SiC Lecture Series

12. High Voltage SiC Chip Technology

High Voltage SiC Chip Technology

By using SiC, it is possible to achieve high-voltage MOSFETs with a rated voltage of 3.3kV or higher. Since MOSFETs are unipolar devices, they do not accumulate minority carriers, enabling extremely low-loss switching. Generally, high-voltage systems handle large currents and need to keep heat generation due to power loss below permissible levels, which typically results in setting a low carrier frequency (switching frequency). However, by using SiC MOSFETs, systems can operate at higher carrier frequencies. This provides unprecedented benefits to the system, such as enhanced performance and miniaturization. Mitsubishi Electric has developed and commercialized high-voltage SiC MOSFETs, leading the industry in applying them to traction inverters for railway vehicles, and currently holds a significant market presence as a device manufacturer.

In high-voltage SiC MOSFETs, the resistance of the drift layer and the JFET region accounts for a large proportion of the on-resistance. The resistance of the drift layer is determined by the breakdown voltage and material properties, making it difficult to reduce through design improvements. Therefore, optimizing the design of the JFET region is crucial for reducing resistance. In designing the JFET region, it is necessary to reduce resistance while also suppressing the maximum electric field to ensure reliability. By leveraging the JFET doping technology developed for the second-generation SiC MOSFETs described in Lecture 11, we have achieved a 3.3kV SiC MOSFET that balances reduced resistance with high reliability. Additionally, short-circuit withstand capability is a critical performance aspect for high-voltage SiC MOSFETs. When high voltages are applied, it is necessary to further suppress short-circuit currents to protect the device from short-circuit failures. In SiC MOSFETs, suppressing short-circuit current is accompanied by an increase in on-resistance, making it essential to design with a balance of these characteristics in mind.

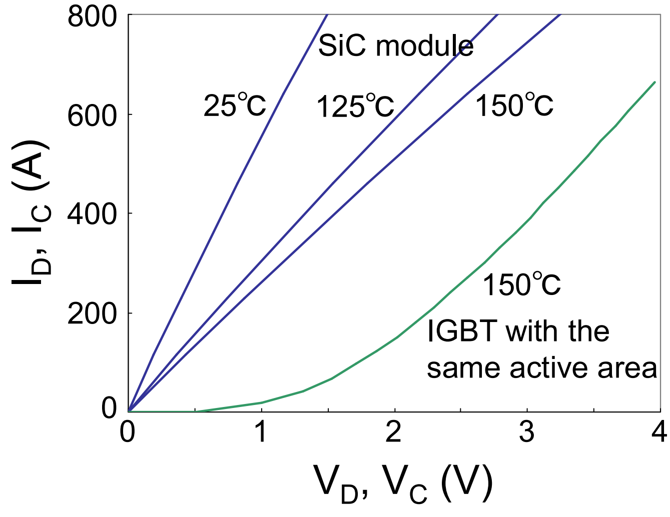
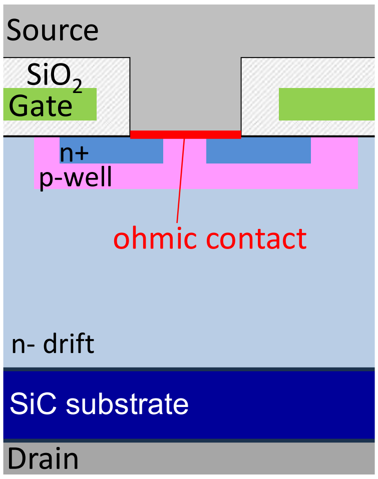


Figure 1 Forward Characteristics of a Module Equipped with a 3.3kV SiC MOSFET

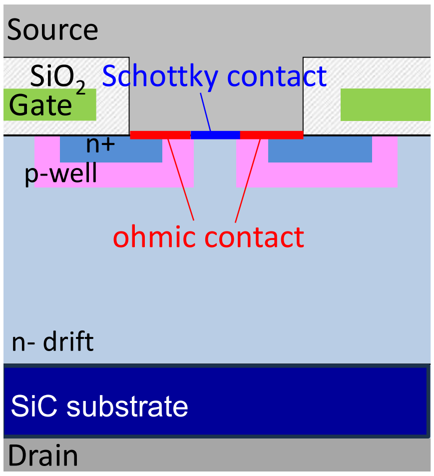
Figure 1 shows the forward characteristics of a module equipped with a 3.3kV SiC MOSFET. The figure also shows the forward characteristics of a Si IGBT with the same active area as the SiC MOSFET. In the low current region, the SiC MOSFET significantly suppresses the on-voltage compared to the Si IGBT, which has a turn-on voltage. This is one of the major advantages of SiC MOSFETs.

Mitsubishi Electric has developed the third-generation SBD-embedded SiC MOSFET as the next-generation high-voltage SiC MOSFET, and the first module equipped with this technology was commercialized in 2024. As mentioned in Lecture 5, there are a few crystal defects in SiC that can degrade device characteristics when bipolar current flows through the crystal. In high-voltage, high-current modules with many parallel chips, the probability of including these defects is higher. Therefore, as a countermeasure, we developed a SiC MOSFET with an embedded Schottky barrier diode (SBD) within the MOS cell to prevent bipolar current from flowing during normal operation.

Figure 2 shows a cross-sectional diagram comparing the structure of the SBD-embedded SiC MOSFET with a conventional MOSFET. In the SBD-embedded SiC MOSFET, a Schottky electrode is formed in part of the area where the source electrode and contact are formed. When a reverse voltage is applied to the MOSFET, the Schottky current (unipolar current) flows, suppressing the bipolar current caused by the body diode. Figure 3 shows the forward characteristics of the SBD-embedded SiC MOSFET. The forward drain current and drain voltage characteristics are the same as those of a conventional SiC MOSFET.



(a) 3.3kV SiC MOSFET



(b) SBD-embedded SiC MOSFET

Figure 2 Cross-sectional Diagram of the MOS Cell Structure

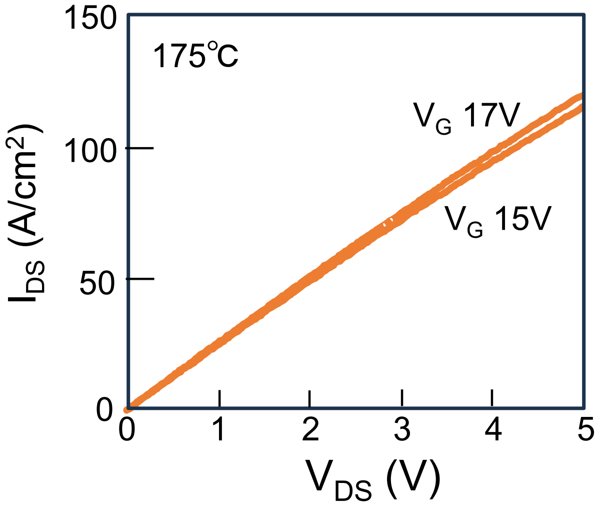


Figure 3 Forward Characteristics of the SBD-embedded SiC MOSFET

Figure 4 shows the reverse characteristics of the SBD-embedded SiC MOSFET. When a reverse voltage is applied to the MOSFET with the gate turned off, a bipolar current due to the MOSFET's body diode flows at around 2.5V in a conventional structure. In contrast, in the SBD-embedded SiC MOSFET, a unipolar Schottky current flows from around 1V, and no current flows through the body diode. Therefore, degradation due to bipolar conduction does not occur.

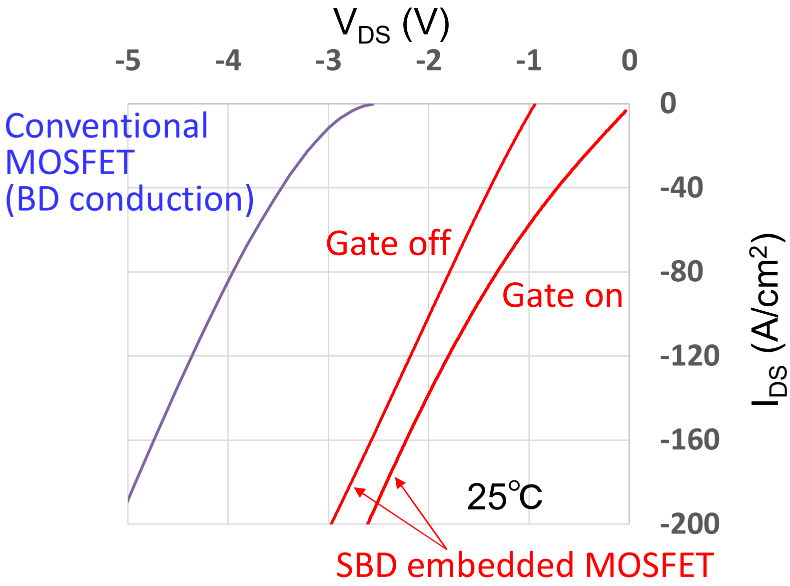


Figure 4 Reverse Characteristics of the SBD-embedded SiC MOSFET

One of the challenges of the SBD-embedded SiC MOSFET was its low surge current tolerance. In response, Mitsubishi Electric developed a unique MOS cell structure that operates in bipolar mode only when a surge current flows. By incorporating this MOS cell into the SBD-embedded SiC MOSFET, they successfully achieved a significant improvement in surge current tolerance.

January 2025
Power Device Works