ISSN 1345-3041

Sep.2024 / Vol.187

Mitsubishi Electric ADVANCE

Power Devices

MITSUBISHI ELECTRIC
Changes for the Better

September 2024 / Vol. 187
Mitsubishi Electric ADVANCE

Power Devices

• **Editorial Inquiries**
Fumitoshi Yoshikawa
Corporate Productivity Planning & Engineering Dept.
Fax: +81-3-3218-2465

Mitsubishi Electric Advance is published on line quarterly (in March, June, September, and December) by Mitsubishi Electric Corporation.

CONTENTS

Overview

Technical Reports

Precis

Mitsubishi Electric's power modules, which employ the latest chip and package technology, realize ideal power electronics systems thanks to their high quality, low loss, and excellent noise performance.

Overview

Author: *Junichi Itoh**

**Professor, Nagaoka University of Technology*

Power Semiconductor Technologies toward 2120

When considering potential concepts for the future, it is good to occasionally cast our eyes far forward into the year 2120 (around a century from now). Electricity poses a challenge to store but generation and conversion is easy—fast forward another century, and electricity will no doubt be the primary source of energy, being converted into various forms throughout our day-to-day lives. In light of this, power electronics and the power semiconductors associated with them will likely play an increasingly important role even 100 years from now.

The development of power semiconductors is intrinsically related to the applications that use them. Yet cost presents the most significant impediment when it comes to innovations that end up transforming society. One way of getting user to accept these costs increases is convenience. Once humans become accustomed to a sense of convenience, we are unable to return to ways prior. Indeed, convenience outweighs costs.

When we take a closer look at desirable positions from the stance of convenience, the following will most likely be possible in 100 years. 1) Flying cars, 2) Electric airplanes, 3) Wireless power supply, 4) Ultra-high-power density power supply systems, 5) Advances to medium and high voltages, 6) Ultra-high-power density actuators, and 7) Space applications.

So, what needs to be accomplished to get to these goals sooner, instead of in 100 years? What will be ideal power semiconductors look like? These are some questions that highlight the importance of backcasting. It is hard enough to find ways of achieving such feats in 10 or 20 years from now, given that various hurdles like cost, standards, corporate relations, politics, and national boundaries exist. Backcasting from a position 50 or 100 years into the future is crucial for the outright pursuit of technology.

I hope people reading this paper take a moment to explore their imagination: “What will things look like 100 years from now?”

Power Module for Automotive "J3 Series"

Authors: *Yukimasa Higashi*, Kazuhiro Nishimura***

**Power Device Works, ** Melco Semiconductor Engineering Corp.*

Abstract

Efforts toward the electrification of vehicles have been gaining momentum around the world in recent years as a means of achieving a decarbonized society. Power modules equipped with Si power devices have been the key device spearheading electrification, but more recently, demand has been growing for power modules equipped with SiC power devices, which are anticipated to facilitate a longer driving range given their more compact size and higher efficiency. Mitsubishi Electric responded to such market trends by launching the Transfer molded Power Module (T-PM), a Si-IGBT-based power module with a compact size and high reliability, and the J1 series with integrated cooling fins for a compact size and high power density[(1)]. We are currently developing a new series of power modules (J3 series) that is even smaller, more efficient and with a higher power density than conventional power modules.

1. Introduction

Efforts toward the electrification of vehicles have picked up pace around the world in recent years with the aim of reducing greenhouse gas emissions. Mitsubishi Electric released the T-PM powered with Si-IGBT for a compact size and high reliability, and the J1 series with integrated cooling fins for a compact size and high power density, with Si power module contributing to the electrification of vehicles (Fig. 1).

Increasing the uptake of electric vehicles requires an extension in the range of vehicles and a reduction in battery costs, and one way of addressing these issues is lower losses and more compact power modules installed in inverters. SiC power devices are drawing increased attention for their potential to achieve lower losses than traditional Si power devices, and are as such viewed as the key devices for reducing loss in power modules. Since the 1990s, Mitsubishi Electric has been developing SiC power devices and SiC power modules equipped with planar Metal Oxide Semiconductor Field Effect Transistors (SiC-MOSFETs) for use in electric railway, industry, consumer electronics, and automotive applications. More recently, development has been advancing into power modules equipped with trench-gate SiC-MOSFETs with lower power losses and higher power output compared to conventional planar gate SiC-MOSFETs[(2)]. Development is currently focusing on new automotive power modules (J3 series) equipped with SiC-MOSFETs and Reverse Conducting Insulated Gate Bipolar Transistors (RC-IGBT) for T-PM that provide a compact design and high reliability[(3)]. This paper provides and outline of J3 series products and the miniaturization technology underpinning SiC power modules utilizing Si chips.

T-PM (Transfer molded Power Module)	J1 series
	

Fig. 1 T-PM and J1 series

2. Outline of J3 Series Product

The appearance and lineup of the J3 series currently being developed are shown in Fig. 2. The J3 series features a combination of SiC device technology developed thus far, with T-PM that features a compact design and high reliability, and in addition to the low loss required of SiC modules, are expected to provide an even more compact size, higher power density and higher reliability. The package dimensions of the 2in1 module J3-T-PM are 26.5mm x 73.9mm x 6.92mm (including main terminals), and can be mounted onto SiC-MOSFET or RC-IGBT with the same package structure (Fig. 2). Changing the number of mounted power chips mounted in the J3-T-PM and the number of parallel modules allows 6in1 modules (HEXA-S and HEXA-L) to be configured that are capable of handling a wide range of motor outputs from 50kW or less up to a maximum of 300kW.

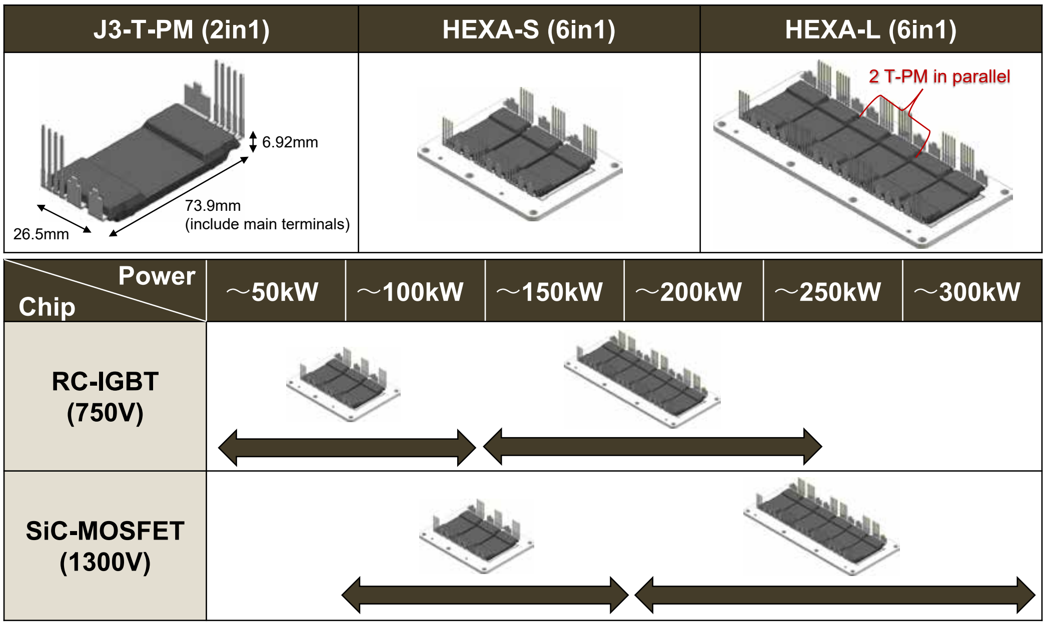


Fig. 2 Appearance and lineup of J3 series

The circuit diagram of J3-T-PM(2in1) is shown in Fig. 3. Modules equipped with RC-IGBTs feature on-chip temperature and current sensors just like conventional Si power modules. The SiC-MOSFET-equipped module has a temperature sensor, Desaturation (DESAT) Diode, balance resistor, and Short Circuit Monitor (SCM), which is a control terminal for short-circuit protection.

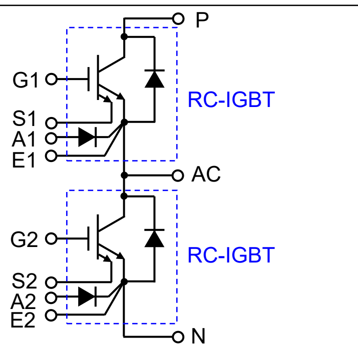
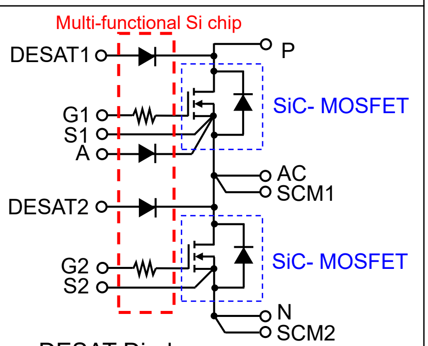
	J3-T-PM (2in1)	
Device	**Si** RC-IGBT	**SiC** MOSFET
Rated voltage	750V	1300V
Rated current	400A	350A
Circuit Configuration **Half bridge**	 ・On-chip temperature sense ・On-chip current sense	 ・DESAT Diode ・Temperature sense (Outside chip) ・SCM terminal (for SC protection)

Fig. 3 Circuit of J3-T-PM(2in1)

3. Multi-functional Si Chip

3.1 Overview of multi-functional Si chip

Many SiC-MOSFET-equipped power modules comprise multiple power chips arranged in parallel, with built-in balance resistors for maintaining the current balance between different power chips. Many power modules also have built-in thermistors for temperature detection. Yet incorporating such circuit elements into power modules requires dedicated circuit patterns—a factor that limits the level of miniaturization and high power density the power module can achieve. The multi-functional Si chip was developed to overcome this restraint. The multi-functional Si chip incorporates the balance resistor, on-chip temperature sense diode, high-voltage diode (DESAT diode), and source wiring on a single Si chip, which contributes to the more compact size of power modules. As the multi-functional Si chip can also be mounted in close proximity to the same conductive substrate as the SiC-MOSFET, the on-chip temperature sensor installed on the multi-functional Si chip has excellent thermal response to the heat generated by the SiC-MOSFET.

3.2 More compact modules with DESAT diodes mounted on multi-functional Si chips

To provide the short-circuit protection function with DESAT in conventional SiC power modules, the drain voltage (high voltage) of the closest SiC-MOSFET needs be taken from the signal terminal and connected to the DESAT diode on the circuit board. The creepage distance to the low-voltage signal terminal needs to be maintained in these cases, which was a factor that limited miniaturization of modules. Yet by mounting a multi-functional Si chip with an incorporated DESAT diode, J3 series SiC power modules no longer need high-voltage signal terminals and space for mounting a DESAT diode on the circuit board, thus making the power module more compact and simplifying the design of the circuit board. In addition to DESAT diodes, integrating the temperature sensor and source wiring into the multi-functional Si chip also simplifies the substrate pattern within the power module, which helps reduce the module size by 16% from the conventional structure (Fig. 4).

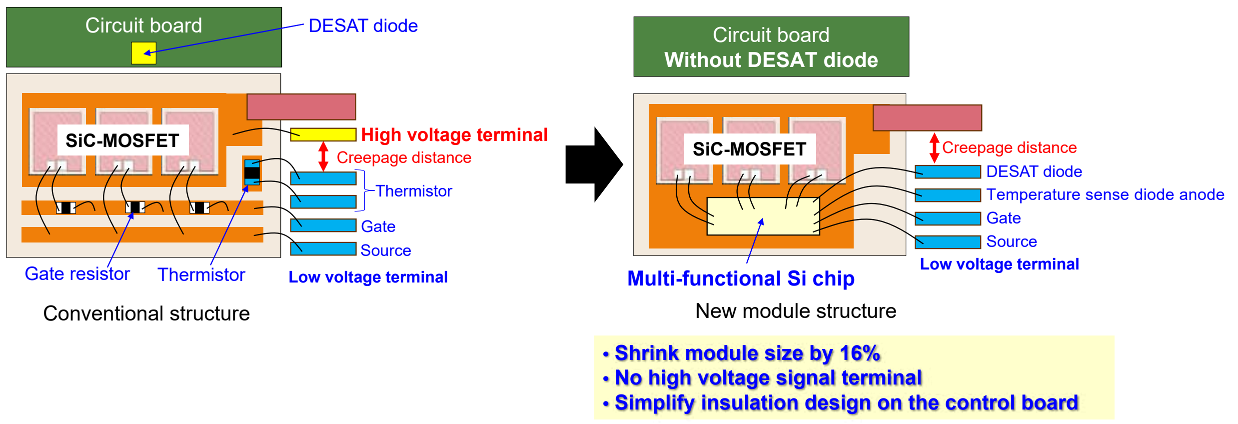


Fig. 4 Module size reduction by function integration into multi-functional Si chip

3.3 High-speed switching operation

As the multi-functional Si chip is mounted on the same conductive substrate as the SiC-MOSFET, to maximize the performance of the SiC-MOSFET, the chip design must not obstruct the high-speed switching operation. More specifically, we believe that SiC-MOSFETs need to be adapted to operate at high dv/dt and surge voltages during high-speed switching operation and in high temperature environments. We have achieved stable operation of SiC power modules after developing numerous prototypes, verifying actual devices, and making improvements to multi-functional Si chips. An example that illustrates how actual devices were verified is some of the results of double-pulse test assembled as a testing kit for J3-HEXA-L(6in1) as shown below.

An appearance of our HEXA-L(6in1) test kit is shown in Fig. 5. For the double-pulse test that was run with this test kit, the typical switching waveforms under the worst conditions where the surge voltage and dv/dt could be maximum when taking into consideration various variations in the supply voltage and driver board are shown in Fig. 6.

First, when T_j = -40°C, V_{DD} = 870V, and I_D = 1000A, the turn-off switching waveform when the gate resistance Rg(off) is adjusted so that the surge voltage near the chip is about 1300V, is shown in Fig. 6(a). In the waveform shown in Fig. 6(a), we confirmed that there were no gate oscillations or malfunctions with the multi-function Si chip, and that switching can be performed normally even under a T_j = -40°C environment.

Next, when T_j = 175°C, V_{DD} = 870V, and I_S = 1000A, the recovery switching waveform when the gate resistance Rg(on) is adjusted so that the surge voltage near the chip is about 1300V, is shown in Fig. 6(b). The dv/dt under these conditions is a high 16.9 [kV/us], but we confirmed that there were no malfunctions with the multi-function Si chip or destruction of the element, and that high-speed switching can be performed normally even under a high T_j = 175°C environment.

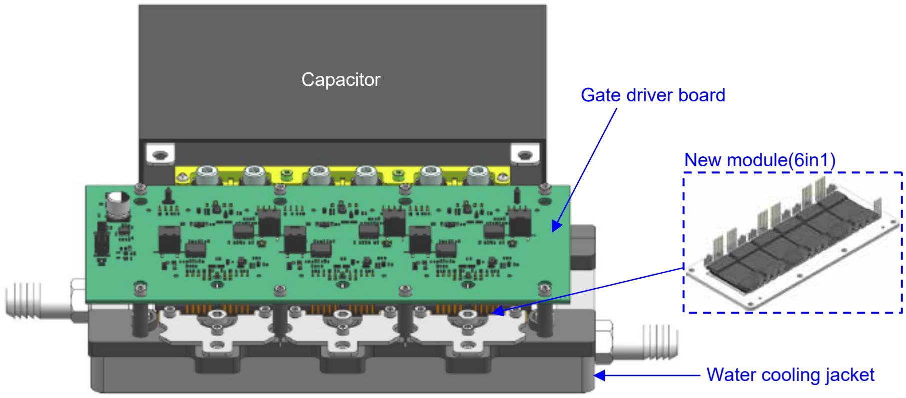
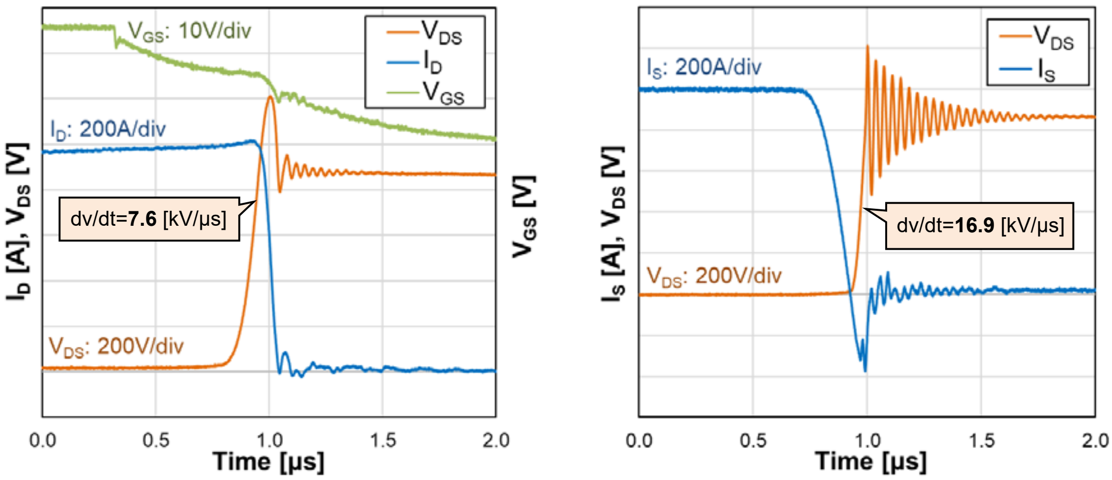


Fig. 5 Evaluation kit of HEXA-L



(a) Turn-off switching
(T_j=-40°C, V_{DD}=870V, I_D=1000A)

(b) Recovery switching
(T_j=175°C, V_{DD}=870V, I_S=1000A)

Fig. 6 Representative switching waveform of HEXA-L evaluation kit

Conclusion

Mitsubishi Electric has been developing and marketing power modules for automotive applications for more than 20 years, which has contributed to the electrification of vehicles. We continue taking a pro-active approach to the development of new devices and power modules by leveraging the technology and know-how we have honed until now, and help contribute to the faster pace of electrification of vehicles around the world.

References

(1) Komo, H., et al.: Automotive SiC Power Module, Mitsubishi Denki Giho, 96, No. 3, 144-147 (2022)
(2) Sugawara, K., et al.: SiC Trench Metal-Oxide-Semiconductor Field-Effect Transistor with Novel Structure Enabling Lower Losses, Mitsubishi Denki Giho, 96, No. 3, 160-163 (2022)
(3) Komo, H., et al.: Automotive Power Module "J3 Series", Mitsubishi Denki Giho, 98, No. 3, 3-01 to 3-05 (2024)

SLIMDIP Series Lineup Expansion and Future Prospects

Authors: *Kazuki Takakura*, Kaito Hamasaki**

**Power Device Works*

Abstract

Mitsubishi Electric has been marketing "DIPIPM" with a transfer-molded structure incorporating a power chip and an IC chip that drives it since 1997, contributing to a greater level of quality and lowering the design load for inverter systems with the use of a single package. Ever since launching the industry's smallest*1 "SLIMDIP-S" and "SLIMDIP-L" packages in 2015, the lineup has been expanded to include the "SLIMDIP-W" suitable for high carrier frequency drive, the "SLIMDIP-X" with lower noise, and the "SLIMDIP-Z" with a higher current rating up to 30A. These are contributing to a greater energy conservation of home appliances such as air conditioners, washing machines and refrigerators, which are increasingly multi-functional and higher performance in recent years.

1. Introduction(1)

After being the first in the industry*2 to market the DIPIPM, Mitsubishi Electric has continued to develop and market a range of products to suit the changing needs of the market. The white goods market has made rapid advances in recent years for greater use of inverters, in response to the increased functionality of home appliances and global awareness of energy conservation. The SLIMDIP series is a low-capacity Intelligent Power Module (IPM) developed for white goods such as home air-conditioners and low-capacity fan drives, and features a smaller product size and lower cost while covering a a broad range of capacities with a single package. The SLIMDIP series comprises an inverter circuit made up of six Reverse Conducting - Insulated Gate Bipolar Transistor (RC-IGBT) elements, driven by three elements, High Voltage Integrated Circuit (HVIC), Low Voltage Integrated Circuit (LVIC) and BootStrap Diode (BSD).

The RC-IGBT used in the SLIMDIP series features Mitsubishi Electric's proprietary 7th generation IGBT technology.

This paper provides and overview of the SLIMDIP series and outlines its features and future prospects.

2. Overview of SLIMDIP Series(1)

2.1 Power section

The three-phase AC output inverter circuit comprises RC-IGBTs (6 elements) featuring IGBTs and Free Wheeling Diodes (FWDs) on a single chip. The RC-IGBT cross-section structure is shown in Fig. 1.

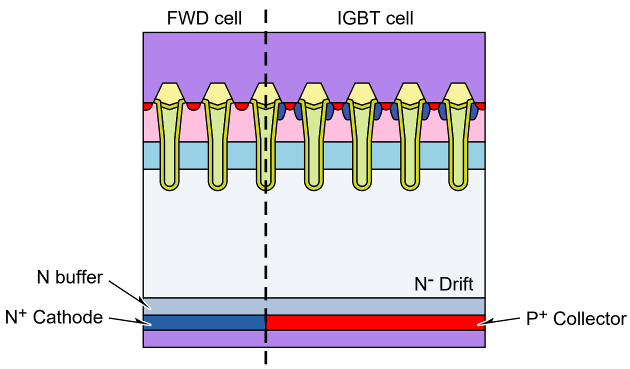
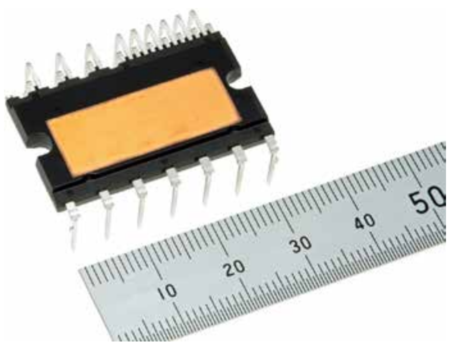


Fig. 1 RC-IGBT cross-section structure(2)

*1 According to our research, April 23, 2015
*2 According to our research, August 25, 1997

2.2 Control section

The SLIMDIP series package and internal circuit are shown in Fig. 2.



SLIMDIP series (18.8 x 32.8 x 3.6mm)

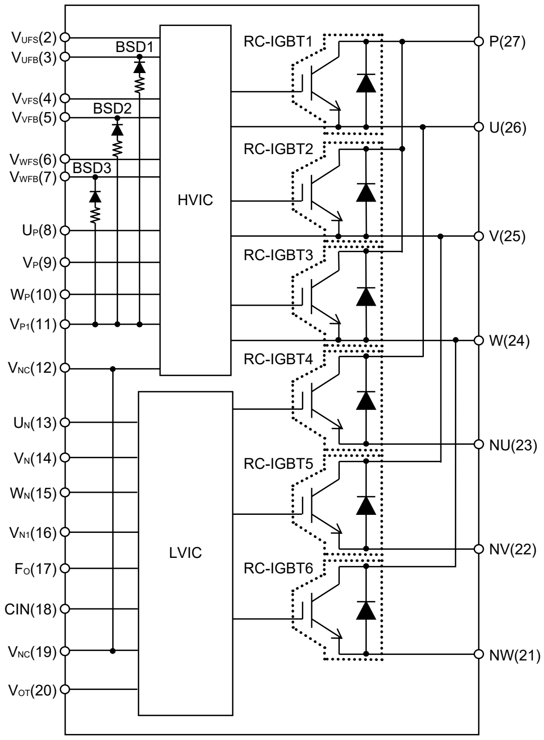


Fig. 2 Inter block diagram

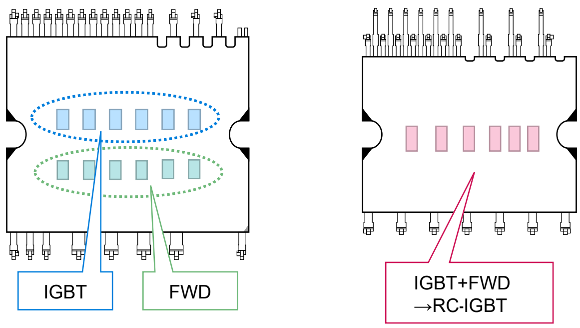
The HVIC (1 element) contains a P-side IGBT drive circuit, a high-voltage level shift circuit, and a floating control supply under voltage protection function (UV, without error signal (Fo) output). The use of a bootstrap type circuit also allows for a single 15V power supply drive.

The LVIC (1 element) contains an N-side IGBT drive circuit, and a control supply under voltage protection function (UV) and short-circuit protection function (SC) as well as an over temperature protection function (OT) and a temperature output function (VOT) as protection function. The short-circuit protection detects over-current with the shunt resistance of the external connection, and feeds back to LVIC to shutoff the IGBT. It outputs Fo when UV, SC and OT are tripped.

3. Features of SLIMDIP Series[1]

3.1 RC-IGBT mounting

The SLIMDIP series uses RC-IGBTs with a structure featuring IGBTs and FWDs that are formed on a single chip, in order to achieve a smaller package size with the aim of reducing area of the board. The RC-IGBT used here features Mitsubishi Electric’s proprietary 7th generation IGBT technology. The number of chips mounted is halved as shown in Fig. 3. As a result, the package size was made 30% smaller than that of the super mini DIPIPM as shown in shown in Fig. 4.



(a) Super mini DIPIPM (b) SLIMDIP series

Fig. 3 Chip layout comparison

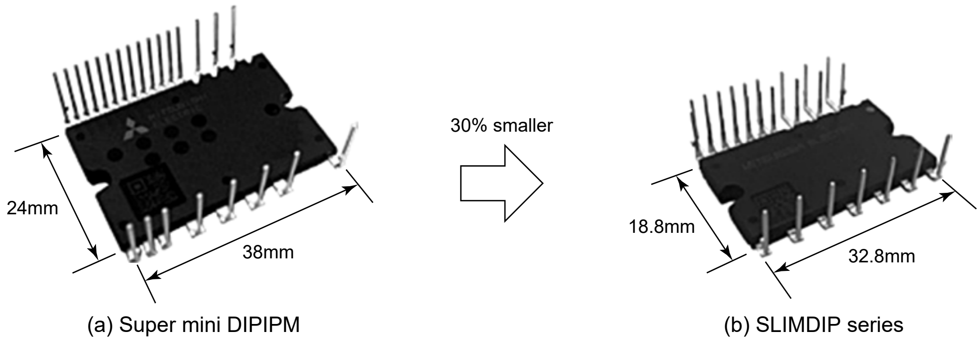


Fig. 4 Package size comparison

3.2 Simplified wiring pattern

In addition to the smaller package size, the SLIMDIP also features a simplified wiring pattern on the system board. The bootstrap circuit used for driving the P-side IGBTs of the DIPIPM needs an external capacitor to be connected to stabilize the control power supply voltage. The conventional pin layout of the super mini DIPIPM series required an extra board area because the control power supply terminal reference was routed to the power side. The SLIMDIP series features three reference terminals of the P-side drive power supply on the control side, eliminating the need to run long wiring patterns on the board and thus contributing to simplified board design and reduced board area (Fig. 5).

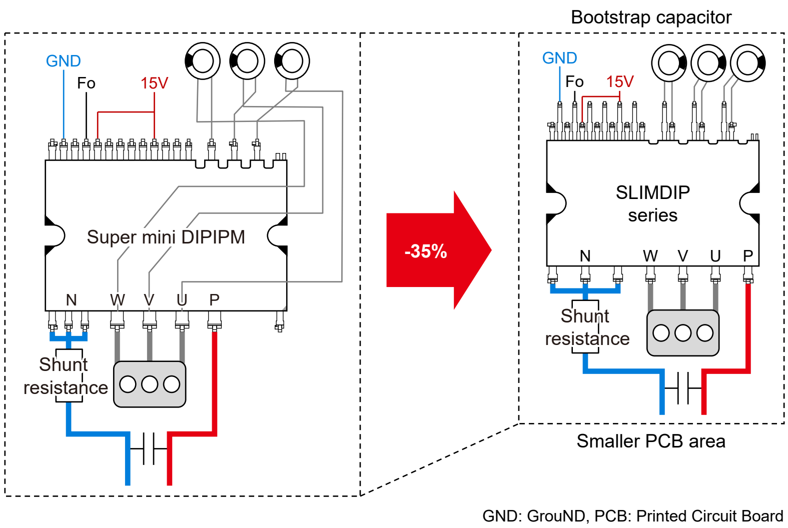


Fig. 5 PCB layout comparison

3.3 Increase in features and maximum ratings

The super mini DIPIPM series specification had either an over temperature protection (OT) or temperature output function (VOT) available as a temperature protection function, but the SLIMDIP series provides both functions. The maximum case temperature Tc and insulation withstand voltage have also been increased compared to the super mini DIPIPM Ver. 6, contributing to better system design by increasing both the functionality and maximum rating.

3.4 Expanded lineup

Beginning with the SLIMDIP-S and SLIMDIP-L lineup in 2015, the SLIMDIP-W, SLIMDIP-M, SLIMDIP-X, and SLIMDIP-Z have been released in the same package with rated currents from 5 to 30A. The addition of the SLIMDIP-X and SLIMDIP-Z lineups as shown in Table 1 increased the scope of applications of the SLIMDIP series. The 15A rated current lineup includes the SLIMDIP-L for low-carrier frequency drive and the SLIMDIP-W for high-carrier frequency drive, enabling the most suitable device to be selected for each application. Figure 6 Effective current-carrier frequency characteristics.

Table 1 SLIMDIP Line-up

Model	Main Applications	Rating	Carrier Frequency
SLIMDIP-S	Refrigerators, Fans	5A/600V	High speed
SLIMDIP-M	Fans, Washing machines	10A/600V	High speed
SLIMDIP-L	Air-conditioners	15A/600V	Low speed
SLIMDIP-W	Washing machines, Air-conditioners	15A/600V	High speed
SLIMDIP-X	Air-conditioners	20A/600V	Medium speed
SLIMDIP-Z	Air-conditioners	30A/600V	Medium speed

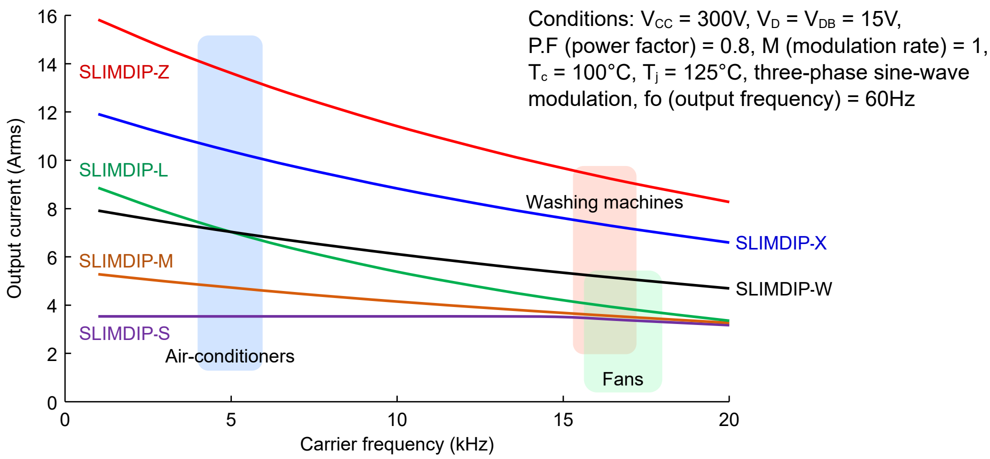


Fig. 6 Characteristics of carrier frequency-output current

4. Future Prospects

There has been a growing focus on energy performance in recent years as countries tighten regulations toward decarbonizing their economies. Yet there is a greater focus on costs, especially throughout Asia, and demand is likely to become increasingly polarized into the future. In response to market requirements, we will use the SLIMDIP series to provide a comprehensive level of support for the shift to inverters and greater efficiency of white goods by focusing on a stable supply of power semiconductors compatible with 12-inch wafers with excellent production efficiency, while also pursuing added value by applying next-generation power semiconductors such as Silicon Carbide (SiC).

5. Conclusion

The SLIMDIP series has significantly lowered the design load of the customer inverter systems with smaller packages using RC-IGBTs, simplified wiring pattern with pin layouts, and greater functionality and ratings compared to current products. Regulations in each country have become increasingly stringent toward decarbonization in recent years, and the expectations placed on power devices are growing every year. We will continue developing products suited to market requirements so that we are able to contribute to the spread of inverter devices across a wide range of applications.

References

(1) Shibata, S., et al.: “SLIMDIP Series” Power Module Using RC-IGBT, Mitsubishi Denki Giho, 90, No. 5, 307-310 (2016)

(2) Yasuda, Y., et al.: Latest Trend and Prospect of Power Module Technology, Mitsubishi Denki Giho, 96, No. 3, 139-143 (2022)

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.

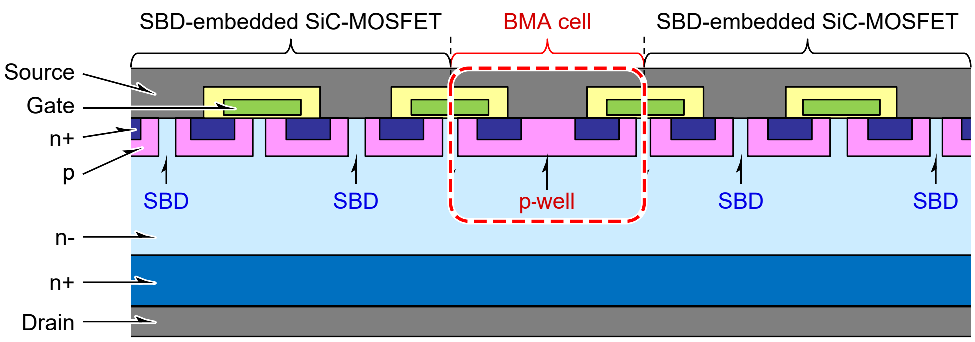


Fig. 2 The novel SBD-embedded SiC-MOSFETs structure for improved surge current capability

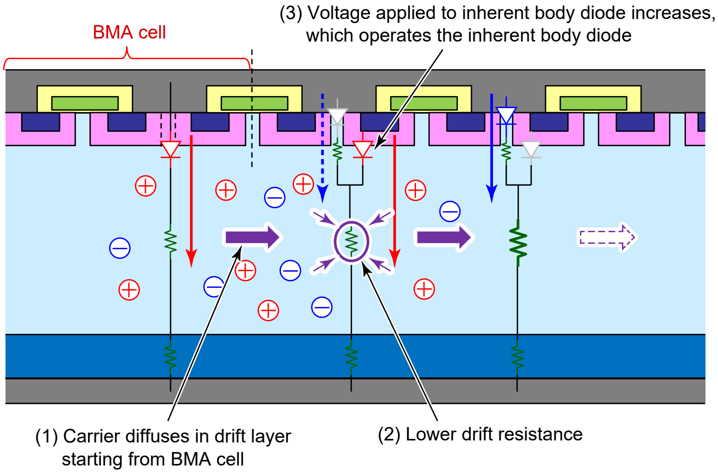


Fig. 3 Propagation of bipolar operation

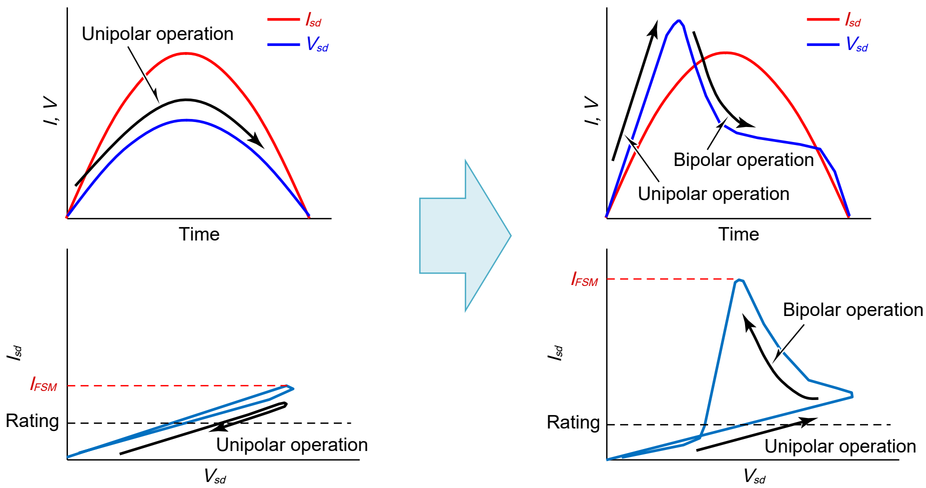


Fig. 4 Improved surge current capability by conductivity modulation

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.

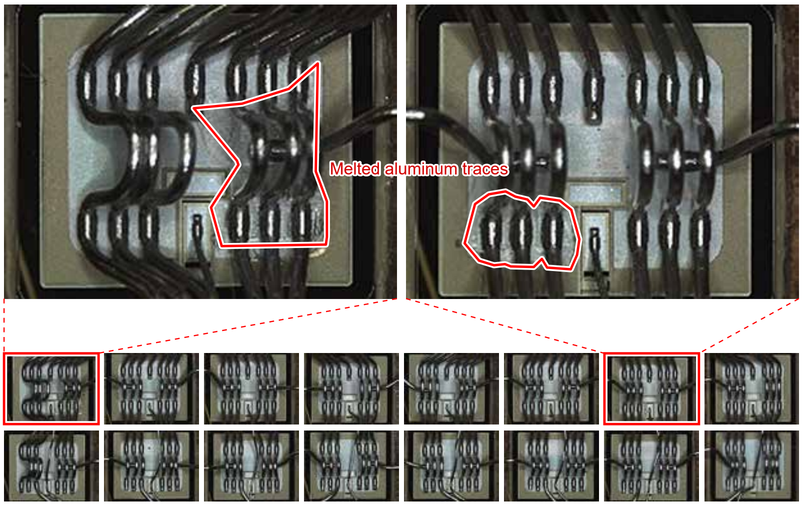


Fig. 5 Premature breakdown due to current concentration

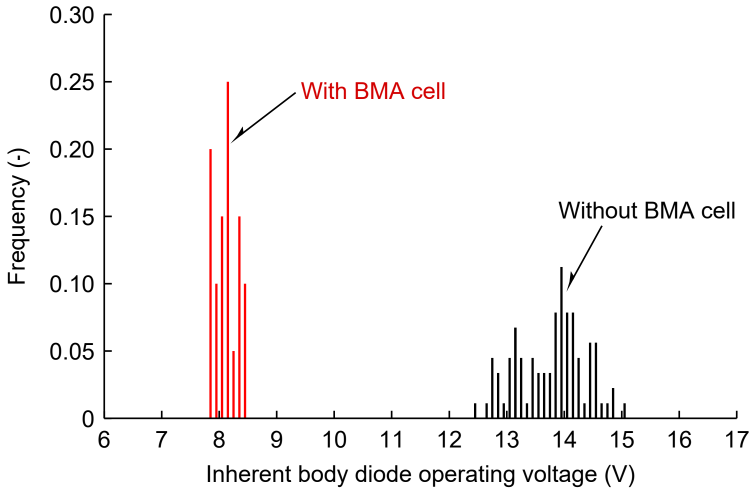


Fig. 6 Characteristic variation of inherent body diode operating voltage

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.

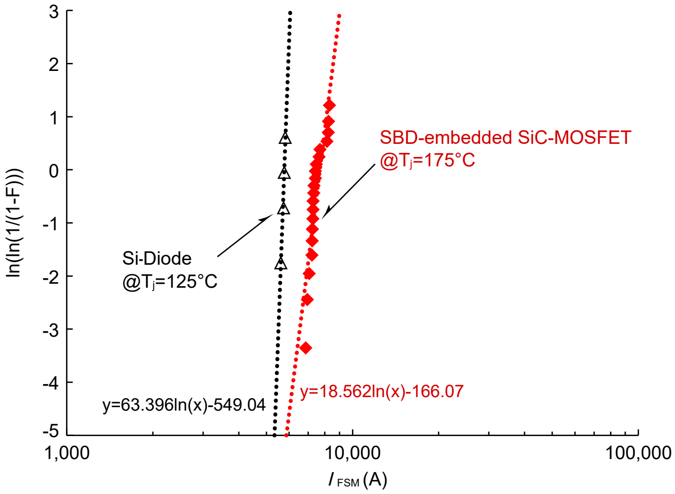


Fig. 7 Surge current capability of SBD-embedded SiC-MOSFET module

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.

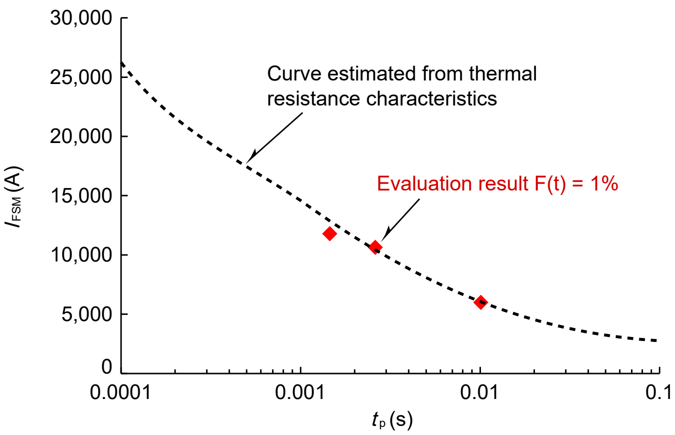


Fig. 8 Pulse width dependency of the surge current capability of SBD-embedded SiC-MOSFET module

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

(1) Hino, S., et al.: Demonstration of SiC-MOSFET Embedding Schottky Barrier Diode for Inactivation of Parasitic Body Diode, Materials Science Forum 2017, 897, 477-482 (2017)
(2) Kawahara, K., et al.: Impact of Embedding Schottky Barrier Diodes into 3.3kV and 6.5kV SiC MOSFETs, Materials Science Forum 2018, 924, 663-666 (2018)
(3) Iijima, A., et al.: Improving Surge Current Capability of SBD-Embedded SiC-MOSFETs in Parallel Connection by Applying Bipolar Mode Activation Cells, Proceedings of ISPSD 2023, 238-241 (2023)

Trench SiC-MOSFET Structure for Controlling Short-Circuit Capability

Authors: *Yutaka Fukui*, Katsutoshi Sugawara***

**Power Device Works, **Advanced Technology R&D Center*

Abstract

With the growing environmental awareness in recent years, there is an increased demand for energy-saving power electronics equipment, so power devices using Silicon Carbide (SiC) as a material are being developed and marketed. Of these, anticipation is high for the trench-type SiC-Metal-Oxide-Semiconductor Field-Effect-Transistor (MOSFET) that features lower loss, but due to the high conductivity of trench-type SiC-MOSFETs, it is extremely difficult to ensure short-circuit capability if a short-circuit occurs in the device. To support a wide range of applications as a switching device, acquiring a means of controlling short-circuit capability in the device structure design is crucial. Mitsubishi Electric has improved the device structure of the trench SiC-MOSFET that has been under development as a way of achieving a trench SiC-MOSFET capable of trade-off control between lower resistance and higher short-circuit capability.

1. Introduction

With the growing environmental awareness in recent years, advances are being made toward energy conservation in power electronics equipment, and SiC has been drawing attention as a next-generation power semiconductor material. SiC exhibits much better properties as power devices, including a larger band gap and higher critical electric field than Si used conventionally. Mitsubishi Electric has been developing and mass-producing SiC-MOSFETs and SiC-Schottky Barrier Diode (SBD) s using SiC, and in the past has marketed products across a broad range of withstand voltage classes, from 600V for home appliances to 3.3kV for electric railways.

Lowering loss of power devices used in equipment is crucial for energy conservation in power electronics equipment, and efforts are advancing for the development and marketing of trench-type SiC-MOSFETs that allow even lower losses. Embedding the gate electrode in the trench allows trench-type MOSFETs to achieve a higher cell integration by reducing the cell pitch, so can achieve a lower resistance in devices. Meanwhile, the electric field is prone to concentrating at the bottom of the trench, so this electric field needs to be alleviated in order to achieve sufficient device reliability.

Mitsubishi Electric has developed trench SiC-MOSFETs with a unique structure that enables lower resistance, higher reliability and lower switching losses(1)(2)(3). The schematic of the trench SiC-MOSFET developed by Mitsubishi Electric is shown in Fig. 1. The characteristics of Mitsubishi Electric's trench SiC-MOSFET structure feature three injection layers: (1) P-type protective layer (BPW: Bottom P-Well) for relaxing the electric field applied to the bottom of the trench, (2) Sidewall P-type pillar (SP: Sidewall Pillar) for grounding the BPW, and (3) N-type Junction Field Effect Transistor (JFET) doping layer (JD: JFET Doping) for preventing narrowing of the current path. The advantage of this structure that utilizes tilted ion implantation into the trench is that it makes it easier to achieve lower loss through high integration and can be fabricated using simple processes.

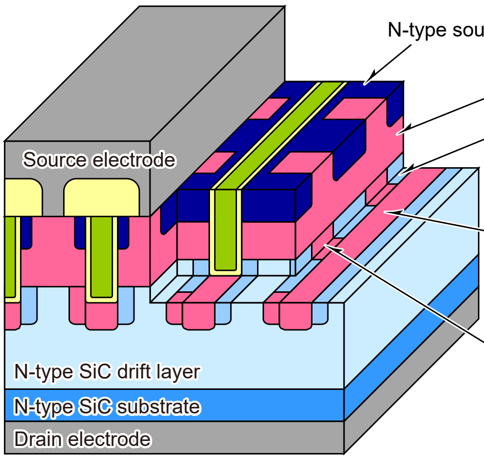


Fig. 1 Schematic of developed trench SiC-MOSFET

Yet while trench SiC-MOSFETs are capable of lower losses, their high conductivity means it is extremely difficult to ensure short-circuit capability if a short-circuit occurs in the device. To support a wide range of applications as a switching device, add methtods for controlling short-circuit capability in the device structure design is essential. Thus the device structure of the conventional trench SiC-MOSFET has been improved as a way of developing a trench SiC-MOSFET capable of trade-off control between lower resistance and higher short-circuit capability.

2. Short-circuit Capability Control Trench-type SiC-MOSFET

2.1 Device structural concept and process flow

The schematic of the fabricated trench SiC-MOSFET that has been developed is shown in Fig. 2. As a way of controlling the trade-off between lower resistance and higher short-circuit capability, a method of adjusting the area density ratio of the SP area that makes up the trench sidewall (sidewall P-type pillar ratio: r_{sp}) has been developed. The SP areas are therefore spaced periodically apart each other on trench sidewall and feature grounding for the BPW and achieving stable switching as described in Chapter 1. As a function of the SP area, this development focused on restricting the Metal Oxide Semiconductor (MOS) channel current and current path of the Junction FET (JFET)-region when the device is conducting (ON). To achieve trade-off control between lower resistance and higher short-circuit capability, devices with different r_{sp} values compared to the conventional structure of r_{sp} = 1 were created, and tests were conducted to assess the effects that r_{sp} has on the electrical characteristics and short-circuit capability of the MOSFETs.

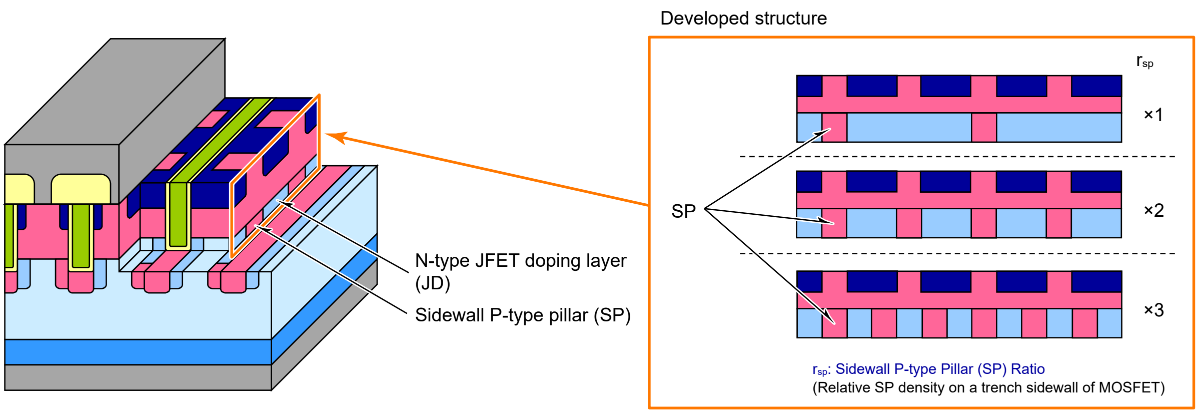


Fig. 2 Schematic of fabricated trench SiC-MOSFET and controlled its Sidewall P-type Pillar (SP) Ratio r_{sp}

The cross-sectional schematic diagram of the process flow of the developed trench SiC-MOSFET separated into (a) Area with SP and (b) Area without SP are shown in Fig. 3. The first step involves implanting Al and N ions into the N-type drift layer before trench etching, to form a P-type well (PW) and N-type source. Next, an SiO_2 film was deposited and photolithography performed to form a trench on the SiC with dry etching. BPW is formed at the bottom of the trench with self-align Al ion implantation by utilizing the SiO_2 film remaining after trench etching (Fig. 3(i)). After the SiO_2 film is removed, the JD is formed with tilted N ion implantation on the trench sidewalls on both sides (Fig. 3(ii)). Next, SP is formed after photolithography using tilted Al ion implantation only for one side of the trench sidewall (Fig. 3(iii)). The r_{sp} can be adjusted with the photolithography mask pattern. Next, P-type contact is formed and after implantation ion activation annealing, the gate formation is performed (Fig. 3(iv)). This is then followed by contact formation, metallization and other processes to complete the device.

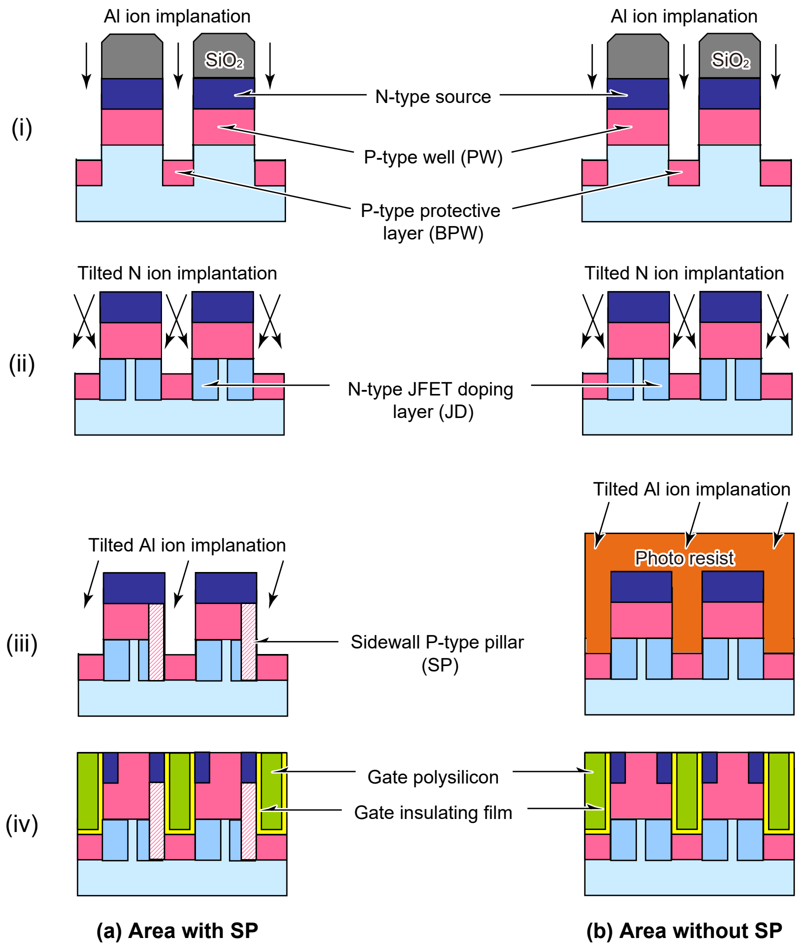
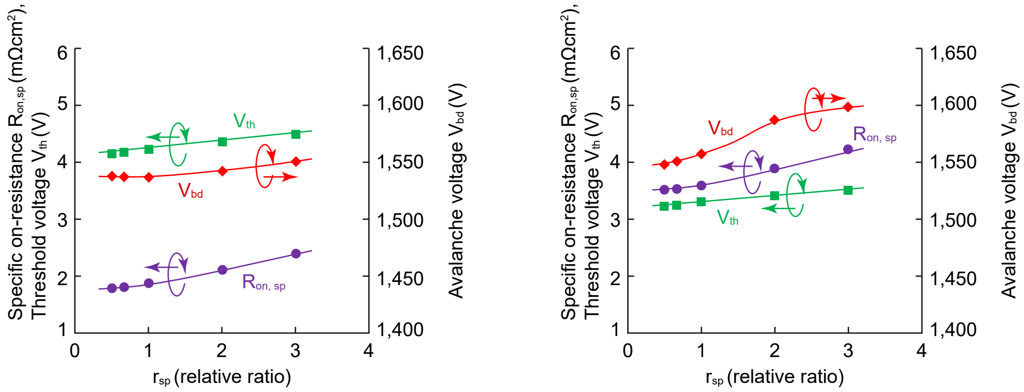


Fig. 3 Fabrication process flow of the trench-gate SiC-MOSFET

2.2 Dependence of static characteristics on sidewall P-type pillar ratio

To assess the effect of the r_{sp} structure design on static characteristics, the electrical characteristics of the prototype trench SiC-MOSFET was tested. The r_{sp} dependences of the specific on-resistance $R_{on,sp}$, threshold voltage V_{th} and avalanche voltage V_{bd} are shown with the measurement results in Fig. 4(a) at room temperature and in Fig. 4(b) at 150°C respectively. With increases in r_{sp}, that is the SP area densely formed on the trench sidewalls, both $R_{on,sp}$ and V_{th} increase gradually at either temperature due to the reduction in MOS channel density and current path of the JFET-region. Furthermore, V_{bd} increases as r_{sp} increases due to the densely formed SP area resulting in relaxation of electric field effect. As a result, with device voltage V_{bd} to 1550V being satisfied, an on-resistance of $R_{on,sp}$ = 2.2mΩcm^2 was achieved at room temperature for the r_{sp} = 2 structure and $R_{on,sp}$ = 2.4mΩcm^2 for the r_{sp} = 3 structure.



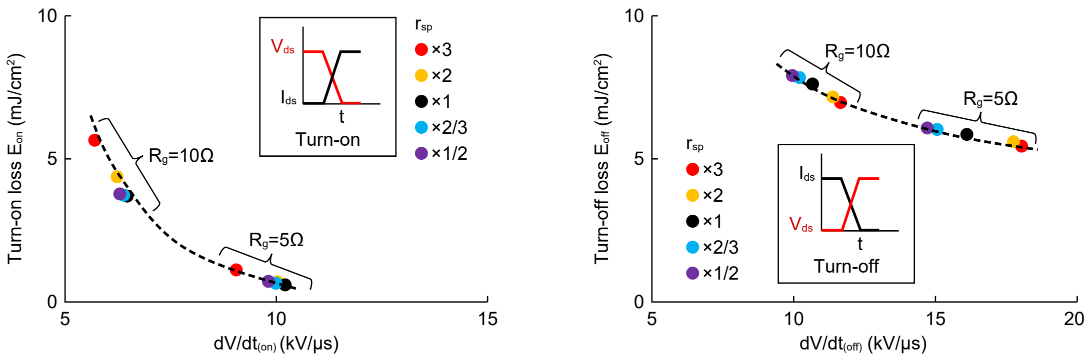
(a) Measurement results at room temperature **(b) Measurement results at 150°C**

*1 Definitions are $R_{on,sp}$ is gate voltage, V_g = 20V, Value of drain current density J_{ds} = 450A/cm^2, V_{th} is voltage between drain-source electrodes, V_{ds} = 10V, Value of drain current density J_{ds} = 100mA/cm^2, Avalanche voltage V_{bd} is V_g = 0V, I_{ds} = 100μA value.

Fig. 4 The r_{sp} dependences of $R_{on,sp}$, V_{th} and V_{bd}*1

2.3 Dependence of dynamic characteristics on sidewall P-type pillar ratio

The dynamic characteristics, where the effect of the r_{sp} structure design on the trade-off relationship between switching speed dV/dt and switching loss, was assessed. Switching measurements were conducted with double-pulse tests, and dV/dt was adjusted by changing the external gate resistance (R_g). The results of dV/dt dependence when changing r_{sp} are shown for turn-on loss E_{on} in Fig. 5(a), and turn-off loss E_{off} in Fig. 5(b). For both E_{on} and E_{off}, the relationship between switching loss and dV/dt for changes in r_{sp} was found to follow the same trade-off line. This suggests that switching losses can be controlled by the external gate resistance (R_g) independently of r_{sp}.



(a) Turn-on loss E_{on} **(b) Turn-off loss E_{off}**

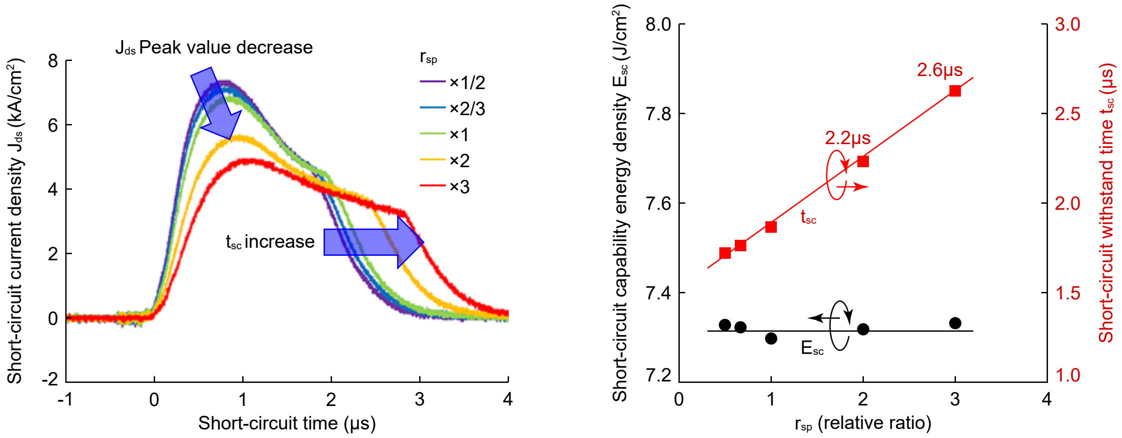
*2 V_{DD}= 600V, Value of drain current density J_{ds}=260A/cm^2

Fig. 5 The dV/dt dependence of turn-on loss E_{on} and turn-off loss E_{off} at various r_{sp}

2.4 Dependence of short-circuit capability on sidewall P-type pillar ratio

The results of the dependence of r_{sp} on short-circuit capability are shown in Fig. 6. Figure 6(a) shows the r_{sp} dependence of the short-circuit current density J_{ds} waveform immediately prior to the device breakdown during arm short-circuit (V_{DD} = 650V, V_{gs} = 20V, at 150°C). As an increase in r_{sp} causes a decrease in the MOS channel density and the current path in the JFET-region, the short-circuit withstand time t_{sc} increases due to significant suppression of the J_{ds} peak value. This revealed that r_{sp} = 2 structure can ensure up to t_{sc} = 2.2μs, while the r_{sp} = 3 structure can ensure up to t_{sc} = 2.6μs.

Figure 6(b) shows the r_{sp} dependence of short-circuit energy E_{sc} and short-circuit withstand time t_{sc}. The structural design with increased r_{sp} leads to an increase in t_{sc}, but E_{sc} was found to be independent of r_{sp}. This indicates that the short-circuit breakdown is a thermal breakdown mode due to the short-circuit current, and as such E_{sc} is limited to a constant (r_{sp} has no effect on the design of thermal conductivity of the MOSFET). As a result, the short-circuit withstand time t_{sc} can be controlled by controlling the sidewall P-type pillar ratio, which is a device structure parameter.



(a) The J_{ds} waveforms of short circuit event with various r_{sp}

(b) The r_{sp} dependence of short-circuit withstand time t_{sc} and short-circuit energy E_{sc}

*3 Either values are V_{DD}=650V, V_{gs}= 20V, 150°C

Fig. 6 The waveforms of short circuit event with various r_{sp} and the r_{sp} dependence of short-circuit withstand time t_{sc} and short-circuit energy E_{sc}*3

2.5 Trade-off control of DC loss/AC loss ratio and short-circuit capability

Based on the results of sections 2.2, 2.3 and 2.4, the dependence of DC loss, AC loss and short-circuit withstand time t_{sc} on the sidewall P-type pillar ratio were calculated. The DC loss was calculated from the $R_{on,sp}$ value, and the AC loss was calculated by referring to the switching loss value at R_g = 5Ω, based on the assumption that the device is driven at 20kHz.

The results are shown in Fig. 7. t_{sc} can be increased with the use of a structure with high r_{sp}, wherein the DC loss increases slowly but the AC loss remains almost constant. The r_{sp} is a key parameter for designing the DC loss and short-circuit withstand time t_{sc}, and this revealed that Mitsubishi Electric's trench SiC-MOSFETs can be adapted to suit various applications required of SiC-MOSFETs by adjusting the r_{sp} design.

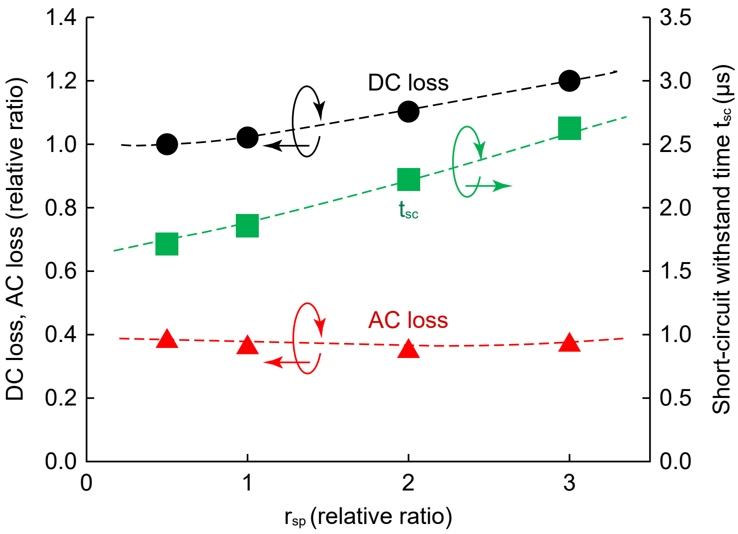


Fig. 7 The relationships between total DC/AC losses, t_{sc} and r_{sp}

3. Conclusion

While trench SiC-MOSFETs are capable of lower losses, their high conductivity means it is difficult to ensure short-circuit capability if a short-circuit occurs in the device. To meet the requirements of a diverse range of applications, a method is needed for controlling the short-circuit capability through the device structure design. Mitsubishi Electric has achieved trade-off control between lower resistance and higher short-circuit withstand time by controlling the short-circuit current resulting from adjustment of the sidewall P-type pillar ratio (r_{sp}) for the device structure of Mitsubishi Electric's proprietary trench-type SiC-MOSFETs. Mitsubishi Electric will continue to move ahead with mass-production of its trench SiC-MOSFETs that are capable of meeting the requirements of a diverse range of applications.

References

(1) Fukui, Y., et al.: Effects of Grounding Bottom Oxide Protection Layer in Trench-Gate SiC-MOSFET by Tilted Al Implantation, Materials Science Forum 1004, 764-769 (2020)
(2) Tanaka, R., et al.: Performance Improvement of Trench-Gate SiC MOSFETs by Localized High-Concentration N-Type Ion Implantation, Materials Science Forum 1004, 770-775 (2020)
(3) Sugawara, K., et al.: A Novel Trench SiC-MOSFETs Fabricated by Multiple-Ion-Implantation into Tilted Trench Side Walls (MIT2-MOS), PCIM Europe 2021, 504-508 (2021)

MITSUBISHI ELECTRIC CORPORATION