3,300-V Withstand Voltage SiC Hybrid Module Technology

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ABSTRACT

There has been increasing demand for electronics to achieve not only energy savings, but also be more compact, lightweight and improved performance such as high output. Fuji Electric is seeking to meet these demands by pursuing the development of a SiC hybrid module with a 3,300-V withstand voltage. By adopting the SiC-SBDs that we developed in partnership with the joint research body Tsukuba Power-Electronics Constellation (TPEC), we have been able to reduce generated loss by 24% compared with current Si modules. In addition, we have also utilized Sn-Sb solder to ensure high reliability and have been able to improve continuous operation temperature by 25 °C. Moreover, we made use of the reducing effect of generated loss to achieve improvements in power density while also reducing the footprint size by approximately 30%.

1. Introduction

With increasing amounts of natural resources and energy being consumed in the world, environmental pollution and resource depletion are posing major problems and the improvement of energy efficiency is strongly desired. According to this background, power electronics equipment, characterized by power saving in transmission, conversion, control and supply of electric power, is attracting attention.

Demands placed on power electronics equipment encompass a wide range from those of society for mitigating environmental load by saving energy to those relating to performance improvements such as high reliability, controllability, size and weight reduction, and high output. In order to meet these demands, it is essential to make technological improvements to power devices, circuits and control that constitute power electronics equipment. In particular, for power devices, which are key components, compact and low-loss power modules are desired.

At present, representative power modules are composed of insulated-gate bipolar transistors (IGBTs), which generally integrate silicon (Si) IGBT and free wheeling diode (FWD) chips. However, the performance of Si chips is approaching the theoretical limit based on physical properties and the dramatic characteristic improvements of the past can no longer be expected. Accordingly, wide band gap semiconductors, which have higher performance than Si, are drawing attention. Silicon carbide (SiC), one such semiconductor, not only features a higher withstand voltage and lower loss than conventional Si but is also capable of high-temperature and high-frequency operation. It allows power modules to increase the power density, achieving the size reduction.

This paper describes the technology used for the 1,200-A SiC hybrid module with a 3,300-V withstand voltage that integrates this SiC chip.

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2. Configuration of SiC Hybrid Module

Fuji Electric has commercialized SiC hybrid modules integrating SiC Schottky barrier diodes (SiC-SBDs) and Si-IGBTs with a withstand voltage of

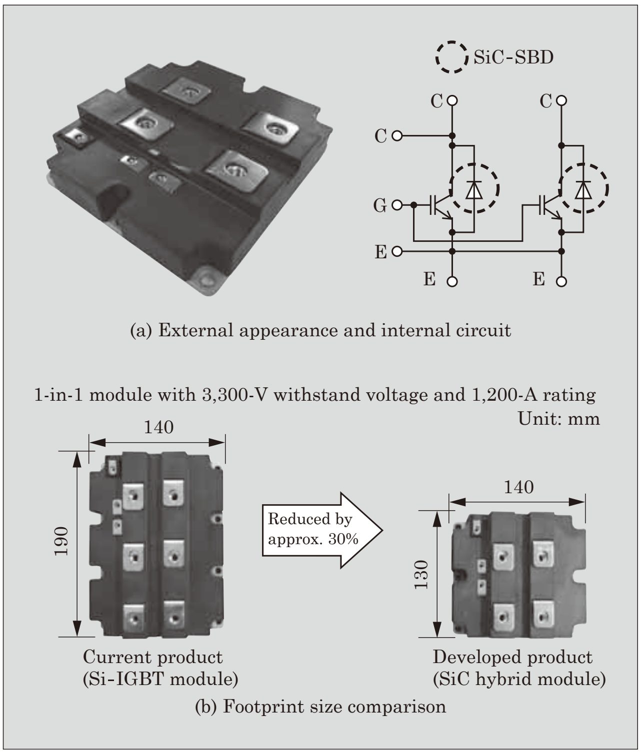

Fig.1 Overview of 3,300-V withstand voltage SiC hybrid module

600 V, 1,200 V and 1,700 V. We have now developed an SiC hybrid module with a 3,300-V withstand voltage in order to meet the demand for even higher withstand voltages.

Figure 1 shows the external appearance and internal circuit of the 3,300-V withstand voltage SiC hybrid module and a footprint size comparison with a Si-IGBT module. As the FWD, we have used the SiC-SBD developed in partnership with the joint research project of the Tsukuba Power-Electronics Constellations (TPEC). Its generated loss is significantly reduced compared to that of present Si-IGBT. We have employed Sn-Sb solder under the chip, which is one of the packaging technologies used for the 7th-generation "X Series" IGBT modules, to ensure high reliability. We have thereby successfully improved the continuous operating temperature from 125 °C of the current Si-IGBT to 150 °C[(1)(2)]. The reduction in generated loss and improvement of operating temperature have enabled us to achieve a power density increase, and the footprint size of the module has been reduced by approximately 30% as compared with the current product as shown in Fig. 1(b).

3. Packaging Technology Challenges Arising from Hybridization

3.1 Issue with and study of multi-parallel connection structure

In order to achieve a 1,200-A rating in hybridization, it is necessary to connect a number of chips in parallel due to the chip rated current limitation. Package structures with this multi-parallel connection are susceptible to a current imbalance due to variations in chip characteristics, leading to the degradation of long-term reliability. To deal with this issue, we conducted thermal analysis in a simulation to verify the conditions of temperature and thermal stress of the individual chips. Based on the results of this verification, we have determined that the effect of variations in chip characteristics on variations of chip temperature can be simulated. We have made use of this analysis to reflect the results in the package structure of the developed product for improving its reliability.

3.2. Improvement of power cycle capability

To achieve miniaturization by hybridization, a package structure that accommodates chip temperature increase is essential. An increase in the chip temperature increases not only the thermal stress on the constituent materials but also temperature variations due to starting and stopping, which requires the product to assure its performance for high thermal fatigue. Accordingly, to improve the ΔT_j power cycle capability, which serves as a guideline for this assurance, we have employed Sn-Sb solder under the chips, a packaging technology for the 7th-generation X Series IGBT modules. Sn-Sb solder offers high strength and has an effect of restraining the progress of cracking resulting from thermal fatigue[(1)(2)].

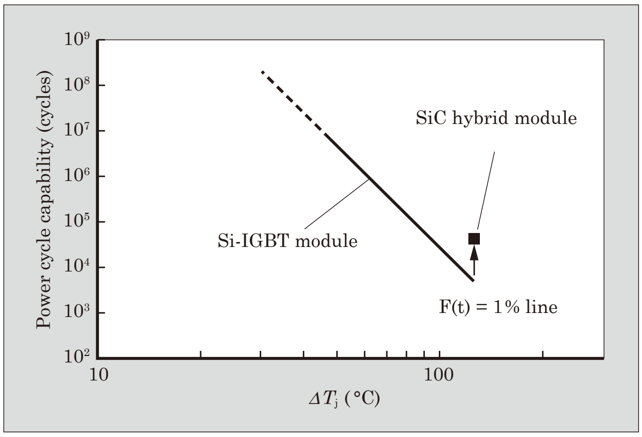

Fig.2 ΔT_j power cycle test results

Figure 2 shows ΔT_j power cycle test results of a SiC hybrid module and Si-IGBT module. As compared with the Si-IGBT module, the SiC hybrid module has been shown to have a power cycle capability about 5 times higher when $\Delta T_j = 125$ °C.

4. Characteristics[(3)(4)]

4.1 Forward characteristics

Figure 3 shows the forward characteristics of SiC hybrid and Si-IGBT modules, and Fig. 4 the temperature dependence of forward voltage V_F at the 1,200-A rating. As shown in Fig. 4, V_F of the SiC hybrid module is smaller by about 29% than that of the Si-IGBT module at 25 °C, which is reversed at 150 °C to be larger by about 30%. However, while the Si-IGBT module has negative temperature characteristics, in which V_F decreases as the chip junction temperature T_j increases, the SiC hybrid module has positive temperature characteristics. When chips with negative temperature characteristics are connected in parallel, the internal resistance decreases as T_j increases. This allows the current to flow more easily, leading to a susceptibility to a current imbalance caused by a concentration of

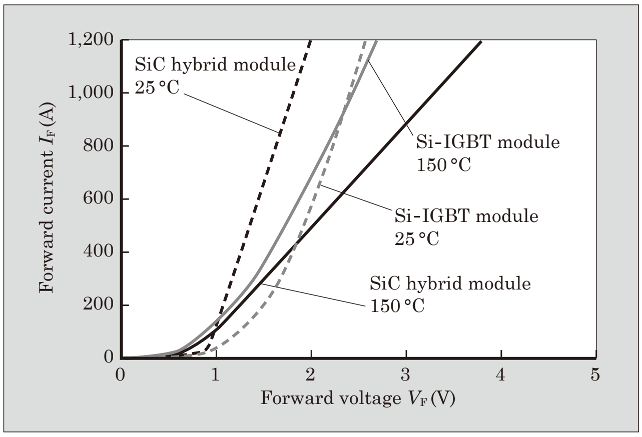

Fig.3 Forward characteristics

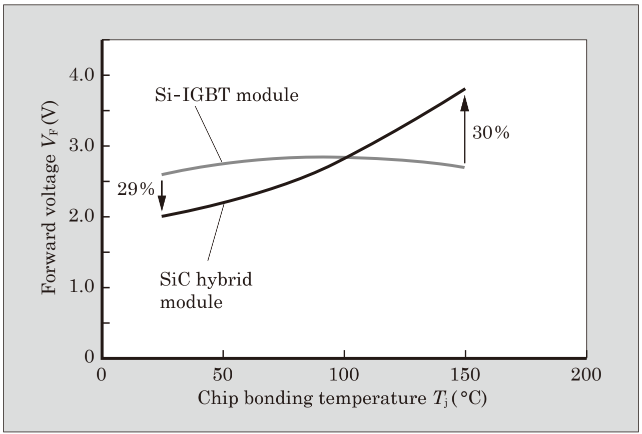

Fig.4 Temperature dependence of forward voltage

current in some of the chips.

Meanwhile, positive temperature characteristics cause the internal resistance to increase as T_j increases, which results in equal sharing of the current by chips connected in parallel. Accordingly, SiC hybrid modules are advantageous in multi-parallel connections.

4.2 Leakage current characteristics

Figure 5 shows the leakage current characteristics of SiC hybrid and Si-IGBT modules, and Fig. 6 the temperature dependence of leakage current. At a temperature of 125 °C and collector voltage of 3,300 V, the leakage current of the SiC hybrid module I_{CES} is smaller by about 11% than that of the Si-IGBT module. At 150 °C, the difference becomes even larger, and reaches 44%. As shown in Fig. 6, I_{CES} of the Si-IGBT module shows a great change according to the temperature. On the other hand, the leakage current of the SiC hybrid module is nearly constant, which shows that its temperature dependence is small. This is because its band gap is about 3 times as large as that of Si and the excitation of the carriers due to the increase of T_j is small. Accordingly, the SiC hybrid module is capable of operating at higher temperatures than the Si-IGBT module.

4.3 Switching characteristics

(1) Reverse recovery characteristics

Figure 7 compares reverse recovery waveforms of

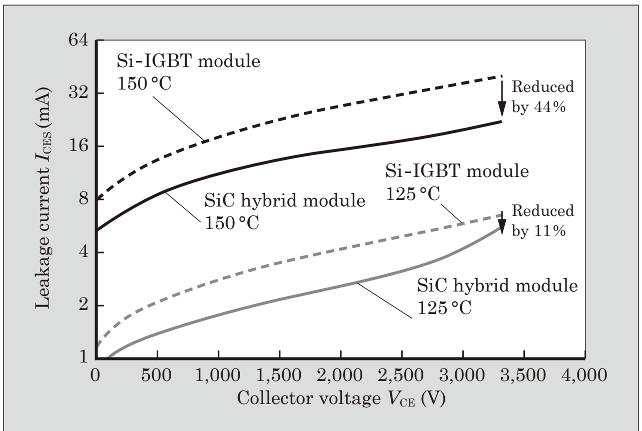

Fig.5 Leakage current characteristics

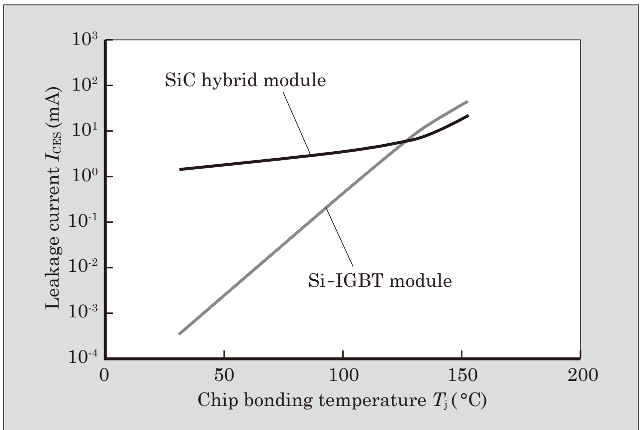

Fig.6 Temperature dependence of leakage current

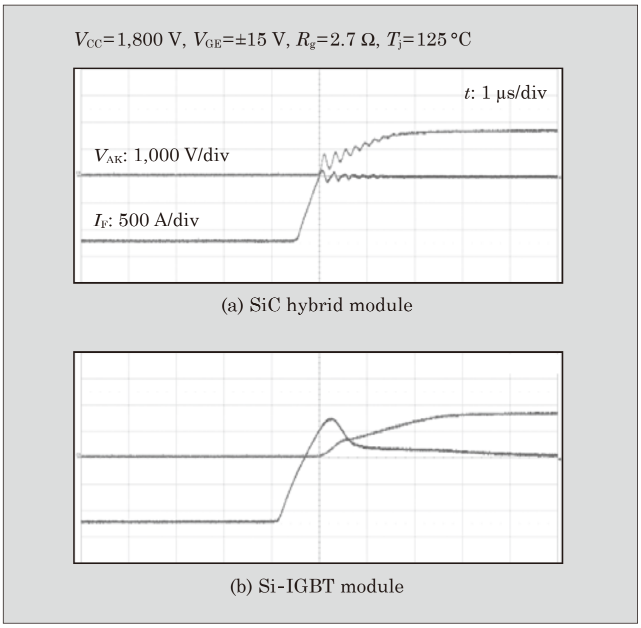

Fig.7 Reverse recovery waveforms

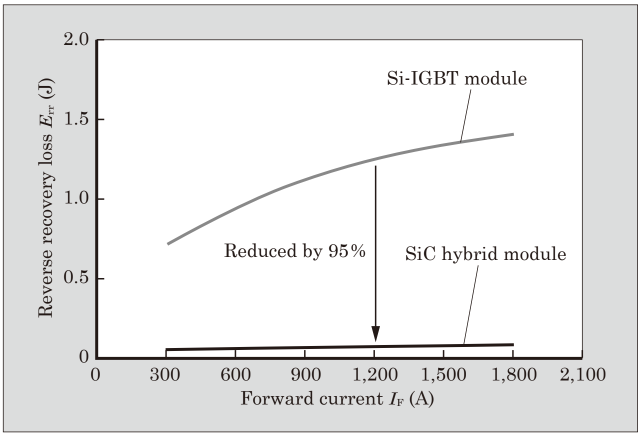

Fig.8 Current dependence of reverse recovery loss

the SiC hybrid and Si-IGBT modules. As compared with the Si-IGBT module, the SiC hybrid module exhibits a much lower reverse recovery peak current. This is because the SiC-SBD is a unipolar device and there is no storage effect caused by minority carriers. Figure 8 shows the current dependence of reverse recovery loss E_{rr}. For E_{rr}, at the 1,200-A rating, the generated loss can be reduced by 95% as compared with the Si-IGBT module. At 300 A or 1,800 A, the generated loss can also be reduced to the same level. Thus, the generated loss can be reduced in a wide range from low- to high-current regions.

(2) Turn-on characteristics

Figure 9 shows a comparison of turn-on waveforms between the SiC hybrid and Si-IGBT modules. The reverse recovery peak current of the SiC-SBD is reflected in the IGBT turn-on current in the opposite arm, and the turn-on peak current can be significantly reduced as well. As shown in Fig. 10, the turn-on loss E_{on} at the 1,200-A rating can be reduced by 28% as compared with the Si-IGBT module.

(3) Turn-off characteristics

Figure 11 shows the current dependence of the turn-off loss E_{off} of the SiC hybrid and Si-IGBT modules. The surge peak voltage generated at turn-off can be generally defined by Equation (1). When the current changing rate dI_c/dt of the IGBT and the main circuit inductance L_s of the evaluation circuit are equivalent, the value of the transient on-state voltages of the diode appears as the difference in the surge peak voltage. The SiC-SBD has a drift layer with a lower resistance than that of the Si-FWD, resulting in the low transient on-state voltage. Accordingly, the turn-off surge peak voltage can be kept low with the SiC hybrid module, and E_{off} can also be reduced.

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

V_{sp} : Surge peak voltage (V)
V_{cc} : Applied voltage (V)
L_s : Main circuit inductance (H)
I_c : Collector current (A)
V_{fr} : Transient on-state voltage (V)

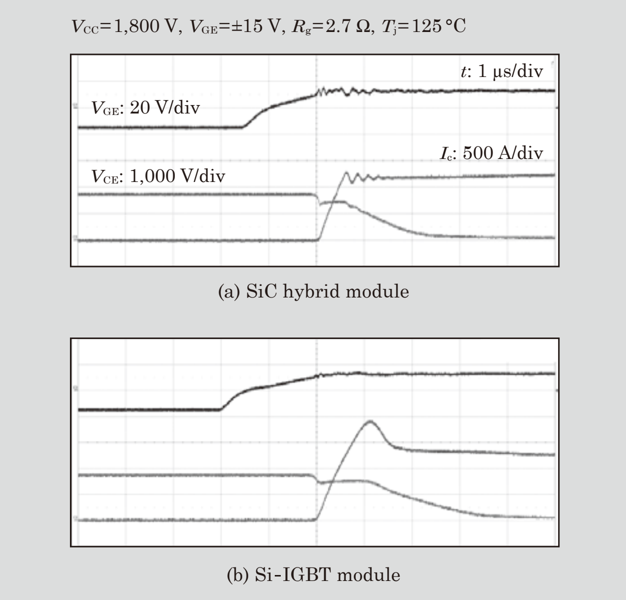

Fig.9 Turn-on waveforms

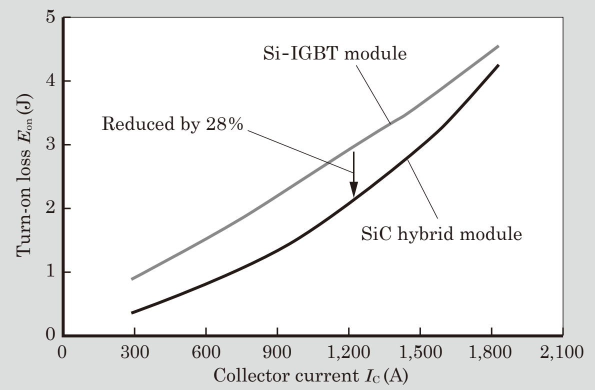

Fig.10 Current dependence of turn-on loss

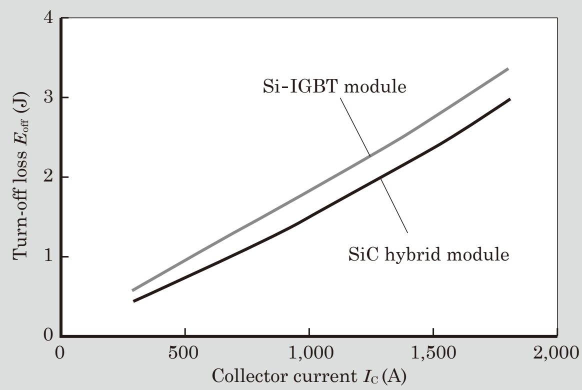

Fig.11 Current dependence of turn-off loss

4.4 Inverter power loss

Figure 12 shows the calculated results of inverter power loss in the SiC hybrid and Si-IGBT modules. At

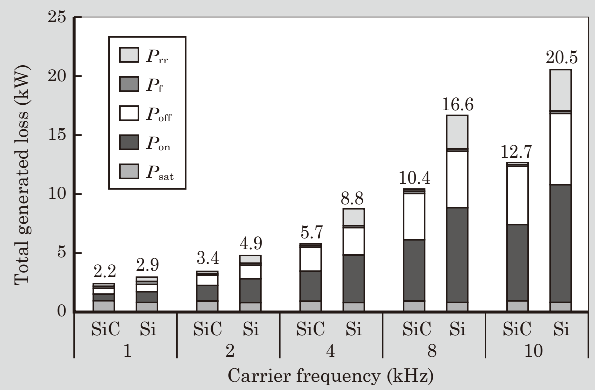

Fig.12 Results of calculating inverter power loss

a carrier frequency of 1 kHz, the total power loss of the SiC hybrid module can be reduced by 24% as compared with the Si-IGBT module. In addition, with a higher carrier frequency, the reduction rate of the total power loss is increased and the reduction can be as large as 38% at a carrier frequency of 10 kHz. This means that the SiC hybrid module can raise expectations for application to products that require high-frequency operation.

We have developed a traction converter for propulsion system (inverter, converter) that integrates the developed product for Central Japan Railway Company, which is mounted on Shinkansen trains (bullet train) and is currently undergoing running test.

5. Postscript

This paper has described the technology of the 3,300-V withstand voltage SiC hybrid module. The technology has been used for the 3,300-V withstand voltage SiC hybrid module that employs the SiC-SBD developed jointly with the cooperative research body Tsukuba Power-Electronics Constellations and Fuji Electric's Si-IGBT. The developed product adopts SiC-SBDs and Sn-Sb solder, thereby realizing an increase in power density and making significant contributions to efficiency improvement and miniaturization of power electronics equipment. In the future, we intend to proceed with study on developing all products with SiC to achieve a further performance improvement and promote energy saving.

We would like to extend our sincere gratitude to the people involved from the joint research body Tsukuba Power-Electronics Constellations who have offered their cooperation to the development of the SiC-SBD.

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