Ultra Low On-Resistance SIC Trench Devices

A new generation of Silicon Carbide (SiC) planar MOSFETs, trench structure Schottky diodes, and trench MOSFETs has been developed. The planar SiC MOSFET technology suppresses the degradation of the parasitic PN junction diodes even if forward current penetrates into the diodes. The trench Schottky diodes exhibit lower forward voltage than conventional SiC diodes while keeping leakage current at an acceptable level. And SiC MOSFETs with a double-trench structure improve reliability of the device while maintaining ultra low on-resistance because the new structure effectively reduce the highest electric field at the bottom of the gate trench, thus preventing gate oxide breakdown. **K. Okumura, N. Hase, K. Ino, T. Nakamura, and M. Tanimura, Rohm, Kyoto, Japan**


Full SiC 1200 V7100 A power module enabling high-frequency operation above 100 kHz

Mass production of SiC planar MOSFETs for the sake of lower switching losses in high voltage applications such as converters and inverters has already started. However, on-resistance increases when current flows into the parasitic body diodes of these MOSFETs. This is because the parasitic PN body diodes, with the base plane dislocation, induce expansion of stacking faults in 4H-SiC epilayers and degrade the on-resistance of both the body diodes and MOSFETs. This is an obstacle for application in circuits which require current penetration from source to drain such as converters and inverters. However, some groups have reported no degradation of PN diodes at the research level.

Our group developed substrate, epitaxy and device fabrication processes to prevent degradation of the body diodes. Figures 1/2 show the MOSFET's on-resistance evaluation and differential on-resistance of the body diodes after continuous current penetration, respectively. We compared two conventional planar 1200 V SiC MOSFETs with 22 newly developed planar MOSFETs. On-resistance is typically 0.09 Ω, die size and active area are 13.2 mm^2 and 10 mm^2, respectively. Applied continuous current from source to drain of the MOSFET is 8 A.

After 24 hours continuous current

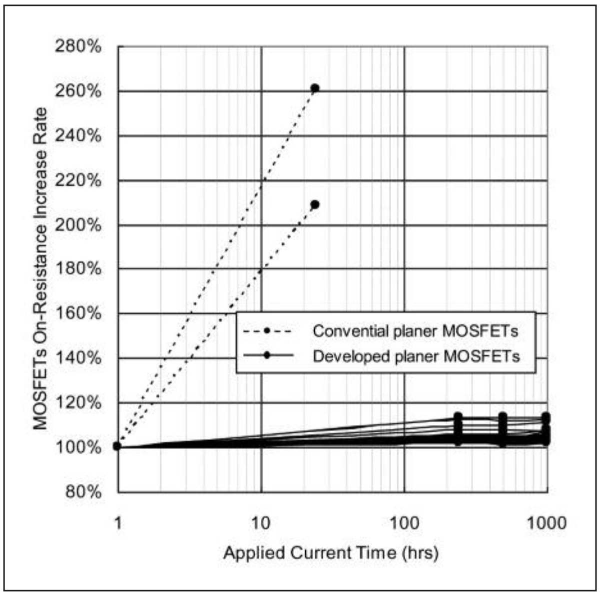

Figure 1: **Comparison of MOSFET's on-resistance increase rate after current application**

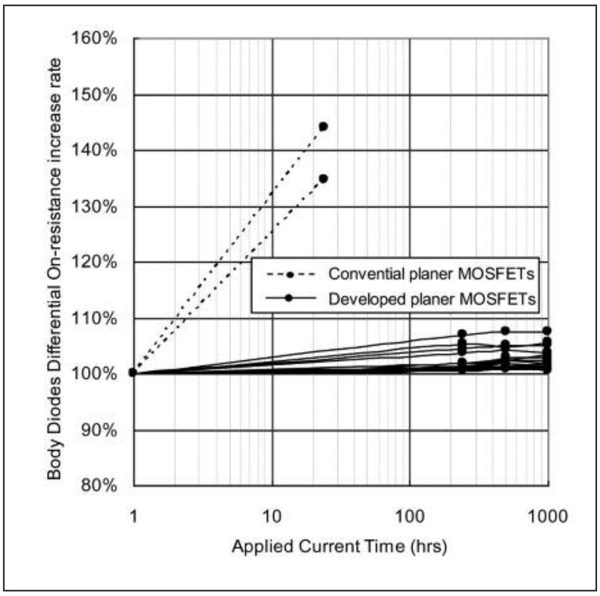

Figure 2: **Comparison of body diodes differential on-resistance increase rate after current application**

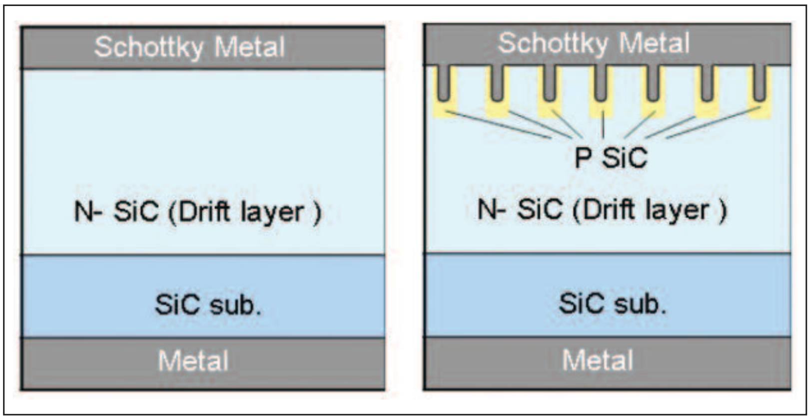

Figure 3: Schematic cross section of the planar (left) and trench Schottky diodes

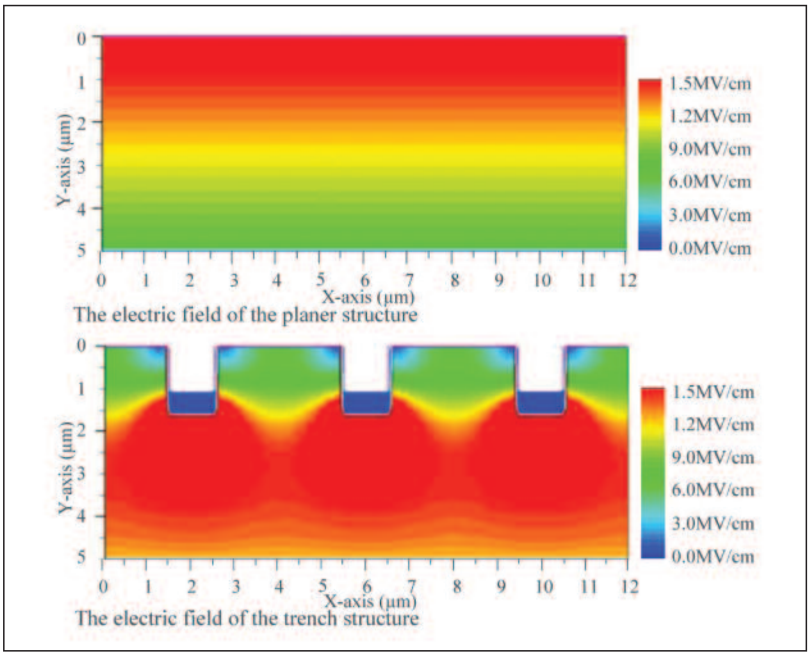

Figure 4: Reverse bias simulation results at 600 V

application, conventional planar MOSFETs show drastically increased on-resistance of MOSFETs and differential on-resistance of body diodes. On the other hand, the planar MOSFETs suppressed degradation of on-resistance even after 1000 hours current application.

SiC trench Schottky diode technology

SiC Schottky diodes are attractive devices to reduce switching losses in high-voltage applications. The reduction of conductive losses is also required to improve efficiency. However, SiC Schottky diodes have higher forward voltage drop when compared to Silicon PN junction diodes. The reason is that SiC Schottky diodes need high barrier heights to block leakage currents because SiC has a breakdown strength 10 times greater than Silicon. The reduction of electric fields at the Schottky interface is crucial for SiC Schottky diodes.

Our group proposes the trench structure Schottky diodes to obtain a lower forward voltage drop while maintaining the same leakage current [1]. Figure 3 shows the schematic cross section of a 4H-SiC planar and trench structure Schottky diode. Trench p region can suppress the concentration of electric field at the Schottky interface.

Figure 4 shows reverse bias simulation results of the electric field distribution. Figure 5 indicated the highest electric field at the Schottky interface of the planar structure and the trench structure is 1.65 MV/cm and 0.68 MV/cm, respectively. The simulation shows a lower barrier height can be obtained by using a trench structure.

The barrier heights of the fabricated TO-220 planar and trench diodes are different at 1.31 eV and 0.85 eV, respectively. Trenches are 1.05 μm deep. The diode die size is 3.06 mm^2.

The threshold voltage of the trench structure is 0.48 V smaller than that of the planar device. The smaller threshold voltage can reduce the conductive losses during forward operation. The leakage current at 600 V is comparable.

SIC double-trench technology for MOSFETs

Compared with planar MOSFETs SiC trench MOSFETs can have lower conductive losses because the planar technology feature JFET regions which increase the on-resistance [2, 3]. Our group previously reported 790 V SiC trench MOSFETs with the lowest Ron at room temperature. However, the trench MOSFETs had issues regarding oxide breakdown at the trench bottom during high drain-source voltage application. To resolve the issue of gate oxide breakdown, a double-trench structure with both source and gate trenches was developed [4, 5].

The structures for the single and double-trench structures are shown in Figure 5. To suppress the electric field at the gate oxide bottom, the source trench is fabricated deeper than the gate trench. Figures 6/7 show drain-source bias simulation results of the electric field distribution at 600 V with a gate-source voltage of 0 V. In the single-trench structure the highest electric field at the bottom of the gate trench was 2.66 MV/cm. On the other hand, that

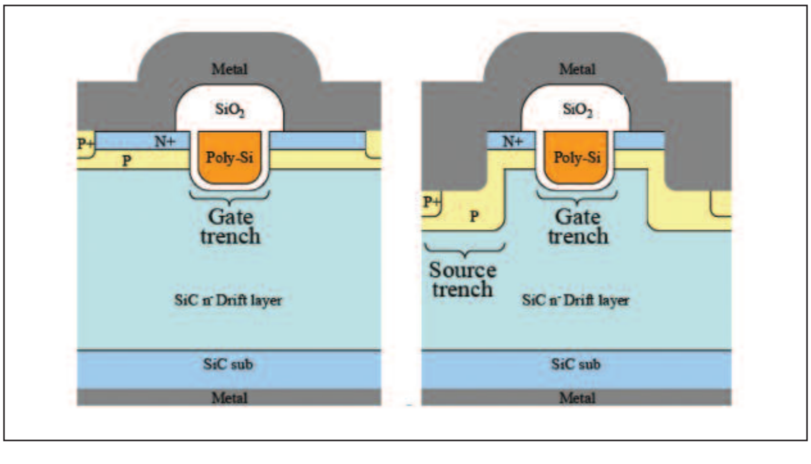

Figure 5: Cross section of 4H-SiC trench MOSFET with single-trench (left) and source/gate trench

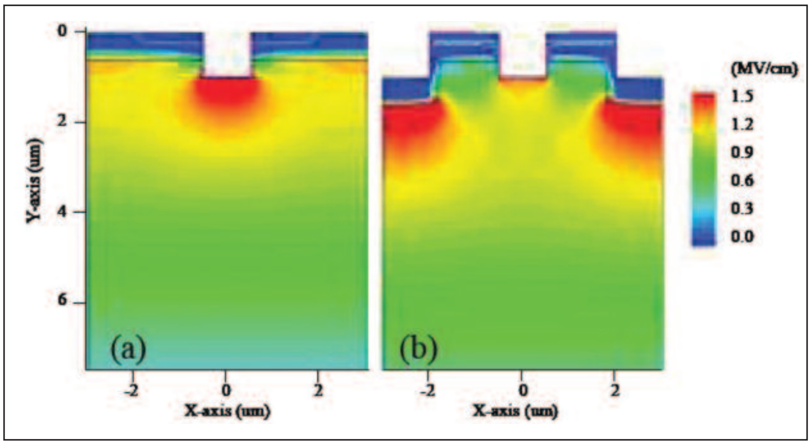

Figure 6: **Drain-source bias simulation results at 600 V with 0V gate-source voltage**

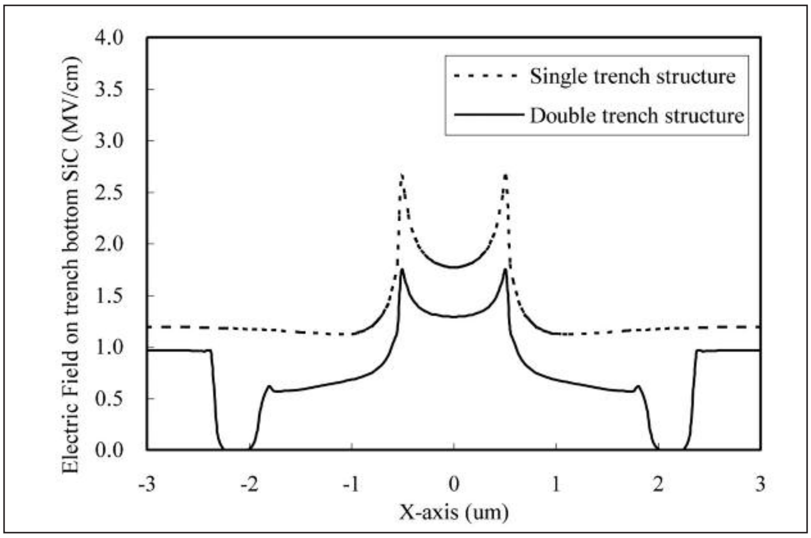

Figure 7: **Electric field for the single and the double-trench structure**

figure was effectively reduced to 1.66 MV/cm in the double-trench structure. Deeper source trenches prevent the concentration of electric fields at the bottom of the gate trench.

Double-trench MOSFETs are fabricated using two different epitaxial layers. The trench depth is typically 1.0 µm, the thickness of gate oxide about 50 nm.

The measured channel mobility on the trench sidewalls of the double-trench MOSFET is about 11 cm²/Vs. The charge to oxide breakdown estimated by CCS-TDDB (constant current stress time dependence dielectric breakdown) test of the gate oxide was typically 15 C/cm² equivalent to that of a Silicon device. The negative gate bias of the commercial SiC MOSFETs is limited to -6 V. This is because continuous negative gate bias causes a negative shift in threshold voltage, possibly due to hole traps in the gate oxide or MOS interface. However, the rate of change in threshold voltage of the SiC trench MOSFETs under negative gate bias testing at V_{gs}=-18 V after 3000 hours covered a range of only 5 %.

Figure 8 shows two kinds of I_d/V_{ds} characteristics of the trench MOSFETs using different epi-layers: 1.8 e^{16}cm^{-3}/ 5 µm and 7.5 e^{15}cm^{-3}/7 µm. The die sizes are the same, 2.56 mm² and the active areas are 1.422 mm². The $R_{on,sp}$ was estimated at 0.79 mΩcm² and 1.41 mΩcm² at I_d=1 A, respectively. The blocking voltage was 690 V and 1200 V at I_d=100 µA, respectively. Figure 9 shows the performance comparison of 4H-SiC switching devices. Low on-resistance while maintaining the high reliability of the gate oxide has been achieved.

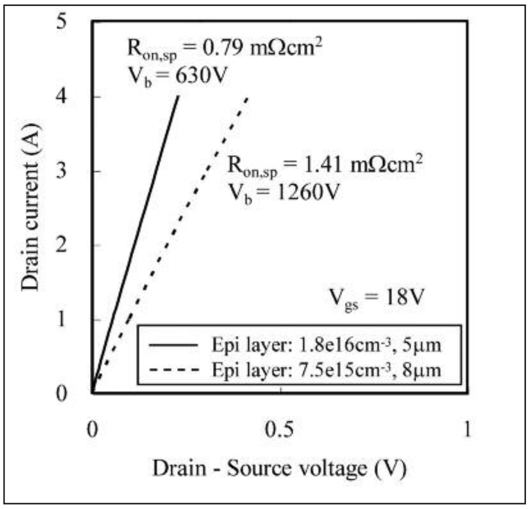

Figure 8: **I_d/V_{ds} characteristics of double-trench MOSFETs at V_{gs}=18 V**

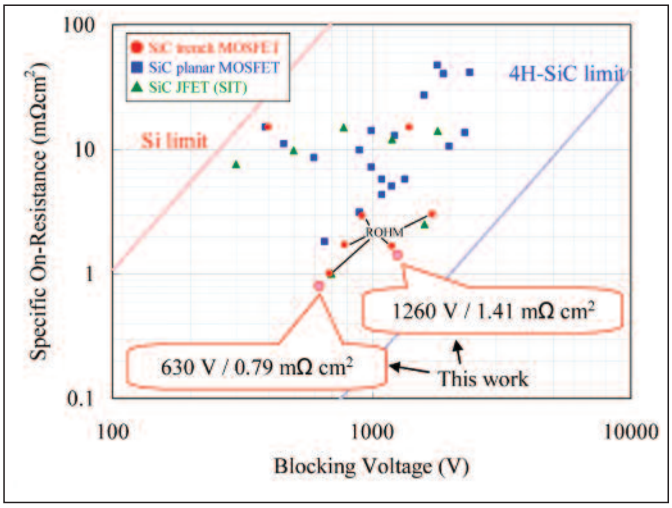

Figure 9: **Performance comparison of 4H-SiC switching devices**

Conclusions

Our newly developed SiC planar MOSFETs suppress the degradation of the parasitic PN junction diodes when forward current penetrates. SiC Schottky diodes with trench structure successfully showed ultra low forward voltage drop while maintaining low leakage current. SiC MOSFETs with a double-trench structure have obtained ultra low on-resistance with improved reliability of the gate oxide. This article has been derived from a paper entitled 'Ultra Low Ron SIC Trench Devices' presented at PCIM 2012. It has been awarded as the best paper [6].

Literature

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Full SiC Power Modules

ROHM announced at PCIM mass production of full SiC power modules (1200V/100A) as custom design comprised entirely of SiC power elements.

The new modules integrate a state-of-the-art dual-element SiC SBD/MOSFET pair that reduces loss during power conversion by 85 % compared with conventional Si IGBT modules. In addition, high-frequency operation of at least 100 kHz is possible. Although the modules are rated at 100 A, their high-speed switching capability, reduced loss, and heat dissipation characteristics make them replacements for 200-400 A Si IGBT modules. Replacing a conventional 400 A-class IGBT with this compact, low-profile package can cut volume by 50 %, and the lower heat generated requires less cooling countermeasures, contributing significantly to end-product miniaturization.

Due to the expertise of Erlangen-based wafer supplier SiCrystal AG, which is part of the corporate group, ROHM possesses total manufacturing capability for SiC semiconductors from ingot formation to power device fabrication. This allows the rapid development of products and complete control of raw materials.