2nd-Generation SiC Trench Gate MOSFETs

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ABSTRACT

Fuji Electric is offering various types of power electronics equipment for the market in order to contribute to the realization of a low-carbon society. To achieve further energy savings, we have developed the 2nd-generation SiC trench gate MOSFETs. As a result, on-resistance has been reduced by 23% compared with the 1st-generation SiC trench gate MOSFETs through the application of smaller design rules for the devices, a thinner SiC substrate and higher channel mobility. Furthermore, usability has improved because recommended gate drive voltage changed to 15 V. We have also confirmed that there were no gate threshold voltage fluctuation due to gate bias and no characteristic degradation (increase in on-resistance) due to body diode conduction, both of which cause reliability issues for SiC-MOSFETs.

1. Introduction

Fuji Electric is offering various types of power electronics equipment for the market in order to contribute to the creation of a low-carbon society. Currently, environmental regulations are being strengthened worldwide. As a result, the demand for power semiconductors is growing and is expected to grow further in the future. Silicon (Si) has been conventionally used as a power semiconductor material, but expectations for silicon carbide (SiC) have been increasing year by year due to its excellent properties. Since SiC has a large band gap and blocking capability approximately 10 times higher than that of Si, it has the advantage of being able to significantly reduce loss in applications where a blocking voltage of 600 V or higher is required.

Fuji Electric has been mass producing SiC based Schottky barrier diodes (SBDs), planar-gate metal-oxide-semiconductor field-effect transistors (MOSFETs) and trench-gate MOSFETs. They are used in solar power conditioning systems (PCSs) and inverters in industrial use[(1)-(5)].

Moreover, we have also been mass producing 1st-generation SiC trench-gate MOSFETs. Recently, we have developed 2nd-generation SiC trench-gate MOSFETs capable of further contributing to energy savings in power electronics equipment. Compared with planar-gate MOSFETs, trench-gate MOSFETs reduce junction field effect transistor (JFET) resistance and increase cell density. This significantly reduces device resistance. Furthermore, its ability to increase the channel concentration makes it possible to achieve a high threshold value and low on-resistance.

In this paper, we describe our characteristic-enhanced 2nd-generation SiC trench-gate MOSFETs.

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2. Structure of the 2nd-Generation SiC Trench-Gate MOSFETs

Figure 1 shows the structure of a 1,200-V 1st- and 2nd-generation SiC trench-gate MOSFETs. The 1st-generation SiC trench-gate MOSFETs adopt a structure that covers the gate oxidation film at the bottom of the trench with a p-well in order to reduce the high electric field applied to the gate oxide film at the bottom of the trench[(6)]. The structure of the 2nd-generation has remained unchanged and the cell pitch is refined to approximately two-thirds through process optimization. In order to reduce board resistance, the thickness of the SiC substrate is reduced to approximately one-fourth by grinding the back surface. In addition, in order to reduce channel resistance, the interface of the gate oxidation film has been improved and channel mobility has been increased by 20%. As a result, on-resistance per unit area is reduced by ap-

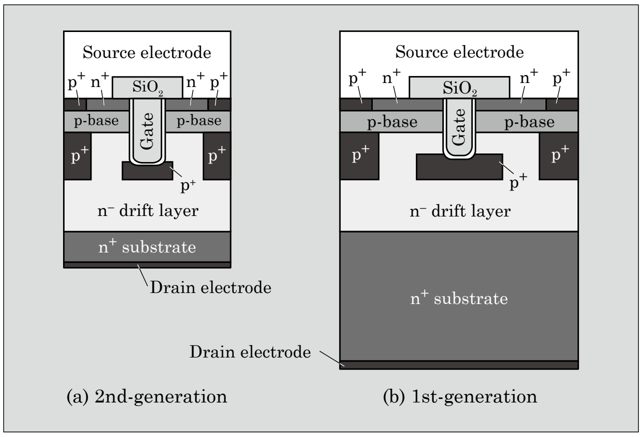

Fig.1 Structure of 1st-generation and 2nd-generation SiC trench-gate MOSFETs

Table 1 Characteristics of 1st-generation and 2nd-generation trench-gate MOSFETs

Item	2nd-generation	1st-generation
On-resistance (assuming 1st-generation is 1)	0.77	1.00
Gate threshold voltage	5.0 V	5.1 V
Gate recommended drive voltage	+15 V/−3 V	+20 V/−3 V
Gate absolute maximum rated voltage	+20 V/−7 V	+25 V/−7 V

proximately 23% while maintaining the gate threshold voltage at 5 V, as shown in Table 1. The device structure is also optimized so that the gate recommended drive voltage could attain +15 V in order to simplify replacement with the Si-IGBT (insulated gate bipolar transistor).

3. Characteristics of the 2nd-Generation SiC Trench-Gate MOSFETs

3.1 Current-voltage characteristics of 2nd-generation SiC trench-gate MOSFETs

Figure 2 shows a comparison of the forward characteristics of the drain current I_D-drain voltage V_{DS} during conduction of 1,200-V 1st- and 2ng-generation SiC trench gate MOSFETs. The applied gate voltage V_{GS} is the recommended drive voltage of each device. Even though V_{GS} = 15 V, it can be seen that the on-resistance of the 2nd-generation SiC trench-gate MOSFETs is lower.

Figure 3 shows a comparison of the characteristics of the third quadrant during reverse conduction. When the trench gate MOSFET is turned ON and current flows from the source to the drain, the JFET resistance is suppressed and the resistance falls below the forward characteristic because the PN junction is positively biased. Similar to the forward characteristic, it can be seen that the on-resistance of the 2nd-generation SiC trench-gate MOSFET is lower.

Figure 4 shows the comparison results of the char-

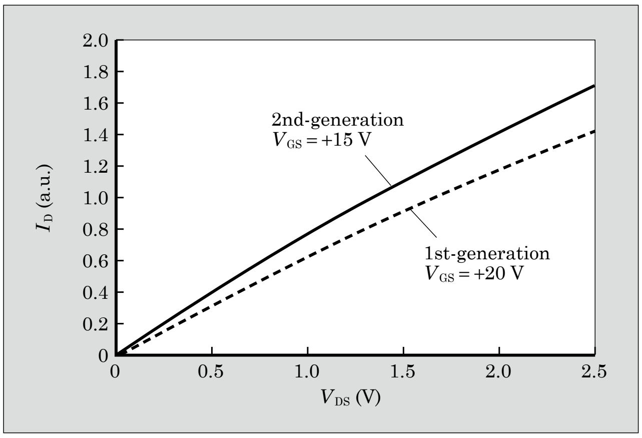

Fig.2 1st-generation and 2nd-generation SiC trench-gate MOSFET I_D-V_{DS} characteristic (first quadrant)

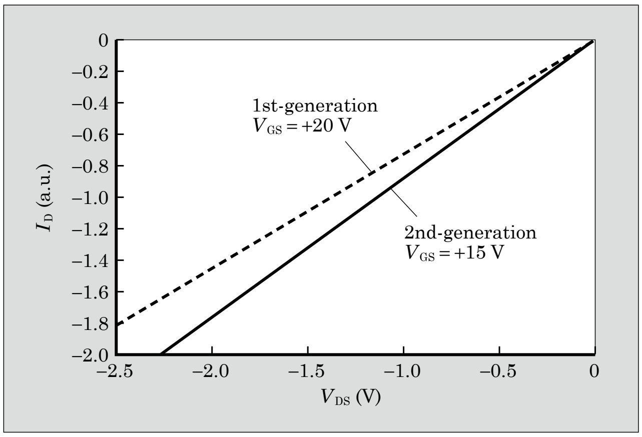

Fig.3 1st-generation and 2nd-generation SiC trench-gate MOSFET I_D-V_{DS} characteristic (third quadrant)

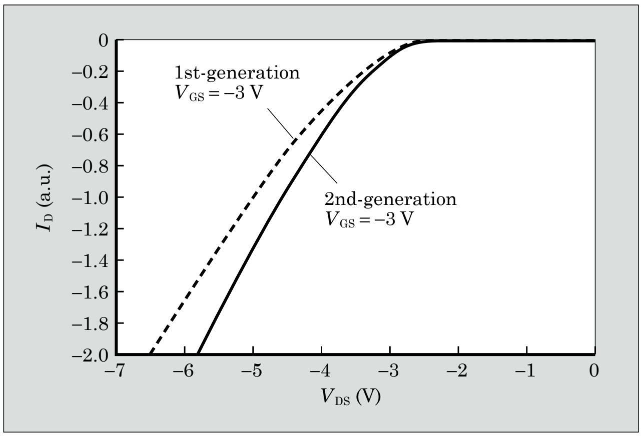

Fig.4 1st-generation and 2nd-generation SiC trench-gate MOSFET body diode I_D-V_{DS} characteristic (third quadrant)

acteristics of the body diode of the MOSFET when the gate is OFF. Current begins to flow when the source-drain voltage reached approximately 2.5 V or higher for both the 1st- and 2nd-generation products due to the built-in potential of SiC. The differential resistance of the body diode after the current starts to flow is lower for the 2nd-generation SiC trench-gate MOSFET due to the effect of thinning the SiC substrate.

These results show that the resistance of the 2nd-generation SiC trench-gate MOSFET is lower in both the forward and reverse directions. It can be said that it is a device capable of reducing conduction loss during actual use. With regard to third quadrant characteristics, since the built-in potential of the body diode is higher than Si, turning the gate ON can lower loss even more when current flows from the MOSFET source to the drain during commutation.

3.2 Temperature characteristics of the 2nd-generation SiC trench-gate MOSFETs

Figure 5 shows the temperature dependence of the threshold voltage and on-resistance. The threshold voltage decreases by approximately 8.6 mV/K as the temperature increases in the range of −50 °C to +200 °C. The on-resistance is almost unchanged between −50 °C and −25 °C. It increases in the range of −25 °C to +200 °C and approximately doubles at 175 °C compared with 25 °C. The on-resistance of the 2nd-generation SiC trench-gate MOSFETs shows a positive temperature coefficient. This means that current imbalance can be effectively suppressed when multiple chips are connected in parallel. It is difficult to increase chip size for the SiC. Therefore, multiple small chips are often connected in parallel in the module to secure the required current for the module. In such a case, thermal runaway rarely happens because the positive temperature coefficient contributes to increased temperature and resistance, and thus suppresses current even when current concentrates in a specific chip.

Figure 6 shows the blocking voltage characteristic between the drain and source when it is OFF. The blocking voltage is 1,600 V at 25 °C and 1,670 V at 175 °C. This secures a sufficiently high blocking voltage for devices rated at 1,200 V. Moreover, similar to 1st-generation SiC trench-gate MOSFETs, blocking voltage increases as temperature rises.

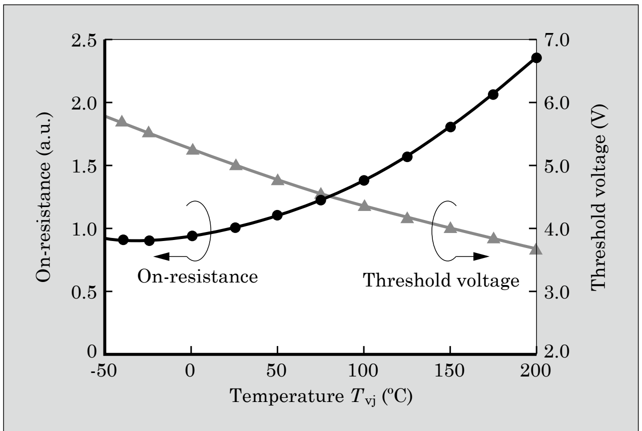

Fig.5 Temperature dependence of on-resistance and threshold voltage of 2nd-generation SiC trench-gate MOSFETs

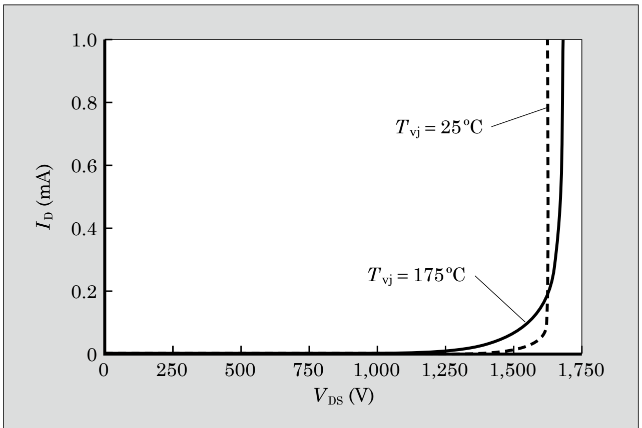

Fig.6 I_D-V_{DS} characteristic during 2nd-generation SiC trench-gate MOSFET off-state

3.3 Switching characteristics of the 2nd-generation SiC trench-gate MOSFETs

Figure 7 shows the switching test circuit. Figures 8 and 9 show switching loss of 1st- and 2nd-generation SiC trench-gate MOSFETs at turn-on and turn-off. di/dt, dv/dt change by changing the gate resistance.

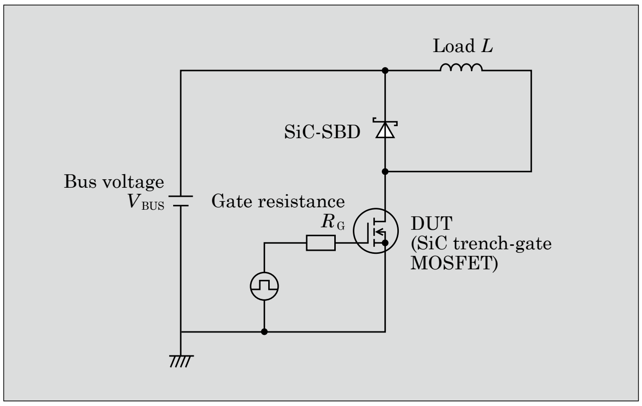

Fig.7 Switching evaluation circuit

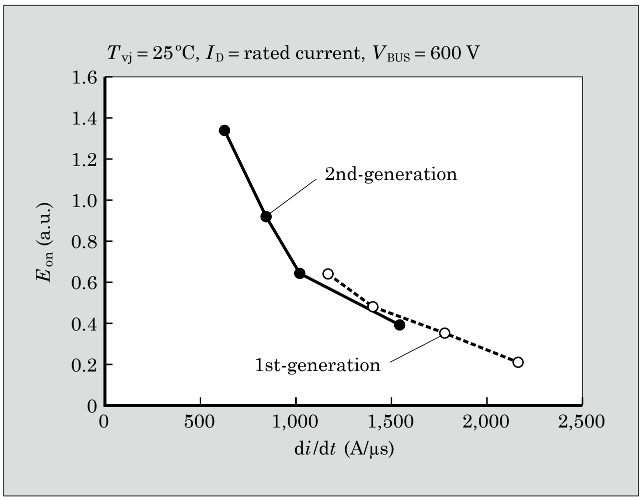

Fig.8 Comparison of turn-on loss

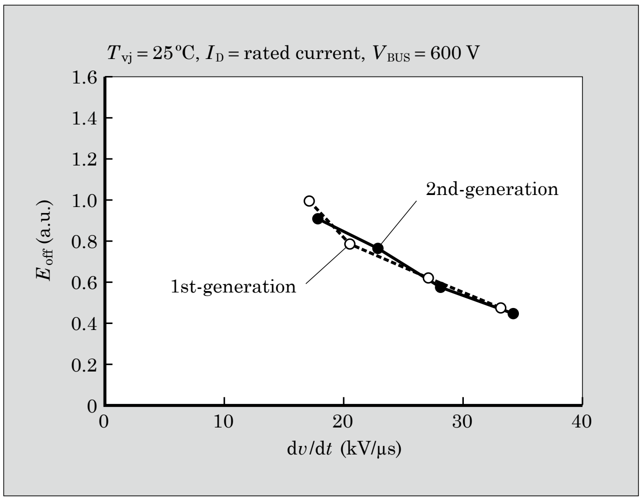

Fig.9 Comparison of turn-off loss

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The gate drive voltages are V_{GS} = +20 V/−3 V for the 1st-generation product and V_{GS} = +15 V/−3 V for the 2nd ones, which are respective recommended ones. Switching loss is the same for both turn-on and turn-off at the same di/dt and dv/dt. These characteristics show that there is no significant differences.

3.4 Reliability of the 2nd-generation SiC trench-gate MOSFETs

We will now describe the reliability of the 2nd-generation SiC trench-gate MOSFETs. Since conventional SiC-MOSFETs have a high interface state density with respect to the gate oxide film, a problem arises in that gate threshold voltage will fluctuate when voltage is applied to the gate. Figures 10 and 11 show the results of a high-temperature gate positive and negative bias test for 2nd-generation SiC trench-gate MOSFETs. We discovered that the 2nd-generation SiC trench-gate MOSFETs display very little fluctuation in the threshold voltage of the gate, regardless of positive-negative bias. This enables it to have stable characteristics.

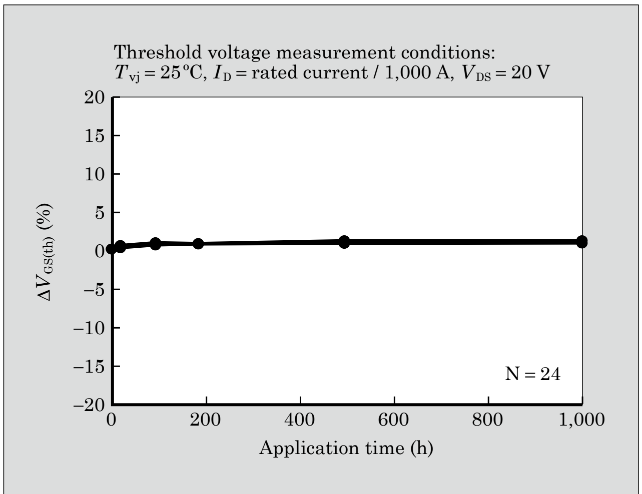

Fig.10 Fluctuation rate of threshold voltage after high-temperature gate positive bias test (Application conditions: T_{Vj} = 175 °C, V_{GS} = 20 V)

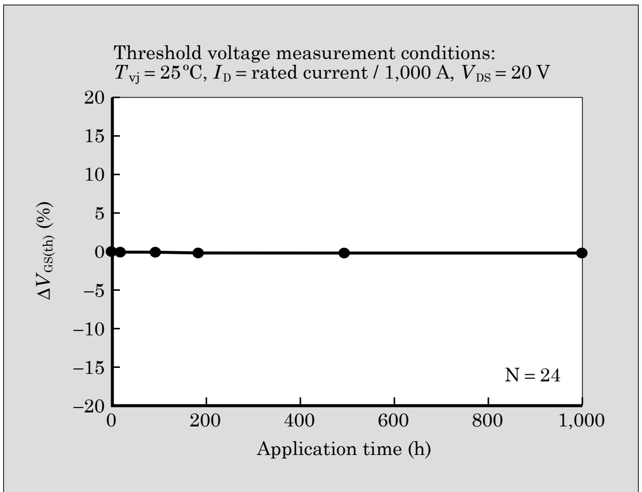

Fig.11 Fluctuation rate of threshold voltage after high-temperature gate negative bias test (Application conditions: T_{Vj} = 175 °C, V_{GS} = −7 V)

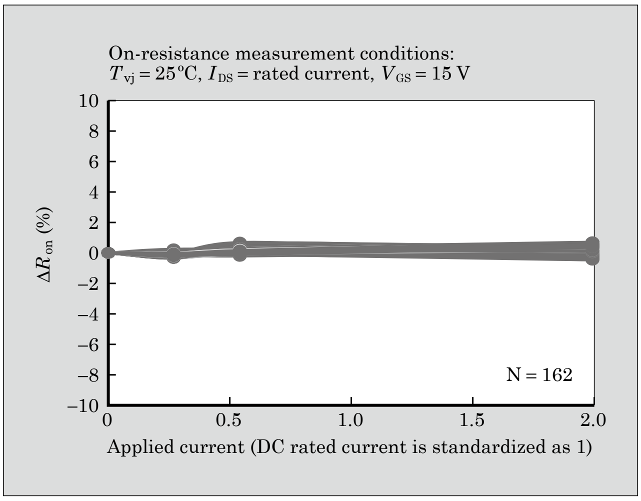

Fig.12 Fluctuation rate of on-resistance after body diode conduction test (Application conditions: T_{Vj} = 175 °C, V_{GS} = −3 V, Time = 10 min)

One of the challenges facing SiC-MOSFET reliability has been that on-resistance increases when current flows to the body diode of the SiC-MOSFET. When current flows through the body diode, stacking faults expand from the basal plane dislocation existing in the SiC substrate. This impedes the current pathways of the device and increases on-resistance. 2nd-generation SiC trench-gate MOSFETs use proprietary technology in the SiC substrate and processes in order to prevent increase in on-resistance due to current flowing to the body diode. Figure 12 shows the results of investigating the rate of increase in on-resistance when the current flowing to the body diode is gradually increased. At each current, T_{vj} = 175 °C was applied for 10 minutes. The results of N = 162 investigations showed that on-resistance did not increase even when a current twice the value of the rated DC current was applied.

4. Postscript

In this paper, we described our 2nd-generation SiC trench-gate MOSFETs. By applying smaller design rules, thinning the SiC substrate and improving mobility, we have decreased on-resistance by 23% compared with the 1st-generation SiC trench-gate MOSFETs. We confirmed that there was no fluctuation in gate threshold voltage due to gate bias and that on-resistance did not increase when applying current to the body diode. In FY 2019, we plan to develop 2nd-generation SiC trench-gate MOSFETs with ratings of 650 V and 1,700 V.

This research was carried out as part of a project of the joint research body "Tsukuba Power-Electronics Constellation (TPEC)." We would like to conclude by expressing our appreciation to all those involved in the project.

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