High integration of SiC power modules using the multi-functional Si chip technology

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Abstract

In recent years, efforts to promote the electrification of automobiles have been accelerating worldwide to achieve a decarbonized society. In response, the demand for power semiconductors which efficiently convert electrical power increases rapidly. Our company has developed power modules equipped with Si-IGBT, such as the T-PM (Transfer molded Power Module) known for its compact size and high reliability, and the J1 Series, which integrates cooling fins for compact size and high-power density [1]. However, in order to further reduce size, improve efficiency, and increase power density, we are developing a new series of power modules equipped with SiC-MOSFET. This paper shows one of the miniaturization technologies of the module utilizing a multi-functional Si chip adopted in the new power module.

1 Introduction

Mitsubishi Electric has been developing SiC devices and SiC power modules with planar-type SiC-MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistors) for railway, Industry, home appliance, and automotive applications since the 1990s.

Recently, we have been developing a new power module with our latest trench-gate-type SiC-MOSFET, which enables us to reduce power losses and increase output power compared to conventional planar SiC-MOSFET [2].

We are in the process of developing a new T-PM (Transfer molded Power Module) for automobiles, which is equipped with a trench gate type SiC-MOSFET. This new power module achieves further miniaturization and higher power density than the conventional T-PM, while also offering high functionality, such as temperature detection and short-circuit protection for the power chip. To realize this module, a highly integrated design approach for the internal structure of the power module is important. Therefore, we propose a multi-functional Si chip as a key device for achieving this high integration. In this paper, we explain the technical features of the multi-functional Si chip.

2 Overview of new power module

Fig.1 shows the images and lineup of our new power module. The new module is our latest generation T-PM, and it is a half-bridge (2in1) module with package dimensions of 26.5mm × 73.9mm × 6.92mm (including main terminals). It can accommodate either SiC-MOSFET or Si-RC-IGBT in the same package structure. By changing the number of chips and the number of modules in parallel, it is possible to configure a 6in1 module that can handle a wide range of outputs from less than 50kW to 300kW for motor applications.

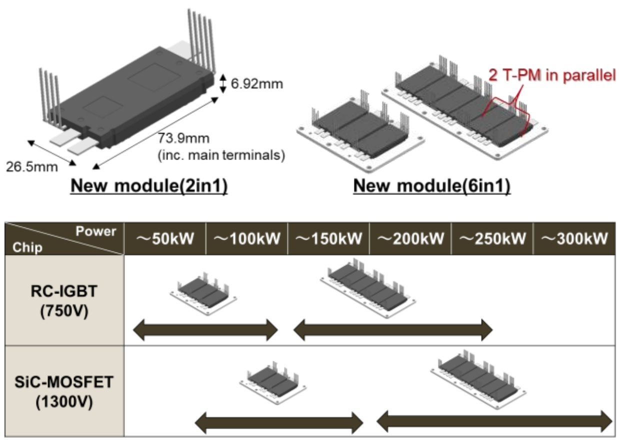


Fig. 1. Images and Lineup of the New Power Module

Fig.2 shows the equivalent circuit of the new module. The RC-IGBT module is equipped with an on-chip temperature sensor and current sensor. The SiC-MOSFET module, on the other hand, features a temperature sensor, DESAT diode, balance resistor, and a control terminal called SCM (Short Circuit Monitor) for short-circuit protection. The temperature sensor, DESAT diode, and balance resistor for the SiC-MOSFET module are integrated into the multi-functional Si chip connected to the SiC chip.

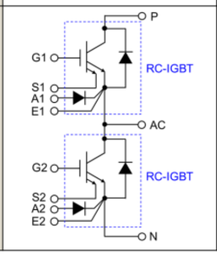
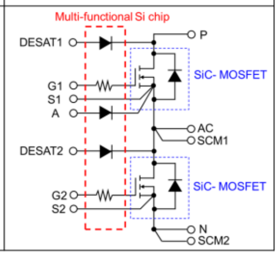
	2in1 New module (Si)	2in1 New module(SiC)
Device	Si RC-IGBT	SiC MOSFET
Circuit Configuration Half bridge		

Fig. 2. Equivalent circuit of the new power module

3 Multi-functional Si chip

3.1 Overview

Many SiC-MOSFET power modules are composed of multiple power chips in parallel, with balance resistors for stabilization of the current balance between the chips and the thermistor or temperature sensing diode for temperature detection integrated into the power module. However, incorporating these circuit elements into the module necessitates dedicated circuit patterns, which can hinder miniaturization and high-power density. To address this issue, we are developing the multi-functional Si chip that consolidates balance resistors, diode for temperature detection, high-voltage diode (DESAT diode), and source wiring onto a single chip, contributing to the miniaturization and high-power density of the module.

We introduce the following three features of the multi-functional Si chip:

(1) The SiC-MOSFET is optimized through its functional integration into the multi-functional Si chip.

(2) Miniaturization of the module is achieved through the integration of the DESAT diode.

(3) It has a temperature sensing function that exhibits excellent thermal response.

In addition, we introduce some of the verification results regarding the feasibility of parallel operation of the multi-functional Si chip with the SiC-MOSFET.

3.2 Effects of functional integration into the multi-functional Si chip

The layout comparison of SiC-MOSFET with and without the use of the multi-functional Si chip is shown in Fig.3. SiC-MOSFET can incorporate temperature sensing diode, gate balance resistor, and current sensor within the chip. However, this can lead to challenges such as a reduction in the active area for main current conduction and an increase in chip size. Additionally, SiC chips are more expensive than Si chips, so increasing chip size or the number of chips in a module can result in higher module costs. To address these challenges, the use of the multi-functional Si chip allows for the consolidation of sensing functions and gate balance resistors into a single chip. As a result of this integration, the size of SiC-MOSFET was reduced by approximately 10% compared to the conventional structure, and the chip layout was optimized to maximize current conduction capability.

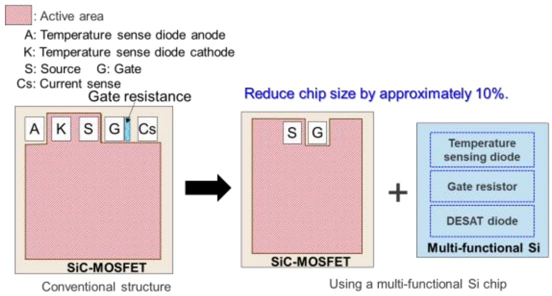


Fig. 3. Comparison of layout images for SiC-MOSFET with and without the use of the multi-functional Si chip

3.3 Miniaturization achieved through the integration of the DESAT diode

In the conventional module structure, to achieve short-circuit protection using DESAT, the high voltage from the SiC-MOSFET drain was directed to the signal terminal and connected to the DESAT diode mounted on the control board. This required ensuring a certain distance between the high voltage signal terminal and the low voltage signal terminal, which hindered module miniaturization. However, by using the multi-functional Si chip with an integrated DESAT diode, the high voltage signal terminal and the space for the DESAT diode on the control board were no longer needed. In addition, by integrating the temperature sensor and source wiring into the multi-functional Si chip along with the DESAT diode, we were able to simplify the substrate pattern within the power module. As a result of this integration, the module size was reduced by approximately 16% compared to the conventional structure.

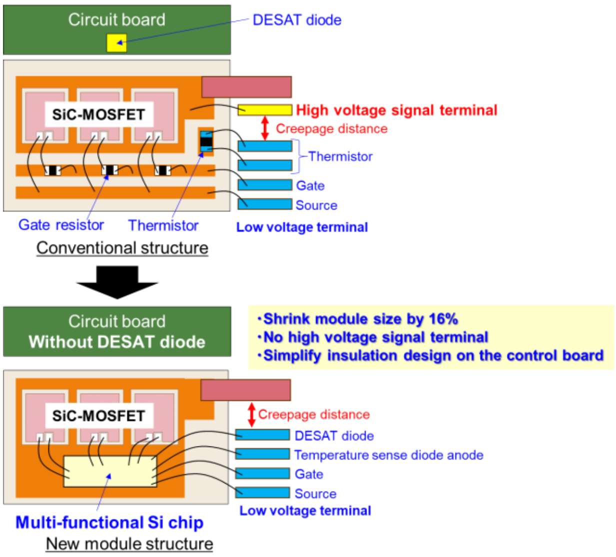


Fig. 4. Miniaturization of the module through the adoption of the multi-functional Si chip

3.4 Temperature detection function

The multi-functional Si chip can be mounted on the same conductive substrate adjacent to the SiC-MOSFET. This setup not only enables the detection of cooling abnormalities in the power module but also the detection of abnormal heat generation in the power chip because of its fast thermal response.Fig.5 shows the thermal response evaluation results of the temperature sensing diode of the multi-functional Si chip. When a DC current of 150A (approximately 50A per chip) was applied to the body diode of the SiC-MOSFET, which was connected in parallel with three chips, the maximum temperature difference between the SiC-MOSFET and the multi-functional Si chip was approximately 40℃ (Fig.5-1). This result confirmed that it is possible to indirectly detect the temperature of the power chip using the temperature sensing diode. Furthermore, the time constant of the temperature sensing diode during DC conduction at 150A was 0.51[sec], confirming that it quickly follows the heat generation of the power chip, demonstrating its excellent thermal response(Fig.5-2).

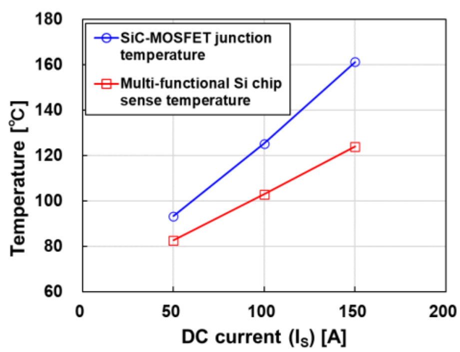


Fig. 5-1. Comparison of saturation temperatures between SiC-MOSFET and the multi-functional Si chip

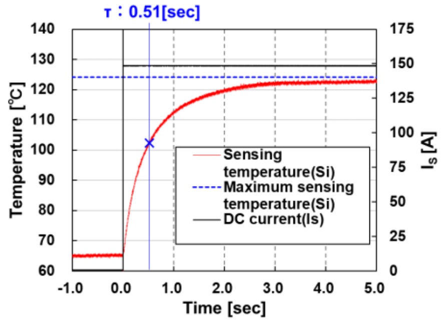


Fig. 5-2. Thermal Response Characteristics of the Temperature Sensing Diode on the multi-functional Si Chip

3.5 Adaptability to operation with SiC-MOSFET

The multi-functional Si chip is mounted on the same conductive board as the SiC-MOSFET, and in order to maximize the capabilities of the SiC-MOSFET, a chip design that does not inhibit high-speed switching operation is required. Specifically, it is necessary to adapt to high dv/dt and surge voltage during high-speed switching operation of SiC-MOSFET, as well as operation in high temperature environments. We made numerous prototypes and conducted actual machine verification. By improving the multi-functional Si chip, we achieved stable operation with the SiC-MOSFET. In this paper, we introduce some of the results confirming the feasibility of operation of the SiC-MOSFET and the multi-functional Si chip in our new module (6in1) evaluation kit (Fig.6).

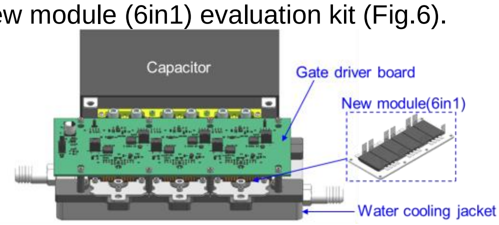


Fig. 6. Evaluation kit for the new module

3.5.1 High-speed switching operation results

In the double pulse test of the new module evaluation kit, considering some variations such as power supply voltage and driver board, we present the representative switching waveform under conditions where the surge voltage and dv/dt could potentially reach their maximum values.

Fig. 7 shows the turn-off switching waveform when the gate resistance Rg(off) is adjusted so that the surge voltage closest to the chip becomes about 1300V at T_j=-40℃, V_{DD}=870V, I_D=1000A. In the waveform of Fig. 7, there is no gate oscillation or malfunction of the multi-functional Si chip, and it has been confirmed that the multi-functional Si chip can switch normally even under the environment of T_j=-40℃.

ISBN 978-3-8007-6414-3

Next, Fig. 8 shows the recovery switching waveform when the gate resistance Rg(on) is adjusted so that the surge voltage closest to the chip becomes about 1300V at T_j=175℃, V_{DD}=870V, I_S=1000A. The dv/dt at this time is 16.9[kV/us], but there is no malfunction of the multi-functional Si chip, and it has been confirmed that the multi-functional Si chip can switch normally at high speed even under the high temperature environment of T_j=175℃.

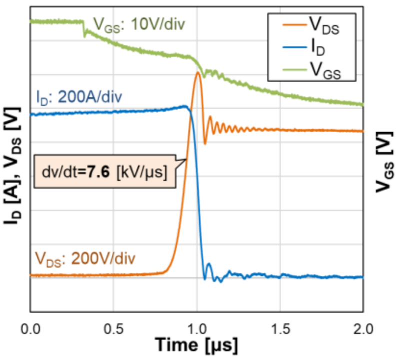


Fig. 7. The representative turn-off switching waveform of the new module at T_j=-40℃

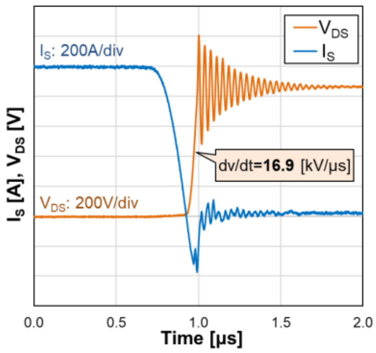


Fig. 8. The representative recovery switching waveform of the new module at T_j=175℃

3.5.2 Short circuit detection by DESAT diode

We introduce a short-circuit protection function utilizing a DESAT diode incorporated in the multi-functional Si chip. Fig. 9 shows a short-circuit detection circuit, and Fig. 10 shows the comparison of the protection capabilities of short-circuit protection using only the DESAT circuit and short-circuit protection combining the DESAT circuit and the SCM circuit . The short-circuit evaluation conditions are as follows : V_{GS}=21.2V, T_j=25℃, V_{DD}=600V.

We explain the short-circuit protection operation of the SCM circuit. When a short circuit occurs in the new module, a reverse electromotive force is generated at the SCM terminal due to the stray inductance of the module package. The SCM circuit detects this reverse electromotive force and attenuates the gate voltage before the DESAT protection operates, suppressing the short-circuit current. After the SCM circuit operates, the DESAT circuit operates and completely cuts off the gate voltage.

As shown in Fig. 10, the short-circuit protection function operates after the typical mask time of the DESAT circuit during a short circuit, and it has been confirmed that a short circuit can be properly detected with the DESAT diode incorporated in the multi-functional Si chip. Furthermore, by combining the DESAT circuit and the SCM circuit for short-circuit protection, it is possible to significantly reduce the short-circuit energy [3],[4].

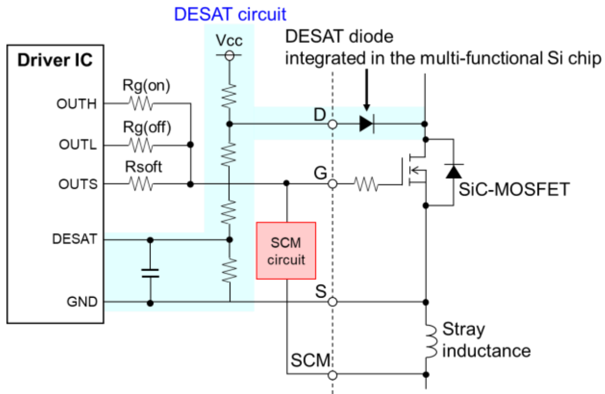


Fig. 9. Short-circuit detection circuit

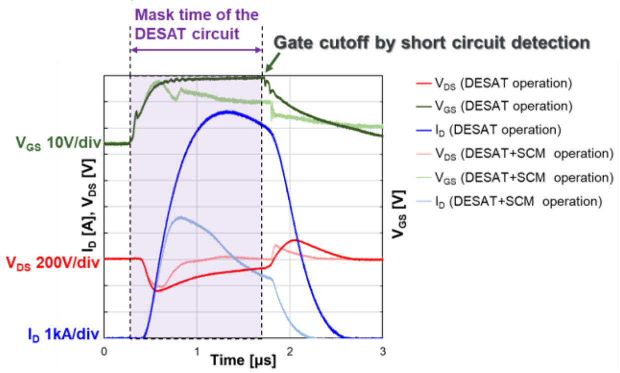


Fig. 10. Short-circuit evaluation results

3.5.3 Inverter operation results

We introduce the results of the inverter operation verification of the new module evaluation kit.

In the inverter evaluation, shown in sample form in Fig. 11, we initially conducted a thermal resistance evaluation to investigate the relationship between the chip temperature of the SiC-MOSFET and the multi-functional Si chip during DC energization. The measurement results of the SiC-MOSFET temperature (T_j) and the multi-functional Si chip temperature (T_s) when a direct current was applied between the source and drain of each T-PM (2in1) are shown in Fig. 12. From this temperature relationship between T_j and T_s, it is possible to indirectly measure the chip temperature (T_j) of the SiC-MOSFET from the chip temperature (T_s) of the multi-functional Si chip during inverter operation.

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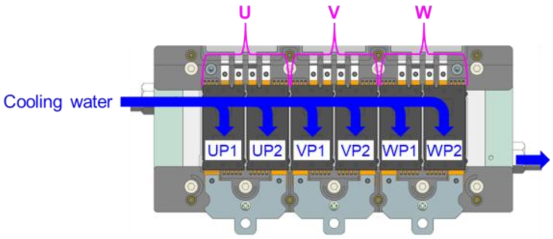

Fig. 11. Sample form during thermal resistance evaluation

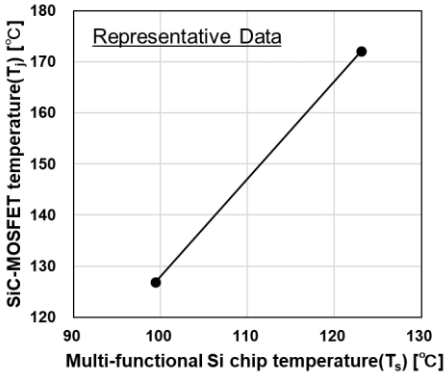

Fig. 12. The relationship between the SiC-MOSFET temperature (T_j) and the multi-functional Si chip temperature (T_s) during DC energization

Next, Fig. 13 shows the chip temperature measurement results during inverter operation. The inverter operation conditions are V_{DD}=800V, I_O=500Arms, fc=10kHz, T_W=65℃, Flow rate=10L/min, and LLC (Long Life Coolant) concentration=50%.

In Fig. 13, the SiC-MOSFET chip temperature calculated from the multi-functional Si chip temperature during inverter operation is approximately 157℃, and it has been confirmed that this is equivalent to the SiC-MOSFET temperature calculated by thermal simulation. Furthermore, it was confirmed that no malfunction of the multi-functional Si chip occurred under the above inverter operating conditions, and that the inverter could operate normally. In addition, the target of T_j=175℃ or less has also been achieved.

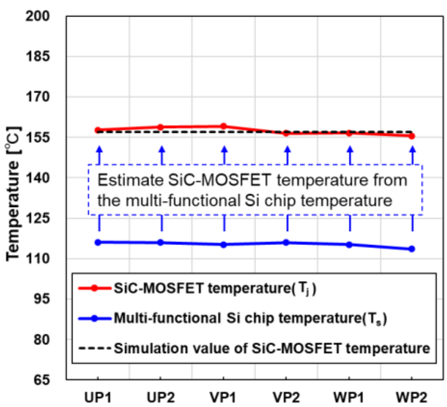

Fig. 13. Temperature of each chip during inverter operation

4 Conclusion

In this paper, we discussed a new SiC power module that combines Mitsubishi Electric Corporation's conventional T-PM technology with a new proprietary technology. We are developing the new SiC power module with the aim of further reducing losses, miniaturizing, and increasing power density compared to conventional Si power modules. Among them, the adoption of a multi-functional Si chip allows us to integrate circuit elements and protection functions, greatly contributing to the miniaturization, increased power density, and enhanced functionality of the power module. We continue to actively work on power module development to accelerate the electrification of automobiles.

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ISBN 978-3-8007-6414-3