High-Performance Flip Chip Bonding Mechanism Study with Laser Assisted Bonding

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***Abstract*— Recent advanced flip chip ball grid array (FCBGA) packages require high input/output (I/O) counts, fine-pitch bumps and large/thin package substrates. One of the key hurdles to accommodate these requirements is the flip chip bonding process. Therefore, advanced flip chip bonding technologies are continuously being developed and one of the promising solutions is laser assisted bonding (LAB) technology. The key advantage of LAB is its extremely short bonding time (less than 1 sec) with a localized heating area which provides low thermal and mechanical stresses.**

In this study, two bonding profiles of "time fixed" and "power fixed" are tested using 15.2 x 15-mm^2 FCBGA test vehicles with three difference die thicknesses. Wetting sequences of the solder joints are inspected with time interval of 100 ms. Solder bump interconnections are analyzed by cross section and reliability tests are performed. LAB is also compared with thermocompression bonding (TCB) for process and solder joint characteristics.

Keywords-component; Laser Assisted Bonding, LAB, Thermocompression Bonding, TCB, Flip Chip

I. INTRODUCTION

The chip interconnection technology in package assembly is increasing in complexity and sophistication with the increasing number of input/output (I/O) signals from the various functionalities and higher performance specifications of integrated circuit (IC) chips [1].

In flip chip packages, there are two bump shapes, i.e., solder bumps and copper pillars bumps. In case of solder bumps, the risk of a solder bridge increases as the bump pitch becomes smaller and the warpage of a package becomes larger. The risk may be reduced by using copper (Cu) pillar bumps because of its minimized solder volume and narrow bump shape. However, the same risk still exists as the sizes of the flip chip and the package increase. So, a new flip chip interconnection method is required to solve these problems.

In flip chip interconnection, the mass reflow (MR) process has been widely accepted because of the advantage of the highest productivity. However, its process time is relatively long (5~10 minutes) and that increases the thermal expansion of die and substrate which causes high warpage during the process. It also increases the risk of solder non-wet or bridge failures.

The thermocompression bonding (TCB) process is another process for flip chip interconnection [2]. The TCB process applies a compression force in addition to heat at the same time, so the solder joint height and shape can be controlled as expected. However, TCB has low productivity which comes from the unit-based process characteristics in comparison with the MR, which is a batch process.

To solve these problems, i.e., high warpage change from MR's high thermal budget and the low productivity of TCB, Amkor invented and introduced a novel laser assisted bonding (LAB) process in 2015 [3]. The laser source enables selective heating at a localized interconnection area. Thereby the thermal expansion of a substrate and its warpage can be minimized. LAB also enables fast temperature ramp-up and short overall bonding time. So, productivity comparable to the MR process can be achieved. That means LAB is a promising technology enabling next generation flip chip bonding for large packages with fine-bump pitches. The comparison for flip chip process is described in TABLE I.

TABLE I. COMPARISON TABLE FOR FLIP CHIP PROCESS

Process	Mass Reflow	TCB	LAB
Productivity	Highest productivity	Lowest productivity	High productivity
Bonding time	Longest bonding time (5~10 minutes)	Short bonding time (a few seconds)	Shortest bonding time (less than 1 second)
Thermal stress	Highest thermal stress	Lowest thermal stress	Lower thermal stress
Warpage control	High warpage risk	Lowest warpage risk	Lower warpage risk

This study introduces LAB technology details. For this purpose, the LAB process was setup and optimized with key parameters using fine-pitch test vehicles. For the verification of the LAB process, bump joints were analyzed by cross-sectional analysis and reliability tests were performed. In addition to comparing the test results with TCB results, the differences between the two bonding methods will be discussed.

II. TEST VEHICLE DESCRIPTION

The test vehicle is a flip chip chip scale package (fcCSP). The package body size is 15.2 x 15.0 mm^2 and the silicon (Si) die size is 12.0 x 12.0 mm^2. Bump pitch is 40/80-µm staggered with the 35.0 x 60.0-µm oblong type bump diameter. The total bump height is 65 µm by 40-µm copper pillar bump with a 25-µm Sn-Ag solder cap. The organic substrate has copper trace with around 15-µm width and the pad finish is organic solderability preservative (OSP). The substrate thickness is 221 µm with 2 layers. Additional information for the test vehicle is described in Fig. 1.

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	Test vehicle information	
Laser	Wavelength	980-nm
	Optic	Rectangular homogenized beam optic
Package	Package type	fcCSP
	Package body size	15.2 x 15.0 mm^2
	Total height	0.73 mm
Die	Die size	12.0 x 12.0 mm^2
	Die thickness	100-µm , 250-µm , 780-µm
	Bump pitch	40/80-µm
	Bump diameter	45 x 70-µm (Oblong)
	Bump height	45-µm Cu / 20-µm SnAg (Total 65-µm)
Substrate	Strip size	CA 74 (2 window)
	Layer count	2 layer
	Total thickness	221 µm
	FC pad finish	OSP

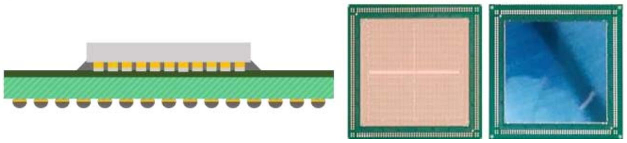


Figure 1. Test vehicle details.

A total of 3 die thicknesses (100-µm, 250-µm and 780-µm) were evaluated in this study. Both TCB and LAB processes were used to confirm the effects of die thickness differences.

III. LAB EXPERIMENTAL DETAILS

A. *Laser mode*

There are two laser modes in LAB. The first is the step mode. It utilizes the maximum capacity of the output power from a laser generator and would be suitable for high heating ramp-up within very short bonding time. This mode is most widely used in LAB because of its short bonding time.

The second one is the linear mode. In this mode, the laser power is raised according to the laser setting time. It can adjust the ramp-up rate of the heating. The output power is automatically calculated by setting the laser power and time. This mode can be utilized for slow and/or intentional heating ramp-up rate, but it generally requires longer bonding cycle time than the step mode. Fig. 2 shows conceptual graphs of each mode. In this study, the step mode is used.

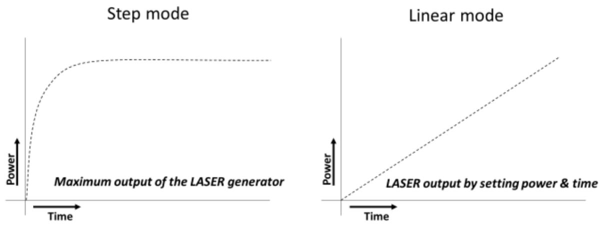


Figure 2. Laser modes: (left) step mode and (right) linear mode.

B. *LAB profile*

A proper bonding profile is essential for good solder joint quality. The temperature bonding profile is adjusted primarily by the laser power and time in LAB. A fine time control is capable since the laser time resolution is 1 ms.

The bonding temperature profile was measured by a thermocouple kit as shown in Fig. 3, where the thermocouple's time resolution is 100 ms. A bonding stage block is also needed for sample loading and the same stage block temperature of 70°C was applied for both the TCB and LAB processes.

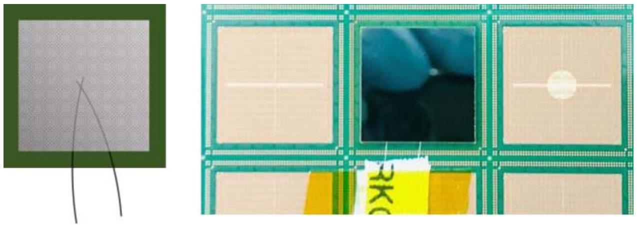


Figure 3. Thermocouple kit: the thermocouple wire is located in the center of the die bump area.

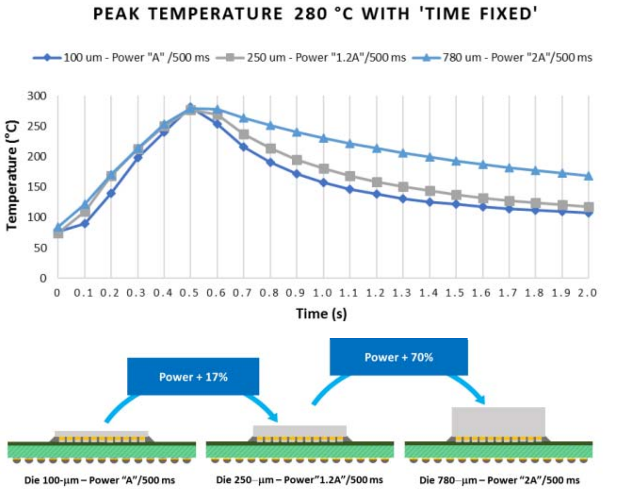


Figure 4. LAB profile with 'Time 500 ms fixed.'

Two different bonding profiles were used: (1) TIME FIXED, and (2) POWER FIXED. In the TIME FIXED bonding profile, the laser power is increased with increasing die thickness. Silicon 100-µm thick showed good bonding quality with optimized power "A" and achieved target 280°C. Silicon 250-µm thick needs around 20% higher laser power and 780-µm thickness die requires twice power of 100-µm thickness. It is also noted that each case shows different cooling rates as shown in Fig. 4. The thicker silicon shows slower ramp-down than the thinner silicon.

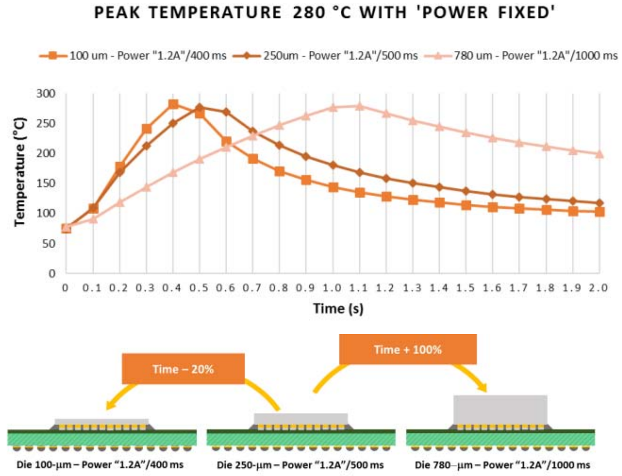


Figure 5. LAB profile with 'Power 135 Watts fixed.'

In the POWER FIXED bonding profile, the power of silicon 250-µm thick at TIME FIXED bonding profile, was used to verify the time reduction in thinner die thickness. As shown in Fig. 5, the silicon 100-µm thick needs 100 ms less time to reach the peak temperature of ~280°C than the silicon 250-µm thick. In the case of silicon 780-µm thick, it takes 1000 ms which is 100% longer time than the silicon 250-µm case.

C. *Cross-section validation*

To verify the solder joint quality, cross-section analysis was performed. Cross-section images show good joint wettability in all 5 bonding profiles as shown in Fig. 6. Especially, good solder joints were verified with laser time 400 ms (die thickness 100-µm and laser power "1.2A"/ 400 ms).

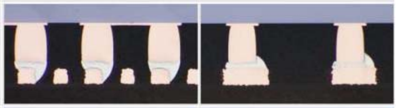
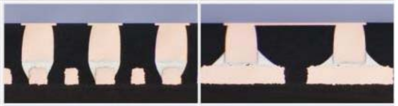
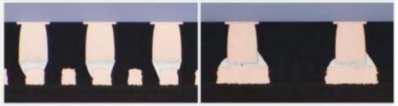
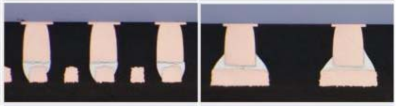
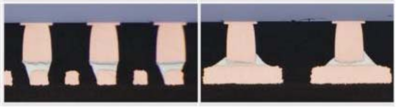
Die thickness	Laser power	Laser time	Cross section
100-µm	Power "A"	500 ms	
250-µm	Power "1.2A"	500 ms	
780-µm	Power "2A"	500 ms	
100-µm	Power "1.2A"	400 ms	
780-µm	Power "1.2A"	1000 ms	

Figure 6. Cross-section validation: LAB process.

D. *Solder joint wetting sequence*

As mentioned, one of the unique characteristics of LAB is a fine bonding time controllability. By this fine time management, solder joint wetting sequence can be observed. The bump joints were inspected with time interval of 100 ms up to 500 ms with 100-µm thickness die. The bonding profile temperature for each step is visualized in Fig. 7.

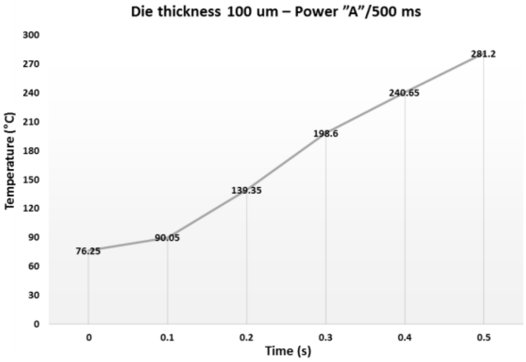


Figure 7. LAB bonding profile for solder joint sequence analysis.

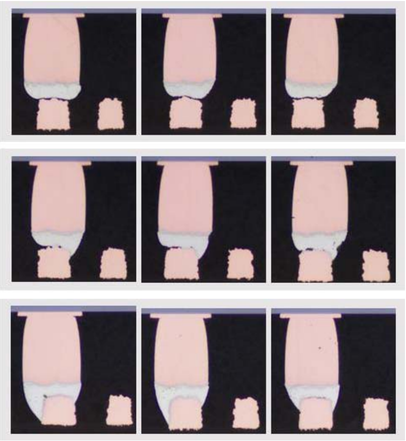
The following descriptions are the details of each joint sequence.

1) Laser time 100~200 ms: The temperature up to 200 ms is lower than 150°C and there is no change of solder bump.

2) Laser time 300 ms: The temperature has around 200°C (198.6°C) and the solder deformation is detected. The solder shape changes similar to the pad shape but the solder is not melted.

3) Laser time 400 ms: It can be seen that the solder starts wetting as it rises above 220°C (240.65°C). The solder wetting is observed at the surface and/or side-wall of the substrate copper trace pad.

4) Laser time 500 ms: When the temperature reached 280°C, which is the target temperature, all solder bumps melted and made full solder joint interconnections.


LASER Power : "A"
LASER time : 300 ms
Temperature : 198.6°C
→ Solder deformation

LASER Power : "A"
LASER time : 400 ms
Temperature : 240.65°C
→ Partial wetting

LASER Power : "A"
LASER time : 500 ms
Temperature : 281.2°C
→ Full wetting

Figure 8. Solder joint sequence – laser time 300 ms, 400 ms and 500 ms.

As shown in Fig. 8, all solder joining was completed in 400 ms ~ 500 ms. It is also noted that the flux, which enables OSP evaporation and solder oxide breaking, was activated within 500 ms. According to a previous study on solder wetting time, the initial wetting time is significantly reduced at temperatures above 250°C [4]. Therefore, the fast temperature ramp-up capability of LAB enabled all the bonding sequences to occur within a second.

With these capabilities, LAB can provide various evaluation options for flux chemical reaction and solder wettability tests. Flux formulation and composition also could be optimized and tested by using the LAB.

E. Reliability test result

To verify the LAB process, reliability test was performed with die 100-µm thick and time fixed condition. This test vehicle has daisy chains to support open/short testing. All the test items are passed without any issue as shown in Fig. 9. All the reliability test was performed based on the JEDEC standard.

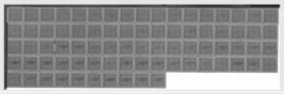
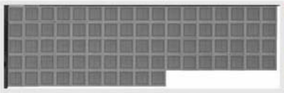
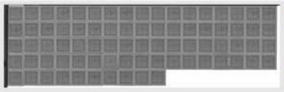
Test item	Test conditions	Electrical test (open/short)	Scanning acoustic microscopy (SAM)	Cross section
MRT (L3)	– 30°C/60%RH 192hrs with 3X 245°C peak reflow	22/22 (100%)		
TCB	-55°C/125°C, 1000X	77/77 (100%)		
HTS	150°C, 1000hrs	77/77 (100%)		
HAST	130°C/85%RH, 264hrs	77/77 (100%)		

Figure 9. Reliability test results: LAB process.

IV. TCB EXPERIMENTAL DETAILS

A. TCB bonding profile

The TCB process was also evaluated to compare the two processes – LAB and TCB. The bonding profile was set by a thermocouple kit like the LAB test. The same target peak temperature of 280°C and the same test vehicles with three different die thicknesses (100 µm, 250 µm and 780 µm) were used. In terms of the temperature ramp-up method, a similar concept of the 'step mode' was applied. The TCB process also applied constant power to the ceramic heater when it was starting the bonding process.

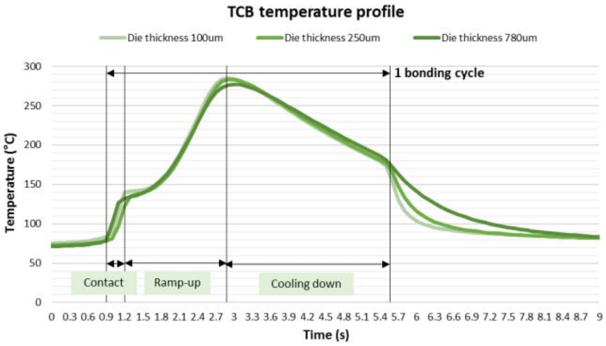


Figure 10. TCB temperature profile.

The TCB temperature profile has 3 steps as shown in Fig. 10. Contact (~150°C) is the first step where the die bumps touch the substrate pad before heating ramp-up, which is the second step. During the heating ramp-up stage, the peak temperature of 280°C is achieved. Finally, it moves to cooling down step for solder solidification. Like the LAB process, TCB profiles showed slower cooling down at thicker silicon thickness after bond head detachment from the die.

Based on the TCB test input parameters, as shown in TABLE II, almost the same parameters were applied for all the die thickness cases to achieve the similar peak temperature of ~280°C. That means, in the TCB process, the silicon thickness does not significantly affect the bond head input parameters.

TABLE II. TCB - BOND HEAD INPUT PARAMETER

Die thickness	Bond head input parameter					Peak temperature (by thermocouple)
	Contact temperature	Step 1		Step 2		
		Temperature	Time	Temperature	Time	
100-µm	150°C	390°C	1.4 s	100°C	3.0 s	**285.25°C**
250-µm		390°C	1.4 s	100°C	3.0 s	**283.45°C**
780-µm		390°C	1.5 s	100°C	3.0 s	**277.4°C**

B. Cross-section validation

To verify solder joint wettability in the TCB process, cross-section analysis was performed, and the results were good joint wetting for the 3 die thicknesses as shown in Fig. 11.

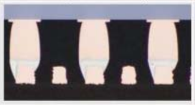
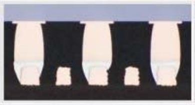
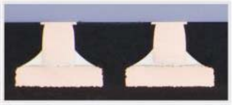
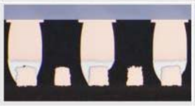
Die thickness	Bond head input parameter	Cross section	
		Peripheral bump	Core bump
100-µm	Step 1 : 390°C / 1.4 s Step 2 : 100°C / 3.0 s		
250-µm	Step 1 : 390°C / 1.4 s Step 2 : 100°C / 3.0 s		
780-µm	Step 1 : 390°C / 1.5 s Step 2 : 100°C / 3.0 s		

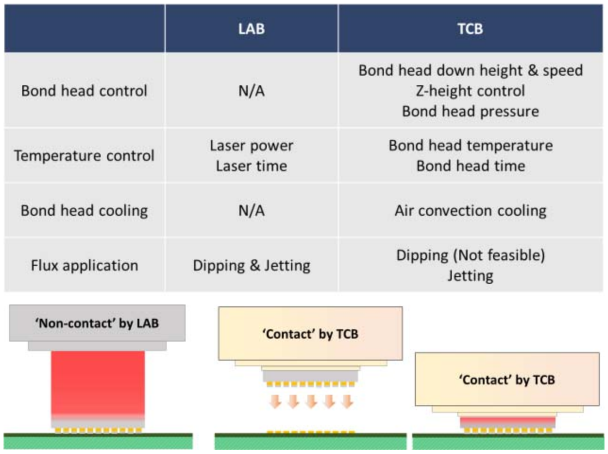
Figure 11. Cross-section validation: TCB process.

V. COMPARISON BETWEEN LAB & TCB

The following sections compare the two processes regarding process, bonding profile, bump alignment capability and characteristics of intermetallic compounds (IMCs).

A. Process comparison

The LAB process is a ‘Non-contact type’, whereas the TCB process is the ‘Contact type’. From this difference, the TCB process requires additional tooling and bonding steps compared to LAB. LAB is a very simple process and laser parameters (laser power and time) are the only adjustable parameters but the TCB process has additional parameters as shown in Fig. 12. The bond head related parameters need more bonding time causing lower throughput. In addition, tooling cost will be added in the TCB process for die chip handling. In terms of the flux application, there is a limitation to apply a dipping type flux in the TCB process due to the high temperature remaining in bond head tool that needs to cool down to room temperature to prevent any side effects. Therefore, dipping flux is hard to be applied for the TCB process. In contrast, the LAB process can use both flux applications. From a simplicity and productivity point of view, if the product quality is same and no other issues exist, the LAB process would be better than the TCB process.



	LAB	TCB
Bond head control	N/A	Bond head down height & speed Z-height control Bond head pressure
Temperature control	Laser power Laser time	Bond head temperature Bond head time
Bond head cooling	N/A	Air convection cooling
Flux application	Dipping & Jetting	Dipping (Not feasible) Jetting

Figure 12. Process comparison – LAB and TCB.

B. Bonding profile comparison

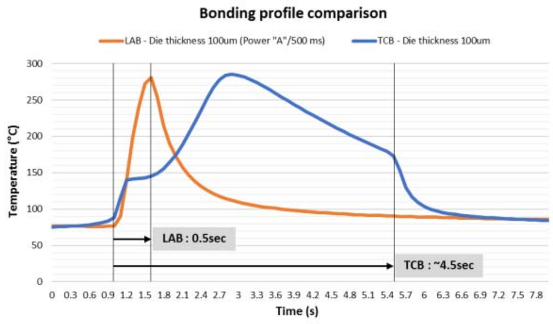


Figure 13. Bonding profile comparison.

With the same conditions for die thickness and profile peak temperature, TCB bonding time is about 4.5s and LAB is 0.5s, as shown in Fig. 13. TCB bonding time is about 8 times longer than LAB. The ramp-up and cooling rate can be different per equipment capability, however, TCB may not be easy to achieve equivalent bonding cycle time as LAB.

C. Bump alignment capability

As the requirement for higher I/O density increases, bonding capability for finer pitch becomes a major item in the flip chip technology. TCB bonding alignment depends on the capability of the bond head accuracy and the bonding position is fixed based on the machine recognition position. To validate the self-alignment, an intentional shift test was performed. No shift and 10 µm of intentional shift cases were evaluated.

Case 1 (Fig. 14) shows the combination of no shift at chip placement and LAB bonding. Due to no shift, case 1 showed no alignment issue. For Case 2 (Fig. 15), even though there was an intentional 10-µm shift during chip placement, the bumps were well aligned after the LAB process by the self-alignment effect. Therefore, results confirmed that self-alignment is possible in LAB. In case 3 (Fig. 16), which is for the TCB process, no shift in TCB showed good alignment. However, the intentional 10-µm shift caused bump solder bridging due to no self-alignment in TCB. This test verified the capability of self-alignment in LAB.

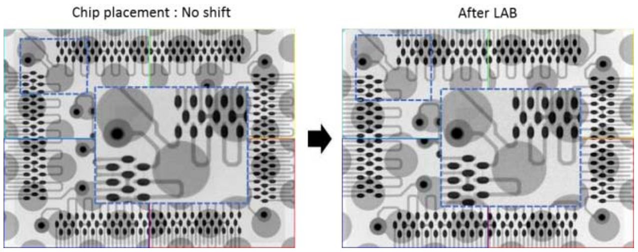


Figure 14. Case 1: No shift / LAB: (left) before and (right) after LAB.

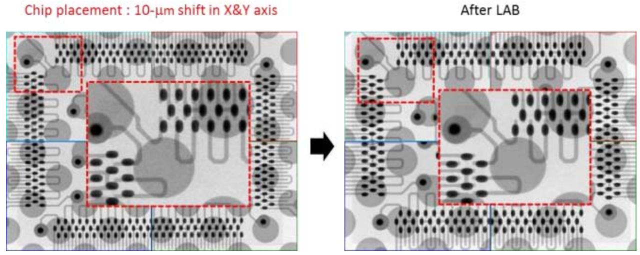


Figure 15. Case 2: 10-µm shift in X&Y axis / LAB : (left) before and (right) after LAB.

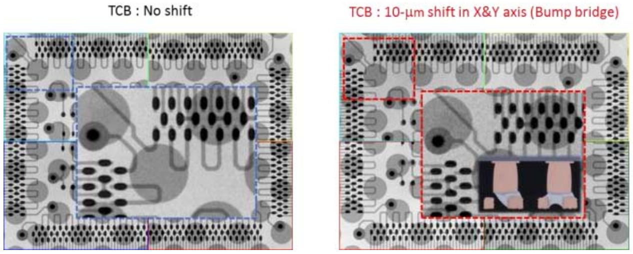


Figure 16. Case 3: (left) No shift and (right) 10-µm shift in X&Y axis for TCB.

D. *IMC comparison*

IMC shape and composition were compared at the end of line (EOL) stage. As shown in Fig. 17, the IMC phase is Cu_6Sn_5 and it shows almost similar IMC thickness for LAB and TCB process.

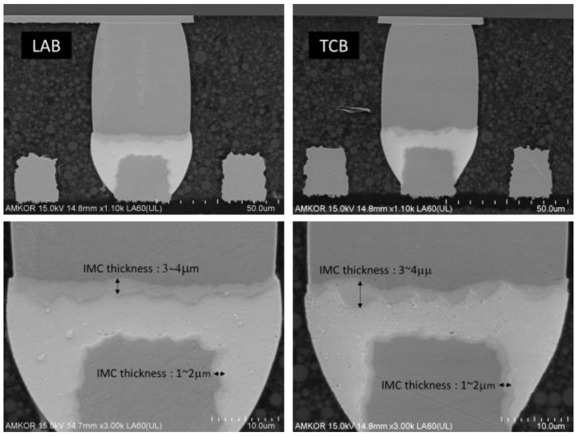


Figure 17. IMC comparison : (left) LAB and (right) TCB process.

VI. CONCLUSIONS

This study demonstrated the advantages of the LAB technology, especially for fine-pitch flip chip package assembly. By comparing LAB with other bonding methods, high bonding quality, workability and productivity was verified. Further study and development of LAB technology will help to expand the scalability of the flip chip technology.

The results from this study are summarized as below.

- LAB has different laser bonding parameter based on silicon thickness. However, TCB process shows almost same bonding parameters regardless of the silicon thickness.
- In the LAB process, solder joint wetting is possible within 0.5 sec which is 8 times faster than TCB.
- Self-alignment capability has been confirmed in the LAB process.
- Similar IMC growth is confirmed for LAB and TCB processes.

VII. ACKNOWLEDGEMENT

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