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1500 V, 4 Amp 4H-SiC JBS Diodes

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***Abstract*—This paper reports the detailed design, fabrication and characterization of 1500 V, 4 Amp 4H-SiC JBS diodes. 2D device simulations show that a grid spacing of 4 μm results in the most optimum trade-off between the on-state and off-state characteristics. JBS diodes with linear and honeycombed p^+ grids, Schottky diodes and implanted PiN diodes fabricated alongside show that while 4H-SiC JBS diodes behave similar to Schottky diodes in the on-state and switching characteristics, they show reverse characteristics similar to PiN diodes. Measurements on 4H-SiC JBS diodes indicate that the reverse recovery time (τ_{rr}) and associated losses are near zero even at a rev. dI/dt of 75 A/μsec. Based on measured waveforms, detailed loss models on diode switching were established for a high frequency switching power supply efficiency evaluation. A DC/DC converter efficiency improvements of 3-6% were obtained over the fastest, lower blocking voltage silicon diode when operated in the 100-200 kHz range.**

***Index Terms*—SiC, Schottky, rectifier, reverse recovery.**

I. INTRODUCTION

Power devices made with Silicon Carbide (SiC) are expected to show great performance advantages as compared to those made with other semiconductors. This is primarily because 4H-SiC has an order of magnitude higher breakdown electric field (2-4X10^6 V/cm) than Si and GaAs, and an electron mobility only ~20% lower than silicon. A high breakdown electric field allows the design of SiC power devices with thinner and higher doped voltage blocking layers. 4H-SiC unipolar devices are expected to replace Si bipolar switches and rectifiers in the 600-3000 V range in the future.

Generally speaking, there are three classes of rectifiers: (a) Schottky diodes, which offer extremely high switching speed but suffer from high leakage current; (b) P-i-N diodes, which offer low leakage current but show reverse recovery charge during switching; and (c) Junction Barrier Schottky (JBS) diodes which offers Schottky-like on-state and switching characteristics, and PiN-like off-state characteristics. In conventional high voltage (>600 V) circuits using Si PiN diodes, the primary source of power loss is the dissipation of reverse recovery charge during the turn-off of the rectifier. A fast recovery from 4H-SiC JBS diodes allows the design of packages with much lower thermal requirements for both the rectifier and the switch, and is expected to increase in the power density of circuits by 3X.

II. DESIGN AND FABRICATION OF 4H-SIC JBS DIODES

A cross-section of a 4H-SiC JBS rectifier operating in the forward and reverse bias is shown in Figure 1. A JBS diode consists of interdigitated Schottky and p$^+$ implanted areas. For on-state drops of <3 V, only the Schottky regions of the diode conduct. The on-state voltage drop (V_F) of the device is determined by the resistance of the drift region (which is the primary source of V_F at operating current density), metal-SiC barrier height of the Schottky metal, and the relative area of the Schottky vs. the p$^+$ implanted regions. It is important to achieve a good quality Schottky interface for a low on-state drop JBS diode. Since the Schottky regions of the diode have to compensate for the unconducting p$^+$ grid area of the JBS diode, the current density in the Schottky regions of the diode exceeds the current density of the entire device. The metal-SiC barrier height of the Schottky metal should be low enough to give a low on-state voltage, while still be effectively pinched off during the off state. As the reverse bias increases, the depletion regions from adjacent p$^+$ implanted regions pinch-off the leakage current arising from the Schottky contacts of the device. The leakage current in the Schottky regions occurs due to Schottky barrier lowering at the metal-N$^-$ junction. The presence of p$^+$ implanted regions reduces the electric field at the metal-SiC junction because of two-dimensional charge sharing. This property is especially useful when the diode is operating at elevated temperatures since the effect of Schottky barrier lowering is enhanced with increasing temperature.

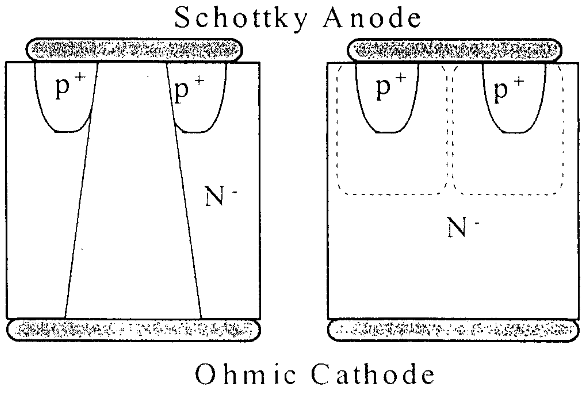

Figure 1: On-state current flows through the Schottky Anode while reverse leakage is limited by depletion from adjacent p$^+$ grids in a JBS diode.

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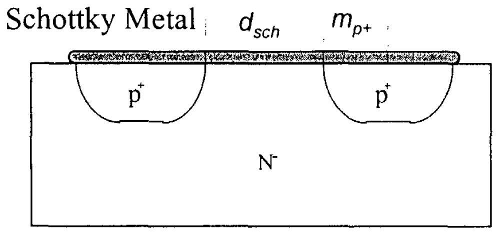

Figure 2: Basic unit cell of a JBS rectifier.

JBS parameter optimization using 2D simulations

These rectifiers were made using a 20 µm/N_D=2E15 cm^{-3} epitaxial layer over 4H-SiC n^+ substrates for a targeted blocking voltage of 2000 V. There exists a fundamental trade-off between the V_F and leakage current of the JBS diode. The design parameters that affect this trade off are: (a) the relative area of the p^+ implanted region; and (b) the geometrical layout of the p^+ implanted region. A large p^+ implanted area is expected to result in a higher the V_F because of smaller conducting area, but may offer lower leakage due to a more effective pinch-off of the Schottky portion. The basic unit cell of a JBS diode is shown in Figure 2. In this figure, the portion of the Anode metal that contacts the n- epitaxial layer (Schottky diode portion of the device) is called d_{sch} and m_{p+} is half the total metal-implanted p+ contact width with Anode metal.

To optimize the design parameters d_{sch} and m_{p+}, detailed 2D device simulations were performed at a nominal cell current density of 200 A/cm^2 in the on-state and 2000 V in the off-state. The three values for d_{sch} analyzed were 2 µm, 4 µm and 10 µm. For the on-state simulations, the peak current densities obtained for d_{sch}=2 µm is 1200 A/cm^2; for d_{sch}=4 µm is 670 A/cm^2; and for d_{sch}=10 µm is 570 A/cm^2. While the V_F for the case of d_{sch}=2 µm is significantly higher (2.75 V), the difference between the V_F at d_{sch}=4 µm (2.45 V) and d_{sch}=10 µm (2.42 V) is not significant. As expected, simulations show that the V_F increases as m_{p+} is increased from 1 µm to 3 µm. Since it is fairly straight-forward to make a 2 µm (corresponding to m_{p+}=1 µm) p+ implanted region, this value was chosen for the fabrication of JBS diodes. To evaluate the effectiveness of d_{sch} on the reverse bias operation (at 2000 V) of JBS diode, the ratio of electric field at the Schottky interface to the peak electric field (at the bottom of the p+ region) is analyzed using device simulations. It was found that the peak electric field at the Schottky interface is only 62% of the peak electric field for d_{sch}=4 µm, but increases significantly to 80% for d_{sch}=10 µm. For d_{sch}=2 µm, this ratio is 57%. From these discussions and simulation results, it can be concluded that a p+ region spacing of 4 µm is optimum for the fabrication of these 2 kV SiC JBS diodes.

The two geometric p^+ layouts implemented on the mask design are the linear p^+ grid and the honeycombed p^+ grid. While honeycombed design offers a more effective pinch-off of the leakage current, a larger area is unconducting for a given distance between adjacent Schottky regions. In order to compare the performance of JBS diodes, four kinds of devices were designed on the same mask: honeycomb grid JBS diode, linear grid JBS diode, implanted PiN diode and Schottky diodes.

The fabrication sequence of these diodes is as follows: Aluminum was implanted at a high temperature to form the p^+ grid of JBS diodes and Anode of the PiN diodes. An optimum dose of Boron was used to implement the JTE edge termination. These implants were annealed at 1625°C followed by a thick LPCVD SiO_2 deposition. Thereafter, Ni deposition and ohmic anneal were performed to form the PiN Anode and backside cathode contacts. A Ni evaporation step was used to form the Anodes of JBS as well as Schottky diodes, followed by a 2 µm Ti/Pt/Au deposition to reduce the resistance.

III. Static Characteristics of JBS Diodes

To determine the effectiveness of the JBS diode concept, it is important to compare the on state and reverse bias I-V characteristics of Schottky diodes, JBS diodes and PiN diodes fabricated on the same wafer. Figure 3 shows the comparison of on-state J-V characteristics of such Schottky, Linear JBS, Honeycomb JBS and PiN diodes. A high on-current of 4 Amps (200 A/cm^2) was obtained on the linear JBS diode with a V_F of only 3.1 V. This corresponds to a specific on-resistance of only 10.5 mΩ-cm^2, and an ideality factor of 1.07 was measured on this diode. The on-state characteristics of the Linear JBS and Schottky diodes are almost identical, indicating excellent current spreading and minimal increase in the V_F due to the introduction of the p+ implanted grid.

The reverse bias characteristics of honeycomb JBS and linear JBS diodes are much more similar to the PiN diodes than the Schottky diodes. At a leakage current of 50 µA, a blocking voltage of Schottky, honeycomb JBS, linear JBS and PiN diodes were measured at 610 V,

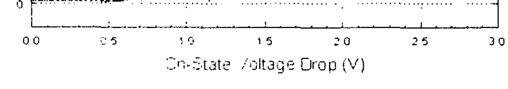

Figure 3: Measured On-state J-V comparison of 1.5mmX1.5mm Schottky, Linear JBS, Honeycomb JBS and PiN diodes fabricated on the same wafer.

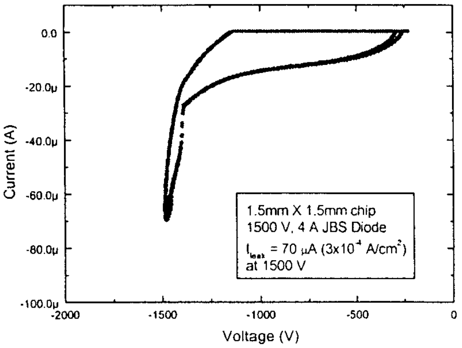

Figure 4: Reverse bias characteristics of a 4 Amp, 1.5mmX1.5mm linear JBS diode.

1380 V, 1480 V, and 1980 V. A blocking voltage of 1500 V was achieved at a leakage current of 70 µA, as shown in Figure 4. This leakage current corresponds to a current density of only $3x10^{-4}$ A/cm^2. The leakage current is negligible up to 1200 V.

IV. DYNAMIC CHARACTERISTICS OF 4H-SIC JBS DIODES

Detailed switching measurements were conducted on some 1200 V blocking 4H-SiC JBS diodes from the same wafer that yielded the 1500 V device to test the reverse recovery currents and the impact of JBS diodes on a standard DC-DC converter. These 0.0045 cm^2 had a low current rating of 0.5 Amp. (111 A/cm^2). In addition, EMI signatures were recorded on the DC/DC converter for Si and SiC diodes.

Reverse Recovery Measurements

The test circuit used for characterizing the diodes for reverse recovery uses the diode under test (DUT) in a boost configuration. A 5-cycle burst current built through an inductor, and measurements are made during the last cycle of the burst. A 6LF6 vacuum tube is used as a switch in place of the usual MOSFET switch to achieve low parasitic capacitance at the anode of the DUT, and extremely fast switching speed. A resistor isolates the DUT from the parasitic capacitance of the inductor, and also is used to quickly reset the inductor current to zero after each 5-cycle test burst so that the DUT is not heated. The dV/dt for the square-wave drive burst to the tube can be adjusted to achieve different dI/dt values for the DUT. With a 700 volt peak drive to the screen grid of the tube, the test circuit can test up to 9 A of combined forward and reverse DUT current, and the applied voltage to the DUT can be up to 2000 V. The value of dI/dt is controlled by varying the pulse generator rise time as described above and the dV/dt is controlled by placing various capacitors across the DUT. Varying the value of dV/dt makes it easier to identify the portion of the diode recovery due to charge storage and the portion due to device capacitance. Adding values of capacitance to the output of the tube emulates the conditions of using anti-parallel switching devices of different output capacitance in an application circuit.

The turn-off characteristics of the JBS diodes were measured for many different. dI/dt values. Data obtained thus showed that even for the fastest turn-off, the recovery of the SiC diode is mostly capacitive in nature. This capacitance is calculated to be 3.3 pF when the reverse voltage is several hundred volts, and this value is consistent with the junction depletion capacitance value calculated using the blocking region doping concentration. In contrast, the bulk of the reverse recovery current in the silicon diode occurs before the voltage rises. This indicates that charge storage is far more important than junction capacitance in the Si diode. Figure 5 shows a reverse recovery comparison between an ultra-fast 600 V silicon PiN diode and the 1200 V SiC JBS diode. The reverse-recovery current in the Si diode is huge in comparison to that of the SiC diode. Furthermore, the nature of the charge storage-type recovery for the Si diode means that the anti-parallel switch (e.g., IGBT, MOSFET, or CoolMOS) in a hard-switched power converter experiences the full supply voltage at full current (load current plus diode current) during the switch turn-on. In contrast, the anti-parallel switch experiences less voltage during turn-on with the SiC JBS diode because the voltage begins to rise at the beginning of the diode recovery.

Efficiency Measurements

A 50-W power supply circuit was designed for 500 V to 100 V step-down application. This test circuit uses a Cool MOS^{TM} transistor for the switch. With conventional ultra fast reverse recovery diodes, the switching frequency is limited. In initial testing, several commercially available ultra fast silicon diodes were destroyed at 100 kHz switching because of excessive diode reverse recovery associated losses. The final comparison can only be applied to the SiC JBS diode rated at 1200 V, 0.5 A and the BYV26C silicon diode, rated at 600 V, 1 A.

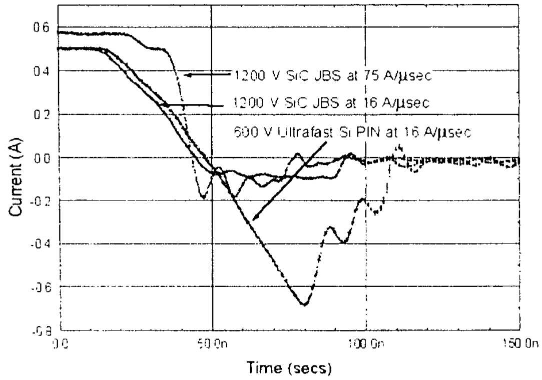

Figure 5: Reverse Recovery waveforms comparing 600 V ultrafast Si PiN and 1200 V SiC JBS diode at reverse dI/dt of 16 A/µsec. No reverse recovery current is observed in JBS diode even at a reverse dI/dt of 75 A/µsec.

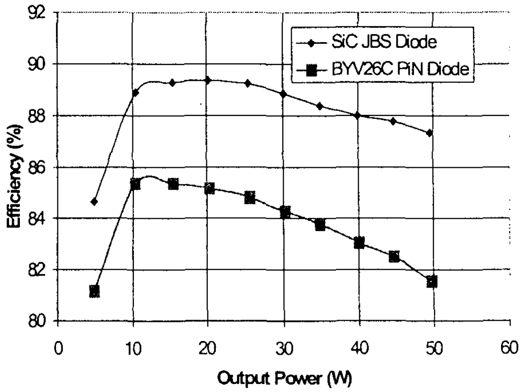

Figure 6: DC/DC converter made using 600 V CoolMOS^{TM} shows a 6% increase in conversion efficiency with a 1200 V SiC JBS diode as compared to the fastest 600 V Si diode at an operating frequency of 186 kHz.

Figure 6 shows the results of the efficiency model and measurements at 186 kHz switching frequency. Both modeling and experimental results indicate that the system efficiency with SiC JBS diode is between 87% and 89% for most load conditions. By comparison, the system efficiency with the BYV26C silicon diode varies between 81% and 85% under the same load conditions. Figure 7 compares the loss distribution between the systems with SiC JBS and the BYV26C Si diodes at 100 kHz switching. The loss model includes five loss components: diode conduction, device conduction, turn-on switching, turn-off switching, and diode reverse recovery. The I^2R loss associated with the power supply inductor is included in the efficiency evaluation. With the Si diode, the most dominant loss component is the turn-on switching loss in the switch. With the same switching device, the turn-on loss can be significantly reduced with a faster reverse recovery diode. In this example, the SiC JBS diode reduces the turn-on loss over the ultrafast Si PiN diode by more than 40%.

EMI Measurements

The diode reverse recovery has been considered as the major source of electromagnetic interference (EMI).

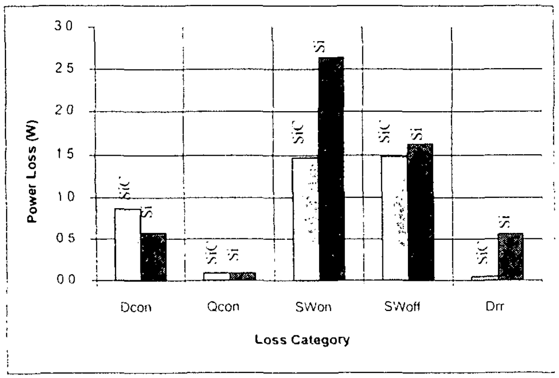

Figure 7: Comparison of Si and SiC power loss components of a DC/DC converter.

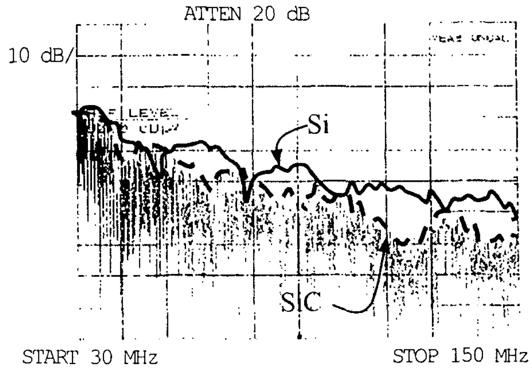

Figure 8: Comparison of EMI spectrum envelope for the switching power supply with Si and SiC diodes.

With nearly zero reverse recovery time, the SiC JBS diode is expected to emit less EMI high frequency noise. Experiments were conducted to compare the EMI performance of the above mentioned converter using both BYV26C Si and SiC JBS diode. Figure 8 shows the experimental EMI spectrum for the frequency range from 30 MHz to 150 MHz. For comparison purposes, the EMI spectrum of the Si diode is only shown with the envelope. The major EMI reduction with the SiC diode appears in the frequency range of 70 MHz to 150 MHz.

V. CONCLUSIONS

Detailed design, fabrication, and characterization of 1500 V, 4 Amp. 4H-SiC JBS diodes are presented. 2D simulations show that for Schottky region spacing of 4 μm, the electric field at the Schottky contact is only 62% of the peak electric field in the device. Diodes with linear p$^+$ grid JBS shows slightly better performance than honeycombed JBS diode. JBS diodes show on-state and switching characteristics similar to Schottky diodes and blocking characteristics similar to PiN diodes. Measurements on 0.0045cm^2, 1200 V, 0.5 Amp 4H-SiC JBS diodes indicate that the reverse recovery time and associated losses are near zero even at a rev. dI/dt of 75 A/μsec. Based on measured waveforms, detailed loss models on diode switching were established for a high frequency switching power supply efficiency evaluation. A 600 V CoolMOS^{TM} was used to compare the conversion efficiency of a dc-dc converter circuit with 600 V ultrafast Si diode and a 1200 V SiC JBS diode. At about 200 kHz switching, the power supply efficiency improvement was about 6%, over the fastest, lower blocking voltage silicon diode. EMI measurements indicate smaller signatures as compared to those observed for Si diodes in a DC/DC converter.

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