Challenges to Be Faced on Flip-chip Bonder to Achieve Precision Requirements in Different Environments

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Abstract

Among different technologies to assemble and interconnect microelectronic chips together, flip-chip technology appears promising. Its main advantages are the potentially very high density interconnect and the much shorter interconnection paths.

We observe an everlasting search for the reduction of the dimensions and the power consumption of electronic systems, driven by all the mobile applications.
In the meanwhile, the communication speed and storage capacities need to be continuously improved.

Moreover, the suppression of wires presents many assets, as reduction of electrical inductance and resistance while using less noble materials.

For all these reasons, flip-chip technology is becoming more and more interesting.

Many different kinds of processes can be done on a flip-chip bonder, including chip to chip (C2C) and chip to wafer (C2W), thermocompression, UV-curing, gluing and 3D stacking.
Applications are also various, as for example assembly of medical electronics, photonics and optoelectronics devices as well as MEMS or sensors.

The general trend to reduce the size of components as described above leads to reduce the pitches between electrical interconnections. Consequently, the post-bonding precision becomes crucial and is getting higher and higher. It generates many challenges in the design of chip, in the elaboration of processes and in the conception of flip-chip bonders.

Through several partnerships and equipment installations at leading research institutes around the world, some technological advancement has emerged, including:
- CEA-LETI, Grenoble, France has presented successful die-to-wafer bonding using 4 µm diameter Au-coated microtubes at 10 µm pitch inserted into pads, as well as a molecular attachment bonding method developed within the Proceed project,
- Sematech USA and IMEC Belgium have each developed a hybrid collective bonding scheme where accurate die-to-wafer initial bonding is followed by gang bonding to finalize many bonds in parallel,
- IME Singapore has developed several solder compositions and methods to create reflow bonding process options.

Each process has its own assets but also its own constraints that equipment manufacturers have to take into account in the design of bonders.
This paper will explore some challenges to be faced by flip-chip bonders, depending on the applications to be achieved and the environment, R&D or production.

Key words: flip-chip, high accuracy, R&D, production

Introduction

Flip-chip technology is a generic term used to describe a way to interconnect a chip with a substrate. This technology was introduced by IBM in the 1960s with the C4 process.
For 50 years, flip-chip technology has evolved. Driven by the Moore's law, the general trend in microelectronics is to reduce size of components while increasing their capabilities and their functionalities.

Consequently pitches between interconnections are smaller and smaller and the post-bonding accuracy becomes a key point and needs to be higher and higher. For achieving high accuracy alignment and bonding on flip-chip bonders, different challenges have to be risen.

First, this paper will discuss about the particularity of processes used and how the design is adapted to those processes. Then we will see that depending on the environment, R&D or production, challenges to be faced are not the same. What can be done to achieve successfully precision requirements?

A Wide Range of Processes

Driven by different goals, many researchers have focused on flip-chip assembly and developed a wide range of processes.

Some of them have emphasized their researches on the way to reduce the bonding cycle time, improve efficiency and consequently reduce the cost of this operation [1], [2]. Others have been led by the wish to push the limits of technology and work with finer and finer pitches [3], [4], [5], [6]. These different processes have their own specifies, their advantages and their constraints. We sum up them in the **Table 1**.

Table 1 – A wide range of processes: what are their advantages and their constraints?

Process	Principle	Requisitions	Pro +	Con -
Molecular attachment	Direct bonding metal to metal	High level of cleanliness Very flat components	Very short adhesion cycle time Very low force requested and consequently less mechanical stress for components No thermal mismatch between substrate and chip	High cleanliness requested for both components and equipment Very sensitive to particle contamination
Room temperature compression	Metal to metal bonding compressing the bumps one onto the other	High force requested Components must stand important compression	No thermal mismatch between substrate and chip No temperature stress on the components	High force requested means stiff equipment Lateral force induced (bumps to bumps) (loss of precision) Long cycle time, compression is applied progressively
Thermo-compression	Compression of the bumps at temperature to soften the bumps	Temperature requested High force requested Components must stand important compression and temperature	Lower force compared to RT compression…	…but still high enough to require stiff equipment Thermal mismatch between substrate and chip
Reflow	Use solder. Temperature is then used to reflow this solder to make a joint between two components	High temperature Low force requested	Low force so low stress on components	High temperature may generate thermal shocks on the components Thermal mismatch between substrate and chip
UV Curing	Use UV-curing glue in between the two components	UV source to cure the glue Transparent chip requested	Large choice of UV glues (ACA, NCA, ICA…) Large possibilities for integration of off the shelf dispensers (screen printing, time-pressure, jet, motorized screw…) Very well suited for optoelectronics assembly (lens, prism, fiber…)	Precise Force Control requested Curing time (long) Shrinkage (loss of precision / parallelism) Transparent chips requested, or fiber for illuminating with UV
Thermal curing	Use thermal cured glue in between the two components	Temperature requested Force control requested	Large choice of UV glues (ACA, NCA, ICA…) Large possibilities for integration of off the shelf dispensers (screen printing, time-pressure, jet, motorized screw…)	Precise Force Control requested Curing time (long) Shrinkage (loss of precision/ parallelism) Transparent chips requested, or fiber for illuminating with UV
Ultrasonic bonding	Use ultrasonic power to attach dies, metal bumps to metal pads	Ultrasonic system and high temperature heater	Very low force Lower temperature Possible use of stud bumps (easy and fast process) Short bonding time	Stress on components induced by ultrasonic vibrations Loss of accuracy generated by vibrations High temperature stress on components

As we can see, each process has its assets and its drawbacks. It is not only important to take them in consideration for the development of the application but also for the design and the assembly of the flip-chip bonder.

For a better understanding, we will develop three examples:

- Reflow process
- Room temperature compression
- Molecular bonding

Reflow

Reflow process requires low force and high temperature. A typical process could be the assembly of a laser diode onto its submount with Gold-Tin solder (Internet communication by optical fiber for example).

When we heat components, a thermal mismatch between chip and substrate may occur if the coefficients of thermal expansion (CTE) of their materials are different. This expansion can be included in the design of components, especially for positioning alignment marks. If not, final alignment may be difficult, even impossible to achieve. A compromise must be done and it could be necessary to choose arbitrarily the most appropriate alignment.

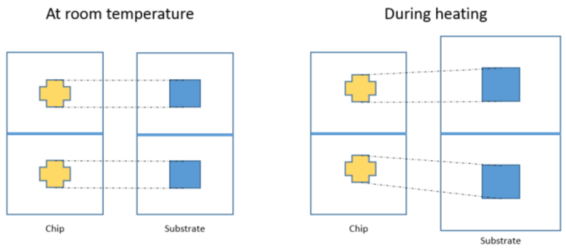


Figure 1 – Thermal Expansion Results in Mismatch Between Alignment Marks

Using low force requires a very accurate force control. The force has to be adjusted during the entire process from tacking to the end of in-situ bonding, including when the solder is above the melting point and then very soft.

High temperature accelerates the oxidation phenomenon on bumps and solder. Oxide is an issue to get a good joint (mechanical adhesion) and for the quality of electrical interconnections. Two processes were developed to remove oxide: chemical flux (wet process) and formic acid vapor (gas process). Flux is deposited and generally has to be removed after the bonding. This cleaning step is extremely difficult to achieve because of the very small gap between the two components. For this reason formic acid vapor is more and more preferred. Formic acid vapor, even if formic acid is a weak acid, is considered as a noxious gas. Precautions must be taken on the equipment and a control of the exhaust is mandatory.

Room temperature processes present the valuable benefits to minimize thermal deformations in mechanical parts (but also in components to be assembled) and thermal mismatch between different materials. Oxidation of bumps or solder is also reduced.

Room temperature compression

However, room temperature compression requires high force. Applying high force generates mechanical stress on the components and on the machine. The machine must be stiff enough and to absorb the force and to avoid definitive deformation. Applying high force on components generates also lateral forces and consequently a loss of accuracy.

Indeed, in theory, the whole matrix of bumps is uniform. In practice, the uniformity of the shape of bumps across the entire matrix varies. Alignment can consequently not be perfect and the contact between these “non-perfect” bumps induces lateral forces during bonding, especially at high force.

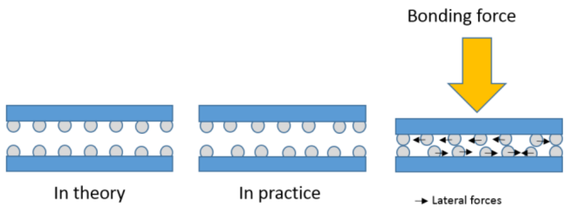


Figure 2 – Lateral Forces Induced

Direct bonding

Direct bonding is a room temperature process. The chips are bonded pillars to pillars without additional materials. To get a good adhesion, this technique requires very flat surfaces on pillars and a very high level of cleanliness. The most popular technique is probably the copper-to-copper process, even if it is not limited to. Pillars are polished on both components with a very high flatness. The components must be cleaned to remove all organic and mechanical contaminations. Then an annealing process is done to offer perfect surfaces [7], [8]

A simple 1 µm residual particle on a pillar will affect dramatically the bonding: it can generate up to 10 mm non-contact area.

This technique can be applied for chip-to-chip or chip-to-wafer approach. Because it is a room temperature process, the wafer can stay on the machine for a long time without being affected by the temperature (contrary to a reflow process).

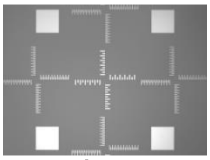
Achieving high accurate alignment and placement is a challenge. But the main challenge is to be able to guarantee high accuracy after bonding. As we saw previously, processes can seriously affect components and consequently induced variation in the alignment.

Potential process effects can be anticipated and counterbalanced by the flip-chip bonder. To manage to keep the pre-bond accuracy, several developments have been done on flip-chip bonders.

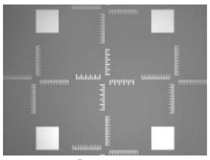
Technical Development Done on Flip-Chip Bonders

Alignment

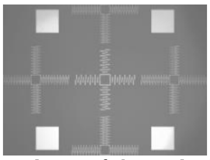
The alignment before bonding must be done much below the final targeted post-bond accuracy. The XYTheta stages of bonders needs to have a very high resolution to allow a very high alignment accuracy. 0.1 µm alignment accuracy is required to get +/-0.5 µm post bond accuracy. To be able to align chips within a so high accuracy, the alignment marks on the components are also extremely important. They must be highly accurate and with a very good quality to avoid any miss-reading. For example contrast, sharpness, size of these features influence a lot the alignment accuracy. Then the quality and the resolution of the optical system on the bonders is a key parameter. The optic looks at both components in the same time. The alignment is done in live mode allowing direct feedback on the screen to guarantee high accuracy.



Substrate view



Chip view



Superimposed view of chip and substrate

Figure 2 – Example of Alignment Marks

Another important parameter for alignment is to have an optical system able to align at high temperature. The best way to minimize the effect of the thermal expansion, it is to reduce the temperature variation between alignment and bonding. The optical system of the bonders must allow an alignment temperature as high as 270°C for gold/tin processes for example.

Repeatability of the bonding arm

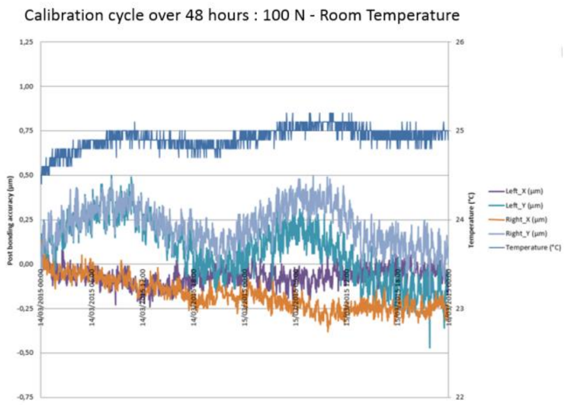
The only way to guarantee high accuracy is to have very repeatable and reliable motions, especially for the bonding arm. This arm is going to move from the alignment position to the bonding position. During this motion, the alignment has to be "locked". The choice of the linear guides is critical. The rails and bearings must be selected to ensure a very smooth and linear motion.

As soon as the motion is repeatable, the system can be calibrated.

Calibration

Calibration of the machine is an essential step. This procedure has to be as similar as possible of the real process, including the temperature and force variations. The idea is to run the calibration using specific samples with the same bonding force and same bonding temperature that the real devices will use.

When reaching so high accuracy, the equipment has to be able to self-calibrate. Any user/operator would induce a personal interpretation and, consequently, an error. Full automatic calibration has been developed to be reliable and avoid this bias. Because it is automatic, the machine can run the calibration all night long. Running calibration cycle during a quite long time, allows having a better accuracy and stability. Moreover, calibration can be done during hidden time and get the bonder immediately ready to use when the operator needs it.



Graph 1 – Repeatability and accuracy of SET-ACCµRA100™ Flip-Chip Bonder

Management of thermal effect

When the calibration is done, the machine has to be stable enough to stay calibrated during the next hours. This includes a very good management of the air flow inside the machine. All the hot air generated by the heating elements and from the electronic has to be exhausted [9].

Flip-chip bonders with heating capabilities are composed of different stacked parts (see **Figure 3**) to hold both the chip and the substrate in the better conditions. Chip is placed on high position, with connections on its lower surface, on what we call the head of the equipment. The substrate is placed on a low position, with its connections on the upper surface, on the chuck. They are placed onto a ceramic part that we call a tool. These tools are positioned on the heater.

Depending on the functions of each part, the materials are not the same. For example, the thermal conductivity is high for the tool and the heater, low for the base part. Thus, thermal expansion coefficients are also different.

While heating, thermal expansion, which of course cannot be avoided, happens and thermal gradient may occur, resulting in deformation. Thus planarity and/or parallelism between chip and substrate may be degraded.

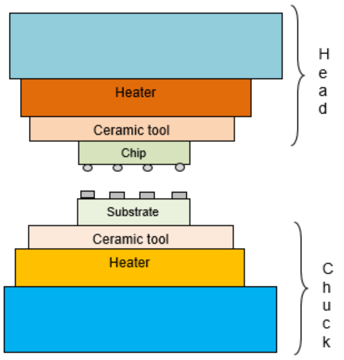


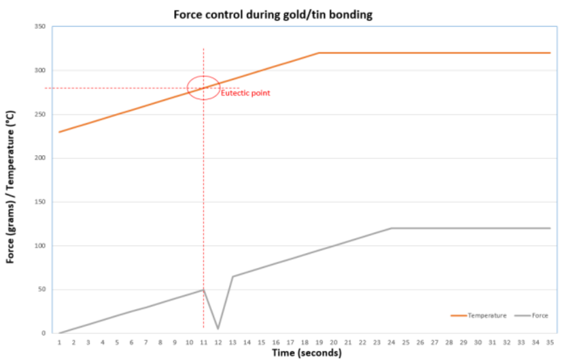
Figure 3 - Bonder Architecture

Therefore, the equipment is designed with low CTE materials to minimize the differential expansion of various machine components and by managing properly the heat inside the equipment.

Accurate force control

According to the required final bonding force (few grams for reflow and several hundreds of kilograms for compression), the flip-chip bonder must control accurately the force over the entire range. From a machine/mechanical point of view, using only one force sensor is not possible on a so large range of force. Different force measurement systems are embedded into the equipment and a very fast electronics monitors and adjusts in real time this force thanks to a real close loop concept.

For example, with a gold-tin solder process, when the solder reaches its eutectic point, the solder becomes liquid/soft, the force drops down because there is less mechanical resistance. It is clear on the **Graph 3**. The machine must immediately compensate this variation to guarantee that the final force is reached.



Graph 3 – Example of Force Control During Gold/Tin Bonding

Stiffness of the equipment

After touch down, the entire machine has to maintain the accuracy during bonding, applying the process. The temperature and the force are increased (sometimes significantly). The stiffness of the mechanism is essential. But the design of the machine is also a key parameter for success. When applying pressure, the parts deform (this is a basic physical rule). The deformation of each of these parts must be perfectly known to stay in the elastic range of the material to avoid permanent deformations. Also, the way the parts are assembled one onto the others is a very important.

The design of the components to be bonded is also a key parameter: the location of the solder/bumps has to be uniformed and ideally centered to minimize lateral forces.

The design of the equipment is important for ensuring accuracy, however, according to the environment, needs and goals are different. These differences can affect the accuracy that is why they have to be taken into account for the design of the equipment.

From R&D to Production Environment

R&D and production equipment are not designed with the same objectives. Of course, achieving high accuracy is for both the main requirement, but in R&D, the key point is flexibility whereas in production it is throughput.

R&D

Needs from R&D are very often the possibility to run many different processes on the same platform: thermocompression for MEMS, UV curing for lenses, reflow for optoelectronics components… Switching from an application to another must be quick and easy to do.

In R&D center, many different people will use the equipment: teachers for teaching and explaining to students, students themselves will use it for their projects and scientists or external engineers will work on it for advanced projects requiring a very high level of technology.

The equipment must have a very accessible and easy-to-use interface but also an expert mode giving access to very detailed parameters and allowing people to develop high technology project and push the limits of flip-chip technologies.

SET equipment have always been developed to be flexible and upgradable. For instance, bonding heads are interchangeable by the user to go from UV to thermocompression to reflow to ultrasonic processes on the same platform.

To follow the evolution of technologies, the flip-chip bonder has to be open enough to add new features developed by the manufacturer. The goal is to keep the machine up-to-date to give the opportunity to research centers to stay on the top of technology without buying new equipment every year. SET has been developing new options and proposes them, keeping in mind that these options have to be upgradable easily on the installed equipment.

Production

Behind the flip-chip concept and the accuracy, expectations from production are very different: high throughput, repeatability and reliability.

The process developed in R&D has to be transferrable on the production tool. It means that the production tool has to be perfectly similar to the R&D tool from a process point of view (same heating cooling ramps and same force control). Thus transfer is done without new development.

To get high throughput, we have to focus on the main functions of the flip-chip bonder: “align and bond”. That means all the other steps as handling have to be done in parallel by a separated system in hidden time.

Having high throughput is possible with an optimized process but, almost important, with a very short machine process cycle time. Flip-chip bonder needs very fast motions on every single axis, very fast heating and cooling ramps, very efficient vision system to recognize patterns and align them…and without deteriorating the post-bond accuracy and without damaging the parts. A good balance has to be found between speed and stabilization time (to avoid vibrations).

Combining high accuracy and high throughput is a real challenge. To be fast, we have to be light. To be accurate, we have to be stiff. The challenge is to improve the design in order to reduce moving masses and maintain the stiffness. The choice of the materials is of course very important.

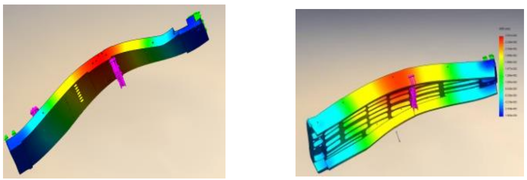


Figure 4 – Finite element analysis

Figure 4 shows two parts. The first one is a solid block with a mass of 30 kg. The design of the second one has been optimized in order to keep the same stiffness while reducing the mass down to 18 kg.

The process and the equipment must be perfectly optimized. The machine must be perfectly sized for the application and for the process.

A laser bar application needs high temperature and low force. The heating and cooling times must be minimized. The way to do it is to reduce as much as possible the thermal masses.

To get fast motion, the moving masses must be as low as possible that means, each module in movement must be lightened. For instance, the bonding arm has to be sized for the required bonding force. If 500 g are enough for the application, the bonding head must be sized accordingly. On SET the weight of the low force arm is 2.5 kg whereas the high force arm weight is 50 kg.

There is not only one machine to cover all the applications. The configuration and the choice of modules are essential to get the best throughput with very high yield.

Conclusion

The design and the characteristics of the flip-chip are essential to achieve precision requirements. However it is also very important to develop the best suitable process combined with the best design of components.

Customers know perfectly well what their final product has to be. He also has full access on the selection of the process.

The flip-chip bonder manufacturer knows perfectly his equipment, what they do, what they can do and what he can develop or adapt.

That is why a very close collaboration between the customers and the flip-chip bonder manufacturer is crucial.

Each of them will bring their knowledge to converge to the best suitable configuration in order to introduce on the market your best products.

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