Transient Thermal Characterization and Analysis for Next Generation SiC Power Module

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Abstract

Power modules play a pivotal role in modern electrical systems, enabling efficient energy conversion and delivery in various applications. Silicon carbide (SiC)-based power modules, with their superior material properties, have emerged as a cutting-edge solution, offering higher efficiency, power density, and temperature tolerance. Nonetheless, the compact form factor of SiC devices poses significant thermal management challenges. This paper introduces a SiC device-based power module with dual-side cooling capability. We present and demonstrate a systematic approach to evaluating its transient thermal characteristics under power cycling conditions. The proposed approach involves fabrication of test vehicles with recommended materials, power cycling tests under specific conditions designed to meet the temperature fluctuation requirements, and structure function-based transient thermal analysis to estimate the thermal characteristics of the SiC power module. Our results underscore the importance of implementing a transient testing and analysis approach for SiC power modules to ensure their reliability in applications subjected to dynamic loads and switching conditions.

Introduction

Power modules serve as fundamental elements in modern electrical systems, facilitating efficient energy conversion and delivery. These modules are essential components in various applications, including motor drives, renewable energy systems, industrial automation, marine and aerospace [1, 2]. Silicon-based power modules offer moderate efficiency and performance. They provide a balance between cost-effectiveness and reliability, making them accessible for various industries [3]. However, after more than half-century of evolution, the performance of the silicon-based power semiconductor devices has approached its physical limits, such as high switching losses, low temperature operation, and low power density. In contrast, silicon carbide (SiC)-based power modules represent a cutting-edge advancement in power electronics. Leveraging the superior material properties of SiC, such as high thermal conductivity and wide bandgap, these modules deliver higher efficiency, higher power density, and higher temperature tolerance[4, 5]. On the other hand, power modules based on the SiC devices have smaller form factors and higher packaging density, which will lead to higher density of heat dissipation. In turn, it will bring a big challenge to their thermal design and thermal management [6,7]. Therefore, systematic thermal analysis and effective thermal management play a critical role in the development of the SiC based high-power modules, especially the transient thermal characterization and analysis under active power cycling conditions[8, 9].

In this paper, a SiC chip based power module with dual side cooling capability is proposed and developed. To evaluate the transient thermal characteristics of the proposed SiC power module under different power cycling test conditions, the test vehicles with the recommended materials are fabricated at first for the transient thermal evaluation. Then, the power cycling test has been conducted using a commercial test setup. The case and junction temperature of the power module at each cycle have been measured. Finally, we conduct a structure-function-based transient thermal analysis using the measured transient thermal data to estimate the power module's thermal characteristics.

SiC Power Module Design and Development

The SiC power module proposed for transient thermal characterization and analysis in this study is a lead-frame based module with double side cooling capability, as shown in Fig. 1, which presents the concept and design of the proposed SiC power module for (a) schematic structure, and (b) perspective view of the power module.

As shown in Fig. 1, the power module is constructed on a lead frame with silver sintering die attachments and consists of two high-power rated SiC power semiconductor devices. The copper lead frame acts as a structural backbone for the module to provide mechanical support, electrical connections, and thermal paths for the SiC devices. Meanwhile, copper clips are soldered on the top side of the SiC devices to establish electrical connections with the SiC devices. On the both sides of the SiC power module, liquid cooled cold plates are integrated, and these cooling plates are designed with intricate fin structures to enhance heat dissipation. Between the leader frame and cooling plates, electrically insulated thermal interface materials (TIMs) with high thermal conductivity are applied to enhance the thermal performance. The SiC power module is with footprint of 40mm x 40mm. the lead frame and the copper clips are made of copper and cold plates are made of aluminum. Additionally, the power module is encapsulated with an epoxy molding compound (EMC) material to provide protection against environmental factors and mechanical stress for the SiC devices and internal components.

Test Vehicle Fabrication

The fabrication process of a SiC (Silicon Carbide) power module involves several steps, including SiC chip attachment, copper clip bonding, molding, dicing, back-grinding, and mechanical milling [10]. The process flow is presented in Fig. 2. In detail, the fabrication starts from a patterned lead frame (Fig. 2a), followed by the following processes to fabricate the test vehicles. (a) Dispense silver sintering die attach materials onto the selective Ag plating area of the customized lead frame (Fig. 2b). (b) Attach SiC devices to the lead frame using die attach materials and perform the curing process (Fig. 2c). Place preformed solder balls on the source and gate pads of the SiC die, as well as on the Ag plating area of the lead frame (Fig. 2d). Attach customized copper clips to the assembly and conduct a reflow process for the preformed solder materials (Fig. 2e). Perform a series of processes of wafer-level molding, wafer singulation, back-grinding, and machine milling to expose the clips and outer leader terminals (Fig. 2f). The fabricated test vehicle is shown in Fig. 2g without cooling plate and Fig. 2h with cooling plate.

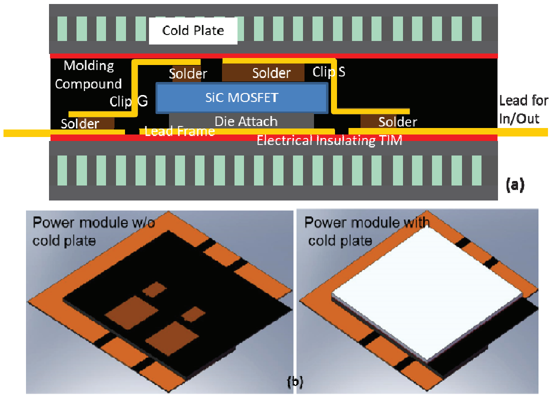

Fig. 1. Concept and design of the proposed SiC power module for (a) Schematic structure, and (b) perspective view of the power module

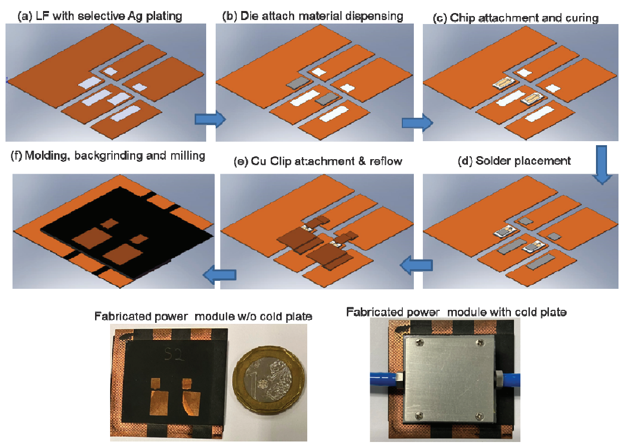

Fig.2 Process flow of test vehicle fabrication and the photo of the fabricated test vehicle

Method for Transient Thermal Test and Analysis

The method for the transient thermal test on a SiC power module and the method for thermal structure function analysis based on thermal measurement result have been demonstrated in this study. The thermal transient measurement is applied to the test vehicle under testing. The sequence of transient thermal test is presented in Fig. 3. At first, the test vehicle is pressed against the liquid cooled cold plates with a constant liquid temperature and heated up by a steady heating current, resulting in a heating power in the SiC chip. Meanwhile, the current and heating power are monitored as shown in Fig. 4 for the structure function analysis. As soon as the test vehicle reached a thermal steady state, the heating current was switched to the sensor level as 10 mA and the cooling temperature curve is measured. The junction temperature derived from the measured forward voltage of the body diode at the end of the cooling phase is the Tjmin, and the junction temperature derived from the measured forward voltage of the body diode after switching the cycling current off is the Tjmax. The ΔTj is calculated through the derived Tjmax and Tjmin. The transient temperature profiles during power cycling test are shown in Fig. 5. After the raw data is measured, the corresponding structure functions can be derived from the temperature curves in postprocessing software T3ster-Master, and the structure function for the test is shown in Fig. 6. As such, thermal characteristics and thermal structure function of the SiC power module can be analyzed.

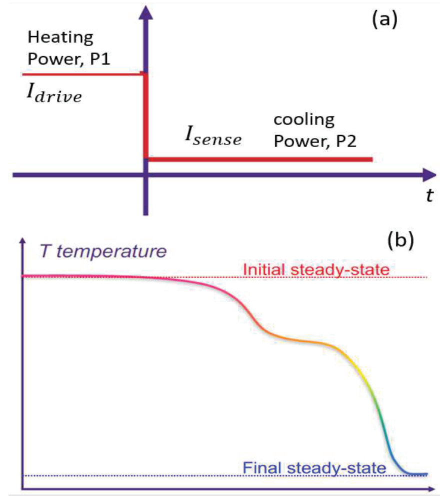

Fig.3 The sequence of transient thermal test

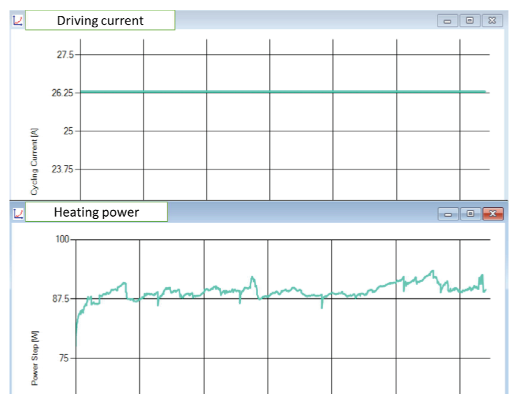

Fig.4 Driving current and heating power apply to the test vehicle for transient thermal test

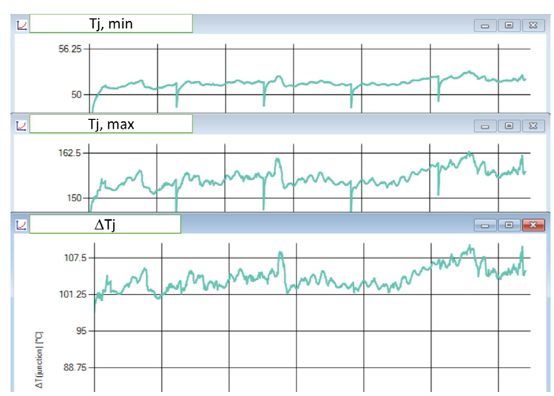

Fig. 5 Junction temperature measurement during the transient thermal test

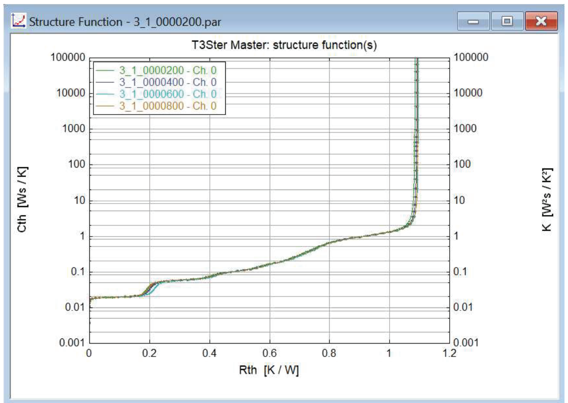

Fig. 6 Derived thermal structure function of the SiC power module

Results and Discussion

Transient thermal measurement during the power cycling test is a valuable way to evaluate the module's thermal performance under dynamic operating conditions. Also, it is critical for assessing the SiC power module's reliability and safety, especially in applications where they are subject to dynamic load and switching conditions. In this study, several test vehicles have been tested. The results of two representative test vehicles are discussed, i.e., a good test vehicle which passed power cycling test (test vehicle 1) and a bad test vehicle which failed power cycling test (test vehicle 2).

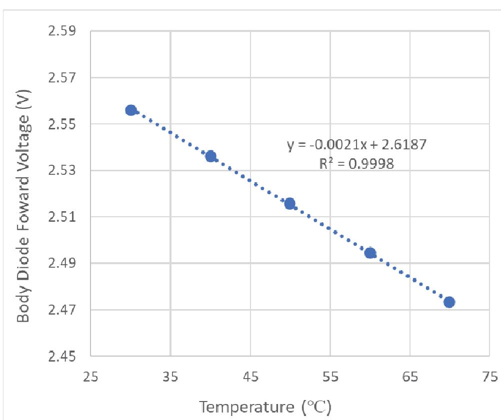

Fig.7 Variation of the forward voltage of the body diode in the SiC module with the SiC temperature for test vehicle 1.

Table 1. Operation conditions of the transient thermal test via the power cycling test for test vehicle 1.

No	Description	Conditions
1	Driving current (A)	~31
2	Target heating power(W)	~120
3	Sensing current (mA)	10
4	Gate voltage on (V)	20
	Gate voltage off (V)	-5
5	Power-on time (s), heating	3
	Power-off time (s), cooling	9

The forward voltage of the body diode in a SiC MOSFET varies with SiC device temperature. Hence, measuring the forward voltage of the body diode in a SiC MOSFET is a common method to estimate the device's temperature. Calibration is essential for accurately measuring temperature using the forward voltage of a diode. The calibration curve relating forward voltage to temperature for test vehicle 1 is shown in Fig.7.

The operation conditions of power cycling test for test vehicle 1 are listed in Table 1. Particularly, the target maximum junction temperature is 175°C and minimum temperature is 25°C for the power cycling test. To meet this temperature requirement, the driving current is fixed at 31A, on/off time is set as 3s on/9s off. The monitored driving current and heating power during the power cycling test for test vehicle 1 is presented in Fig. 8.

The junction temperature is continuously monitored using during the entire power cycling test for test vehicle 1. The junction temperature, including the Tjmax, Tjmin and ΔTj, under these operation conditions for the power cycling test are presented in Fig. 9. It can be found that the heating power climbs at initial cycles and then becomes stable. That is reasonable since the electrical resistance of the power module increases with the increased chip temperature at initial cycling period. Then the chip temperature becomes stable in each cycle, hence the heating become stable.

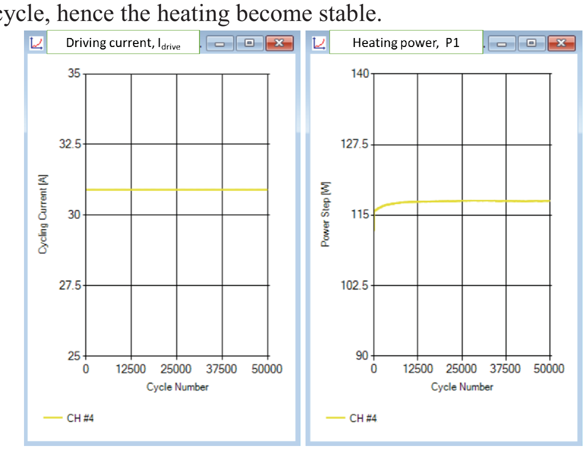

Fig. 8 Driving current and heating power apply to the test vehicle for transient thermal test via the power cycling test for test vehicle 1

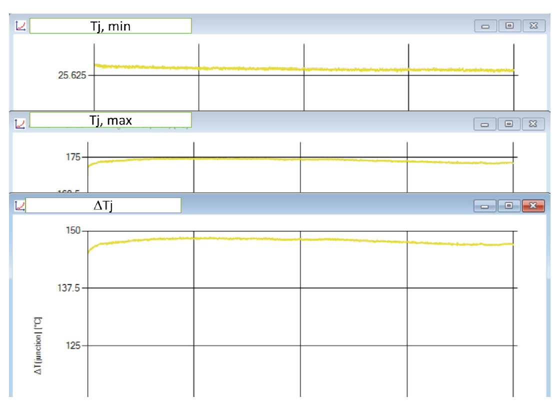

Fig. 9 Junction temperature measurement during the transient thermal test via the power cycling test for test vehicle 1

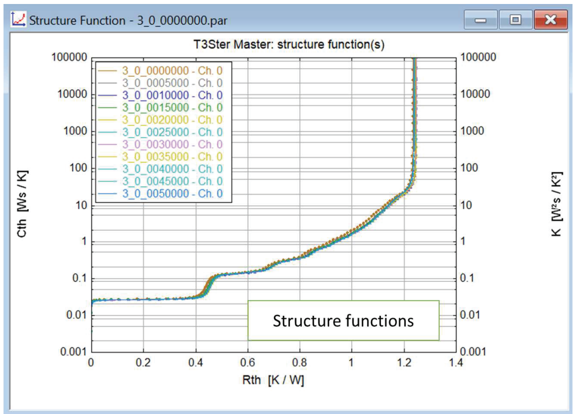

Fig. 10 Thermal structure function of the SiC module for test vehicle 1

The structure function of the SiC module for test vehicle 1 is shown in Fig. 10. The structure function is generated at intervals of every 5000 cycles during the power cycling test. The total number of cycles for the power cycling test is 50000 cycles. It can be observed from Fig. 10 that the structure function remains consistent at each specified cycle interval, indicating that there have been no failures in the SiC module during the power cycling test for the entire 50000 cycles.

Table 2. Operation condition for the transient thermal test via the power cycling test for test vehicle 2

No	Description	Conditions
1	Driving current (A)	~33
2	Target heating power (W)	~105
3	Sensing current (mA)	10
4	Gate voltage on (V)	20
	Gate voltage off (V)	-5
5	Power-on time (s), heating	1.5
	Power-off time (s), cooling	14

The operation conditions of power cycling test for test vehicle 2 are listed in Table 2. Similar to test vehicle sample 1, the target maximum junction temperature is 175℃ and minimum temperature is 25℃ for the power cycling test. To meet this temperature requirement, the driving current is fixed at 33A, on/off time is set as 1.5s on/14s off.

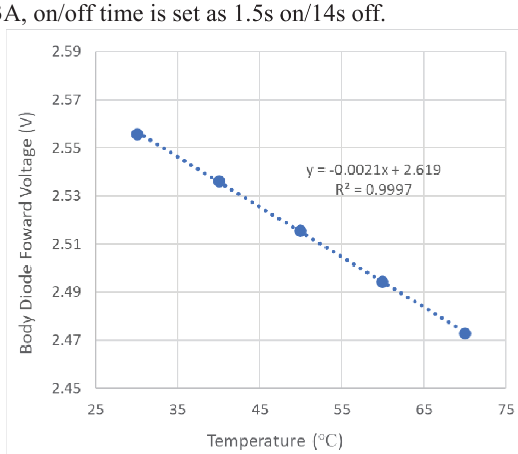

Fig. 11 Variation of the forward voltage of the body diode in the SiC MODSFET with the SiC temperature for test vehicle 2

Prior to the transient thermal measurement for the power cycling test for test vehicle 2, the temperature dependent forward voltage of the body diode in the SiC device is calibrated. The calibration curve relating forward voltage to temperature for test vehicle 2 is shown in Fig.11.

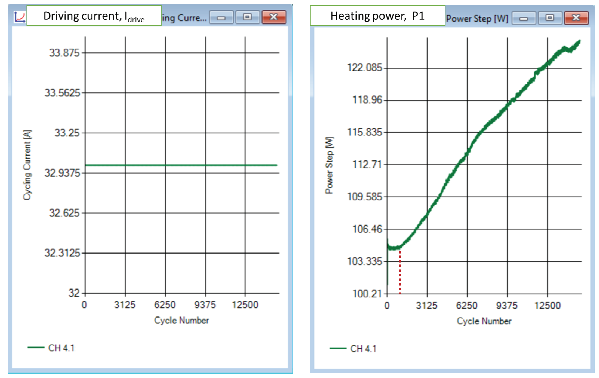

Fig. 12 Driving current and heating power apply to the test vehicle for transient thermal test the power cycling test for test vehicle 2

As per the power cycling test for the test sample 2, the driving current is set as 33A. The monitored current and heating power during the test is presented in Fig. 12. It can be seen from this figure that the heating power remains stable during the initial phase of the power cycling test (approximately 1000 cycles), then it starts to climb with the increasing power cycles continuously and does not attain a stable state any more. In sequence, the sustained rise in heating power leads to a continuous increase in both the maximum junction temperature (Tj, max) and the temperature gradient (ΔTj) of the SiC module, despite the cooling junction temperature (Tj, min) remaining constant as shown in Fig. 13, which presents the transient junction temperature variation during the power cycling test for test vehicle 2. Furthermore, this uninterrupted growth of the junction temperature subsequently drives an increase in heating power. Finally, the sample failed the power cycling test because the junction temperature exceeded the predefined maximum allowed junction temperature.

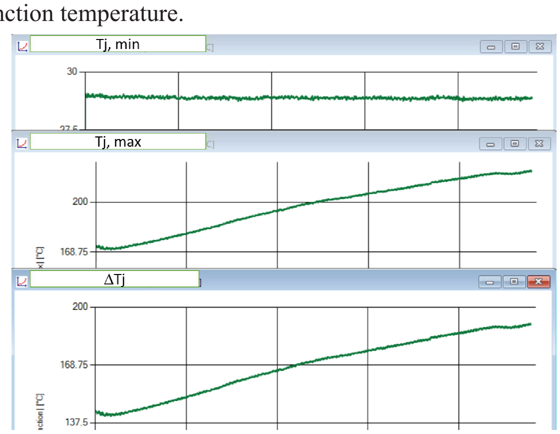

Fig. 13 Junction temperature measurement during the transient thermal test via the power cycling test for test vehicle 2

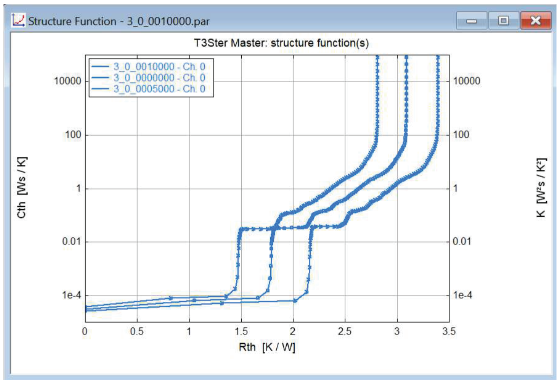

Fig. 14 Thermal structure function of the SiC module for test vehicle 2

The structure function of the SiC module for test vehicle 2 is shown in Fig. 14. Similar to the test for test sample 1, the structure function is generated at intervals of every 5000 cycles during the power cycling test, and the target total number of cycles for the power cycling test is 50000 cycles. However, due to the continuous increase in junction temperature, the test was terminated around 12000 cycles when the maximum junction temperature reached the predefined maximum allowed value. A significant discrepancy in the structure function is evident at 0 cycles, 5000 cycles, and 10000 cycles in Fig. 14, indicating a degradation in reliability at 5000 cycles and 10000 cycles. Ultimately, this test sample failed the power cycling test at approximately 12000 cycles.

Summary

The study demonstrates the importance of transient thermal measurements in evaluating the thermal performance and reliability of SiC power modules under dynamic operating conditions. The results of power cycling tests on two test vehicles have been analyzed and discussed in this study. The major findings include:

- Test vehicle 1 passed the power cycling test, and its structure function remained consistent throughout the test.
- Test vehicle 2 experienced a continuous increase in heating power, leading to a rise in maximum junction temperature and temperature gradient.
- A significant discrepancy in the structure function is evident at 0 cycles, 5000 cycles, and 10000 cycles for test vehicle 2
- Test vehicle 2 ultimately failed the power cycling test around 12000 cycles.

These findings highlight the need of transient test and analysis methodology for SiC power modules to ensure their reliability in applications subject to dynamic load and switching conditions.

Acknowledgments

This work was supported by the Science and Engineering. Research Council of A*STAR (Agency for Science, Technology and Research) Singapore, under Grant No. A20H9a0242.

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