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4,308V, 20.9 mΩ·cm² 4H-SiC MPS Diodes Based on a 30µm Drift Layer

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Abstract. This paper reports the design, fabrication and characterization of high voltage 4H-SiC merged PiN/Schottky-barrier (MPS) diodes with an active area of 1.4mm^2. For comparison purposes, Schottky barrier, PiN and MPS diodes of smaller size (8.1×10^{-2}mm^2) have also been designed and fabricated on the same wafer with a 30µm, $n=2\times10^{15}$cm^{-3} doped drift layer. The Schottky spacing between the adjacent p+ regions in the MPS diodes has been designed to be 7, 8, 9, and 10µm so that the trade-off between the forward current capability and the reverse leakage current can be investigated. A multi-step junction termination extension (MJTE) structure is utilized to terminate the device edge because it is capable of providing a near theoretical breakdown voltage. MPS diodes have achieved similar breakdown voltages to that of the PiN diodes while providing a forward current close to that of SBDs. MPS diodes have also shown reliable avalanche operations with avalanche breakdown voltage up to 4,308V, limited only by the SiC critical field. One of the best MPS diode achieves a blocking voltage (V_B) of 4,308V and conducts a forward current density of 142 A/cm^2 at a forward voltage drop (V_F) of 4V with a differential specific on-resistance (R_{SP_ON}) of 20.9 mΩ·cm^2, yielding a V_B^2/R_{SP_ON} of 888 MW/cm^2, which is among the highest figure-of-merit (FOM) reported to date.

Introduction

4H-SiC power devices have received increased attention over the past decade for high-power applications due to the much higher critical breakdown field and high temperature capability of 4H-SiC in comparison to that of Si. Although 4H-SiC PiN diodes can offer low leakage current, they suffer from the high forward voltage drop for voltage ratings below ~3kV to 5kV range and the reliability problem related to the drift of V_F over time. SBD diodes show better performance in terms of switching speed and forward voltage drop, but have larger leakage currents, especially at higher voltages and temperatures. Merging the structures of both PiN and SBD diodes monolithically results in the highly desired MPS diodes which behave like SBDs in forward conduction while maintaining low reverse leakage current of PiN diodes under reverse operation. There is no major difference between MPS diode and Junction Barrier Schottky (JBS) diodes. Historically, diodes capable of operating under conditions with minority hole injections are called MPS diodes. One of the reported high performance MPS diodes could block up to 1,300V with an R_{SP_ON} of 3.2 mΩ·cm^2 using a 10.5µm, 1.3×10^{16}cm^{-3} drift layer, corresponding to a FOM of 528 MW/cm^2[1]. The highest blocking voltage for this type of merged diodes was 3.7kV with R_{SP_ON} of 31mΩ·cm^2 realized by a 50µm, $\sim2\times10^{15}$cm^{-3} drift layer, corresponding to a FOM of 441 MW/cm^2[2]. This paper reports the design and fabrication of MPS diodes blocking 4,308V, using only 30µm, $\sim2\times10^{15}$cm^{-3} doped drift layer, resulting in an R_{SP_ON} of 20.9 mΩ·cm^2 and a FOM of 888 MW/cm^2.

Device Design and Fabrication

Fig.1 shows the cross sectional view of the MPS diode. MeV ion implantation has been used to form the p+ regions in the MPS diodes as well as the p+ edge regions required for the formation of MJTE structure[3]. The p+ regions are designed to be 2µm in width and 2.3µm in depth, which are

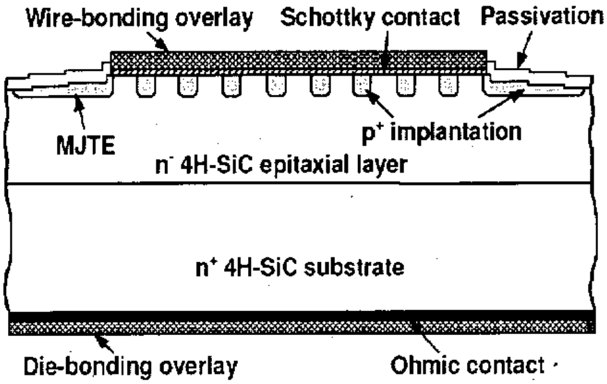

Fig.1 Cross-sectional view of the MPS diode.

formed by $2x10^{18}cm^{-3}$ Al implantation and annealed at 1550°C for 30min in controlled Ar ambient. The Schottky spacing dimensions are designed to be 7, 8, 9 and 10μm. MPS diodes of $8.1x10^{-2}mm^2$ (small devices) and $1.4mm^2$ (large devices) have been designed. PiN and SBDs of $8.1x10^{-2}mm^2$ have also been designed along with the MPS diodes for comparison purposes. The widths of the MJTE's innermost and middle steps are both 30μm, and the outermost step is 40μm wide, all formed by ICP etching. Thermal oxide plus PECVD SiO_2/Si_3N_4 layers are used for surface passivation. The backside ohmic contact metal is sputtered Al(200Å)/Ni(3000Å), annealed at 1050°C for 10min in forming gas. The frontside Schottky contact is formed by 500Å thick sputtered Ti covered by thick Au overlay.

Characterization

The DC J-V characteristics of the small PiN, SBD and MPS diodes with 7μm Schottky spacing, are shown in Fig.2. With the MJTE providing excellent edge termination, most MPS diodes block over 4kV when tested at chip level. However, SBDs show substantially higher leakage current. Fig.2 clearly demonstrates the expected trade-off effects of the MPS diode. The forward J-V characteristics of the MPS diode are very close to that of the Schottky diode, indicating minimal influence on the on-state voltage drop due to the introduction of implanted p^+ regions. The SBD is seen to conduct a forward current density of $116A/cm^2$ at $V_F=4V$. Because of the unannealed p-contact, PiN shows a very low current level. The MPS diode can be driven into avalanche operation with an avalanche voltage of 4,378V and an avalanche current density of $97mA/cm^2$. A forward current density of $84A/cm^2$ is achieved with $V_F=4V$. The diode has an R_{SP_ON} of 30.5 $m\Omega \cdot cm^2$, which yields a FOM of 628 MW/cm^2. Some SiC MPS diodes have been tested up to $1A/cm^2$ avalanche current density at 4.3kV without failure, representing an excellent failure power density of SiC larger than $4.3kW/cm^2$ measured by a quasi-DC pulse width of 1 second, which is higher than the fitting value reported by P.G. Neudeck et al.[4] for a quasi-DC measurement pulse width of 1ms.

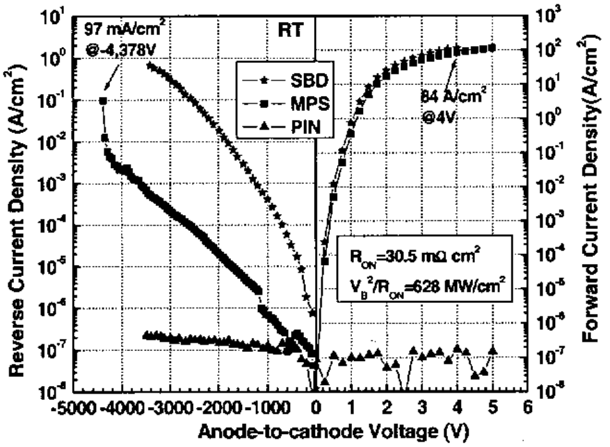

Fig.2 Reverse and forward characteristics of small SBD, MPS and PiN diodes

Fig.3 shows the J-V characteristics for a large MPS diode with a Schottky spacing of 9μm, measured at room temperature. The MPS diode can be driven into avalanche with V_B=4,283V and an avalanche current density of 230mA/cm^2. A forward current density of 102A/cm^2 is achieved with V_F=4V. The diode has a differential R_{SP_ON} of 25.6 mΩ·cm^2, which yields a high FOM of 717 MW/cm^2 for high voltage MPS diodes. All the results presented in this paper are obtained from the testing of as-fabricated chips by using a standard probe station unless mentioned otherwise. In the reverse characteristics, the diodes are either driven into avalanche breakdown or stopped with the leakage current of 1mA. The J-V characteristics of large MPS diodes with 7, 8, 9 and 10μm Schottky spacings are presented in Fig.4. It is evident that leakage current decreases with smaller Schottky spacing, showing the screening effect to the Schottky surface by the p+-n depletion regions. However, forward current decreases as well due to the narrower conductive channel between p+ implanted regions at smaller Schottky spacing, resulting in a higher series resistance. The MPS diodes with 7, 8, 9μm Schottky spacing can all be driven up to about the same avalanche voltage, namely 4,316V, 4,270V, 4,283V, despite different leakage currents. With 10μm Schottky spacing the breakdown voltage is 3,260V and the leakage current is the highest, which substantially limits its performance. MPS diodes with 7μm and 8μm Schottky spacing show similar forward current densities of 92 A/cm^2 and 94.3 A/cm^2 at V_F=4V and R_{SP_ON} of 26.7mΩ·cm^2, 25.5 mΩ·cm^2 respectively. MPS diodes with 9μm Schottky spacing show a forward current density of 102 A/cm^2 and R_{SP_ON} of 25.6mΩ·cm^2. Based on above comparison, we can conclude that a Schottky spacing of 9μm is close to the optimum value, which results in a minimal reduction in forward current density in comparison to that of Schottky diode but allows the MPS diode to reach its theoretical limit of avalanche voltage. Compared with the small MPS diode with 7μm Schottky spacing presented in Fig.2, the large MPS diode with the same 7μm Schottky spacing has a higher leakage current density, because more wafer defects could be involved in the MPS diode with the larger device area, giving rise to the increased leakage current. Detailed switching characteristics are presented in an accompany paper[5].

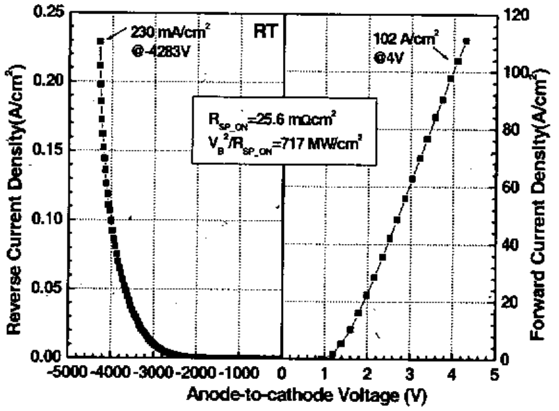

Fig.3 Reverse and forward characteristics of a large MPS diode with 9μm Schottky

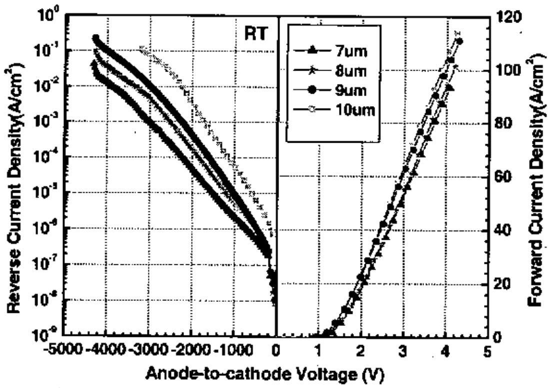

Fig.4 Comparison of the reverse and forward characteristics for large MPS diodes with 7μm, 8μm, 9μm, 10μm Schottky spacing.

Temperature-annealing Effect

As shown in Fig.3 and 4, the on-set voltage is higher than expected for Ti-base Schottky contact. An annealing experiment has been done to try to improve the wetting of Ti to SiC surface, so that the true Schottky barrier height can be achieved for Ti. The temperature-annealing is done at 500°C for 12.5min in N_2 ambient. Fig.5 shows the J-V characteristics of a small MPS diode with 8μm Schottky spacing, measured at room temperature before and after 12.5min annealing at 500°C. It is seen that the forward current density rises after annealing from 91.5 A/cm^2 to 142 A/cm^2 at 4V, representing a near 55% increase. The MPS diode can be reliably driven into avalanche with V_B=4,308V and an avalanche current density of 540mA/cm^2, slightly higher than the blocking voltage of 4,288V before annealing. With the significant decrease of R_{SP_ON} from 27mΩ·cm^2 to 20.9mΩ·cm^2, the FOM is substantially improved from 681 MW/cm^2 to 888 MW/cm^2, which is among the highest reported to date.

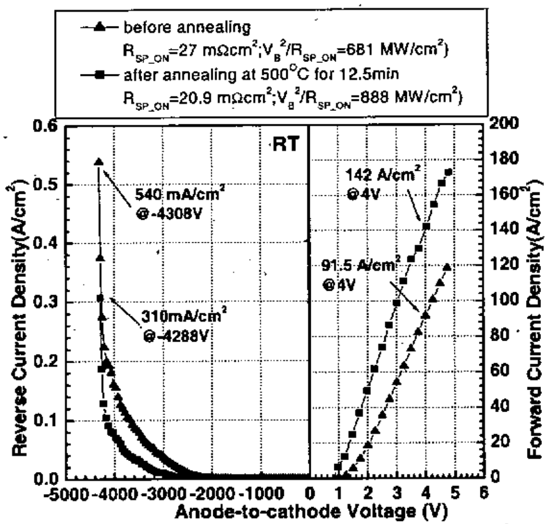

Fig.5 Reverse and forward characteristics of a small MPS diode with 8μm schottky

Summary

4H-SiC MPS diodes with MJTE structure have been designed and fabricated along with PiN and Schottky diodes. The comparison shows MPS diodes have the advantages of low on-state voltage drop and low leakage current. Up to 4,283V blocking voltage has been achieved by a large MPS diode, resulting in an R_{SP_ON} of 25.6 mΩ·cm^2 and a high FOM of 717 MW/cm^2. The study on MPS diodes with different Schottky spacings shows the trade-off between the forward current capability and the reverse leakage current, and indicts an optimum Schottky spacing of 9 μm in our case. Temperature-annealing at 500°C for 12.5min has been demonstrated to be effective in improving the performance of MPS diodes, resulting in a near 55% increase in forward current density and improvement of the FOM to the highest value of 888 MW/cm^2.

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