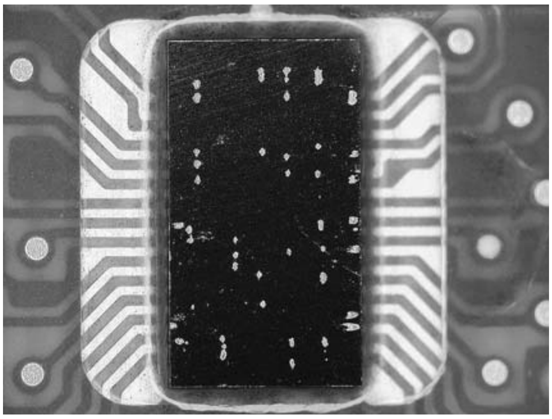
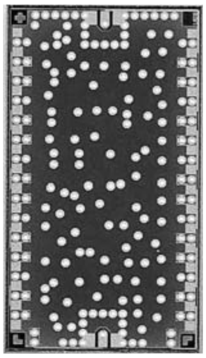
Development of Ultrasonic Flip Chip Bonding Technology

Motoaki TANI
Hiromichi WATANABE
Akihiko NISHIMURA
Shigetaka KACHI
Nobuhisa KATADA
Shinichi SUGIURA





Abstract

Millimeter wave radars have been developed and marketed for the purpose of reduction in deaths in traffic accidents and traffic congestion. However, the millimeter wave radars need to be cheaper to be used more widely.

In order to make the radars cheaper, we developed a new MMIC (Monolithic Microwave IC) structure and bonding technology, focusing on reducing costs of RF- modules. This article describes the new technology of bonding the MMIC to a resin substrate, and analyzing technology of MMIC and its bonded conditions.

1 Introduction

FUJITSU TEN began mass production of in-vehicle front millimeter wave radars in 2003. Recently we have mass-produced millimeter wave radars to detect objects not only in front but also in wider angles of rear and front-sides. An increasing number of radars are expected to be mounted in inexpensive cars as well as high-end cars, as standard equipment, and multiple radars will be mounted in a car to detect objects in all directions to improve safety. Therefore, radars are required to be smaller and low price. This article explains our ultrasonic flip chip bonding technology developed for the purpose of cost-reduction of RF-modules that are one of main parts of millimeter wave radars.

2 New Structure and Bonding Method for RF-modules

Currently mass-produced RF-modules are of ceramic package wherein a MMIC (Monolithic Microwave IC) is hermetically sealed[1)-3)] and a substrate is bonded to a metal frame to be fixed. Au pillar bumps need to be used to mount a MMIC in the thermocompression bonding method at an interval of 100 μm between terminals to ensure high frequency characteristic. As a result, in addition to the cost of the package using ceramic, the conventional module costs a lot for a metal frame compatible with low linear thermal expansion of the ceramic and for processes such as application and setting of a bonding material to bond the substrate and the metal frame.

In order to cut cost of the RF-module by fewer parts and fewer processes, we developed a new MMIC structure, and adopted plasma cleaning and ultrasonic bonding as the method for bonding the MMIC.

Fig. 1 shows structures of RF-modules. In the new structure[4)], a chip has multilayer wiring (hereinafter referred to as 3D) on its surface, which provides moisture resistance, miniaturization and cost-reduction. Moreover, we reduced the RF substrate cost by adopting resin substrates and process cost by screwing the substrate to the metal frame and simplifying the assembly process.

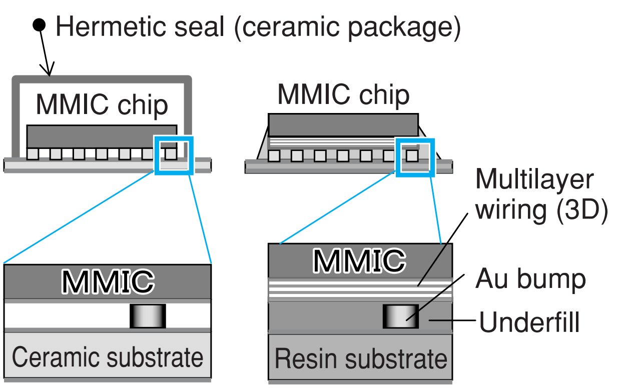


Fig.1 Outline of RF-Module Structures

The ultrasonic bonding method that enables bonding at low temperature is used to mount MMIC chips of the new structure because 3Ds of MMICs are deformed by heat during bonding in the conventional thermocompression method. Additionally bonding at low temperature is required to prevent the resin substrate from deforming or degrading by high temperature in the MMIC bonding process.

It is possible to bond at low temperature in the ultrasonic bonding method. However, 200 Au bumps should be bonded evenly on a resin substrate. That leads to a challenge of how ultrasonic waves are evenly applied to those bumps to bond them to the substrate. Application of conventional consumer-product technologies could not ensure that resin substrates achieved the reliability required for an in-vehicle device due to their large heat expansion, and we needed to develop a fundamentally-new approach.

3 Outline of Ultrasonic Bonding

Au bumps of a 3D-MMIC are bonded by being rubbed against Au-plated electrode pads (hereinafter referred to as pads) in the ultrasonic bonding method. The surfaces of the bumps and the pads are both Au so that metal bonding occurs at the interface between them. Ultrasonic vibration moves the surfaces closer to each other. Metal atoms of the bumps and the pads diffuse and the metal diffusion bonds the bumps and the pads. Metal bonding refers to creating the status where a bonded interface disappears. **Fig. 2** shows bonding process and changing condition of the bonded interface.

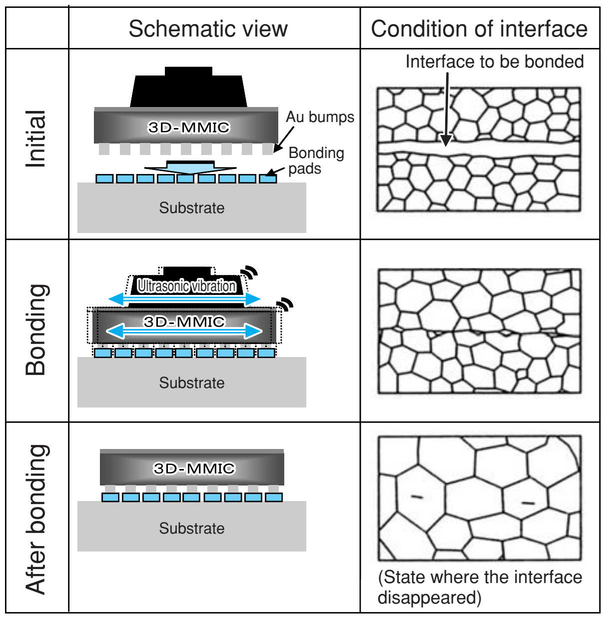


Fig.2 Relation of Bonding Process and Bonded Interface Condition

4 Assembly Process of RF-module and its Challenges

Fig. 3 shows the assembly process of RF-modules. First, the surfaces of the Au bumps and the pads that are to be bonded are cleaned by plasma to remove objects from those surfaces. Dusts and other objects on those surfaces cause voids which lead to a bonding defective. Therefore, those surfaces are cleaned by plasma.

Second, the bumps and the pads are bonded with flip-chip bonder using ultrasonic waves. In the ultrasonic bonding, a bonding load and ultrasonic amplitude is simultaneously applied to the 3D-MMIC and thus the Au bumps are bonded to the pads.

Next, the bonded area is filled with resin strengthening agent called underfill and heated to be hardened.

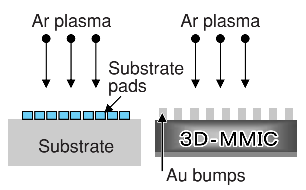
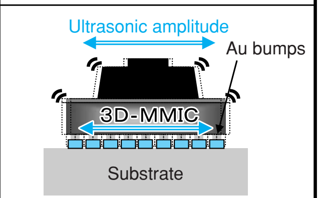
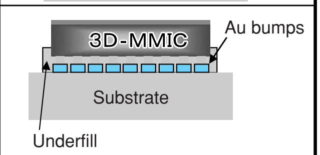
Process	Schematic view
Plasma cleaning Clean the surfaces of substrate pads and Au bumps by plasma cleaning using argon gas.	
Ultrasonic mounting Bond Au bumps and pads by applying ultrasonic amplitude, bonding load and heat.	
Filling and hardening of underfill Bonded area is filled with underfill and then hardened.	

Fig.3 RF-Module Assembly Process

In order to evenly bond 200 Au bumps to a resin substrate, solutions were needed for the two conflicting problems: less deformation of wiring and prevention of fracture (sufficient bond strength) of the bonded area.

It is known that there was a problem of deformation or even breaking a wire, in an extreme case, of multilayer wiring due to deformation of an Au bump by ultrasonic bonding in the conventional wiring process of a wafer. **Fig. 4** shows an example of deformation of wiring pattern.

MMIC Wiring Pattern Deformation

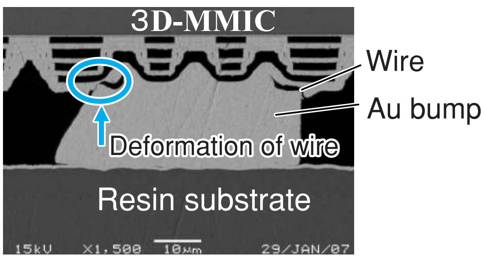


Fig.4 Example of Wiring Pattern Deformation

In the beginning, we tried to determine bonding conditions for solving the problem by ensuring sufficient bond strength while avoiding breaking of a wire. However, we found some cases where the bonded area became fractured by thermal stress at the time when the underfill was hardened. **Fig. 5** shows an example of fracture of an interface between Au bump and Au plating.

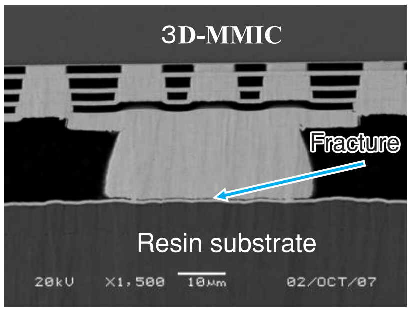


Fig.5 Example of Fracture of Interface between Au Bump and Au Plating

The next section explains our effort to solve those conflicting problems.

4.1 Effort to Prevent Wiring Pattern Deformation

Since Au bumps are formed on multilayer wiring, stress applied to the bumps during ultrasonic bonding may deform wires under the bottom edges of the bumps. We challenged to reduce the deformation with changing as few processes of 3D-MMIC wafer as possible. Originally, a protective resin film lay under the bottom of the Au bump. Therefore, when an Au bump was deformed by stress during ultrasonic bonding, the protective resin film was also deformed, and so were the wires under the Au bump. We analyzed the stress to Au bumps and added to them structures (reinforcing structures) which allow them to endure the stress. By adding the reinforcing structures, we achieved reduction of the deformation and breaking of wiring pattern during the bonding. **Fig. 6** shows the structure of an Au bump and the structure of a reinforced Au bump. **Fig. 7** shows the cross-section result of a reinforced Au bump bonded to a resin substrate.

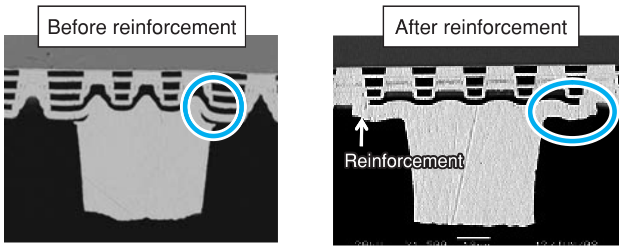


Fig.6 Reinforced Au Bump Structure (Cross-sectional)

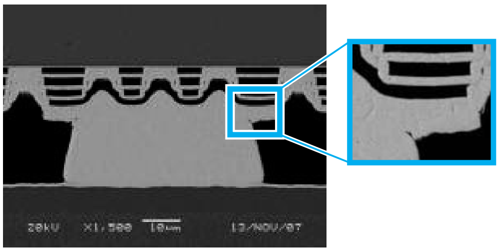


Fig.7 Cross-section Result of Reinforced Au Bump After bonding

We established the new wiring structure for ultrasonic bonding in the approach mentioned above.

4.2 Effort to Prevent Bonded Interface Fracture

In order to prevent fracture of the bonded, bond strength needs to be enhanced to endure the thermal stress applied to Au bumps. To increase each bump bonding strength is very difficult because 3D-MMIC Au bumps vary in height by 3D wiring pattern design and Au plating thickness. Therefore, we evaluated the bond conditions where the 200 bumps are evenly bonded, using each bump bonded area measuring.

Fig. 8 shows an outline of a conventional bonding profile.

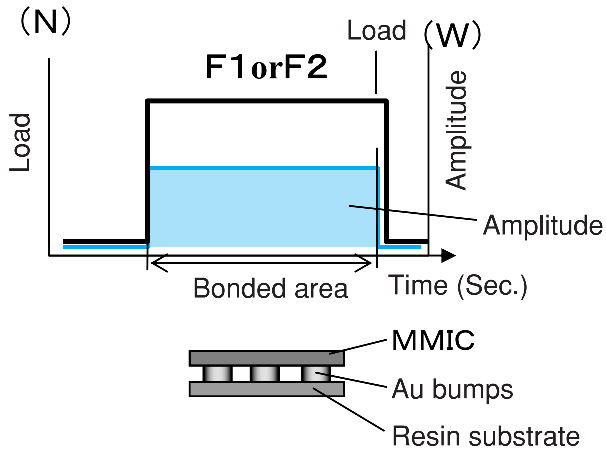


Fig.8 Outline of Conventional Bonding Profile

The load (F1) is applied to the entire 3D-MMIC during ultrasonic bonding. Therefore, load applied to each Au bump differs according to the number of Au bumps that touch the pads. Accordingly, the bonded conditions of individual bumps differ. At the initial stage of bonding, only a small number of tall Au bumps touch the pads. Application of a certain load to the 3D-MMIC means excessive load for the tall Au bumps and they cannot be rubbed by ultrasonic waves. Therefore, even those bumps are deformed, their areas for bonding are not large enough and thus their bond strength is not sufficient. **Fig. 9** shows an image of the bonding.

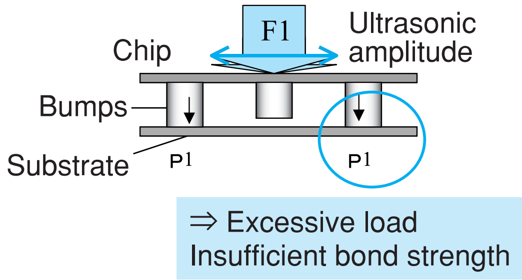


Fig.9 Image of Excessive Load

On the other hand, when a load (F2) is too light at the initial stage of bonding, small Au bumps are not sufficiently deformed at the later stage of bonding where all Au bumps should touch the pads and areas for bonding are not large enough and thus bond strength is not sufficient again because some bumps do not touch the pads and/or some bumps only slide on the pads. **Fig. 10** shows an image of the bonding.

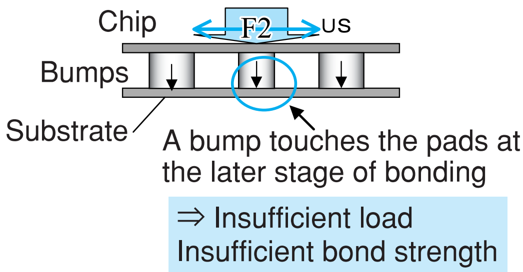


Fig.10 Image of Insufficient Load

To solve the problem, we developed a bonding technology that ultrasonic waves are applied with incremental load from a small load (F1) for making the taller bumps the same height as smaller bumps or leveling the height of the bumps at the initial stage of bonding to a load (F2) required for actual bonding at the time when all bumps touch the pads. **Fig. 11** shows an outline of the profile of our developed ultrasonic bonding.

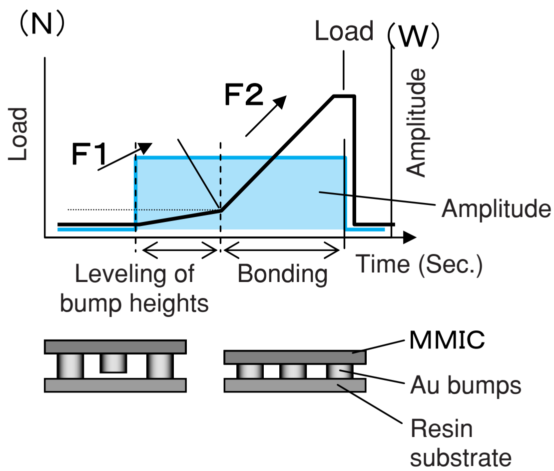


Fig.11 Outline of Developed Ultrasonic Bonding Profile

The conventional bonding profile with a constant load resulted in uneven bonding of bumps of the 3D-MMIC.

However, in the case of the developed bonding profile, the bumps of the 3D-MMIC were bonded very evenly. Consequently, the developed bonding profile eliminated the fracture of the bonded portions that had occurred during the bonding in conventional conditions.

Here, we explain the process for measuring a bond area. First, the thermal history that was used for hardening the underfill is applied to a bonded 3D-MMIC, and then the 3D-MMIC is debonded in a pull test. Second, shear strength of the individual Au bumps remaining on the substrate is measured and then their bonded areas are also measured. **Fig. 12** shows an outline of measurement of bonding strength and **Fig. 13** shows an example of measurement of a fractured surface.

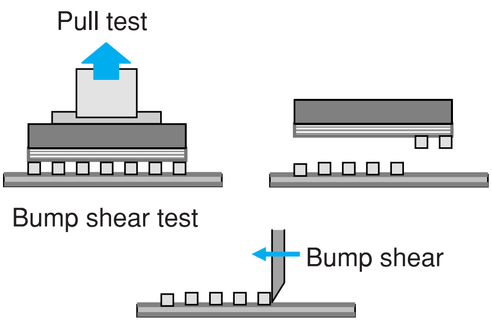


Fig.12 Outline of Measurement of Bonding Strength

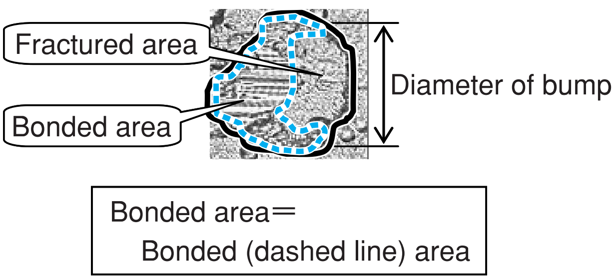


Fig.13 Example of Measuring Fractured Surface

Fig. 14 shows the relation of the bonded areas and shear strength of bumps.

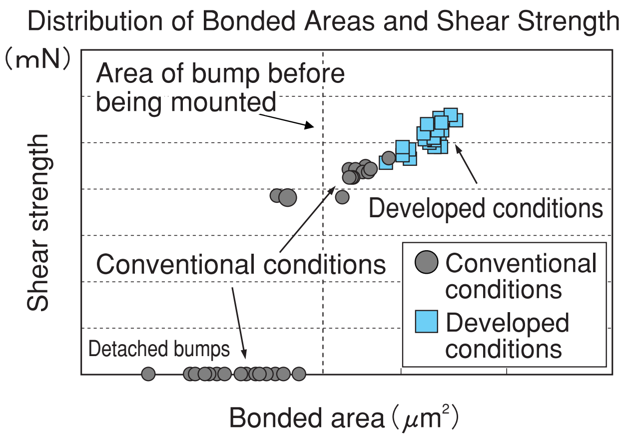


Fig.14 Relation of Bonded Area and Shear Strength

As shown in **Fig. 14**, the shear strength is correlated with the bonded area. We could prevent fracture of the bonded portions by parameter design using the bonded areas as index.

5 Reliability Test Results

We conducted temperature cycle test (at -40℃ and 125℃ for 30 minutes each) on substrates bonded with MMICs to observe the change rate of their electrical conductive resistance and conditions of the cross-section surfaces of their bonded areas. **Fig. 15** shows the results.

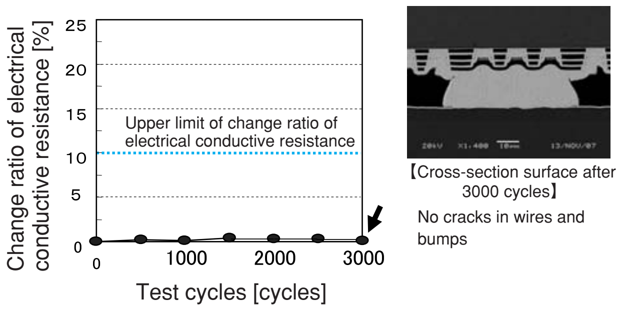


Fig.15 Results of Thermal Cycle Test

We confirmed from the test results that the bonding was very reliable with less than 10%, a standard value, of electrical conductive resistance change rate after 3000 cycles, no damage in wiring pattern, and no fracture of bonded portions on the cross-section surface.

6 Development of Bond Evaluation and Analysis Methods

We were successful in improving bond strength in this development, but in order to achieve the results, it was also important to develop evaluation technology for parts and analysis technology for bonded portions.

For evaluation technology for parts, we needed to know limits of controllable height of Au bumps. For analysis technology for bonded portions, we not only measured bond strength and electrical conductive resistance but also observed physical bonded conditions. As a result, we confirmed that parameter design mentioned above is appropriate for flip chip bonding. In the following sections, we explain the evaluation and analysis methods.

6.1 Assessing of Height of Au Bumps

We have discussed bonding profile as measures against fracture of bonded portions in the previous sections. However, there was another problem of limits of controllable differences in height of bumps. For the purpose of eliminating fracture of bonded portions, we developed a multipoint measurement technology to know the limits of controllable height of Au bumps.

We measured the height of all bumps using a small diameter laser beam of a displacement meter and colored those bumps per height. The intervals between those bumps are so small that it had taken about one hour to measure a bump. However, after the measurement method was reviewed, the measurement time per a bump was cut to some minutes. Thus, the variation of height of the Au bumps became visible. **Fig. 16** shows an example of the measurement results of Au bump heights.

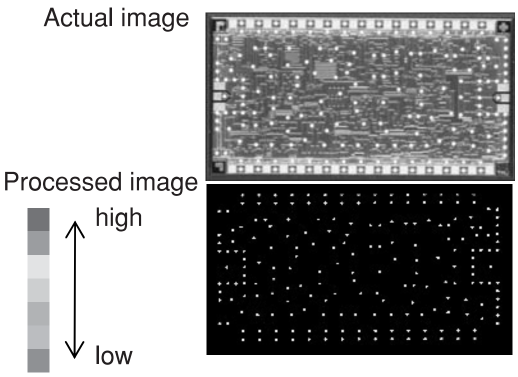


Fig.16 Measurement Example of All Bump Heights on 3D-MMIC

Based on the results, we discussed the bonding profile and decided specifications of the bump height.

6.2 Evaluation and Analysis Methods for Bonded Interfaces

We used the following two methods for evaluating bonded interfaces.

1) Conditions of bonded interfaces in numerical terms (disappearance rate of bonded interfaces)

2) Analysis in EBSD (Electron Back Scatter Diffraction)

1) Analysis by expressing conditions of bonded interfaces in numerical terms

As shown in **Fig. 2**, the grain boundaries of the bonded interface disappear by metal bonding when a 3D-MMIC is completely bonded to a substrate. CP (Cross-section Polishing) method for cross-section processing and FE-SEM (Field Emission Scanning Electron Microscopy) allowed us to observe as small as metal crystal, and we tried to determine good bonding or bad bonding based on disappearance of the bonded interface. We defined disappearance rate as disappeared length of the interface to the bonded length measured in the observation of the cross-section surface. **Fig. 17** shows an example of the observed cross-section surface after being bonded and length of the disappeared interface.

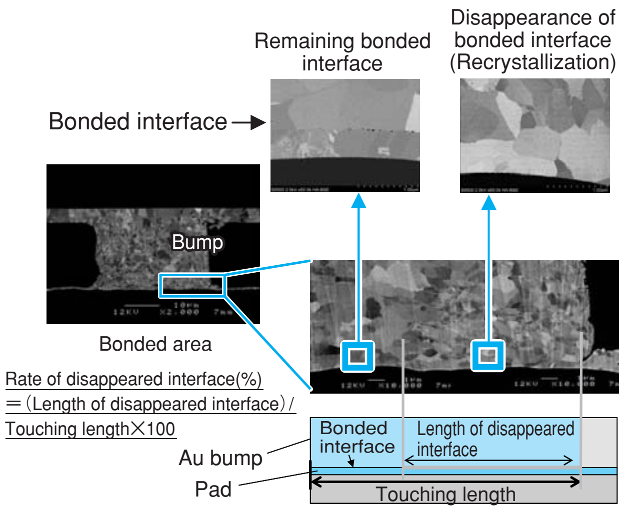


Fig.17 Example of Disappeared Interface after Bonding

Moreover, rate of disappeared interface seems correlated with the number of bumps (transcription rate) on a substrate after a 3D-MMIC is debonded from the substrate as explained in **Fig. 12** two pages ago. The rate of disappeared interface enables us to determine good bonding or bad bonding. **Fig. 18** shows the relation of disappeared bonded interface rate and transcription rate.

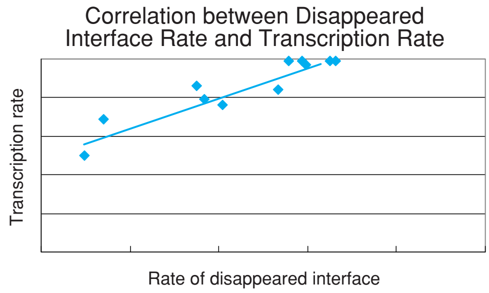


Fig.18 Relation of Disappeared Bonded Interface Rate and Transcription Rate

2) Analysis in EBSD

We checked, in EBSD analysis, conditions of Au crystallized at the interfaces where the bumps were bonded to the pads to confirm that ultrasonic bonding causes complete metal bonding.

Fig. 19 shows EBSD analysis results of bonded Au bumps. As can be seen from the distribution of crystal orientation discriminable by the differences in color in (b) Inverse Pole Figure Map, crystals of the Au bump are laterally stretched and flattened in general although they slightly remain in the original column shape before bonding. We confirmed that the Au crystals themselves were deformed in accordance with deformation of the Au bump and that crystal deformation increased the areas for bonding on the top of the bump. That leads us to the conclusion that plastic deformation that brings Au atoms close to each other and contributes to metal bonding occurs mainly on the bumps.

From the results of (c) Boundary Map, we confirmed the conditions where Au crystals were tightly engaged with each other without space at the interface between the Au bump and the pad and also where the bonded interface was not clear and crystals grew across the bonded interface. The possible reason for that is because the Au atoms move across the bonded interface from the bump.

Those results provide a possible conclusion: Au atoms contact to each other at high density between the bumps and the pads even immediately after bonding, which means excellent metal bonding. The disappearance of bonded interface shown in **Fig. 19** was confirmed from a viewpoint of crystal grain boundaries.

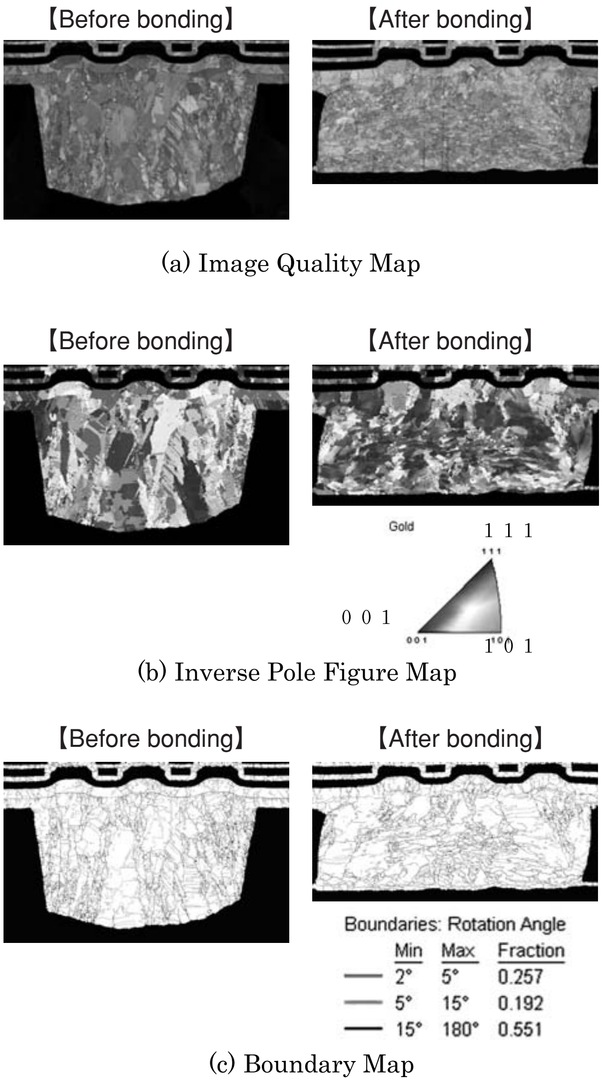


Fig.19 EBSD Analysis Results of Bonded Au Bumps

7 Conclusion

We established a bonding technology employing ultrasonic bonding for bonding MMICs on resin substrates which replaces conventional thermal compressing bonding method used for bonding MMICs on ceramic substrates at high temperature. Our newly-developed technology reduced the cost of RF-modules to one-third compared to the cost in the conventional method. For the assessment of bonding, we confirmed the status of Au bumps bonded to pads at the bonded interfaces at a level of metal crystal in addition to bond strength and connection resistance, and we improved evaluation and confirmation level.

In the future, we would like to commercialize RF-modules having 3D-MMIC and contribute to expansion of the millimeter wave radar market.

Reference

1) N. Motoni, H. Yagi, and S. Yamano, Development of 76 GHz Single Chip MMIC High Frequency Unit, No. 1 of Vol. 20 in Japanese Version (Vol. 19 in English Version), FUJITSU TEN TECHNICAL JOURNAL, June 2002
2) S. Yamano and H. Higashida, 76 GHz Millimeter Wave Automobile Radar using Single Chip MMIC, No. 1 of Vol. 22 in Japanese Version (Vol. 23 in English Version), FUJITSU TEN JOURNAL, June 2004
3) Y. Aoki, Y Watanabe and N Okubo, HEMT Monolithic Microwave IC (MMIC) for 76 GHz Automotive Radar, Vol. 51, 3, FUJITSU, May 2000
4) Technology Development of Inexpensive RF- modules for in-vehicle millimeter wave radars, FUJITSU Ten Press Release, May 19, 2005

Profiles of Writers

Motoaki TANI

Entered FUJITSU LABORATORIES LTD. in 1987. Since then, has engaged in research and development of materials and technologies for electronics packaging. Currently, being Senior Researcher, Device Integration Technology Lab. Device & Materials Laboratories, Fundamental Technology Research Center, FUJITSU LABORATORIES LTD.

Hiromichi WATANABE

Entered the company in 1989. Since then, has engaged in the manufacturing engineering, production engineering and mounting element technology development. Currently, in the Sensor Development Division, AE Group.

Akihiko NISHIMURA

Entered the company in 1983. Since then, has engaged in the manufacturing engineering and mounting technology development. Currently, in the Sensor Development Division, AE Group.

Shigetaka KACHI

Entered the company in 2000. Since then, has engaged in the manufacturing engineering and mounting technology development. Currently, in the Sensor Development Division, AE Group.

Nobuhisa KATADA

Entered the company in 1997. Since then, has engaged in the material engineering and mounting technology development. Currently, in the Production Engineering Dept, Production Group.

Shinichi SUGIURA

Entered the company in 1990. Since then, has engaged in the mounting technology development of automobile electronics devices. Currently, Department General Manager of the Radar Revolution Project Dept, Sensor Development Division, AE Group.