

3.3 KV SiC Power Module with Low Switching Loss

Mitsuhiko SAKAI*, Shigenori TOYOSHIMA, Keiji WADA, Masaki FURUMAI, Takashi TSUNO and Yasuki MIKAMURA

Silicon Carbide (SiC) devices are promising candidates for high power, high speed, and high temperature switches owing to their superior properties. We have been developing SiC metal-oxide-semiconductor field effect transistors (MOSFETs) and SiC Schottky barrier diodes (SBDs) of 3.3-kilovolt class. The fabricated SiC power module successfully reduced switching losses to one-third to that of the conventional Si IGBT module. This paper evaluates the performance of a full SiC module compared to the conventional one.

Keywords: high voltage, low switching loss, SiC MOSFET, SiC SBD, SiC power module

1. Introduction

Due to the rise of consumers' electric bills and a shortage of electric energy, a major crisis awaits. In 2010, the world average ratio of electrical energy consumption to a total of all energy consumption was about 20%, and this ratio is expected to increase rapidly in the future. Therefore, the power converter is required to exhibit high conversion efficiency. The power converter consists of power semiconductor devices (power devices). Power devices are being developed while compatibly attaining high voltage and low power loss. The realization of high-performance power devices will lead not only to enormous energy savings but also to the movement away from fossil fuels and the reduction of environmental pollution.

Silicon (Si) has been the most commonly used semiconductor for power devices, and it has been significantly improved through the development of metal-oxide-semiconductor field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs) and fast recovery diodes (FRDs).

However, now that Si power device technology is relatively mature, it is difficult to achieve innovative breakthroughs using present technology. Finally, silicon carbide (SiC) with wide bandgap seems promising for use in advanced power devices because of its superior physical properties. SiC has superior properties compared to Si, such as higher critical electric field strength, higher saturation drift velocity, and higher thermal conductivity.^{(1), (2)} Now, SiC is making advancements into new markets such as power conditioners for solar power and railroad vehicles.⁽³⁾

We have been developing a SiC power device⁽⁴⁾⁻⁽⁸⁾ as well as 3.3-kilovolt class MOSFETs and Schottky barrier diodes (SBDs). In this paper, we evaluate the performance of a full SiC module compared to a conventional Si IGBT module.

2. Structure and Fabrication of 3.3-kilovolt Class SiC Devices

2-1 Structure and fabrication of MOSFETs

Figure 1 shows the carrier concentration and the thickness of epitaxial growth film to fabricate SiC MOSFETs and SBDs. The target of carrier concentration was $3.0 \times 10^{15} \text{ cm}^{-3}$ and the film thickness was 30 μm . The uniformity of carrier concentration and film thickness within a whole wafer were less than 3% by maximum - minimum.

Figure 2 shows the schematic cross-sectional view of 3.3-kilovolt class MOSFETs. SiC epitaxial layer was grown on a 4° off-axis n-type 4H-SiC (0001) substrate by chemical vapor deposition. A guard ring termination was adopted for the edge.

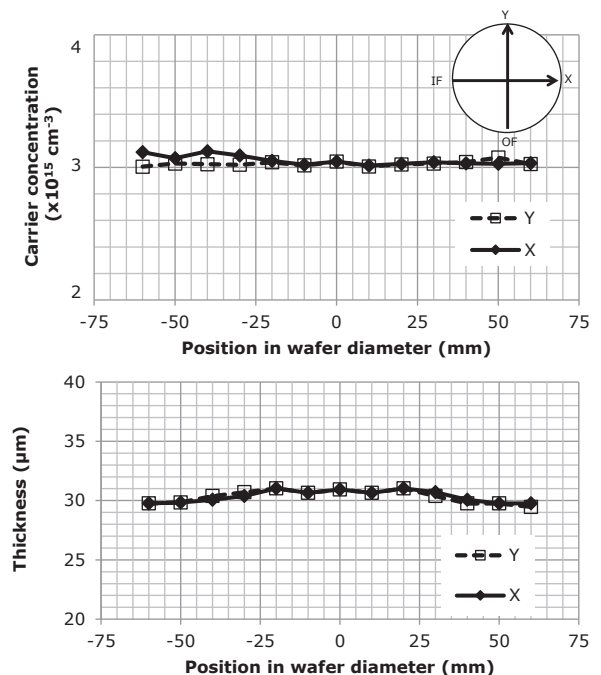


Fig. 1. Uniformity of carrier concentration and thickness of epitaxial layer

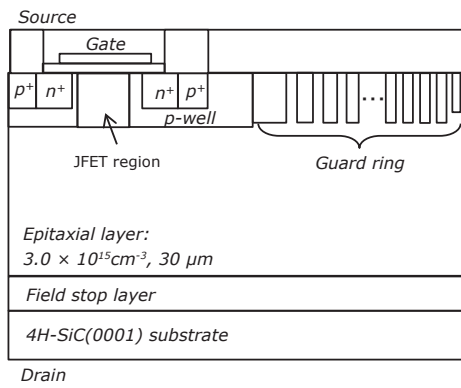


Fig. 2. Schematic cross-sectional view of MOSFET

Guard rings were p regions and formed by an ion implantation. Channel and source regions were similar. In addition, ion implantation to the junction field-effect transistor regions was introduced to improve the on-resistance of MOSFETs. The ion implantation was carried out at 500°C, then an activated anneal was done at 1800°C. Gate oxide was thermally grown, followed by nitridation and post oxidation annealing, resulting in an oxide thickness of about 50 nm. Then a TiAlSi source electrode was fabricated. Next, an Al electrode was deposited and covered by passivation film. Finally, a SiC substrate was thinned by grinding. Some metals were deposited on the backside of the thinned substrate. Then a drain contact was fabricated by a laser anneal. Channel length is 0.8 μm and die size is 6 mm square.

2-2 Structure and fabrication of SBDs

Figure 3 shows the schematic cross-sectional view of 3.3-kilovolt class SBDs. SiC epitaxial layer was grown on a 4° off-axis n-type 4H-SiC (0001) substrate by chemical vapor deposition. Junction barrier Schottky (JBS) structure was adopted. A guard ring termination for the edge was applied. This structure follows that of MOSFETs. JBS and guard rings were fabricated by an ion implantation and activated anneal, and then anode electrode was

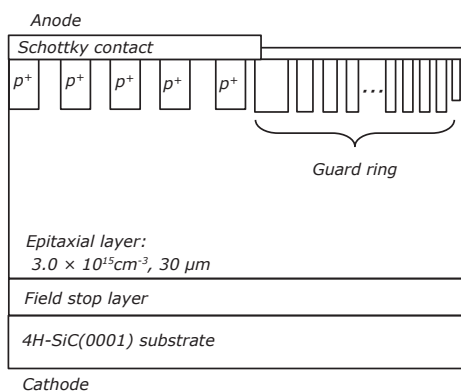


Fig. 3. Schematic cross-sectional view of SBD

deposited. The SiC substrate was thinned by grinding. Then a cathode electrode was deposited, and it formed ohmic contact by a laser anneal. Die size is 6 mm square.

3. Characterization of 3.3-Kilovolt Class SiC Devices

3-1 Characterization of MOSFETs

Figure 4 shows the on-state forward I_D - V_{DS} characteristics of the 3.3-kilovolt class SiC MOSFET. The specific on-resistance with respect to the active area size was estimated to be 14.2 mΩcm² ($V_{GS} = 15$ V, $V_{DS} = 2$ V) at room temperature. Figure 5 shows the blocking characteristics. The blocking voltage is approximately 3850 V. Figures 6 and 7 show the time dependence of the threshold voltage shift (ΔV_{th}).

Figure 6 shows the time dependence of positive gate bias, and Figure 7 shows the negative one. A number of 22 dies are tested. Both results show that the shift of threshold voltage is within the range of ±0.2 V at high temperature for 1000 hours. This means that our MOSFETs are derived from the low trap density at the SiO₂/SiC interfaces.⁽⁸⁾

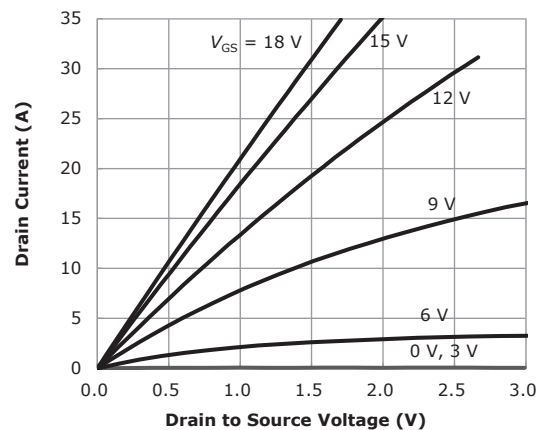


Fig. 4. Forward I_D - V_D characteristics of MOSFET

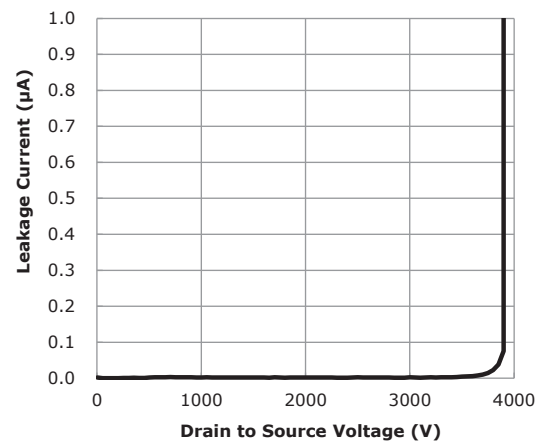


Fig. 5. Blocking voltage characteristics

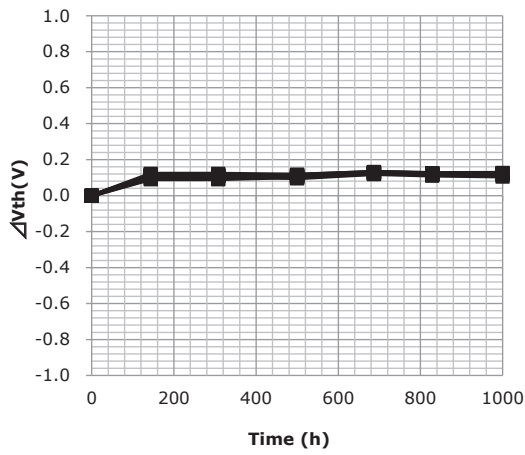


Fig. 6. Time dependence of the threshold voltage shift at positive V_{GS} of 20 V

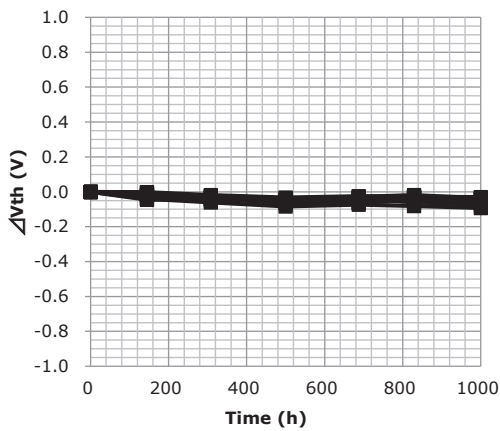


Fig. 7. Time dependence of the threshold voltage shift at negative V_{GS} of -10 V

3-2 Characterization of SBDs

Figures 8 and 9 indicate the forward and reverse I - V characteristics of a 3.3-kilovolt class SBD measured under the temperature range of 25°C to 175°C. The JBS

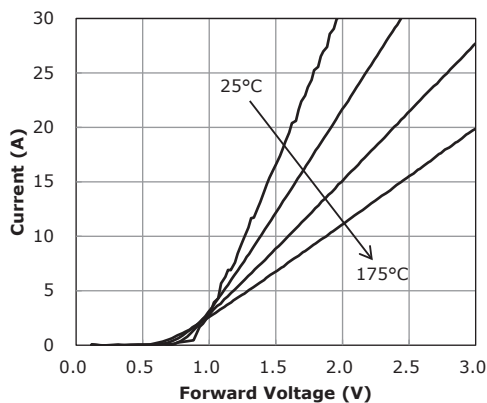


Fig. 8. Forward I - V characteristics of SBD

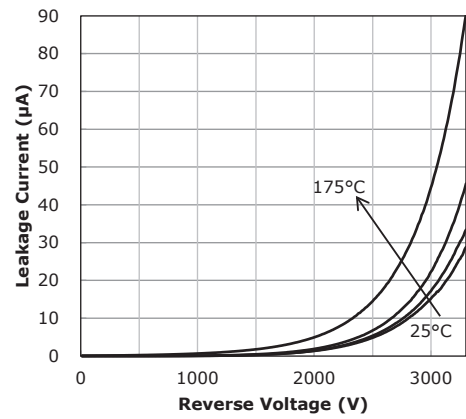


Fig. 9. Reverse I - V characteristics of SBD

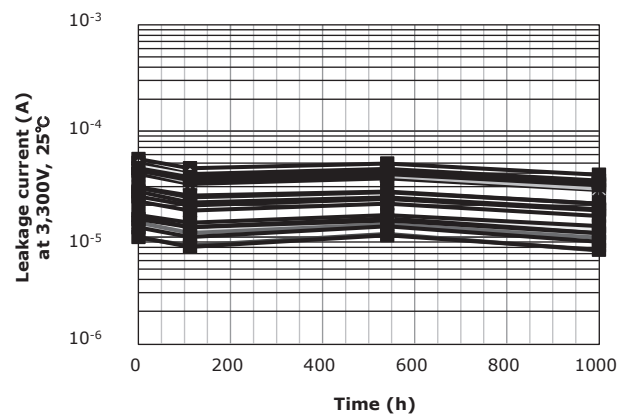


Fig. 10. High temperature reverse bias test

structure with partial p^+ regions under the Schottky contact is formed, sufficiently suppressing the leakage current even at the elevated temperature of 175°C, as well as the well-designed edge termination.⁽⁹⁾ Figure 10 shows the reverse bias test at a high temperature. A number of 22 dies were tested with reverse 3000 V at 150°C. No dies were broken for 1000 hours.

4. Characterization of 3.3-Kilovolt Class SiC Module

4-1 Fabrication of module and estimation of static characteristics

By using the 3.3 kV MOSFETs and SBDs with multi parallel setup, we fabricated a 3.3 kV 400 A full SiC 2 in 1 module and evaluated the static characteristics. Figure 11 shows the appearance of a SiC module. Figure 12 shows the forward I - V characteristics at V_{GS} of 5 V, 10 V, 15 V, and 20 V at room temperature. Figure 13 shows the I - V characteristics at V_{GS} of 0 V. The solid line is our full SiC module, and the dashed line is a conventional IGBT one.

As shown in Fig. 12, the I - V characteristics of MOSFET are different from IGBT because MOSFET can drive a

large current at a low drive voltage. Accordingly, this current flows linearly at a low voltage field and we obtained a low on-resistance below 400 A of rated current. **Fig. 13** shows the current at V_{GS} of 0 V for applying from source to drain. It shows the characteristics of SBDs in this setup. On-resistance of SBDs is lower than that of conventional ones. **Table 1** is a list of the on-resistance of transistors and diodes at 400 A.

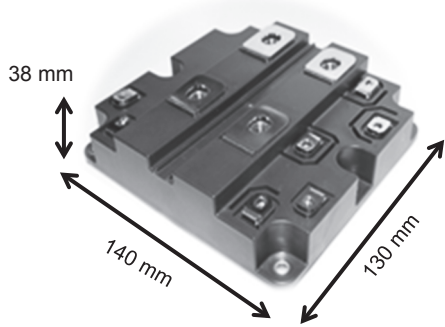


Fig. 11. 3.3 kV 400 A full SiC module

Table 1. Module characteristics of SiC MOSFET and Si IGBT

Module	On-resistance (mΩ)	On-voltage (V)
SiC MOSFET	6.0	2.3
Si IGBT	8.5	2.8

Measurement condition of transistor
 $V_{GS} = 15 \text{ V}$, $I = 400 \text{ A}$
 Measurement condition of diode
 $V_{GS} = 0 \text{ V}$, $I = 400 \text{ A}$

4-2 Estimation of dynamic characteristics

Figure 14 shows the evaluation circuit of a SiC MOSFET module. We have investigated by using an inductive load switching measurement at a high drain voltage of 1650 V with a drain current of 400 A. The gate voltage range was applied from -5 V to 15 V. The gate-resistor in between the gate terminal and the driver IC is 2.2Ω. A 100 μH inductance was used. The test environment was room temperature. **Figure 15** shows the switching waveforms of turn-on, and **Figure 16** shows the switching waveforms of turn-off.

Table 2 shows the 3 kinds of switching losses: turn-on loss (E_{on}), turn-off loss (E_{off}), recovery loss (E_{rr}).

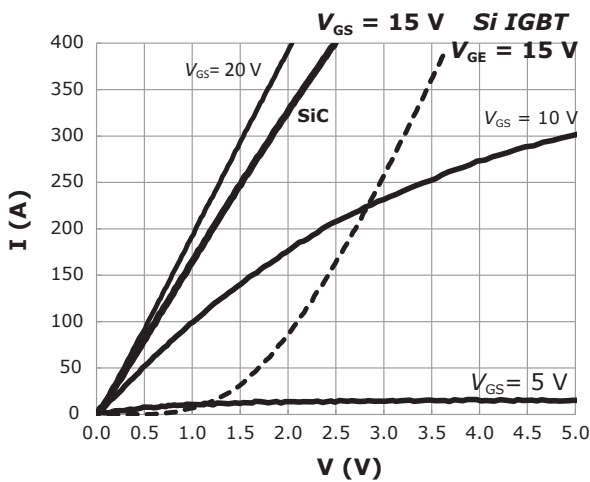


Fig. 12. Forward I - V characteristics with a positive V_{GS}

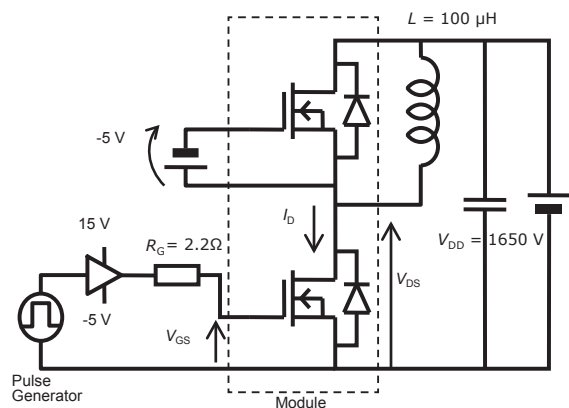


Fig. 14. Evaluation circuit of SiC MOSFET module

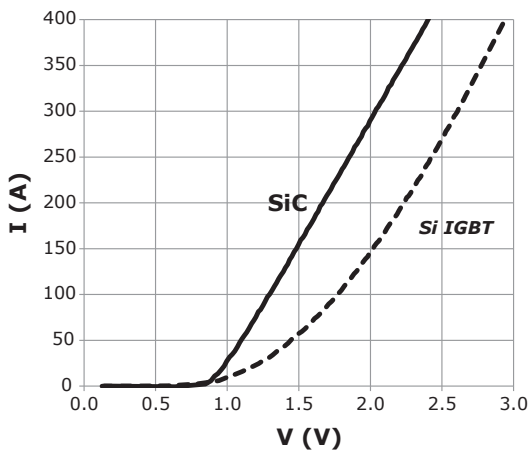


Fig. 13. Forward I - V characteristics with V_{GS} of 0 V

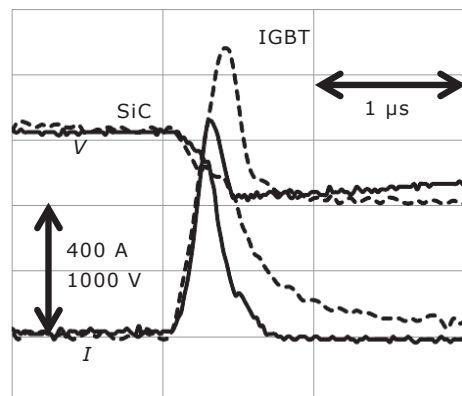


Fig. 15. Switching waveforms of turn-on

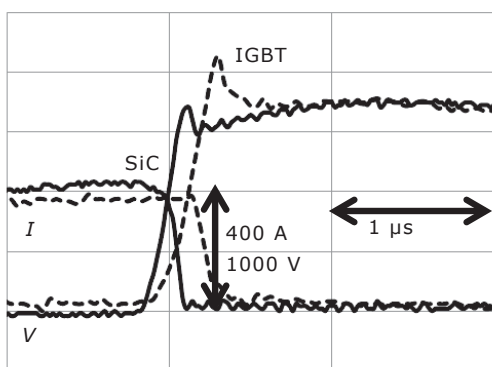


Fig. 16. Switching waveforms of turn-off

Table 2. Switching losses of SiC MOSFET and Si IGBT module

Module	E_{on}	E_{off}	E_{rr}	E_{total}
SiC MOSFET	193	58	15	226
Si IGBT	524	186	96	805

Measurement condition
 $V_{BD} = 1650 \text{ V}$, $I_D = 400 \text{ A}$
 $V_{GS} = -5 \text{ V}/+15 \text{ V}$, $R_G = 2.2\Omega$, $L = 100 \mu\text{H}$

IGBT generates the high recovery loss because of the reverse peak current (I_{rr}) and reverse recovery time (T_{rr}) of Si FRD. In contrast, SiC SBD decreases that loss because of the very low I_{rr} and T_{rr} . E_{on} decreases for same reason. IGBT has the high E_{off} due to the tail current. Opposed to this, MOSFET has no tail current in principle and E_{off} was decreased. Due to these reasons, the fabricated SiC power module successfully reduced switching losses (E_{total}) to one-third of the conventional IGBT module.

5. Conclusion

We developed SiC MOSFETs and SiC SBDs of 3.3-kilovolt class. The fabricated SiC module has low on-resistance and low switching losses to one-third compared to the conventional IGBT.

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Contributors (The lead author is indicated by an asterisk (*))

M. SAKAI*

- Assistant General Manager, Power Device Development Division



S. TOYOSHIMA

- Power Device Development Division



K. WADA

- Assistant General Manager, Power Device Development Division



M. FURUMAI

- Group Manager, Power Device Development Division



T. TSUNO

- Doctor of Science
Group Manager, Power Device Development Division



Y. MIKAMURA

- Manager, Power Device Development Division

