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3.3 kV/1500 A Power Modules for the World's First All-SiC Traction Inverter

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1. Introduction

Silicon carbide (SiC) power devices have attracted much attention as next-generation alternatives to conventional Si power devices for their exceptional material properties. Taking advantage of their benefits, we have already produced large-capacity hybrid SiC power modules with 1.7 kV SiC-SBDs (Schottky Barrier Diodes) and Si-IGBTs (Insulated Gate Bipolar Transistors) [1]. The traction inverter system incorporating the modules was field-tested in commercial railcars operating on a Japanese subway, demonstrating 38.6 % energy reduction compared with the conventional system [2]. SiC power devices have potential for higher blocking voltage such as 3.3 kV, which is required for high-power trains. In the field of handling high voltage and high frequency, SiC unipolar devices, especially MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) show potential for low switching losses while offering comparable conduction losses to conventional Si-IGBTs as well. In this paper, we introduce our SiC-MOSFETs and SiC-SBDs of the 3.3 kV rating for the world's first all-SiC traction inverter.

2. Device Fabrication

The SiC vertical MOSFETs and SBDs were fabricated on n-type 4H-SiC (0001) wafers with a 30 μm lightly doped n-type drift layer (N_D–N_A=3.0×10^{15} cm^{-3}). An originally-developed field limiting ring structure was employed for the junction termination, which guarantees a stable avalanche breakdown at around 4 kV [3]. For reduction of the JFET (Junction Field-Effect Transistor) resistance, multiple high-energy nitrogen implantations (JFET doping, JD) were performed in the JFET region of the MOSFET. The depth and the doping concentration of the JD region were designed to be about 1 μm and 1×10^{17} cm^{-3}, respectively, noting that the profile of the JD was designed not to influence any channel characteristics or the electric field of the gate oxide; therefore, shallow nitrogen implantation was not performed. The MOSFET consists of a parallel conjunction of square-shaped unit cells with a cell pitch of 11 μm. The active areas of the MOSFET and the SBD are 0.83 cm^2 and 0.74 cm^2, respectively. A more detailed fabrication process is described in the literature [4, 5].

3. Results and Discussion

Figures 1 and 2 show the typical static electrical characteristics of the MOSFET and the SBD, respectively. The on-state voltage (V_{DSon}) of the MOSFET estimated at a drain current (I_{DS}) of 94 A and a gate voltage (V_{GS}) of 15 V increased from 2.1 V at 25 °C to 4.3 V at 175 °C. A stable avalanche breakdown of ~4 kV was also recorded. Similar avalanche characteristics were obtained with the SBD. The forward voltage (V_F) of the SBD estimated at a forward current (I_F) of 94 A increased from 2.1 V at 25 °C to 4.6 V at 175 °C. Figure 3 shows the measured turn-off waveforms of the MOSFET with a gate resistance of 67 Ω and a stray inductance of 370 nH at 175 °C. The power supply voltage and the drain current were set at 2.5 kV and 540 A, respectively. The MOSFET can clearly demonstrate its ruggedness in blocking a drain current of more than five times larger than the rated current. We used an internal body diode, which forms in the MOSFET parasitically, in conjunction with the SBD. The body diode showed stable behavior under forward current operation as indicated in Fig. 4 as a result of optimization of the drift layer growth conditions and the originally-developed screening method [6].

We have successfully developed a 3.3 kV/1500 A power module consisting of the SiC-MOSFETs and the SiC-SBDs of the 3.3 kV rating connected in parallel. Figure 5 shows the I_{DS}-V_{DS} characteristics of the module at a V_{GS} of 15 V. The module can handle a current over 1500 A, the largest current for the 3.3 kV rating to date. Figures 6 and 7 show the measured turn-on and turn-off waveforms of the module at 175 °C with a gate resistance of 2.4 Ω and 4.1 Ω, respectively. The turn-on and turn-off power losses were estimated to be 1.44 J and 0.53 J. Nevertheless, the generation loss of the SiC module is reduced by approximately 55 % compared to the Si counterparts. The developed modules are mounted on the world's first all-SiC traction inverter as shown in Fig. 8.

4. Summary

We have successfully developed a 3.3 kV/1500 A all-SiC power module. The generation loss of the SiC module is reduced by approximately 55 % compared to the Si counterparts. The developed modules are mounted on the world's first all-SiC traction inverter.

Acknowledgements

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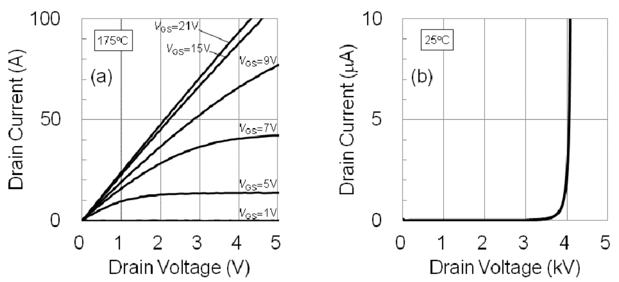

Fig. 1 (a) Output and (b) blocking characteristics of the MOSFET. Specific on-resistance at I_{DS}=94 A and V_{GS}=15 V increases from 19 mΩcm^2 at 25 °C to 38 mΩcm^2 at 175 °C. Threshold voltage at V_{DS}=10 V decreases from ~2 V at 25 °C to ~1 V at 175 °C. Avalanche breakdown with occurs at ~4 kV.

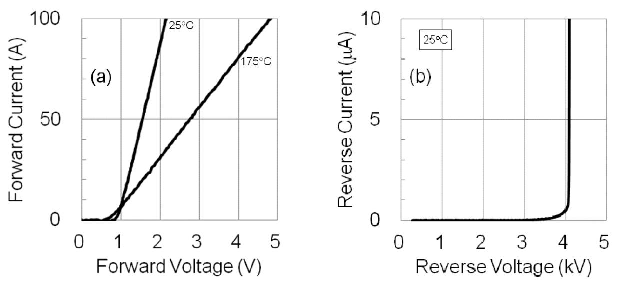

Fig. 2 (a) Forward and (b) reverse characteristics of the SBD. V_F at I_F=94 A increases from 2.1 V at 25 °C to 4.6 V at 175 °C.

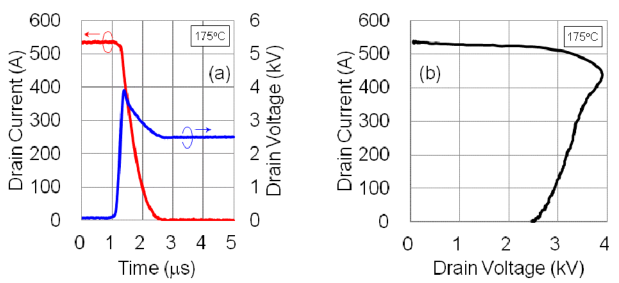

Fig. 3 (a) Turn-off waveforms and (b) RBSOA of the MOSFET. The MOSFET can block drain current of more than five times larger than the rated current.

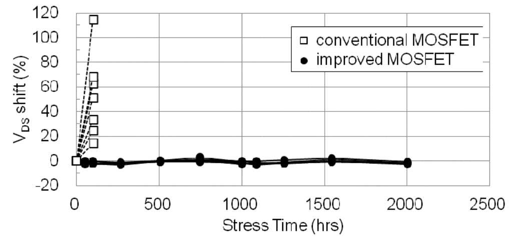

Fig. 4 V_{DS} shifts as a function of the stress time during the long term stress of forward current for body diodes.

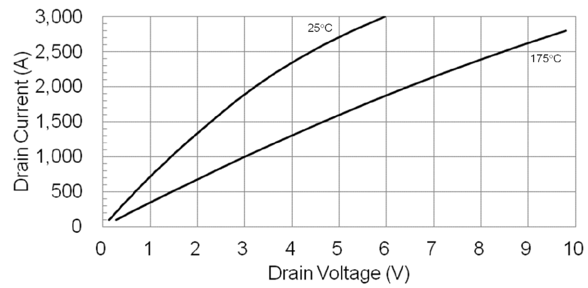

Fig. 5 I_{DS}-V_{DS} characteristics of the developed 3.3 kV/1500 A all-SiC power module. V_{DSon} of I_{DS}=1500 A and V_{GS}=15 V increases from 2.3 V at 25 °C to 4.7 V at 175 °C.

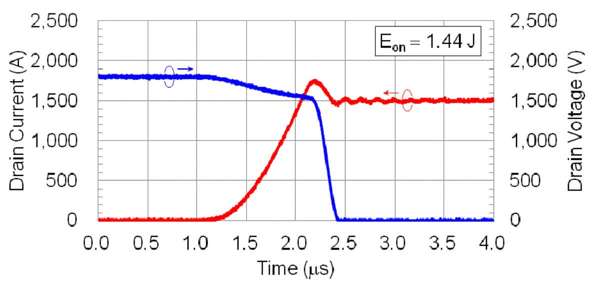

Fig. 6 Turn-on waveform of 3.3 kV/1500 A all-SiC power module (V_{DS}=1.8 kV, I_{DS}=1500 A, V_{GS}=±15 V, T_j=175 °C, R_G=2.4 Ω).

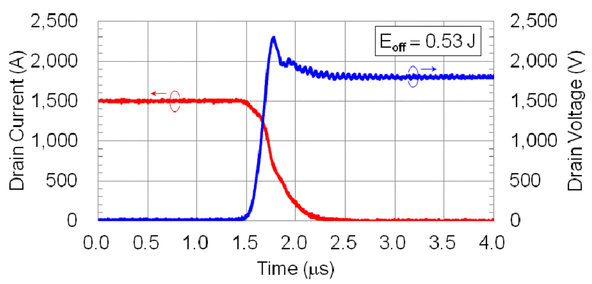

Fig. 7 Turn-off waveform of 3.3 kV/1500 A all-SiC power module (V_{DS}=1.8 kV, I_{DS}=1500 A, V_{GS}=±15 V, T_j=175 °C, R_G=4.1 Ω).

Fig. 8 Railcar traction inverter with all-SiC power modules.