All-SiC Modules Equipped with SiC Trench Gate MOSFETs

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ABSTRACT

There are increasing expectations placed on products that utilize SiC modules to achieve higher efficiency, smaller size and larger capacity in power conversion equipment. Fuji Electric has been producing products that incorporate All-SiC modules with a rated capacity of up to 1,200 V/100 A in a package with a new structure. This package achieves higher performance and higher reliability for SiC modules. In order to expand the rated capacity, Fuji Electric has recently developed a large-capacity package with a new structure. This new package utilizes an All-SiC module with a rated capacity of 1,200 V/400 A, being equipped with an SiC trench gate MOSFET that achieves both low on-resistance and high-speed switching characteristics.

1. Introduction

In order to mitigate environmental problems such as global warming and achieve a low-carbon society, it is necessary to develop energy-saving power conversion equipment and actively utilize renewable energies. Power semiconductors play a major role in efficient power conversion. Up until now, silicon (Si) has been used as a major semiconductor material. However, in spite of characteristic improvement efforts for Si semiconductor devices, their performance is already approaching the theoretical limit determined by the physical properties. It is against this backdrop that wide band gap semiconductor silicon carbide (SiC) has been focused as a next generation semiconductor material. SiC devices can achieve significantly lower loss than Si devices, it is thus expected that they will contribute to further energy savings.

Fuji Electric commenced operation of the industry's first 6-inch SiC wafer production line at the Matsumoto Factory in 2013 as shown in Fig. 1. In 2014, Fuji Electric developed and started producing an All-SiC chopper module that combined SiC metal-oxide-semiconductor field-effect transistor (SiC-MOSFET) and SiC Schottky barrier diode (SiC-SBD) for the booster circuit used in mega solar power conditioning systems (PCSs).(1) This All-SiC chopper module has achieved the world's highest level of conversion efficiency at 98.8% while also contributing to miniaturization of about 60% when compared to conventional PCSs. Furthermore, Fuji Electric developed an All-SiC 2-in-1 module in 2016 and has utilized its features (low loss, high-temperature working guarantee, high reliability and low thermal resistance) to successfully develop a totally-enclosed self-cooled inverter (IP65 inverter).(2)

Fig.1 6-inch SiC wafer

Fuji Electric has already developed an All-SiC module with a maximum rated capacity of 1,200 V/100 A.(3) In order to meet the demand for further expansion of power module capacity, Fuji Electric developed a large-capacity package with a new structure. This new package utilizes an All-SiC 2-in-1 module with a rated capacity of 1,200 V/400 A, being equipped with a 1st-generation SiC trench gate MOSFET that achieves both low on-resistance and high-speed switching characteristics. The following sections introduce this module.

2. Line-Up of All-SiC 2-in-1 Modules

Table 1 shows the line-up of All-SiC 2-in-1 modules. A line-up of Type 1, Type 2 and Type 3L newly structured packages are provided for their respective rated current. Compared with the conventionally highest rated Type 2 module of 1,200 V/100 A, the current product development utilizes a newly developed

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Table 1 Line-up of All-SiC 2-in-1 modules

		Type 1	Type 2	Type 3L
External dimensions (mm)		W68 × D26 × H13	W68 × D26 × H13	W126 × D45 × H13
External appearance				
Rating	Voltage (V)	1,200		
	Current (A)	25, 50	75, 100	200, 300, 400
Terminal	Main terminal	Solder pin		Screw terminal
	Auxiliary terminal	Solder pin		
Connection point	Main terminal	Printed circuit board		Bus bar
	Auxiliary terminal	Printed circuit board		

large-capacity Type 3L package to achieve a 2-in-1 module with a maximum rating of 1,200 V/400 A.

3. All-SiC Module Elemental Technologies

3.1 Newly structured large-capacity package

Figure 2 shows a comparison of the newly structured package developed for All-SiC modules and the conventionally structured package for Si-IGBT modules.[4] The conventional package utilizes aluminum bonding wire for the wiring, silicone gel resin for the insulation sealing resin and a thin copper ceramic insulating substrate for the insulating substrate. In contrast to this, the newly structured package utilizes implant pins for the wiring, high heat-resistant epoxy resin for the sealing resin and a thick copper ceramic insulating substrate for the insulating substrate. As a result, it facilitates high-density mounting in which multiple SiC chips are connected in parallel, while also achieving reduced internal inductance, low thermal resistance and high reliability.

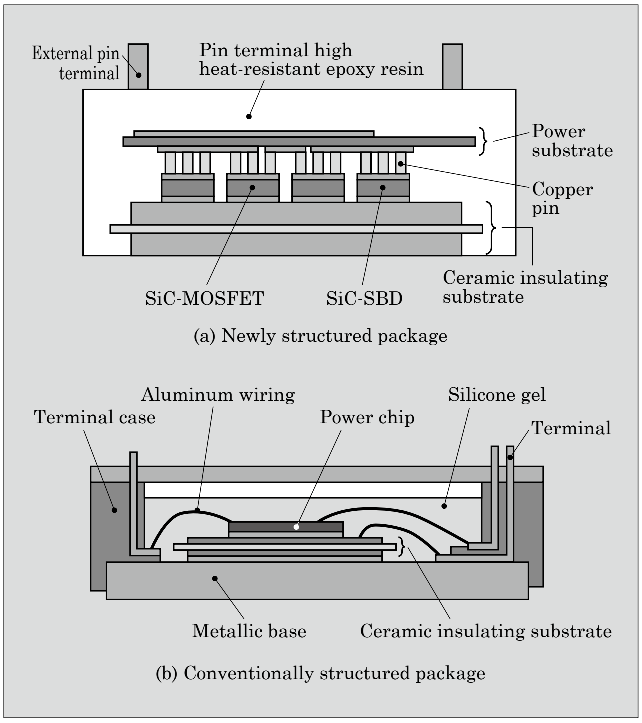


Fig.2 Comparison of package structures

The large-capacity newly structured package is based on these technological characteristics and is distinguished by the following 3 development points:

(a) Making it easy to connect the main terminals and laminated bus bar
(b) Making it easy to connect the auxiliary terminals and the printed circuit board
(c) Securing an isolating distance between terminals, and between terminals and ground, while simultaneously achieving low inductance

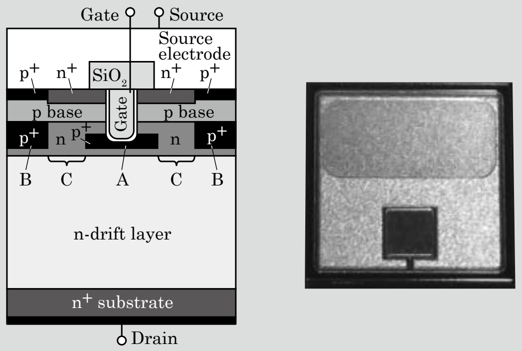
Laminated bus bar is preferred to achieve low inductance when connecting an input power supply with a power module. This large-capacity newly structured package utilizes a screw terminal structure for connecting the laminated bus bar and the power module. The screw terminal structure is designed by laser welding together the external pin terminals and a copper bar with a threaded hole located on the top part of the external pin terminals.

Furthermore, to achieve high-speed high-frequency switching, it is necessary to reduce gate-source wiring inductance. Therefore, a solder pin is used for the auxiliary terminals to enable direct connection with the circuit board via soldering. This made it possible to arrange the gate driver circuit in the vicinity of the module.

In addition, it is necessary to secure a sufficient isolating distance to comply with IEC 60077 and IEC 62497 for the insulation while also obtaining an external shape that enables expansion of the absolute maximum rated voltage to 1,700 V. However, in this respect, there was the issue of increasing the package size. Furthermore, to suppress surge voltage during high-speed turn off current, there was the issue of reducing internal inductance of the module. Therefore, external shape of this package has the same low height as the conventional Type 2 package to secure a sufficient isolating distance, shorten the main circuit path and achieve low inductance.

3.2 SiC trench gate MOSFET with rated withstand voltage of 1,200V

Fuji Electric has been providing the market with All-SiC modules equipped with planar gate MOSFET. As is well known, one effective way to further reduce on-resistance per unit area for planar gate MOSFET is



(a) Cross-sectional structure (b) External appearance

Fig.3 SiC trench gate MOSFET cross sectional structure and chip external appearance

to reduce the cell pitch. However, excessive reduction of the cell pitch can lead to increased junction field-effect transistor (JFET) resistance. As a result, on-resistance can't be lower.

Therefore, the trench gate MOSFET is adopted to suppress the increase in the JFET resistance resulting from reduction of the cell pitch, and thus, make it possible to achieve low on-resistance. Figure 3 shows the cross sectional structure of the recently developed SiC trench gate MOSFET and the external appearance of the chip.[5]

In order to simultaneously establish a low on-resistance and a high threshold voltage that does not induce malfunction, the cell pitch was reduced, and the channel length was also optimized. Furthermore, to improve the reliability of the oxide film, a p-well is used to enclose the gate oxide film at the bottom of the trench to help ease the high electric field on the gate oxide film. Moreover, as shown in Fig. 3, the JFET region (see C in the figure) that is between the p-well at the bottom of the trench (see A in the figure) and the p-well connected to the source (see B in the figure) was optimized.

By adopting the above-mentioned trench gate MOSFET and optimizing various parameters, the development of an SiC MOSFET with a rated withstand voltage of 1,200 V with the world's highest-level of on-resistance at 3.5 m$\Omega \cdot cm^2$ and a threshold voltage of 5 V has been achieved.

4. Characteristics of 1,200-V/400-A All-SiC 2-in-1 Module

4.1 Output characteristics

Figure 4 shows the output characteristics of All-SiC module (1,200-V/400-A rated product) that is achieved by the large-capacity newly structured package equipped with the trench gate MOSFET and 7th-generation "X Series" Si-IGBT module (1,200-V/450-A rated product).[6] Because MOSFETs have no built-in voltage unlike as IGBTs, the steady-state loss during continuous operation of the All-SiC module is lower than that of the Si-IGBT module.

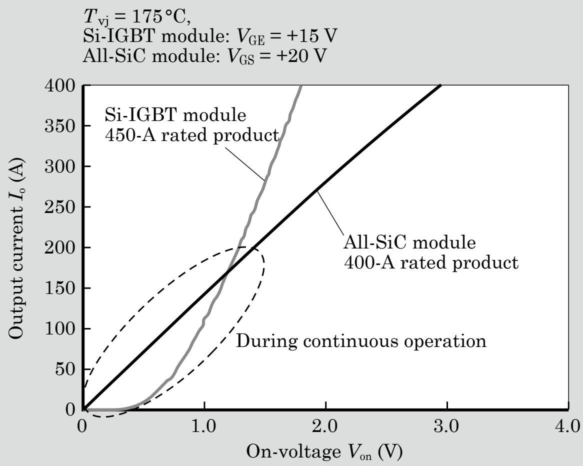


Fig.4 Comparison of output characteristics

4.2 Switching characteristics

Figure 5 shows the turn-on, turn-off and reverse recovery switching waveforms of the All-SiC module. The waveforms are stable and that there is no malfunction.

Figure 6 shows a comparison of turn-on losses, Fig. 7, turn-off losses, Fig. 8, reverse recovery loss, and Fig. 9, total switching losses. Compared with the 7th-generation Si-IGBT module, the All-SiC module reduces turn-on loss by approximately 87%, turn-off loss

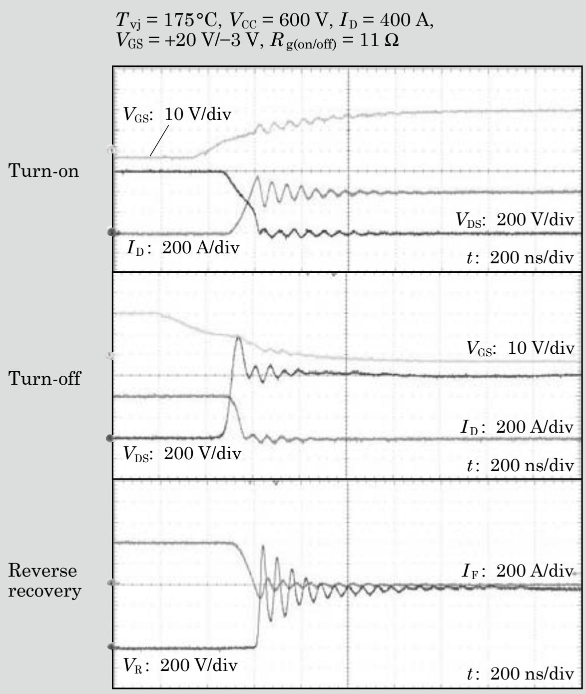


Fig.5 All-SiC module switching waveforms (1,200 V/400 A)

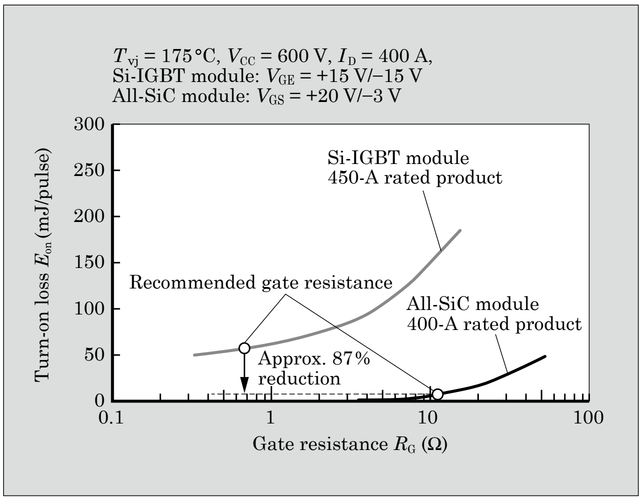


Fig.6 Turn-on loss

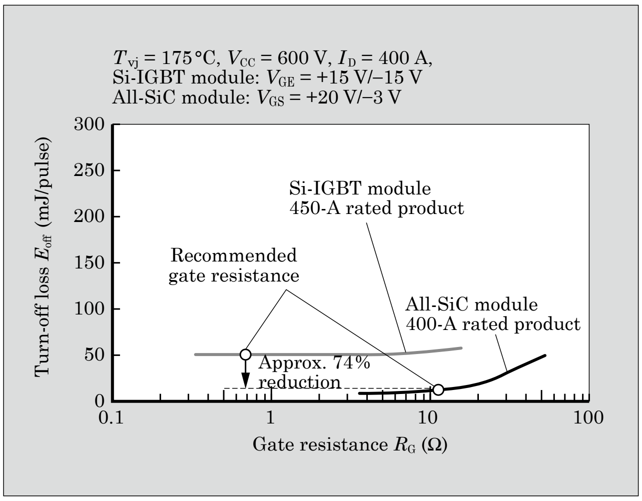


Fig.7 Turn-off loss

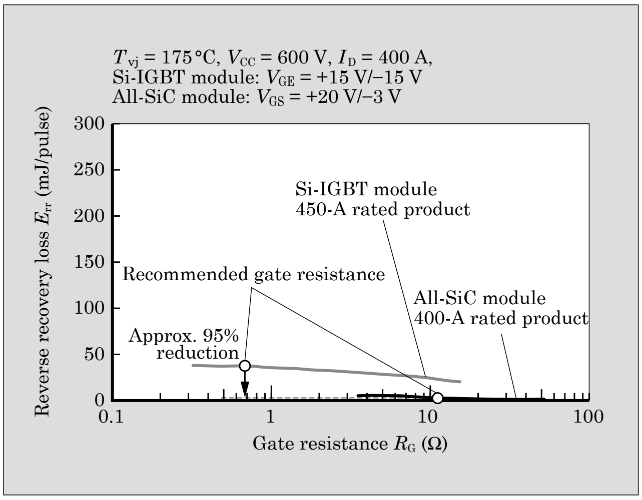


Fig.8 Reverse recovery loss

by approximately 74% and reverse recovery loss by approximately 95%. As a result, total switching loss was reduced by about 84%.

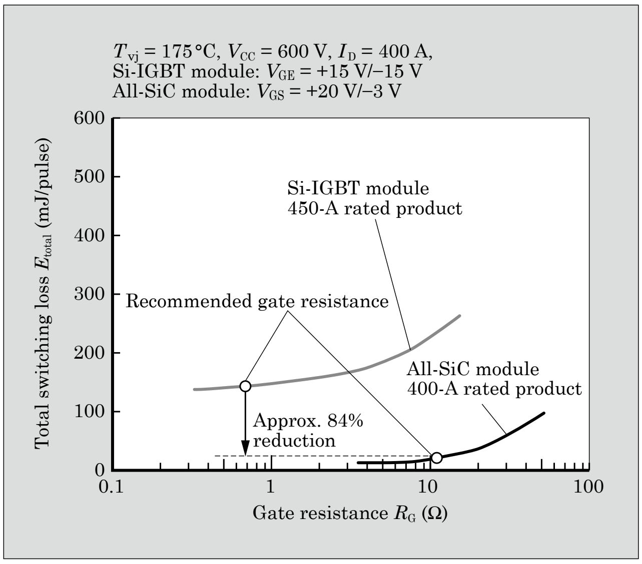


Fig.9 Total switching loss

4.3 Inverter loss simulation

Figure 10 shows the simulation results for inverter loss under general use conditions for the inverter mounted All-SiC module and 7th-generation "X Series" Si-IGBT module. Compared with the Si-IGBT module, the All-SiC module reduced inverter loss for the inverter by approximately 57%.

Figure 11 shows the simulation results with respect to the carrier frequency dependence of the inverter loss. Compared with the Si-IGBT module, the switching loss for the All-SiC module was extremely low. The results shows that using the All-SiC module with high carrier frequency can lead to the significant miniaturization of passive components such as DC reactors and isolation transformers. As one example, the auxiliary power supplies of electrical rolling stock can achieve device weight savings and miniaturization of about 50% compared with conventional utility frequency link

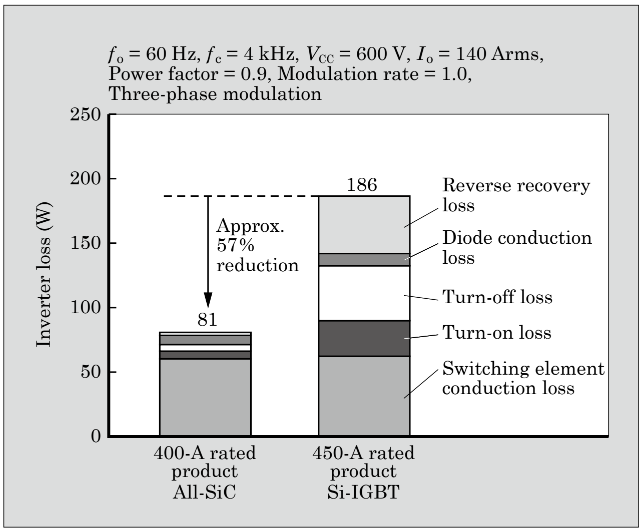


Fig.10 Inverter loss simulation results

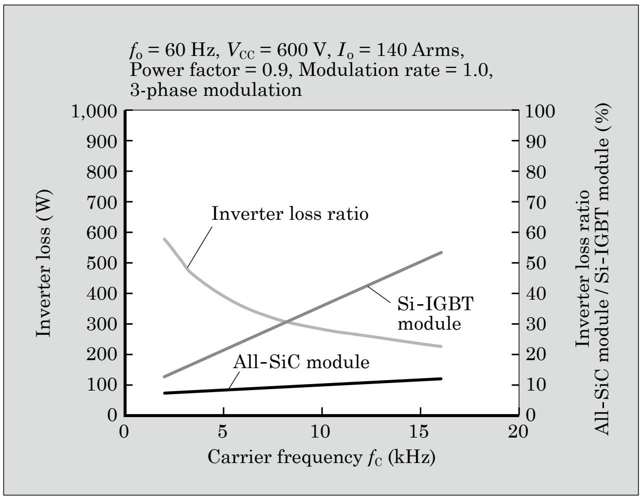


Fig.11 Inverter loss carrier frequency dependence

system.

5. Postscript

In this paper, All-SiC module that comes equipped with SiC trench gate MOSFETs was introduced. By equipping the newly developed large-capacity package with a new structure with SiC trench gate MOSFETs, 2-in-1 module with a rated capacity of 1,200 V/400 A has been successfully developed. In the future, we plan to increase the power density and expand our line-up of All-SiC modules to contribute to the miniaturization, high-efficiency and high-reliability of various types of power conversion equipment.

Some of the development work has been carried out as part of a project of the joint research body Tsukuba Power Electronics Constellations (TPEC). We would like to conclude by expressing our appreciation to all those involved in the project.

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