Room-temperature Wafer Bonder Applicable to Manufacturing of Semiconductor Devices in Various Fields

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The room-temperature bonding technique enables strong bonding without applying heat. As it can be used with diverse materials, this technique has recently been applied in various device fields.

Mitsubishi Heavy Industries Machine Tool Co., Ltd. manufactures and markets room-temperature wafer bonders that can be used for various purposes, ranging from research and development (R&D) to device mass production and is expanding the applicable fields for room-temperature bonding.

1. Introduction

The principle of room-temperature bonding has long been known, and related research has been energetically conducted, including that by Honorary Professor Suga of the University of Tokyo(1). As a result, it has become a highly-competitive bonding technique that can be said to be a Japanese specialty. However, it was not until recently that the technique was actively applied in actual industrial fields.

The room-temperature bonding technique, which holds bonding materials (wafers) together by activating their surfaces in a vacuum, enables strong bonding without applying heat. The use of room-temperature bonding has primarily been used in the field of sealed packaging for Micro Electro Mechanical Systems (MEMS). Because this technique can be applied to diverse materials, it has recently been used in other device fields such as surface acoustic wave (SAW) device, light-emitting device and power device.

We manufacture and market room-temperature wafer bonders that can be used for various purposes corresponding to each wafer size, ranging from R&D to device mass production, and are expanding the applicable fields of room-temperature bonding. These bonders are utilized in the manufacture of various devices due to their high-quality bonding characteristics. This paper presents the principles and features of room-temperature bonding, fields of application, bonding equipment and bonding examples.

2. Principles and features of room-temperature bonding

2.1 Classification of wafer bonding techniques

Various processes have long been used for wafer bonding. Typical wafer bonding techniques are roughly classified into bonding with an intermediate material and direct bonding as shown in **Figure 1**. In the case of all processes other than room-temperature bonding, it is necessary to heat the wafer to a high temperature, and there are issues in terms of the reduction of temperature stress on the device and low thermal strain bonding of materials with different thermal expansion coefficients.

2.2 Principle of room-temperature bonding

Figure 2 illustrates the principle of room-temperature bonding. Under normal circumstances, the bonding material surface is covered with an oxide film and an adsorption layer. In this state, joining cannot be made by contacting and pressurizing at room temperature. However, if these

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materials are placed in a high-vacuum chamber and neutral atoms or ions of an inert element such as Ar are irradiated to remove the oxide film layer and adsorption layer on the bonding surface, dangling bonds appear on the surface. At this time, the surface is in a high energy state and is called an "activated surface." When surfaces activated by such means are brought into contact with each other in a high vacuum, the dangling bonds are bonded to each other and a strong bonding force is generated. In this way, room-temperature bonding is a process that proceeds entirely at room temperature without heating, and is also known as "surface activated bonding," because the surfaces are activated and bonded thereby.

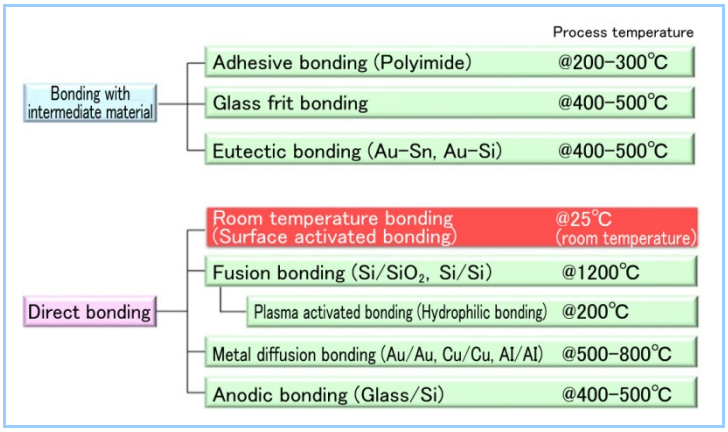

Figure 1 Classification of wafer bonding techniques

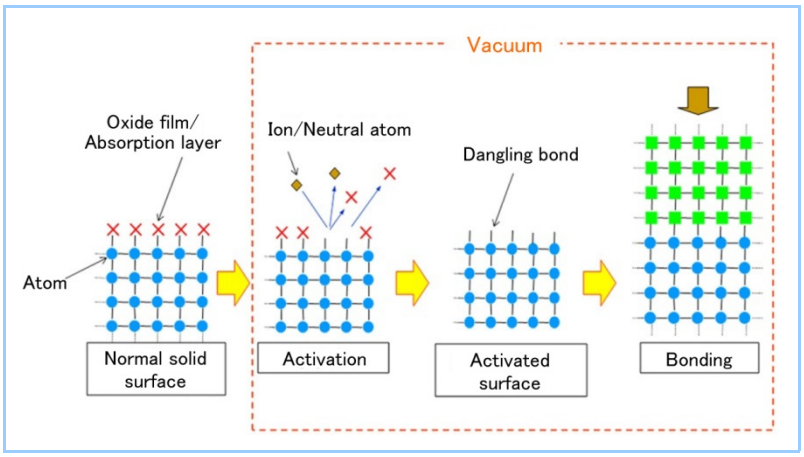

Figure 2 Principle of room-temperature bonding

When the degree of vacuum in the vacuum chamber is low, residual gas components in the chamber are adsorbed again on the activated surface and terminate the dangling bonds, so a degree of vacuum of 10-6 Pa is generally required. For bonding, the dangling bonds need to be close to each other at the atomic level. Therefore, the surface roughness of the bonding interface greatly affects the possibility of bonding. Specifically, the arithmetic average surface roughness Ra must be 0.5 nm to 0.7 nm or less. In addition, particles existing at the bonding interface cause voids, so sufficient cleaning is required.

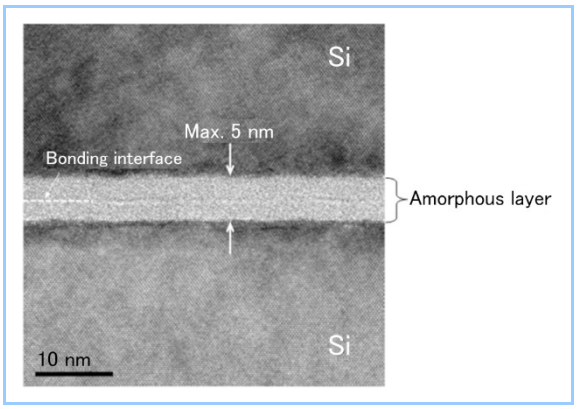

Figure 3 TEM image of Si to Si bonding interface

Figure 3 is a TEM(Transmission electron microscope) image of the bonded interface between silicon materials. As shown in the figure, there is an amorphous layer with a thickness of several nanometers at the bonding interface. An amorphous layer formed at the bonding interface in this way allows the bonding of materials with different crystal orientations and lattice constant.

2.3 Features of room-temperature bonding

Based on the aforementioned bonding principle, room-temperature bonding has the following features.

(1) Provides bonding strength equivalent to that of the base material even when bonded at room temperature

The resulting bonding strength depends on the material, but in the case of bonding silicon materials, for example, it is possible to easily obtain a bonding strength similar to that of the base material.

(2) No thermal strain due to bonding

Due to room-temperature bonding, even materials with greatly different thermal expansion coefficients can be bonded without being affected by thermal distortion. This greatly expands the range of applicable material combinations and contributes to device miniaturization.

(3) Achieves high productivity by eliminating the need for a heating/cooling process.

(4) Capable of bonding a wide range of materials, such as silicon-based materials, compound semiconductors, oxides and metals, as well as bonding different kinds of materials to each other.

3. Application fields of room-temperature bonding

Use of room-temperature bonding began in the MEMS field. However, the areas of application have been expanding in recent years as the technique has been noted for its capability to bond a wide range of materials and to provide solid-state direct bonding at room temperature. In this section, the applications of room-temperature bonding are categorized below and discussed.

3.1 Wafer-level packaging in MEMS and other fields

Wafer-level packaging is a method used to perform seal-packaging at the wafer level by bonding a cover wafer to another wafer on which MEMS structures are formed.

In MEMS manufacturing, fine MEMS structures are formed on a wafer by bulk micromachining[(2)]. Depending on the wafer size, hundreds to tens of thousands of devices are formed on a single wafer. Seal-packaging is performed after dicing, but at that time, it is inefficient to perform packaging separately for each singulated device. Therefore, sealing is performed collectively by bonding at the wafer level, and then dicing is performed to singulate the devices. Compared to separate packaging of singulated devices, wafer-level packaging has significant advantages in terms of cost and yield. Heating during bonding causes thermal stress and thermal distortion, leading to a decrease in yield and device performance. On the other hand, by bonding at room temperature using the room-temperature bonding technique, a high yield and improvement in device performance can be realized. **Figure 4** is a schematic diagram of wafer-level packaging. It is mainly used for the mass production of acceleration sensors and pressure sensors. The use of wafer-level packaging is gradually expanding in the MEMS field, as well as the field of quartz crystal devices.

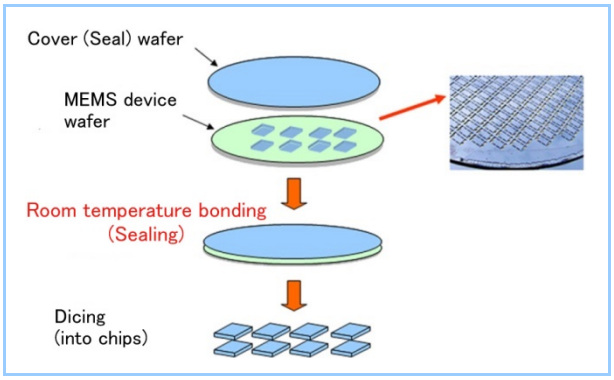

Figure 4 Wafer-level packaging of MEMS

3.2 Production of engineered substrate

A engineered substrate is produced by bonding different kinds of materials, such as oxides, dielectrics and optical materials. The resultant engineered substrate is then subjected to micro fabrication such as patterning to obtain the desired devices. Room-temperature bonding is well suited for bonding materials with significantly different thermal expansion coefficients.

As shown in **Figure 5**, SAW filters used for smartphones are manufactured by bonding a silicon or sapphire wafer, which is a supporting substrate, to a lithium tantalate ($LiTaO_3$) wafer, which is a engineered substrate, and then performing patterning and thinning. A SAW filter allows necessary frequencies to pass and blocks unnecessary frequencies. Several tens of SAW filters are used for a single smartphone.

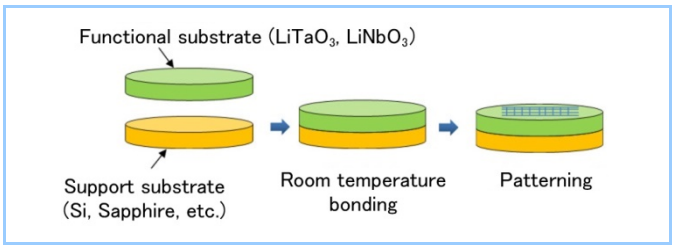

Figure 5 Manufacture of engineered substrate for SAW filter

In recent years, as smartphones have become more multifunctional and sophisticated, the mounting density of components has increased, and higher internal temperatures in smartphones have become an unavoidable issue. Lithium tantalate is used as a engineered substrate for SAW filters, but its thermal expansion coefficient is large (16.1 ppm/°C), so it is necessary to reduce the frequency shift associated with the increased temperatures. Therefore, a method was devised to improve the frequency temperature characteristics of SAW filters by bonding a wafer with a low thermal expansion coefficient such as silicon (3.4 ppm/°C), sapphire (7.7 ppm/°C), etc., as a support substrate on a lithium tantalate wafer to suppress the thermal expansion. This type of filter is known as a temperature compensated-surface acoustic wave (TC-SAW) filter.

Since there is a significant difference between the thermal expansion coefficients of lithium tantalate and silicon or sapphire, heat bonding of these materials causes a large amount of warpage or cracking. However, room-temperature bonding makes it possible to perform high-quality bonding.

3.3 Application to high value-added devices enabled by direct bonding

For example, room-temperature bonding is used to improve the efficiency of semiconductor materials by direct bonding or to enhance cooling efficiency by directly bonding a heat source and a cooling layer. **Figure 6** depicts a method to manufacture a engineered substrate for power semiconductors or light emitting devices by bonding a functional substrate of single crystal SiC, GaN, etc., to a supporting substrate of polycrystalline SiC, sapphire, etc., and thinning it using Smart cut™ (3). This method makes it possible to manufacture several hundreds of bonded substrates from a single functional substrate by Smart cut™ the functional substrate and performing bonding repeatedly, and to greatly reduce the manufacturing cost as a result.

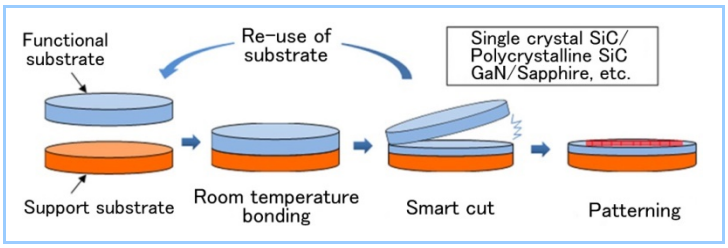

Figure 6 Manufacture of engineered substrate for high value-added devices

4. Room-temperature wafer bonders

Our product lineup features various types of room-temperature wafer bonders compatible with different diameters of wafers made from a variety of materials that satisfy their intended purposes, ranging from R&D and prototyping to device mass production. **Figure 7** presents our lineup of room-temperature wafer bonders.

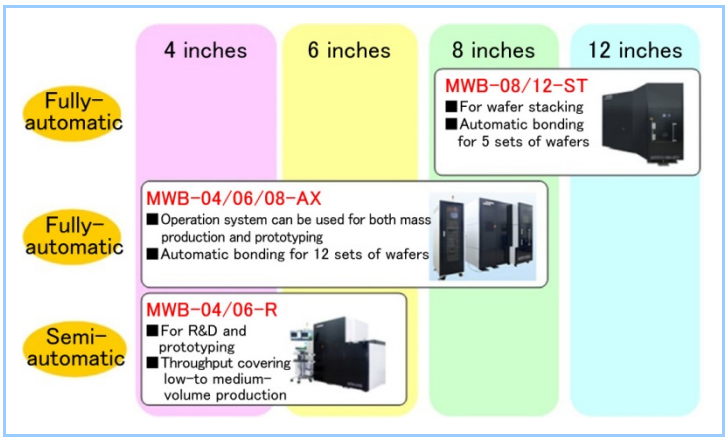

Figure 7 Our lineup of room-temperature wafer bonders

The bonders support four wafer sizes (φ100 mm (4 inches), ϕ150 mm (6 inches), ϕ200 mm (8 inches) and ϕ300 mm (12 inches)) and are also adaptable to other sizes and non-standard wafer shapes.

Equipped with built-in wafer transfer and alignment mechanisms (to position two wafers for bonding), all models can be used for production shortly after installation. In addition, by making full use of the digital simulation technology cultivated in machine tools, the bonders provide both precision alignment (bonding accuracy after bonding of 2 μm or less) and high load application at bonding (up to 200 kN in the case of a bonder capable of handling 300 mm wafers), and realize uniform activation of the wafer surface using activation simulation. As a result, high-quality room-temperature bonding can be achieved, which enables stable production quality even in mass production.

The fully-automatic bonder, used for device mass production, is designed to successively bond 12 sets (24 pieces) of wafers. All processes, including wafer transfer and alignment, are automated. Furthermore, it can be adapted to various styles of small-lot production because specific bonding conditions can be set separately for each bonding batch. The specifications for two models, one for R&D and prototyping and the other for mass production (capable of handling 200 mm wafers), are listed in **Table 1**.

Table 1 Main specifications of room-temperature wafer bonders

	Semiautomatic bonder (For R&D prototyping, low- to medium-volume production)	Fully-automatic bonder (For mass production: 200-mm compatible)
Type	MWB-04/06R	MWB-04/06/08AX
Unit of operation	1 set	12 sets (max.)
Wafer diameter	100 mm/150 mm	100 mm/150 mm/200 mm
Operation mode	Semiautomatic	Fully/semi-automatic
Alignment accuracy	±2 μm	±2 μm
Press unit	Max. load: 20 kN	Max. load: 100 kN
Alignment method	Infrared transparent/reflection image	Infrared transparent/reflection image

4.1 Bonder for R&D and prototyping

This bonder consists of a load lock chamber in which two wafers—upper and lower—are inserted and a process chamber in which bonding is performed. The two wafers to be bonded are set on a tray in a station in the load lock chamber.

The rough bonding flow is as follows.

(1) The upper wafer is carried into the process chamber and held by the electrostatic chuck.
(2) The lower wafer is carried into the process chamber.
(3) An Ar beam is irradiated to activate the bonding surface.
(4) Alignment is performed with the alignment marks formed on the left and right sides of the wafer.
(5) Bonding is performed.
(6) The bonded wafer is returned to the load lock chamber.

All these operations are displayed on a PC screen along with the flow and device status, and the operator can confirm the flow and proceed with the work simply by clicking a button on the screen. The image processing system also supports labor-intensive alignment, so it can be completed in a short amount of time. As for the Ar beam irradiation conditions and other bonding conditions, both the conditions specified as a "recipe" and the actually-measured conditions are saved as a process log, which can be analyzed by commercially available software.

4.2 Bonder for mass production

A bonder for R&D and prototyping opens the load lock chamber and performs tooling change every time a batch (bonding) ends. On the other hand, a bonder for mass production stores 12 upper wafers and 12 lower wafers in the wafer cassettes and automatically carries out all operations of wafer transfer, alignment, surface activation and bonding. Since vacuum exhaustion is performed once for the bonding of 12 batches, the cycle time per a batch can be reduced. As the bonding conditions for each batch can be registered as individual "recipes," it is possible to handle wafers of different parts in a mixed manner and to flexibly deal with the production of many kinds of small quantities.

5. Bonding examples

5.1 Silicon-to-silicon bonding

The photograph in **Figure 8** shows the tensile test results of silicon-to-silicon bonding. For a tensile test, the bonded test piece is attached to the tensile test tool using an adhesive. When the test is conducted, however, since the adhesion strength of the adhesive is smaller than the bonding strength of room-temperature bonding, peeling at the bonding interface does not occur and the test piece comes off the tool. Therefore, the tensile test was performed using a mesa-shaped (trapezoidal-shaped) test piece as shown in Figure 8 prepared so that the room-temperature bonded area fractures first. As a result, the fracture occurred at the base material rather than the bonding interface as shown in the photograph, indicating that the bonding strength was equivalent to the base material.

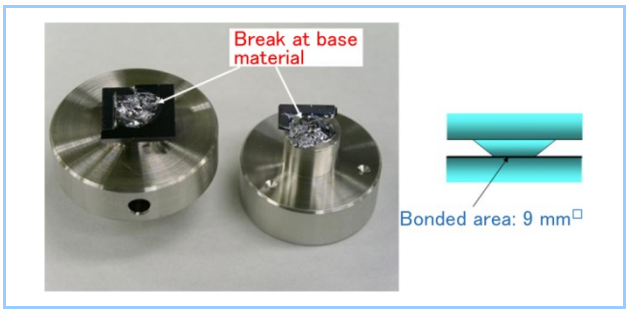

Figure 8 Si to Si bonding (after tensile test)

5.2 Metal-to-metal bonding

Figure 9 shows the tensile test of bonding between Au films formed on silicon substrates. As in the case of silicon-to-silicon bonding described above, a mesa-shaped test piece was used. It is indicated that the fracture occurred at the silicon base material, rather than the Au-to-Au bonding interface.

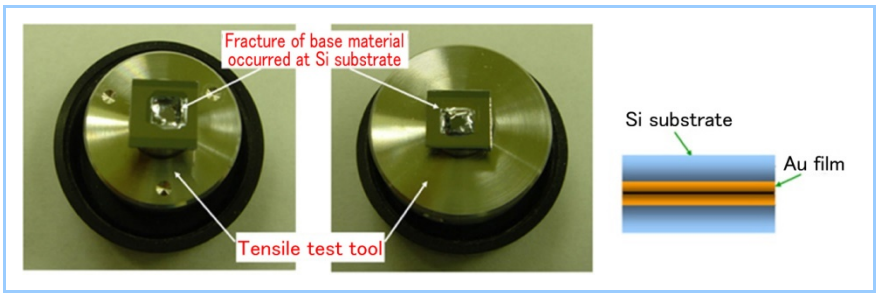

Figure 9 Bonding between Au films (after tensile test)

In a similar manner, **Figure 10** presents the results of a tensile test of bonding between Cu films formed on silicon substrates using a meta-shaped test piece. Since the adhesion strength between the SiO_2 film and the Ti film, which are formed in order to improve the adhesion between the silicon substrate and the Cu film, is smaller than the bonding strength between the Cu films, peeling occurred first at the interface between the SiO_2 film and the Ti film. The adhesion strength between the SiO_2 film and the Ti film measured at that time was 8 MPa. Therefore, it can be seen that at least the bonding strength between the Cu films was higher than 8 MPa.

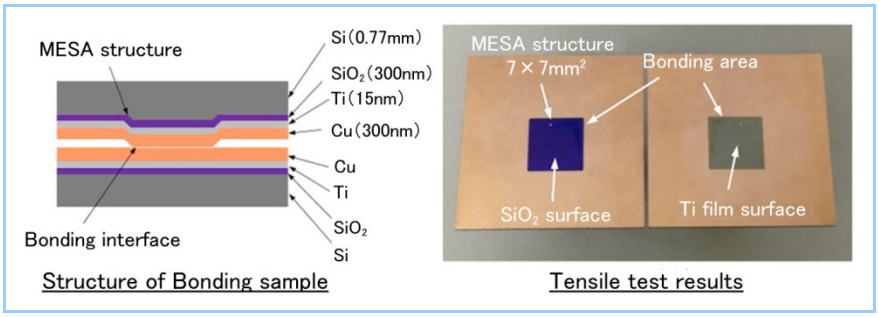

Figure 10 Bonding between Cu films (after tensile test)

When wafers with Cu electrodes are bonded as shown in **Figure 11**, there is an issue with the electrical characteristics at the interface. **Figure 12** gives the results of measuring the electrical characteristics (I-V characteristics) after bonding the Cu films. As a result, it is found that the electric resistance at the bonding interface is 20 mΩ or less and good electrical characteristics are obtained.

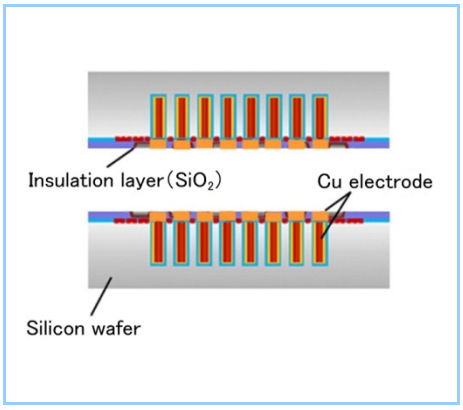

Figure 11 Bonding between wafers with Cu electrodes

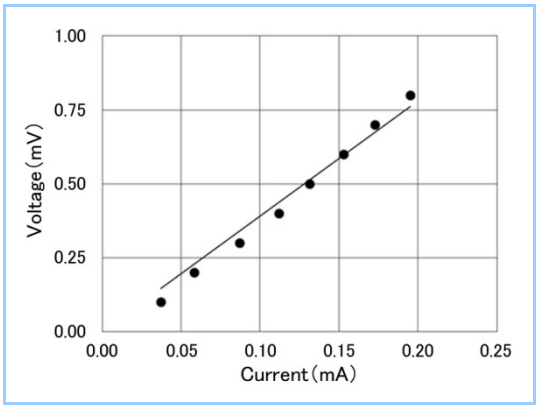

Figure 12 Electrical characteristics at Cu bonding interface

6. Conclusion

Room-temperature bonding is a unique bonding technique that can provide strong direct bonding of a wide range of materials at room temperature, and its applicable fields are expected to further expand. A large number of our room-temperature wafer bonders have been delivered in the fields of MEMS and SAW filters and used for mass production. We will continue to contribute to the manufacture of a wide variety of semiconductor devices.

References

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