Development of Wiring Technologies to Improve Power Module Performance

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1. Introduction

In the power electronics industry, to save energy and protect the environment, power modules are being widely used in home appliances, industrial equipment, automobiles, and railway application. There are needs to improve the performance of power modules, including downsizing, higher current density, and longer lifetime, depending on each application. To satisfy such needs, it is important to develop internal wiring technologies.

Table 1 lists the typical internal wiring technologies used for power modules. Previously, wire bonding using Al wires was commonly used. To improve the current density and lifetime, Al alloy wires and Cu wires have been applying. In addition, the use of the direct lead bonding (DLB) structure, in which main terminals are directly soldered on the chips, has been also applying. This report describes packaging technologies, focusing on these internal wiring technologies.

2. Wire Bonding

A general internal wiring technology for power modules is wire bonding with a diameter of 200–500 μm of Al by ultrasonic wedge bonding. This technology provides a higher flexibility in wiring. On the other hand, the lifetime of the products is often determined by the lift-off lifetime of the bonded wires. Lift-off is the phenomenon in which a crack develops at the bonded-junction of a wire due to stress caused by a difference in the coefficients of thermal expansion (CTE) between the wire and chip and the wire eventually remove from the chip. Mitsubishi Electric Corporation has been studying ways of solving such problems by optimizing the module structure and using new wire materials.

2.1 Al alloy wire

Al alloy wires, which are developed by adding trace quantities of different kinds of metal to Al wires to strengthen the wire material, improve the lift-off lifetime.[1]

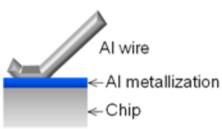
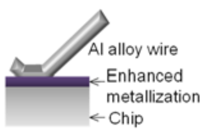
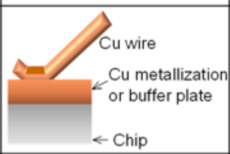
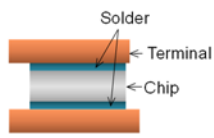
Figure 1(a) shows the comparison results of the degradation rate of shear strength of samples in which the conventional type of Al wire and the new type of Al alloy wire were wire bonded on Al and enhanced electrode after a temperature cycling test (50 to 150°C). If an Al alloy wire is applied to the conventional Al metallization (Sample B), the degradation rate of shear strength is not further improved than Al wire bonded to conventional Al metallization (Sample A). However, when an enhanced electrode is combined with an Al alloy wire, the degradation rate of the bonded junction of the wire is substantially improved (Sample C). Cross-sectional images at the bonded junction of each Sample after the temperature cycling test are shown in Fig. 1(b). Al alloy wire bonded to a conventional Al electrode (Sample B) shows the crack is selectively propagated into Al electrode where is concentrated of strain.

Meanwhile, in Al alloy wire bonded to an enhanced electrode (Sample C), the crack is propagated into the wire. From the results, applying Al-alloy wire which has high mechanical strength in combination with enhanced electrode can contribute to improve the lift-off lifetime on wire bonding junction.

2.2 Cu wire

Since the recrystallization temperature of Cu wires is higher and the CTE mismatch between wire and chip is less than Al wires, the lift-off lifetime is expected to be much longer.[1] To confirm the improvement of lift-off

Table 1 Types of wiring technology

Technology	Wire bonding	Wire bonding	Wire bonding	DLB (Soldering)
Wiring material	Al wire	Al alloy wire	Cu wire	Cu terminal
Structure				
Current density	Ref.	○	+	++
Fatigue life	Ref.	+	++	++

+ Shows the degree of performance improvement

* Power Device Works

lifetime, the power cycling lifetime of Al and Cu wire bonded samples are compared. Figure 2 shows the appearance of a sample with Cu wires bonded and the power cycling test results. The lift-off lifetime of the sample with Cu wires bonded is approximately 35 times longer, which is the remarkable extension of lift-off lifetime. For this sample, to reduce a deterioration of the die attach junction, an Ag sintering material was applied.(2)

Cu wires are harder than Al wires and are required larger energy for bonding. Various structures have been proposed to prevent chips from breaking when the wires are bonded. For example, chip electrodes are plated with a thick layer and a buffer plate is installed on top of an electrode.(3) To take advantage of superior property of Cu wire, it is not enough to apply Cu wire, but needs to optimize a package structure.

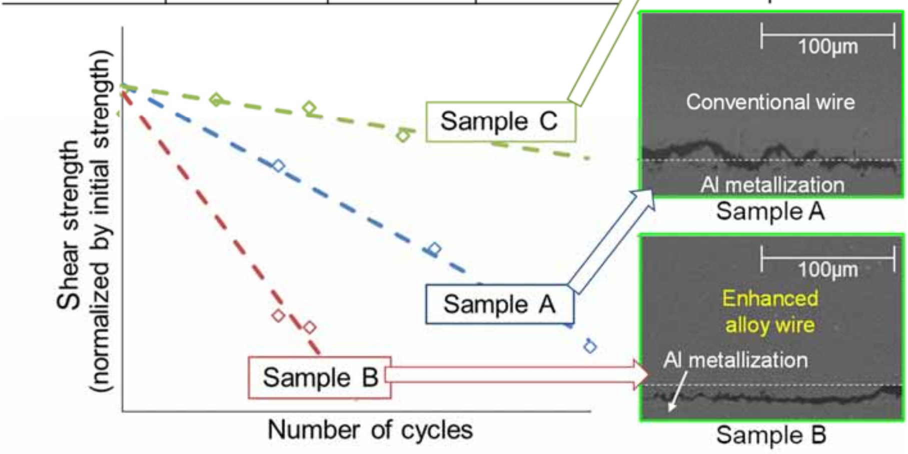
3. Direct Lead Bonding (DLB)

The DLB structure in which external terminals are directly soldered onto chips eliminates any internal wires to connect to terminal. Therefore, the area required for such wires can be reduced, which helps downsize packages. In addition, DLB structure has advantageous for high power density because terminal can be bonded a larger junction area compared to wire bonding.

3.1 DLB for case type modules

In 2011, we released the J-series transfer-molded power module T-PM for automobiles, featuring the DLB structure and transfer molded structure. Due to expansion of the xEV market in recent years, there is more demand for smaller power modules with higher current density. To satisfy this need, we have developed case type modules (J1 series). In this product, a grease-

	Sample A	Sample B	Sample C
Wire	Conv. Al	Enhanced Al	Enhanced Al
Metallization	Conv. Al	Conv. Al	Enhanced material
Crack position	Near interface	Metallization	Wire
Degradation	(Reference)	Larger	Smaller



(a) Degradation of shear strength (b) Cross-sectional SEM image

Fig. 1 Comparison of conventional Al wire and enhanced Al alloy wire

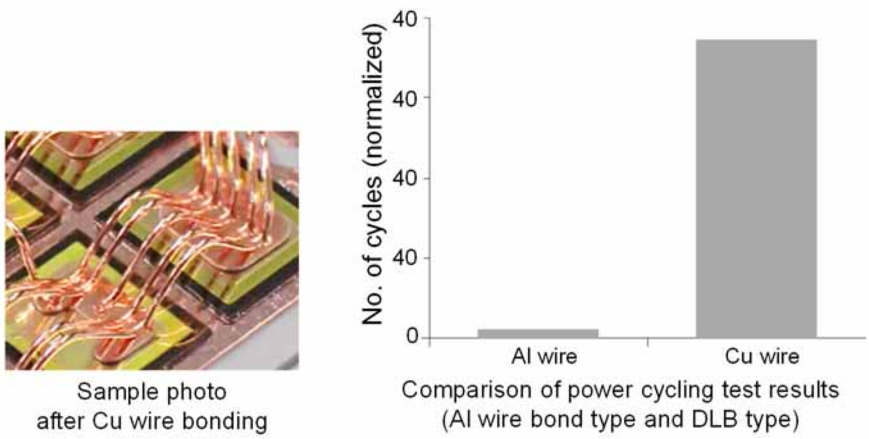


Fig. 2 Results of power cycling test of Cu wire bonded sample

free structure with a built-in cooling fin was combined with the DLB structure. Figure 3 shows the appearance and cross-sectional structure of the J-series T-PM and J1 series. For the J1 series, our proprietary seventh-generation IGBT/diode was applied and the DLB technology was combined with direct potting (DP) resin encapsulation technology. This has made it possible to provide smaller high-power modules even for larger case type modules by utilizing the advantages of the DLB structure. In addition, we released the high-power J1 series: the output capacity was approximately doubled while the increase in size was suppressed to only approximately 1.5 times by optimizing the internal wiring layout. Thus, we have been expanding line-up of this kind of products Figure 4 compares the high-power J1 series to the conventional type. The adopted DLB

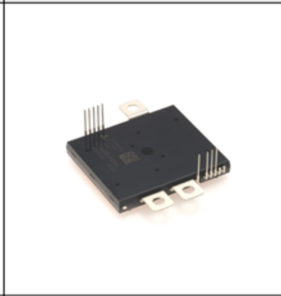
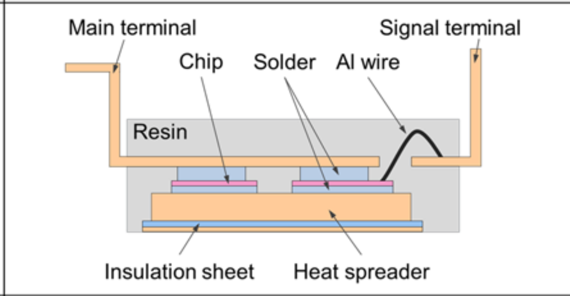
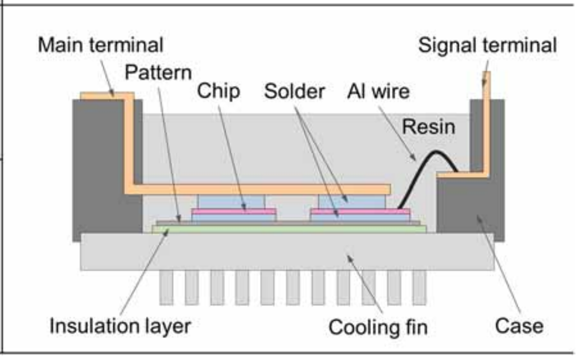
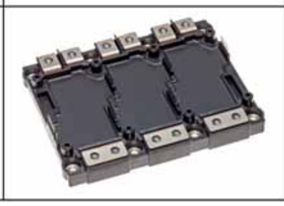
Module type	Series	Photo	Cross-sectional diagram
Molded type	J-series T-PM		
Case type	J1-series		
	High-power J1-series		

Fig. 3 Sample photo and cross-sectional diagram of DLB type modules

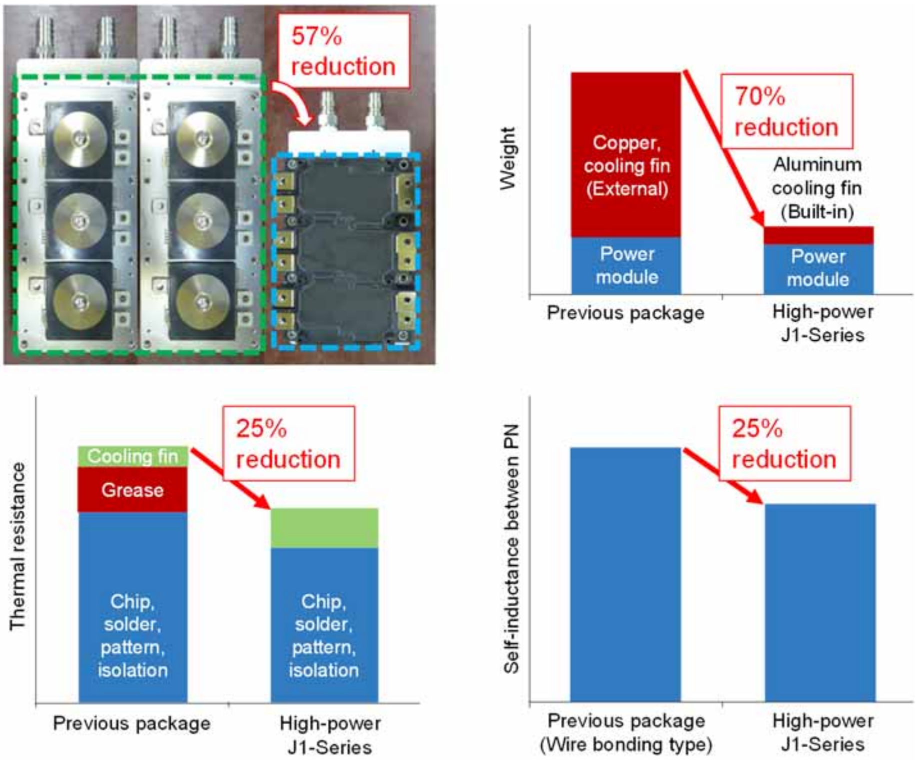


Fig. 4 Improvement in characteristics of high-power J1 series

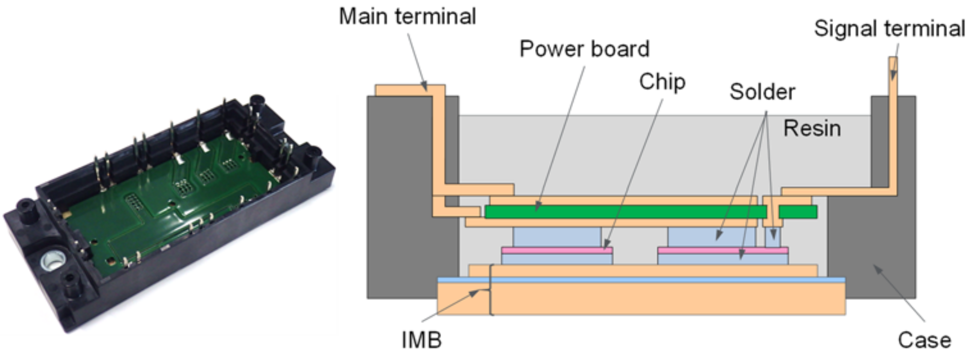


Fig. 5 Sample photo and cross-sectional diagram of case type module using power board

structure, built-in fin and optimized internal wiring layout reduced the mounted area by 50%, weight by approximately 70%, and thermal resistance by 25% compared to the conventional transfer-mold type with the same output. In addition, optimization of the wiring layout reduced the self-inductance by 25% compared to the wire-bonding type.

In the DLB structure, the lifetime of soldered junctions is greatly affected by the solder shape. However, for large case type modules, the clearances between the chips and terminals tended to be unstable and it was difficult to control the solder shape. Meanwhile, providing a through hole at the soldered joints of terminals can stabilize the solder shape. This enables to applied DLB structure for large case type and to realize the longer lifetime which is feature of the DLB structure. We will apply the DLB technology used in case type modules to products in other applications to provide smaller but higher-power modules.

3.2 Direct power board bonding

We are developing the new structure shown in Fig. 5 by the improving DLB technology in which Cu leads used to be wired two-dimensionally. In the new structure, heavy-current power boards (multilayer circuit boards) are directly soldered onto the chips. The power board with multilayer wiring patterns above and below the insulating layer allows wiring in two layers (upper and lower), including signal wires by one board. This new structure allows further downsizing of modules and optimization of the electrical characteristics. The optimization of balancing currents and switching timing of each chips is become easier by 2 layers wiring design. Moreover, it has been confirmed that reduction in parasitic inductance by using mutual inductance between the upper and lower patterns.

Thus, by using power boards it is possible to make modules smaller, optimize the electrical characteristics, and cope effectively with complex topologies in the future.

4. Conclusion

Mitsubishi Electric will continue developing wiring technologies to increase the current density and lifetime to offer suitable products that satisfy market needs as follows;

- Wire bonding

Improving the lifetime by using new wiring materials with optimizing electrode structure to match new materials.

- Direct lead bonding (DLB)

Applying the DLB technology (for case type modules) to other types of products for downsizing and longer service life

- New wiring structure

Applying the DLB technology involving multiplayer circuit boards for downsizing, improving the characteristics, and coping with complex topologies

References

(1) Uchida Y., et al.: Wiring technology for upcoming generation power module, Proc. PCIM Europe, Nuremberg Germany (2020)

(2) Nakahara K., et al.: Development of Package Structure for High-Temperature Operation, Mitsubishi Electric ADVANCE, Vol. 165 (2019)

(3) Uchida Y., et al.: Investigation of Highly Reliable Structure with Cu Wire for Power Module, Proc. 24th Symposium on Microjoining and Assembly Technology in Electronic, Yokohama, Japan (2018)