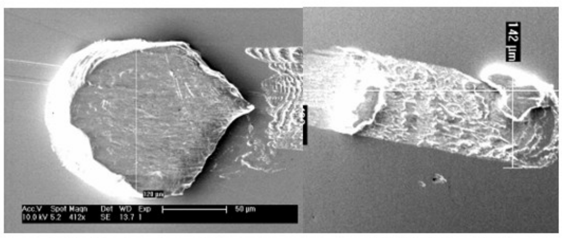


Figure 12: Die shears strength prior and after thermal shock cycling – bond force of 50 g/bump and ultrasonic power of 1500 mW/bump

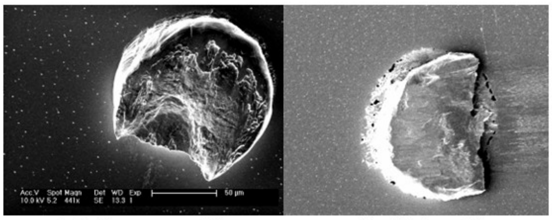
4. Shear test failure mode

Typical fractures of sheared samples are shown in Figure 13 and Figure 14. Fractures of both as-bonded samples and samples subjected to TSC were mainly on body of Au-bump



a) Substrate side **b) Chip side**

Figure 13: Bond fracture of samples prior TSC

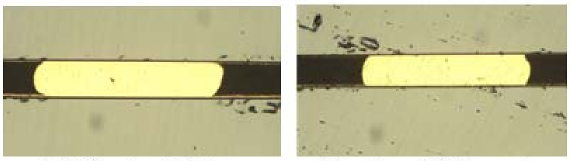


a) Substrate side b) Chip side

Figure 14: Bond fracture of sample after 1000 cycles

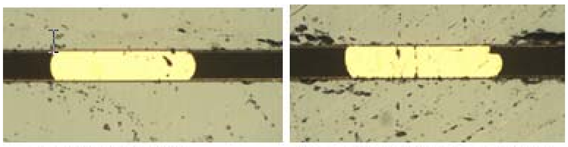
5. Cross sections after thermal cycling

Cross sections of samples prior to and after TSC test are shown in Figure 15, Figure 16 and Figure 17. From the inspection, there was no significant change of Au bump prior to and after TSC. No voids, cracks or delaminitations of the bond interface, which could be caused by thermal stress during temperature cycling, can be observed**.**



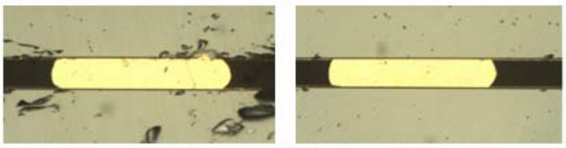
a) Prior to TSC b) after 1000 cycles

Figure 15: Cross section of sample bonded at 50 g/bump, 1500m W/bump and 100°C



a) Prior TSC b) after 1000 cycles

Figure 16: Cross section of sample bonded at 50 g/bump, 1500 mW/bump and 200°C



a) Prior to TSC b) after 1000 cycles

Figure 17: Cross section of sample bonded at 50 g/bump, 2000 mW/bump and 100°C

IV. Discussion

1. Effects of bonding parameters

Ultrasonic energy is the most important parameters of thermosonic bonding, which softens material joint [6] and causes the vibration of chip, which enhance metallic interface [7], to form bond strength. The softening effect of ultrasonic energy for aluminum and some metals were investigated by L.Bertwin [8]. Figure 18 shows the stress-elongation of aluminum at different ultrasonic power applied and at different temperatures. The more ultrasonic energy absorbed in the material, the softer the material will be. Ultrasonic energy causes the same effect as the raising of temperature.

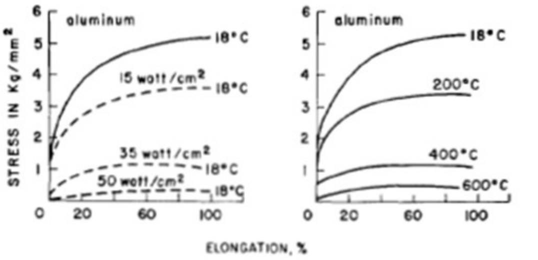


Figure 18: Ultrasonic softening effect for aluminum [8]

In our bonding system, the propagation of ultrasonic energy from bonding tool-tip to the chip and the material joint depends on the ultrasonic power and the bond force. Refer to the characterization results in Figure 5 and Figure 6. When ultrasonic power or bond force increases, more vibration energy of the bonding tool is propagated to the chip and the material joint. This makes the chip vibration energy increases and the material joint softens and forms higher bond strength. However, when too high ultrasonic energy is applied, the vibration of chip damages the bond interface which again decreases the bond strength. For too high bond force, the vibration of chip is obstructed. This reduces contact area and then reduces the bond strength.

Softening effect of ultrasonic energy to material joint also gives one explanation for the improvement of the bond strength of thermosonic compared to thermocompression bonding. Referring to the characterization result of bond temperature in Figure 7; with thermosonic bonding, we reached high bond strength even using lower bond force and lower bond temperature. For Au-Au thermocompression, Nguyen et al. [2] showed that the maximum achieved is around 100 g/bump using bond force above 30 g/bump and bond temperature above 150°C. However, for thermosonic bonding, shear force of 100 g/bump is obtained even at 50°C using bond force of 20 g/bump and ultrasonic power of 1000 mW/bump. Maximum bond strength that we achieved in thermosonic bonding is around 400 g/bump.

The increasing of bond temperature also contributes a larger contact area and then contributes to higher bond strength, as seen in Figure 9.

2. Effects of thermal shock test

During TSC test, the heating and cooling process caused thermal stress to harden material. This caused the change of material properties and reduced the ductility of the material, makes it easier to fracture. This explains for significant reducing of the bond strength after TSC.

Although TSC test significantly reduces the bond strength of bonded component, the remaining bond strength aster TSC is still high; ranging from

82 to 140 g/bump. For thermocompression, the maximum bond strength that can be achieved after TSC has been shown in [2] is 70 g/bump. Therefore, thermosonic bonding does not only significantly improve the bond strength, but also the bond reliability compared to thermocompression bonding. One explanation for this is the change of material properties due to the absorption of ultrasonic energy.

Estimated shear stresses of Au bump after TSC is given in

Table **5**. We found that these stress values reaches the shear yield point of gold, around 60 MPa. Shear yield point of gold is estimated by Equation 3.

Equation 3: Shear yield stress[9]

$$\tau_{yield} = \frac{1}{\sqrt{3}} \sigma_{yield}$$

Where τ_{yield} is shear yield point and σ_{yield}=130 Mpa [10] is tensile yield point of gold.

Table 5: Shear stress of Au bump

Sample	Contact diameter [µm]	Shear force [g/bump]	Shear stress [MPa]
50g/bump, 1000mW/bump, 100°C	141	82	53
50g/bump, 1500mW/bump, 100°C	142	114	72
50g/bump, 1500mW/bump, 200°C	127	139	110

Prior to TSC, there is the residual stress of thin film, which causes the variation of the shear force. During TSC process, the heating and cooling releases this stress. This explains the decreasing standard deviation of the shear force after TSC.

For the decreased dependence on ultrasonic power and bond temperature of the bond strength after TSC and the brittleness of gold bumps, a further study of material and bond fracture mechanism is needed.

V. Conclusion

For Au-Au stud bumps interconnect, thermosonic bonding improves the bond strength and reliability compared to thermocompression bonding. With thermosonic bonding, a lower bond temperature may be used. High bond strength is obtained even using temperature as low as 50°C.

The highest bond strength is obtained when ultrasonic power is 1500 mW/bump, bond force is 50 g/bump and bond temperature is 200 g/bump. Bond strength up to 400 g/bump is achieved. Thermosonic bonding is good for the bonding that needs moderate force or low temperature.

TSC of the bonded interconnects reduces the bond strength. However, the final shear strength is still above 80 g/bump. Maximum bond strength that we achieved after TSC is 140 g/bump with the following bond parameters: ultrasonic power 1500 mW/bump, bond force 50 g/bump and bond temperature 200°C. The shear stress after TSC reaches the yield point of gold. This study confirms that Au-Au thermosonic bonding can be used for high-temperature applications

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