Improvement of Surge Current Capability of High Voltage SBD-embedded SiC MOSFET Module

Authors: *Shigeru Okimoto*, Yoichi Hironaka**

**Power Device Works*

Abstract

A new high voltage Schottky Barrier Diode (SBD) -embedded Metal-Oxide-Semiconductor Field-Effect-Transistor (MOSFET) module has been developed as a product using Silicon Carbide (SiC) material that is drawing attention as a wide bandgap semiconductor. SBD-embedded SiC-MOSFETs minimize the risk of bipolar degradation—a critical reliability issue when handling SiC products—and ensure a high level of product reliability. In contrast, SBD-embedded SiC-MOSFETs are commonly known to suffer from disadvantages of low surge current capability. Mitsubishi Electric has developed a novel device structure for enhancing the surge current capability of SBD-embedded SiC-MOSFETs. Accordingly, this has improved the surge current capability of SBD-embedded SiC-MOSFET module to the same level or higher than conventional Silicon (Si) products that are bipolar devices.

1. Introduction

The market for power modules handling high currents and high voltages is currently transitioning from conventional Si products to SiC products. MOSFET using SiC, being wide bandgap semiconductors achieve significantly lower loss than Si Insulated Gate Bipolar Transistors (IGBT), thereby contributing to lower power consumption and smaller sizes of power conversion equipment. In contrast, SiC has a short history compared to Si, which has long been studied in the power electronics field, and debates on SiC-MOSFET reliability are still being conducted in earnest around the world today. One of the debates on the reliability of SiC-MOSFETs is related to bipolar degradation. With the structure of MOSFETs, an inherent body diode is formed within the device, and when a bipolar current flows, stacking faults expand starting from the basal plane dislocation of SiC caused by positive hole injection. This leads to concerns regarding the increase in on-voltage over prolonged use of products. The risk of bipolar degradation increases particularly for high-voltage products with a large total chip area and thick drift layers, so technology for controlling this is important when handling SiC.

Mitsubishi Electric was the first in the world[*1] to develop and market full-SiC products for railroad applications featuring withstand voltages of 3.3kV or more, and we have built up knowledge and technologies related to SiC while contributing to the development of a carbon-free society. Conducting special screening tests to prevent bipolar degradation of SiC-MOSFET chips and incorporating an SBD chip that functions as a free wheel diode in the module ensures a high level of reliability for supplied products. Yet preventing bipolar current from flowing through the inherent body diode of a MOSFET chip with a withstand voltage of 3.3kV requires an SBD chip around 1.3 times larger than the MOSFET chip(1)(2). Mounting SBD chips called for a large space in the module and significantly higher costs. For high-voltage band applications that need a high level of product reliability, Mitsubishi Electric has developed a new SBD-embedded SiC-MOSFET module (Fig. 1) with a withstand voltage of 3.3kV incorporating the SBD within the MOSFET chip. Issues related to bipolar degradation are resolved by suppressing current flow to the inherent body diode through the SBD-embedded SiC-MOSFET structure. In contrast, SBD-embedded SiC-MOSFETs are generally known to suffer from disadvantages of small surge current capability due to high conduction losses in the high current region.

This paper discribes the method used to improve the surge current capability of SBD-embedded SiC-MOSFET modules.

[*1] According to our research, May 11, 2017

Fig. 1 High-voltage SBD-embedded SiC-MOSFET module

2. The Novel SBD-embedded SiC-MOSFETs Structure for Improved Surge Current Capability

The novel structure of SBD-embedded SiC-MOSFETs for improved surge current capability is shown in Fig. 2. Part of the SBD region is filled with p-wells to inactivate the SBD, intentionally creating a very small region for operation of the inherent body diode. This is called Bipolar Mode Activation (BMA). The BMA cell plays two major roles for improving the surge current capability of SBD-embedded SiC-MOSFETs. The first role is to operate the inherent body diode of the SBD-embedded SiC-MOSFET only when the power module requires surge current capability during abnormal equipment operation. When a large short-circuit current is applied to the power module, the carrier injected into the BMA cells within the SBD-embedded SiC-MOSFET chip diffuse toward the cells adjacent to the BMA cells. The diffused carrier reduces the drift resistance of the adjacent cells, and the voltage applied to the inherent body diode increases, causing the inherent body diode of that cell to start operating (Fig. 3). The propagation of this inherent body diode operation spreads instantaneously throughout the chip(3). As a result, the area required for BMA cells is very small at less than 1% of the total area of the SBD-embedded SiC-MOSFET chip, and the electrical characteristics are equivalent to those of modules without BMA cells, which is another advantage of this structure. Operating the inherent body diode in the overcurrent region limits power consumption during high current flow and improves surge current capability by using conductivity modulation (Fig. 4). The degree of influence of bipolar degradation on the inherent body diode caused by current flow is easy to assume for limited times such as during emergencies, thereby minimizing the risk. The dimensions and number of BMA cells in the developed SBD-embedded SiC-MOSFET have been designed so that operation of the inherent body diode does not propagate during normal equipment operation.

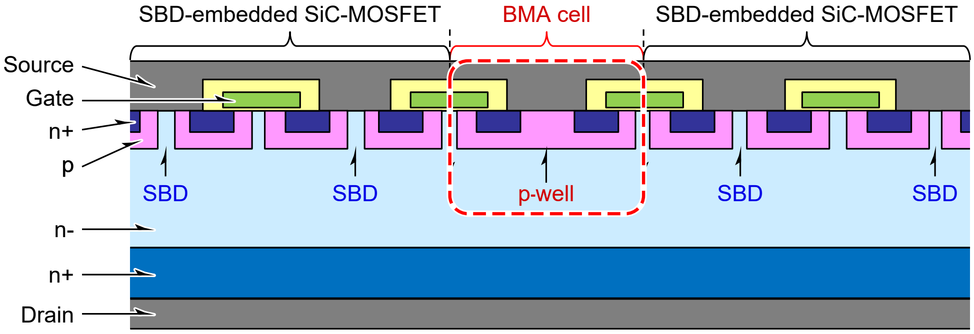

Fig. 2 The novel SBD-embedded SiC-MOSFETs structure for improved surge current capability

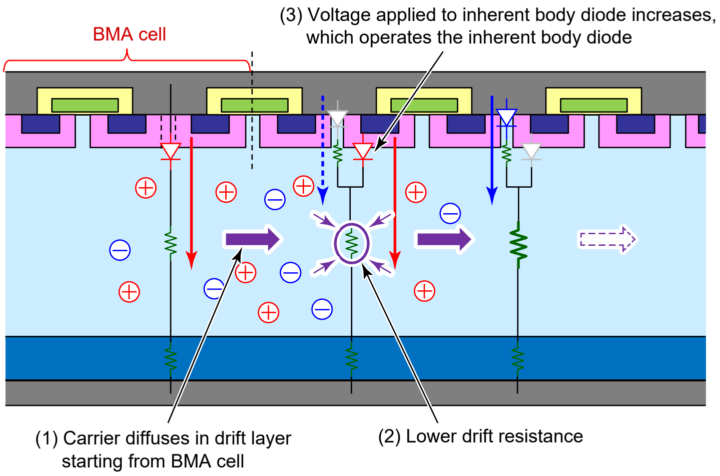

Fig. 3 Propagation of bipolar operation

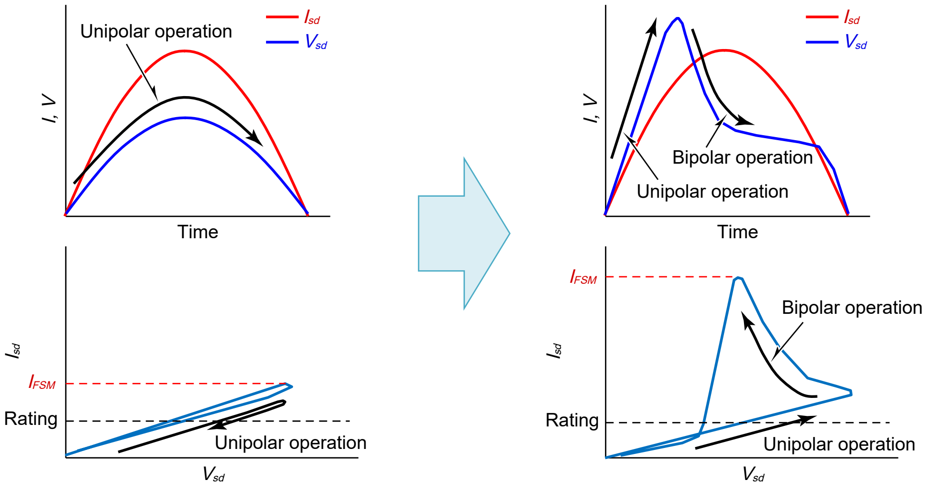

Fig. 4 Improved surge current capability by conductivity modulation

The second key role of BMA cells is to minimize the effects of variations in characteristic of SBD-embedded SiC-MOSFET chips mounted on the module. Power modules that handle high power generally have multiple semiconductor chips mounted in the module connected in parallel. Even when individual semiconductor chips have a large surge current capability, it is difficult to make the sum of the surge current capability of the chips when it is assembled as a power module. This is because variations in characteristics among multiple chips cause the current becoming concentrated in chips that operate early, leading to destruction. This is supported by the appearance of the chips after the test of the surge current capability of the power module that were connected in parallel. When testing modules without BMA cells, melting of aluminum used as the electrode material on the chip surface was observed in some of the chips, suggesting that high current flowed through them (Fig. 5). The chip characteristic value determining the operating timing of the inherent body diode is highly dependent on the width of the SBD region embedded on the MOSFET chip. The width of the SBD region varies due to the constraints during wafer processing, so at the moment it is difficult to control this to significantly improve manufacturing precision. To combat this, an inherent body diode region was intentionally created as a BMA cell to suppress the variation of snapback voltage and allow the characteristic value to be designed as required. The measurement results of the inherent body diode operation start voltage of SBD-embedded SiC-MOSFET is shown in Fig. 6. Compared to chips without BMA cells, the measurement results of chips with BMA cells reveal a smaller variation in the inherent body diode operating voltage. Suppressing variations in characteristics between chips and thus preventing the current from concentrating on specific chips during overcurrent flows helped to improve the surge current capability.

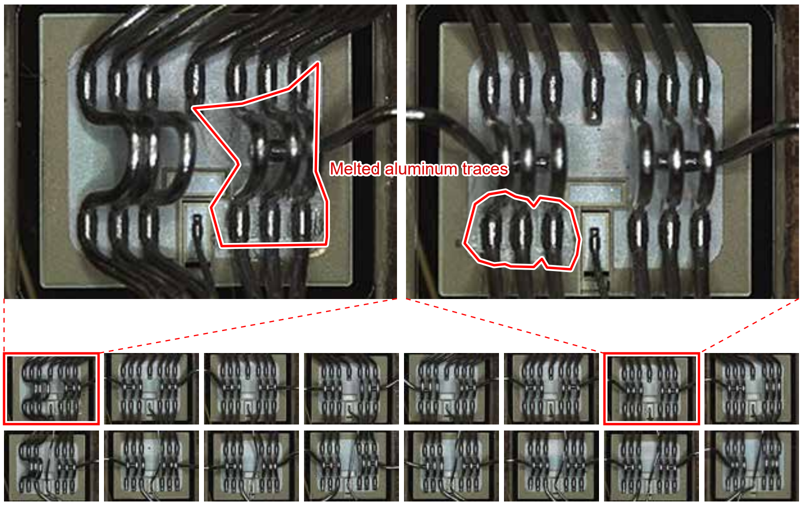

Fig. 5 Premature breakdown due to current concentration

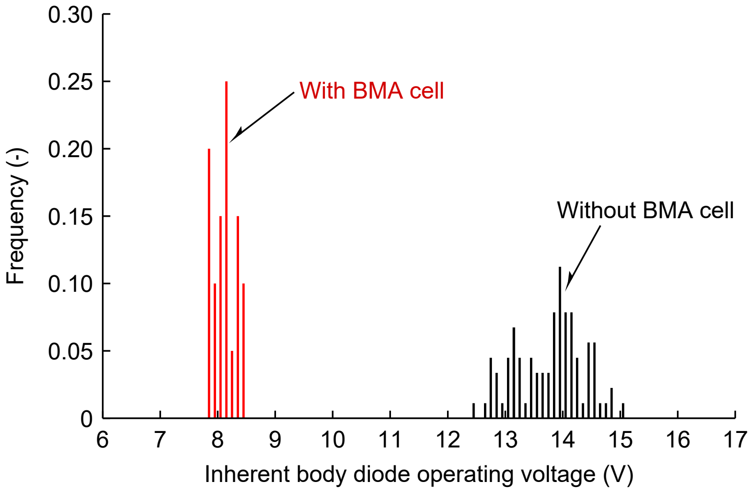

Fig. 6 Characteristic variation of inherent body diode operating voltage

3. Surge Current Capability of the Developed SBD-embedded SiC-MOSFET Module

The surge current capability of the SBD-embedded SiC-MOSFET module using BMA cells was measured. This product is a 3.3kV full SiC power module (FMF800DC-66BEW) with a rated current of 800A. Measurements of the surge current capability were conducted under the initial temperature T_j = 175°C and pulse width t_p = 10ms conditions before conduction, with current applied gradually until destruction. The failure modes of the SBD-embedded SiC-MOSFET for this measurement were all gate shorts, and the breakdown voltage between drain and source remained 3.3kV even after the determining the failure. As discribed in Chapter 2, thermal energy from the surge current melted the aluminum on the chip surface, which is thought to have resulted in damage to the barrier metal and interlayer dielectric of the gate section located near the chip surface, causing a gate short failure. The measurement results of the SBD-embedded SiC-MOSFET module are shown in Fig. 7. For reference, the measurement results were compared with those of an Si module (CM600DA-66X) with a rated current of 600A. When the rated current value of each module is taken into consideration, the SBD-embedded SiC-MOSFET module was confirmed to have the same or higher surge current capability than conventional Si modules.

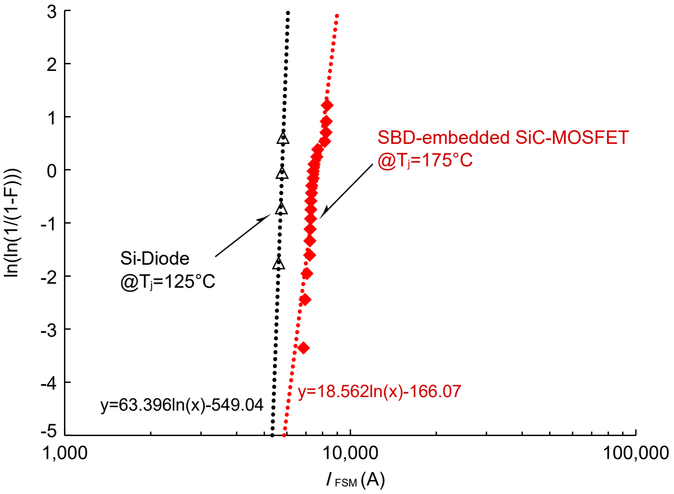

Fig. 7 Surge current capability of SBD-embedded SiC-MOSFET module

The pulse width dependence data of the surge current capability is also crucial for the design of power conversion equipment applied to power modules. This developed SBD-embedded SiC-MOSFET in particular propagates bipolar operation starting from the BMA cell, so it needed to be tested to check whether bipolar operation propagation to the entire chip completes even under short pulse width conditions, and that the module has the expected surge current capability. In addition to the pulse width conditions t_p = 10ms that normally define surge current capability characteristics, measurement was also conducted at t_p = 1ms and 2ms conditions. For the expected surge current capability, assuming that the electrical resistance R of the SBD-embedded SiC-MOSFET is constant when the inherent body diode is fully operational, the pulse width dependence of the surge current capability can be calculated approximately using the following equation with the thermal resistance characteristics $Z_{th(j\text{-}c)}$.

$$Z_{th(j-c)}(t_p) = \sum_{i=1}^{n} R_i \left\{1 - e^{\left(-\frac{t_p}{\tau_i}\right)}\right\}$$

$$I_{FSM}(t_p) = I_{FSM}(10ms) \times \sqrt{\frac{Z_{th(j-c)}(10ms)}{Z_{th(j-c)}(t_p)}}$$

The pulse width dependency of the surge current capability calculated from the thermal resistance characteristics of the SBD-embedded SiC-MOSFET module is shown in Fig. 8. The points with a failure rate of 1% as calculated based on the measurement results of the surge current capability are plotted on this graph. The expected surge current capability and the measurement results are seen to have similar trends. This indicates that even in short pulse width regions, the propagation of bipolar operation coming from the BMA cell is instantaneous and sufficiently complete to improve the surge current capability of the SBD-embedded SiC-MOSFET module.

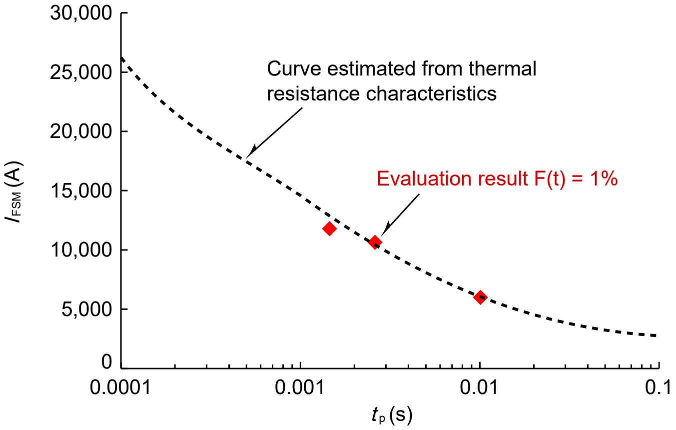

Fig. 8 Pulse width dependency of the surge current capability of SBD-embedded SiC-MOSFET module

4. Conclusion

A high level of product reliability is essential for railroad and power system applications, given their key role as social infrastructure. In applications with high voltage levels, the risk of bipolar degradation—one of the reliability issues of SiC—is relatively high, which makes technologies that ensure product reliability extremely important. This developed SBD-embedded SiC-MOSFET minimizes the risk of bipolar degradation due to current flow of the inherent body diode, and ensures high product reliability. SBD-embedded SiC-MOSFETs are widely known for their disadvantage of low surge current capability, and this paper discribes a way of resolving this issue. Mitsubishi Electric will continue contributing to the development of a carbon-free society by supplying SiC power module products that enable significantly higher efficiency than conventional Si semiconductor products.

References

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