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Characterization of SiC power module for high switching frequency operation

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Abstract: The authors developed SiC power module with large rated current by connecting multiple SiC MOSFETs in parallel. This paper characterizes and evaluates its high switching frequency operation performance by comparing it with the conventional Si IGBT module. First, the static current–voltage characteristics and terminal capacitance–voltage characteristics are evaluated. Then, the switching behavior of the SiC power module is experimentally evaluated in the DC–DC boost converter circuit. The results clarified the superiority of the developed SiC power module for fast switching capability and low switching loss.

Keywords: SiC device, power module, high frequency switching, terminal capacitance, switching loss

Classification: Electron devices, circuits, and systems

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1 Introduction

Power conversion circuits are indispensable for high efficiency and high functionality utilizing of electrical power and energy. Various types of SiC power switching semiconductor devices have been researched and developed in an effort to reduce loss in power conversion circuits, and also to establish additional functionality in energy usage by overcoming the limitations stemming from conventional Si power devices. Lorenz et al. and B. Ozpineci et al. presented the reduction of switching loss in a converter circuit by applying a high voltage SiC Schottky barrier diode [1, 2], and T. Funaki et al. reported the power conversion circuit operation in high temperature ambient (450°C) with SiC JFET [3, 4]. However, the evaluation of SiC power device for large current application circuit has not been sufficiently discussed due to the difficulty in manufacturing defect-free large area SiC device. The authors developed large current rating SiC power module by parallel-connecting multiple SiC MOSFETs in one package; its switching characteristics are evaluated in this paper. The experiments are evaluated using the practical power conversion circuit of DC-DC boost converter. The low switching loss and fast switching capability of the developed SiC power module is established by comparing it with the conventional Si IGBT module having comparable voltage and current ratings.

2 SiC power module

The developed SiC power module had a one-leg configuration consisting of an upper and lower arm with a rated current of 80 A. This current rating was achieved by connecting four vertical-type SiC MOSFET chips in parallel. Each chip was 2.4×4.8 mm in size and had voltage and current ratings of 1200 V and 20 A, respectively. The summed gate width for the total cells in a chip of SiC MOSFET is 2.48 m. The SiC MOSFET chips were attached on the direct bond aluminum (DBA) substrate, which was then mounted on the copper heat spreader to attain sufficient thermal diffusion. The source and gate electrode located at the top surface of the chip were electrically connected to the respective module terminal using heavy aluminum bonding wire. The module was then filled and sealed with heat resistive nanotech resin [5], reaching a high-temperature operation capability. The overview of the developed SiC power module is shown in Fig. 2 (d). The comparative Si IGBT module (CM75TU-24F) had 1200 V and 75 A rated voltage and current, respectively, and one-leg part in a three-leg configuration was used in the experiment.

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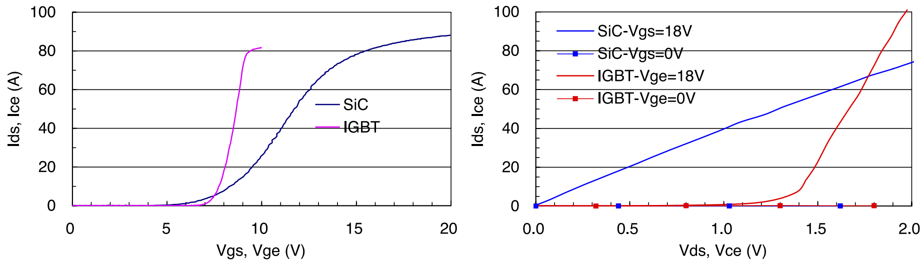
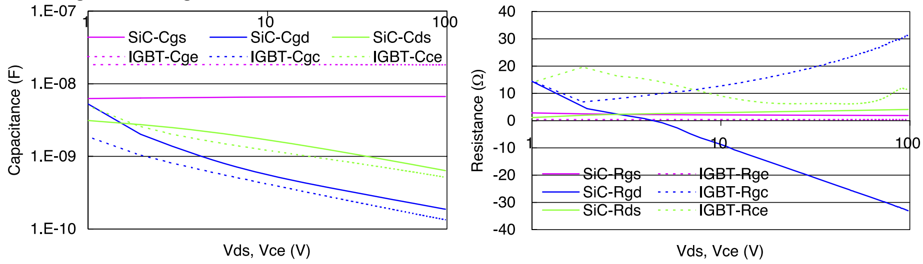
The static electrical characteristics of SiC and Si modules are shown in Fig. 1. The current–voltage characteristics were measured with a curve tracer (Tektronix 371B), and the capacitance–voltage characteristics were measured with an LCR meter and C–V measurement fixture [6, 7]. The threshold gate voltage extracted from V_{gs}-I_{ds} (V_{ge}-I_{ce}) characteristics in Fig. 1 (a) is 5.64 V for the SiC module and 7.01 V for the Si module. The figure also shows the forward transfer admittance of 13.7 S for the SiC module and 55.3 S for the Si module. The threshold gate voltage of the SiC module is lower than that of the Si module; however, the transfer admittance of the SiC module is low and almost one-fourth of the Si module. The transfer admittance corresponds to the voltage gain and results in suffering a reduced Miller effect in the switching operation of the SiC module. The forward voltage and current characteristics are shown in Fig. 1 (b). The current in the SiC module is proportional to V_{ds} with 2.73 mΩ for conducting condition (V_{gs} = 18 V). The Si module shows 1.3 V knee voltage drop for the pn junction, and gives 25.0 mΩ at the rated current (75 A) for V_{ge} = 18 V. The effective on resistance of the Si module becomes higher for smaller current operation. The voltage (V_{ds}, V_{ce}) dependency of terminal capacitances in the power modules are shown in Fig. 1 (c). The gate-source (C_{gs}) and gate-emitter (C_{ge}) capacitance does not vary with V_{ds} and V_{ce}. C_{gs} in the SiC module is 6.25 nF at V_{ds} = 0 V, which is almost one-third of C_{ge} = 18.3 nF in the Si module at V_{ge} = 0 V. This can be attributed to the difference in total active area between SiC and Si module. C_{gd}, C_{ds}, C_{gc}, and C_{ce} change significantly with the applied voltage V_{ds} (V_{ce}). C_{ce} is larger than C_{ds} at V_{ds} = 0 V, but their relation inverts for higher V_{ds}. This reflects the smaller active area and higher impurity concentration in the drift region of the SiC MOSFET than in that of the Si IGBT. The input capacitance C_{iss}



(a) V_{gs}-I_{ds} (V_{ge}-I_{ce}) characteristics. (b) V_{ds}-I_{ds} (V_{ce}-I_{ce}) characteristics.



(c) C-V characteristics (d) ESR-V characteristics.

Fig. 1. Static characteristics of SiC power module and Si IGBT module.

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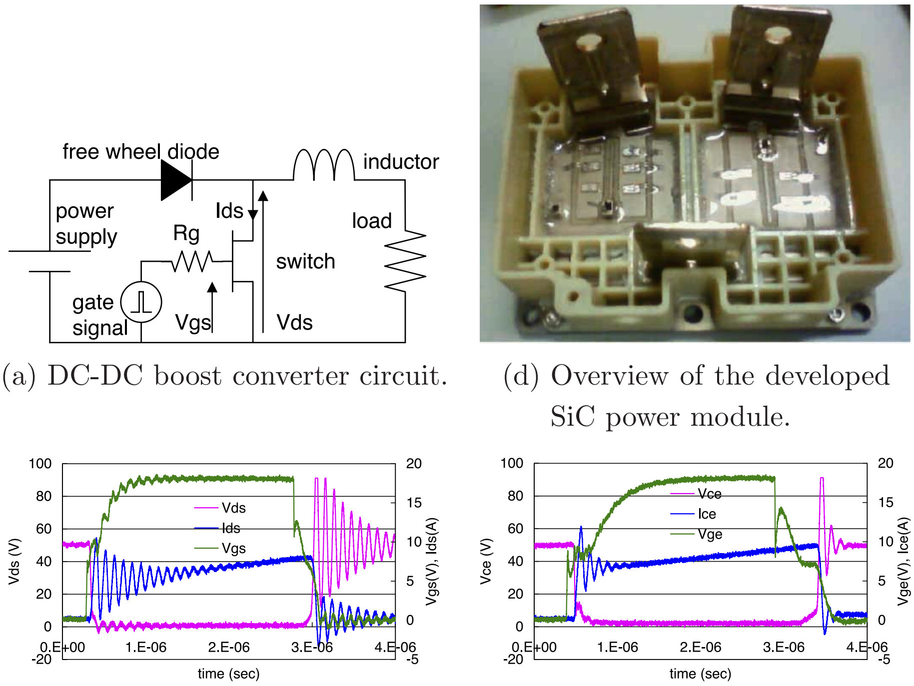
(= $C_{gs} + C_{gd}$) of the SiC module is smaller than C_{ies} (= $C_{ge} + C_{gc}$) in the Si module. The SiC module has slightly larger reverse transfer capacitance C_{gd} than the Si module C_{ge}, but their difference is smaller than the difference in their voltage gain. Thus, less gate charge-up time and less Miller effect is expected for the SiC module, which results in faster switching operation.

3 Switching characteristics of SiC power module

3.1 Transient behavior in switching operation

This section discusses the transient behaviors of the SiC and Si modules in switching operations. The circuit diagram of the DC-DC boost converter used for characterization is shown in Fig. 2 (a). The power module used in this study has a one-leg configuration, in which the lower arm is used as the switch of the boost converter, and the body diode of the SiC MOSFET or fast recovery diode of the Si IGBT module in higher arm is used as the free wheel diode of the converter. Figure 2 (b) shows the V_{gs}, I_{ds}, and V_{ds} behaviors of the SiC module in the switching operation with a 200 kHz switching frequency, 50% duty. Figure 2 (c) is for the Si module. The gate of power modules are driven by 18 V pulse through 5 Ω gate resistance, R_g. A 15.8 Ω load resistance and 19.9 μH inductor is used for continuous current conduction mode operation. The SiC module turns on within 500 ns, but the Si IGBT module takes 1 μs due to larger input capacitance and Miller effect, which can be identified in V_{gs} (V_{ge}) behavior. Also, the SiC module turns off faster than the Si module, though the Si IGBT does not show tail current at turn-off. The switching operation initiates ringing oscillation and the SiC module suffers from less damping than the Si module, although the peak volt-



(a) DC-DC boost converter circuit. (d) Overview of the developed SiC power module.

(b) SiC power module. (c) Si IGBT module.

Fig. 2. Switching behaviors of the tested power modules.

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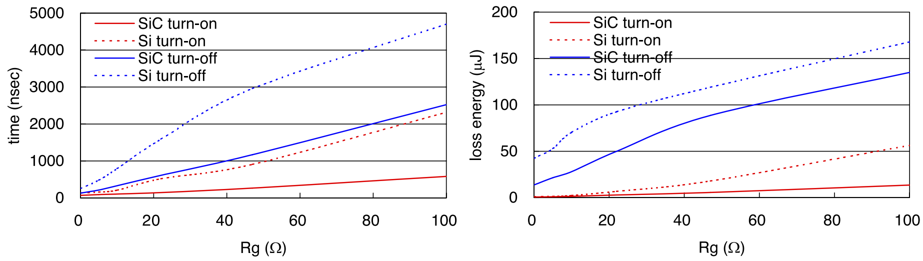
age is the same. The ringing oscillation stems from the mutual interaction between parasitic inductance in the circuit and terminal capacitance in the power module. Both modules were tested using the same circuit setup; therefore, they have the same parasitic inductance intrinsic in the experimental circuit. Thus, the difference in the damping of the ringing can be attributed to the device characteristics. The effective series resistances (ESRs) in the terminal capacitance of the modules are shown as voltage dependency in Fig. 1 (d). The Si module has higher ESR than the SiC module because IGBT attains high conductivity with conductivity modulation by injected minority carrier, then the conductance of the drift region in Si IGBT is much lower than in SiC MOSFET. However, the reason for the negative resistance of R_{gd} in the SiC module is unclear. The higher ESR in Si IGBT module results in fast damping of the ringing. The damping of the ringing for the SiC MOSFET can be improved by decreasing the impurity concentration in the drift region; however, it results in increased on resistance. Therefore, the trade-off between resistance and damping of the ringing should be discussed for the SiC power module.

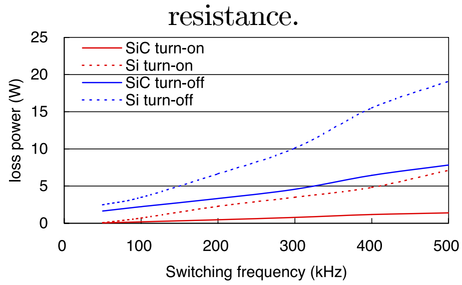
3.2 Evaluation of switching characteristics

Figure 3 shows the extracted switching characteristics of the power module. The switching time to the gate resistance is shown in Fig. 3 (a). All the switching times are almost proportional to the gate resistance. The required switching times for the SiC power module for turn-on and turn-off are one-third and one-half of the Si IGBT module, respectively. Thus, the SiC module achieves fast switching.

Figure 3 (b) shows the switching loss energy for one turn-on and turn-



(a) Switching time to gate resistance. (b) Switching loss energy to gate resistance.



(c) Switching loss power to switching frequency.

Fig. 3. Characterized switching performance of the tested power module.

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off operation of the power module to the gate resistance. It shows that the turn-off loss energy of the Si module is highest and the turn-on loss energy of the SiC module is lowest, regardless of the gate resistance value. The higher gate resistance results in longer switching time, and consequently switching loss energy increases. Figure 3 (c) shows the switching loss power to the switching frequency. The switching loss is in proportion to the number of switching operations, and then it is proportional to switching frequency. The difference in the switching loss between the SiC and the Si module is smaller for a low switching frequency, but the difference increases in accordance with the switching frequency. It shows that the switching loss of the SiC module is less than half of the Si module. This result also shows the suitability of the SiC module for high switching frequency operation.

4 Conclusion

This paper experimentally evaluated the switching characteristics of the developed SiC power module in a DC-DC converter circuit. The comparative study with the conventional Si IGBT module pointed out the fast switching capability of the SiC power module due to small input capacitance and low Miller effect. The short switching period also suppresses the switching loss. Therefore, the suitability of the SiC power module for high switching frequency operation is presented. The improvement of damping for the ringing oscillation occurring at switching operation is regarded as future work.

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