

Room-temperature Wafer Bonders Applicable to Devices in Various Fields



KENSUKE IDE*1

TAKAYUKI GOTO*2

JUN UTSUMI*2

TAKENORI SUZUKI*3

The room-temperature bonding technique, which holds bonding materials (wafers) together by activating their surfaces in a vacuum, can provide strong bonding without applying heat. The use of room-temperature bonding has primarily been used in the field of sealed packaging for MEMS (Micro Electro Mechanical Systems), but because this technique can be applied to diverse materials, it has recently been used in fields other than MEMS, such as light-emitting and radio-frequency (RF) devices. Mitsubishi Heavy Industries, Ltd. (MHI) has released a line of room-temperature bonders applicable to different wafer sizes for various purposes, ranging from research and development (R&D) to device mass production. The company is also trying to expand the application fields of room-temperature bonding by providing various kinds of bonding support services.

1. Introduction

Although the principle of room-temperature bonding has long been known, it was not until recently that the technique was actually applied in industry. Because it enables strong bonding without the application of heat, it was originally used in wafer-level packaging in the field of MEMS (Micro Electro Mechanical systems) devices. However, the application of room-temperature bonding for device fabrication has expanded into various fields over the last couple of years.

2. Principles and Features of Room-temperature Bonding

Room-temperature bonding is a technique in which wafers are irradiated with atoms or ions in a vacuum to remove the oxide film and absorption layers on the bonding surfaces so that the activated surfaces can bond (**Figure 1**). This method, which enables strong bonding without applying heat, has the following features.

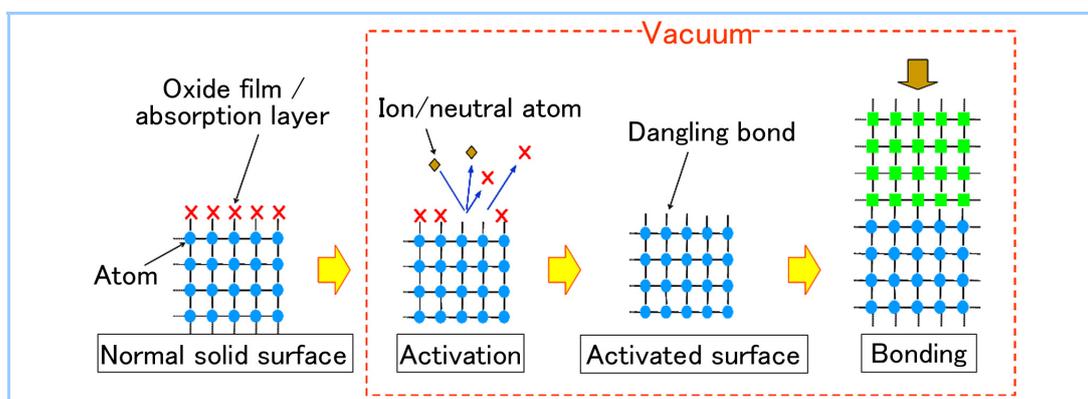


Figure 1 Principle of room-temperature bonding

Wafers are bonded by irradiating the bonding surfaces with ions or neutral atoms in a vacuum.

*1 Engineering Manager, Engineering Department, Machine Tool Division

*2 Research Manager, Advanced Technology Research Center, Technical Headquarters

*3 Engineering Department, Machine Tool Division

- (1) It provides bonding strength equivalent to that of the base material even when bonded at room temperature.
- (2) It does not cause thermal strain due to bonding.
- (3) It achieves high productivity by eliminating the need for a heating/cooling process.
- (4) It can bond a wide range of materials, such as silicon-based materials, compound semiconductors, oxides, and metals, and is capable of bonding different kinds of materials to each other.

3. Mitsubishi Heavy Industries' (MHI) Room-temperature Wafer Bonders

MHI provides a line of various types of room-temperature 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 2**).

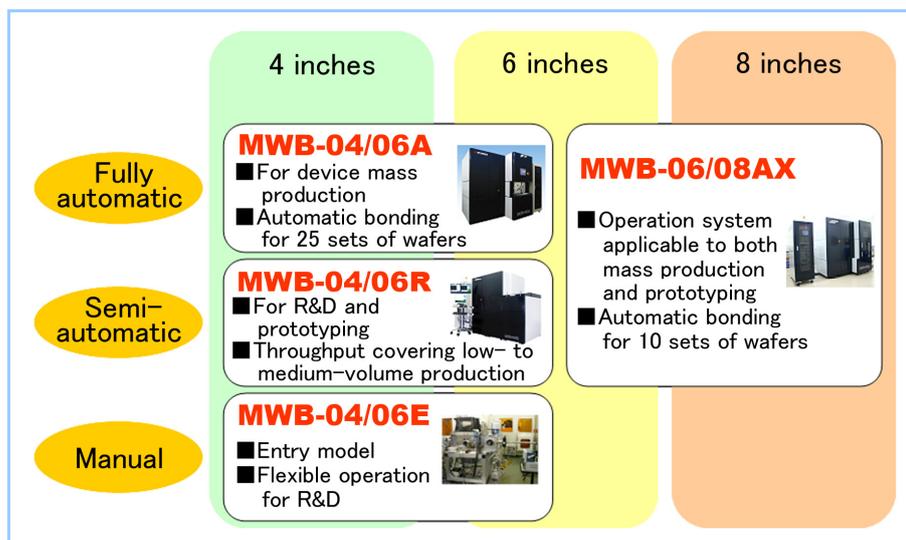


Figure 2 Lineup of MHI's room-temperature wafer bonders

The bonders support three wafer sizes (4, 6, and 8 inches) and are also adaptable to other sizes and nonstandard wafer shapes.

Equipped with built-in wafer transfer and precision alignment mechanisms (to position two wafers for bonding), all models can be used for production shortly after installation. Additionally, the bonders allow precise alignment (2 μm) and high-load application (100 kN), which are the most crucial features of bonding machines.

The fully automatic bonder, used for device mass production, is designed to successively bond 10 sets (20 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 of the 10 sets. Specifications for two fully automatic models, respectively designed for R&D prototyping and mass production (compatible with 8-inch wafers), are listed in **Table 1**.

Table 1 Specifications of bonders for R&D prototyping and mass production

	Semiautomatic bonder (For prototyping, low- to medium-volume production)	Fully automatic bonder (For mass production: 200-mm compatible)
Type	MWB-04/06 R	MWB-06/08 AX
Unit of operation	1 set	10 sets (max.)
Wafer size	100/150 mm	150/200 mm
Operation mode	Semiautomatic	Fully/semiautomatic
Alignment accuracy	$\pm 2 \mu\text{m}$	$\pm 2 \mu\text{m}$
Surface activation	Ion gun	Ion gun
Press unit	Max. load: 20 kN	Max. load: 100 kN
Alignment method	Infrared transparent image	Infrared transparent image

4. Application Fields and Examples of Room-temperature Bonding

As discussed above, the use of room-temperature bonding began in the field of MEMS. However, the areas of application are expanding recently 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 paper, the applications of room-temperature bonding are categorized below and discussed using examples.

(1) Wafer-level packaging in MEMS and other fields

Wafer-level packaging is a method used to seal packaging by bonding a cover wafer to another wafer on which MEMS devices are formed. Compared to separate packaging of singulated devices, wafer-level packaging has advantages of lower cost and higher yields.

Figure 3 is a schematic diagram of wafer-level packaging. **Figure 4** shows an example of acceleration sensors packaged on the wafer level. In this example, packaging is performed by three-layer bonding, which is a process that bonds cover wafers on the upper and lower surfaces of a wafer with sensors formed thereon. The use of wafer-level packaging is gradually expanding in the MEMS field as well as the field of quartz crystal devices.

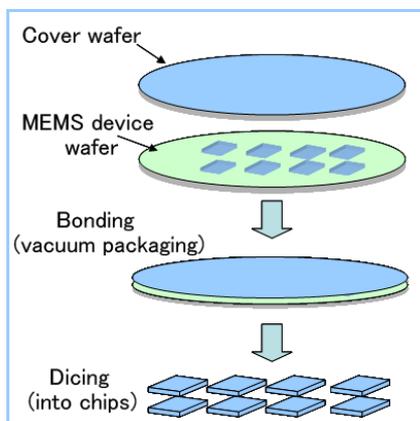


Figure 3 Schematic diagram of wafer-level packaging

Cover and device wafers are bonded on the wafer level and then diced into chips.

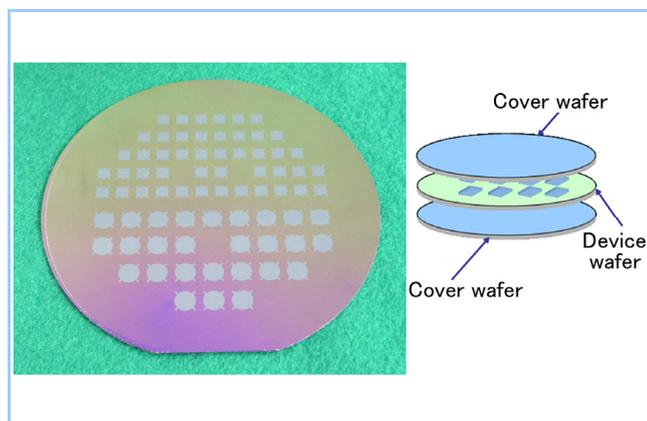


Figure 4 Acceleration sensors made by wafer-level packaging

An example in which cover wafers are bonded on the upper and lower surfaces of a wafer with sensors formed thereon.

(2) Production of functional wafers

A functional wafer is produced by bonding different kinds of materials, e.g., oxides, dielectrics, and optical materials. The resultant functional wafer is then subjected to micro fabrication to obtain the desired devices. Room-temperature bonding is well suited for bonding materials with significantly different thermal expansion coefficients. Functional wafers can be used for optical and radio-frequency (RF) devices. **Figure 5** shows an example of bonding between lithium niobate (LiNbO_3), a dielectric material, and a silicon wafer. Despite the significant difference between their thermal expansion coefficients, high-quality bonding can be achieved between lithium niobate and silicon using the room-temperature bonding technique.

(3) Application to high-value devices enabled by direct bonding

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. The method is primarily applicable to light-emitting devices. **Figure 6** shows an example of bonding between gallium nitride (GaN) and silicon. GaN has recently been highlighted as a material used in light-emitting, RF, and power devices. **Figure 7** shows an example of bonding between silicon carbide (SiC) and silicon. SiC is used as a material in high-efficiency power devices.

(4) Application to three-dimensionally stacked devices

Several layers of wafers, with a circuit provided thereon, are stacked by bonding through silicon vias (TSVs) that form through the wafers. The method is applicable to high-integration MEMS, image sensors, and large-capacity memory devices. **Figure 8** shows an example of aluminum TSV bonding.

As discussed above, room-temperature bonding is currently being applied in various fields, depending on the materials and structures of wafers to be bonded. High expectations for future applications of this technique are anticipated, especially to light-emitting and power devices.



Figure 5 Example of lithium niobate (LiNbO₃) and silicon (Si) bonding

An example in which a 3-inch LiNbO₃ wafer is bonded to a 4-inch Si wafer.

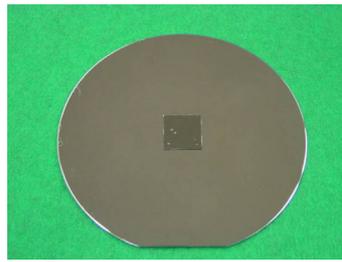


Figure 6 Example of gallium nitride (GaN) and silicon (Si) bonding

An example in which a GaN chip is bonded to a 4-inch Si wafer.

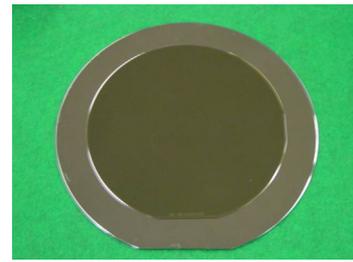


Figure 7 Example of silicon carbide (SiC) and silicon (Si) bonding

An example in which a 3-inch SiC wafer is bonded to a 4-inch Si wafer.

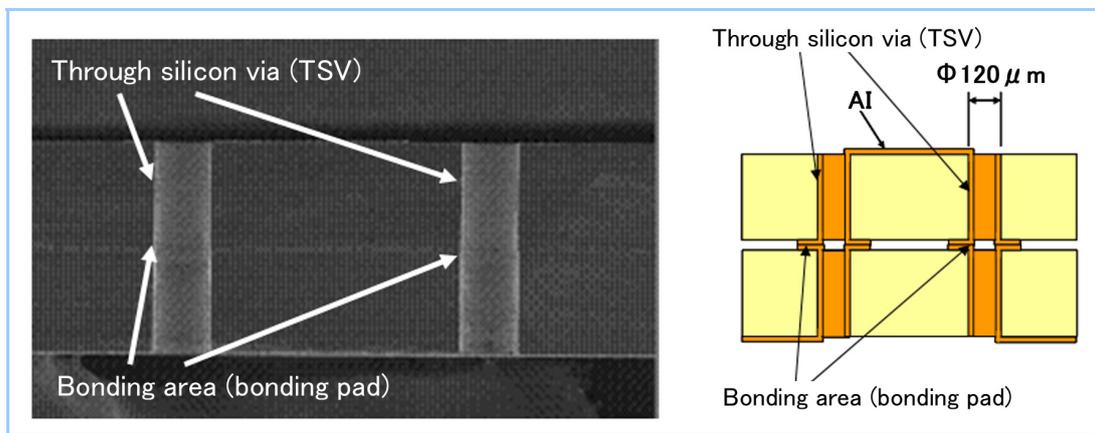


Figure 8 Example of aluminum through silicon via (TSV) bonding

An example in which bonding pads are formed and bonded to aluminum TSVs with diameters of 120 μm (scanning electron micrograph).

5. Device Development Support System

MHI has a line of bonders applicable to various wafer types and production styles, as described above. To enable more users to utilize the room-temperature bonding technique, the company offers a development support program called the “Mitsubishi Bonding Support Program” (MBSP) to assist device development on the user level (Figure 9).

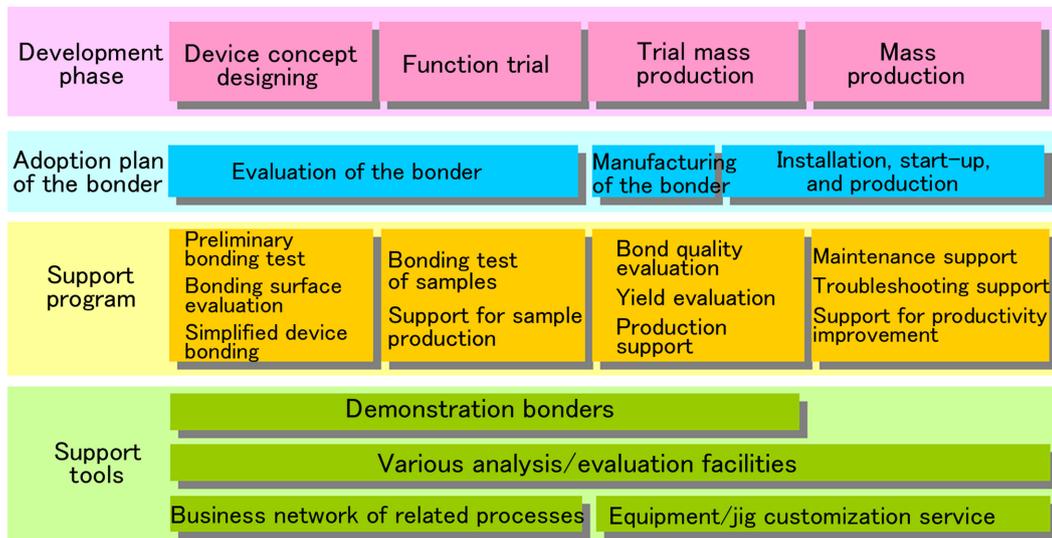


Figure 9 Mitsubishi Bonding Support Program (MBSP)

In general, the device development phase on the user level can be classified into the (1) device concept designing phase, (2) function trial phase, (3) trial mass production phase, and (4) mass production phase. In each of these phases, MHI offers support as outlined below.

- (1) Device concept designing phase: In this phase, the user examines the materials of the device and establishes the basic concept, including the fundamental structure. MHI evaluates the bonding condition and quality of the materials adopted by the users and performs preliminary bonding tests using simplified devices, thereby determining the feasibility of room-temperature bonding.
- (2) Function trial phase: This phase prototypes a device that actually functions. Among a series of user-level processes, MHI takes charge of the bonding process and provides support for bonding the prototyped samples. In some cases, several prototypes are required as engineering samples, and the company assists the production of bonding samples as well.
- (3) Trial mass production phase: This phase prototypes and evaluates the device for the primary purpose of productivity and yield improvement, thereby determining whether the prototyped device can be mass produced. MHI enables the improvement of productivity and yield by optimizing the bonding conditions. The company also assists the sample production in this phase.
- (4) Mass production phase: In this phase, the user actually begins mass producing the device. An MHI bonder has already been delivered, and maintenance support, after-sales, and overhaul services are provided to assist the stable device production and productivity enhancement at the user level.

To ensure that these services of the MBSP function effectively, MHI has three demonstration machines to bond user sample wafers on a daily basis. Additionally, the company has ample facilities for testing and evaluating the bonding quality as well as an adequate staff to handle user technical problems. Currently, the company has assisted more than 3,000 cases of bonding, and the program helps many users accelerate the development of their devices.

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 application fields are expected to further expand. This paper presents some examples of bonding and explains that the technique is expected to be applied to a broader range of fields, including MEMS and RF, light-emitting, power, and three-dimensionally stacked devices. In the meantime, providing high-quality bonders and a system to support user-level device development is essential to expand the application fields. MHI intends to gain more experience, especially in the development of bonders with higher bonding quality and the provision of bonding support programs for users, so that room-temperature bonding will be used in a wider range of fields.