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Current and Future Technologies of SiC Power Devices

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Abstract

This paper gives an overview about recent development of Silicon Carbide (SiC) power devices. SiC trench MOSFETs are newly commercial devices which show the extremely low on-resistance (R_{on}). In order to resolve issue of gate oxide break-down, we developed double-trench MOSFET structure. Trench-SBDs and reverse blocking (RB) MOSFETs are new devices under development. Trench SBDs can reduce the conductive losses by smaller threshold voltage. RB-MOSFETs can block 3kV in both the forward and reverse bias directions, construct bi-directional switch by using anti-parallel connection of two transistors.

1. Introduction

SiC devices have the potential to reduce energy losses in high power applications. However SiC devices haven't yet achieved the ideal performance levels. This paper presents SiC MOSFETs and SBDs with advanced trench structures. These devices succeeded in improving performance by reduction of the internal electric field. In addition, SiC devices have been established by the benefits such as efficiency and size reduction of system. In order to challenge for implementation in new applications, we are developing 3.3 kV-class RB-MOSFETs for high voltage applications such as a matrix converter with multiple bi-directional switches.

2. SiC Double-Trench MOSFETs

SiC trench MOSFETs can have lower conductive losses compared with planar MOSFETs because planar MOSFETs have JFET regions which increase R_{on} [1, 2]. We previously reported 790 V SiC trench MOSFETs with the lowest R_{on} at room temperature. However, the trench MOSFETs had issues regarding gate oxide break-down at the trench bottom under high drain-source voltage bias. To resolve the issue, we developed double-trench MOSFET structure, which has both source and gate trenches. Those device structures are shown in Fig. 2, respectively.

In order to suppress electric field at the gate oxide, the source trench is fabricated deeper than gate trench. Deeper source trenches prevent the concentration of electric fields at the gate trench bottom. Fig.2 shows simulation results of the electric field distribution at drain-source bias 600V with a gate-source voltage of 0V. The highest electric field of the single-trench structure is 2.66 MV/cm at the gate trench bottom. In contrast, that of double-trench is 1.66 MV/cm. This structure enables preventing the gate oxide destruction.

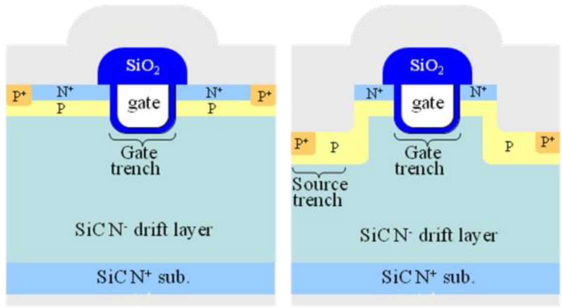

Fig. 1 Schematic cross section of trench MOSFET (a) conventional structure and (b) double-trench structure.

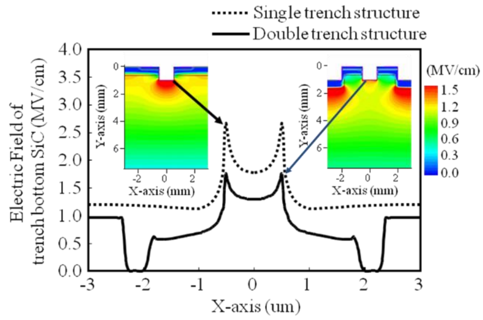

Fig. 2 Simulated electric field distribution (V_{ds} = 600V).

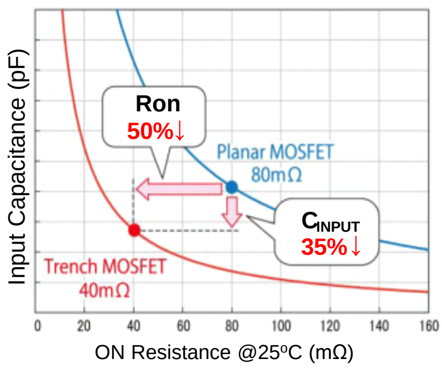

Fig. 3 Characteristics of SiC trench MOSFETs.

Fig. 3 shows R_{on} vs. input capacitance of trench and planer SiC MOSFET. As compared with conventional planer MOS of the same area, R_{on} and input capacitance were decreased by about 50% and about 35%, respectively.

We succeeded in the world's first commercialization of the SiC trench MOSFETs in 2015.

3. SiC Trench Structure Schottky Barrier Diodes (SBDs)

SiC SBDs are attractive devices to reduce switching losses in high voltage applications such as Power Factor Correction (PFC) [3, 4]. The reduction of conductive losses is also required to improve efficiency. However, SiC SBDs have higher forward voltage drop compared to silicon PN junction diodes. We have proposed the trench structure Schottky diodes to obtain a lower forward voltage drop while maintaining the same leakage current. As in Fig. 4, the p region around trench can suppress the concentration of electric field at the Schottky interface. The threshold voltage of the trench structure is 0.48 V smaller than that of the planar structure. It enables reducing the conductive losses during forward current operation.

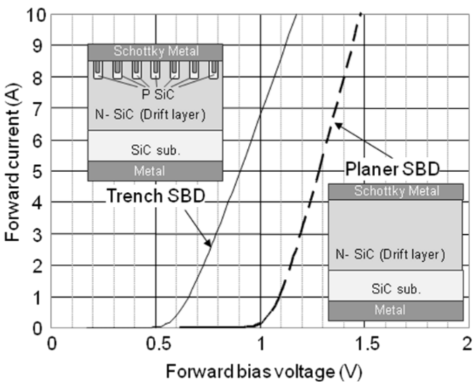

Fig. 4 Forward characteristics of planer SBD and trench SBD.

4. SiC RB-MOSFETs

We designed and fabricated 4H-SiC RB-MOSFETs and achieved both forward and reverse blocking voltage over 3 kV for the first time by adopting a ultrathin-wafer technology [5]. The cross-sectional structure of the developed RB MOSFET is shown in Fig. 5. The drift layer is 40 μm-thick, doped to 2×10^{15} cm^{-3}. To achieve reverse blocking capability, a substrate was removed by polishing and the drain electrode (Ti Schottky) was directly contacted to the SiC epitaxial layer (C-face) after CMP polishing. The final thickness of the processed wafer is 40 μm. A termination region was also formed on the C-face by alignment to the front side patterns through the SiC epitaxial layer to ensure the reverse blocking capability. As regards the forward I_d–V_{ds} characteristics of a developed RB-MOSFET (active area: 1.3 mm^2), the differential specific on-resistance is 20 $m\Omega cm^2$ when V_{gs} = 20 V and V_{ds} = 1.5 V (V_{th} = 2.8 V at I_d = 500 μA). In the on-state, the offset voltage of 1 V was observed due to the backside Schottky barrier. The ideality factor of Schottky properties is 1.04, indicating that a good Schottky contact is formed between the backside of the SiC epitaxial layer and the drain metal. Fig. 6 depicts the forward and reverse leakage current of the RB-MOSFET when V_{gs} = 0 V. Both forward and reverse leakage currents are lower than 100 μA at V_{ds} = ±3 kV, demonstrating the bi-directional blocking capability. The forward blocking voltage exceeded 4 kV.

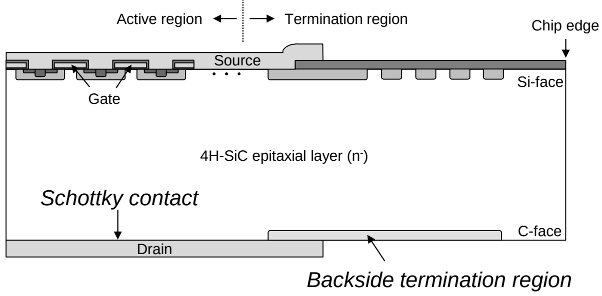

Fig. 5 Cross-sectional structure of the developed SiC RB-MOSFET.

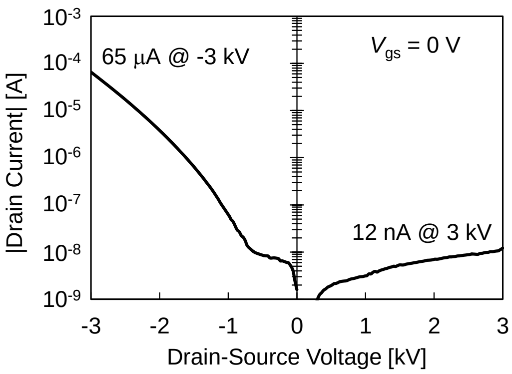

Fig. 6 Bi-directional blocking characteristics of a fabricated SiC RB-MOSFET.

5. Conclusions

SiC trench structure MOSFET and SBD demonstrate the significant performance improvements over conventional devices. The double-trench MOSFET achieves world-class leading low R_{on} in parallel with resolving issues regarding gate oxide destruction. In the case of SBD, the incorporation of trench structure allows reduction in leakage current by reducing the electric field at the Schottky interface. It consequently enables reducing the threshold voltage. Toward new applications, we designed and fabricated 3.3 kV-class RB-MOSFETs and achieved both forward and reverse blocking voltage over 3 kV for the first time.

References

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