4H-SiC MPS Diode Fabrication and Characterization in an Inductively Loaded Half-Bridge Inverter up to 100 kW

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Abstract. In this work, 600V 4H-SiC MPS diodes were designed, fabricated and tested. The diodes were designed with a multi-step junction termination extension (MJTE) to improve the blocking voltage. The highest forward current capability of a packaged MPS diode showed a current of 50\(\text{A}\) at 2\(\text{V}\) and 140\(\text{A}\) at 4\(\text{V}\). The SiC MPS diode reverse voltage showed excellent suppression of the Schottky leakage current at temperatures up to 250\(^\circ\text{C}\). Switching measurements using a half-bridge circuit, at currents up to 230\(\text{A}\), showed a substantial reduction in diode dissipation, compared to a state of the art Si diode; a 47% energy loss reduction at room temperature (RT) and 84% at 200\(^\circ\text{C}\). The IGBT energy loss reduction, when using an MPS diode, was 15% at room temperature and 45% at 150\(^\circ\text{C}\). The diodes should result in improved efficiency when used in electric vehicles.

Introduction

A general trend in modern power systems is the reduction of passive component size and increase of system efficiency. Toward this goal, one must seek the development of semiconductor components which are capable of operating at higher operating frequencies and higher temperatures. If we consider Si diodes, the Schottky barrier diode (SBD) is a unipolar device and as such is inherently faster than the bipolar PIN diode. However, because of its high reverse leakage current and low breakdown voltage, the SBD is not appropriate for high-voltage applications. Until recently, therefore, the only choice for high-voltage systems was the PIN rectifier. However, the switching speed of the PIN device is limited by its long reverse recovery time, due to the large amount of charge stored in the drift region during forward conduction.

The MPS diode, or JBS diode depending on if the p-n junction in the diode is forward biased during switching, is a device which combines the best features of a p-n junction and a Schottky contact [1]. The application of the MPS concept to SiC, as a high power diode, is an attractive idea since SiC has a large breakdown electric field strength and a high thermal conductivity. Fig. 1 shows the cross-sectional view of the SiC MPS diode, which behaves as a p-n junction under reverse bias, and a fast switching Schottky diode in the forward direction. This behavior favors the SiC MPS over the SiC Schottky diode, since the relatively low barrier height of the pure Schottky diode results in excessive reverse leakage current, especially at large blocking voltages and high temperatures. Nevertheless, although the basic cell structure of the MPS is expected to provide excellent reverse leakage and high breakdown levels, one must consider the inevitable field crowding and reverse leakage which occurs at the periphery of the device. In order to insure that high breakdown levels and low leakage are maintained at the periphery, an MJTE design [2] is employed. As shown in Fig. 1, the MJTE consists of three steps. The thickness of each step is reduced by dry etching.


**Fabrication**

The implanted p⁺ regions and MJTE sections were designed in the form of concentric rings. The width of each of the p⁺ concentric rings was 1.5μm. The Schottky ring width was 3μm. For the MJTE sections, the inner and middle sections were 75μm in length, and the outer one was 50μm. Two types of Cree, Inc. wafers were used to make diodes. In the first, the thickness and doping density were 10μm and 1.4×10¹⁶ cm⁻³, respectively, and 6 μm and 2.1×10¹⁶ cm⁻³ for the second wafer. The Al implantation had a concentration of 2×10²⁰ cm⁻³ and a depth of 1.5 μm. Devices with diameters of 0.3mm and 1.0mm were fabricated based on processes described in [3]. The implantation anneal was done at 1.550°C for 30 min in Ar ambient. MJTE regions were formed by inductively-coupled plasma etch using CF₄/O₂ gas mixture. Surface passivation was done by a thermal-LPCVD SiO₂ bilayer of about 1.0 μm in thickness. Ni was used as ohmic contact to the substrate while Ti was used as the Schottky contact metal. The maximum breakdown voltages measured for the 10 μm and 6 μm MPS diodes with the 1.5 μm deep junction were 1400V and 950V, respectively.

**DC Results**

After the chip level probing of the single cells, multi-cell MPS diodes were packaged and tested. At RT, the forward current was 354 A at 2V and 90 A at 4V for the 10μm epilayer. Nevertheless, we were able to achieve the target of 600V with a total current of 140A by packaging MPS cells fabricated in the 6 μm, 2.1×10²⁰ cm⁻³ doped epilayer structure despite the thinner epilayer. Fig. 2 shows the forward and reverse characteristics of a packaged device, based on the 6μm epilayer structure. Measurements at RT, 125°C, and 250°C are shown (by way of comparison, a state-of-the-art Si diode has a smaller voltage drop at RT, but at 200°C the drop in the Si diode is prohibitive). This packaged MPS diode has a total active area (Schottky plus PiN) of 9.4mm². Reverse breakdown for the MPS occurred at over ~800V for the individual cells although the packaged diode was only measured up to 600V. The decrease in forward current with temperature is expected, based on a reduction of the carrier mobility. Assuming a mobility temperature dependence of T⁻¹⁰, Fig. 2
provides a value of $m = 1.6$, close to the value of 3/2 for scattering dominated by lattice vibrations. Note that the change in the reverse leakage current is very small at 125°C, in contrast to that of Si diodes. The leakage current may be decreased further by the elimination of the “weakest link” among the cells; this then becomes a yield issue. The trend toward SiC wafers with smaller defect densities will help in reducing diode leakage. The packaged diodes have been used in $V_{ge}=400V$ motor control systems and the conduction power loss due to the reverse leakage current is negligible even at 250°C.

![Graph](image1)

![Graph](image2)

Fig 2. Current vs. voltage (a) and current density vs. voltage (b) of packaged multi-cell MPS diode on 6μm thick and 2.1x10^16 cm^-3 doped epilayer, tested at room temperature, 125°C, and 250°C.

## Transient Results

The SiC packaged diodes were evaluated in an inductively-loaded ($L=1000 \mu H$) half-bridge circuit [2], consisting of a pair of Si IGBT switches and free-wheeling diodes. The MPS diode turn-off was tested from room temperature up to 250°C. Measurements have been done at switching voltages of 400V and 500V. The maximum tested on-state current was 230A at RT, corresponding to a $J_F = 2447 A/cm^2$. The $dI/dt$ rate was 320A/μs. The MPS diode was intentionally examined at power levels up to 100kW to see if there is any degradation in the reverse recovery property of the MPS diodes. A similarly rated state of the art, commercially available ultrafast silicon PIN diode (rated 600V-120A, 35ns turn-off time) was also measured for comparison under the same conditions. At RT the reverse recovery in the MPS showed negligible change when compared to that at lower current densities, and was always much lower compared to that of the Si PIN. At 230A forward current, the charge stored in the Si PIN was 0.97μC and the charge in the SiC MPS was only 0.30μC.

One important feature of the MPS diode is its ability to operate at high temperature (high-T). As we increase the temperature, the advantage of the MPS diode over the Si PIN becomes more evident. Fig.3 shows the current recovery waveforms measured at up to 250°C for SiC and up to 200°C for Si, while keeping all other switching conditions the same ($V=400V$, $I=50A$). The Si PIN reverse recovery current increased substantially with temperature because of increased carrier lifetime at higher-T. The charge $Q_r$ increased from 1.08μC to 4.95μC as the temperature changed from RT to 200°C in Si. For the MPS diode, however, the corresponding increase was from 0.31μC to 0.54 μC, and there was practically no difference at higher-T, even at 250°C. The stored charge in SiC was nearly one order of magnitude lower than that of Si PIN at 200°C. The disparity between Si and SiC were found to be larger when both high-T and high current conditions prevail simultaneously. Another observation that is clear from Fig.3b is that there was no substantial current oscillation in the SiC diode, as opposed to the Si PIN. The effect of the very high current densities (~2447A/cm²) on SiC MPS diode recovery behavior is negligible.
As one may surmise, the energy loss during recovery was greater in the Si PIN, compared to the MPS diode. At RT and a switching current of 50A, the turn-off energy loss in the Si PIN was 154μJ and increased to 656μJ at 200°C. For the same conditions, the MPS diode energy loss was 82 μJ at RT and only 104μJ at 200°C. Thus, the energy loss in Si is more than 6X greater than that of SiC at 200°C. At 250°C the energy loss in SiC was almost the same (101μJ).

![Graphs of current vs. time for Si PIN and SiC MPS diodes](image)

**Fig.3:** Reverse recovery part of the turn-off characteristics of an ultrafast Si PIN diode (a) and a SiC MPS diode (b) tested in an inductively loaded half-bridge inverter at different temperatures.

**Conclusions**

MPS diodes with optimized MJTE structures have been developed. The results clearly show that the MPS diodes combine the best features of the SiC PIN and the SiC Schottky diodes. Diodes using multiple MPS cells have been packaged and successfully operated at 125°C and 250°C. Up to 140A DC current has been achieved for a packaged 4H-SiC MPS diode, which represents the highest level reported for a SiC MPS diode. With respect to the transient recovery, the SiC MPS diode and a state of the art Si diode have been compared at high current levels (up to 230A) and high temperatures (up to 200°C). The SiC MPS diode has been shown to be far superior compared to the Si PIN diode. Significantly smaller stored charge and IGBT/diode energy loss were observed when using SiC MPS diodes. The disparity is the largest when both high current and temperature co-exist. The effect of high current densities on SiC MPS recovery behavior is negligible.

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**References**