SiC Power Module for Automotive

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1. Introduction

In recent years, in order to reduce greenhouse gas emissions, governments around the world have been actively promoting vehicle electrification. From 2025, sales of gasoline-fueled automobiles will be gradually restricted and thus sales of new electric-powered automobiles are expected to increase.

Mitsubishi Electric Corporation released small, highly-reliable T-PMs in 2001 and the J1 Series case-type automotive power module in 2015, contributing to vehicle electrification by supplying Si power devices (Fig. 1). To encourage the spread of xEVs in the future, the cruising distance of automobiles needs to be increased. One way of doing this is to reduce the loss in inverters. The loss in semiconductor devices for SiC power devices is approximately 70% smaller than that for Si power devices. Therefore, SiC power devices are being developed as next-generation semiconductor devices to reduce the loss in inverters.

Mitsubishi Electric is developing SiC T-PM (provisional name) by combining its accumulated know-how on SiC power devices and T-PM packages. This paper introduces emerging issues in the development and countermeasures.

2. SiC T-PM

2.1 SiC power devices[1]

Mitsubishi Electric started developing SiC power devices in the 1990s and in 2010, released power modules for electric railways that included first-generation SiC metal-oxide-semiconductor field-effect transistors (MOSFETs). In 2013, we started mass-producing the second-generation devices with optimized cell size and injection conditions, and have been supplying them for use in consumer goods, industry, and automobiles. Currently, we are developing the trench type as the third generation (Fig. 2).

Technological issues of the trench structure include the degradation of gate insulators due to high electric field and limitations on reducing the on-resistance (Ron) due to densification. To solve these issues, the third-generation trench-type SiC power device (multiple ion-implantation into tilted trench sidewall metal oxide semiconductors (MIT2-MOSs)) currently being developed uses an electric field relaxation structure and n+ JFET doping (JD) (n layer) formation, which are our proprietary technologies.

The gate insulator may deteriorate and the device may become damaged by the high electric field that occurs at the corner of the trench gate. To prevent these problems, a p+ bottom P-well (BPW) is provided at the bottom of the trench gate to protect the gate oxide from the high electric field that occurs when a current is carried, thus enhancing the reliability. At this time, electric charge accumulation up on the BPW may hinder high-speed operation and thus increase the switching (SW) loss. To avoid this, a p sidewall connection (SC) is provided to allow the BPW to have electrical continuity with the p layer and source electrode. This stabilizes the electric potential of the BPW and encourages the discharge of electric charges accumulated on the BPW, reducing the SW loss.

Fig. 1 Automotive Si power module

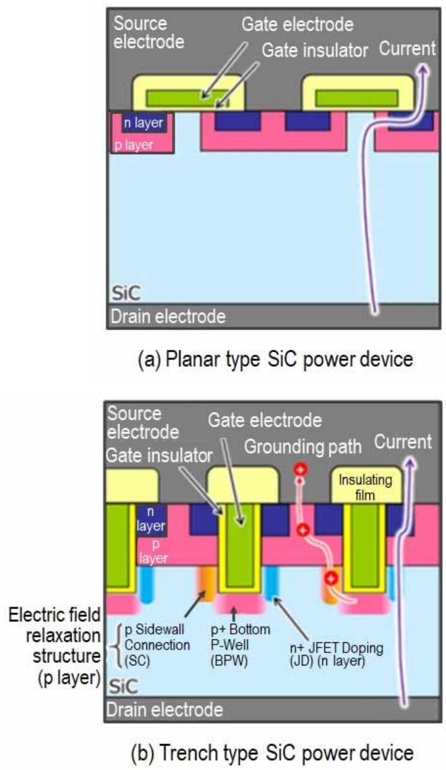


Fig. 2 Schematic diagrams of Mitsubishi Electric SiC MOSFET

**Power Device Works*

For the trench gate structure, Ron was reduced through densification. However, there was a limit on reducing Ron because the drain current density increases as a result of densification. To solve this, JD (n layer) is provided on the side of the trench gate to increase the density of carriers on the drain current path and reduce Ron.

Compared to the planar type, on MIT2-MOSs, Ron was reduced though densification of carriers and the trade-off curve between Ron and gate threshold voltage (Vth) was also improved. Thanks to this improvement, the standardized on-resistance of MIT2-MOSs with high-withstand-voltage devices (rating of 1,200 V) (avalanche voltage of 1,500 V) is 1.9 mΩ·cm^2 at room temperature when Vth is 4.1 V.[(2)]

2.2 T-PM packages[(3)]

Previously, Mitsubishi Electric released DIPIPM for consumer goods. We applied the package technologies used for DIPIPM to T-PM to create a small, low-profile, highly-reliable transfer molded product for automotive applications.

One characteristic of this product is that the thermal cycle reliability is higher than that of case-type modules, which was achieved by matching the coefficients of thermal expansion (CTE) of the chips and the molding sealing resin. In addition, the electric connection with chips was changed from wire bonding to direct lead bonding (DLB), which allows the power cycle reliability to be retained longer and reduces the interconnection resistance and self-inductance.

Regarding the cooling structure of the chip, thick copper (heat spreader) is provided immediately below the chip, and an insulation sheet that has higher thermal conductivity than the molding sealing resin is provided below that. While the electric insulation performance remains high, the heat from the chip is spread by the heat spreader and passes through the insulation sheet. This structure reduces the steady thermal resistance and also transient thermal resistance, which is important for automotive applications.

The output of 2-in-1 T-PMs can be changed by changing the number of devices connected in parallel depending on the application, like discrete devices, and thus the circuit can be configured flexibly. Figure 3 illustrates the structure of a typical case-type module and T-PM package.

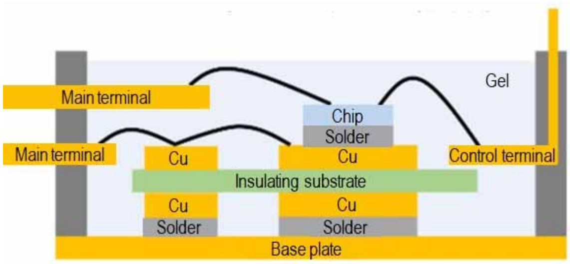
2.3 SiC T-PMs

By combining our accumulated SiC power device technologies with the high-reliability, low-inductance characteristics of T-PMs, we have achieved the low loss that is required for SiC power modules, while increasing the output density, reducing the size, and raising the reliability. However, SiC power devices are semiconductor devices that can work at high temperatures at 200°C or higher and at high speed, therefore to make the most of these characteristics, the conventional T-PM packages need to be improved, with increased heat resistance, lower thermal resistance, and lower inductance. Regarding the higher heat resistance and lower thermal resistance, in particular, new elemental technologies need to be developed.

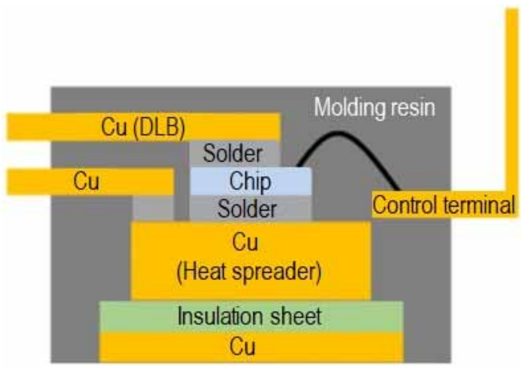
The two main types of materials for which new elemental technologies need to be developed are as follows (Fig. 4).

(1) Chip bonding materials

As chip bonding materials, Mitsubishi Electric has been using mainly an Sn (tin) alloy solder material in accordance with the regulations banning the use of lead. When SiC power devices are mounted on T-PMs, to make the most of the functions of the SiC power devices, a method of use that increases the maximum chip junction temperature is required. However, the thermal resistance of conventional solder materials is not sufficient for the increased junction temperature, which could impair the power cycle reliability.



(a) Case-type power module (typical one)



(b) T-PM

Fig. 3 Representative example of case-type power module and package structure of T-PM

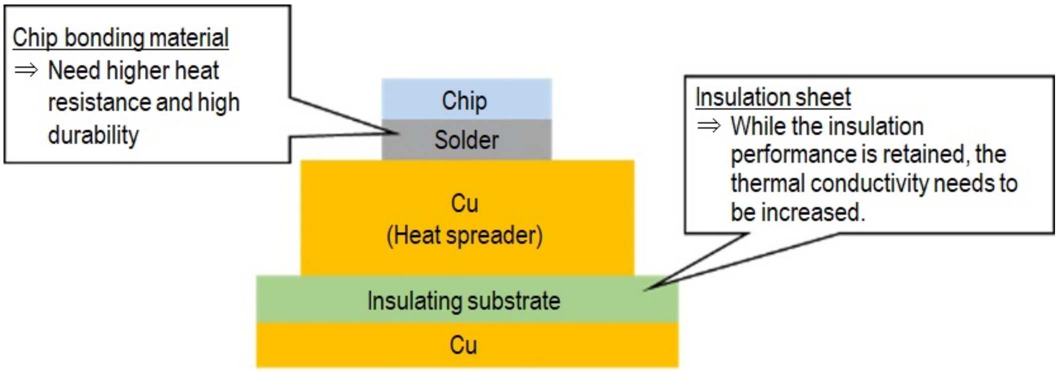


Fig. 4 Material issues of SiC T-PM

(2) Insulation sheets

Mitsubishi Electric has been developing insulation materials to increase the heat dissipation of insulation sheets, improving the thermal conductivity. To cope with the high output density and high junction temperature of SiC power devices, the thermal conductivity needs to be further improved while retaining the insulation performance of insulation sheets.

Chapter 3 describes technological issues with these materials and countermeasures.

3. Technological Issues with SiC T-PMs and Countermeasures

3.1 Chip bonding materials

Generally, to realize high-temperature operation, high-temperature solder in which lead was the main component was adopted. However, restrictions on the use of certain hazardous substances in electrical and electronic equipment under the RoHS Directive have been imposed, and so global efforts are being made to develop lead-free solder that mainly contains tin (Sn).

The solidus temperature of lead-free solder mainly containing tin is 200-250°C. Therefore, even if high-temperature operation is realized by SiC power devices, the durability of the chip joints may be lower. To counter this loss of durability, various types of elements need to be added to the solder. However, doing this reduces the thermal conductivity and SiC power devices may not exert their full performance due to the poorer heat dissipation.

In order to realize both highly durable chip joints and high heat dissipation, a new bonding material is needed. Mitsubishi Electric focused on silver (Ag) sinter bonding. For the Ag sintering material, the phenomenon of reduced melting point is utilized by using Ag particles covered with a thermal-decomposable organic protective coating to realize bonding at 300°C or lower, equivalent to the temperature of solder bonding. Thanks to this, after bonding, the melting point of the bonding material is 900°C or higher and its thermal conductivity is approximately 200 W/m·K.

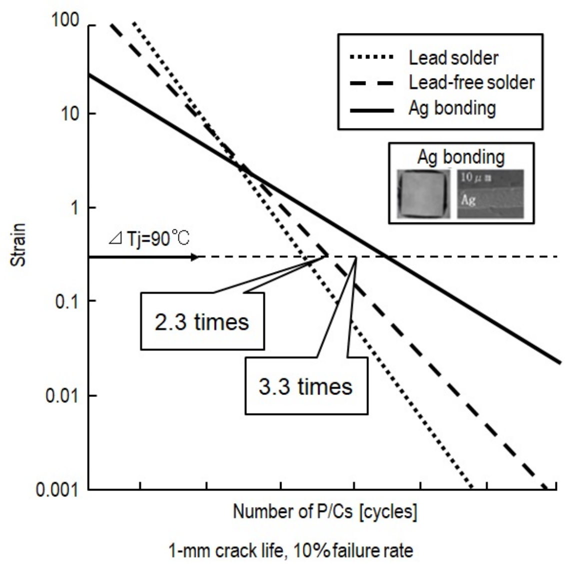


Fig. 5 Stress endurance diagram of various bonding materials

Figure 5 shows the results of thermal cycle tests (Mitsubishi Electric's proprietary method) of lead solder, lead-free solder, and Ag sintering material assuming power cycle reliability. When the values of the strain that occurred in the thermal cycle tests were converted with reference to those that occurred in a power cycle test (Tjmax = 175°C, ΔTj = 90 K), the overload tolerance of the lead-free solder was 2.3 times that of the lead solder, while the overload tolerance of the Ag sintering material was 3.3 times that of the lead-free solder. These results show that the Ag sintering material is suitable for enhancing the power cycle reliability in high-temperature bonding.

3.2 Insulation sheets[4]

An insulation sheet consisting of a high-thermal conductive ceramic filler (hereinafter "filler") and resin has heat dissipation and dielectric voltage. The material, shape, filling factor, and other properties of the filler are closely related to the heat dissipation of the insulation sheet. The dielectric voltage sometimes has a trade-off relationship with the heat dissipation. Accordingly, although the heat dissipation can be improved by adjusting the filler, it may be difficult to secure the dielectric voltage. Thus, insulation sheets need to be designed such that the heat dissipation and dielectric voltage are well balanced by optimizing various elements (Fig. 6).

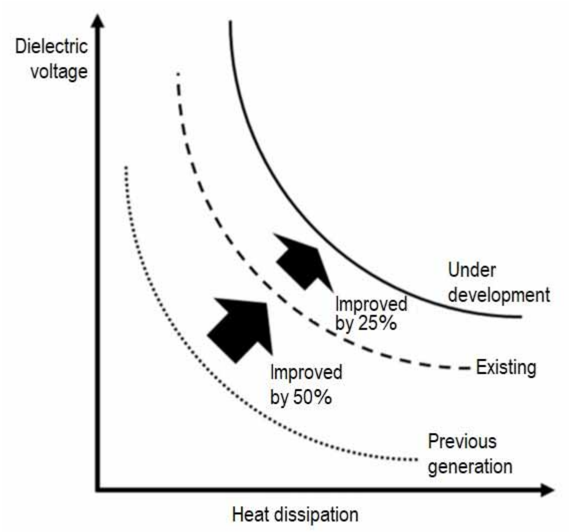


Fig. 6 voltage of insulation sheet

4. Future Application of Automotive Power Modules

The xEV market is rapidly expanding and small- to large-size automobiles are becoming electric-powered. This is generating various needs for power modules. Mitsubishi Electric will continue to develop power module products with reverse conducting insulated gate bipolar transistors (RC-IGBTs), which may help to downsize inverters, in addition to the high-performance SiC power modules described in this paper. We will develop and apply products that satisfy various needs.

5. Conclusion

Mitsubishi Electric has been developing and releasing automotive power modules for more than two decades, contributing to the spread of xEVs. We will continue such development by drawing on our accumulated technologies and know-how and actively develop and use new devices and package technologies to contribute to the accelerating electrification of vehicles.

References

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