The Influence to Uniform Current Distribution of SiC MOSFET Modules Based on the 3rd Quadrant Characteristics

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Abstract. This paper concentrated on the 3rd quadrant characteristics of 1200V/300A full SiC MOSFET modules produced by four SiC mainstream manufacturers; and compared the diode forward voltage (VSD) performances of “SiC MOSFET only” and SiC MOSFETs modules with SiC Schottky barrier parallel diode. The characteristics of the diode forward voltage showed that module A exhibits the same trend with the PiN diode, whereas modules B, C and D exhibit the characteristics of SBD. Through the failure analysis, it was verified that there is no parallel SBD in module A, meanwhile, it was assumed that modules B, C and D integrate a positive temperature characteristic SBD by wire bonding. The existence of SBD can prevent the modules from burning out due to excessive heating caused by non-uniform current distribution. From the analysis, it illustrated that the body diode can be used as the parallel SiC SBD, but further research on the uniform current distribution of the body diode is needed.

1. Introduction

Silicon carbide (SiC) has the advantages of wide bandgap, high breakdown electric field strength and high saturated carrier drift speed. It is considered as the ideal material for high-temperature, high-voltage and low-loss power devices. Through recent progress in the crystal growth and process technology of SiC, the production of medium-voltage (600-1700V) SiC Schottky barrier diodes (SBDs) and power metal-oxide-semiconductor field-effect transistors (MOSFETs) has finished [1].

SiC MOSFETs can replace the traditional Silicon (Si) insulated gate bipolar transistors (IGBTs), due to the advantages of SiC material. For traditional Si IGBT modules, a parallel Si-FRD is needed by wire bonding, when it comes to SiC MOSFETs, the body diodes can replace the FRD completely. The operating frequency can be increased with the parasitic capacitances of SiC MOSFETs reduced without the parallel FRD. Nowadays Si IGBTs are widely used because of low saturation voltage, characteristic of ease of driving and so on while the improvement of response speed and size is not easy to solve [2]. SiC MOSFETs can avoid these problems due to the unipolar device structure and higher breakdown electrical field. SiC MOSFETs, as the perfect substitutes for IGBTs, can significantly reduce the size and cost of power electronic devices by lowering conduction and switching losses. Besides, the use of the built-in SBD by SiC MOSFETs can not only omit the external...
freewheeling diode, but also prevent the forward degradation [3]. An excellent example is a novel device called an SBD-wall-integrated trench MOSFET (SWITCH-MOS) [4].

Dr. Wada and his colleagues demonstrated the availability of high voltage SiC power systems by using the MOSFETs and SBDs [5]. Dr. Kawahara et al. achieved compact 3.3 kV and 6.5 kV SiC MOSFETs whose active area is only about a half/quarter of the total active area of a conventional MOSFET and a coupled external SBD [6]. The team of Dr. Fukunaga verified this structure enables us to get an accurate time response of junction temperature for SiC MOSFETs [7]. However, it is still not clear if there are problems with the 3rd quadrant characteristics of SiC MOSFETs with a parallel SiC SBD, and the influence mechanism of uniform current distribution is ambiguous and inadequate.

To investigate the relationship between reverse conduction characteristics and current distribution, the 3rd quadrant characteristics of “SiC MOSFET only” and SiC MOSFETs with SiC Schottky barrier parallel diode were analysed in this work.

2. Experiments

In order to better analyse the uniform current distribution of SiC MOSFET module with a parallel SiC SBD, the 3rd quadrant characteristics and body diode characteristics are necessary which can be extracted some important information such as knee voltage, forward voltage and the trend of drain-source current. In this experiment, the main objects are different SiC MOSFET modules (A, B, C, D) from four SiC mainstream manufacturers. Figure 1 depicts the circuit diagrams of these modules. The diodes shown in the Fig. 1 (D1 and D2) are the body diodes for the corresponding MOSFETs. As the most basic reference, module A has a common structure of SiC Trench MOSFET as shown in Fig. 1 (a). Module B, as an improved product, is a half-bridge module consisting of SiC DMOSFET and SiC SBD as shown in Fig. 1 (b). The circuit diagrams of the remaining two modules are the same as module B’s, and they only make some changes to the device models.

![Figure 1. Circuit diagrams of four modules.](image)

In terms of performance parameters, the four modules have the same maximum drain-source voltage ($V_{DSS}$)~1200V, and the gate-source voltage ($V_{GSSop}$) can vary from -5V to +20V. To analyse the effect of conducting channel on the 3rd quadrant and body diode characteristics, the test values of $V_{GS}$ were taken as -5V, 0V and 5V in the experiment, corresponding to the states of accumulation, depletion and inversion. As the value of the drain-source voltage ($V_{DS}$) changed, the change of relevant drain-source current ($I_{DS}$) was measured while keeping the $V_{GS}$ at a certain value. The simplified test circuit schematic for these modules is shown in Fig. 2.

The following parameters were determined according to the device characteristics and set as inputs to the test. The gate voltage ($V_{G}$) ranged from -5V to 5V in steps of 5V so that $V_{GS}$ could be three different values as mentioned above when the source voltage ($V_{S}$) was 0. The value of the drain voltage ($V_{D}$) varied from 0V to -4V, and its linear step was 10mV. Drain current compliance was 100A and drain power compliance was 200W, which were used as the limiting conditions of the experiment.
In order to ensure the accuracy of the experiment, every module was measured separately five times for the upper and lower bridge circuit due to the half-bridge structure of the modules. Continuous measurements of the same module can increase the temperature of the device, which is detrimental to the stability of data. Therefore, there was an appropriate time interval between each measurement.

3. Results
Four SiC MOSFET modules were packed for this test. Each module was measured under the test circuit with $V_{DS}$ varying from 0V to the suitable negative voltage in accordance with the proposed approach. The measurements shown in Fig. 3 illustrated that the drain-source current curves of the upper and lower bridge circuit for the same module are basically overlapping (module A and module B, $V_{GS}$=0V). Besides, the current curves of upper and lower bridge circuit (not shown in this paper) are almost identical for $V_{GS}$=5V and $V_{GS}$=-5V. For modules C and D, the same is true for the same $V_{GS}$, which means either of the curves can represent the characteristics of the corresponding module.

Fig. 4 shows the results of this test at room temperature. For module A with only a body diode, the changing trend of the curve is approximately same when $V_{GS}$ is different. However, there is a large gap in the forward voltage drop for different $V_{GS}$. And compared with $V_{GS}$=5V, the threshold voltage for $V_{GS}$=-5V increases by about quintupling. Relatively, for the other modules with a parallel SiC SBD, the measured curves of $I_{DS}$ basically overlap for $V_{GS}$=-5V and $V_{GS}$=0V. The curve of $I_{DS}$ moves down slightly for $V_{GS}$=5V, and it can be noted that the forward voltage drop in the third quadrant is further lowered if a parallel SiC SBD is used in addition to turn on the SiC MOSFET.

4. Discussion
Figure 5 illustrates the structure of one of the SiC power devices: double-implanted MOSFET (DIMOSFET) and shows the current directions by the arrows for $V_{DS}>0V$ and $V_{DS}<0V$. The body
diode is in the off state when the power MOSFET is on. Relatively, when the power MOSFET is turned off, the body diode will be turned on and play the role of freewheeling current [8, 9]. Therefore, the characteristics of the body diode have a direct impact on the power MOSFET. That means it is very important to improve the characteristics of the body diode, which can improve the efficiency of power MOSFET.

![Graph 4: The \( I_{DS} - V_{DS} \) curves of four modules.](image4)

Figure 4. The \( I_{DS} - V_{DS} \) curves of four modules.

![Graph 5: Structure and current direction of DIMOSFET.](image5)

Figure 5. Structure and current direction of DIMOSFET.

SiC MOSFET without a parallel SBD (Module A) clearly exhibits the same trend with the PiN diode. And it has the large knee voltage so that there are relatively large conduction losses in the freewheeling operation. The limitation of this body diode is its high forward voltage particularly at low negative gate voltages [10]. In addition, current conduction induces the bipolar and reliability
degradation of body diode due to expansion of stacking faults (SF) by the recombination of injected minority carriers.

Modules B, C and D exhibit the characteristic of SBD in the experiment. As the freewheeling diode, SBD can suppress the current conduction of intrinsic body diodes in SiC MOSFETs during the dead-time phase of inverters which causes bipolar degradation. And the voltage drop through the SBD needs to be lower than the built-in potential of the PN junction in order to suppress the body diode conduction of the MOSFET. When it works, the reverse current flows through SBD rather than through the PN body diode, which results in suppressing conduction losses and bipolar degradation, and increasing the operating frequency. When $V_{GS}=5V$, the channel of SiC MOSFET is formulated so that the drain-source current is larger due to the channel current as shown in Fig.4.

Multiple chips are often connected in parallel within MOSFET modules to increase current capability and power ratings. However, non-uniform current distribution is a common problem in these Multichip Power Modules (MPMs). Power diodes are the key components in MOSFET modules. Figure 6 schematizes the forward current-voltage characteristics of a SiC PiN diode and a SiC SBD, where the temperature characteristics ($25^\circ\text{C}$, $100^\circ\text{C}$ and $200^\circ\text{C}$) of SiC power diodes are compared [11, 12].

The minority carrier lifetime of the bipolar devices increases with increasing temperature, resulting in an increase in the number of minority carriers. As the bipolar device, the forward voltage drop of the SiC PiN diode decreases with the increase of temperature because the high dose of minority carriers injects into the epitaxial region. However, this negative temperature coefficient of the forward voltage drop for SiC power device is unfavorable to the uniform current distribution. The thermal mismatch will occur in the whole system if the imbalance reaches a certain order of magnitude.

On the other hand, SiC SBD mainly shows the positive temperature coefficient of the forward voltage drop, which makes the system more stable in parallel circuits. The uniform current distribution can be achieved automatically due to this characteristic. Once the current of one of the parallel SiC devices is larger, the rising temperature will increase the on-resistance and the current will decrease as a result. In addition, due to the lower barrier of SBD, its threshold voltage is smaller than other diodes. It means that the thermal mismatch of SBD is less severe even if the non-uniform current distribution occurs. Therefore, connecting the MOSFET module and SiC SBD in parallel is very meaningful for the uniform current distribution.

![Forward I-V characteristic curves of SiC PiN and SiC SBD.](image)

**Figure 6.** Forward I-V characteristic curves at the different temperatures ($25^\circ\text{C}$, $100^\circ\text{C}$ and $200^\circ\text{C}$).

5. Conclusion
The measurement of the $3^\text{rd}$ quadrant characteristics for SiC MOSFET modules produced by four SiC mainstream manufacturers were mainly carried out. The results showed that module A uses the body diode for freewheeling directly, while modules B, C and D integrate the parallel SiC SBD to
improve the reliability of devices. The body diode of module A is directly used to get the good reverse recovery behavior, but higher requirements are put forward in terms of uniform current distribution due to its negative temperature coefficient. On the contrary, this problem is avoided in modules B, C and D because of the positive temperature coefficient of the parallel SiC SBD and they also suppress conduction losses and bipolar degradation. Designers of the manufacturers usually give priority to the reliability, performance and manufacturing cost of the products. Hence the advantages and disadvantages of different degrees are reflected in the overall performance and single index of the device. According to the different applications and characteristics of SiC devices, we suggest that manufacturers give priority to the advantages of reliability, and the requirements of individual parameters should be appropriately reduced in the design process.

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