Power Module for Automotive "J3 Series"

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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.

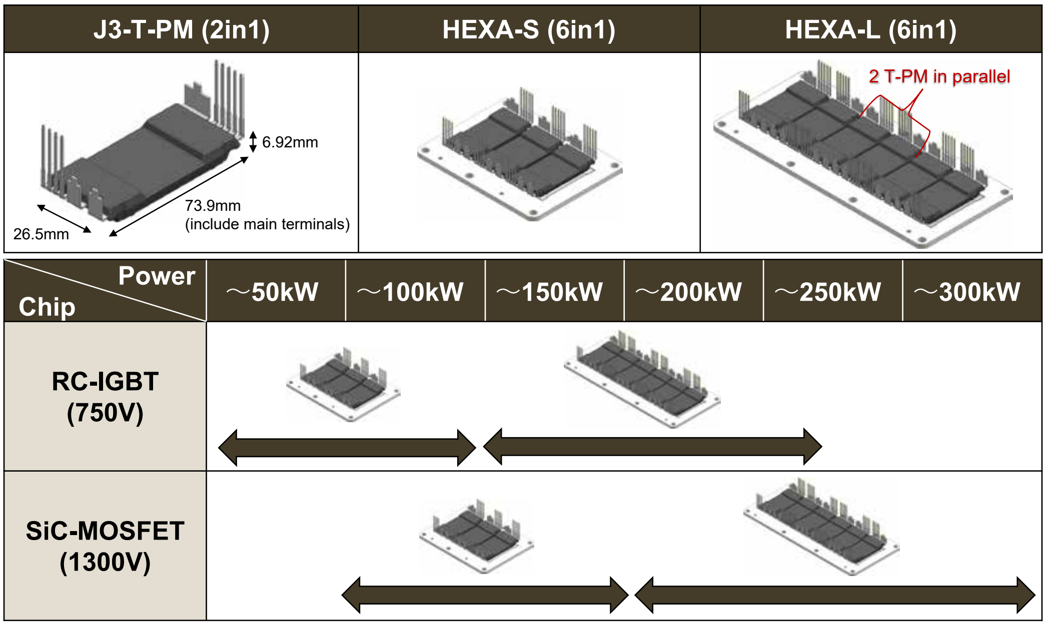


Fig. 2 Appearance and lineup of J3 series

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.

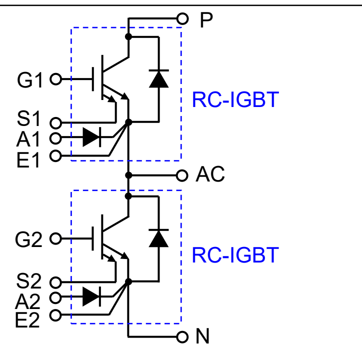
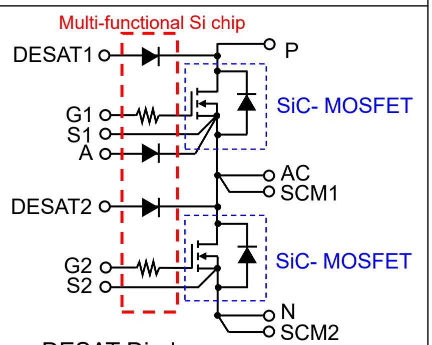
	J3-T-PM (2in1)	
Device	**Si** RC-IGBT	**SiC** MOSFET
Rated voltage	750V	1300V
Rated current	400A	350A
Circuit Configuration **Half bridge**	 ・On-chip temperature sense ・On-chip current sense	 ・DESAT Diode ・Temperature sense (Outside chip) ・SCM terminal (for SC protection)

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).

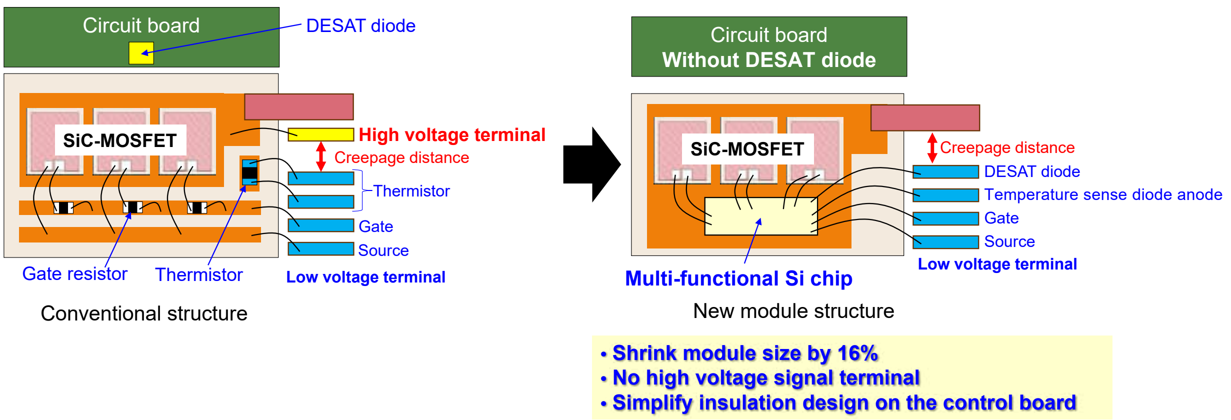


Fig. 4 Module size reduction by function integration into multi-functional Si chip

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.

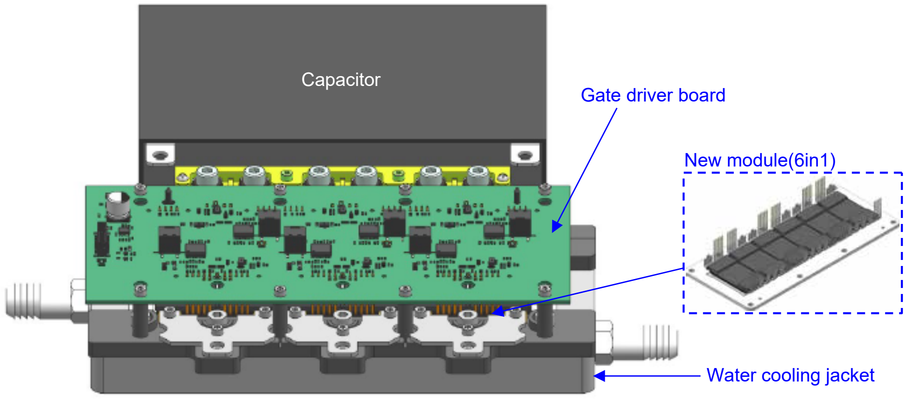
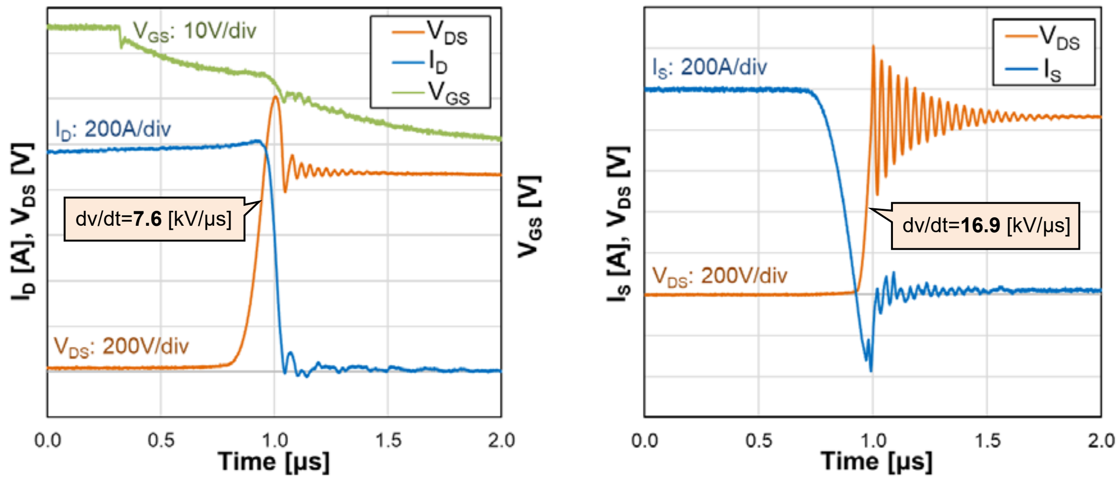


Fig. 5 Evaluation kit of HEXA-L



(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)