“HPnC” High-Current SiC Hybrid Module

SEKINO, Yusuke* MITSUMOTO, Takahiro* MORIYA, Tomohiro*

ABSTRACT

Fuji Electric has been developing the “HPnC” high-current power module to be used with electric railcars and photovoltaic and wind power generation facilities. The chip uses 7th-generation “X Series” technology, enabling it to achieve lower power loss. The package employs an aluminum nitride (AlN) insulating substrate that utilizes a high heat-dissipating member, as well as base materials consisting of magnesium and silicon carbide composite materials (MgSiC). Adopting a laminated structure for the enclosure of the terminal makes the internal inductance decrease to 10 nH. Furthermore, Ultrasonic terminal welding is used to comply with the RoHS directive. With these technologies, the module achieves a high current density, which is 12% greater than the conventional HPM.

1. Introduction

In recent years, there has been increasing demand to improve energy efficiency and reduce CO_2 emissions as measures for preventing global warming. As a result, the use of power conversion equipment that employs power semiconductors has been spreading to a wide variety of fields. In particular, there has been advancements in equipment capacity and miniaturization in the fields of electric railcars, photovoltaic power generation and wind power generation. In this respect, the high-current insulated gate bipolar transistor (IGBT) modules used for these types of equipment have been required to be compact by increasing current density.

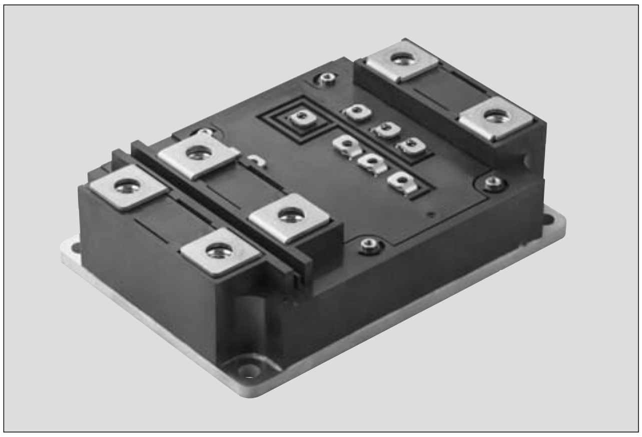


Fig.1 “HPnC” high-current SiC hybrid module

In order to meet this demand, Fuji Electric has been developing the “HPnC” (High Power next Core) high-current power module. It uses a new package equipped with 7th-generation “X Series” IGBT chips(1) and SiC Schottky barrier diode (SiC-SBD) chips(2) (see Fig. 1).

2. Product Line-Up Considerations

Table 1 shows the HPnC product line-up and features. Fuji Electric has been considering two series for the HPnC line-up, namely, a 3,300-V/450-A series and 1,700-V/1,000-A series. The HPnC line-up uses the X Series IGBT. As for FWD, it uses Si based X Series PiN diodes and SiC-SBDs that have enhanced characteristics. In this paper, Fuji Electric will introduce the 3,300-V/450-A HPnC that comes equipped with a 3.3-kV X Series IGBT and SiC-SBD.

Circuit configuration is 2 in 1 with a thermistor for detecting temperature rise inside the module. For the insulating substrate, an aluminum nitride (AlN)

Table 1 Product line-up

Product type	Rated voltage (V)	Rated current (A)	IGBT	FWD	Package type	Circuit configuration	Thermistor	Insulating substrate	Base
2MBI450XUF330-50	3,300	450	X Series	SiC-SBD	M288	2 in 1	Built-in	AlN	MgSiC
2MSI450XUF330-50				X Series					
2MBI1000XUF170-50	1,700	1,000		SiC-SBD					
2MSI1000XUF170-50				X Series					

---

* Electronic Devices Business Group, Fuji Electric Co., Ltd.

ceramic is used to ensure high heat dissipation and high reliability. As for the base plate, a magnesium and silicon carbide (MgSiC) material is used, which is the same coefficient of thermal expansion as the aluminum and silicon carbide composite material (AlSiC) of conventional products. It secures the high reliability needed for electric railcars. Moreover, MgSiC base plate is higher thermal conductivity than AlSiC base plate. Figure 1 shows the external appearance of the module. The package has mounting compatibility with the modules of other manufacturers.

3. "HPnC" Features

Table 2 shows a comparison of characteristics with the conventional for electric railcar module "HPM" (High Power Module). Compared with the HPM, this new module reduces surge voltage by improving parasitic inductance (internal inductance for the module), increases current density, improves assembly during parallel connections and complies with the RoHS Directive[*1].

3.1 Low inductance package

The internal inductance for the HPnC module achieves 10 nH, a 76% improvement compared with the HPM's value of 42 nH. Figure 2 shows the cross-sectional structure of HPnC. A laminate structure is used between the collector terminal and the emitter terminal to reduce internal inductance. Figure 3 shows a comparison of waveforms during turn off for the HPnC and HPM. When both modules are evaluated at same $\mathrm{d}i/\mathrm{d}t$ 5-kA/μs, surge voltage for the HPnC during turn off is about 150 V lower than that of the HPM as a result of reducing inductance. This means that the HPnC can be faster $\mathrm{d}i/\mathrm{d}t$ than the HPM during turn off, in order to reduce switching loss.

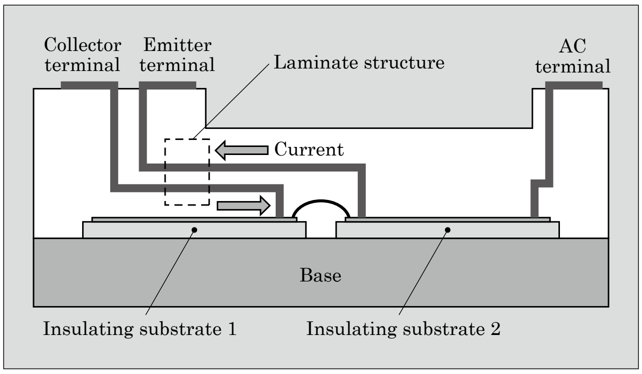


Fig.2 HPnC cross-sectional structure

3.2 Higher current density

The HPnC achieves a footprint-based current density of 6.43 A/cm^2, which is about 12% higher than that of the 3.3-kV breakdown voltage HPM, which is 5.76 A/cm^2. This is the result of reducing thermal resistance $R_{\mathrm{th(j\text{-}c)}}$ using a low-loss 7th-generation IGBT chip and utilizing an MgSiC base, which has 1.5 times the heat conductivity of the HPM's AlSiC base.

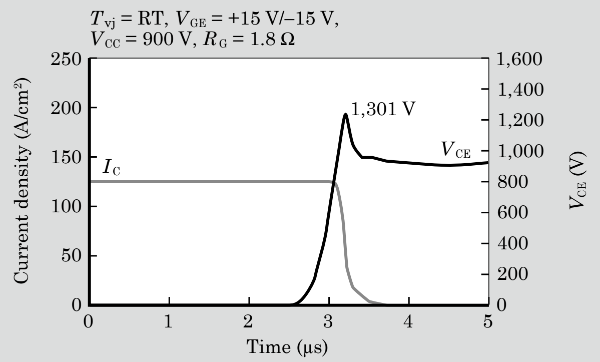
3.3 Easy parallel connection assembly and superior inductancee

High-current IGBT modules are often paralleled to use for high current circuits. Table 3 shows a comparison of inductance and assembly during parallel connection for the HPM and HPnC. Total rated current for the HPM was 2,000 A, with a pair of two 1,000-A 1-in-1 configuration modules connected in series, that are made to be in a 2-in-1 configuration, connected in par-

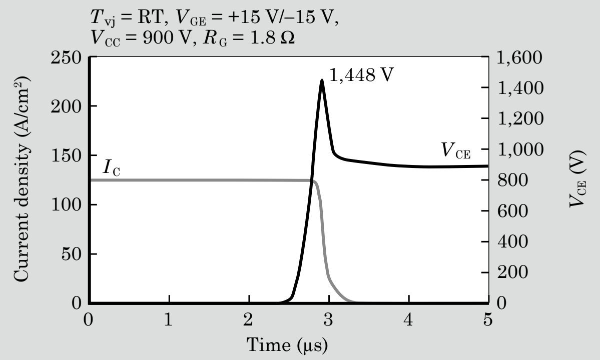
Table 2 Package characteristics

Package	HPnC	HPM (conventional product)	Improvement rate (%)
External appearance/dimensions (mm)	W: 100 D: 140 H: 38 	W: 130 D: 140 H: 38 	–
Circuit	2 in 1	1 in 1	–
Rating (typical)	3,300 V/450 A + 450 A	3,300 V/1,000 A	–
Module internal inductance (L_P)	10 nH	42 nH (for 2-in-1 configuration)	76.2
Surge voltage (V)	401	548	26.8
Footprint (cm^2)	140	173.7	19.4
Current density (A/cm^2)	6.43	5.76	11.6
Parallel connectivity	Excellent	Poor	–
Inductance during 2 in parallel connection (L_P)	2.5 nH	21 nH	89.0
RoHS Directive	Compliant	Not compliant	–

[*1] RoHS Directive: Directive issued by the European Union (EU) concerning restrictions of the use of certain hazardous substances in electrical and electronic equipment.



(a) HPnC



(b) HPM

Fig.3 Turn-off comparison

allel. In contrast to this, rated current for the HPnC is 1,800 A, with four 450-A 2-in-1 configuration modules connected in parallel.

Assembly of parallel connections for the HPM is not easy when assembling bus bars to the main circuit since it involves 3 overlapping layers depending on the terminal position, which include the collector bus bar, AC bus bar and emitter bus bar. Assembly has improved with use of the HPnC since it avoids this 3 layer overlap by positioning the AC terminal by itself on the opposite side of the collector terminal and emitter terminal.

Furthermore, the position of the emitter terminal is far from the capacitor in the HPM, and thus the emitter bus bar needs to be lengthened, which causes an increase in main circuit inductance. As for HPnC, the positions of the collector terminal and emitter terminal are close to the capacitor, which shortens the length of the bus bar and reduces the inductance of the main circuit. Module internal inductance for the 2 HPM modules connected in parallel was 21 nH, while 4 HPnC modules connected in parallel was 2.5 nH, equating to about a 90% reduction. Inductance is determined by the internal inductance of the module and the main circuit. Therefore, by reducing both of these values, it is possible to achieve even faster switching.

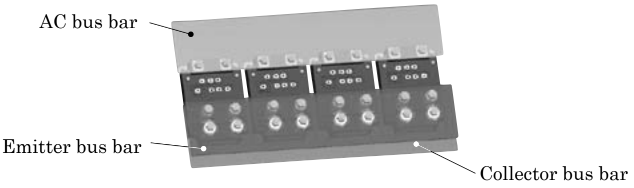
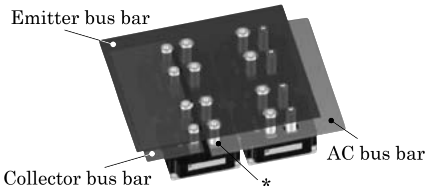
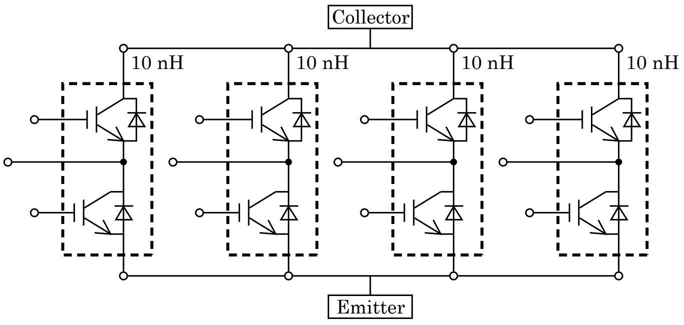
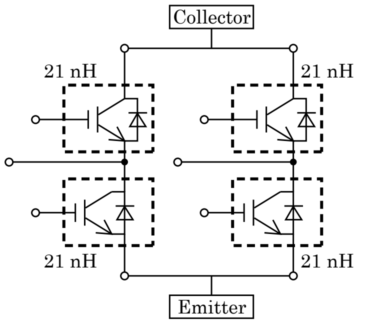
3.4 RoHS compliance

In order to comply with the RoHS Directive, the HPnC uses ultrasonic bonding instead of solder bonding to join the terminals and insulating substrate. Fuji Electric achieves higher reliability than the conventional product by matching the coefficients of linear thermal expansion of the materials to be joined.

4. Improvement of Chip Characteristics

Improving generated dissipation for the IGBT module, which is important in miniaturizing the mod-

Table 3 Comparison of parallel connections for HPM and HPnC

	Four 2-in-1 HPnC modules connected in parallel (total of 3,300 V/1,800 A)	Two 1-in-1 HPM modules connected in parallel (total of 3,300 V/2,000 A)
Comparison of assembly during module parallel connections	 	
Comparison of module inductance during parallel connections	 Total inductance: 10/4 = 2.5 nH	 Total inductance: (21 + 21)/2 = 21 nH

*: In order to make the structure easier to understand, it was represented using a spacer.

ule (increasing current density), is greatly dependent on IGBT chip and FWD chip characteristics.

4.1 Improvement of IGBT chip characteristics

Figure 4 shows the improvement in characteristics compared with conventional IGBT chips at T_{vj} = 150 °C. Turn-off loss E_{off} has remained the same as before, but collector-emitter voltage $V_{CE(sat)}$ for the X Series IGBT chip is 2.5 V, which is an improvement of 1.2 V compared with the 3.7 V of conventional IGBT chips. The X Series IGBT has been able to improve the trade off between $V_{CE(sat)}$ and E_{off} by expanding the active area through edge structure optimization and thinner the drift layer.

4.2 Reduction of switching loss through use of SiC-SBD

Figures 5 and 6 show comparisons of waveforms for the conventional 3.3-kV Si-IGBT module (HPM) and 3.3-kV X Series SiC hybrid modules (HPnCs). In this comparison, 2 HPnCs are connected in parallel to match the rated current to the HPM. The SiC hybrid significantly reduces turn-on loss E_{on}, and recovery loss E_{rr} does not occur through reduction of peak current I_{rr} during reverse recovery. This is due to the fact that the SiC-SBD is a unipolar device, and this means that there is no I_{rr} because no carrier occurs. As shown in Table 4, E_{on} is greatly improved by 32% and E_{rr} by 99.8%.

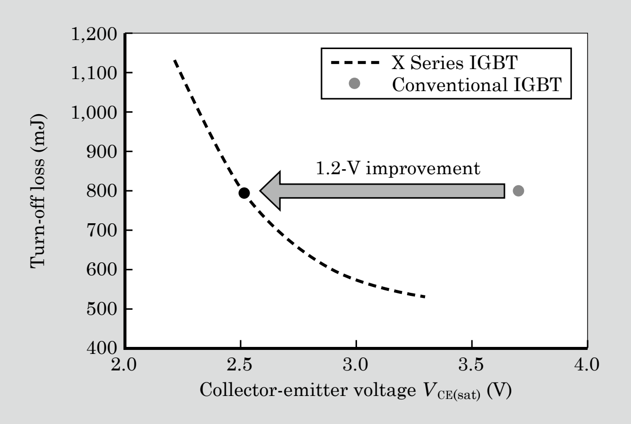


Fig.4 Improvement of 3.3-kV “X Series” IGBT chip characteristics

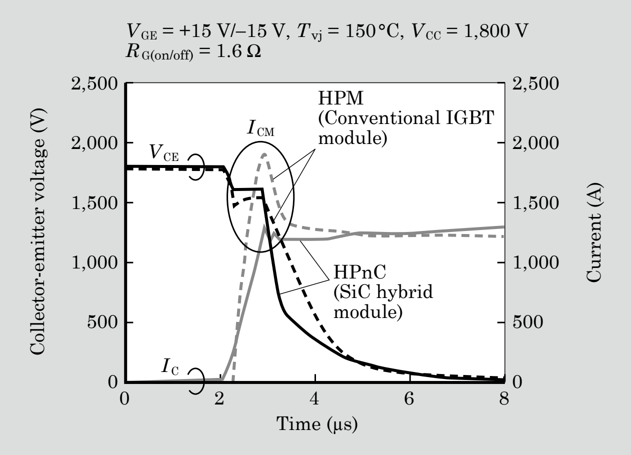


Fig.5 Comparison of turn-on waveforms

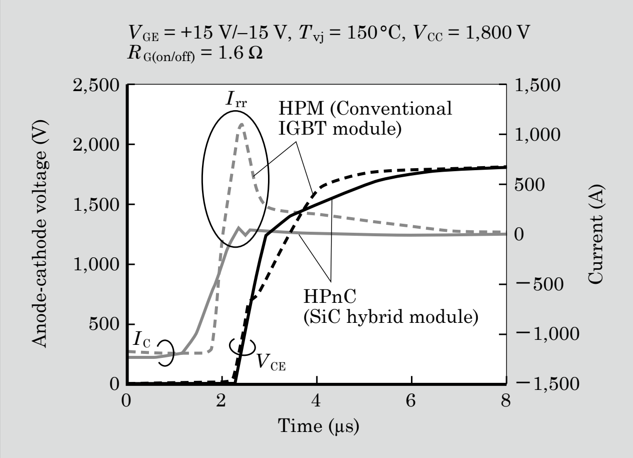


Fig.6 Comparison of recovery waveforms

Table 4 Comparison of switching loss (unit: mJ)

	Turn-on loss E_{on}	Turn-off loss E_{off}	Recovery loss E_{rr}	Total loss E_{total}
HPM (conventional product)	3,493	2,417	903	6,813
HPnC (SiC hybrid)	2,374	2,294	2	4,670
Improvement rate (%)	32	5	99.8	31

4.3 Inverter generated loss

A comparison of the results of inverter generated dissipation simulations for a 3,300-V/1,000-A HPM and two 3,300-V/450-A HPnC modules connected in parallel is shown in Fig. 7.

Total loss is improved by about 40% compared with the HPM at a carrier frequency fc of 5 kHz and an output current of 450 A. Furthermore, at the same output current, the f_c value for the HPnC can be achieved to 9 kHz, which was 1.8 times higher than the 5 kHz value for the HPM. Moreover, when f_c for both

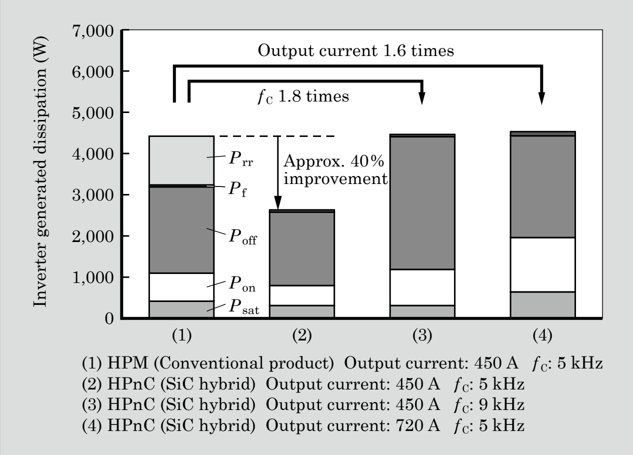


Fig.7 Results of inverter generated dissipation simulation

modules was 5 kHz, output current could be increased 1.6 times from 450 A to 720 A. The expansion in current density and output current increasing contributes to the miniaturization of the filter through expansion of f_c contributes to miniaturization and lower loss in inverters.

5. Postscript

In this paper, Fuji Electric introduced the "HPnC" high-current SiC hybrid module. The 3.3-kV breakdown voltage SiC hybrid module HPnC is capable of suppressing surge voltage, improving high-speed switching and supporting high current applications through parallel connections as a result of employing a laminate structure and reducing inductance through optimization of the main terminal position in the module's package structure. Moreover, the utilization of ultrasonic terminal welding technology secured a reliability just as high as conventional products while also fulfilling compliance with the RoHS Directive.

In addition, the improvement in characteristics through use of the X Series IGBT and SiC-SBD for the chip enabled the module to reduce inverter generated dissipation, increase current density, expand f_c and achieve miniaturization. In the future, Fuji Electric will work to further improve our packages and our chip technology in order to contribute to the development of power electronics technology.

Some of our research was 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.

References

(1) Kawabata, J. et al. 7th-Generation "X Series" IGBT Module. FUJI ELECTRIC REVIEW. 2015, vol.61, no.4, p.237-241.
(2) Onezawa, T. et al. 1,700-V Withstand Voltage SiC Hybrid Module. FUJI ELECTRIC REVIEW. 2015, vol.61, no.4, p.228-231.

Fuji Electric

Innovating Energy Technology