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Gold Stud Bump Flip Chip Bonding on Molded Interconnect Devices

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Abstract

A molded interconnect device (MID) is an injection molded thermoplastic substrate which incorporates a conductive circuit pattern and integrates both mechanical and electrical functions. The thermoplastic material is doped with a metal-plastic additive which can be activated by laser. A laser beam is pointed on the surface of the injection molded plastic to form a metallization track by aggregating the metal additives. The metallized path is then plated with copper, nickel and gold finishes subsequently. MID Technology offers great advantages in design flexibility, device miniaturization, and true 3D integration of complex shapes.

Flip chip bonding of bare die on MID can be employed to fully utilize MID's advantage in device miniaturization. Compared to the traditional soldering process, thermo-compression bonding with gold stud bumps provides a clear advantage in its fine pitch capability. However, challenges also exist. Few studies have been made on thermocompression bonding on MID substrate, accordingly little information is available on process optimization, material compatibility and bonding reliability. Unlike solder reflow, there is no solder involved and no "self-alignment," therefore the thermo-compression bonding process is significantly more dependent on the capability of the machine for chip assembly alignment.

This paper presents the studies on flip chip thermo-compression bonding (TCB) of gold stud bumps on MID substrate. Non-conductive paste (NCP) is applied on the MID substrate before attachment of bare dies, and subsequently the dies are compressed at elevated temperatures to bond the gold stud bumps to the substrate pads and to cure NCP simultaneously. Daisy chained test vehicles were designed and built to demonstrate this process with multiple assembly challenges resolved. The test vehicles successfully passed long term reliability testing based on IPC standard IPC-SM-784, although the substrate bond pads experienced excessive deformation during the thermo-compression bonding process at higher bonding forces. Regardless of the bonding forces evaluated, a certain degree of atomic bonding is observed between gold stud and gold plating on the substrate, However, such small scale bonding is not adequate to secure the chip in place, the assembly relies on the contraction of non-conductive paste during the cure process to maintain a reliable bonding interface. Based on reliability test results, the bonding force can be further reduced to minimize the substrate pad deformation while maintaining bonding reliability.

Key words: Molded interconnect device, MID, Flip chip, Thermocompression bonding, TCB, Reliability, Laser direct structuring, LDS.

Introduction

A molded interconnect device (MID) is an injection molded thermoplastic substrate which incorporates a conductive circuit pattern and integrates both mechanical and electrical functions (1). The thermoplastic substrate is doped with a metal-plastic additive which can be activated by laser to form the metallized path. The metallized path is then plated with copper, nickel and gold finishes successively. There are mainly thee variations of MID fabrication process: one short injection molding, two shot injection molding, and insert molding. MID technology offers great advantages in design flexibility, device miniaturization, and true 3D integration of complex shapes.

Flip chip bonding of bare die on MID can be employed to fully utilize MID's advantage in device miniaturization. Compared to the traditional soldering process, thermo-compression bonding (TCB) with gold stud bumps provides a clear advantage in its fine pitch capability. However, challenges also exist.

Few studies are made on thermocompression bonding on MID substrate, accordingly little information is available on process optimization, material compatibility and bonding reliability. Unlike solder reflow, there is no solder involved and therefore no “self-alignment.” Accordingly the thermo-compression bonding process is significantly more dependent on capability of the machine for chip assembly alignment.

This paper presents the studies on flip chip thermo-compression bonding of gold stud bumps on the MID substrate. The purpose of the study is to demonstrate the stud bump bonding process on the MID substrate and at the same time to understand the fundamentals of the bonding process to assist process optimization.

Experimental

There are a variety of methods to make molded interconnect devices. For this experiment, one short injection molding method is used. The process is described in Figure 1 (2). The MID material supplier provided the MID substrate made from glass fiber filled PPA compounds with metallized traces for this evaluation.

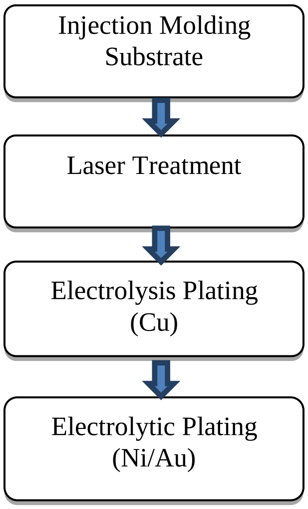


Figure 1: MID fabrication process (2)

Figure 2 shows the evaluation process for the flip chip Thermocompression bonding on MID substrate. Test boards and dies are designed with daisy chains to check electrical continuity after flip chip thermocompression bonding. A production stud bumping machine was used to bump gold studs on the silicon wafers which were then sawed into individual dies. Shear testing was performed to examine the integrity of the gold stud bumps. The thermocompression bonding process was done using a production flip chip bonder. Non-conductive paste (NCP) was at first dispensed on the MID substrates, the dies were compressed against the substrates while the temperature was quickly ramped to preset value and held for a very short duration. After bonding, the assemblies were checked in terms of daisy chain continuity, bump to pad alignment and voids in the NCP material. Reliability testing was done on the assemblies based on IPC standard SM-784, including high temperature aging, high temperature/high humidity and temperature cycling (3). Cross sectioning was used to examine the bump height and bonding interface integrity.

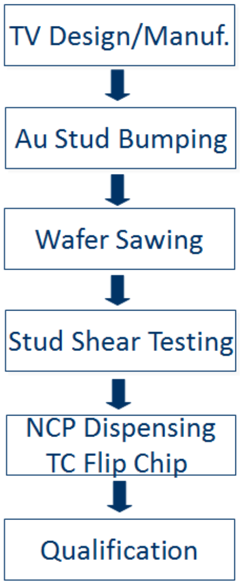
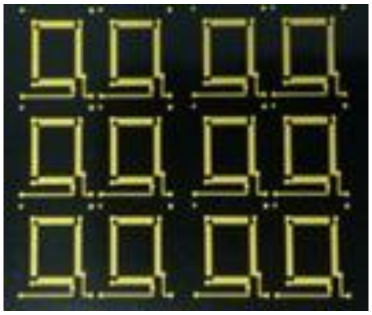


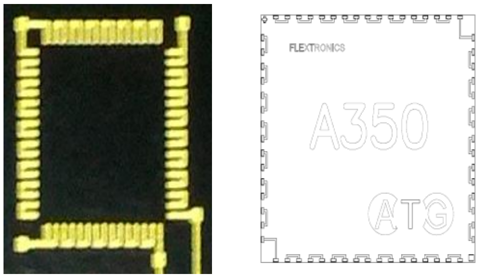
Figure 2: Thermocompression bonding evaluation process.

Figure 3 shows the test vehicle design. The MID substrate is made from a commercial laser direct structuring (LDS) material with a thickness of 2.0mm. After laser beam structuring and copper electrolysis plating, a minimal 120 micro inch electrolytic nickel was deposited on the substrate followed by a minimum 1.0 micro inch flash gold. The line width is 0.15mm and the spacing between lines is 0.20mm. The pitch between bond pads is 0.35mm.

For the dies, the die size is 6.5mm x 6.0mm with thickness 0.42mm. The bond pad opening for the gold stud bump is 75 x 150um. There are a total 64 bumps on each die.



Test board design



Test board daisy chained pads

Test die daisy chained pads

Figure 3: Daisy chained test vehicle design

Figures 4 to 6 show the processes of gold stud bumping, NCP dispensing and flip chip bonding. All the work was done at the facility of the bonding machine supplier. The gold stud bumping process is similar to the gold ball bonding process, with the only difference being that after the bonding process the gold wire is cut off at the neck by squeezing the tail between the capillary edge and bump to create a stud.

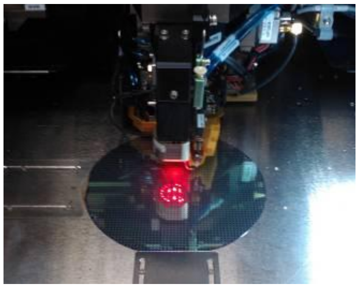


Figure 4: Gold stud bumping process

Before the thermocompression bonding process, the NCP material was dispensed on the substrate. During the flip chip bonding process, a collet picked up the die and then the machine automatically aligned the die to the substrate. A pre-set force was then applied on the die to squeeze out the NCP material to ensure an intimate contact between gold bumps and substrate pads, while the temperature ramped up quickly to a preset value and the temperature maintained for a short period of time to form bonds between gold studs and pads while simultaneously curing the NCP material.

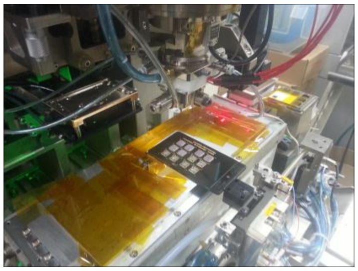


Figure 5: NCP dispensing process.

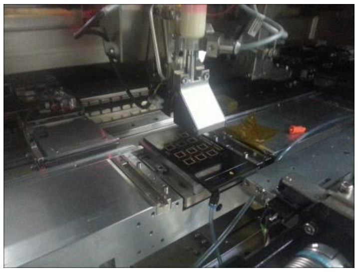


Figure 6: Flip chip bonding process.

In order to examine the effect of the bonding force on the bonding interface integrity, five bonding forces from 1kg to 5kg are evaluated in the experiment, accordingly forces per pad are: 15.6g, 31.2g, 46.9g, 62.5g, and 78.1g respectively.

Non-conductive paste (NCP) is applied during the flip chip bonding process. It needs to be cured while the bonding is formed. Differential scanning calorimetry (DSC) was used to characterize the cure properties of NCP at temperature ramp. The percentage of cure is determined by comparing the heat of cure of partially cured resin with fully cured resin. Table 1 shows the measurement results on the NCP material. At 235ºC for 12 seconds, a cure percentage of 93% can be achieved.

Table 1: DSC measurement of NCP material.

Curing condition		DSC results	
Temperature (ºC)	Time (s)	ΔH(J/g)	Cured Percentage (%)
25	0	-135.40	0
235	8	-15.33	88.68
235	10	-10.91	91.94
235	12	-8.74	93.54

Based on DSC measurements, the flip chip bonding parameters were finalized. Figure 7 shows the actual temperature measurement process. A thermocouple was attached to the center of footprint of pads for the measurement. Figure 8 shows the actual temperature profile for the bonding process. A temperature profile of 235-240 ºC for >12 seconds can be achieved to satisfy the NCP curing requirement.

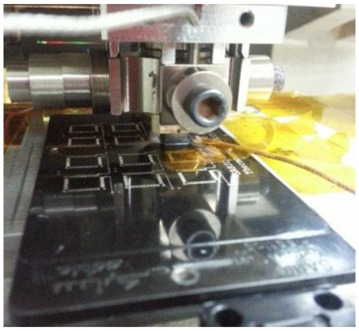


Figure 7: TCB bonding temperature measurement.

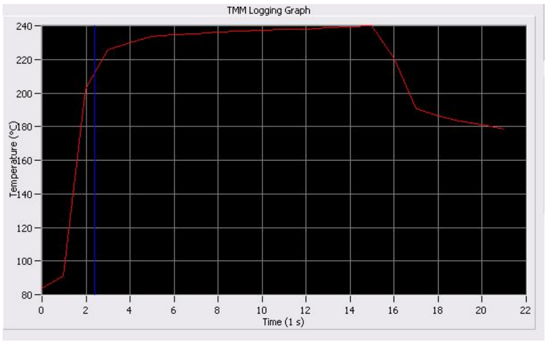


Figure 8: Actual temperature profile for the bonding process.

Results and Discussions

Gold wires with a diameter of 1 mil are used for the experiment. After bumping, the diameter, height and shear forces of the bumps were measured. Figure 9 shows a typical gold stud bump.

Figure 9: Gold stud bump.

Table 2 gives the measurements results on the gold stud bumps. The preset requirements are derived either by the physical constrains or standard requirements (4). Tight process control is achieved as reflected from Cpk values.

Table 2: Gold stud bump characteristics

	Bump diameter (um)	**Bump height (um)**	**Shear force (g)**
Min.	66.9	40.0	29.86
Max	69.4	42.9	35.45
Mean	67.85	41.42	32.14
Requirement	63.5-75	Min. 30	Min. 20.6
Cpk	2.73	6.39	3.99

After flip chip thermocompression bonding, the continuity of daisy chains was checked without showing any opens. X-ray imaging showed all the bumps were bonded to the center of pads without obvious misalignment. C-SAM demonstrated that there was no void at the bonding areas. Figure 10 shows post bonding inspection results.

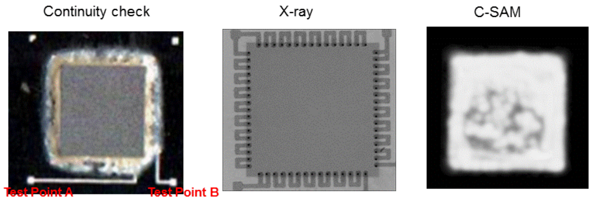


Figure 10: Post bonding inspection (continuity check, X-ray imaging and C-SAM)

Figure 11 shows the optical photos of cross sectioned samples bonded at the bonding force of 87.1grams per pad. It is expected that the soft gold stud bump will deform under the compressive forces; however, significant deformation of substrate pads is observed. More seriously some pads show breakage and cracks. This raises serious concern on the bonding interface integrity and long term reliability.

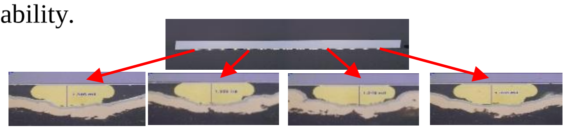
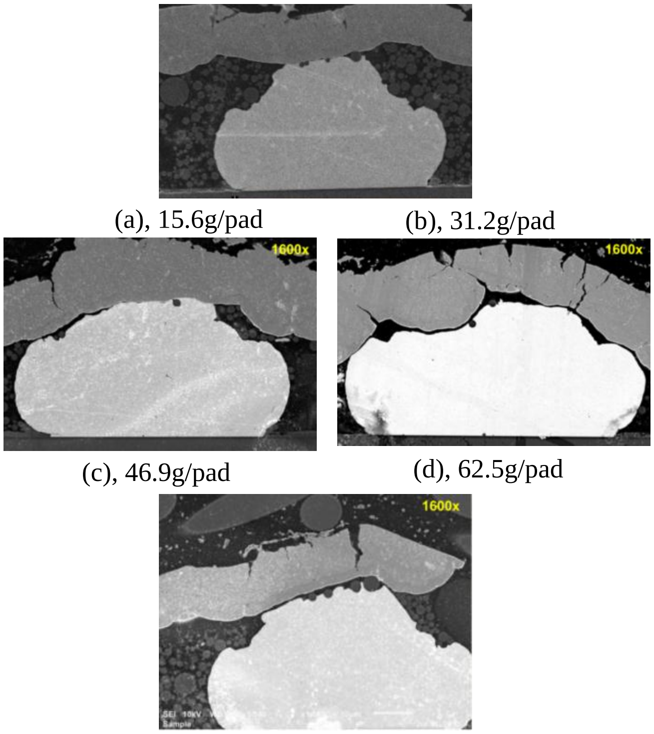


Figure 11: Substrate pad deformation during the TCB process.

In order to compare how the bonding forces affect the pad deformation, cross sectioning on assemblies with other bonding forces was performed. Figure 12 shows typical bonding interfaces at different bonding forces under SEM. Pad deformation can be clearly observed for the bonding force of 31.2 grams per pad and above. Significant pad breakage and crack can also be clearly observed. At the lower force, 15.6 grams per pad, no obvious pad deformation is observed.



(a), 15.6g/pad (b), 31.2g/pad

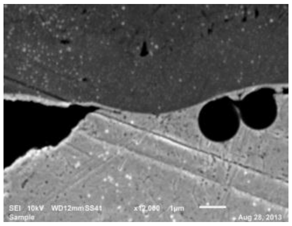
(c), 46.9g/pad (d), 62.5g/pad

(e), 78.1g/pad

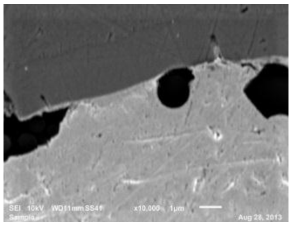
Figure 12: Deformation of substrate pads during thermocompression bonding

Multiple factors could be responsible for the deformation of pads: bonding force, bonding temperature, MID substrate material, and plating quality. As shown in the previous photos, a high bonding force causes more deformation of pads. A high bonding temperature is necessary to form bonds between gold studs and pads and to fully cure the NCP resin (5); however, it is found that the bonding temperature (240°C) is close to the softening temperature of the NCP resin with a HDT temperature at 263°C (6). Under the flip chip bonding conditions, the NCP substrate may not provide adequate mechanical support to the pads, especially when the stress is mainly concentrated on the tips of the gold studs. Accordingly the pads deform under compressive load with the contact areas deforming the most. The metal trace on the MID substrate is made through the electrolytic plating process after laser structuring of the substrate resin. The roughness of the substrate surface after laser structuring will affect the plating uniformity, which then affects the bonding interface integrity and makes the traces more prone to crack and breakage.

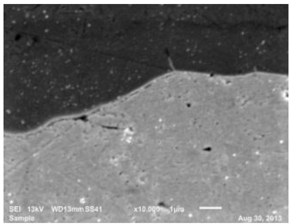
From the cross sectioning, no obvious deformation is observed on the bulk of the gold studs, except the tips of the studs, due to softening of the MID substrate at the bonding temperature. The small contact area between gold studs and deformed substrate pads raises a concern about bonding reliability in terms of whether metallic bonding is formed at the contact interface. Figure 13 shows the contact interface between gold studs and substrate pads under very high magnification for all the bonding forces evaluated. All the samples show some degree of metallic atomic bonding, a continuous path between the flash gold plating and the gold stud, regardless of the width of the area successfully joined, although gaps between gold studs and substrate pads exist for more areas.



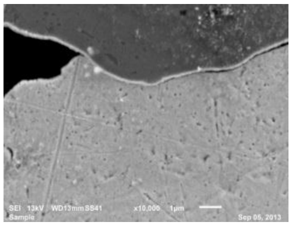
(a), 15.6g/pad



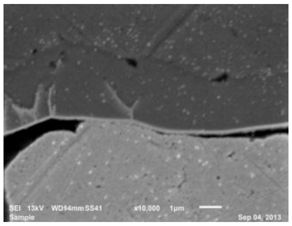
(b), 31.2g/pad



(c), 46.9g/pad



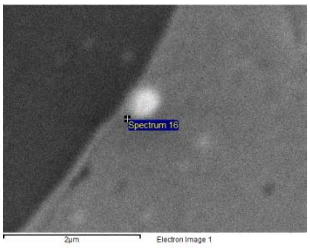
(d), 62.5g/pad



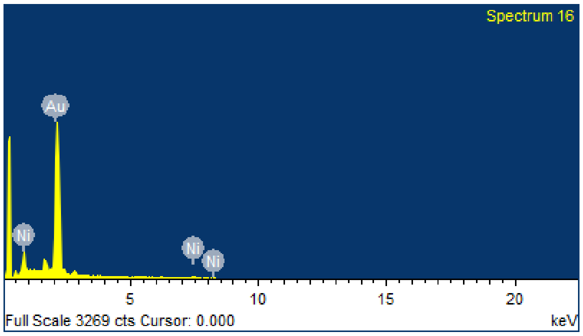
(e), 78.1g/pad

Figure 13: Bonding between Au stud and substrate pad Au plating at different bonding forces

The gold-gold atomic bonding is accompanied by the formation of a thin intermetallic layer, as shown in the EDX measurement (Figure 14). EDX analysis suggests a formula of Au_3Ni. The intermetallic layer is not clear in the SEM images; deductions made from the EDX spectra within this report suggest it is rarely more than 0.1nm thick and never more than 0.3nm thick.



(a), EDX measurement spot



(b), EDX measurement spectrum

Figure 14: EDX measurement on the bonding interface.

Although there is a certain degree of bonding between the gold stud and gold plating, the tiny bonding area may not be strong enough to secure the chips in place. To examine this, we purposely bonded a few samples without dispensing the NCP material. After the process, the chips fall off easily without using external forces. Therefore NCP material is essential for the thermocompression bonding process. The contraction of NCP material during curing causes a compressive stress on the contact interface to enable a reliable bonding interface between gold stud bumps and substrate pads.

After the thermocompression bonding process, reliability tests were done based on IPC-SM-784 standard (3):

- Thermal cycling: -55ºC ~ +125ºC (1000cycles).
- Humidity test: 85ºC/85%RH (500hours).
- High temperature storage: 125 ºC (500 hours).

Due to limited samples available, the reliability was only performed on samples with selected bonding forces.

- 78.1g/pad: 10 samples each for all above three tests.
- 46.9g/pad: 3 samples for temperature cycling.
- 15.6g/pad: 3 samples for temperature cycling.

After prolonged testing, the continuity of all the samples was checked. No opens were detected. This demonstrated that the samples bonded with lower forces can have the same reliable bonding interface as the samples with higher forces. It is possible to optimize the bonding force to reduce the substrate pad deformation while maintaining bonding reliability.

Summary

The flip chip thermocompression bonding has been successfully demonstrated on the molded interconnect device substrate.

Significant pad deformation and cracks during the thermocompression flip chip bonding process were observed, primarily due to high bonding temperature and bonding force, and softening of MID substrate material at the elevated bonding temperature.

A certain degree of gold to gold bonding is formed at the bonding tips and surrounding areas for all the evaluated forces. However, the tiny bonding area does not provide adequate strength to secure chips in place; contraction of NCP during curing is essential for a stable interconnect.

Bonding force needs to be further optimized to reduce the substrate pad deformation while maintaining a stable and reliable bonding interface.

Acknowledgments

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