

A Comparative Study: Thermosonic Bonding of Flip Chips with Gold Stud Bumps to a Variety of Organic Substrates

Nick Stolper, Fei Ding

Panasonic Factory Solutions Company of America
909 Asbury Drive
Buffalo Grove, IL 60089
Tel: 847-495-6240, Fax: 847-495-6095, Email: stolpern@us.panasonic.com

Abstract

Thermosonic flip chip bonding to ceramic substrates is a well understood and reliable connection method usually reserved for lower I/O devices. This process facilitates smaller package sizes and improved electrical performance over the traditional wire bonding process. Recently there has been increased interest among package designers to expand the range of available substrates to include organic materials. This move also improves the cost-competitiveness of the package while maintaining required high performance requirements of the device. This article will define the requirements necessary for gold to gold bonding of a flip chip die to organic substrates, and will investigate the effect and reliability of various organic substrate materials such as FR4, BT and HT (high temp) under different process conditions using a Au to Au interconnect flip chip process. Device assembly processes covering Au to Au interconnections as well as the underfill process is investigated with special emphasis on product reliability for each type of organic substrate mentioned above. Critical Au to Au process parameters such as temperature, bonding pressure, ultrasonic power setting and time duration for optimal bonding conditions will also be established. The reliability evaluation will concentrate on thermo-mechanical robustness and electrical functionality of the final assembly.

The reliability tests used are Ball Bond Shear Test, Electrical Testing, Die Shear Testing and Temperature Cycling. Au bump alignment accuracy with respect to the Au bond pads is checked using X-ray inspection. Underfill quality is revealed by C-SAM inspection concentrating on voids, cracks and de-lamination defects. The evaluation will compare low cost flip-chip mounting processes using 70um diameter gold stud bump connections on three different types of organic (FR4, BT and HT) substrates that are high performance, high Tg substrates with Au/Ni/Cu material plating. Flip Chip samples consist of 7mm x 7mm test chips bumped with 112 gold stud bumps with a bump pitch down to 150um. The dies were prepared with coined bumps of 1mil Au-wire.

The assembly methodology consists of four primary steps: 1) Bumping of the silicon IC utilizing common wire bonding equipment, 2) Connection of the bumped IC directly to the organic substrate by gold to gold thermosonic interconnects. 3) Underfill post-process and 4) Reliability Testing per JEDEC specifications. With recent improvements in the thermosonic bond horn design along with high Tg substrates, the ability to bond to organic substrates will be demonstrated. In particular, the bonding is accomplished by applying the required heat by means of a heated bond head, allowing the organic substrate with a significantly lower Young's modulus (as compared with ceramic) to remain relatively cool and hence capable of forming mono-metallic Au joints.

Key word: Thermosoni, bonding, flip chip, GGI, Au to Au, Stud Bump

Introduction

GGI – acronym for Gold to Gold Interconnections is a lead free process where the Au bumps and Au bond pads are joined together by heat and ultrasonic power under a mechanical pressure head. The ultrasonic die attach process uses low bonding temperatures usually between room temperature and 100 ° C. This low temperature bonding is desirable for bonding to low cost organic

substrate materials because they have properties that absorb ultrasonic energy at higher temperatures. It is a well known fact that organic substrates can not be heated the same as a ceramic substrate due to the low Young's modulus of the organic substrate. Without the heated bond head technology, heating to the required bond temperature would have to come from the bond stage. This direct method of heating causes the board to become soft thereby dampening the

ultrasonic energy causing improper bump collapse resulting in a failed joint connection.

Attempts to increase ultrasonic power to improve the Au-Au inter-connection will increase the probability of micro-crack damage to the die pad. By applying the heat through the heated bond head while maintaining a lower bonding stage temperature, the low thermal coefficient substrates will retain enough rigidity to absorb the ultrasonic energy producing reliable Au-to-Au inter-connections. The Heated Bond Head is the key to this process.

The latest flip chip trend is to use organic substrates however the move to organic substrate introduces the problem of significant thermo mechanical mismatch because of the high CTE of these materials. In addition, the organic substrate can flex more as compared to ceramic substrates. To enhance the fatigue life of flip chip Au-Au interconnects, an epoxy underfill is dispensed between the die and the package. Under filling adequately reduces joint stress, and reliability can be regained.

Chip Used For Evaluation

Thermosonic flip chip assembly evaluation was conducted using TEG (Test Element Group) dies. The TEG die has a silicon nitride passivation material with aluminum metallization coating on the bond pads for interconnections. The TEG is an electrically daisy chained test die used in evaluating assembly techniques, board continuity, and the affects of temperature cycle and life testing by allowing the resistance of the device to be measured during the evaluation process. If a failure occurs the indication would be an open in the circuit. Fig. 1 shows the design of the TEG chip. The TEG is 7mm x 7mm square die that is 0.350mm thick. The chip has 112 pads on the periphery with an input/output pad size of 100-um square and pad pitch of 150um.

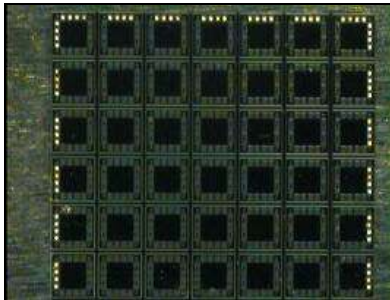


Figure 1. TEG Test Die

Bumping Process

The coined Au bumps were formed on the chip pads using a Panasonic wire bonder with 1mil 99% Au-1% Pd alloy doped wire. Bond Parameters

such as power, time and force for the 1st bond were optimized and then the bump was coined. The coining process produces high quality, repeatable bumps resulting in less tail variation. After the bumping process the bumps have a diameter of 65um and a height of 50um. Using post-bump coining with the same capillary creates a more consistent bump height and provides stability for the flip chip process. Coining the bump increase the shear strength of the bump but also increases the bump diameter slightly.

Bump properties such as bump diameter, bump height and shear strength were used to validate the bumping parameters. Bump diameter and height were measured using a Hirox digital optical microscope. The ball shear strength was measured using a Dage 4000 Series Shear/Pull Tester. Thirty (30) bumps were tested at a time in ball shear mode. The final result of the ball bump testing is shown in figures 2, 3, and 4.

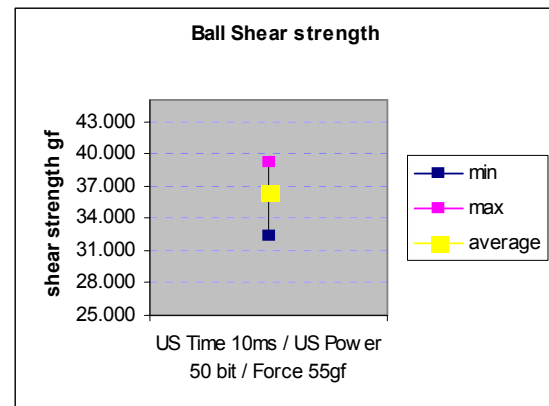


Figure 2. Ball Shear Strength

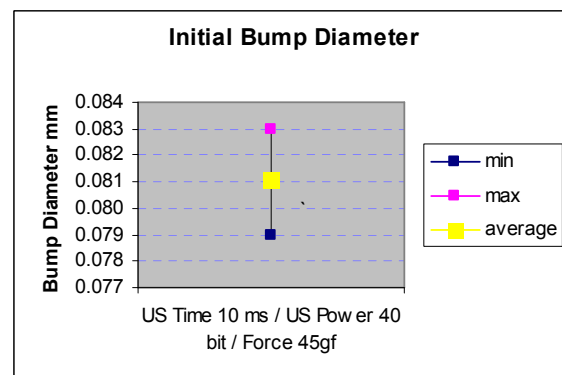


Figure 3. Initial Bump Diameter

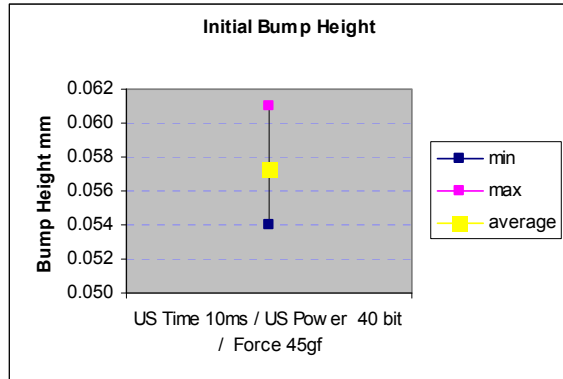


Figure 4. Initial Bump Height

Substrates Used In the Evaluation

The substrates used in this study are FR4, BT, and HT. All substrates are 0.25mm thick made of a two layer organic board with Ni/Au surface finish. The gold plating on the substrate electrode surface is 0.5 μm thick. Each substrate has thirty six (36) bonding sites and each bonding site has a daisy chain pattern with four probe traces used for electrical testing.

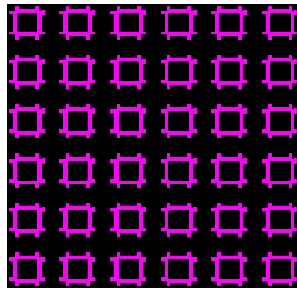


Figure 5. Test Board

The assembly process of attaching the die is identical for all three substrates (FR4, BT and HT). Figure 5 shows the unpopulated test board that is used for this evaluation.

Process Flow

A standard ultrasonic flip chip bonding process is shown in Figure 6. It consists of three main processes.

1. The bonding pad on the substrate is cleaned using plasma cleaners.
2. The component with gold bumps is bonded onto the substrate using an ultrasonic bonding machine. Force, ultrasonic energy and temperature are applied to the device to form a monometallic gold bond between the pad on the substrate and the bumps on the die.
3. Under fill is required to reduce the affect of CTE mismatch between the Si die and the laminate

substrate.

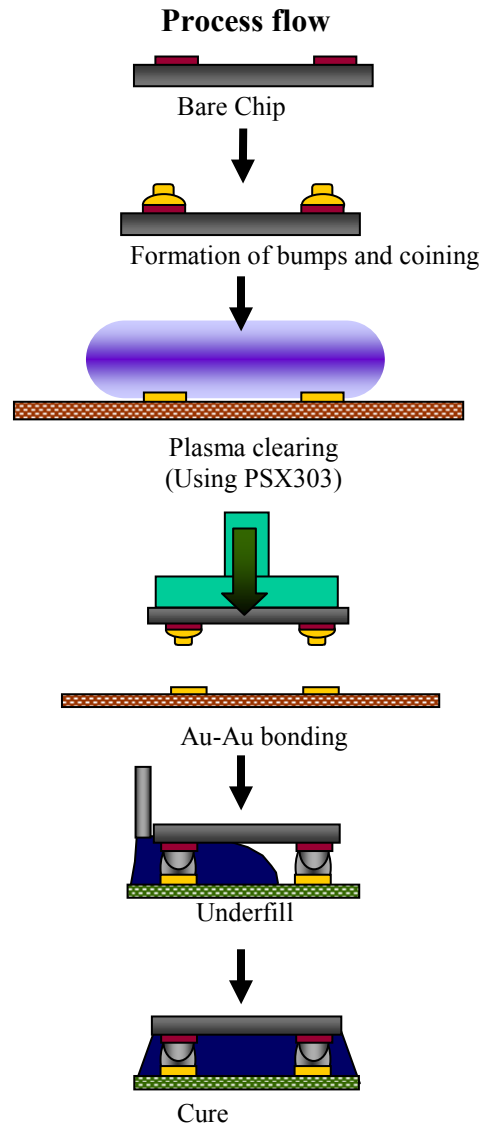


Figure 6. Assembly Flow Chart

Evaluation Procedure

The bonding of the die to the organic substrates was carried out with a Panasonic FCX501 bonder utilizing thermosonic bonding. In order to define a common recipe to use for all three substrate materials, the transducer temperature was set to 200°C and the bonding stage set at room temperature. For each substrate material a process window was establish defined by die shear strength and bump transfer percentage. Prior to flip chip bonding onto the test board, the substrates were baked at 125° C for 2 hours to remove any residual moisture. The

substrate was plasma cleaned immediately prior to the bonding process using Panasonic PSX303 plasma cleaner. The existence of inorganic and organic surface contamination is one of the greatest inhibitors to the production of a reliable Au thermosonic bond. The plasma recipe includes the use of Argon at a vacuum pressure of 10Pa and power of 600W at 13.6MHz. The plasma application time was 15 seconds and was performed on all three substrates before the flip chip bonding operation. When plasma cleaning is used the die shear strength can improve 15% to 50% compared to non plasma cleaned parts. This is illustrated in figure 7.

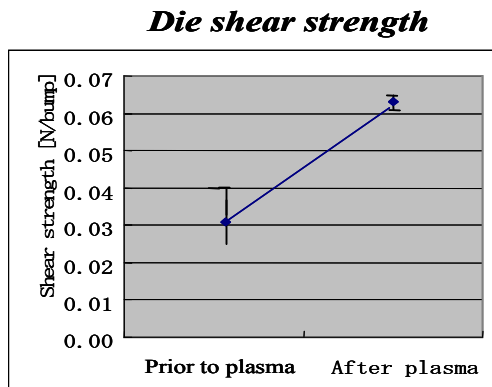


Figure 7. Die Shear Strength Before & After Plasma Cleaning

After flip chip bonding is completed, all test vehicles are under filled, then put into thermal cycling chamber for reliability testing.

Case Study #1: Bonding Stage at Room Temperature

Bond strength is a very important factor related to interconnection quality and reliability. Bonding force was maintained to 150 N/mm² for each bump. At this force level the TEG die were successfully bonded to FR4 test substrates under room temperature and the bumps adhered well between the substrate and the die.

To establish the process window for each substrate a matrix table was designed to determine the optimized bonding parameters. The matrix table for each substrate type was then used to find the best common bond parameters to use for all three different laminates. Bond stage temperature was maintained at room temperature (25 °C), and the horn temperature was set to 250 °C. The bonding time was set at 300 milliseconds.

The ultrasonic power was varied from 3.3W to 5W to establish the optimal parameters. Figure 8 represents the bonding strength of the gold bump

bonded onto the gold electrode with different ultrasonic power settings. The average bonding strength was approximately 17.09gf / bump when the ultrasonic power was set at 3.3W. When the ultrasonic power was increased to 5W, the bonding strength was enhanced to 23.5gf/bump this indicating that bonding strength increases with an increase of ultrasonic power. The die shear data results were acceptable and indicated that good joints were formed. Figure 9 shows the plot of bump transfer which represents the average of the bonding die shear strength as well as percentage of the bumps that had transferred onto the substrate. The cross-section of the gold bumps bonded on the FR4 substrate were investigated using SEM. Figure 10 shows that the contact diameter of the gold bumps after bonding was approximately 80um when the ultrasonic power of 5W was applied. Also, the collapsed part of the bumps or the stand off height is about 37um.

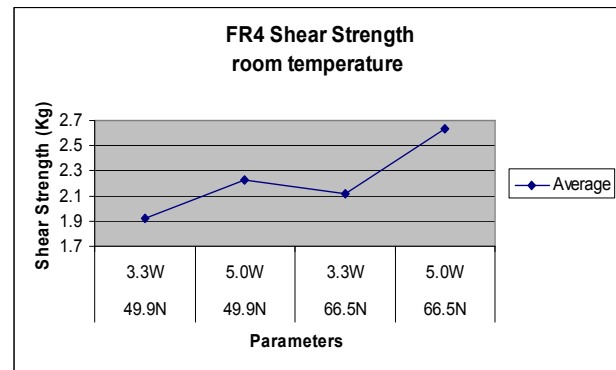


Figure 8. FR4 Die Shear Graph

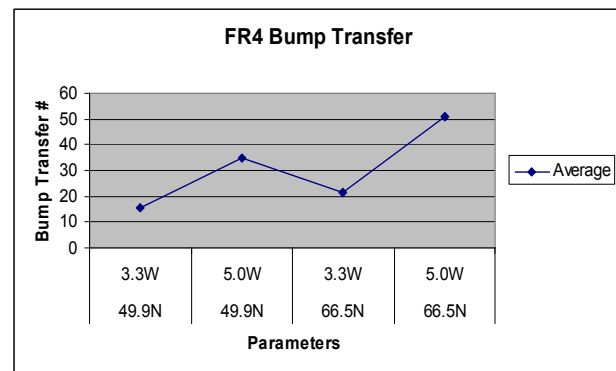


Figure 9. Bump Transfer Graph

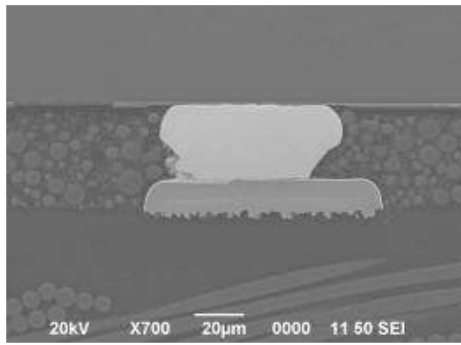


Figure 10. Deformed Bump on FR4

Typically the stud bump should collapse down to 25µm in height. Because the cross sectional shapes of the stud bump were not fully collapsed, we concluded that the power of ultrasonic vibration distributed to all bumps may not have been sufficient.

Further optimization of bond parameters was conducted. Our test showed that more bonding force, higher temperature, and increased amplitude of ultrasonic vibration made for more collapsed bump area and higher strength. However, when increasing these parameters, it is important to recognize the risk of an electric short between adjacent bumps as well as possible cratering of the silicon die. Based on our findings, strengths with the bond stage at room temperature could be as high as 50g/bump if good process parameters are selected. All nine (9) parts that were thermosonically bonded had acceptable ball shear strengths. After assembly of the flip chip onto FR4, the electrical resistance of each component was measured to ensure all bumps bonded to the pads. The bonding strength between the die and substrate was measured.

A second and third test was conducted respectively utilizing BT and HT substrates under room temperature bonding, applying the same process parameters as discussed above for FR4 substrate. The die shear data results were acceptable and the bonding strength indicated that good joints were formed. Figure 11 and shows the graph of the BT die shear strength. Figure 12 shows the graph of BT bump transfer which represents the average of the bonding die shear strength as well as percentage of the bumps has transferred onto the substrate after die shear at various bonding force and power.

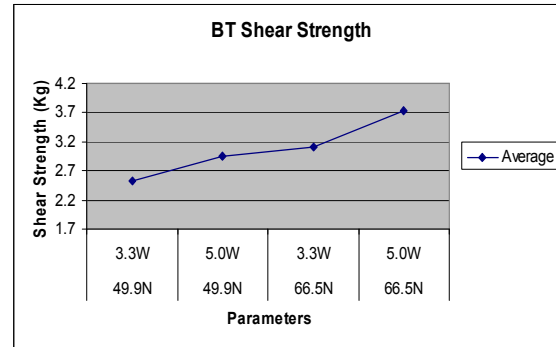


Figure 11. Graph of BT Shear Strength

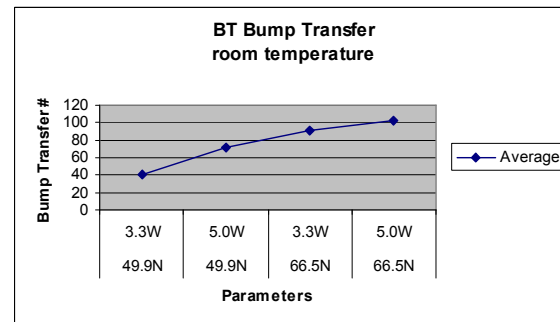


Figure 12. Graph of BT Bumps Transferred

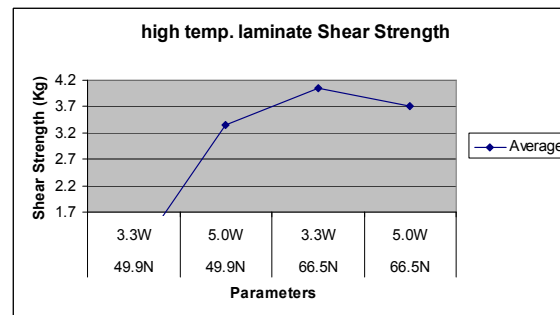


Figure 13. Graph of HT Die Shear Results

Figure 13 shows the graph of the HT shear strength. Figure 14 shows the graph of HT bump transfer that represents the average of the bonding die shear strength as well as percentage of the bumps has transferred.

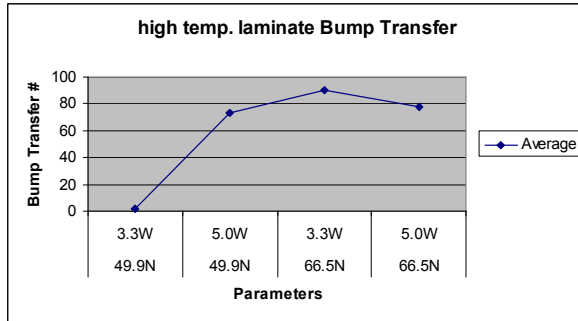


Figure 14. Graph of HT Bumps Transferred

The Case #1 experiment showed Au bumped flip chips bonded to three different substrate materials at room temperature. It is noted that the shear force for flip chips bonded on HT substrates is greater than the BT and FR4 substrates. This is consistent for bonding pressure of 66.6N and 40 g/bump.

The next experiment will include the bonding of the same TEG chips onto the same substrate materials mentioned above with the exception of applying bonding stage temperatures of 100° C and 150° C. It was noted that flip chip bonding at room temperature with the selected recipe performed better than the other samples incorporating a heated bond stage on all three laminate substrates. Therefore, we have chosen the following process recipe to continue the next experiments. Table 1 shows a common process recipe for all three substrates will be used hereafter: The recipe consists of a 2-step bonding force system for the mounting profile with 23N serving as the step 1 force and 66.5N as the step 2 force. The US power setting is 5W. The substrate was not heated, and the chips were bonded at room temperature.

Table 1. Selected Recipe

Bonding Conditions for Laminate Substrates				
Laminate	Bond Force			US Power
	Load	Load Time	U/S power	U/S Time
1 st step	23N	0.1sec	0	0
2 nd step	66.5 N	0.29sec	5W	0.29sec
Stage Temperature	25°C, 100°C, 150°C			
Bond Tool Temperature	250 °C			

Case Study #2: Bonding Stage at 100° C

Due to the characteristic softness increase of the FR4, as it was heated it was observed that no

bonding was formed above 100° C. So it was determined that sufficient die shear strength levels within the process range established in the study were not capable on FR4. Next we experimented bonding the same TEG chip type onto the BT laminate substrate. The substrate was heated to 100° C and the same bond parameters mentioned above were applied.

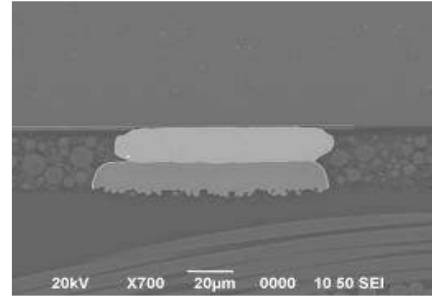


Figure 15. BT Bonded Under 100° C

The cross-section of the gold bumps bonded on the BT substrate were inspected using a SEM. Figure 15, shows that the contact diameter of the gold bumps after bonding was approximately 90um when the ultrasonic power of 5W was applied. Hence, the increased bonding strength could be attributed to the large contact area between the gold bump and the Al pad bonding layer when ultrasonic power increased from 3.3 to 5W. Figure 15 also shows these bumps deformed from 65um diameter x 50um high to 82um x 35um during the bond process which representing a 27% ratio of the bump collapse.

Similar observations were noticed when bonding on the HT substrate. The increase in the bump deformation established good metal joint connections however lower die shear strength compared with room temperature die share results.

It is noted that for the bump size and metallurgy used in the test, if the shear failure force of each bump is up greater than 0.1N, the reliability requirements can be satisfactory. Since the assemblies incorporated in this project had 112 I/Os the shear failure force of more than 3.2Kg for each assembly would be expected for good reliability.

Figure 16 and 16a, show 90% of the stud bump transfer after die shear. The device sheared off during the shear test, leaving the majority of the gold bumps still bonded to the gold pads. This means the strength of the bonding is as strong as the original metal strength. As a result of the electrical testing, we confirmed that conductivity was present at all the bumps.



Figure 16. TEG Die after Die Shear

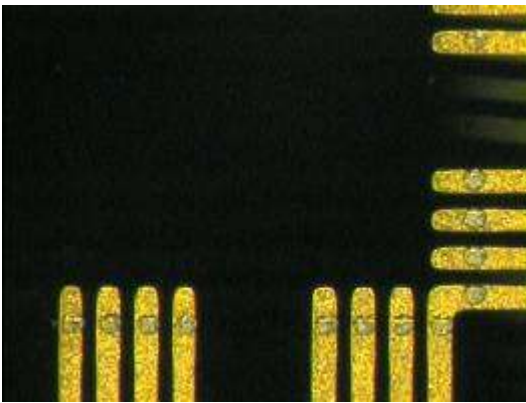


Figure 16a. Substrate Pads after Die Shear

Case Study #3: Bonding Stage at 150°

The third bonding case used 150° C at the bonding stage with 250° C at the Heated Bond Head and 150 N/mm² bump. Increasing the bonding stage temperature from 100° C to 150° C caused most of the gold bumps to peel off the bonding interface. Only a few residual gold bumps can be found on the deformed fractured interface over the organic substrates as shown in Figure 17.

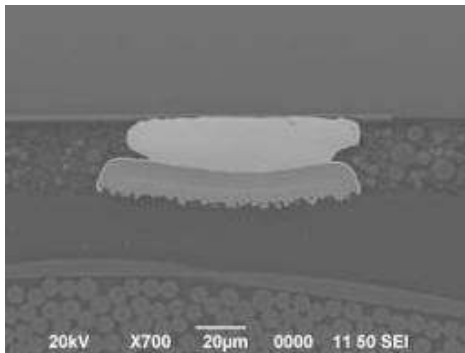


Figure 17. Deformed Bump on BT Substrate at 150° C

The stand off height is about 25µm for the samples bonded above 40gf. The Au-Au diffusion was observed on the thermosonic bonded interface, and it can also be seen that the contact area increased with the elevating of the stage temperature even though the bonding parameters remained unchanged. Figure 18 and 18a below show pictures was taken by the Hirox digital microscope of shear surface on both the substrate and the die after shear test.

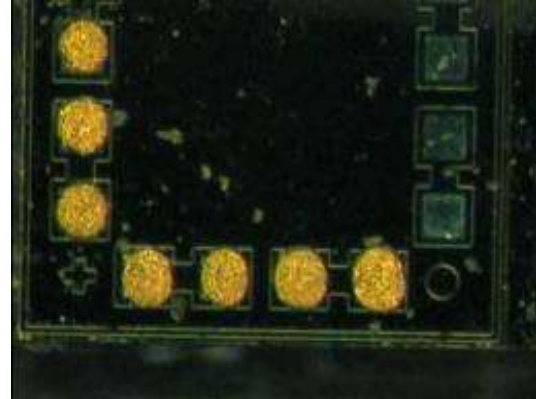


Figure 18. Stud Bumps Remaining on the Die after Die Shear

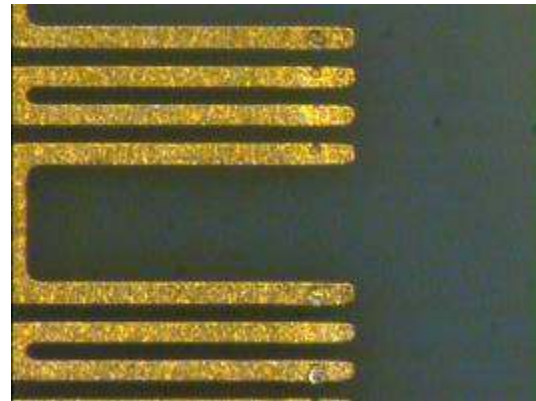


Figure 18a. Lack of Bumps Remaining on the Substrate Pad after Die Shear

The increase in bump deformation is seen in Figure 18(a). Most of the gold stud bumps cannot be bonded well to the organic substrate. The Au stud bumps remains on the TEG die after die shear testing at 150° C. The bonding onto the BT substrate under high temperature resulted in inconsistent gold to gold interconnection and also weakened Al-Au interconnection due to the high heat.

Bonding resulted in inconsistent die shear results and very low amount of Au from the bump remained on the BT substrate after die shear.

Additional tests were performed by bonding the TEG die onto the HT substrate at 150° C and the bond head at 250° C with 150 N/mm². Similar results were noticed when bonding on HT substrates at 150° C as were seen when bonding at 100° C. Rather than inducing degradation on the bond, it appears that at higher temperature bonding was unable to provide sufficient die shear strength level within the process ranges in the study. This is very likely due to the board softness at the higher temperatures.

Table 2 below shows the affect of increasing the temperature of the bonding stage to the reliability of the bonds of the three substrate types.

Table 2. Effect on Quality by Bond Stage Temperature

Stage Temp [°C]		US Tool Temp. [250°C]		
		R. T	100°C	150°C
	FR4	●	✗	✗
	BT	●	○	✗
	high temp	●	○	○

● - Excellent
 ○ - Good
 ✗ - Fail

Underfill Dispensing

The use of an underfill can minimize the shear stress generated by the CTE mismatch between the die and PCB. This shear stress is well known to lead to early fatigue failure in the bump joints. Underfill dispensing was performed with an Asymtek dispensing system using a 20-gauge needle. Prior to underfilling, assembled parts were treated with plasma to enhance underfill flowing. Namics CHIPCOAT U8437-2 was selected as the underfill material. This underfill has high adhesion strength. The recommended cure condition is 20 minutes at 150 °C. To reduce thermal shock, a curing profile at 125 °C for 2.5 hours was used.

Reliability Test

54 parts with FR4, BT and HT substrate were assembled for reliability testing. The reliability test was a 90 minutes -55/125 °C air-to-air thermal cycle consisting of 10 minutes of dwell time at each temperature extreme and 35 minutes transition between the temperature extremes. The test parts were inspected every 50 cycles. The failure of an assembled die was defined to occur when its resistance increased by 10% over its initial resistance. Failures will be removed from the thermal cycle chamber and failure analysis will be performed. The reliability test has passed 500 cycles without failure. The test is still ongoing.

Conclusion

Our finding is generally consistent with previous studies indicating that elevated temperature on organic boards during ultrasonic bonding reduced the reliability of the bonds and decreased the bond strength and bump transfer amount. Increasing the heat of the bonding stage caused the mechanical rigidity of the substrate to degrade enough to not form a reliable bond. This is due to the increase in temperature causing the ultrasonic power to dissipate during the gold to gold bonding. The Au-Au interface then becomes compromised which is reflected in lower die shear measurement and transfer amounts.

After bonding the TEG samples to the three different substrate types, the electrical resistance of each component was measured. Most of the units were failing electrical resistance testing immediately after bonding at the higher temperatures. This is an indication that the bond formation between the die bumps and the substrate pads was compromised.

The samples bonded under room temperature were then sent to the underfill process to prepare the devices for thermal cycling. The Thermal cycling testing will confirm that the reliability of the products bonded at room temperature is unaffected. The key technology to permit room temperature bonding is the heated head which provides the local die heating necessary to bond while keeping the organic substrate at the cooler temperature.

Acknowledgement

The authors would like to extend thanks to Jaime Mungcal of Panasonic who contributed to the testing for this paper.