TMBS®, Trench MOS Barrier Schottky Rectifiers Address Weaknesses of Traditional Planar Schottky Devices

By Max Chen, Henry Kuo, and Sweetman Kim

Until recently, silicon-based Schottky barrier rectifiers were limited to operating voltages below 100 V for most applications. However, the trend in high-frequency applications has been towards greater power consumption, requiring higher reverse bias voltages (100 V and above) for higher-output adapters. In consumer electronics, there has been a rapid increase in the power consumption of computers, game consoles, and LCD TVs. A similar development has occurred in the design of high-power, high-efficiency telecom base station power supplies. Higher voltage spikes and / or higher switching frequencies are the inevitable outcome of this trend.

Consequently, Schottky rectifiers are now being designed with higher operating voltage ranges. To meet the requirements of the consumer electronics and telecom applications, 100 V Schottky rectifiers have become more common, with new designs moving toward reverse bias voltage ratings of 120 V and 150 V, or even 200 V. However, as higher operating voltages have become more common, the performance limitations of Schottky devices have become more obvious.

As shown in Fig. 1, planar structures typically implement a carefully designed P-type guard-ring structure, a high-resistivity silicon epitaxial layer, and a high Schottky barrier height to achieve breakdown voltages of 100 V and above with an acceptable reverse leakage current. In this structure, the P-type guard-ring injects minority carriers into the semiconductor drift region; these carriers slow down the Schottky rectifiers under switching conditions.

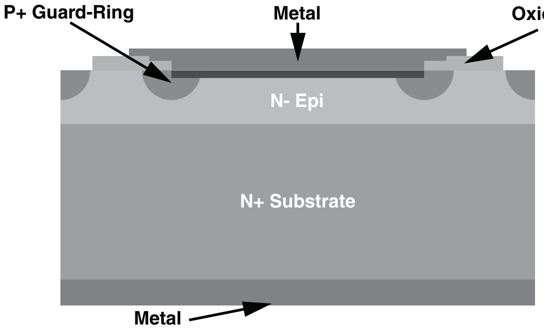

Fig. 1 - Planar Structures Achieve Breakdown Voltages of 100 V and Above by Utilizing a P-type Guard-Ring Structure, a High-Resistivity Silicon Epitaxial Layer, and a High Schottky Barrier Height

As the operating voltage moves to 100 V and above, the high-resistivity silicon and high Schottky barrier height become factors in significantly increasing on-state voltage drop and slowing switching speeds. These limitations can be alleviated by using an innovative device built on a trench metal oxide (MOS) technology.

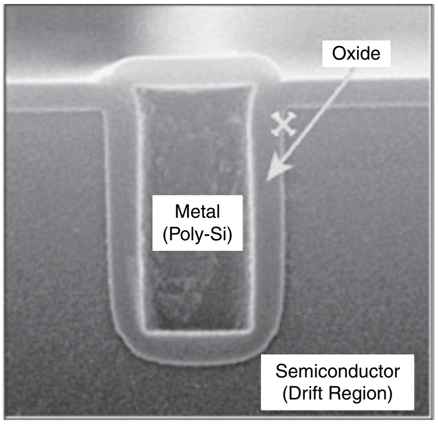

Fig. 2 - SEM Photograph of a Single TMBS Sub-Micron Cell

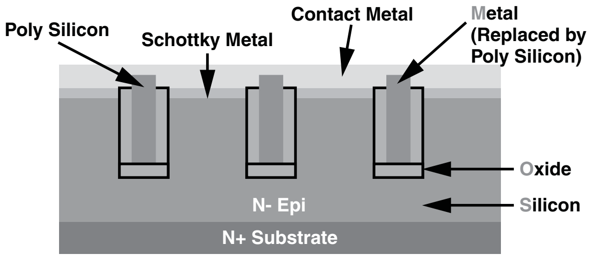

Fig. 3 - Multi-Cell Structure of a TMBS

The increased on-state voltage drop and slower switching speeds of traditional planar Schottky rectifiers can be overcome by a new series of 100 V rectifiers that apply the Trench MOS Barrier Schottky (TMBS®) structure. A single TMBS sub-micron cell is shown in the SEM photograph of Fig. 2 and the multi-cell structure of the device is illustrated in Fig. 3. The parameters that affect TMBS performance include the trench depth, mesa width, trench oxide thickness, doping of the epitaxial layer, and electric field termination. These parameters are related to stress, charge coupling, optimized forward voltage drop (V_F), and reverse current (I_R).

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As shown in Fig. 4, depletion regions occur when the TMBS device is in reverse bias, and the MOS couples the charge along its sidewall. The depletion regions of two adjacent MOS transistors will overlap as the reverse bias increases, resulting in "pinch-off" (an overlapped depletion region). The Schottky diode's interface leakage current (I_R) is reduced by this pinch-off electric field.

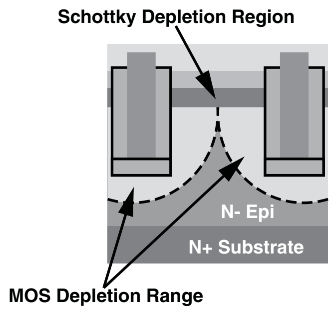

Fig. 4 - The Depletion Regions of two Adjacent MOS Structures will Overlap as the Reverse Bias Increases, Resulting in an Overlapped Depletion Region

In the Trench MOS Barrier structure, stored charges are minimized under switching conditions as depletion regions diminish minority carrier injections to the drift region. The switching speed is much improved, especially under high working temperature and high conduction current conditions.

As depicted in Fig. 5, the Trench MOS structure provides charge-coupling effects in the drift region that will change the shape of the electric field distribution from linear to non-linear, where same reverse breakdown voltages (which is the integration of electric field along the distance of drift region) will be obtained even with much lower resistivity silicon, as indicated by the sharp gradient of TMBS electric-field curve.

By altering the electric field distribution, the TMBS structure moves the stronger electric field away from the Schottky metal-silicon interface to the silicon bulk. As indicated in Fig. 5, the surface electric field (E-field) of the TMBS device is much lower than the planar Schottky devices. The reduced surface field will suppress the barrier-lowering effect, which significantly reduces the leakage current for a given Schottky barrier height. This allows lower Schottky barrier heights to be used without sacrificing reverse leakage performance, which in turn results in a lower forward on-state voltage drop.

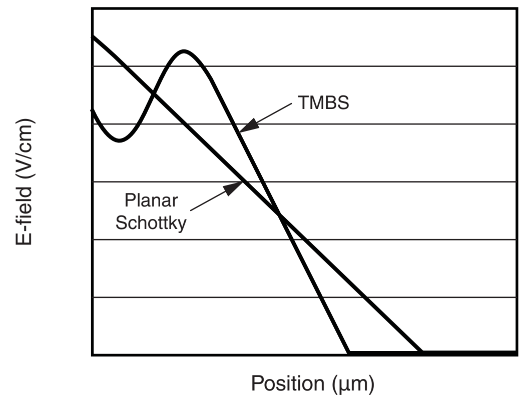

Fig. 5 - A Comparison of the Electric Field Curves of the TMBS and Planar Schottky Along the Semiconductor Drift Region Shows the Surface Electric Field of the TMBS is Much Lower than the Planar Schottky

TMBS AND PLANAR SCHOTTKY PERFORMANCE AND ELECTRICAL COMPARISON

When compared to conventional planar Schottky rectifiers with the same chip sizes and barrier heights, a 100 V TMBS device shows remarkable forward voltage drop performance (Fig. 6). The switching performance of the TMBS is also better, as shown in Fig. 7.

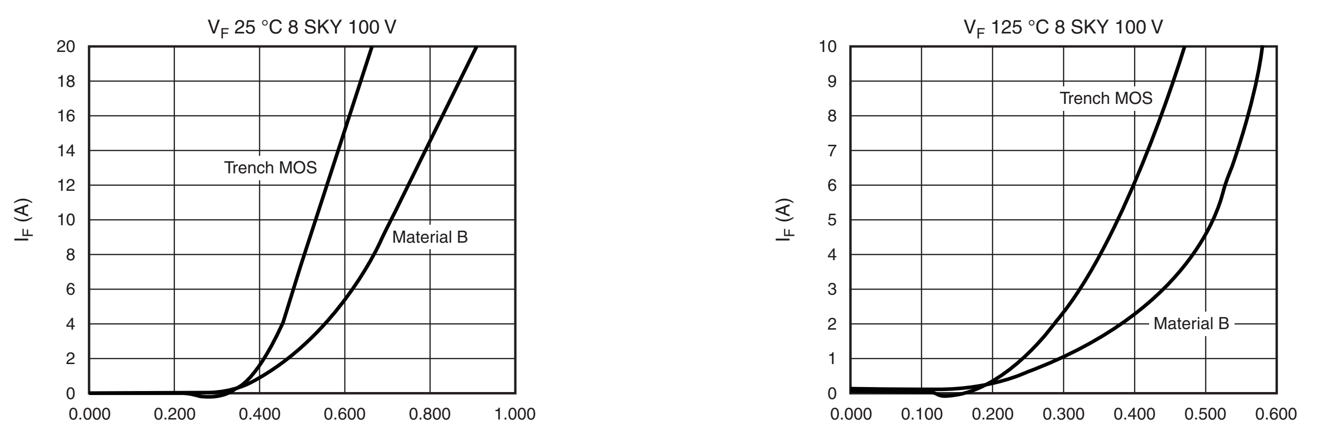

Fig. 6 - V_F Comparison of TMBS and Conventional Planar Schottky Rectifiers

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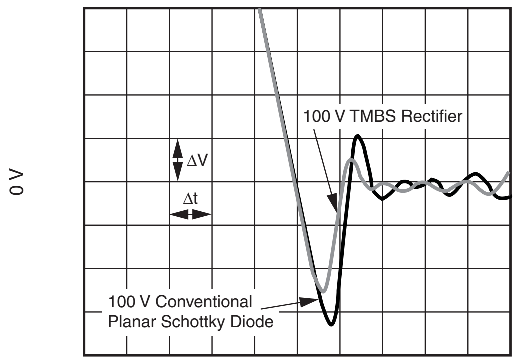

ΔV = 200 mV   Δt = 25.0 ns

Fig. 7 - t_{rr} Curves of TMBS and Planar Schottky Rectifiers Show TMBS has Better Switching Performance

We performed a series of experiments in which TMBS rectifiers were tested against benchmark planar Schottky rectifiers to compare the two structures in an actual application. In the first test, we used a 350 W switch mode power supply (SMPS) as a test vehicle. TMBS devices rated at 40 A and 100 V were compared to industry-standard Schottky rectifiers rated at 20 A and 100 V (MXXXXH100CT) and two such devices with ratings of 60 A and 100 V (XXCTQ100 and STXXXXH100CT). All devices in this evaluation are packaged in the standard TO-220.

The results show that at a 67 % output (about 235 W) to full rated power levels, the 20 A rated device has the lowest total power supply efficiency of 78.3 % (Table 1). When the 60 A rated devices were substituted for the 20 A devices in the same power supply slot, efficiency improvements of 0.8 % and 0.9 % were observed. These improvements translate into a savings of 2.35 W and 2.77 W, respectively, for the power supply. Even when the 40 A TMBS rectifier is used to replace a traditional planar device rated at 60 A, we see an improvement in efficiency of 0.4 %. Compared to a baseline 20 A planar Schottky rectifier, the efficiency improvement is 1.3 %, for a power savings of 3.72 W.

TABLE 1

PART NUMBER	INPUT POWER (W)	OUTPUT POWER (W)	EFFICIENCY	POWER SAVING
Industry 20 A planar Schottky (MXXXXH100CT)	299	234	78.3 %	0 (Base)
Industry 60 A planar Schottky (XXCTQ100)	298	236	79.1 %	2.35 W
Industry 60 A planar Schottky (SXXXXXH100CT)	297	235	79.2 %	2.77 W
Industry 40 A TMBS (VTS40100CT)	297	236	79.6 %	3.72 W

Note

- Efficiency evaluation on a 350 W SMPS (switch mode power supply), comparing TMBS with industry-standard planar Schottky products. TMBS provides efficiency improvement of 1.3 %, for a power saving of 3.72 W

By evaluating TMBS rectifiers with ratings of 40 A and 100 V (VTS40100CT) in a 120 W adapter, we were able to further demonstrate the capabilities of the new TMBS devices. The typical solution for this application is a synchronous rectification approach implemented with two 40 A, 100 V MOSFETs and a matching driver IC. From test data as described in Table 2, and under full-rated 120 W output conditions, the pair of TMBS rectifiers provide the same total adapter efficiency of 87 % as the more complicated, more costly, and less robust synchronous rectification solution.

TABLE 2

ORIGINAL 40 A/100 V SR SOLUTION			CHANGE TO 40 A/100 V TMBS		
INPUT VOLTAGE	**90 V_{AC}**	**100 V_{AC}**	**INPUT VOLTAGE**	**90 V_{AC}**	**100 V_{AC}**
I_{in} (A)	1.56	1.39	I_{in} (A)	1.56	1.40
P_{in} (W)	140	139	P_{in} (W)	140	139
V_0 (V)	20.2	20.2	V_0 (V)	20.2	20.2
I_0 (A)	6.0	6.0	I_0 (A)	6.0	6.0
P_0 (W)	121	121	P_0 (W)	121	121
Efficiency %	86.4	87.1	Efficiency %	86.2	87.0

Note

- Efficiency evaluation on 120 W adapter. The TMBS rectifier pair provides the same efficiency as the more complicated, more costly, and less robust synchronous rectification solution

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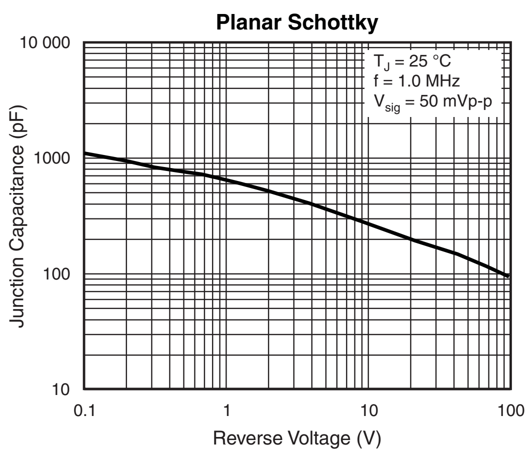
The ability to withstand higher energy transients during reverse bias is another advantage of the TMBS structure. The strongest electric field of a conventional planar Schottky rectifier is at the surface of the device, which will limit heat dissipation and avalanche energy absorption. The strongest electrical field of a TMBS device, by contrast, distributes at the bottom of each trench well. The silicon bulk can thus absorb and dissipate more avalanche energy than at the surface.

For high ESD or rectification applications such as OR-ing diodes in hot-plug systems and diodes in SMPS, the ability to enable high reverse avalanche energy makes the TMBS rectifier the more suitable structure. The average of 8/20 μs reverse surge energy of the 40 A, 100 V VTS40100CT is about 170 mJ. This is about twice the conventional planar Schottky diode's reverse surge energy under the same test condition.

At a low reverse bias, TMBS devices have a much higher capacitance (C_J) than planar Schottky diodes. This high capacitance is caused by the trench sidewall and bottom capacitance being in parallel with the original Schottky barrier capacitance. When reverse bias increases, however, the TMBS capacitance falls significantly. Depletion regions will completely overlap when reverse biases are high enough.

TMBS and planar Schottky diodes have a similar electrical field distribution. Fig. 8 shows the capacitance of Vishay TMBS and a planar Schottky having the same chip size. We can see that the C_J of the 100 V TMBS is close to that of the planar Schottky rectifier for reverse bias voltages over 30 V. However, since TMBS has a higher current density, a smaller chip with lower capacitance may be used for a particular application.



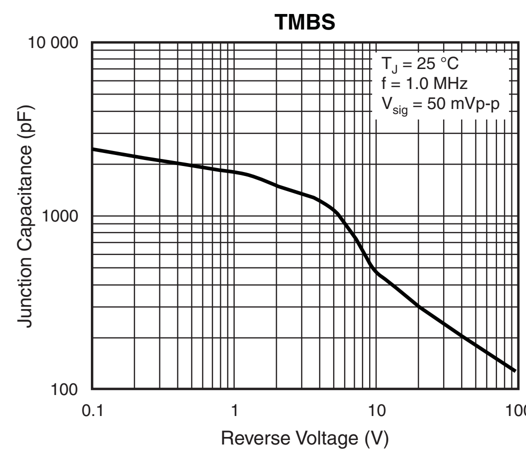


Fig. 8 - Capacitance Comparison Between TMBS and Planar Schottky Diodes Shows that TMBS is Close to That of the Planar Schottky Rectifier for Reverse Bias Voltages Over 30 V

So far, benchmark and application tests have focused on TMBS products with a 100 V reverse bias voltage. However, 120 V products have been developed and released for applications that see higher voltage spikes and where a 100 V rated product might provide inadequate headroom to ensure long-term reliability. These 120 V products offer current ratings from 15 A to 60 A and are offered in the ITO-220, TO-220, TO-262, TO-263, and TO-247 packages.

200 V devices are the next stage for TMBS rectifiers. The devices are currently under development, and the preliminary test results as described in Table 3 have been very encouraging, showing that the TMBS rectifier provides lowest on-state voltage drop compared to the industry-benchmark 200 V planar Schottky rectifiers and 200 V ultra-fast p-n junction diodes. The comparison underscores the switching performance advantages of the TMBS rectifier.

In addition to offering half the stored charge of industry-benchmark devices, the peak switching reverse recovery current (I_{rr}) of TMBS rectifiers is also 34 % lower by comparison. This low I_{rr} will contribute to the lower switching losses of the transistor switches and improve the power conversion efficiency of the complete circuit, particularly in designs with switching frequencies above 300 kHz. The first 200 V rated TMBS rectifier has been released in Q4, 2006.

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TABLE 3 - ADVANTAGES OF TMBS OVER PLANAR SCHOTTKY IN RECTIFICATION APPLICATIONS				
PRODUCT TYPE		INDUSTRY 200 V PLANAR SCHOTTKY (MXXXX200CT)	INDUSTRY 200 V ULTRAFAST DIODE (SXXX3002CG)	VISHAY 200 V TMBS (EXPERIMENTAL)
V_R (V)	at 1 mA/25 °C	259	296	210
I_R (mA)	at 200 V/125 °C	0.10	0.01	6.70
V_F (V)	at 5 A/125 °C	0.57	0.64	0.53
V_F (V)	at 15 A/125 °C	0.69	0.80	0.65
I_{rr} (A)	5 A, 300 A/µs, 100 V, 10 %, 125 °C	7.2	7.0	4.7
t_{rr} (ns)		33	29	25
Q_{rr} (nC)		122	104	60

Note

- Comparison of electrical characteristics for the experimental 200 V TMBS rectifier and 200 V planar Schottky rectifier and ultrafast diode.

As demonstrated in Table 1, the lower forward voltage drop and faster switching speed of the TMBS allow switch mode power supplies to achieve higher efficiency operation. The performance comparisons above (see Table 2) also show that TMBS achieves the same efficiency as a MOSFET synchronous rectifier in a 120 W adapter application, but at a lower cost. This application will be discussed further below, as well as other applications for the TMBS.

Due to the higher efficiency and better thermal performance of low on-resistance MOSFETs, synchronous rectification circuits have used them instead of planar Schottky rectifiers. However, as we have shown, TMBS is a cost-effective alternative to MOSFET synchronous rectifiers. Furthermore, TMBS offers the better performance in low output current devices such as adapters and open-frame power supplies. Synchronous MOSFET rectifiers may indeed provide good performance in high-current rectification applications, but the percent of MOSFET switching losses grows higher in the total power loss at output rectification in small current applications.

In addition, by requiring complex circuitry to control it, the MOSFET creates additional failure risks that can reduce the reliability of power supply systems. Therefore, low-V_F TMBS rectifiers are more suitable for lower-current adapters and open frame power supply designs. The performance of TMBS can compete with MOSFET in lower-current rectification applications and enjoys the advantages of shortened design cycles and lower production costs by requiring no additional control circuits. A block diagram showing a MOSFET implementation of synchronous rectification is shown in Fig. 9, and an alternate circuit using TMBS is shown in Fig.10. As illustrated in these two figures, a single TMBS diode may replace the MOSFETs and drive circuit, thus simplifying the circuit significantly.

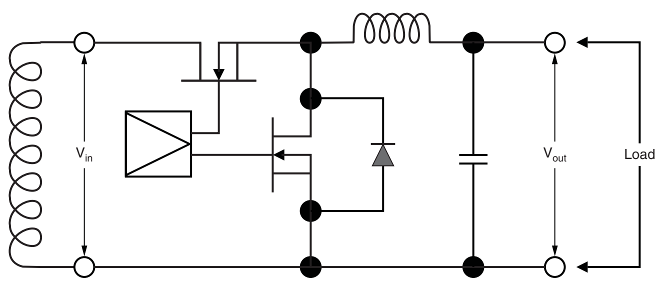

Fig. 9 - MOSFET Implementation of Synchronous Rectification

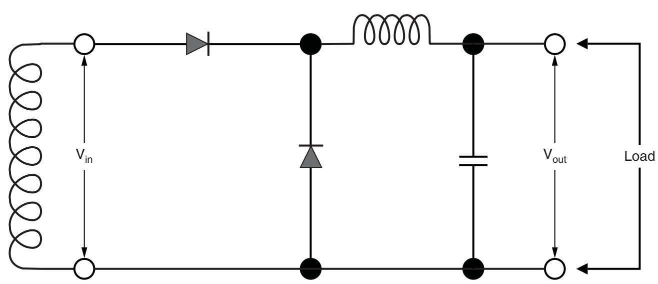

Fig. 10 - Alternate Circuit Using TMBS

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Diodes for redundant power supplies used in high-reliability power systems (Fig. 11) are called OR-ing diodes, which are widely used in computer servers and telecommunication systems. The OR-ing diode at SMPS 2 must have a reverse breakdown voltage greater than the output voltage of SMPS 1 in order to protect SMPS 1. It must also have a low reverse leakage current. However, if SMPS 1 malfunctions and shuts down and SMPS 2 turns on, it is important that the OR-ing diode have a low forward voltage drop to minimize power losses from SMPS 2.

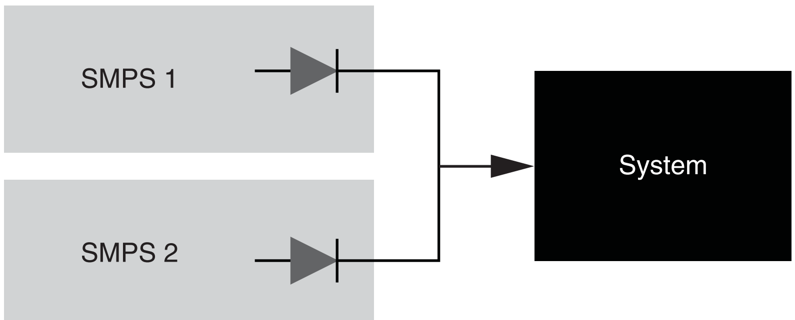

Fig. 11 - Redundant Power Supply Used in a High-Reliability Power System with OR-ing Diodes

In high-reliability power systems, the system is protected from a shutdown resulting from malfunctions in one of the power supplies by having redundant power supplies share electrical loads. The design aims to isolate the failed SMPS from the common bus if an SMPS failure occurs, and thus requires a switch to isolate the failed SMPS. This switch must be highly sensitive and able to react with high interrupt speed when an SMPS fails; but it must also have low conductivity for big transient loads.

For OR-ing functions in isolated redundant power supplies, TMBS diodes offer significant improvements over conventional diodes. Low-$R_{(DS)on}$ MOSFETs (OR-ing FETs) are sometimes used in these applications. However, OR-ing FETs have a lower turn speed than OR-ing diodes, which may cause undesirable 0.8 V to 1.5 V voltage drops by the body diode of the OR-ing FET after it is tripped by high-transient voltage changes from high loading to low loading. The more reliable redundant-power-system design is to use one OR-ing FET in parallel with one low-V_F Schottky diode. The 100 V TMBS Schottky diode offers an outstanding design solution in telecom redundant power systems.

Another advantage of TMBS diodes is a higher reverse energy capability, allowing them to better withstand transients when power supplies switch on. The unique trench well structure and silicon bulk in the TMBS absorb and dissipate more avalanche energy than the plain interface structure of conventional planar Schottky rectifiers. This ability to enable higher reverse avalanche energy makes the TMBS more suitable for use in high-ESD or rectification applications than the average 8 µs by 20 µs reverse surge energy of the VTS40100CT is about 170 mJ, which is about two times that of conventional planar Schottky diodes under the same testing conditions.