1,700-V Withstand Voltage SiC Hybrid Module

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ABSTRACT

Fuji Electric has developed a SiC hybrid module with a 1,700-V withstand voltage. It is designed for use in the traction market as a power device that can be utilized in inverters that contribute to energy savings. This module is equipped with 6th-generation IGBT chips and applies SiC-SBD chips to its FWDs. It has a product rating of 1,700 V/1,200 A (2 in 1) and has 2 specifications: standard specifications that make much of power dissipation, and low $V_{CE(sat)}$ specifications suitable for low switching frequencies. The standard specifications reduce loss by 18% compared with conventional Si modules. Furthermore, the low $V_{CE(sat)}$ specifications achieve 6% loss reduction compared with the standard specifications at low switching frequency condition.

1. Introduction

In recent years, reduction of emissions of CO_2 and other greenhouse gases has been demanded for restraining the progress of global warming. Power electronics including power conversion devices are not exempt from the demand and further energy saving is required for more reduction of emissions of greenhouse gases. Power conversion devices have become widespread in the entire society including those for social infrastructure such as electric railways and those for consumers such as air conditioners and energy saving can make significant contributions to the reduction of greenhouse gases. Energy saving of inverters, which are mounted on power conversion devices, can be realized by technological innovation of their components such as power devices, circuits and control. For power devices, continuing to achieve further reduction of power dissipation is an important mission.

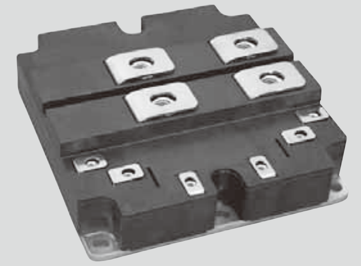
At present, the mainstream of power devices is insulated-gate bipolar transistor (IGBT) modules that use silicon (Si) IGBT and free wheeling diode (FWD) chips. However, performance of Si devices is approaching its theoretical limit based on physical properties and significant reduction of power dissipation cannot be expected. Silicon carbide (SiC) devices, which are characterized by high heat resistance and high breakdown field tolerance, have achieved a dramatic reduction of power dissipation that is difficult to realize with Si devices and opened up the potential for realizing efficiency improvement and size reduction of inverters.

Fuji Electric has commercialized SiC hybrid modules, which combine the 600-V, 1,200-V and 1,700-V withstand voltage SiC-Schottky barrier diode (SiC-SBD) chips developed and Si-IGBT chips. Above all, we have focused our attention on the development of 1,700-V withstand voltage SiC hybrid module products intended for main power supply of electric railways to expand the product line. This application essentially requires enhancement of the blocking voltage and capacity and we have developed SiC hybrid modules by applying the high-power IGBT module technology accumulated up to now[(1) to (3)].

This paper describes SiC hybrid modules with a rating of 1,700 V/1,200 A (2 in 1).

2. Overview

Figure 1 shows the external appearance of the 1,700-V withstand voltage SiC hybrid module. It has a high-reliability package that uses AlSiC, a composite material of aluminum and silicon carbide, for the base material and aluminum nitride (AlN) featuring high thermal conductivity for the insulating substrate material. AlSiC has a linear expansion coefficient of 7.5×10^{-6}/°C, which is close to 4.5×10^{-6}/°C of an AlN substrate, and offers improved heat cycle life and power cycle life as compared with a copper (Cu) base.



M278 package, 140 × 130 × 38 mm, mass 0.9 kg

Fig. 1 1,700-V withstand voltage SiC hybrid module

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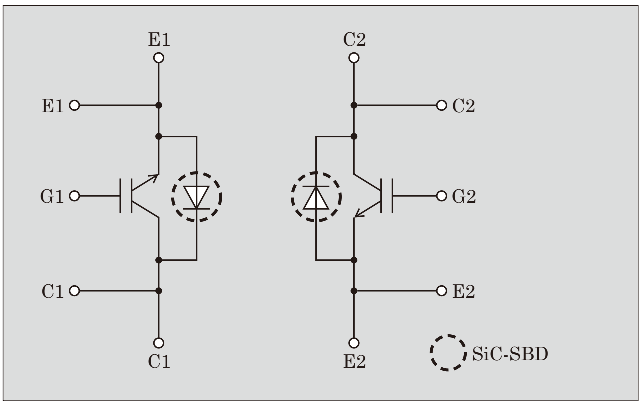

Fig. 2 Equivalent circuit of 1,700-V withstand voltage SiC hybrid module

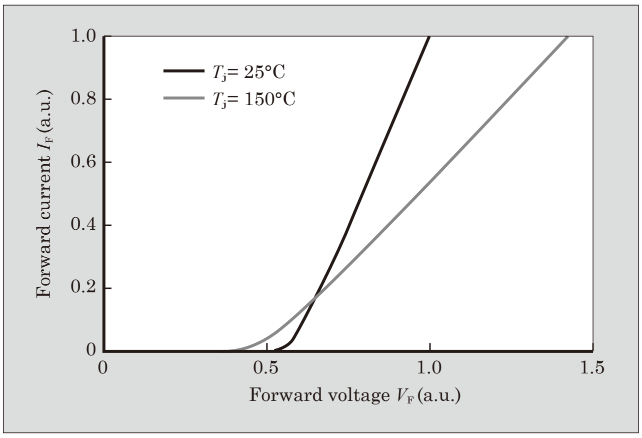

Fig. 3 V_F-I_F characteristics

Figure 2 shows an equivalent circuit. This module integrates the 6th-generation IGBT chips and applies 1,700-V withstand voltage SiC-SBD chips to its FWDs.

In electric railway traction applications, operation is mostly at a low switching frequency of up to approximately 0.5 kHz in carrier frequency and steady-state loss is dominant. Accordingly, low saturation voltage $V_{CE(sat)}$ characteristic is preferable. In the main circuit of high capacity inverters, the main circuit inductance L_s is larger than those of low to medium capacity inverters. As shown in Equation 1, the effect of L_s and gradient of the turn-off current di/dt causes the turn-off surge voltage V_{sp} generated to increase and low V_{sp} is preferable. However, decreasing the turn-off speed to suppress this V_{sp} causes increased loss, which poses a problem. From this perspective, in order to satisfy the low $V_{CE(sat)}$ and low V_{sp} requirements, we have added to the product line the low $V_{CE(sat)}$ specifications with the priority on the steady-state loss and V_{sp} on top of the standard specifications with the priority on the switching loss. By optimizing the thickness of the IGBT chips mounted, we have improved the E_{off}-$V_{CE(sat)}$ trade-off and realized the minimization of the total loss by adjusting the amount of carriers injected from the collector.

$$V_{sp} = V_{cc} + L_s \frac{dI_c}{dt} \qquad (1)$$

V_{sp} : Turn-off surge voltage (V)
V_{cc} : Circuit voltage (V)
L_s : Main circuit inductance (H)
I_c : Collector current (A)

3. Characteristics

3.1 1,700-V withstand voltage SiC hybrid module with standard specifications

(1) FWD output characteristics

Figure 3 shows the forward current (I_F) versus forward voltage (V_F) characteristics of the 1,700-V withstand voltage SiC-SBD used for the SiC hybrid module. If a current that is about to flow into one of the chips connected in parallel is larger than that into other chips, the resistance increases because of the strong positive temperature characteristics of the SiC-SBD, which prompts self-adjustment to restrain the current increase, making current imbalance less likely to occur. For that reason, the characteristics are effective in high-power IGBT modules with many parallel connections of chips.

(2) Switching characteristics

Figure 4 compares the reverse recovery waveforms of the SiC hybrid and Si modules. With the SiC hybrid module, the reverse recovery current peak value I_{rp} is significantly lower. This is because that the SiC-SBD is a unipolar device and minority carrier injection and sweep-out do not take place. Figure 5 shows a comparison of turn-on waveforms between the SiC hybrid

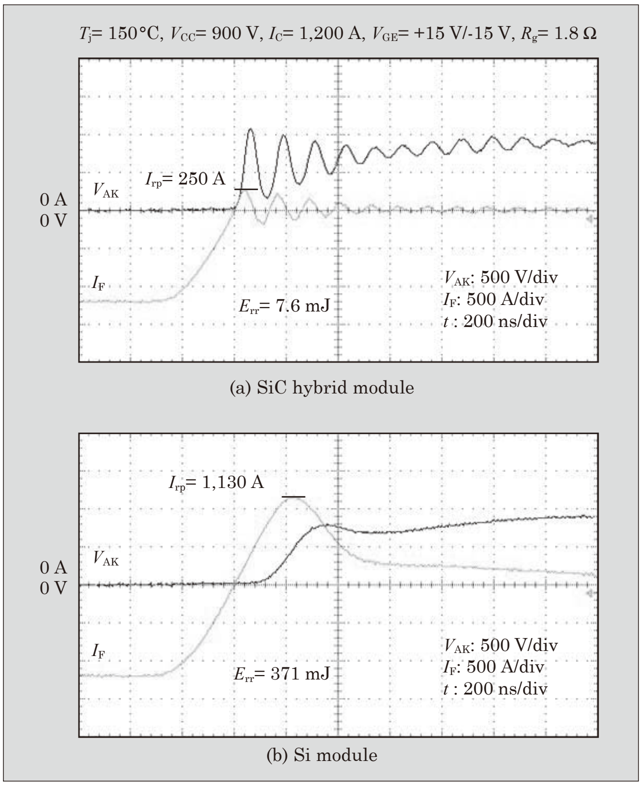

Fig. 4 Reverse recovery waveforms

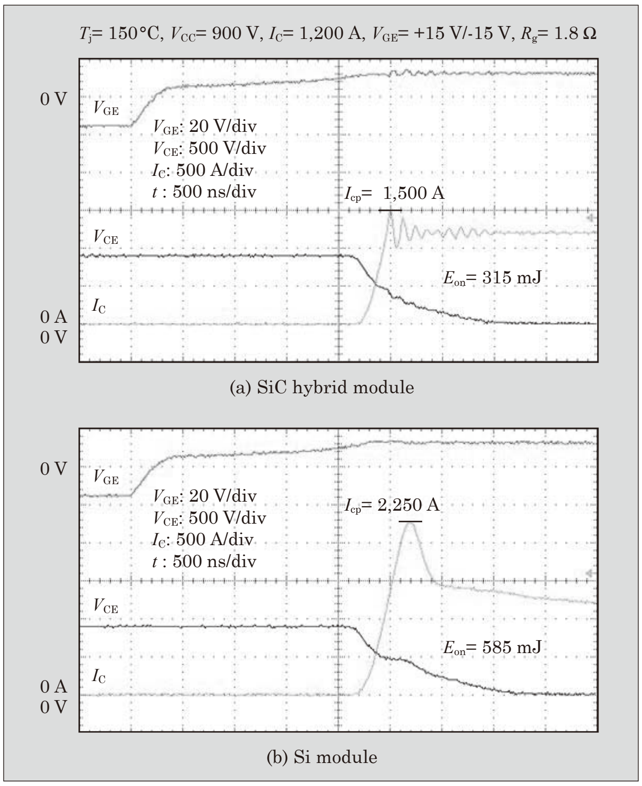

Fig. 5 Turn-on waveforms

and Si modules. The SiC hybrid module allows a significant reduction in the reverse recovery current as described above and the turn-on current peak value I_{cp}, which reflects it, can be significantly reduced as well.

In this way, while the Si module has the E_{rr} of 371 mJ, it is 7.6 mJ with the SiC hybrid module, which is a reduction of approximately 98%. In addition, as compared with the E_{on} of 585 mJ with the Si module, it is 315 mJ with the SiC hybrid module, a reduction of approximately 46%.

(3) Generated loss of module in inverter

Figure 6 shows the results of simulation of generated loss in an inverter. It indicates that the generated loss of the SiC hybrid module can be reduced as compared with the Si module by 5%, 18% and 32% for the carrier frequency of 0.3 kHz, 1 kHz and 3 kHz respectively. In this way, increasing the carrier frequency increases the loss reduction rate, which raises expectations for application of the SiC hybrid module in high-frequency operation.

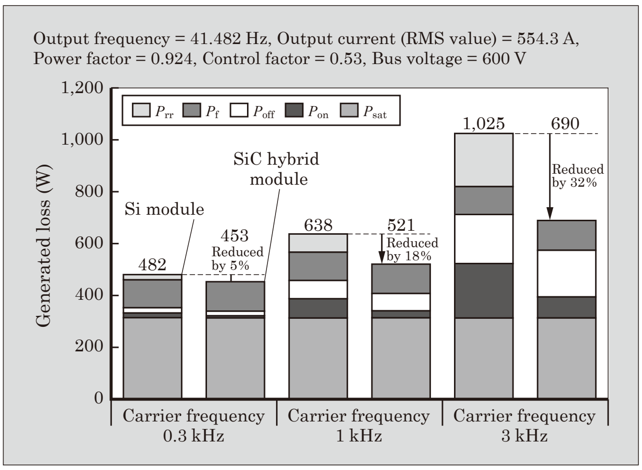

Fig. 6 Simulation of generated loss in inverter

3.2 1,700-V withstand voltage SiC hybrid module with low $V_{CE(sat)}$ specifications

(1) IGBT output characteristics

Figure 7 shows the $V_{CE(sat)}$-I_C characteristics. The standard and low $V_{CE(sat)}$ specifications both have a positive temperature characteristic and current imbalance is unlikely to occur, which allows easy parallel connection. The low $V_{CE(sat)}$ specifications offer a reduction of 0.20 V at T_j = 25 °C and 0.22 V at T_j = 150 °C from the standard specifications.

(2) Switching characteristics

Figure 8 compares turn-off waveforms. While V_{sp} is 1,420 V with the standard specifications, it is 1,260 V with the low $V_{CE(sat)}$ specifications, a reduction of 160 V. Figure 9 shows the V_{sp}-I_C characteristics. It indicates a reduction of approximately 10% at the rated current of 1,200 A. Figure 10 shows the turn-off loss E_{off}-I_C characteristics. With the low $V_{CE(sat)}$ specifications, E_{off} is shown to increase by approximately 70% at the rated current as compared with the standard specifications. This is because that, with the low $V_{CE(sat)}$ specifications, the tail current is increased by optimization of the amount of carriers injected from the collector in order to suppress the surge voltage.

(3) Generated loss of module in inverter

Figure 11 shows the results of simulation of generated loss in an inverter. With the low $V_{CE(sat)}$ specifications, P_{off} increases when the carrier frequency is 0.3 kHz but the generated loss is reduced by 11% as compared with the Si module and by 6% as compared with the standard specifications. Accordingly, in a region with a small carrier frequency, the low $V_{CE(sat)}$ specifications offer a reduction not only of V_{sp} but also of the generated loss as compared with the standard specifications.

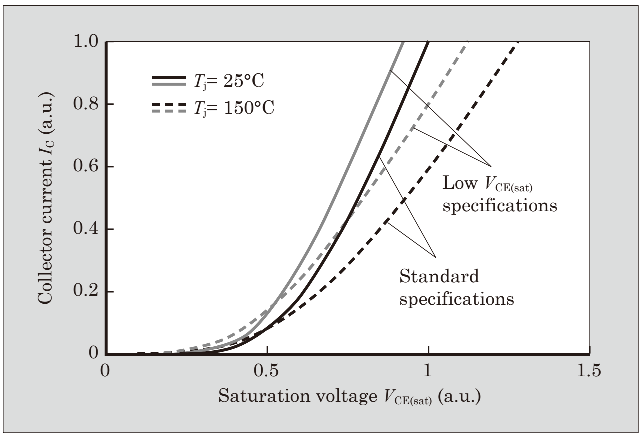

Fig. 7 $V_{CE(sat)}$-I_C characteristics

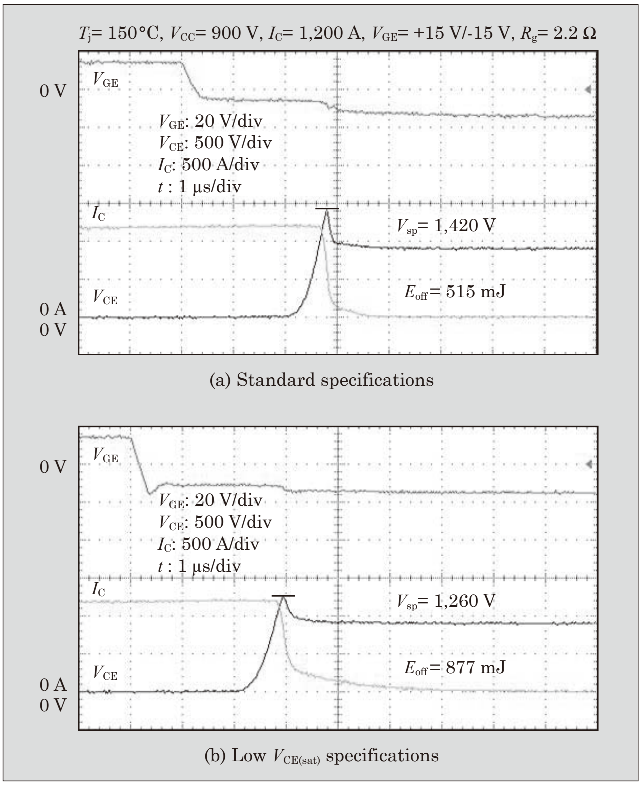

Fig. 8 Turn-off waveforms

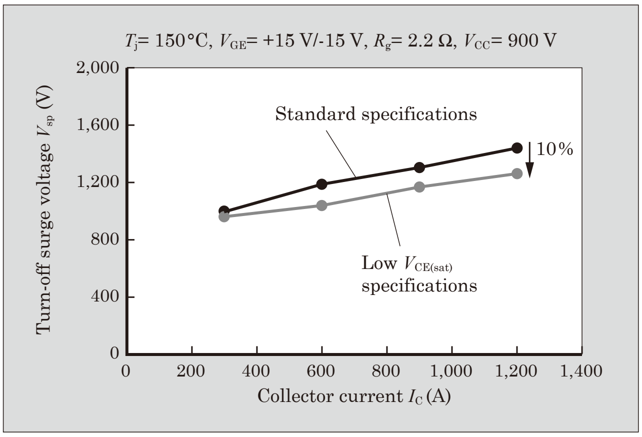

Fig. 9 V_{sp}-I_C characteristics

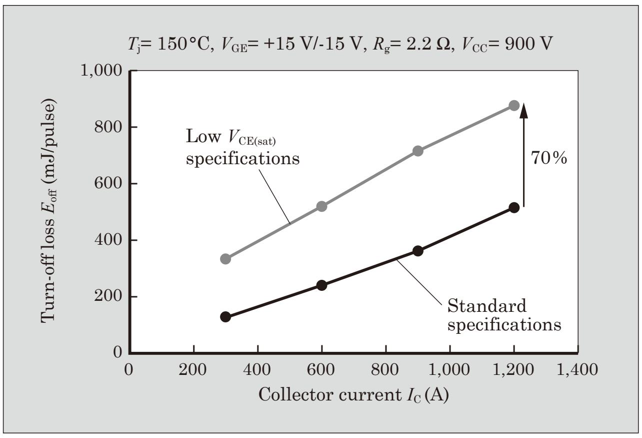

Fig. 10 E_{off}-I_C characteristics

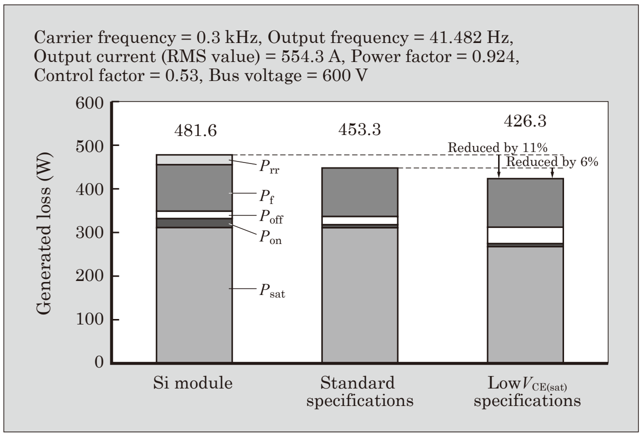

Fig. 11 Results of simulation of generated loss in inverter

4. Postscript

This paper describes a 1,700-V withstand voltage SiC hybrid module. This product, which has realized a significant reduction of power dissipation of the device itself, is expected to make substantial contributions to efficiency improvement and size reduction of inverters. In the future, we intend to promote further product line enhancement of SiC hybrid modules and work on the building of a product line of All-SiC modules, which use SiC-MOSFET chips instead of IGBTs and SiC-SBD chips instead of FWDs, to contribute to energy savings.

References

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