Hybrid Si-IGBT and SiC-SBD Modules

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ABSTRACT

Fuji Electric has developed hybrid modules that combine silicon-insulated gate bipolar transistor (Si-IGBT) and silicon carbide-Schottky barrier diode (SiC-SBD) for high-efficiency inverter applications that contribute to energy savings. The SiC-SBD chip was developed jointly with the National Institute of Advanced Industrial Science and Technology, a public research institute, and the Si-IGBT chips are the latest 6th-generation "V-Series" IGBTs from Fuji Electric. The product lineup are 600 V class rated at 50/75/100 A, and 1,200 V class rated at 35/50 A. Inverter power loss in the 1,200 V 50 A class has been reduced by 23% compared to the V-series module.

1. Introduction

To prevent global warming, the further reduction of greenhouse gases (such as CO_2) is a pressing issue. The greatest benefit of using power electronics technology to reduce greenhouse gases is that electrical power becomes more energy-efficient. In such an undertaking, increasing the efficiency of inverters is an important factor. To do so requires technical innovation of the power devices, circuits, controllers and other components used in inverters. Since power devices are the main elements used in inverters, there is increasing demand for low loss power devices that realize higher efficiency. The insulated gate bipolar transistor (IGBT) is such a power device, and the use of silicon (Si) IGBT and free wheeling diode (FWD) chips is common. However, Si semiconductor device performance is approaching its theoretical limits based on its material properties, and future breakthroughs that achieve significantly lower loss cannot be expected. For this reason, wide bandgap (WBG) semiconductors, which exhibit material properties superior to those of Si semiconductors, are promising.

Fuji Electric is advancing the development of silicon carbide (SiC) semiconductor devices, which are a type of WBG semiconductors. With an SiC device, higher breakdown voltage and lower on-state resistance can be achieved than with a Si device. In theory, the on-state resistance of a SiC can be made lower than that of a Si device having the same breakdown voltage. For this reason, SiC devices do not necessarily need to be bipolar devices as was essential for reducing the on-state resistance in high-voltage Si devices. Bipolar devices are associated with the injection of minority carriers and generally exhibit greater switching energy than unipolar devices. Thus, unipolar devices are desirable for reducing the switching energy. Accordingly, the use of a SiC unipolar device enables low on-state resistance and low switching energy to be achieved simultaneously.

2. Product Overview

Figure 1 shows an internal circuit diagram of a power integrated module (PIM). Si-IGBT and silicon carbide schottky barrier diode (SiC-SBD) hybrid modules, which enabled to reduce power loss than ever before, have been developed using SiC-SBD unipolar devices as FWDs. A chip developed in collaboration with the National Institute of Advanced Industrial Science and Technology is used as the SiC-SBD, and Fuji Electric's latest chip, a 6th generation "V-Series" IGBT chip is used as the Si-IGBT.

Figure 2 shows the appearance, and Table 1 lists the product lineup of the Si-IGBT and SiC-SBD hybrid modules. For high efficiency inverter applications, 50 A, 75 A and 100 A rated products have been de-

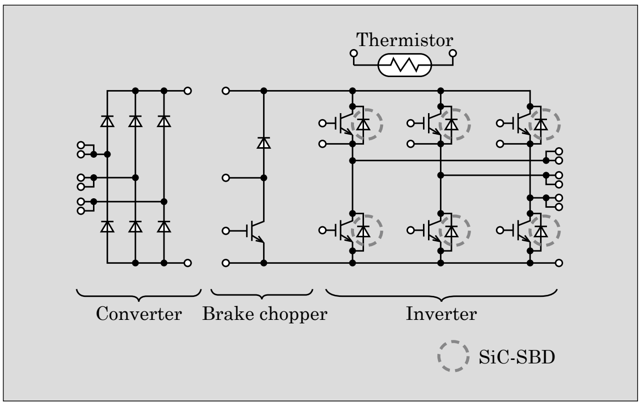

Fig.1 PIM internal circuit diagram

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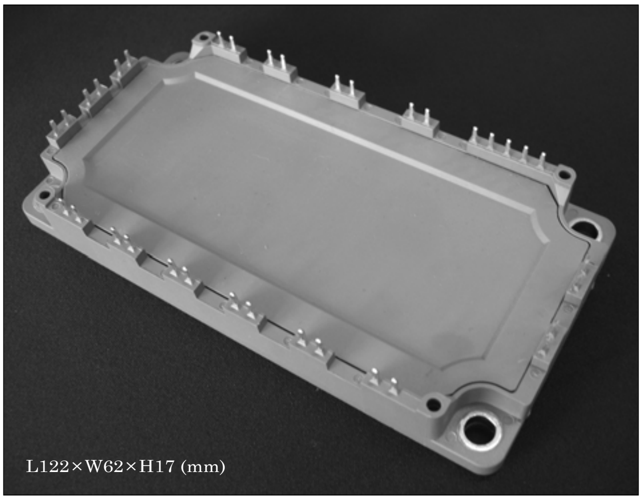

Fig.2 Appearance of the hybrid Si-IGBT/SiC-SBD module

Table 1 Lineup of hybrid Si-IGBT/SiC-SBD modules

Rated voltage (V)	Rated current (A)	Hybrid module model
600	50	7MBR50VB060S-50
	75	7MBR75VB060S-50
	100	7MBR100VB060S-50
1,200	25	7MBR25VB120S-50*
	35	7MBR35VB120S-50
	50	7MBR50VB120S-50

* : To Be Determined

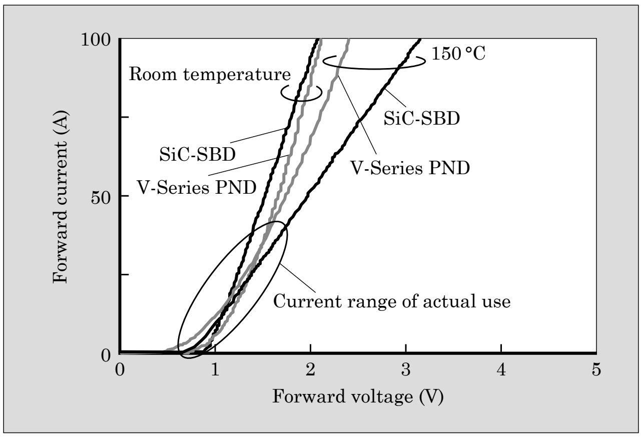

Fig.3 Forward characteristics

veloped for the 600 V series, and 35 A and 50 A rated products have been developed for the 1,200 V series. Product performance and characteristics are presented below for the 1,200 V/ 50 A product, as a representative example.

3. Static Characteristics

3.1 Forward characteristics

Figure 3 shows the forward characteristics of a SiC-SBD and a V-Series PN junction diode (V-Series PND), and Fig. 4 shows the temperature characteristics of the

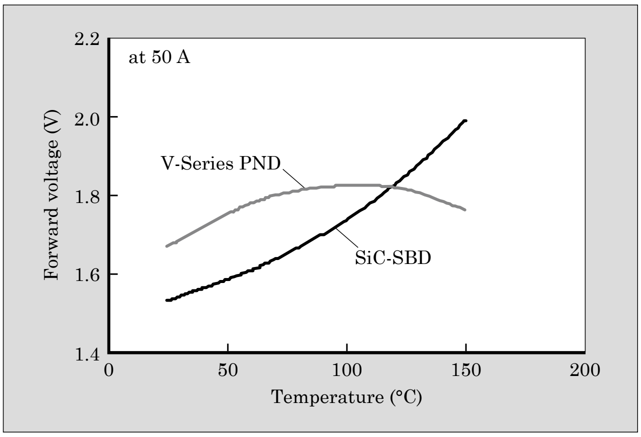

Fig.4 Temperature characteristics of the forward voltage

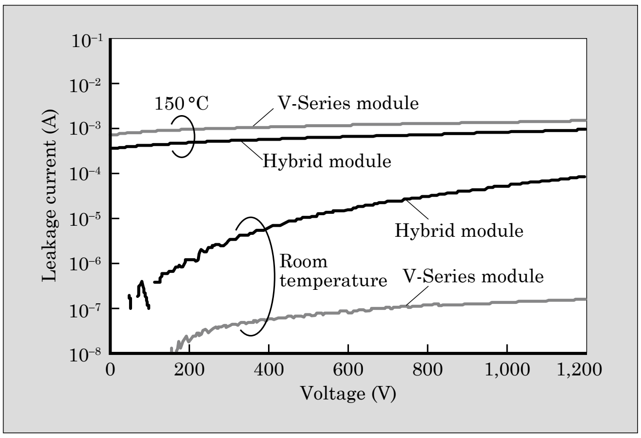

Fig.5 Leakage current characteristics

forward voltage V_f at the rated current of 50 A. In the current range that is actually used, the V_f of the SiC-SBD is the same as that of the V-Series PND. From Fig. 4, it can be seen that at temperatures higher than 100 °C, the V-Series PND exhibits a negative temperature coefficient with reducing V_f. A device with a negative temperature coefficient is prone to current imbalance when in a multi-parallel connection. On the other hand, the SiC-SBD, which has a strong positive temperature characteristic, is unlikely to create a current imbalance, even when in a multi-parallel connection.

3.2 Leakage current characteristics

Figure 5 compares the leakage current characteristics of the hybrid module and a V-Series module. The leakage current of the hybrid module is about 1,000 times as large as that of the V-Series module when at room temperature, but is only slightly less than that of the V-Series module when at 150 °C. As shown in Fig. 6, the leakage current of the hybrid module is nearly constant at temperatures of around 100 °C and below, and increases similarly as the V-Series at higher temperatures. The SiC-SBD, which has a wide bandgap and therefore very few thermally excited carriers, is less affected by temperature rise. The increase in leakage current at temperatures above 100 °C is a result of

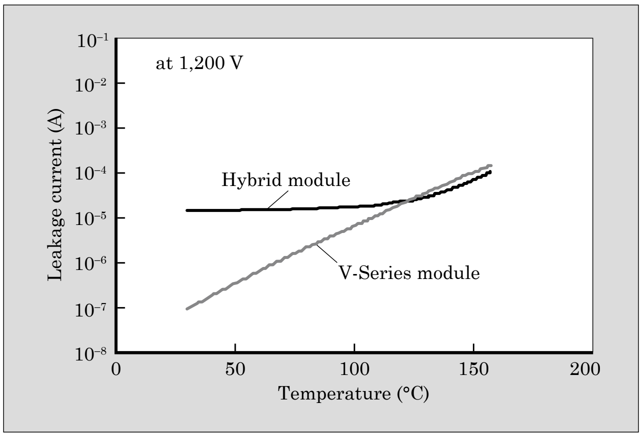

Fig.6 Temperature characteristics of leakage current

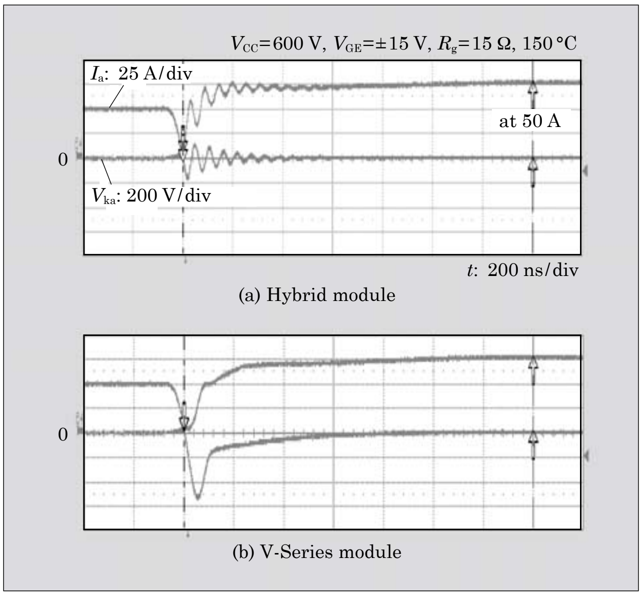

Fig.7 Reverse recovery waveforms

the leakage current of the IGBT becoming dominant. Thus, even if the SiC-SBD exhibits a large leakage current at room temperature, because its leakage current during high temperature operation is the same as that of a V-Series device, the SiC-SBD is similarly able to operate at junction temperatures of up to 175 °C.[1]

4. Switching Characteristics

4.1 Reverse recovery characteristics

Figure 7 compares reverse recovery waveforms of the hybrid module and a V-Series module. The hybrid module exhibits extremely lower reverse recovery peak current. This behavior can be explained from little injection of minority carriers since the SIC-SBD is a unipolar device. As can be seen in Fig. 8, at the rated current of 50 A, reverse recovery energy can be reduced significantly by 70% compared to the V-Series module.

4.2 Turn-on characteristics

The reverse recovery peak current of the FWD is

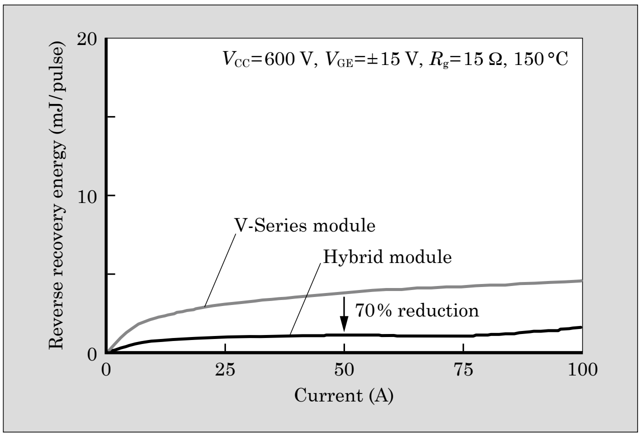

Fig.8 Current characteristic of reverse recovery loss

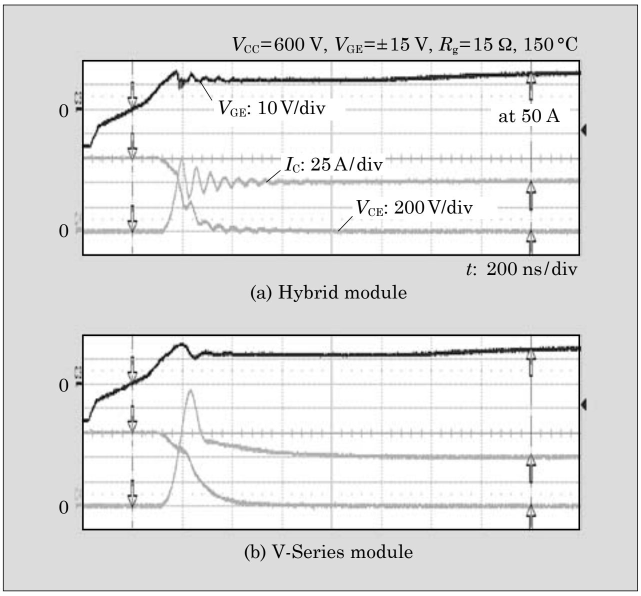

Fig.9 Turn-on waveforms

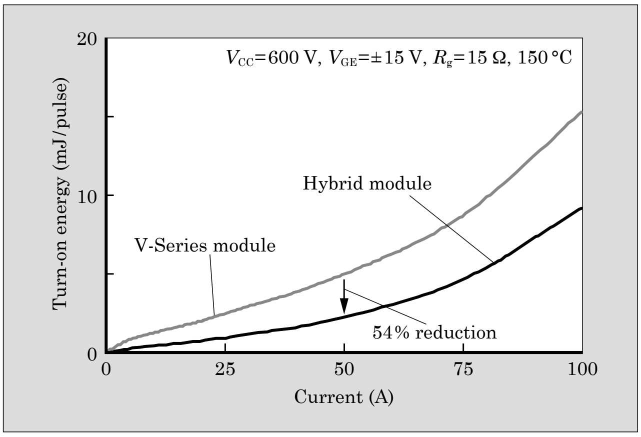

Fig.10 Current characteristics of turn-on energy

reflected in the turn-on peak current of the IGBT in the opposing arm, and a reduction in turn-on energy can be attained as a result of the reduction in reverse recovery energy.

Figure 9 compares turn-on waveforms of the hybrid module and V-Series module. As in the reverse recovery waveform, there is extremely lower current peak. At the rated current of 50 A, as is shown in Fig. 10, the turn-on energy can be reduced significantly by 54% compared to the V-Series module.

4.3 Turn-off characteristics

Figure 11 shows a comparison of the turn-off waveforms of the hybrid module and V-Series module. At the rated current of 50 A, the turn-off surge voltage of the hybrid module is 47 V lower than that of the V-Series module. In general, the surge peak voltage can be defined by Equation (1), and if the IGBT element characteristics and the main circuit inductance are equivalent, the difference in the surge voltages is originated from the difference of the transient on-state voltages of the diodes. Figure 12 compares transient on-state waveforms of the diodes. Because the drift

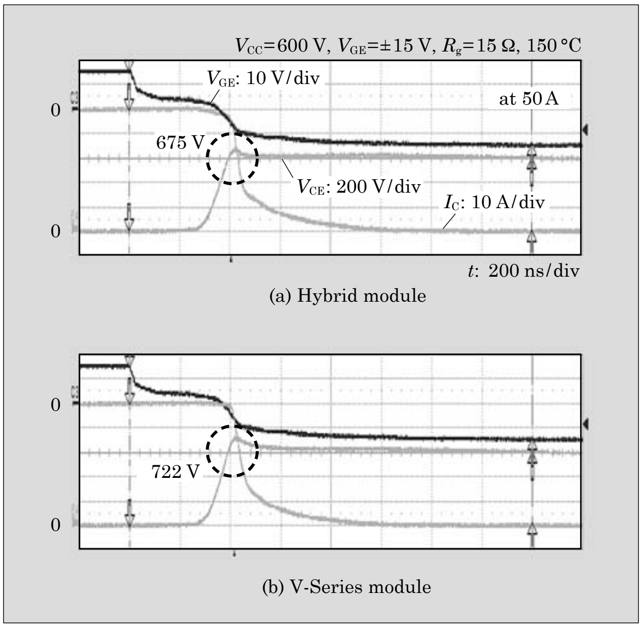

Fig.11 Turn-off waveforms

layer of the SiC-SBD has a much lower resistance

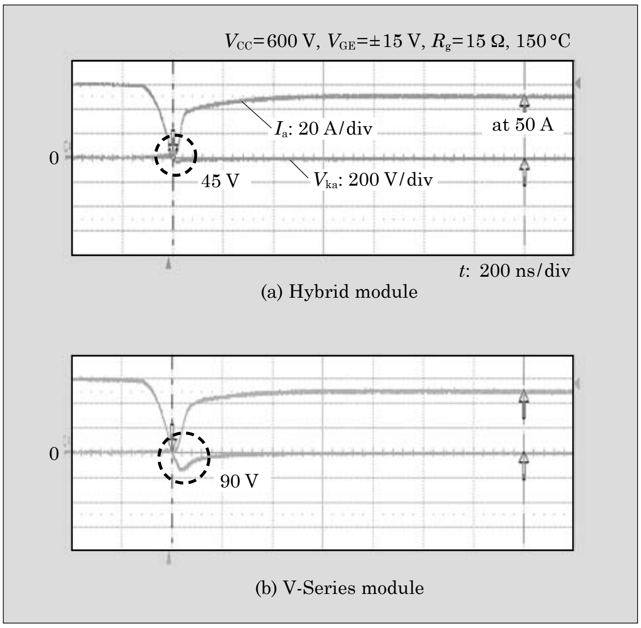

Fig.12 Diode transient on-state recovery waveforms

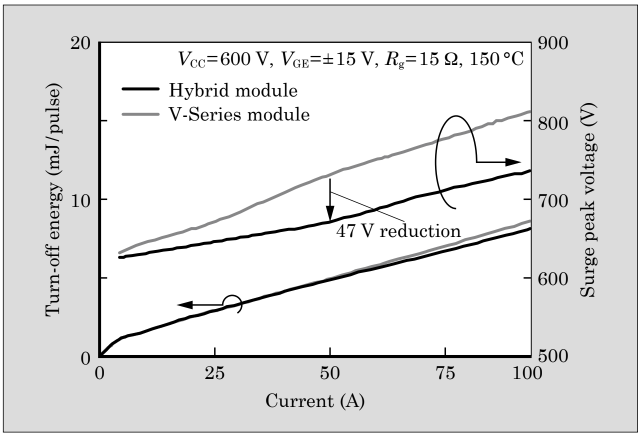

Fig.13 Turn-off energy and surge peak voltage/current characteristics

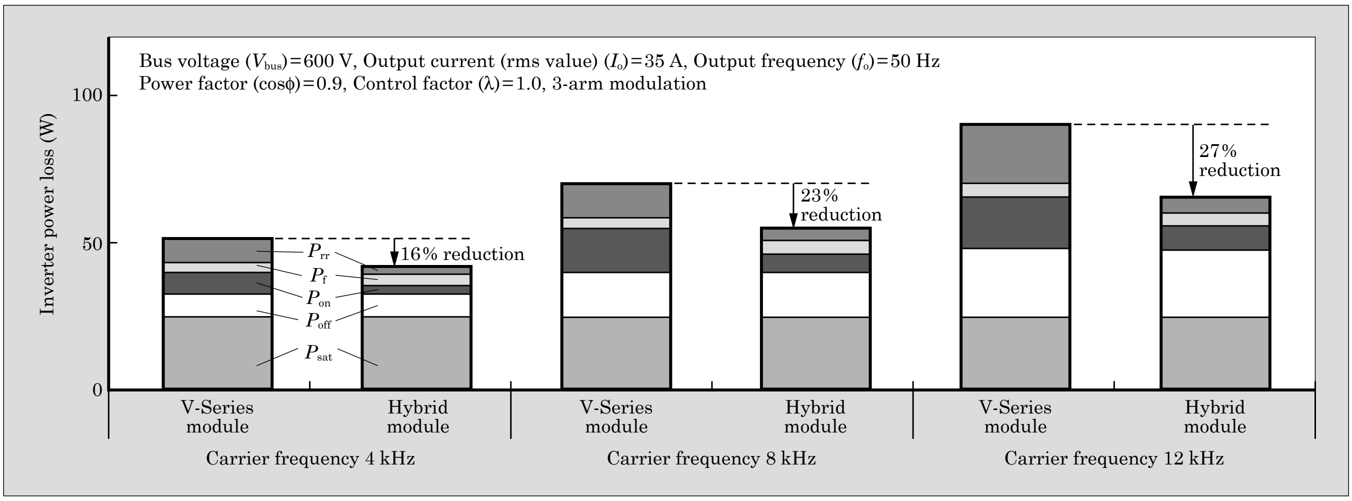

Fig.14 Inverter power loss

than that of the V Series PND, the transient on-state voltage of the SiC-SBD is reduced from 90 V to 45 V. Therefore, as shown in Fig. 13, the surge voltage at turn-off can be kept low and the turn-off energy can be reduced.

$$V_{Sp} = V_{CC} + L_s \cdot \frac{dI_C}{dt} + V_{TR} \quad \cdots\cdots (1)$$

V_{Sp} : Surge peak voltage
V_{CC} : Applied voltage
L_s : Inductance of main circuit
I_C : Collector current
V_{TR} : Transient on-state voltage

5. Inverter Power Loss

Figure 14 shows the calculated results of inverter power loss in the newly developed hybrid module and the V-Series module. When the carrier frequency is 8 kHz, the total power loss of the hybrid module can be reduced significantly by 23% for that of the V-Series module. Moreover, because the rate of loss reduction increases with hisher carrier frequency, the hybrid module is more effective for applications involving high frequency operation.

6. Postscript

This paper introduced the Si-IGBT and SiC-SBD hybrid module that combines a SiC-SBD, developed in collaboration with the National Institute of Advanced Industrial Science and Technology, and a 6th generation "V-Series" IGBT chip, which is Fuji Electric's latest chip. By greatly reducing the power loss of the device itself, this product is expected to contribute significantly to the achievement of higher efficiency inverters. In the future, Fuji Electric intends to expand the lineup of products that use SiC chips, and to contribute to efforts for preventing global warming.

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References

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