Line-Up Expansion of 2nd-Generation 1,700-V All-SiC Modules

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ABSTRACT

Fuji Electric has developed 1,200-V All-SiC modules, which are expected to significantly reduce dissipation losses of power converters compared with silicon (Si) power semiconductors. We have newly developed an All-SiC module equipped with a 1,700-V SiC-MOSFET using the 2nd-generation trench gate structure. It is designed for high-voltage power converters used in motor drives, renewable energy and traction. The All-SiC modules reduce dissipation losses in the power converters by 68% compared with Si-IGBT modules with the same power ratings. It is expected to increase the density and miniaturization of the power conversion systems.

1. Introduction

To realize a sustainable society, it is vital to pursue carbon neutrality by making energy use more efficient, reducing energy consumption, and expanding photovoltaic (PV), wind, and other forms of renewable energy. To achieve this, the efficiency of power converters, which are essential for the generation and conversion of electricity, and the power semiconductors that are their components needs to be improved. Currently, the characteristics of Si devices, which are the mainstream power semiconductors, are approaching their physical limits, making it difficult to significantly improve their efficiency. Under these circumstances, the application of SiC devices is expanding as a means to further improve the efficiency and energy-saving performance of power conversion systems.

Previously, Fuji Electric has developed All-SiC modules for industrial applications rated at 1,200 V, 300 to 600 A, using the 2nd-generation SiC trench gate metal-oxide-semiconductor field-effect transistor (MOSFET).

On the other hand, power semiconductor modules rated at 1,200 V do not have sufficient blocking voltage for the power converters with a DC bus voltage of 900 to 1,100 V used for 690-V AC motor drives and traction. Moreover, there is a movement in renewable energy applications, such as PV and wind, to increase the DC bus voltage from 1,000 to 1,500 V to improve the efficiency and reduce the costs.(2) Therefore, neutral-point-clamped three-level inverter circuits are often used and power semiconductors with a blocking voltage of 1,700 V are applied.

Fuji Electric has developed a 1,700-V All-SiC module mounted with a 2nd-generation SiC trench gate MOSFET for industrial applications that require a high blocking voltage.(3)

This paper presents the All-SiC modules rated at 1,700 V as a new series of products.

2. Characteristics of the 1,700-V All-SiC Module

2.1 2nd-generation 1,700-V SiC trench gate MOSFETs

Figure 1 shows the circuit configuration and external appearance of the 1,700-V All-SiC module developed in this project. The module has a half-bridge circuit configuration, in which the 2nd-generation 1,700-V SiC trench gate MOSFETs (SiC-MOSFETs) and 1,700-V Schottky barrier diodes (SiC-SBDs) are connected in anti-parallel, and the two pairs are connected in series. The 1,700-V SiC-MOSFET suppresses the increase of on-state resistance and ensures long-term reliability by optimizing the drift layer and the junction field-effect transistor (JFET) width in the 2nd-generation 1,200-V SiC trench-gate MOSFET technology.(3)

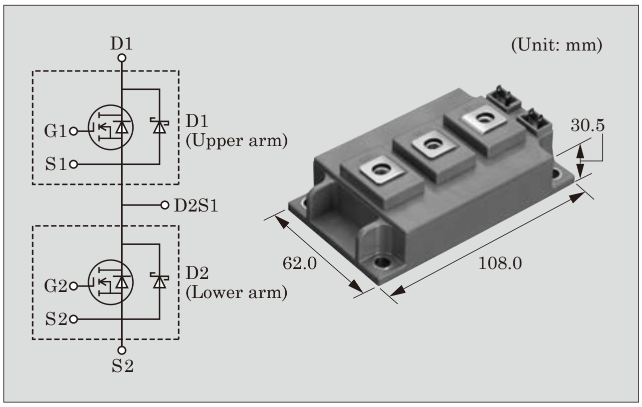

Fig.1 Circuit configuration and external appearance of the 1,700-V All-SiC module

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2.2 New structure "M295" package[4]

SiC-MOSFETs are majority carrier (unipolar) devices, and they are capable of faster switching than Si-insulated gate bipolar transistors (IGBTs), which are minority carrier (bipolar) devices. However, under high-speed switching conditions, it has the disadvantage of causing high surge voltages due to the wiring inductance inside the module. To solve this problem in the new line-up of the All-SiC modules, the wiring inductance has been reduced by 24% by using a laminated bus bar structure for the internal P and N terminals, as shown in Fig. 2. Furthermore, this package makes it easier to replace from Si-IGBTs, as the external dimensions and the terminal layout are compatible with a 2-in-1 package "M276" of the 7th-generation "X Series" IGBT.

2.3 Output characteristics

Figure 3 shows a comparison of the output characteristics of the All-SiC module using 2nd-generation SiC trench gate MOSFETs and the conventional 7th-generation X-Series Si-IGBT module rated at 1,700 V/300 A. The All-SiC modules are composed of MOSFETs, which are unipolar devices, and therefore do not have the built-in voltage found in IGBTs, which are bipolar devices. The on-state voltage V_{DS} of the All-SiC module is lower than the on-state voltage V_{CE} of the Si-IGBT module, and the V_{DS} is 0.4 V at I_D = 150 A.

In general, the RMS current of a power conversion system is often designed to be 30% to 50% of the rated

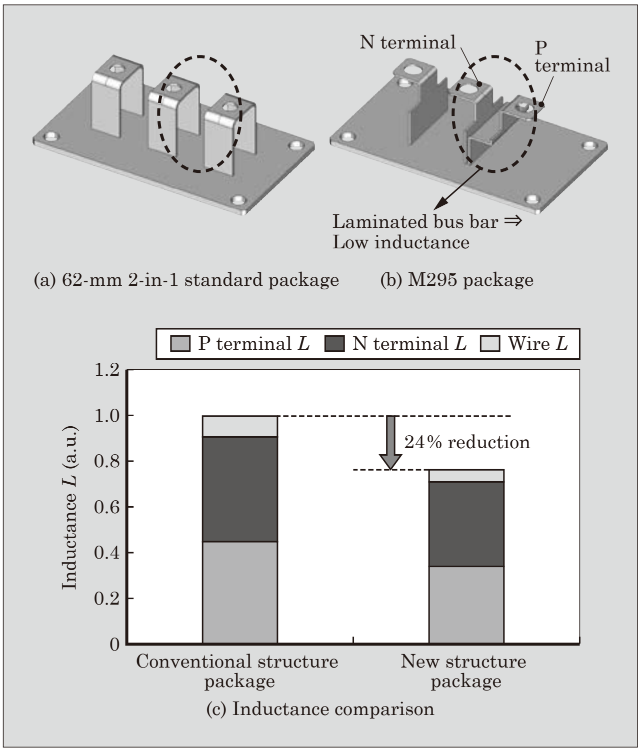

Fig.2 Internal package structure

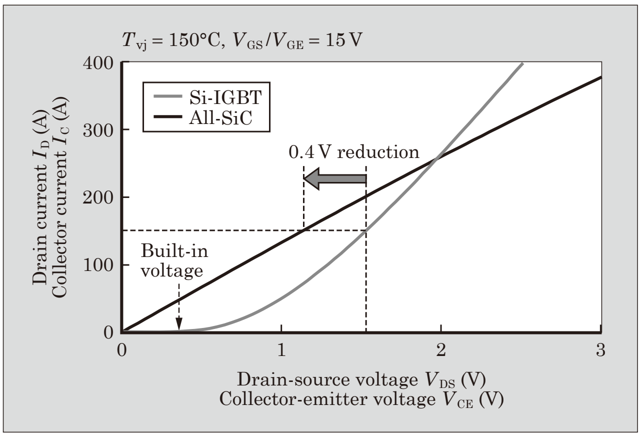

Fig.3 Comparison of output characteristics

current of the power semiconductor module. Therefore, in the case of I_D = 150 A, the conduction loss of the All-SiC module can be reduced by 33% in comparison with the Si-IGBT modules with same rated current.

2.4 Switching characteristics

To clarify the difference in the switching loss characteristics between the All-SiC module and the conventional Si-IGBT module, the switching waveforms were compared at the same turn-off dv/dt and turn-on di/dt conditions. Table 1 shows the gate resistance R_G values for the turn-off dv/dt and the turn-on di/dt.

Figures 4(a), 4(b), and 4(c) show the comparisons of switching waveforms of the All-SiC and the Si-IGBT modules at a rated current of 300 A under the conditions listed in Table 1.

The All-SiC module has a significantly reduced tail current during turn-off and reverse recovery compared with the Si-IGBT module [see Figs. 4(a) and (c)]. The peak currents during turn-on and reverse recovery are also significantly reduced [see Figs. 4(b) and (c)]. In the case of the Si-IGBT module, which is a bipolar device, the excess carriers caused by a minority carrier injection affect the switching operation, whereas in the case of the All-SiC module, which is a unipolar device, the operation is with majority carriers only.

In addition, as shown in Fig. 4(a), the turn-off surge voltage of the All-SiC module is kept at a low level even though the di/dt value of the All-SiC module is larger than that of the Si-IGBT module. This is due to the effect of the reduced internal inductance of the new package developed for the All-SiC as described in Section 2.2.

Table 2 shows a comparison of turn-off loss E_{off},

Table 1 Turn-off dv/dt and turn-on di/dt

Switching condition T_{vj} = 175°C	Turn-off		Turn-on	
	R_G (Off)	dv/dt	R_G (On)	di/dt
Si-IGBT	0.39 Ω	4.19 V/ns	0.39 Ω	3.28 A/ns
All-SiC	27 Ω	4.15 V/ns	3 Ω	3.48 A/ns

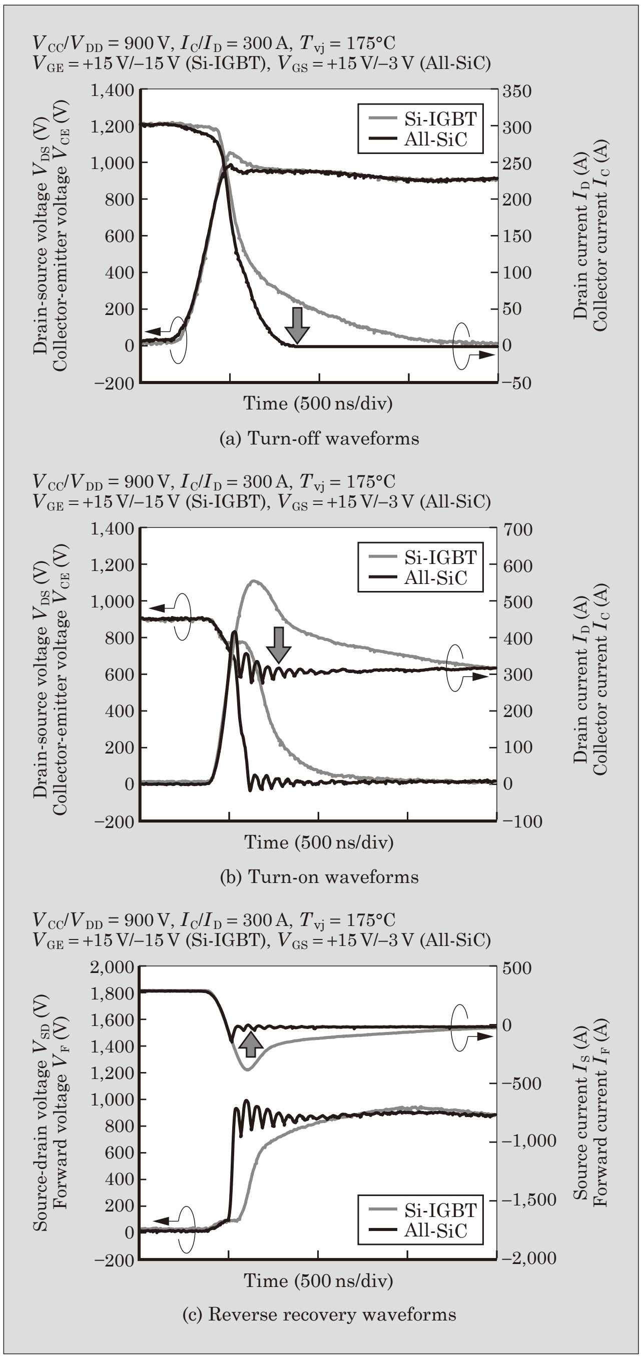

Fig.4 Switching waveform comparison between All-SiC and Si-IGBT modules

Table 2 Switching loss comparison

Switching condition T_{vj} = 175°C	Turn-off loss E_{off}	Turn-on loss E_{on}	Reverse recovery loss E_{rr}	Total
Si-IGBT	96.0 mJ	109.1 mJ	98.4 mJ	303.5 mJ
All-SiC	61.1 mJ	24.6 mJ	0.98 mJ	86.7 mJ
Reduction	36%	77%	99%	71%

turn-on loss E_{on} and reverse recovery loss E_{rr} of the All-SiC module and the Si-IGBT module. The E_{off}, E_{on} and E_{rr} of the All-SiC module are reduced by 36%, 77% and 99%, respectively, compared with those of the Si-IGBT module.

As a result, total switching loss of the All-SiC module is reduced by 71% compared with the Si-IGBT module under the same switching speed condition.

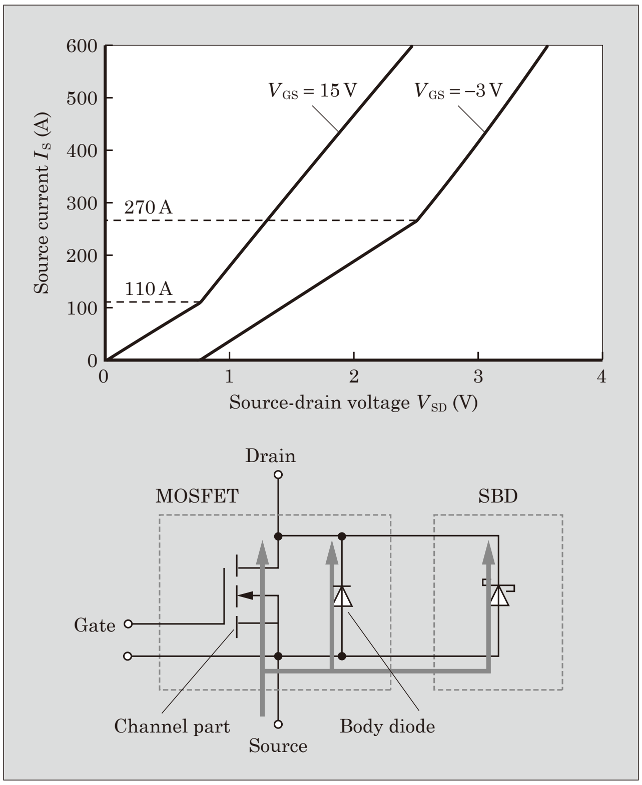

Fig.5 Source current output characteristics

2.5 Reverse output characteristics

Current (source current I_S) flows to the SiC-MOSFET in the opposite direction to that of the drain current when an inductive load current is turned off. Figure 5 shows the output characteristics under these conditions. Because the newly developed All-SiC module has SiC-SBDs connected in anti-parallel configuration to the SiC-MOSFET, the output characteristic has an inflection point because it is a combination of the characteristics of the SiC-MOSEFT's body diode (BD) and the SiC-SBD.(5) In the case where the gate-source voltage V_{GS} is −3 V, the current flows through the SiC-SBD only when the I_S is below the inflection point of 270 A. The current is split between the BD and SBD of the MOSFET when the current exceeds 270 A. Meanwhile, the V_{GS} is 15 V, the current flows the MOSFET's channel only when I_S is at or below the inflection point of 110 A, and the current flow splits to the MOSFET and SBD when the current exceeds 110 A.

3. Simulation Result of Dissipation Losses for Power Converters

We simulated the dissipation losses of the All-SiC module applied to the neutral point clamped (NPC)

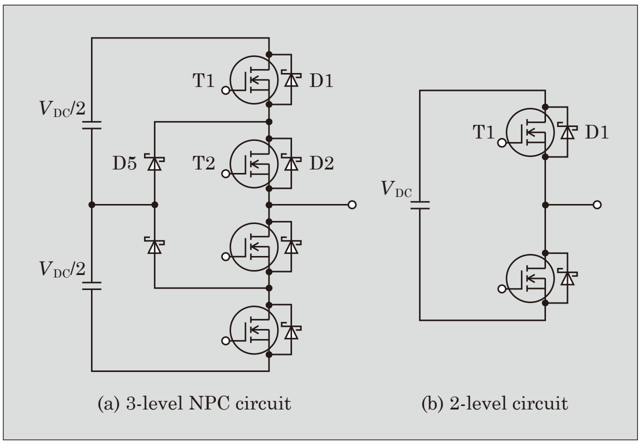

Fig.6 3-level and 2-level inverter circuits

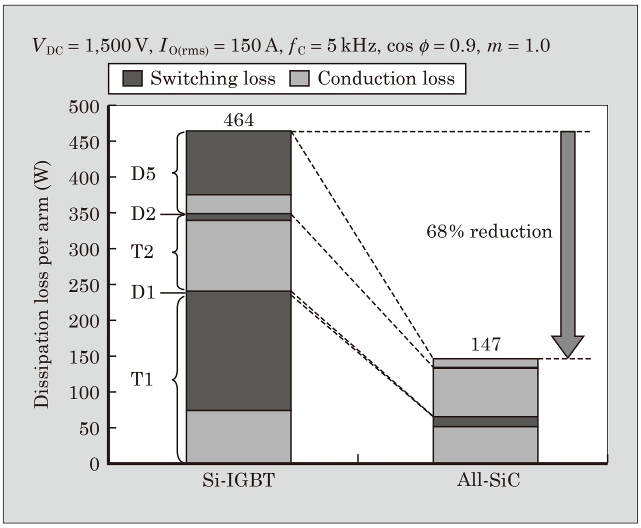

Fig.7 Loss comparison with a 1,500-V DC 3-level inverter circuit

circuit as shown in Fig. 6(a) in power converters with a DC bus voltage of 1,500 V and an output current of 150 A, as seen in PV and wind power generation. Figure 7 shows a comparison of the losses of the 1,700-V/300-A All-SiC module and the same rated Si-IGBT module. The All-SiC module has a 68% lower total inverter loss due to the significant reduction in switching losses at T1 and D5. This suggests that the size of the heatsink required for cooling can be reduced to approximately one-third, resulting in a significant reduction in the size of the inverter and higher efficiency.

Figure 8 compares the losses of a 3-level circuit and a 2-level circuit in power converters with a DC bus voltage of 1,100 V. For the Si-IGBT module, the following two cases were compared: a 1,200-V module in a 3-level NPC circuit shown in Fig. 6(a) and a 1,700-V module in a 2-level circuit shown in Fig. 6(b). By changing the configuration from the 3-level circuit with the 1200-V Si-IGBT to the 2-level circuit with the 1,700-V Si-IGBT, the number of semiconductor devices is reduced but the total loss is increased because of the

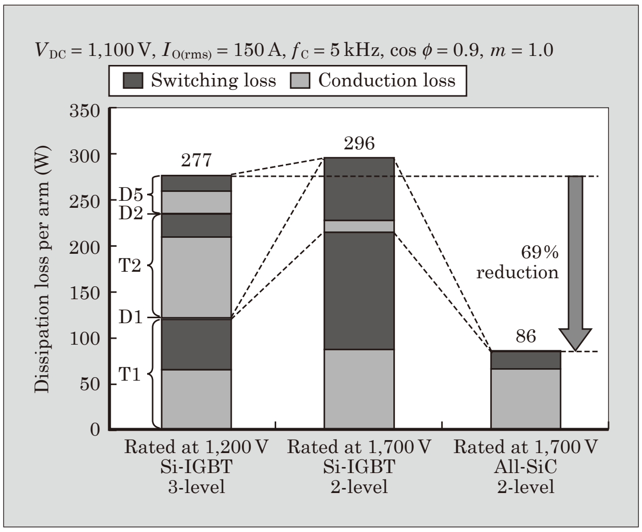

Fig.8 Loss comparison with 3-level and 2-level circuits

Table 3 “M295” package All-SiC module line-up

MOSFET generation	Package	Circuit	Rated voltage	Rated current
2nd generation trench gate	M295 	2 in 1	1,200 V	300 A
				450 A
				650 A
			1,700 V	200 A
				300 A
				400 A

large switching losses. On the other hand, the 2-level circuit with the 1,700-V All-SiC module significantly reduces the switching loss and consequently reduces the total loss by 69% compared with the 3-level circuit. This result shows that the 1,700-V All-SiC module can not only achieve higher efficiency but also can simplify a power conversion system with a DC bus voltage of 1,100 V by reducing the number of required power semiconductor devices and drive circuits, from 10 to 4 and from 4 to 2, respectively.

4. All-SiC Module Line-Up

Table 3 shows the product line-up of the M295 package All-SiC modules. The new 1,700-V rated products with rated currents from 200 to 400 A use the same M295 package as the existing 1,200-V rated products. The M295 package is compatible with the 7th-generation X-Series IGBT modules and it can be applied to various types of power converters.

5. Postscript

This paper has described the newly developed All-SiC modules with a rated voltage of 1,700 V. These new products are expected to enable higher efficiency, higher power density and smaller size of power conversion systems for the markets that have grown significantly in recent years such as renewable energy and traction.

We will develop other All-SiC modules with different ratings and packages in order to meet varied market demands and contribute to the creation of a sustainable society.

References

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