6.5 kV Full-SiC Power Semiconductor Module

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1. Introduction

Mitsubishi Electric Corporation has developed 6.5 kV full-SiC power semiconductor modules with the world's highest power density (calculated from rated voltage and current). These modules have made it possible to increase the power density and operating frequency and reduce switching loss significantly, contributing to smaller and more energy-efficient high-voltage power electronics systems.

Characteristics of these modules include: (1) the use of Mitsubishi Electric's original Schottky-barrier-diode (SBD) embedded SiC-MOSFETs has significantly reduced the chip footprint; and (2) a new type of small package for high heat dissipation and high heat tolerance has been realized thanks to ceramic substrates having both excellent thermal conductivity and thermal resistance and a highly reliable bonding technology.

2. SBD-embedded SiC-MOSFETs

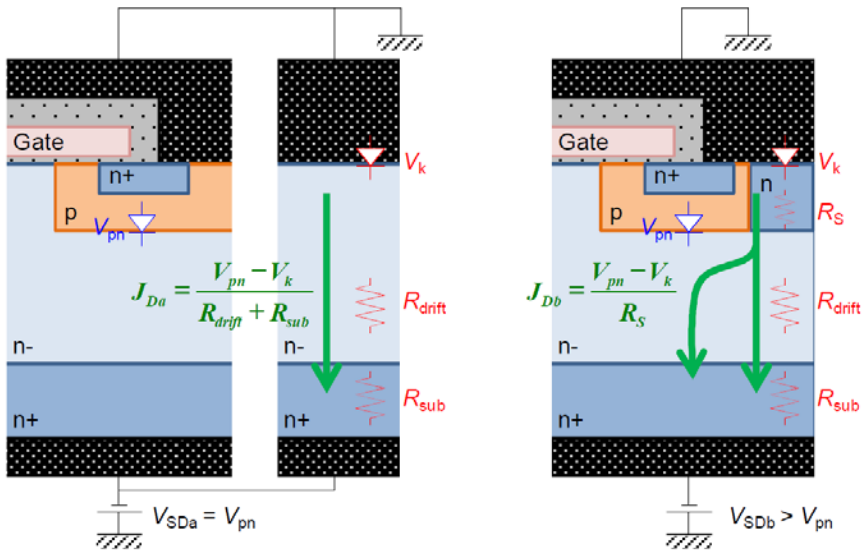
It is known that current conduction of the body diodes of SiC-MOSFETs causes bipolar degradation following the expansion of stacking faults. For higher-voltage SiC modules, larger external SBD chips are required as free-wheel diodes to suppress this current conduction.

In this development, a new type of switching device that is free from bipolar degradation without an external SBD has been realized by embedding an SBD into each unit cell of a 6.5 kV SiC-MOSFET. Figure 1(a) is the cross section of a conventional MOSFET with an external SBD and Fig. 1(b) is that of an SBD-embedded unit cell. The figures show that the embedded SBD section can pass a larger current than the external diode (See the reference (1) for details). As a result, Mitsubishi Electric has succeeded in reducing the chip footprint significantly compared to the conventional type.

3. Newly Developed Packages for High Heat Dissipation and High Heat Tolerance

3.1 Power semiconductor module structure

As the power density of a device increases, the loss per unit area increases, so measures against generated heat become more important. Mitsubishi Electric has developed elemental technologies for heat dissipation



Conventional MOSFET external SBD
(a)

SBD-embedded MOSFET
(b)

V_{pn}: built-in potential of pn junction
V_k: Schottky voltage

J_{Da}: current density in (a)
J_{Db}: current density in (b)

Fig. 1 Schematic cross sections of (a) a conventional MOSFET with an external SBD and (b) an SBD-embedded MOSFET

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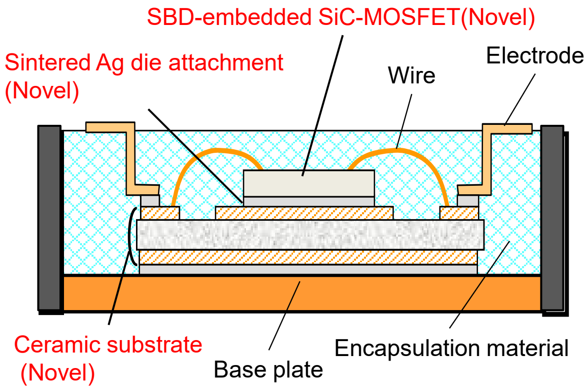

Fig. 2 Schematic cross section of the novel power module

and heat tolerance and designed highly reliable 6.5 kV full-SiC power semiconductor modules using such elemental technologies. Figure 2 illustrates the schematic cross section of such power module.

3.2 Ceramic substrates

Mitsubishi Electric focused on ceramic substrates, which were bottleneck of heat dissipation on power modules, and has been working to increase their heat dissipation. In addition, temperature cycling reliability also needs to be secured in this project. Two types of ceramic were used as shown in Fig. 3: aluminum nitride (AlN) and silicon nitride (SiN).

The thermal conductivity of AlN is high at approximately 180 W/(m·K), but its mechanical strength is low, so when the operating temperature is high, it breaks due to thermal stress. This problem was solved by inserting an Al electrode between the Cu electrode and AlN as a stress relaxation layer to reduce the thermal stress acting between the Cu and AlN. On the other hand, SiN has high mechanical strength and so is suitable for higher temperature, but its thermal conductivity is low at approximately 70 to 90 W/(m·K). To address this problem, the National Institute of Advanced Industrial Science and Technology has a technology to improve the thermal conductivity significantly by reducing impurities in particles and the amount of grain boundary phases that hinder heat conduction. This technology was used to obtain SiN with improved thermal conductivity.

These AlN and SiN substrates were mounted in modules and a thermal cycling test and thermal conductivity evaluation were carried out. It was showed that both AlN and SiN substrates are reliable during thermal cycling between −55 and 175°C, and that the thermal resistance R_{th} of the power modules was reduced by approximately 15%.

3.3 Sintered Ag bonding

As the operating temperature of a chip approaches the melting point of solder, which is the conventional

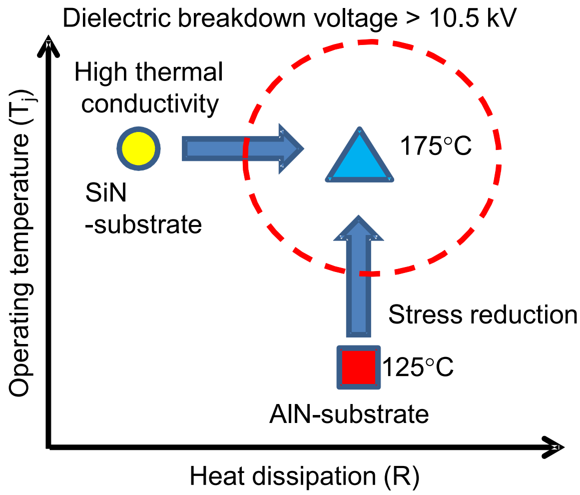

Fig. 3 Direction of ceramic substrate development

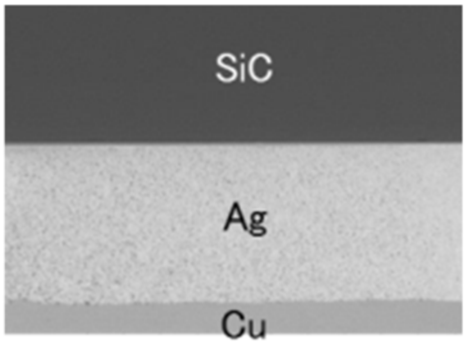

Fig. 4 SEM cross section image of die attachment using low-pressure-sintered Ag

bonding material, the temperature cycling reliability at the junction immediately below the chip becomes a problem. Sintered Ag bonding is a technology to bond a chip and substrate electrode using Ag, which has a high melting point at the process temperature the same as that of solder, by using Ag nanoparticles covered with organic protective film. The melting point of Ag is high at 962°C, so the thermal cycling reliability is high. However, for the conventional Ag bonding material, a high pressure of several tens of MPa is required for pressurization to form the connection. It is necessary to reduce this pressure to simplify the bonding process.

It has been succeeded that forming sintered Ag bonding between the SiC power device and the copper electrode on a ceramic substrate at a low welding pressure of 5 MPa using a newly developed Ag bonding material (Fig. 4). In addition, it has demonstrated that the thermal cycling reliability of this junction can be secured between −55 and 175°C.

4. 6.5 kV Full-SiC Power Semiconductor Module

Figure 5 shows the appearance of the developed power module. This shape is compatible with the package which we aim to be used as the industry

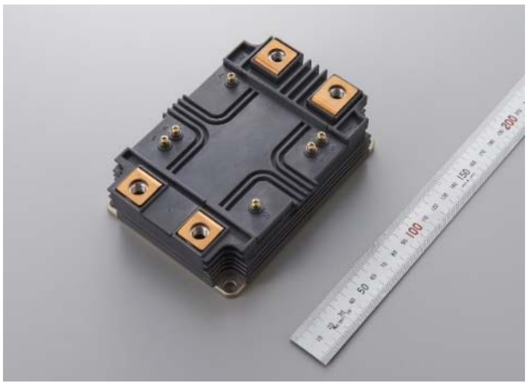

Fig. 5 6.5 kV full-SiC power module

Table1 Full-SiC power semiconductor module vs. conventional silicon IGBT module

	Power density	Power loss	Assumed operating frequency
Full-SiC module	1.8*	1/3	4
Conventional silicon IGBT module	1**	1	1

Note: Values normalized to corresponding values of Mitsubishi Electric's conventional silicon IGBT module
* Corresponds to 9.3 kVA/cm^3
** Corresponds to 5.1 kVA/cm^3

standard (Mitsubishi Electric HV100). Table 1 shows a comparison with a conventional Si-IGBT module. The rated power density is 1.8 times (9.3 kVA/cm^3) that of the conventional type. In addition, it has been confirmed that the electrical stability during switching operation is excellent.(2)

5. Conclusion

The 6.5 kV full-SiC power module has achieved the world's highest power density (9.3 kVA/cm^3) as a power semiconductor module thanks to the SBD-embedded SiC-MOSFET and newly developed package for high heat dissipation and high heat tolerance. Mitsubishi Electric expects the module to lead to smaller and more energy-efficient power equipment for high-voltage railcars and electric power systems.

Acknowledgement

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References

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(2) Nakashima, J., et al.: 6.5 kV Full-SiC Power Module (HV100) with SBD-embedded SiC-MOSFETs, Proceedings of Power Conversion and Intelligent Motion, 441–447 (2018)