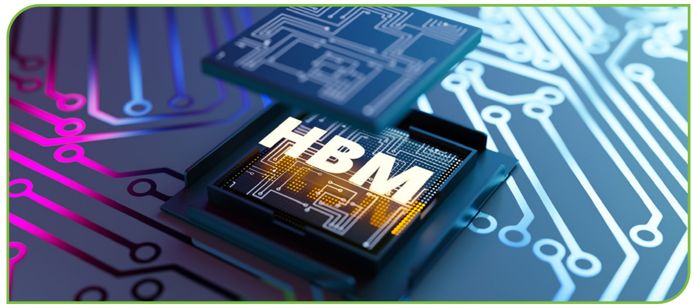
WHITE PAPER



BRINGING HYBRID BONDING INTO PRODUCTION

Hybrid bonding promises to substantially advance semiconductor packaging by enabling smaller, denser assemblies that offer higher performance and improved reliability. Hybrid bonding and similar technologies will become increasingly important as more sophisticated 3D packaging methods come into greater use, and as interconnection pitches shrink below 10 µm – and with the current roadmap already pointing towards sub-micron. It will be a key enabling technology for high bandwidth memory (HBM), 3D NAND, and high-performance computing 3D system on chip (HPC 3D SoC).

One of the critical elements in a hybrid bonding system is accurate and stable motion and positioning. This is necessary to ensure the precise alignment essential to successful hybrid bonding.

MKS Instruments excels in this domain, leveraging over 60 years of expertise to provide cutting-edge motion and positioning solutions to hybrid bonding tool-builders. Our technologies support all levels of integration – from components through turnkey subsystems – driving innovation and enhancing the capabilities of semiconductor manufacturing.

Here we'll learn about the specific requirements of hybrid bonding, and some of the ways in which MKS can aid system developers with motion platforms.

Key Hybrid Bonding Advantages

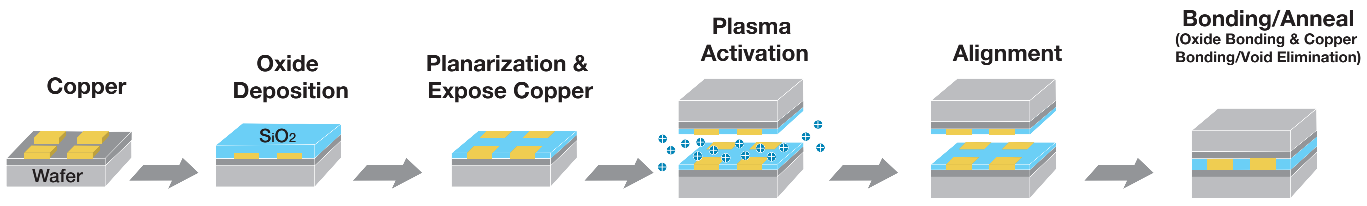
What is hybrid bonding and why is it needed? The need is relatively simple to understand. Achieving further miniaturization in microelectronic devices requires assembling chips into stacks with increased packing density. Furthermore, these stacked chips themselves must shrink, in part by utilizing more closely spaced (finer pitch) interconnects. And even the height (thickness) of these interconnects needs to be minimized to reduce total stack thickness.

Hybrid bonding is the most promising way to assemble these smaller, finer pitched dies. It offers numerous advantages over traditional bonding methods such as wire bonding, flip-chip, and thermo-compression bonding (TCB). These advantages include:

- High Density and Fine Pitch: often less than 10 µm, compared to the larger pitches required by wire bonding and flip-chip methods. Plus, the standoff distance between each die is reduced to essentially zero.
- Low Power Consumption: shorter interconnects reduce parasitic capacitance and resistance, leading to lower power consumption.
- Improved Thermal and Electrical Performance: direct metal-to-metal connections provide excellent thermal conductivity, improving heat dissipation. Electrical performance is enhanced due to reduced inductance and resistance, resulting in faster signal transmission and lower signal loss.
- Enhanced Reliability: robust mechanical bonds with high resistance to thermal and mechanical stress delivers long-term stability.
- Scalability: Hybrid bonding is scalable to future technology nodes, supporting the ongoing trend towards smaller, more powerful semiconductor devices. Its compatibility with various materials and processes makes it adaptable for future advancements in semiconductor manufacturing.

Hybrid Bonding Basics

In hybrid bonding, two extremely flat, smooth, and clean surfaces of like materials are brought into contact. This creates strong interatomic bonds between the two surfaces without the need for adhesives or solders. The actual bonding mechanism differs depending on substance. Specifically, direct bonding of two dielectric (SiO_2) surfaces produces covalent bonds, while direct bonding of two copper surfaces yields a metallurgical bond during a two-step annealing process.



Key process steps of hybrid bonding.

The graphic shows the main steps in the hybrid bonding process. These are:

1. Fabrication of a hybrid bond layer on top of a finished wafer (a wafer where all front end of line and back end of line processes are complete). The hybrid bond layer consists of a dielectric, which is typically SiO_2, with copper pads.
2. Cleaning and chemical mechanical polishing (CMP) to make the surface of the bond layer extremely smooth and flat. The copper is "dished," that is, made slightly concave. This is necessary because it will expand more than the dielectric during annealing. So, a slight gap is needed to allow for this differential expansion.
3. Plasma activation then follows to modify the bond layer surface properties, enhancing its ability to bond with other materials.
4. The wafer or dies to be bonded are precisely aligned to the original wafer. The surface(s) of all these have been prepared in the same way just described.
5. The components are all brought into contact and the actual bonding of the dielectric material begins. This is done at ambient temperature.
6. Annealing is then performed under pressure and at an elevated temperature. Annealing typically consists of two stages. First, a lower temperature annealing phase completes the bonding of the dielectrics. Next, there is a higher temperature step in which the copper expands to completely fill the small remaining gaps and form direct bonds.

There are many different specific embodiments of hybrid bonding. Plus, the process can be performed wafer-to-wafer (W2W), die-to-wafer (D2W), or die-to-die (D2D). Each of these methods has its own advantages and drawbacks in terms of throughput speed, yield, and cost, and therefore specific applications for which it is most useful.

Motion Requirements

Virtually every step of the hybrid bonding process is demanding and exacting. Specifically, it requires the ability to prepare extremely flat and clean surfaces, and then to position and hold these surfaces relative to one another with high accuracy and repeatability. And the mechanical tolerances become increasingly tight as die geometries and pitch dimensions shrink.

The specific requirements of the motion system depend upon the exact implementation. But some broad generalizations can be made about hybrid bonding for W2W and D2W which serve to highlight the key differences between these applications.

The motion system parameters of greatest interest are usually alignment, stability, and repeatability. Because hybrid bonding is critically dependent upon surface cleanliness, the system must completely avoid the potential for introducing contamination. And, of course, throughput – which ultimately translates into cost – is always a factor in semiconductor capital equipment. It's worthwhile to review each of these areas.

Alignment

The first function of the motion system is to move the two surfaces (two wafers or dies and wafer) with high accuracy, repeatability and control to achieve the desired alignment and positioning. This process is most commonly aided with a vision system (operating in either the visible or infrared) which identifies fiducial marks on the components.

Generally, alignment for W2W bonding is more demanding than D2W. For W2W, the overall alignment precision is often in the hundreds of nanometers or less range. But, for wafers this precision must be maintained over a range of tens of centimeters.

For hybrid bonding, placement precision depends upon pad size. Alignment accuracy of 500 nm is typically a minimum requirement. It can extend down into the 100 nm – 200 nm range for some applications. Depending on whether the motion system is performing pick and place operations for D2W, or if off-axis alignment is required for W2W, the movement range can be hundreds of centimeters. If Though Silicon Alignment (TSA) using IR is possible, then the XY motion is minimal (less than a centimeter). Once the location of the fiducials for both pieces are located, the wafer/die is moved in XYΘ to the approximate location before final fine alignment is made and the surfaces are precisely brought together in Z for bonding. Various methods (edge-first or center-first) are used to control the bond front propagation to eliminate the possibility of air pockets interfering with the bonding process.

Repeatability

Repeatability is really the key specification of the motion system. High repeatability ensures that variations in the mechanical components or vision system won't significantly affect the final alignment outcome across different bonding cycles. The performance of the motion system is the key determining element in repeatability, although it can be influenced by variations from factors like camera resolution, lighting conditions, or calibration inaccuracies, or from external factors like ambient temperature, humidity, or vibration.

Stability

Stability is another critical factor, especially during the bonding process itself, as well as during inspection steps. Maintaining stability during bonding is challenging given that this cycle might last several seconds. Furthermore, vibration damping and active vibration isolation are required to mitigate the effects of both internal and external sources of perturbation. Typically, positional stability must be maintained within a fraction of the specified alignment tolerance throughout the bonding process.

Newport Solutions

The preceding discussion was just a broad overview of the key considerations in specifying a motion platform for hybrid bonding. But even this summary underscores the complexity and precision required.

Successfully navigating these challenges demands specialized expertise and tailored solutions. There are no "off-the-shelf" answers when it comes to achieving the highest levels of performance, efficiency, and reliability. Delivering these customer specific solutions is where MKS Instruments excels.

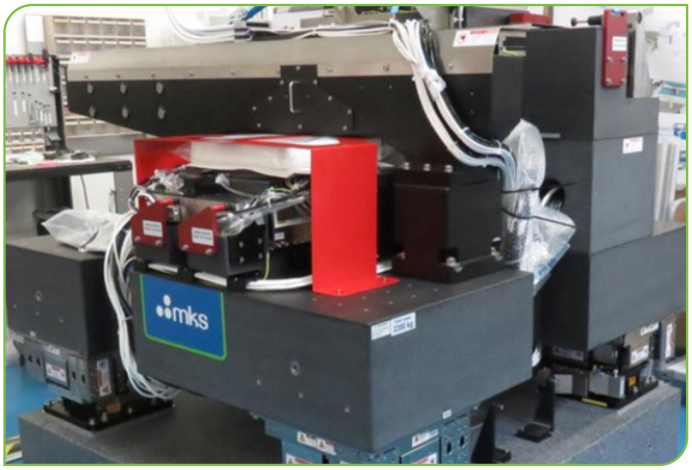
There are several reasons why we're able to make this bold claim. First is the fact that we're able to integrate and customize systems based on a deep understanding of customer needs. Next, we have large and diverse set of the motion control products and technologies related to hybrid bonding that enable and enhance our ability to do this. For example, these include:

- Air bearings, including the technology to ensure Z axial rigidity and stability during bonding
- Complex parallel robots for six degree of freedom wafer positioning
- The ability to use ceramics for high stiffness, multi-axis monolithic structures
- Advanced rails systems
- High accuracy and repeatability stages for camera positioning
- Metrology capabilities needed to validate performance
- Thermal simulation and management for long-term repeatability
- Passive and active isolation integration
- High power and precise motion electronics for dynamic positioning
- Simulation and prototyping software to optimize and accelerate time to market
- The ability to offer a solution to customers' specific problems and optimize the criteria that matter most to them

Building on this, we provide, integrated advanced motion platforms for OEMs that feature compact, lightweight designs with high dynamic capabilities. These ensure superior performance in demanding environments including cleanrooms and other challenging settings.

Additionally, MKS Instruments also has substantial experience in semiconductor manufacturing, including sub-micron precision systems used in inspection, metrology, lithography and other semi applications. We have already been involved in the development of both wafer-to-wafer (W2W) and die-to-wafer (D2W) bonding alignment platforms and associated inspection systems, proving our ability to address the complex challenges of hybrid bonding, in particular.

Examples of a complete motion system and specific sub-systems we designed for hybrid bonding:



Fully integrated hybrid bonding motion module

Parallel Robot for W2W Hybrid Bonding

Monolithic chuck holder

Finally, the global reach of MKS Instruments ensures prompt and effective support from the beginning stages of consultation through ongoing service of installed systems. We maintain facilities and expert teams in the US, France, Korea, China, and Taiwan, to provide comprehensive service and support for our motion control solutions. And, our vertically integrated manufacturing footprint, including ISO 6 and ISO 7 cleanrooms, ensures that we maintain high-quality standards and can deliver complex motion systems efficiently.

Conclusion

With our deep expertise and comprehensive capabilities, MKS Instruments can help you maximize performance, minimize costs, and mitigate risks in the development of hybrid bonding systems. And we are dedicated to building long-term partnerships with our customers. We understand that the semiconductor industry is dynamic and requires continuous innovation. By working closely with our clients, we ensure that our technology roadmap aligns with their needs and helps them stay ahead of the technology demands – and the competition.

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