Characteristics of 4H-SiC Dual-Metal and MOS Trench Schottky Rectifiers

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Abstract

This work provides the results of a systematic study by simulations to compare the performances of SiC parallel plate SBD, dual-metal trench SBD and TMBS. SiC TMBS with 0.1µm oxide thickness provides good characteristics of leakage current pinch-off and low forward voltage drop. The maximum electric field in oxide is about 4MV/cm at the reverse bias of 600V.

INTRODUCTION

4H-SiC Schottky rectifiers have advantages of providing low forward voltage drops (V_F), high breakdown voltages (V_{BD}) and fast switching [1]. Among approaches of reducing reverse leakage current (I_R), the dual-metal trench Schottky barrier diodes (DM-TSBD) and the trench MOS barrier Schottky diodes (TMBS) are of interest because they don't need costly implantations. The improvements of I_R of DM-TSBD and TMBS as compared with parallel-plane SBD (PP-SBD) have been demonstrated at reverse bias up to 300V and 20V, respectively [2,3]. However, a systematic comparison of these two approaches is absent. Here we used 2D numerical simulations to study characteristics of these two technologies as well as simple PP-SBD and single-metal TSBD (SM-TSBD) for control purpose.

SIMULATION RESULTS

The structures used in simulations are shown in Fig.1, all with a drift region of 6×10^{15} cm^{-3} doping concentration and 10 µm thickness. The trench has a depth (d) of 2 µm and a width of 3 µm, with a half-mesa width (w) from 1 to 4 µm. Note that a rounded corner is critical to prevent premature breakdown caused by field crowding in trench rectifiers (as an example, the silicon TMBS with trenches of rounded bottoms shown in Fig.2 could support a reverse bias larger than 100V). Therefore all trenches in simulations were intendedly processed to form rounded corners with a radius of curvature of 1µm to better represent the real situation of field crowding. The simulations results are summarized in Table 1. The forward and reverse bias characteristics of high barrier PP-SBD-H (Φ=6.35eV) and low barrier PP-SBD-L (Φ=5eV) are shown in Fig.3 and Fig.4, respectively. Fig.3 and Fig.4 show clearly the trade-off between low V_F and low I_R of PP-SBD. Though the PP-SBD with low Φ Schottky metal provides a much lower voltage drop and turn on threshold voltage at forward bias which are important to reduce power dissipation in the on-state, it also shows much higher leakage current at reverse bias because of barrier lowering effect which should be avoided to reduce the power dissipation in the off-state.

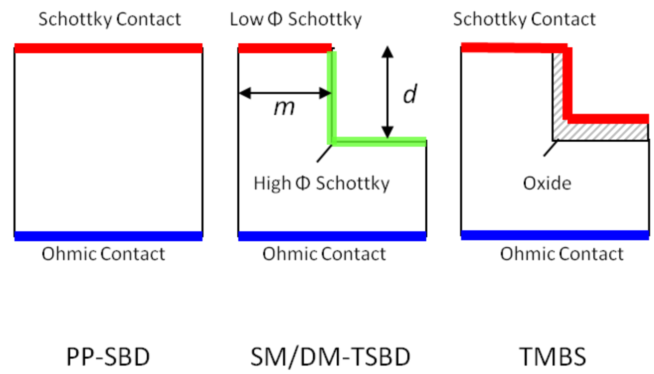

Figure 1. Rectifier structures used in simulations

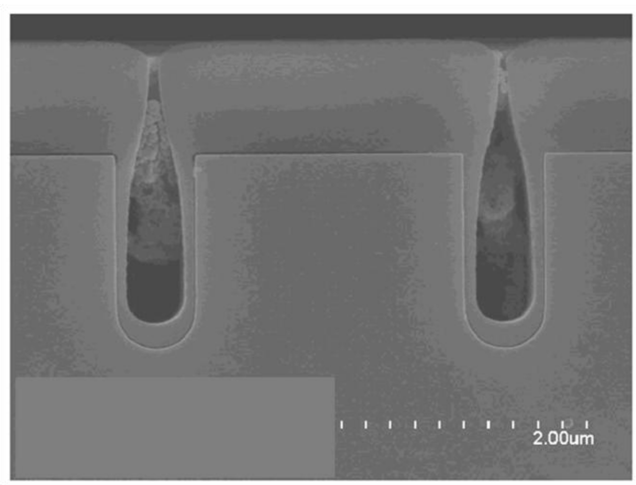

Figure 2. Trench structures for Si TMBS, fabricated by dry etching

The DM-TSBD can solve this problem because the trenches extended into the drift region shield the electric field on the low Schottky barrier contacts thus reduce the reverse leakage current to a level close to PP-SBD-H. Although the forward voltage drop of DM-TSDB is also a little higher than PP-SBD-L, it has been much better than that of PP-SBD-H.

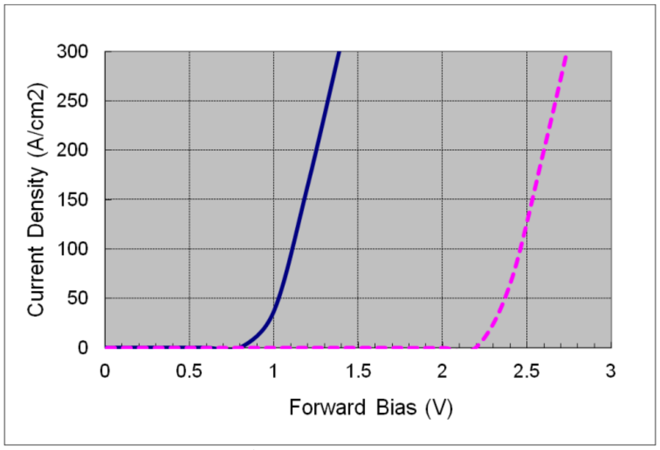

Figure 3. Forward bias IV of PP-SBD with low Φ (solid line) and high Φ (dashed line) Schottky contact

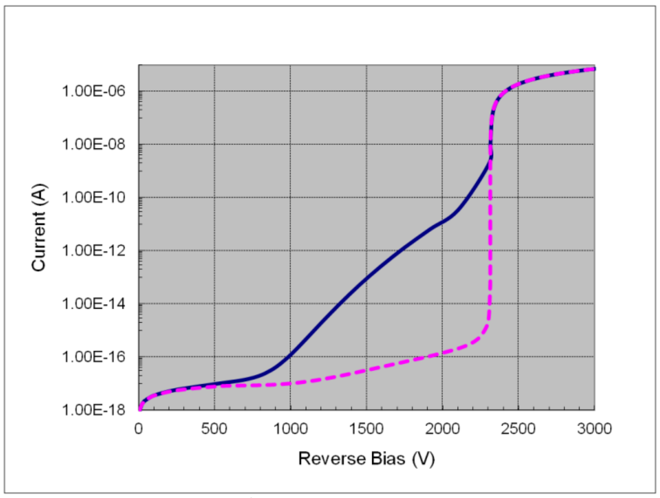

Figure 4. Reverse bias IV of PP-SBD with low Φ (solid line) and high Φ (dashed line) Schottky contact

The improvement on V_F and I_R of DM-TSBD is at the expense of the smaller drift layer thickness being able to support the reverse bias voltage depending on the depth of trenches. This can be observed from a lower breakdown voltage of DM-TSBD than that of PP-SBD. The DM-TSBD with a wider mesa has more area covered by low barrier height Schottky metals which gives a lower V_F but also trades off some I_R because the electric field shielding provided by high barrier height Schottky metals also less effective.

An even lower V_F can be achieved by TMBS structure for which provides larger effective zones for forward currents than DM-TSBD as can be seen from the current contour of Fig. 5. In DM-TSBD, the high barrier height Schottky metal adjacent to the low barrier height Schottky reduces the available area for forward currents. On the contrary, in TMBS, the SiC adjacent to the trench oxide forms accumulation layer of electrons which is more conductive than bulk drift layer. The TMBS provides also a higher V_{BD} than DM-TSBD because the avalanche of TMBS occurred on the edge of well-shielded mesa contacts, whereas the avalanche of DM-TSBD occurred on the field-crowding trench bottom which can be observed in Fig.6. However, this remark holds only if the oxide layer in the trenches is safe from breakdown before avalanche of SiC occurs. The TMBS also possesses the potential of providing a lower I_R as compared to DM-TSBD if being able to effectively deplete the whole drift layer at the reverse bias. Nevertheless, the trade-off between low V_F and high I_R is more significant in TMBS. The leakage current surges for half mesa wider than 2μm due to depletion layers failed to pinch off the current.

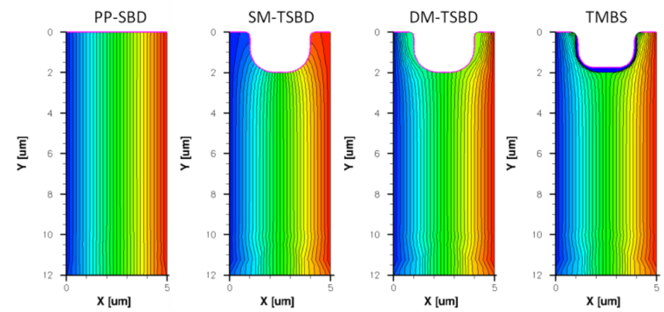

Figure 5. The current contours at forward bias of 10V

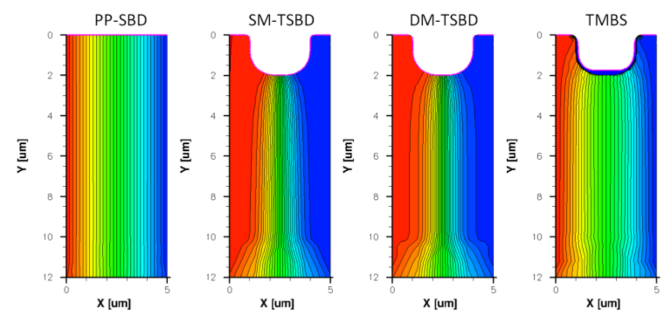

Figure 6. The current contours at reverse bias when avalanche occurs

The oxide thickness of TMBS would also need to be taken into account for determining the optimal mesa width because it will influence the depletion layer width in the SiC at the reverse bias. In above simulations, the sidewall oxide thickness is 0.1μm. The reverse bias voltage of TMBS is shared by the oxide and the semiconductor. For trenches with right angle corners, the electric field crowds around the corner of the trench, whereas for trenches with rounded corners such as those in this study the maximum electric field would appear around the bottom of the trench. The TMBS was sometimes considered not a workable structure for SiC because the high electric field in the oxide may easily exceed its breaking strength and lead to catastrophic failure before the avalanche of SiC occurs [4]. In above simulations, however, we showed that with proper design (rounded trenches with bottom oxide thickness of 0.25μm), the maximum electric field in the oxide when SiC avalanche occurred (about 2000V) was about 8×10^6 V/cm (see Fig.7), which is the strength that quality oxides should be able to endure.

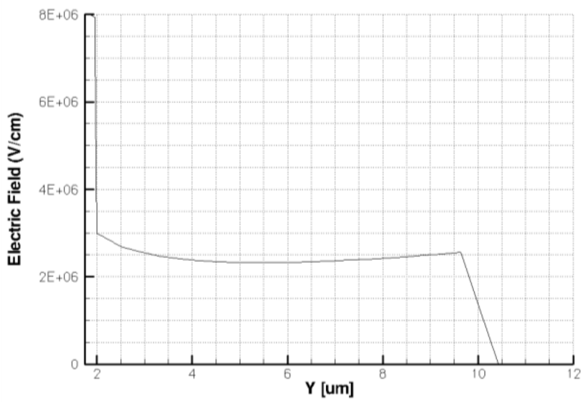

Figure 7. Electric field variation in SiC TMBS at reverse bias when avalanche occurs

To further investigate the performance and the reliability of TMBS devices targeting lower voltage ratings, we simulated the devices with uniform oxide thickness varying from 0.1μm to 0.5μm. Figure 8 shows the reverse leakage current characteristics of TMBS with different oxide thicknesses given half mesa width of 1μm. The leakage current, as one could expect, increases with increasing oxide thickness. Oxide thickness thicker than 0.1μm could not create wide enough depletion layers to pinch off the mesa region and thus significant leakage current occurs because of barrier lowering of low barrier Schottky contacts at the reverse bias.

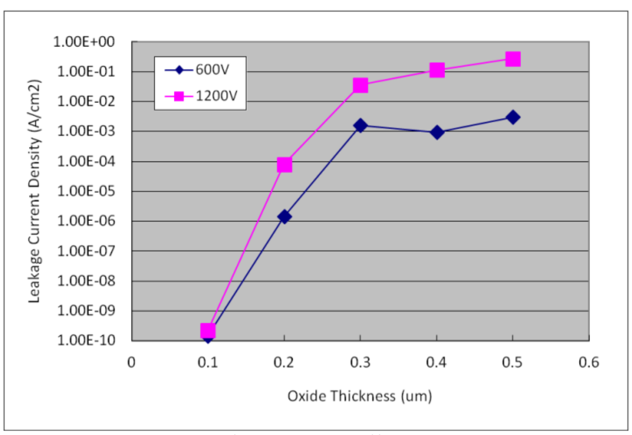

Figure 8 Leakage currents of TMBS with different trench oxide thicknesses at the reverse bias of 600V and 1200V

Figure 9 shows the maximum electric field probed in the oxide for different oxide thicknesses. The maximum electric field of TMBS with 0.1μm oxide is about 1 MV/cm higher than that with 0.5μm oxide. The maximum field of 0.1μm oxide is about 4MV/cm at the reverse bias of 600V. These results suggest that SiC TMBS may have chance to find applications at lower voltage ratings since the products at this range would be cost sensitive and TMBS can reduce the cost by getting rid of costly high temperature implantation and annealing required by SiC JBS devices. However considering relatively less mature processes of etching and oxidation for SiC, a lot of engineering problems have to be solved first to deliver a reliable SiC TMBS.

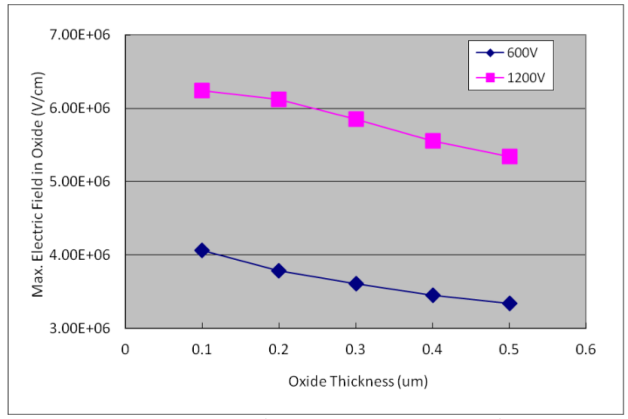

Figure 9. Maximum electric field in the oxide layer for TMBS with different oxide thicknesses

Table 1. Summary of Simulation Results

	PP-SBD-H	PP-SBD-L	SM-TSBD-H	SM-TSBD-L	DM-TSBD	TMBS
half mesa width (μm)	Breakdown Voltage (V)					
1	2307	2314	1825	1827	1826	2070
2			1740	1741	1739	2020
3			1668	1671	1670	1983
4			1642	1641	1632	1960
half mesa width (μm)	Reverse Leakage Current Density (A/cm2) @1500V					
1	6.25E-10	1.74E-06	5.15E-09	9.81E-03	4.84E-09	1.84E-10
2			8.55E-09	3.96E-02	7.16E-09	1.56E-09
3			1.50E-08	6.34E-02	6.79E-09	5.48E-07
4			3.00E-08	1.62E-01	8.92E-09	5.16E-07
half mesa width (μm)	Forward Current Density (A/cm2) @1.5V					
1	2.33E-10	387	2.19E-10	460	207	269
2			1.74E-10	446	282	312
3			1.57E-10	436	310	332
4			1.69E-10	428	328	343
half mesa width (μm)	Forward Voltage Drop (V) @200A/cm2					
1	2.5987	1.2417	2.5506	1.1627	1.4813	1.3649
2			2.5581	1.1701	1.3435	1.3068
3			2.5641	1.1800	1.3008	1.2859
4			2.5685	1.1855	1.2980	1.2852

CONCLUSIONS

We simulated and compared the performances of parallel plate and trench-based Schottky Rectifers. DM-TSBD and TMBS have the potential to provide both low reverse leakage current and low forward voltage drop at low cost but there are many engineering issues remained to be solved.

REFERENCES

[1] M. Östling, R. Ghandi, C.-M. Zetterling, “SiC power devices – present status, applications and future perspective”, *Proceeding of 23th International Symposium on Power Semiconductor Devices & IC’s* , pp. 10-15, May, 2011.
[2] K. J. Schoen, J. P. Henning, J. M. Woodall, J. A. Cooper, Jr., M. R. Melloch, “A dual-metal-trench Schottky pinch-rectifier in 4H-SiC”, *IEEE Electron Device Lett.*, vol. 19, no. 4, pp.97-99, May, 2000.
[3] V. Khemka, V. Ananthan, T. P. Chow, “A fully planarized 4H-SiC trench MOS barrier Schottky (TMBS) rectifier”, *IEEE Electron Device Lett.*, vol. 21, no. 5, pp.286-288, Apr. 1998.
[4] B. J. Baliga, *Advanced Power Rectifier Concepts*, Springer, 2009.