Super Barrier Rectifier – A New Generation of Power Diode

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***Abstract*- The main principle behind the new Super Barrier Rectifier (SBR) approach is to create the "Super" barrier for majority carriers without unreliable metal-semiconductor Schottky contact. SBR technology creates such barrier in the MOS channel. The height of this barrier can be easily adjusted by the doping concentration in the channel. This paper demonstrates that the new power diodes combine high performance and high reliability for low voltage applications (below 100V). The underlying concepts and analysis of operation are presented as well as the lab test results that compare performance and reliability between Schottky and the new SBR diode.**

I. INTRODUCTION

The performance and reliability of power diodes often limit the design of modern power devices. Schottky diode is the dominant technology for rated voltage below 250 V. Schottky diodes are attractive to power electronic applications due to their high performance: low forward voltage (V_F) at reasonable leakage current (I_R) and small reverse recovery times (t_{RR}) [1]. Schottky technology is well known for its relatively high level of leakage current in off state compared to PN diodes. The leakage in traditional Schottky diodes does not stay constant, but increases exponentially with the applied bias due to the image charge potential barrier lowering [1]. The main problem of Schottky diodes is the low reliability of metal-semiconductor contact, which limits their ability to operate at high temperatures, and reduces capability to withstand forward and reverse surges. Schottky diodes rapidly lose their performance and reliability with temperature, thus requiring additional consideration of heat removal.

The alternative PN-junction technology in comparison provides lower performance but higher reliability. PN-junction diodes typically have larger V_F and t_{RR}. Being a minority carrier device, PN diode has larger than Schottky reverse recovery time [1]. Lifetime control methods allow reduction of recovery time at the expense of the increase of the forward voltage. Despite these disadvantages, PN diodes dominate rectifier market when high breakdown voltage or high reliability is required, e.g. at high operation temperatures or high currents.

[1] Diodes Inc. acquired APD Semiconductor Inc. assets in October 2006.

Previously, the channel diode technology [2, 3] has been suggested to combine high performance with high reliability, but it did not provide viable competition to Schottky diodes. This paper introduces new SBR technology, which has both high performance and high reliability, a combination which cannot be achieved with Schottky or PN-junction technologies. We discuss the operation of SBR diodes with rated voltage 100 V and lower. SBR operation at higher rated voltage is complicated due to carrier density modulation, which will be addressed in separate publication. We also demonstrate that real SBR diodes can readily compete with Schottky for a number of practical applications.

II. SBR STRUCTURE AND OPERATION PRINCIPLES

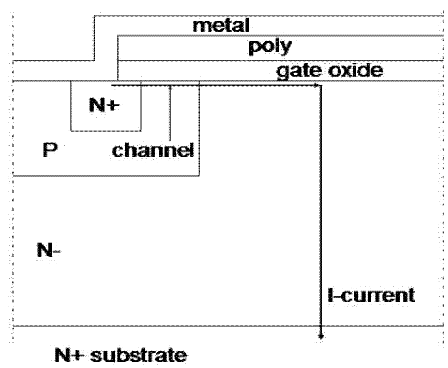
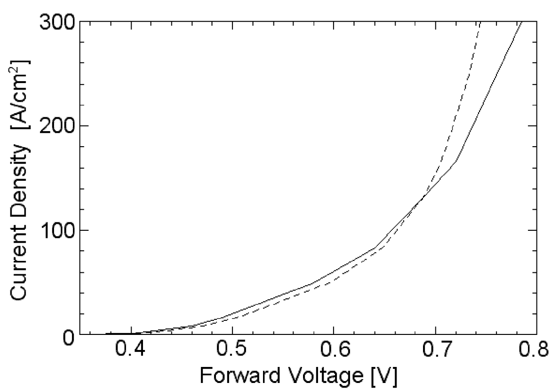


Figure 1. Cross-section of Super Barrier Rectifier (SBR) cell.

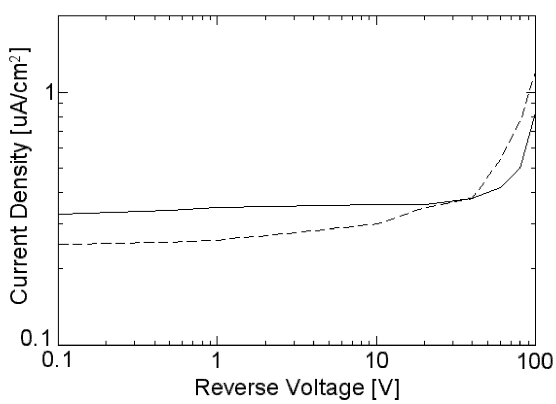
The SBR diode overcomes the aforementioned issues with Schottky and PN diodes by using the MOS structure as illustrated in Figure 1. The most important part of the structure is the MOS channel formed under the thin gate oxide, where the "Super" barrier for majority carriers is created without unreliable Schottky contact. The "Super" barrier guarantees that forward bias performance will be similar to Schottky with higher reliability. Moreover, SBR technology improves reverse bias performance. The absence of image charge potential barrier reduction results in constant leakage (current limiting function) and abrupt breakdown (good for voltage regulation and protection). In order to make the SBR an effective rectifier, the channel has to be very short (approximately 0.2 microns [4]). The N+ contact region is introduced to ensure ohmic contact with the metal.

The transient behavior of SBR is similar to Schottky for devices rated below 100 V. Injection of minority carriers is not involved in this case, since it can occur at the PN junction of SBR structure only when applied forward bias is above 0.6 V [5]. Such injection is important for high forward surge capability. For the forward bias the depletion layers of PN junctions in the region between the channels do not overlap and allow the current to flow through the N- region. The particular concentrations and dimensions of various regions can be adjusted for desired diode behavior. The thickness and donor concentration of the N- region control the maximum operation voltage. The acceptor concentration in P region controls the barrier height and the reverse leakage current in such a way that one can trade between low forward voltage and low reverse current [4].

The P-N diodes in parallel to the channel are essential for keeping the leakage current small. In reverse bias regime, when applied reverse voltage reaches a few hundred millivolts, the pinch-off effect takes place due to overlap of these depletion layers. At this point reverse leakage current through MOS channels changes much slower with the increase of reverse voltage. At higher reverse biases the depletion regions spread into N- region and into P-regions of the P-N junctions. This increases a generation current contribution to the reverse leakage.



(a)



(b)

Figure 2. (a) Forward (A/cm^2) and (b) Reverse (μA/cm^2) current density versus applied voltage: simulation (dashed) vs. measured (solid).

III. Tests and measurements

In order to test the above operation principles, we performed computer simulations with ISE TCAD software [6] and compared the results to the measurement on the real SBR device. Figure 2a shows such comparison for SBR diode with 100 V rated voltage. It shows a very good agreement between simulation result (dashed line) and real measurement (solid line). At current density of 140 A/cm^2, both results show a forward voltage V_F = 0.7 V. The discrepancy at higher voltages is due to the voltage drop on wires outside the actual SBR diode.

The behavior of SBR for reverse bias is shown in Figure 2b, which demonstrates a steady leakage up to breakdown voltage. The potential barrier lowering due to the image charge, which is essential for Schottky diode, is absent in SBR. The SBR reverse current is typical of P-i-N diode, where reverse current consists of the constant injection and growing ionization currents. As an example, the actual 10 A 100 V SBR diode with V_F = 0.72 V, the leakage current was found to be less than 50 nA, outperforming Schottky diodes which have much higher leakage for similar forward voltage.

To demonstrate the performance and reliability of SBR diode, it is compared to Schottky diodes of comparable ratings and package size (TO-220) in Table I. SBR diode combines very high performance (V_F and I_R are similar or better than Schottky) with much better reliability parameters (maximum reverse repetitive surge current I_{RRM}, maximum energy during avalanche surge (E_{AS}), thermal runaway temperature, and forward surge current I_{FSM}).

TABLE I
Performance and reliability comparison of 20A 100V diodes.

20A 100V Diode	APD SBR20U100	ST STPS20H100	Vishay MBR20100
Typical VF (V)	0.65	0.71	0.72
IR (typ) (μA)	35	1	0.02
IRRM (A)	3	1	0.5
EAS (mJ)	205	120	24
Thermal Runaway (ºC)	225	205	160
IFSM (A) (square, 10 ms)	285	230	170

The comparison of 1 A 30 V devices in SOD-323 typical for cell phone and other handheld applications is provided in Table II. Some applications need diodes with low leakage and others require low VF. Thus, Toshiba and other companies make two types of 1A 30V diodes. SBR diode has both low leakage and low V_F, thus demonstrating the high performance advantage of SBR technology over Schottky for low breakdown voltages.

TABLE II
Performance comparison of 1A 30V diodes in SOD-323 package.

1A 30V Diode	APD SBR130	Philips	Toshiba (Low I_R)	Toshiba (Low V_F)
V_F (typical) [V]	0.39	0.455	0.47	0.4
I_R (typical) [µA]	15	20	10	500

To put SBR diode into a real circuit test, a 12 V 30 W Buck converter was designed and built to show its performance compared with that of a Schottky diode of the same voltage and current ratings (20 A, 40 V) and package size (TO-220). Laboratory measurements show that the overall efficiency of the Buck converter with SBR is overall better than that using comparable Schottky. Figure 3 depicts that the overall converter's efficiency is improved with SBR throughout loading conditions higher than about 16%. As shown in Figure 3, efficiency improvement varies up to 6% at full load current.

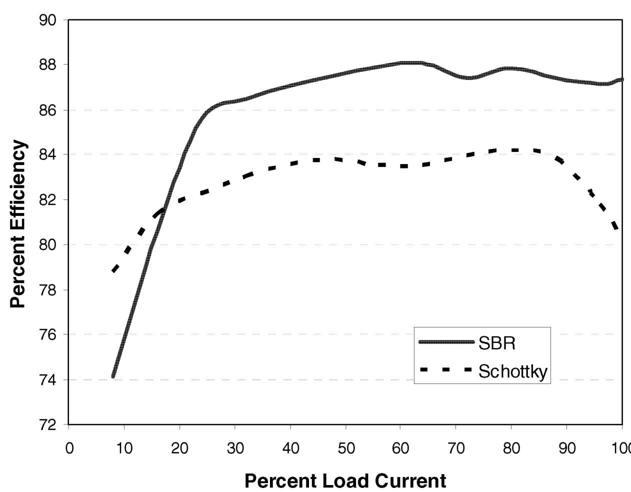


Figure 3. Buck converter's efficiency with SBR (solid) and Schottky (dashed)

Furthermore, diode case and MOSFET case temperature measurements using the same 30 W Buck converter were conducted. As shown in Figure 4, the case temperature of SBR has a more gradual slope than that of Schottky. It is interesting to note that for this particular converter operated above 55% loading, the SBR diode is cooler than the Schottky. At 10% load for example, the Schottky is about 0.9 °C cooler than the SBR. However, at 100% load, SBR is actually cooler by about 1.25 °C.

The difference in performance between SBR and Schottky becomes more noticeable when the results of MOSFET's case temperature measurements are plotted as shown in Figure 5. Here, clearly SBR outperforms Schottky under most of the loading conditions. Beyond about 15% loading, the MOSFET runs cooler with SBR than with Schottky. This further accentuates the benefit of SBR's softer and more stable recovery than that of Schottky.

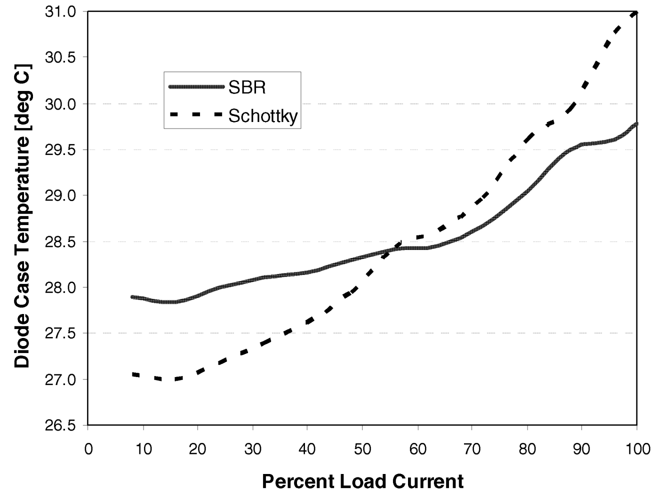


Figure 4. Case temperature measurements of SBR (solid) vs. Schottky (dashed)

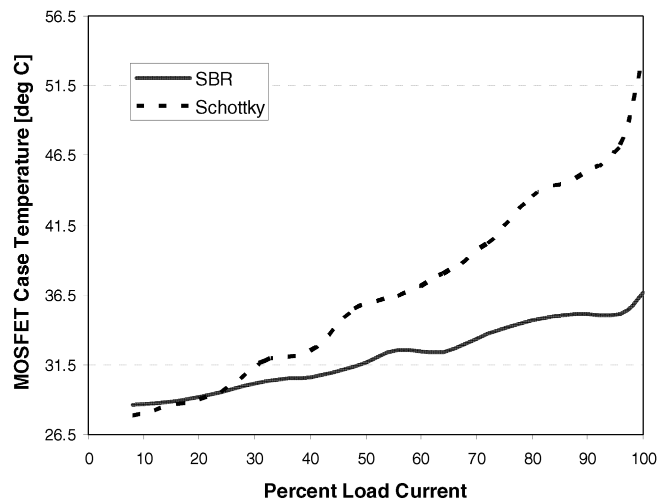


Figure 5. MOSFET's case temperature measurements when the converter is using SBR (solid) vs. Schottky (dashed)

IV. SUMMARY

The Super Barrier Rectifier (SBR) demonstrates attractive properties as a practical power diode. The SBR diodes show a combination of good performance with good reliability. The forward bias behavior for the low voltage devices is similar to that of the Schottky diode. This is expected since by construction the SBR channel region serves as a potential barrier for the majority (electron) carriers. The barrier height can be tuned for particular application in SBR diodes, while in Schottky diodes it is fixed to the metals that make good contact with silicon. SBR diodes typically have lower leakage current compared with the Schottky for the same forward characteristic, due to the pinch-off effect and absence of image charge potential barrier reduction. Thus SBR performance is distinctively better than Schottky rectifiers for rated voltage below 100V. SBR technology can be used to make diodes in smaller packages or reduce the supply chains. SBR diode's performance is similar to Schottky, but its reliability is much

better (20 °C higher thermal runaway, 3 times higher reverse surge capability, which is essential for protection). These advantages of SBR technology permit the development of practical devices that can successfully compete with existing Schottky or PN junction diodes for a number of practical applications based on better performance or better reliability.

REFERENCES

[1]. S. M. Sze, *Physics of Semiconductor Devices*, John Wiley & Sons, 1983.
[2]. Qin Huang and G. A. J. Amaratunga, "MOS controlled diode, a new power diode." *Sol. St. Elec.*, vol. 38, pp. 977-980, 1995.
[3]. H. P. Yee, P. O. Lauritzen and S. S. Yee, "Channel Diode, a new fast switching power diode." in *Proceedings of 1992 ISPSD*, pp.72-79, 1992.
[4]. P. Chang, G.-C. Chern, W. Y. W. Hsueh and V. Rodov , "Method of fabricating power rectifier device to vary operating parameters and resulting device", US Patent 6448160; September 10, 2002.
[5]. C. T. Sah, R. N. Noyce, W. Shockley, *Proc. IRE*, vol. 45, p. 1228, 1957.
[6]. *ISE TCAD user manual*. ISE Integrated Systems Engeneering AG.