The First Commercial 200 V TMBS® Rectifier vs. Traditional Rectifiers in Telecom Applications

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ABSTRACT

The design and manufacturing process for the first commercial 200 V Trench MOS Barrier Schottky (TMBS®) rectifier is described. Its electrical characteristics are compared to traditional 200 V planar Schottky and 200 V ultrafast recovery diodes, showing the strengths of the TMBS rectifiers compared to both technologies. The 200 V TMBS is subsequently evaluated in telecom switch mode power supply (SMPS) and DC/DC converter applications, where its impact on improving system efficiency is analyzed and reported.

1. INTRODUCTION

Traditionally, the reverse blocking voltage of Schottky barrier rectifiers has been limited to well below 200 V. This is partly because, when the reverse blocking capability approaches 200 V; the forward voltage drop (V_F) of the Schottky rectifier will approach that of a PIN rectifier, making it less effective in the application. Another reason for this limitation is the need to terminate the high reverse electric field properly. A P-type guardring structure is usually built into the N-type silicon, and this guard-ring structure will induce a high degree of minority-carrier injection to the N-type drift region under forward conduction mode. When this happens, the Schottky rectifier will incur high switching losses in the circuit, also making it a less attractive component choice compared to ultrafast recovery diodes.

Addressing the weaknesses of high V_F and high switching losses in traditional 200 V Schottky rectifiers, the industry's first 200 V Trench MOS Barrier Schottky (TMBS) rectifier, constructed with a shallow trench and thin gate oxide structure, is proposed and presented in this paper.

The edge termination of this 200 V TMBS device is accomplished by a novel design fabricated together with the main cells of the device, such as that described by Hsu et al [1]. By properly selecting the critical device dimensions, a reverse blocking capability meeting 200 V application requirements is achieved using multi-trenches with dimensions of only 2.0 μm to 2.5 μm deep and a thin gate oxide layer of 0.30 μm or less. This design greatly facilitates manufacturing throughput and process control while eliminating the need for deep trench fabrication.

2. DESIGN, SIMULATION AND FABRICATION

2.1 The 200 V TMBS Design

For the design of the 200 V TMBS rectifier shown in Fig. 1, including the main cells and edge termination structure, comprehensive numerical analysis using the SILVACO two-dimensional device simulator was performed to show the relationship between device's electric characteristics and critical structural parameters.

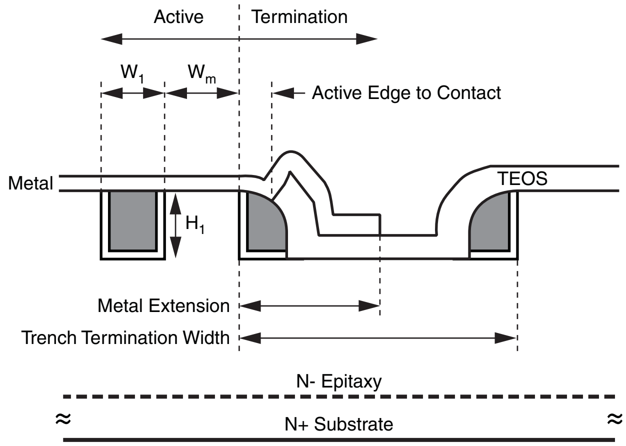

Fig. 1 - The Schematic Cross Section of a TMBS Diode with the Novel Trench Termination Design. W_t, W_m, and H_t Represent Trench Width, Mesa Width, and Trench Depth Respectively

The structural parameters were recursively simulated based on those relationships to meet our target specifications for on-state voltage drop and reverse leakage at 125 °C. With an eye towards manufacturing throughput, we found the optimum structure has a trench depth of 2.1 μm and oxide thickness of 0.27 μm. These dimensions are much smaller than those previously published for 100 V trench rectifiers by Shimizu et al. [2]; they are also smaller than the published figures for 150 V GD-trench rectifiers with a device simulation with trench depth of 8.0 μm and oxide thickness of 0.7 μm presented by Mahalingam and Baliga [3]. This shallow-trench thin-oxide TMBS (STTO-TMBS) structure can greatly reduce the process cycle time required for trench etching in fabrication and thus improve manufacturing process throughput.

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2.2 Simulation Results

The electric field distribution along the centerline of an active cell was plotted against the depth into the N-type drift region for the optimized design, under 200 V reverse bias voltage. A similar simulation was carried out on a traditional 200 V planar Schottky device and the electric field curve was overlapped to the TMBS curve as depicted in Fig. 2.

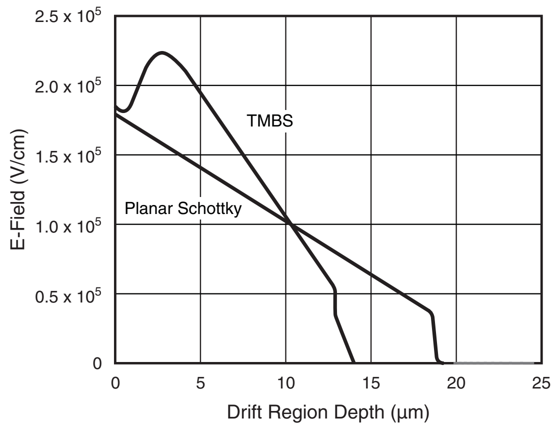

Fig. 2 - The Simulated Electric Field Strength at a Reverse Voltage of 200 V for TMBS and Traditional Planar Schottky

As described in Fig. 2, under 200 V reverse bias, we find that the TMBS rectifier has an electric field distribution with peaks at the depth of 2.8 µm and a value of 2.2×10^5 V/cm; this field strength is 73 % of the critical electric field of the silicon at 3.0×10^5 V/cm. On the other hand, the planar Schottky rectifier's electric field strength curve follows that of a typical metal-semiconductor junction characteristic, with a linear distribution. Due to the nonlinear electric field strength behavior of TMBS rectifier, we have been able to achieve the desired 200 V reverse blocking capability with a higher concentration of silicon than that found in a planar Schottky rectifier as indicated by gradients of the respective electric field strength curves which follow the formula:

$$\frac{dE(x)}{dx} = -\frac{qN_A}{\varepsilon_S}$$

Another TMBS advantage is the narrowness of the required drift region, which is 13 µm for TMBS and much less than the 19 µm found in a planar Schottky rectifier. Combining the above two factors, the TMBS rectifiers provide much less drift region conduction resistance, which is sufficient to negate the area loss contributed by the non-conducting MOS trench structures.

Besides the active cells, the electric field distribution was also analyzed for the edge termination regions. As shown in Fig. 3, under 200 V reverse bias voltage, the maximum electric field strength is uniform across the active cell trench corners and the termination regions. With this result, we have ensured the device performance is optimized per the material used and the design envelope of the trench physical dimensions. It also paves the way for ensuring excellent avalanche capability when reverse overstress occurs.

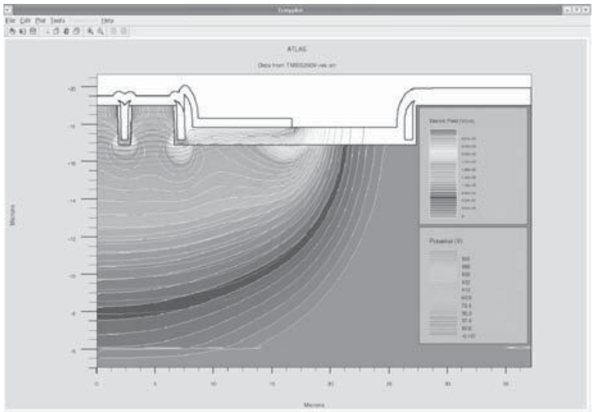

Fig. 3 - The Simulated Electric Field Distributions and Equipotential Lines of a TMBS Diode Under 200 V Reverse Bias

2.3 Fabrication

The fabrication process starts with trench etching in the active and termination regions (Fig. 1). After gate oxidation, an N+ polysilicon layer is deposited and an etching back process forms the poly spacer in the termination region. With the MOS structure formed in the trenches by the polysilicon-oxide-silicon configuration, a passivation layer is deposited, followed by definition of the metal-semiconductor (M-S) contact region. After the formation of the M-S Schottky contact with a selected barrier metal, a conduction metal layer is deposited, and a mask is used to define the metal region. The wafers are then subjected to a back grinding and backside metalization process to form the ohmic contact for the wafer backside. For the critical Schottky contact in this process flow, and to achieve specific device characteristics, a proprietary sputtering process and salicide structure have been developed to enable selection of Schottky barrier heights from 0.70 eV to above 0.80 eV.

3. DEVICE CHARACTERIZATION

3.1 Parametric Measurement

Our 200 V TMBS wafers were sawn to chips and assembled in TO-220 packages for parametric measurement. Their static DC characteristics were checked by multifunction production testers and high-power curve tracers (Tektronix-371A). A constant temperature chamber was used for specific-T_J measurement to simulate the actual device working environment. An LEM tester with module LEM Q_{rr} 50 A was used for device switching performance characterization, where several combinations of I_F, dI/dt, and V_R conditions were measured.

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The 200 V TMBS is designed to have optimized V_F performance with the current density near 180 A/cm^2. As far as switching performance is concerned, in high forward-current and high-frequency switching applications, 200 V TMBS limits the minority carrier injection and quickly recombines minority carriers through high-concentration majority carriers. The device's punch-through design, which enhances this recombination effect, also contributes to the excellent switching performance of the 200 V TMBS rectifier.

3.2 Benchmarking Test with Planar Schottky and Ultrafast Rectifier

The electrical characteristics of packaged 200 V TMBS rectifiers were compared to industry standard planar Schottky barrier rectifiers with a 90 A datasheet rating and to three types of 30 A rated ultrafast recovery diodes (UFRD) from leading power semiconductor manufacturers. When compared to planar Schottky rectifiers, the forward voltage drop (V_F) of 200 V TMBS device achieved a better than 13 % improvement at a current density of 180 A/cm^2 and junction temperature of 125 °C (Fig. 4). In fact, the 200 V TMBS provided various degrees of V_F improvement over the whole forward current range. On the other hand, when compared to an UFRD having the same die size, the 200 V TMBS showed a V_F improvement of 16 % at a current density of 180 A/cm^2 (at T_J = 125 °C) while its switching characteristics are the same (see Table 1).

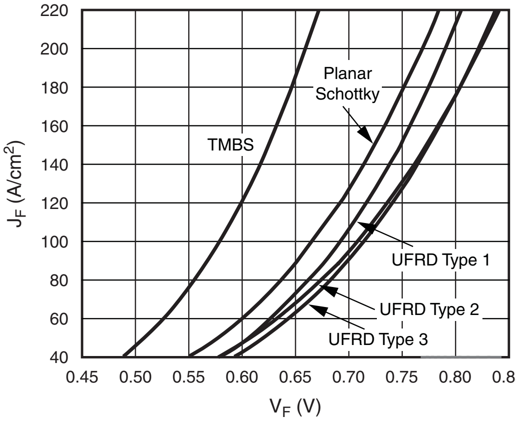

Fig. 4 - J_F - V_F Curves for 200 V Rectifiers Under Benchmark (T_J = 125 °C)

TABLE 1 - ELECTRICAL CHARACTERISTICS COMPARISON OF 200 V RECTIFIERS

200 V RECTIFIERS COMPARISON		TMBS	PLANAR SCHOTTKY	UFRD TYPE 1	UFRD TYPE 2	UFRD TYPE 3
Die size (cm^2)	Die size	9.1 x 10^{-2}	2.0 x 10^{-1}	9.1 x 10^{-2}	7.7 x 10^{-2}	9.9 x 10^{-2}
V_R (V)	at 1 mA	210	222	269	266	287
I_R (mA)	at 200 V/125 °C	8.3	1.1	0.1	1.8	0.1
V_F (V)	at 15 A/125 °C	0.63	0.63	0.76	0.81	0.77
I_{rr} (A)	I_F = 15 A, dI/dt = 200 A/μs, V_R = 200 V, 125 °C	5.8	8.6	7.2	5.8	7.1
t_{rr} (ns)		45	63	43	34	42
Q_{rr} (nC)		136	280	155	100	152

One commercial UFRD (Type 2) was observed to have better reverse-recovery performance compared to 200 V TMBS under condition of I_F = 15 A, dI/dt = 200 A/μs, V_R = 200 V, and T_J = 125 °C (Fig. 5), but its V_F was the highest observed also. According to data comparisons at 125 °C, this commercial UFRD was calculated to have a 19 % higher V_F than the 200 V TMBS under the same current density of 180 A/cm^2.

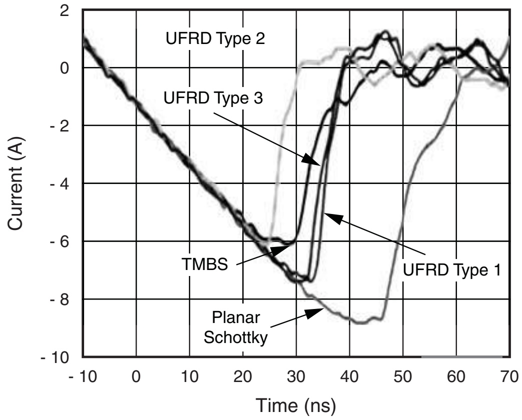

Fig. 5 - Switching Performance Comparisons Between 200 V Rectifiers (I_F = 15 A, dI/dt = 200 A/μs, V_R = 200 V, T_J = 125 °C)

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4. APPLICATION TEST

4.1 Efficiency Benchmark on SMPS

To assess the benefits of the device within an application, the 200 V TMBS rectifiers with the die size specified in Table 1 were used in a state-of-the-art AC/DC telecom SMPS with a 1800 W maximum output. The SMPS is built with a phase shift full-bridge ZVS (zero voltage switching) topology. When measured at a 30 A, 51 V_{DC} output current, the 200 V TMBS solution provided a 0.44 % efficiency improvement compared to a commercial 200 V planar Schottky rectifier. It is worth noting that the die size of the TMBS used in this evaluation occupies only 46 % of the area of the planar Schottky. Four Schottky rectifiers were used in this SMPS, each with a common-cathode dual-rectifier configuration. The total silicon usage with the TMBS approach is 0.73 cm^2, compared to 1.60 cm^2 for the traditional planar Schottky technology in the 1800 W SMPS evaluation. Following is the test result in a chamber with constant 50 °C ambient temperature.

TABLE 2

PRODUCT	POWER LOADING	P_{in} (W)	P_{out} (W)	EFFICIENCY	POWER SAVING (W)
TMBS	~ 30 %	573	515	89.9 %	1.13
Planar Schottky		574	515	89.7 %	0 (base point)
UFRD Type 1		574	515	89.8 %	0.41
TMBS	~ 90 %	1685	1551	92.1 %	7.42
Planar Schottky		1691	1549	91.6 %	0 (base point)
UFRD Type 1		1688	1550	91.8 %	3.29

Note

- Efficiency comparisons between TMBS, planar Schottky, and UFRD used in a 1800 W rated SMPS at 50 °C ambient temperature; all devices packaged in the TO-247. Die sizes as described in Table 1.

4.2 Efficiency Benchmark on DC/DC Converter

To understand the benefit of the TMBS device, we tested one full-brick, 48 V input, and 32 V/18 A output isolated telecom DC/DC converter. This DC/DC converter topology has two forward converters in parallel with a 350 kHz switching frequency and uses four 200 V-rated 30 A rectifiers. Both of the UFRD Type 2 and UFRD Type 3 devices are ultrafast rectifiers with a typical t_{rr} of less than 17 ns.

The TMBS rectifier can deliver a 1 % efficiency improvement over the ultrafast rectifier in this application at an ambient temperature of 25 °C. Translated into power savings, this means the TMBS can reduce power dissipation by more than 5 W compared to ultrafast rectifiers in this DC/DC converter application. This power reduction is very important in DC/DC converter designs; and in particular from a thermal management point of view. Based on our comparisons to date with commercially available parts, there are no available planar Schottky rectifiers that can function within this 350 kHz application; when attempted, the converter shut down immediately due to its overload protection function.

In the next stage of testing, with the ambient temperature increased to 35 °C, the TMBS rectifier has demonstrated power savings of more than 9 W compared to the UFRD Type 2 sample, while the UFRD Type 3 sample would cause converter overload protection function to be triggered in this 35 °C ambient temperature test.

TABLE 3

PRODUCT	POWER LOADING	P_{in} (W)	P_{out} (W)	EFFICIENCY	POWER SAVING (W)
TMBS	~ 50 %	310	284	91.7 %	2.72
UFRD Type 2		312	284	90.9 %	0 (base point)
UFRD Type 3		312	284	90.9 %	0.15
TMBS	~ 100 %	621	569	91.6 %	7.14
UFRD Type 2		627	569	90.7 %	1.71
UFRD Type 3		628	568	90.5 %	0 (base point)

Note

- Efficiency comparisons between TMBS and two types UFRD on 600 W rated DC/DC converter at 25 °C ambient temperature; all devices packaged in the TO-263. Die sizes as described in Table 1.

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5. SUMMARY

The development of a new 200 V TMBS rectifier built on a high-efficiency fabrication process and achieving improved electrical characteristics has been reported. The device parameters and specifications are carefully optimized to maximize efficiency in the manufacturing process and achieve target electrical characteristics. The forward voltage drop of the fabricated 200 V TMBS rectifier is 13 % lower than same-size planar Schottky rectifiers while exhibiting a reverse recovery charge of only 49 % of the comparable performance planar device value. The 200 V TMBS was evaluated in an 1800 W SMPS as the output rectifier, where the TMBS device required less than half the die size area to achieve 0.3 % better efficiency than the traditional planar Schottky rectifier. In the DC/DC converter evaluation, the overall performance of the 200 V TMBS is far superior to 200 V ultrafast diodes. These results indicate that TMBS rectifiers have high potential to become the preferred rectifier choice for 200 V applications in the future.

6. REFERENCES

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