1,200-V 2nd-Generation All-SiC Modules

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ABSTRACT

Fuji Electric has been commercializing Si-IGBT modules for use in a variety of power conversion systems in order to contribute to the realization of a low-carbon society. We have developed All-SiC modules equipped with 2nd-generation trench gate SiC-MOSFET chips to improve the power conversion efficiency. While maintaining compatibility with conventional products, internal inductance and power loss has been reduced by taking advantage of the low on-resistance of the 2nd-generation SiC trench gate MOSFET. As a result, the inverter generation loss can be reduced by 63% compared to the conventional Si-IGBT module, which contributes to higher density and miniaturization of power electronics equipment.

1. Introduction

To realize a low-carbon society, it is necessary to achieve energy savings in power electronics equipment. To ensure energy savings, it is necessary to improve the power conversion efficiency of power electronics equipment. In this respect, power semiconductor are playing an important role. Currently, the characteristics of mainstream silicon (Si) devices are approaching the performance limit of their physical properties. Therefore, is getting difficult to significantly improve their characteristics. Under these circumstances, devices using silicon carbide (SiC), which is a wide-band gap semiconductor, are attracting attention as a next-generation semiconductor. SiC devices are capable of significantly decreasing power dissipation compared with Si devices. These devices are expected to further improve the power conversion efficiency of power electronics equipment and realize energy savings.

In 2017, Fuji Electric released an All-SiC 2 in 1 module[(1),(2)] that has a rated capacity of 1,200 V / 400 A and is equipped with 1st-generation SiC-metal-oxide-semiconductor field-effect Transistor (MOSFET) chips[(1),(3),(4)] having a trench-gate structure in a full-mold package. In addition, Fuji Electric developed the All-SiC 2 in 1 module used with the standard 62-mm 2 in 1 package (W108 mm × D62 mm) of a conventional Si-IGBT module to ensure compatibility for the outline and terminal layout.

The newly developed 2nd-generation 1,200-V All-SiC module has reduced internal inductance while maintaining compatibility with current products. The reduced power dissipation was achieved by using a 2nd-generation SiC trench-gate MOSFET, which has lower on-resistance than the 1st-generation MOSFET.

In this paper, the All-SiC module with a rated capacity of 1,200 V / 600 A in the M295 package [2 in 1 package (W108 mm × D62 mm)], which is the same as the standard 62-mm 2 in 1 package for Si-IGBT modules are described.

2. 2nd-Generation SiC Trench-Gate MOSFET

By reducing the chip thickness and narrowing the cell pitch of the trench-structure for 2nd-generation products, the normalized on-resistance $R_{on}{\cdot}A$ of the 2nd-generation SiC trench-gate MOSFET[(5)] with a rated voltage of 1,200 V was reduced by 23% compared with the 1st-generation SiC trench-gate MOSFET as shown in Fig. 1. In addition, the channel mobility was improved by 20% from the 1st-generation SiC trench-gate MOSFET.

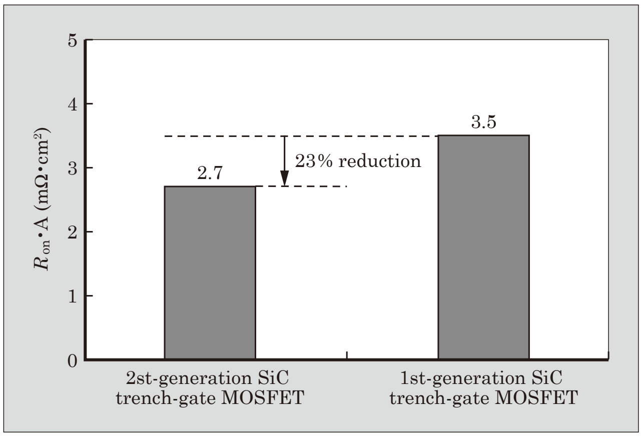

Fig.1 Comparison of the $R_{on}{\cdot}A$ for a 2nd-generation SiC trench gate and 1st-generation SiC trench gate

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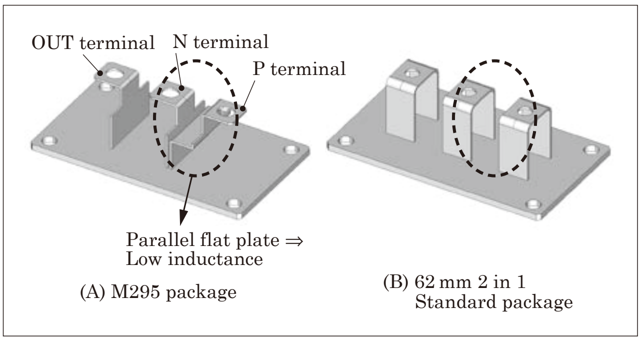


Fig.2 Difference in the internal structure of the M295 package and standard 62-mm 2 in 1 package

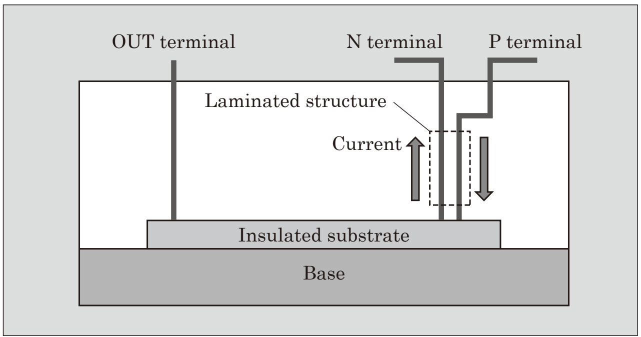


Fig.3 Cross-section structure of the M295 package

3. M295 Package

Since SiC-MOSFETs are majority carrier devices (unipolar devices), fast switching can be available compared with Si-insulated gate bipolar transistors (IGBTs), which are minority carrier devices (bipolar devices). However, fast switching has the adverse effect of causing high surge voltage due to the internal inductance inside the module.

To reduce the internal inductance in the M295 package while maintaining the compatibility of the outline and terminal layout with the standard Si-IGBT 62-mm 2 in 1 package, the following improvement was made. Figure 2 shows the internal structure of the standard Si-IGBT 2 in 1 package and the newly developed M295 package. As shown in Fig. 3, All-SiC module has a laminated structure between P and N busbars in order to utilize the electromagnetic mutual inductance effect by keeping parallel and very close to each other as long as possible. The internal inductance could be reduced by 24% compared to the conventional product.

4. Electrical Characteristics of All-SiC Module with the 2nd-Generation SiC Trench-Gate MOSFET (rated of 1,200 V / 600 A)

4.1 Output characteristics

Figure 4 shows a comparison of output characteristics of the 1,200-V/600-A rated All-SiC module equipped with the 2nd-generation SiC trench-gate MOSFET in the M295 package (All-SiC module) and the 7th-generation “X Series” Si-IGBT module equipped with the standard package (Si-IGBT module). As is well-known MOSFETs are characterized by no built-in voltages found in bipolar devices such as IGBTs. As a result, the on-voltage of the All-SiC module equipped with MOSFET is lower than that of the Si-IGBT module when below the rated current I_D of 600 A.

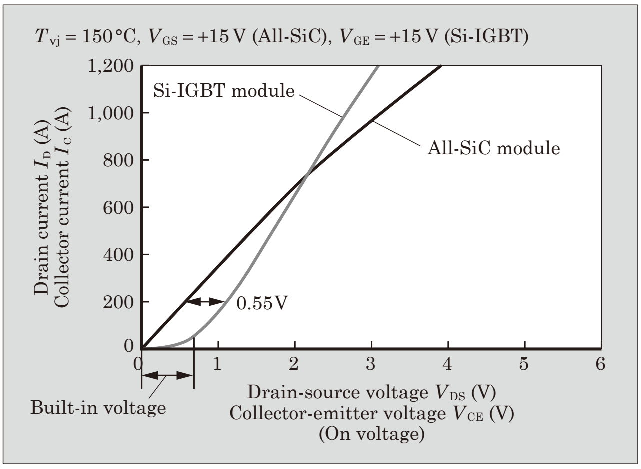


Fig.4 Comparison of output characteristics

Since it is common for a power conversion device such as an inverter to operate normally at approximately 30% of the current rating of the module, the comparison was made at 200 A. As a result, the on-voltage of the All-SiC module is approximately 0.55 V lower than that of the Si-IGBT module, and the steady-state loss can be reduced to approximately half as shown in P_{sat} of Fig. 9.

4.2 Switching characteristics

In general, the switching speed of Si-IGBT modules slows down as the temperature increases, as shown in Fig. 5.

On the other hand, for the All-SiC module, as

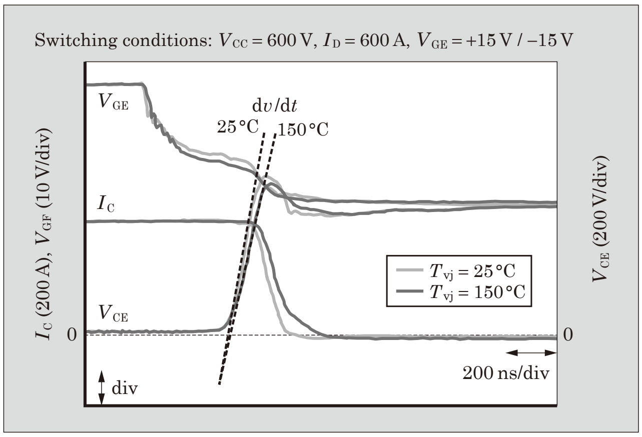


Fig.5 Comparison of switching waveforms of the Si-IGBT module at T_{vj} = 25 °C and 150 °C

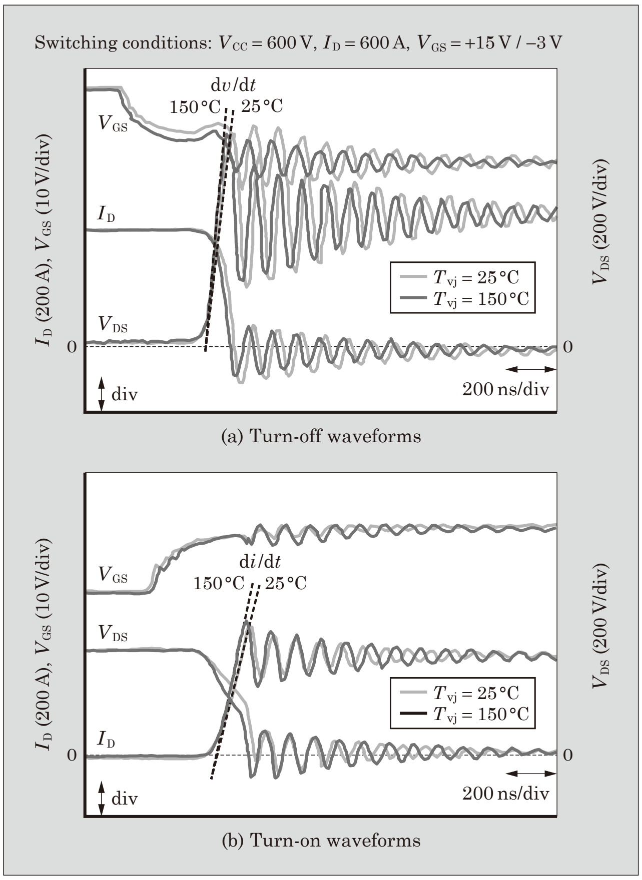


Fig.6 Comparison of switching waveforms of All-SiC module at T_{vj} = 25 °C and 150 °C

shown in Fig. 6, the switching speed is almost the same at T_{vj} = 25 °C and 150 °C. This is because All-SiC modules have almost no tail current during turn-off and reverse recovery as seen in Si-IGBT modules, and the low temperature dependence of carrier mobility.

The driving gate resistance R_G was selected so that dv/dt and di/dt, which are indicators of the switching speed, are roughly equivalent between the All-SiC module and the Si-IGBT module at T_{vj} = 150 °C. Figure 7 shows the results of the comparison of the switching characteristics.

It is found from Fig. 7(a) that the tail current at turn-off of the All-SiC module is much lower than that of the Si-IGBT module. In addition, at the reverse recovery, significantly reduced tail current and peak current can be seen as shown in Fig. 7(c). This is because during switching, Si-IGBT modules operate with the injection of minority carriers, while All-SiC modules operate only with majority carriers. Although the turn-off di/dt of the All-SiC module is larger than that of the Si-IGBT module, the turn-off surge voltage is kept almost the same. This is due to the effect of the low internal inductance of the M295 package as described in Chapter 3.

As a result, the All-SiC module is lower than the Si-IGBT module in the turn-off loss E_{off} by 25%, the turn-on loss E_{on} by 72%, and the reverse recovery loss

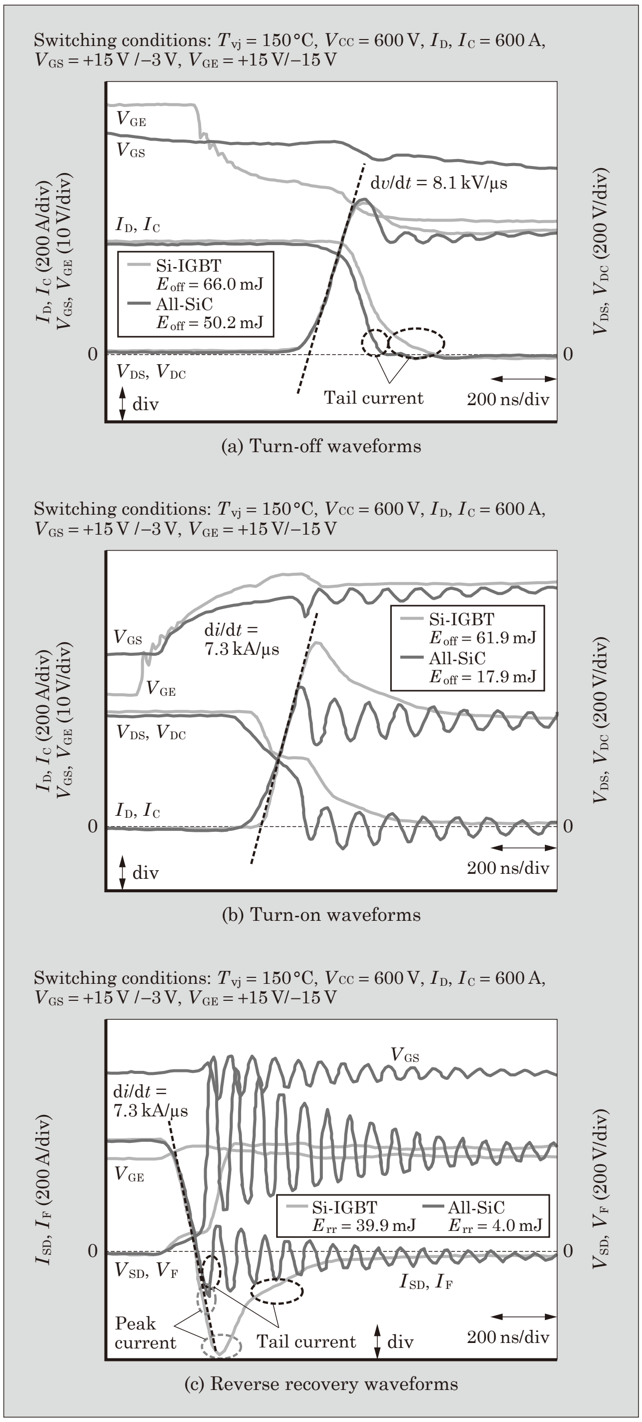


Fig.7 Switching waveforms of the All-SiC module and Si-IGBT module rated at 1,200 V / 600 A

E_{rr} by 90% at the rated current of 600 A as shown in Fig. 8.

Thus, the total switching loss of the All-SiC module is 57% lower than that of the Si-IGBT module when the switching speeds are assumed to be roughly equal.

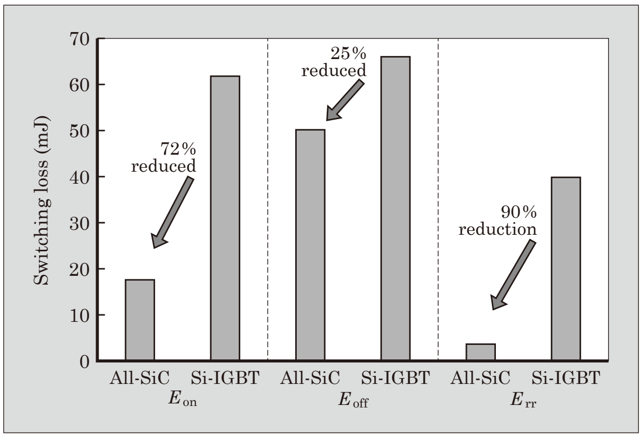


Fig.8 Comparison of the switching loss between All-SiC module and Si-IGBT module rated at 1,200 V / 600 A

5. Inverter Power Dissipation Result

Figure 9 shows the loss simulation results for the power dissipation of 2-level inverter system between the All-SiC and the Si-IGBT module under the condition of the same turn-off dv/dt and turn-on di/dt as described in Chapter 4. If the All-SiC module is installed under the same output current of 200 A, the inverter power dissipation is reduced by 59% at a carrier frequency of 5 kHz due to the significant reduction in switching loss, and the temperature between the junction and case $\Delta T_{vj\text{-}c}$ is reduced by 4 °C. Even at the high carrier frequency condition of 20 kHz, the inverter power dissipation is reduced by 63%, and $\Delta T_{vj\text{-}c}$ is lowered by 14 °C. The power dissipation at 20 kHz, when equipped with the All-SiC module, is almost the same as the loss at 5 kHz equipped with the Si-IGBT module. Thus, the All-SiC module equipped with the 2nd-generation SiC trench-gate MOSFET enables higher density and capacity because of low power dissipation.

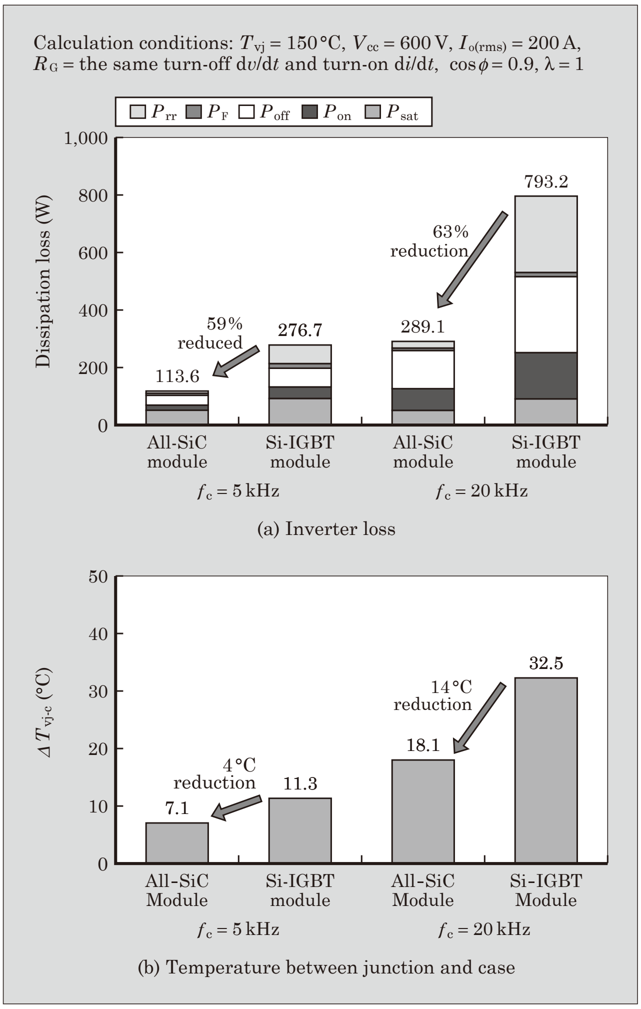
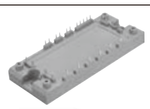
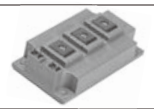


Fig.9 Simulation results of inverter power dissipation

In addition, the inverter operation at higher frequency enables the use of smaller passive components, which can contribute to the miniaturization of power electronics equipment.

Table 1 Planned lineup of the 2nd-generation 1,200-V All-SiC module

Package		Dimensions W × D × H (mm)	Circuit pattern	Rated current							
				50 A	75 A	100 A	150 A	200 A	300 A	450 A	600 A
Small1B		33.8 × 62.8 × 12.0	2 in 1	✓	✓	✓	–	–	–	–	–
			6 in 1	✓	–	–	–	–	–	–	–
Small2B		56.7 × 62.8 × 12.0	2 in 1	–	–	✓	✓	✓	–	–	–
			6 in 1	✓	✓	✓	–	–	–	–	–
Econo PACK™*2		45.0 × 107.5 × 20.5	6 in 1	✓	✓	✓	✓	–	–	–	–
62 mm (M295)		62.0 × 108.0 × 30.5	2 in 1	–	–	–	–	–	✓	✓	✓
			Common source circuit	–	–	–	–	–	✓	–	–

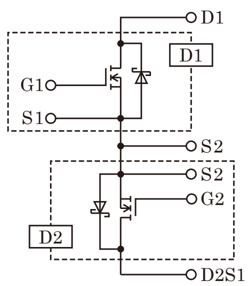
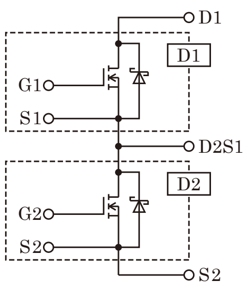
* EconoPACK™: A trademark or registered trademark of Infineon Technologies AG

6. Line-up Expansion of 2nd-Generation 1,200-V All-SiC Modules

Table 1 shows the planned line-up of All-SiC modules equipped with 1200-V rated 2nd-generation MOSFET. Currently, we are developing a series from small-capacity Small 1B, Small 2B, and EconoPACK™2* modules to medium-capacity M295 62-mm modules. These products have a package that is compatible with the outline and terminal layout of the conventional Si-IGBT module.

In recent years, applications in the field of renewable energy have been increasingly using 3-level inverters that utilize a neutral point in the inverter circuit. This is because 3-level inverters achieve better efficiency by suppressing harmonics for the output and reducing power dissipation compared with the 2-level inverters used in many power conversion systems[(6),(7)]. Therefore, in addition to the 2 in 1 module, Fuji Electric is planning to enhance the line-up with the module whose internal circuit is equipped with a common source as shown in Table 2.

Table 2 Internal circuit of the All-SiC module equipped with M295 62-mm package

Type	Common source	2 in 1
Module Internal circuit		

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7. Postscript

In this paper, the series expansion of the 2nd-generation 1,200-V All-SiC module has been described.

Based on the results from the simulation of the inverter power dissipation, a significant reduction in power dissipation loss can be achieved, which will lead to higher power density and smaller and lighter equipment. Fuji Electric will continue contributing to the development of All-SiC technology so that All-SiC modules can be installed in various power electronics equipment and enable them to achieve energy savings.

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