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# Numerical Analysis of SiC Merged PiN Schottky Diodes

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**Abstract.** We present numerical simulation results of 1500-V SiC merged PiN Schottky (MPS) diode which exhibited Schottky-like on-state and switching characteristics, and PiN-like off-state characteristics. The key parameters that alter the overall device performance have been optimized using the device simulator MINIMOS-NT. The Schottky spacing between the adjacent $p^+$ implanted regions has been varied so that a trade-off between the forward current capability and lower reverse leakage current can be investigated. MPS diodes have shown reliable avalanche operations with blocking voltage of 1350 V which is 90% of the desired value, and a high current density magnitude of 900 A/cm$^2$ for an on-state voltage drop of only 3 V.

## Introduction

There has been a continuous trend toward higher operating frequencies especially in motor control and switch mode power supplies. In motor control circuits, operation at frequencies above the acoustic range is attractive for consumer application. In power supplies, operation at high frequencies is attractive because of the reduction in size and power losses in the passive components which leads to a more efficient, compact system design. To accomplish higher frequency operation it is essential to use power rectifiers with improved switching performance. SiC's electronic parameters superiority would enable dramatic improvement in this regard [1].

SiC's power rectifiers are categorized into three classes: Schottky diodes which offer extremely high switching speed, but suffer from high leakage current; PiN diodes which offer low leakage current but show reverse recovery charge during switching and have a large junction forward voltage drop due to the wide band gap of SiC; merged PiN Schottky (MPS) diodes which offer Schottky-like on-state and switching characteristics, and PiN-like off-state characteristics [2].

Numerical simulation-based analysis to verify the performance of SiC MPS diode has been carried out using the general-purpose device simulator MINIMOS-NT [3]. The key parameters that alter the overall device performance have been optimized. The design primarily consists of selecting the optimum Schottky metal, size and spacing of the $p^+$ implanted regions, and thickness and dopant density of the drift region. The relative area and geometrical layout of the $p^+$ implanted region are fundamental design parameters that affect the device characteristics. A large $p^+$ implanted area is resulting in a higher on-state voltage due to a smaller Schottky conducting area, but offers lower leakage due to a more effective pinch-off of the Schottky portion.

### MPS Diode Structure

A cross-section of a 4H-SiC MPS rectifier is shown in Fig. 1. The MPS diodes consists of interdigitated Schottky and $p^+$ implanted areas. It is important to achieve a good quality Schottky interface to obtain a low on-state drop when operated in the Schottky barrier diode mode. The metal-SiC barrier height of the Schottky metal was selected to be low enough to give a low on-state voltage, while still enabling effective pinch-off during the off state. This is achieved by using Ni as the Schottky metal.

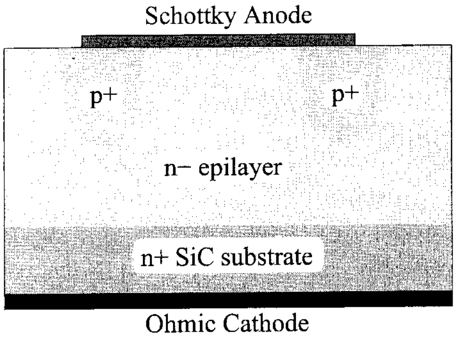

Fig. 1: Cross section of a MPS diode in SiC.

| parameter | value |
|---|---|
| $n^-$ epilayer thickness | $10.5\,\mu$m |
| $n^-$ concentration | $9\times10^{15}$ cm $^{-3}$ |
| $p^+$ length | $2\,\mu$m |
| $p^+$ thickness | $1.5\,\mu$m |
| $p^+$ concentration | $1.0\times10^{17}$ cm$^{-3}$ |
| spacing between $p^+$ | $4.0\,\mu$m |

Table 1: Optimized device parameters used for a simulation of a MPS in 4H-SiC.

For on-state voltage drops less than 3 V, only the Schottky regions of the diode should conduct. The on-state voltage drop of the MPS diodes is determined by the resistance of the drift region, the metal-SiC barrier height, and the relative area of the Schottky versus the $p^+$ implanted regions. For reverse bias conditions, 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 the Schottky barrier lowering at the metal-$n^-$ junction. The presence of the adjacent $p^+$ 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.

A detailed design of 1500-V MPS diodes is described in [4]. The design primarily consists of selecting the optimum Schottky metal, size and spacing of the $p^+$ implanted regions, and thickness and dopant density of the drift region. The optimized diode has an epitaxial layer thickness of $10.5\,\mu$m over a 4H-SiC $n^+$ substrate doped at $9\times10^{15}\,\mathrm{cm}^{-3}$ to obtain the desired blocking voltage capability of 1500 V. The relative area and geometrical layout of the $p^+$ implanted region are fundamental design parameters that affect the device characteristics. A large $p^+$ implanted area is expected to result in a higher on-state voltage due to a smaller Schottky conducting area, but may offer lower leakage due to a more effective pinch-off of the Schottky portion. The MPS diode used in this work has a $2\,\mu$m wide p+ implanted region with $4\,\mu$m spacing. The optimized device parameters are listed in Table 1.

### MPS Diode Simulation

The MPS diode shown in Fig. 1 is simulated and compared with measurement results extracted from [5]. Fig. 2 illustrates the on-state characteristics of the MPS diode for different temperatures. The result shows very good agreement between the simulated and measurement results

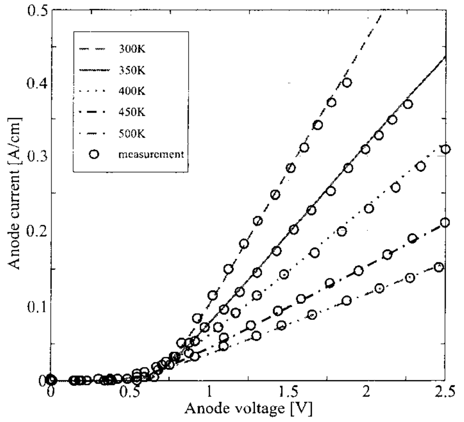

Fig. 2: Comparison of measured and simulated forward characteristics of the MPS diode at different temperatures.

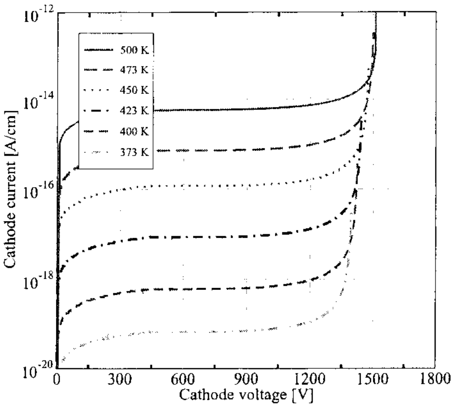

Fig. 3: Reverse voltage characteristics of the MPS diode at different temperatures.

obtained from [5]. The result is also indicative of an excellent rectifier ability of the MPS diode. The on-state characteristics of the MPS and Schottky diodes are almost identical, indicating excellent current spreading and minimal increase in the on-state voltage due to the introduction of the $p^+$ implanted region. The current flow in the MPS diode occurs primarily across the Schottky region as shown in Fig. 4. A high current density magnitude of 900 A/cm$^2$ for an on-state voltage drop of only 3 V was obtained as depicted in Fig. 5.

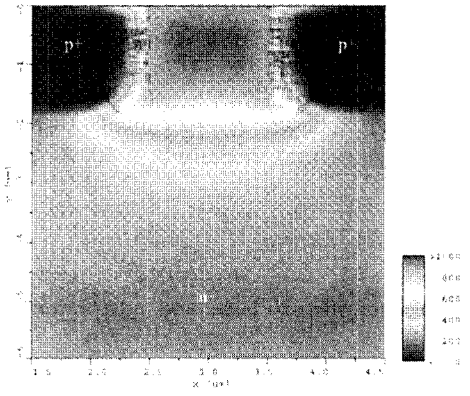

Fig. 4: Magnitude of the current density in the MPS diode on forward bias operation.

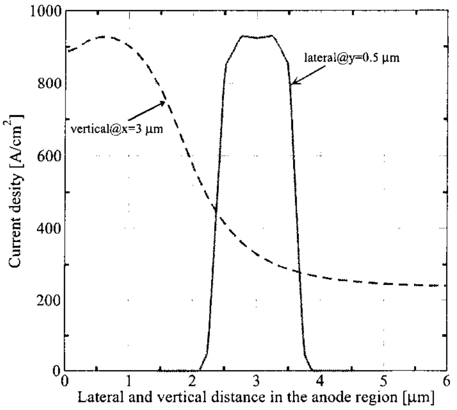

Fig. 5: The lateral and vertical cut of the current density in the MPS diode on forward bias operation.

The reverse bias characteristics of the MPS diode displayed in Fig. 3 is much more similar to the PiN diode than to the Schottky diode. A blocking voltage of 1350 V which is 90% of the desired value with negligible leakage current density was achieved for the MPS diode operating at room temperature. The presence of the adjacent $p^+$ implanted regions reduces the electric field at the metal-SiC junction because of two-dimensional charge sharing. To evaluate the effectiveness of the $p^+$ region on the reverse bias operation, the ratio of the electric field at the

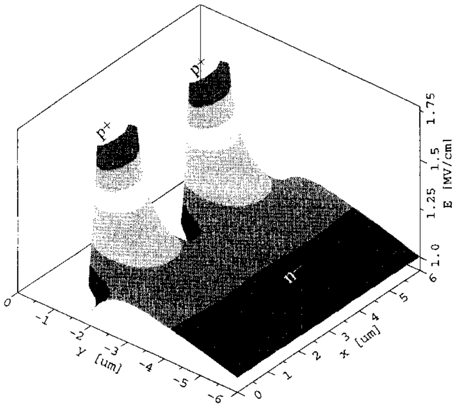

Fig. 6: The electric field profile in the MPS diode at 1000 V reverse voltage operation.

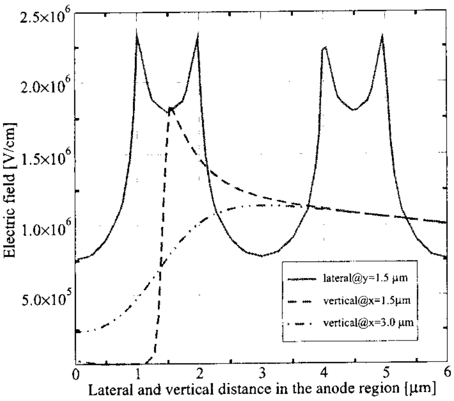

Fig. 7: A horizontal and vertical cut of the electric field in the MPS diode at 1000 V reverse voltage operation.

Schottky interface to the peak electric field (at the bottom of the $p^+$ region) is analyzed by simulation as shown in Fig. 6. For the optimized device geometry listed in Table 1 this ratio is found to be only 26% as depicted in Fig. 7. When the spacing between the $p^+$ regions is increased, this ratio also increases and the reverse blocking characteristics becomes poor due to the Schottky barrier lowering effect as obviously observed in the case of Schottky rectifiers.

## Conclusion

Numerical simulation to verify the performance of 1500-V SiC MPS diode was carried out using the device simulator MINIMOS-NT [3]. Very good agreement between the simulated and measured results have been achieved. The on-state characteristics of the MPS and Schottky diodes, and the reverse bias characteristics of the MPS and PiN diodes are almost identical. The optimized MPS diode has exhibited an excellent rectifier ability with a blocking voltage of 1350 V which is 90% of the desired value, and a high current density magnitude of 900 A/cm$^2$ for an on-state voltage drop of only 3 V.

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