TOWARD A FLIP-CHIP BONDER DEDICATED TO DIRECT BONDING FOR PRODUCTION ENVIRONMENT

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ABSTRACT

3D vertical integration of components is now an industrial reality. To reduce interconnection pitch between the various dies, the hydrid bonding technique, which can offer sub-10µm interconnection pitch, is widely demonstrated for Wafer-to-Wafer bonding. Die-to-Wafer direct bonding remains today more challenging due to additional particle contamination and handling complexity.

The purpose of this paper is to demonstrate the performance of a fully automated Die-to-Wafer bonder, SET FC1, specifically designed for direct bonding. After a description of the elements developed specially for direct bonding (loader…), it will be demonstrated that a throughput up to 500 dph (dies per hour) with an accuracy of ± 1µm can be reached today. If progresses still need to be done, the particle contamination is low enough to enable the 1st demonstration of oxide/oxide Die-to-Wafer direct bonding.

First results with dummy dies are promising with similar alignment accuracy and significant improvement of the throughput compared to previous equipment SET FC300.
These performances have been confirmed on bare dies.
If these results are very encouraging, current tests are ongoing with copper/oxide patterned dies.
Trade-off between short cycle time and high bonding precision seems less crucial and industrialization appears feasible.

Key words: Flip-Chip, Direct Bonding, Fine Pitch, High Precision, High Throughput.

INTRODUCTION

Miniaturization of devices, increase of speed and bandwidth between dies and reduction of power consumption lead to finer vertical interconnection pitches below 20 µm. However, at these dimensions, conventional microbump processes face dramatic challenges as undercut and microbridging. Therefore, direct hybrid bonding process has been developed since early 00's to address high density 3D market by offering connection pad dimensions as small as 1 µm [1-3]. As an example, Back-Side Illuminated imagers (BSI imagers) players have released since 2012 many 3D prototypes achieved thanks to Wafer-to-Wafer hybrid bonding, and some of those demonstrators are now in production mainly driven by mobile phone applications [4]. However, hybrid bonding technic is also interesting for other markets from high performances (HPC, server) to consumer (medical, display), which require Die-To-Wafer hybrid bonding. Indeed, Die-to-Wafer is required for multi dies stacking on interposer and for Known-Good-Dies assembly strategy.

Previous work has already shown the Die-to-Wafer hybrid bonding feasibility and electrical performances thanks to an SET FC300 equipment [5]. Nevertheless, die handling without particle contamination as well as high throughput remain today very challenging. Indeed, published work mentioned a throughput not over 60 dies per hour in order to ensure ± 1 µm alignment [7]. Reaching simultaneously the throughput/ accuracy & cleanness objectives is very challenging as these parameters are linked to each other. Indeed, high throughput means fast movements which favors particles generation. It also means additional heat generated by motors. Yet this heat leads to mechanical deformation of module parts and then further accuracy loss which can be dramatic when dealing with fine pitch interconnection.

To realize better the accuracy challenges, let's take the example of one 10 mm chip to bond @ ± 1 µm onto a substrate. Keeping the same proportions, it is equivalent to park his car in a garage with only 0.17 mm space on each side of the vehicle between the walls of the garage!

The purpose of this paper is to present the performances of an innovative high precision Die-to-Wafer Flip-Chip equipment specifically designed for direct bonding, following considerations exposed on a previous paper [6]. The final throughput target of the new equipment SET FC1 is 1000 dph with an accuracy of ± 1µm, which aimed throughput is very aggressive compared to the one of previous equipment FC300 [7].

After a brief reminder of the Die-to-Wafer direct bonding flow, the first part of the article will introduce the tool specifications and modules mandatory to meet the throughput / accuracy / cleanness objectives [6]: loader dedicated to holders filled with ready-to-bond dies, the double picking head, the alignment and bonding module.
The second part will be dedicated to expose the current tool performances: particle level measurements, alignment accuracy and throughput.

At the end of the paper, the first direct bonding obtained with oxide/oxide Die-to-Wafer bonding will be presented.

PROCESS AND TOOL DESCRIPTION

Die-to-Wafer direct bonding process

Die-to-Wafer direct hybrid bonding is less mature than Wafer-to-Wafer because the overall process flow is more complex after surface preparation due to die and not wafer handling. Description of the main steps constituting the Die-to-Wafer and Wafer-to-Wafer hybrid bonding process flows are shown in the figure 1 below:

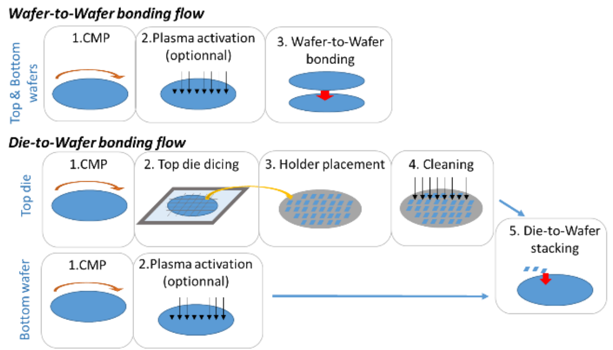


Figure 1: Main steps of the Die-to-Wafer and Wafer-to-Wafer direct bonding**.**

It can be seen that in the die-to-Wafer stacking flow, the top die preparation steps are much more complex and require specific holders after dicing in order to ensure the die handling during the cleaning and the stacking process.

Today some holders using vacuum or electrostatic charge are under development.

Therefore, the loaders of the direct Die-to-Wafer stacking equipment should not be designed for wafer on tape and frames (as in conventional stacking process) but for 200mm or 300mm wafer holders.

Tool Overview

The architecture of the bonding equipment has been thought to optimize throughput: minimized mobiles masses to get high acceleration, choice of material to get a good compromise stiffness / lightness, locations of different modules to reduce strokes and optimize movements and use of dual heads system to enhance cycle time.

General view of the machine can be seen on the figure 2 below.

Figure 2: Bonding Equipment in cleanroom

The main module ("Process") can be seen on the right of the picture. It contains all the axis to align in X, Y, Theta and parallelism and, of course, the Z axis, the vertical movement to bring into contact the chip with its substrate. This module contains also a high-resolution microscope allowing the alignment of the components.

A feeder module, on the left of the picture, is fixed close to the process module to store holders for the chips to be bonded. It contains also XYZ movements. It has been adapted to store and handle carefully and cleanly the dies from their holder to the bonding head.

PICKING TOOL PERFORMANCES EVALUATION

Particle Contamination

Cleanliness Requirement

The materials have been carefully selected and shielding have been installed in critical locations. Air flow system, to minimize particles contamination and evacuate, as much as possible, particles from bonding space, has been put in place.

Cleanliness Measurement

We have measured the number of particles induced by the equipment under various test conditions (airflow ON/OFF, movement of different axis at different speed…). As an example, on figures 3 and 4, we have counted 150 added particles on a wafer, positioned onto the chuck for one hour when the Y chuck axis was moving at a throughput of 1000 dph without any airflow.

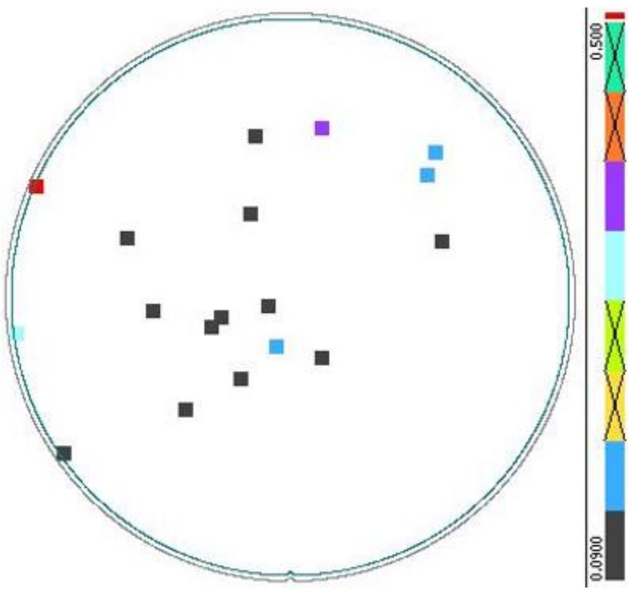


Figure 3: Example of measurement of particle contamination on Chuck: Before processing

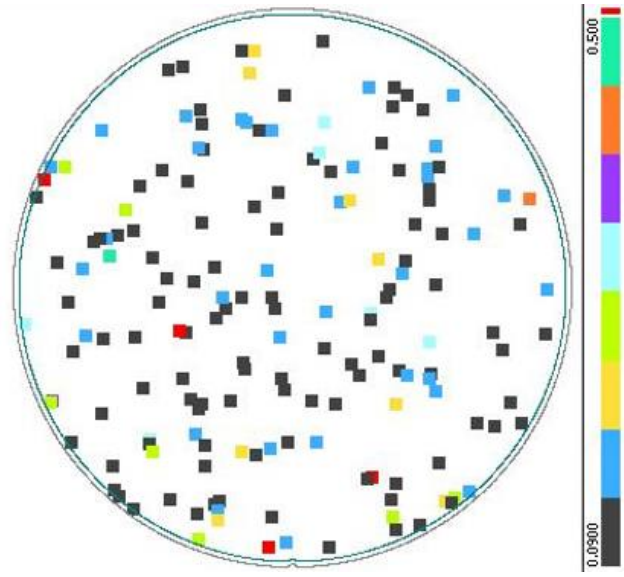


Figure 4: Example of measurement of particle contamination on Chuck: After processing

Synthetic table of results is shown below on figure 5. Particles counting has demonstrated that the process module of the equipment was sufficiently clean. Indeed, the number of particles brought by the process module is very low as shown below (green cells).

However, it can be seen on this table that the number of large particles induced today by the loading module is much higher than the one measured in process chamber. It can be explained by the fact that this module contains many mechanical displacement axis. Today, work is ongoing to improve the cleanliness of the feeder module. Redesign has been done, some mechanical elements have been changed, special protections have been added, cable management has been completely modified and air flows have been adapted.

Particle size [nm]	Reference Wafer	Cleanroom	Chuck	Support Holder
Particles counts before processing				
90-500	13	43	17	19
> 500	0	1	1	0
Particles counts after processing				
90-500	200	121	147	322
> 500	16	5	3	67

Figure 5: Synthesis of tests of particle contamination

ALIGNMENT ACCURACY

Methodology of Precision Tests

As a first step to qualify the precision of the bonding, we have used transparent quartz chips with verniers made of chromium deposited on one surface. These chips are loaded onto the machine, aligned (X, Y and Theta) as shown on figure 7 and put one onto the other, both chromed surfaces in contact, to simulate the bonding. The precision of the superposition is measured by the microscope through the quartz as shown on figure 8.

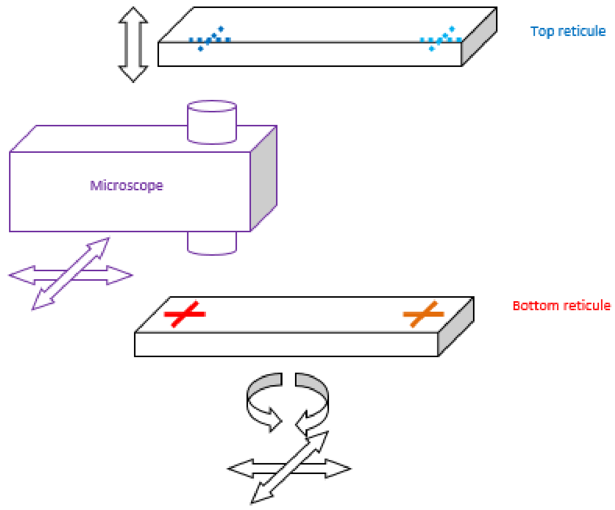


Figure 7: Principle of alignment between both reticles

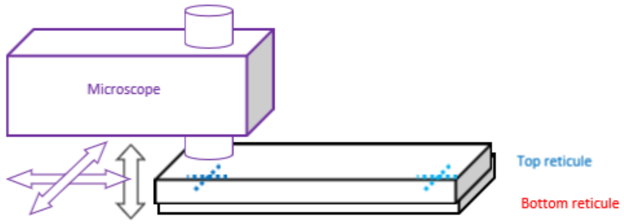


Figure 8: Principle of measuring post-bond accuracy

Several measurement campaigns, in automatic mode, have been achieved, generally overnight to collect high numbers of measurements.

Results of Precision Tests

The purpose of this first test was to check the equipment repeatability and dispersion of the bonding between the top and bottom reticles at the center of the chuck.

The dispersion is the amplitude of the variation of several measurements on a short period of time. A low dispersion means that the measurements are consistent and the equipment is repeatable. A low dispersion is mandatory but not sufficient to get a reliable and precise bonder.

The figure 9 presents the first record of post-bond accuracy measured on equipment described in previous paragraph. The blue and the dark orange curves represent the misalignment, after bonding, between top and bottom reticles, respectively in X and Y axis.

The light orange curve, "T Head", represents the temperature of the head holding the top reticle.

The target throughput is 500 dph. For this test, no preliminary calibration has been done. This means that even if the alignment between verniers of top and bottom reticles is achieved, those verniers are not necessarily superimposed once the bonding is done (when the upper reticle is in contact with the lower one).

We can notice that the dispersion is very low, in the range of ± 0.25 µm in X and Y axis. It means that the bonding repeatability is very good.

We also see that on the first 220 measurements (approximately 0.5 hour) precision varies, in particular on Y axis. On a longer period, there is still a trend, but with a much smaller variation. This can be explained by a "warm up" of the equipment, which is shown by the shape of the head temperature curve. Thus, it confirms that the temperature stability has an influence on the precision. Temperature increase is induced by the high throughput, which favor motors heating that can spread into the mechanical modules. However, it is important to note on the graph 9 that once the system reaches a temperature plateau (much slower ramp-up after approximately 220 bondings), the post-bond accuracy is very stable and remains in the range of ± 1 µm.

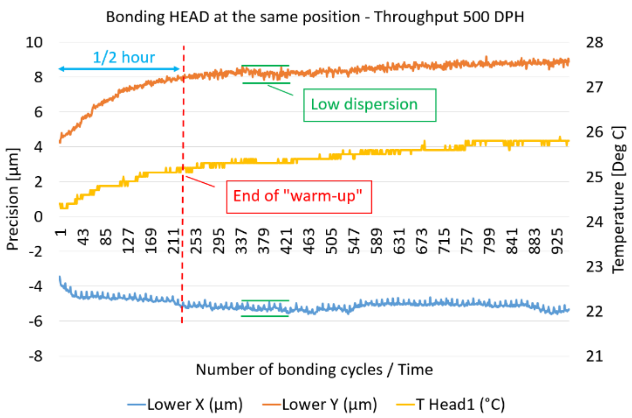
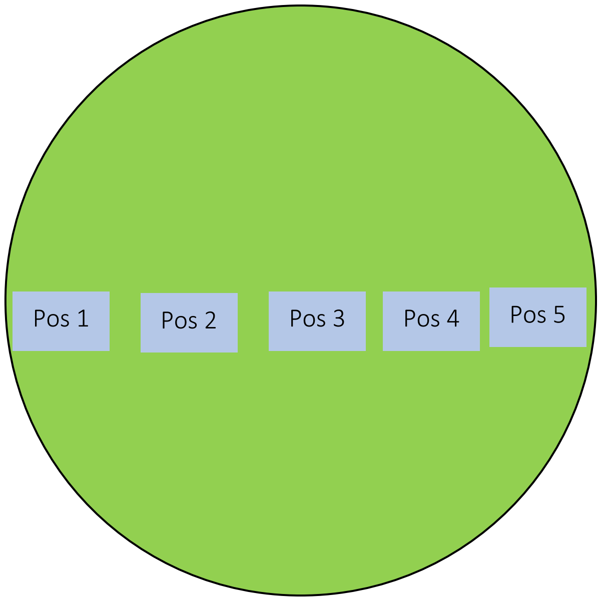


Figure 9: Test #1. Post-bond accuracy at the center

The goal of our second test is to evaluate the bonding accuracy reproducibility over the all bonding chuck surface. Therefore, the test conditions were very similar to the previous one, except that we have done the bonding at five different locations on the diameter of the chuck (see figure 10). In parallel, we have tested a method to compensate the dispersion on X axis.

We observe on the graph that the "warm-up" is still visible, especially on Y measurement (left side of each portion of orange curve) and a couple of measurements present a 1µm error at the left side of each portion of X Measurement (blue curve). Despite these two phenomena, dispersion is still very good (< ± 0.5 µm), as well as the precision (< ± 1 µm) which confirms the repeatability of the bonding process over the entire chuck area. The compensation in X seems fruitful, as no trend appears.



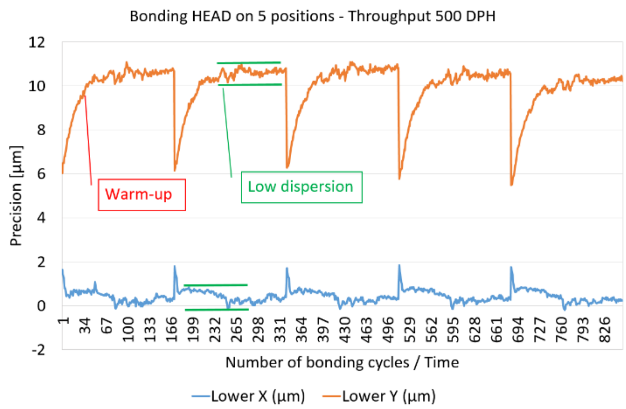


Figure 10: Test #2. Post-bond accuracy on 5 positions

Equipment Throughput

The goal of this equipment is to get a dry cycle as short as possible and to reach an ideal throughput of 1000 dph. Thus, each phase of the cycle of the machine itself must be rapid and optimized. Motors must be sufficiently powerful, on their entire stroke, for high acceleration and masses must be as light as possible, while permitting to get high stiffness and to have fast movements.

Logically, if the equipment is rapid, the process itself also must be rapid. That is why direct bonding is very interesting here, for HVM applications, as it is almost instantaneous. Therefore, the architecture of the machine has been imagined optimizing each single step, while working with two bonding heads. Based on our knowledge of our actual equipment and the technical characteristics of the motorization chain of the new equipment, we have simulated the duration of each elementary phase. Taking a process time of 1.5 second, the total throughput theoretically achievable is 900 dph, as can be seen on the figure 11. This value is not too different from the "ideal" 1000 dph.

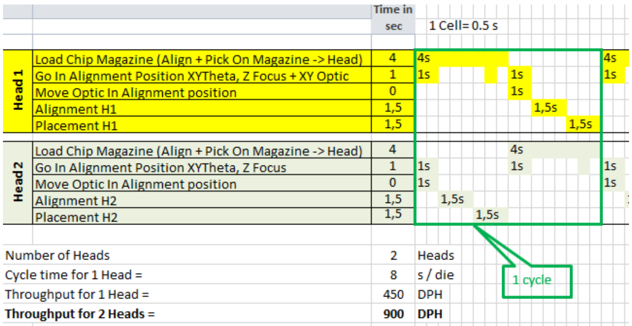


Figure 11: Simulation of cycle time of the equipment

From the first trials done, a throughput up to 400 dph on one head, therefore 800 dph on the equipment (two heads), have been reached, which is quite close to our theoretical estimation.

Relation Between Throughput and Precision

As mentioned above, because the difficulties to overcome are contradictory, we anticipate having a trade-off to make. If the requested final post-bond accuracy is high, it may be necessary to reduce the throughput and vice versa.
To check the repeatability of the equipment, we have introduced a "checking procedure". Automatically, the equipment verifies its precision and stability every n bonding cycles. We have tested the influence of the frequency of this checking on the post-bond precision with a specific bonding cycle.

On the graph 12 below, the equipment does this checking every 100 cycles. Thus, the total throughput is slightly reduced, by about 1%, compared to no checking at all, and the deviation is somehow high, but still remaining below ± 0.6 µm. We also can see a kind of "warm-up" phenomena at the beginning of each of the 5 portions of the curves. On position 3, we see an important defect, especially on the Y curve with a 0.7 µm drop (only 0.2 µm step on the X curve). We suspect a particle contamination in the center of the wafer. This highlights the huge importance of the cleanliness. Particle contamination can at best degrade the post-bond accuracy, at the worst prevent a good adhesion between chip and substrate.

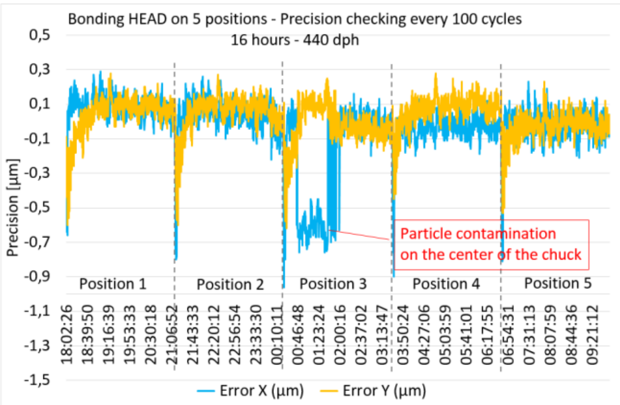


Figure 12: Checking of the repeatability every 100 cycles

On the graph 13 below, the equipment does this checking every 10 bonding cycles, thus ten times more often. Thus, the total throughput is slow down by about 10%. This leads to a throughput of 400 dph, to be compared to 440 dph obtained on the previous test. The advantage is the dispersion remaining at a lower level, below ± 0.25 µm.

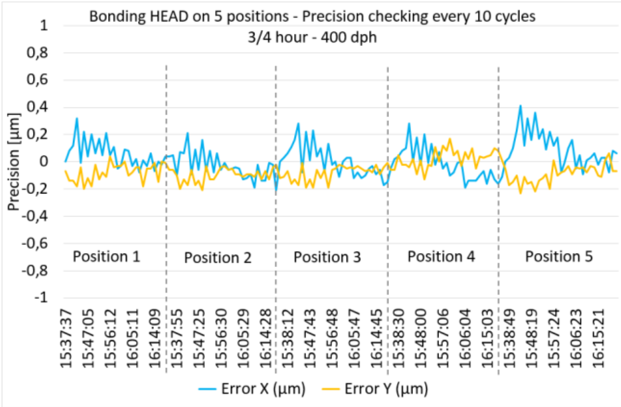


Figure 13: Checking of the repeatability every 10 cycles

As expected, a more frequent check of the precision slows down the throughput. This reduction is about 10%. Nevertheless, it permits, with a throughput of 400 dph, with the specific bonding cycle used, to reach a precision better than ± 1 µm with quartz reticles. These results are very encouraging and need to be validated on silicon components.

APPLICATION ON OXIDE/OXIDE DIRECT BONDING THROUGHPUT OF THE EQUIPMENT

Conditions of Tests

Some first stacking trials using oxide/oxide dies have been done in order to confirm throughput and bonding performances obtained on quartz reticles.

The dies are 1x1.4mm^2 with 2 verniers alignment marks etched into the silicon layer at left and right side of the die. A thickness of 750 nm of TEOS oxide has been deposited on the surface of both top and bottom silicon wafers. After CMP and dicing, the top dies were cleaned and placed into vacuum holders for stacking.
The throughput was around 450 dph.

Results of Tests

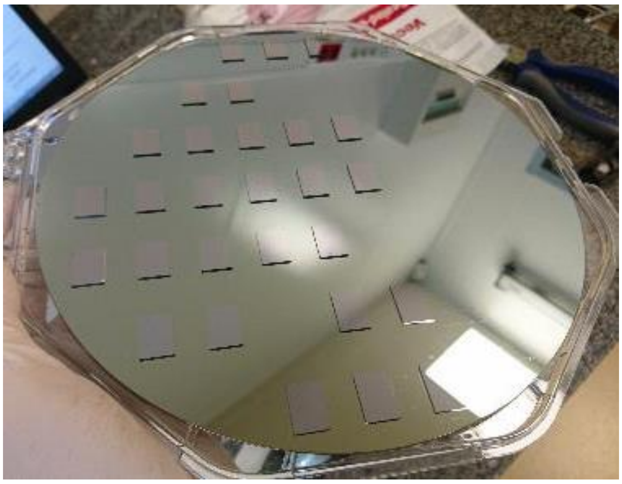


Figure 14: Direct bonding of real chips on Ø200mm wafer

Infrared inspection revealed a good bonding quality, as shown on the next picture (15).

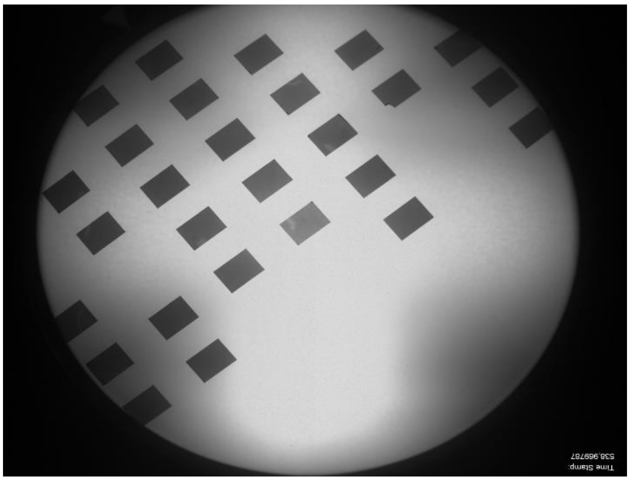
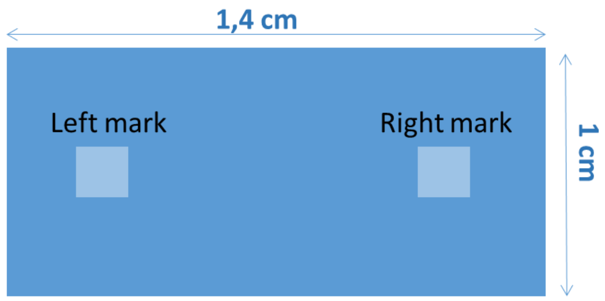


Figure 15: Infrared inspection of bonded real chips

The table in the figure 16 below presents the X and Y alignment accuracy measured on the left and on the right vernier marks of the die.



	X	Y
Left mark	+/- 0,8µm	+/- 1µm
Right mark	+/- 0,8µm	+/- 0,9µm

Figure 16: Alignment accuracy measured on oxide chips.

It can be seen that the alignment accuracy was always measured < +/-1 µm. The throughput, even if the number of dies bonded is low, was around 450 dph as said above. These primary results are very encouraging as they are very similar to the ones obtained on quartz reticles. They confirms the potential of throughput vs alignment of Die-to-Wafer using direct bonding technique.

CONCLUSIONS

These first harvest of measures has been done at SET facilities. They are very encouraging as precision is in the range of ± 1 µm and throughput is close to 500 dph. Cleanliness seems to be at an acceptable level to permit to achieve direct bonding with good adhesion of chips onto wafer.

FUTURE WORK

The beta tool has been installed at CEA-Leti facilities during summer. Thus, new campaigns will be driven during the coming months to fully qualify the equipment, on calibration reticles but also with real electrical components presenting hybrid bonding interfaces. Influence of the temperature will be intensively investigated, as well as quality and repeatability of the quality of bonding. Throughput in real conditions with real components, thus a real bonding cycle, will also be an important topic to explore.

ACKNOWLEDGEMENTS

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