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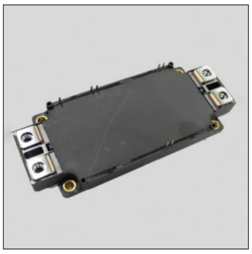

Full SiC Power Module with 4H-SiC V-groove Trench MOSFETs

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In recent years, the importance of improving the efficiency of power devices used for electric power control has been increasing. Silicon carbide (SiC) is a wide bandgap semiconductor with superior material properties such as high breakdown electric field and high thermal conductivity. Commercialization of SiC MOSFET (metal-oxide-semiconductor field effect transistor) has already begun, and the market size is expected to expand further in the future although Silicon (Si) is mainly used for power devices currently. We have been developing a low on-resistance "V-groove" trench MOSFET (VMOSFET), which uses the patented crystal face as the channel region. In addition to the transistor technology, we have been developing the full SiC modules with the VMOSFET. This report introduces the feature, the electrical characteristics, and the reliability test results of the full SiC power module (1200 V 400 A). The module package has compatibility with Silicon (Si) power module package and is designed for easy replacement for existing users of Si power modules.

Keywords: SiC power module, trench MOSFET, low loss, reliability test

1. Introduction

Since the Sustainable Development Goals (SDGs) were adopted by the United Nations, attention to energy conservation and reduction of CO_2 emissions has increased further. In the fields of industrial equipment, natural energy power generation, and electric vehicles, there is a social need for technology that can efficiently control electric power. Power control technology is called power electronics. Semiconductor devices for power control (hereafter, power devices) are important in configuring power electronics systems, and their characteristics are directly linked to system performance.

Power devices are required to have high voltage, high current capacity, and high speed switching in order to save energy and reduce the size of equipment. Silicon (hereafter, Si) is currently used as a material for power devices, and insulated gate bipolar transistors (hereafter, IGBTs) are widely used, especially for high voltage applications. However, Si IGBT technology reaches the theoretical limit estimated from their physical properties.(1) In such a situation, silicon carbide (hereafter, SiC) and gallium nitride (hereafter, GaN), which are wide bandgap semiconductors, are attracting attention as new semiconductor materials to replace Si. SiC is superior to Si in terms of physical properties such as breakdown electric field, electron saturation velocity, and thermal conductivity, and it can utilize many Si processes and facilitate the manufacture of vertical power devices. Because of such advantages, SiC is expected to be used in a high voltage range of 600 V or more. In particular, SiC MOSFETs (metal oxide semiconductor field effect transistors) are being actively developed because they can achieve both low on-resistance and high-speed operation compared to Si-IGBTs, and are superior in terms of low power consumption.

At Sumitomo Electric Industries Ltd., we have developed our own SiC technology to commercialize SiC power devices. In 2017, we launched "EpiEra", an epitaxial substrate for SiC power devices, which has achieved high uniformity in doping concentration and thickness, and low defect density in a 6 inches wafer.(2) We are currently developing a SiC V-groove trench MOSFET (VMOSFET) having a V-groove gate structure. In this VMOSFET, a patented crystal face that is advantageous in reducing channel resistance is used in the channel region.(3)–(5) In addition to the above SiC activities, we have recently developed a SiC power module rated at 1,200 V and 400A by connecting VMOSFET chips in parallel to increase the current capacity.

A feature of the power module is that it is compatible in shape with Si IGBT modules on the market, making it easy for existing Si IGBT module users to replace them. Additionally, the module takes advantage of VMOSFET performance to achieve both low resistance and fast switching speed. Since we have confirmed that the module achieved the reliability requirements of each standard, the details of the module are reported below.(6)

2. Advantage of VMOSFET

One of the features of VMOSFET (Fig. 1) is the use of the {0-33-8} face on the trench sidewall, which is the channel region. This crystal face has higher electron channel mobility than other crystal faces,(7)–(9) and it is advantageous in terms of channel resistance reduction.

It is known that the trench structure is advantageous in reducing the on-resistance, but it tends to apply a high electric field to the gate oxide at the trench bottom. In order to improve the gate oxide reliability (reduction of an electric field in gate oxide), the buried p-region is introduced in the n-type drift layer.(3)–(5) Further, by electrically connecting the buried p-region and the source electrode, the parasitic capacitance between the gate and the drain electrodes, which affects the switching speed performance, was reduced.(4)

As described above, the VMOSFET is a SiC MOSFET that can achieve both low on-resistance and high-speed operation, and can reduce both conduction loss and switching loss.

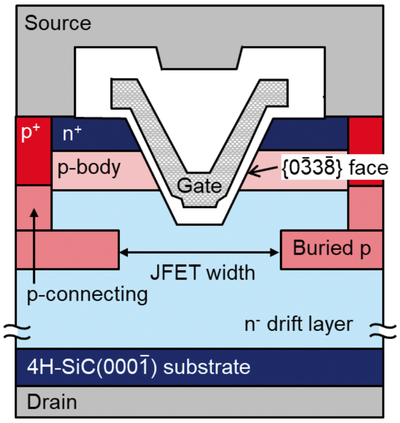

Fig. 1. Cross-Section of VMOSFET(5)

3. Design and Features of VMOSFET Module

The developed VMOSFET module (Photo 1) is compatible in shape with Si IGBT modules on the market and measures 152 mm × 62 mm × 17 mm. As shown in Photo 2, the module can be controlled by attaching a commercially available gate driver. Since gate drivers can be attached in the same way as that for Si IGBT modules, it is easy for conventional Si IGBT users to replace their modules with VMOSFET modules.

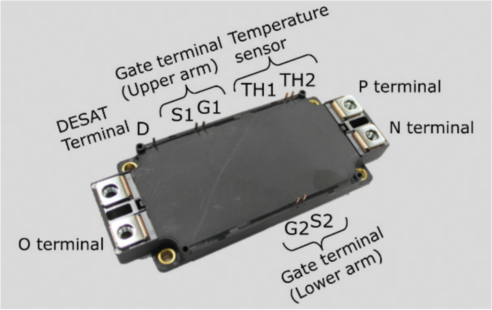

Photo 1. VMOSFET module

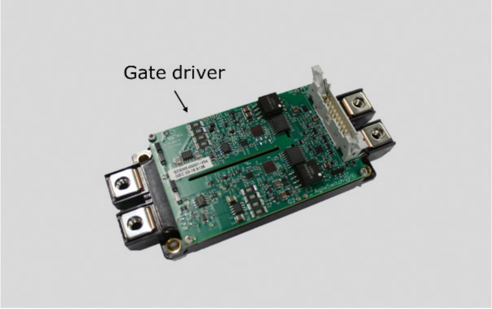

Photo 2. Example of attaching a commercially available gate driver to a VMOSFET module

In this module, Sumitomo Electric's SiC Schottky Barrier Diodes (hereafter, SBD) is connected in parallel to the VMOSFET in order to pass current during commutation. The circuit diagram is shown in Fig. 2. It is a 2 in 1 module with two series pairs of parallel connections of VMOSFETs and SBDs. A thermistor for measuring the temperature is also built in.

Figure 3 shows the cross-sectional image of the module. A Direct Bonded Copper (hereafter, DBC) substrate is soldered to the base plate, and the circuit pattern is formed on the upper surface of the DBC substrate. VMOSFETs and SBDs are soldered onto the circuit pattern. The external terminals are electrically connected to the VMOSFETs and SBDs with aluminum wires. The module is encapsulated by silicone gel. With regard to the solder material, lead-free solder is used in consideration of the environment.

The maximum thermal resistance between the junction and the case is 0.1 K/W for $R_{th(J-C)MOS}$ and 0.07 K/W for $R_{th(J-C)SBD}$. Figure 4 shows the transient thermal resistance of $R_{th(J-C)MOS}$.

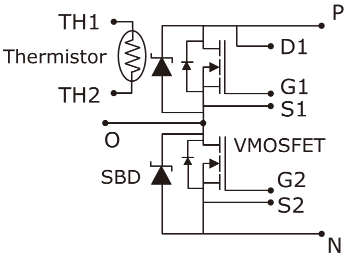

Fig. 2. Internal circuit of module

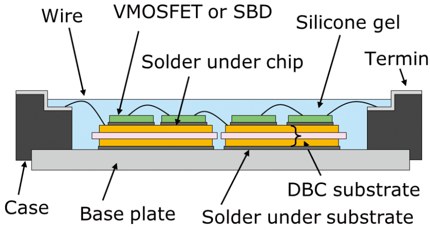

Fig. 3. Cross-sectional image of module

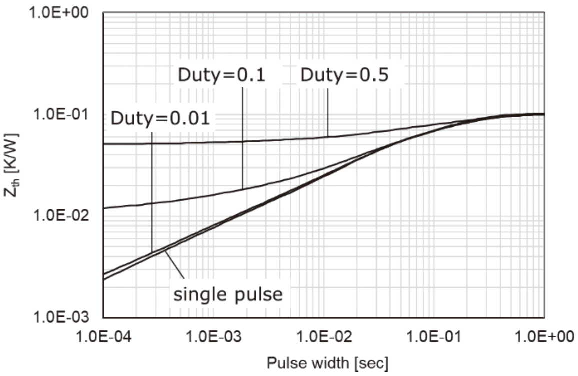

Fig. 4. Transient thermal resistance of module

4. Electrical Characteristics of VMOSFET Module

Figure 5 shows the I_D - V_{DS} characteristics of the VMOSFET module. The on-resistance at room temperature was 4.0 mΩ (V_{GS} = 15 V, I_D = 400 A). Furthermore, the on-resistance is 3.8 mΩ at V_{GS} = 18 V, indicating that the dependence of the on-resistance on the gate voltage is small. This is a feature of VMOSFET with sufficiently low channel resistance. Figure 6 shows the temperature dependence of on-resistance. In the VMOSFETs with small channel resistance, the resistance of the n-type drift layer becomes dominant, and the on-resistance is positively correlated over a wide temperature range.

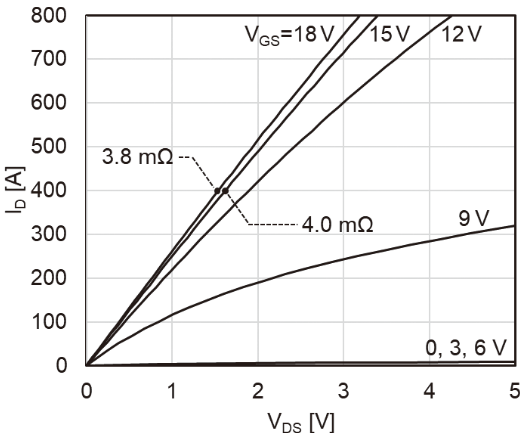

Fig. 5. I_D – V_{DS} characteristics (room temperature)

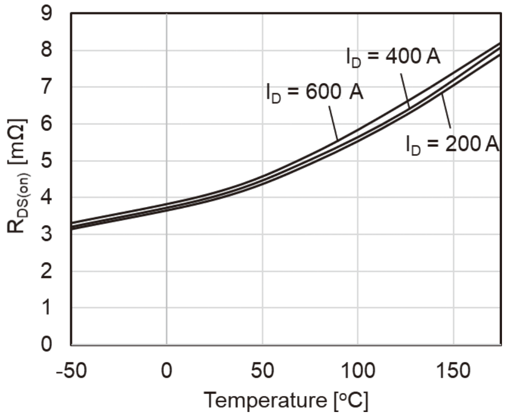

Fig. 6. Temperature dependence of on-resistance

As an evaluation of the switching characteristics, the results of the switching evaluation with the inductive load circuit (Fig. 7) are shown. The switching conditions are V_{DD} = 600 V, I_D = 400 A, R_g = 4.7 Ω, L = 100 μH, and V_{GS} = +15 V/-5 V. The turn-on and turn-off waveforms are shown in Figs. 8 and 9, respectively. The turn-on and turn-off losses were suppressed to very small values of 6.5 mJ and 9.9 mJ, respectively. Figure 10 shows the dependence of switching loss on the gate resistance at room

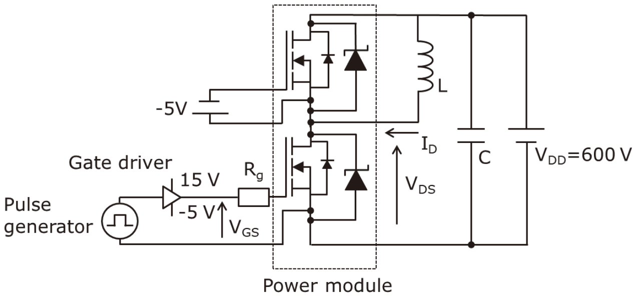

Fig. 7. Inductive load switching circuit

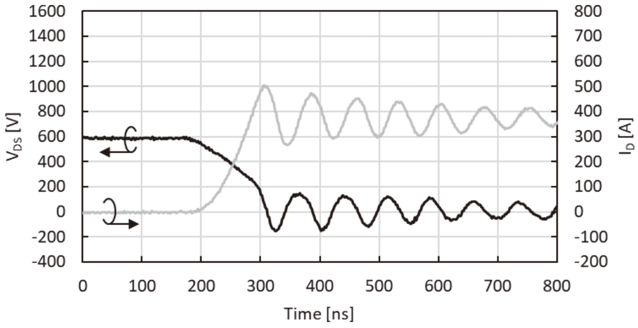

Fig. 8. Turn-on switching waveform

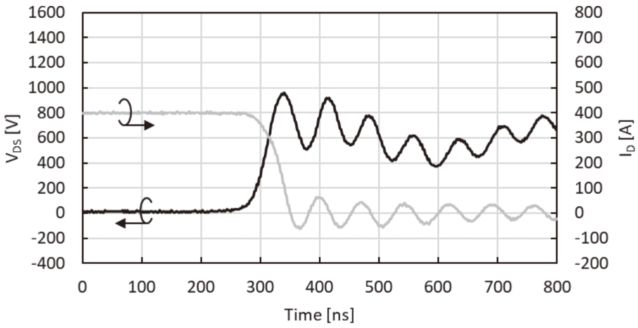

Fig. 9. Turn-off switching waveform

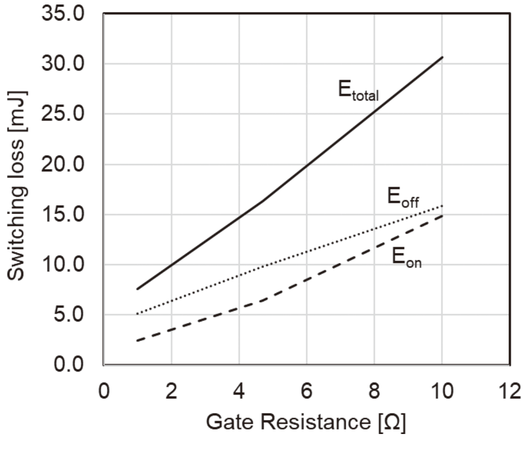

Fig. 10. Dependence of switching loss on gate resistance (room temperature)

temperature. It shows the positive correlation with the gate resistance, and the very low switching loss is achieved when the gate resistance is 10 Ω or less.

The results of I_D-V_{DS} characteristics and switching measurements confirmed that the developed 1200 V 400 A SiC module achieved both low conduction loss and low switching loss. The characteristics of the SiC module are listed in Table 1.

Table 1. Characteristics of 1200 V 400 A VMOSFET module

Item	Value	Unit	Condition
I_D	400	A	-
V_{DSS}	1,200	V	-
$R_{DS(on)}$	4.0	mΩ	V_{GS} = 15 V, I_D = 400 A, T_j = 25°C
V_{SD}	1.9	V	V_{GS} = -5 V, I_S = 400 A, T_j = 25°C
$V_{GS(th)}$	3.9	V	V_{DS} = 10 V, I_D = 4 mA
t_{ri}	70	ns	Inductive Load V_{DS} = 600V, I_D = 400 A, L_{load} = 100 μH, V_{GS} = +15 V/-5 V R_G = 4.7 Ω, T_j = 25°C
t_{fi}	50	ns	
E_{on}	6.5	mJ	
E_{off}	9.9	mJ	

5. Reliability Test Results

The reliability test results for the SiC module are summarized in Table 2. Based on the AQG-324 standard for automotive power modules, the passing conditions were set at an increasing rate in thermal resistance within 20%, an increasing rate of on-resistance within 5%, and an increasing rate in leakage current within 5 times.

Table 2. Summary of the reliability test for SiC module

Item	Standard	Duration	Condition	Quantity
High temperature reverse bias	AQG-324	1,000 h	V_{DS} = 1,200V, T_j = 175°C	n = 6
Low temperature storage	AQG-324	1,000 h	-40°C	n = 6
Temperature humidity reverse bias	AQG-324	1,000 h	85°C, 85%, V_{DS} = 960 V	n = 6
Temperature cycle	JESD22 A104-E	1,000 cycles	-40/165°C, 30 min	n = 6
Thermal shock	MIL-STD-750-1 M1056 Condition D	15 cycles	-40/150°C, 5 min	n = 6
Power cycle (sec)	AQG-324	15,000 cycles	T_{on}/T_{off} = 4 sec/14 sec ΔT_j = 100°C, 25/125°C	n = 4
Power cycle (min)	AQG-324	5,000 cycles	T_{on}/T_{off} = 16 sec/14 sec ΔT_j = 100°C, 25/125°C	n = 4
Vibration	JESD22 B-103	4 times	20-1000 Hz, 1.524 mmP-P, 20 G, 4 min, 3 axis	n = 6
Shock	JESD22 B-104	10 times	Half sine wave, 500 m/s2, 6 ms, 3 axis, 6 direction	n = 6
Terminal strength (Signal terminal)	JEITA ED-4701/401	30 sec	20 N	n = 6
Terminal strength (Main terminal)	JEITA ED-4701/401	30 sec	40 N	n = 6
Resistance to solder heat	JIS C 60068-2-20	10 sec	Soldering iron test, 370°C	n = 6

In the high-temperature reverse bias test and the low-temperature storage test, it was confirmed that there were no problems with the mounted VMOSFETs, SBDs, and module housing. By applying a polyimide coating to the chip edges of the VMOSFET and SBD to improve moisture resistance, the module satisfied the high-temperature, high-humidity reverse-bias test standards even when the module is sealed with Silicone gel. The temperature cycle test and the thermal cycle test mainly apply stress to the solder under the substrate, but by using solder with high toughness, the increasing rate in thermal resistance was kept within 20%, which met the passing criterion. The power cycle test is a test to check the performance of the connection between the chip and wire, and the solder layer under the chip, and this module passed both the long cycle test and the short cycle test.

In addition, as shown in Table 2, it was confirmed that various mechanical reliability related to the housing also passed.

6. Conclusion

In this report, we introduced the full SiC power module (1200 V 400 A) with the Sumitomo Electric's original VMOSFET. The package is compatible with Si IGBTs and can be equipped with commercially available gate drivers. The module showed a low on-resistance of 4.0 mΩ (V_{GS} = 15 V, I_D = 400 A, 25°C) and an extremely low switching losses (E_{total}) of less than 35 mJ at RG < 10 Ω. This module has also passed various reliability tests and is on track for mass production.

- EpiEra is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.

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