Simulation study of a mixed terminal structure for 4H-SiC merged PiN/Schottky diode*

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(Received 3 September 2010; revised manuscript received 26 June 2011)

In this paper, a mixed terminal structure for the 4H-SiC merged PiN/Schottky diode (MPS) is investigated, which is a combination of a field plate, a junction termination extension and floating limiting rings. Optimization is performed on the terminal structure by using the ISE-TCAD. Further analysis shows that this structure can greatly reduce the sensitivity of the breakdown voltage to the doping concentration and can effectively suppress the effect of the interface charge compared with the structure of the junction termination extension. At the same time, the 4H-SiC MPS with this termination structure can reach a high and stable breakdown voltage.

Keywords: 4H-SiC, merged PiN/Schottky diode, junction termination technology, breakdown voltage

PACS: 84.30.Jc, 85.30.Kk, 85.30.De, 85.30.Mn **DOI:** 10.1088/1674-1056/20/11/118401

1. Introduction

Silicon carbide has been widely researched in the fields of power devices due to its superior material properties, such as a wide band gap, high critical breakdown field ($\sim 3 \times 10^6$ V/cm), large electron saturation drift velocity and high thermal conductivity.[1] In a power system, a good rectifier should have a small turn-on voltage, a low reverse leakage current, a low on-resistance, a high breakdown voltage (BV) and a high switching speed.[2] The merged PiN/Schottky diode (MPS) proposed by Baliga[3] combines the advantages of PiN and Schottky barrier diode (SBD) to have an SBD-like forward characteristic and a PiN-like reverse characteristic, which means that it has a low leakage current, a high breakdown voltage and a high switching speed, so the 4H-SiC MPS is an ideal rectifier and has been studied recently.[4,5]

Today, the planar process, as a mature technology, is the first choice for manufacturing SiC devices, because this technology has obvious advantages, which have been demonstrated in the fabrication of silicon integrated circuits and devices. However it will cause some problems, such as the electric field crowding effect on the edge of the junction, which reduces the BV. In order to alleviate the crowding of the electric field and improve the BV, the junction termination technique (JTT) is indispensable. In silicon carbide power devices, the commonly used terminal technologies are the field plate (FP),[6] the field limiting ring (FLR),[7,8] and the junction termination extension (JTE).[9] Each of them has its own advantages and disadvantages. In order to bring their advantages into full play, two or more of them are often combined together, such as the FP-assisted-JTE,[10,11] the FGR-assisted-JTE,[12] and the guard ring assisted reduced surface field (RESURF).[13] In this paper, a mixed termination structure constructed by the combination of JTE, FP and FLR used in the 4H-SiC MPS is systematically studied by using the simulation with the ISE-TCAD.

2. Design and optimization

Figure 1 shows the schematic view of the 4H-SiC MPS with a mixed terminal structure. The main parameters of the device are as follows. The epitaxial layer thickness and the doping concentration are 14 μm and 1.65×10^{15} cm^{-3}, respectively. The P^+ region of the MPS main junction has a doping con-

*Project supported by the National Natural Science Foundation of China (Grant No. 61006060) and the Shaanxi Provincial 13115 Innovation Engineering, China (Grant No. 2008ZDKG-30).

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centration of 1×10^{18} cm^{-3}. The outer floating rings are formed simultaneously with the JTE, so they have the same depths and the same doping concentrations.

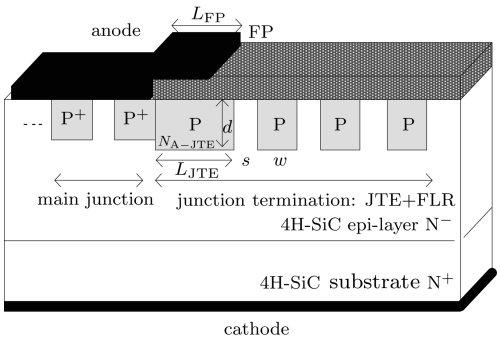


Fig. 1. Schematic view of 4H-SiC MPS diode with the mixed terminal structure.

Simulations are carried out by using the two-dimensional simulator ISE-DESSIS[14] based on solving the Poisson's equation and the continuity equation. In the simulation, the Okuto–Crowell avalanche model is used as the breakdown model, and the electron and the hole impact ionization coefficients at room temperature can be presented as $\alpha_{n(p)} = a_{n(p)} \exp(-b_{n(p)})/E)$, where E is the electric field, $a_{n(p)}$ and $b_{n(p)}$ are constants, subscripts n and p indicate electron and hole, respectively. The electric field distribution without any JTT is shown in Fig. 2, we can see that the breakdown happens on the edge of the junction due to the electric field crowding effect.

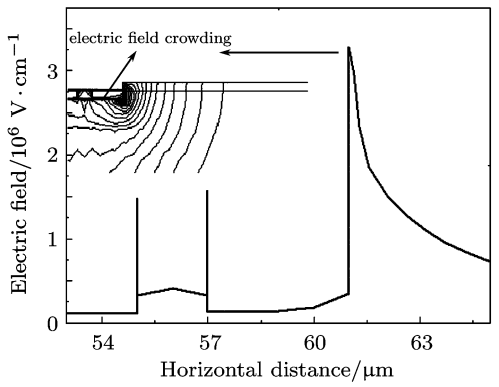


Fig. 2. Electric field distribution without JTT.

Figure 3 shows the simulated BV values versus the parameters of the JTE. As can be seen from Fig. 3(a), the BV is strongly dependent on the JTE doping concentration N_{A-JTE}, so any deviation from the optimized value of N_{A-JTE} will cause the BV to decrease seriously. When the JTE is optimally doped, there are equal electric field intensities at the two sides of the JTE, resulting in a maximum of the BV.[15] Figure 3(b) shows that the BV is sensitive to the JTE length L_{JTE} if $L_{JTE} < 30$ μm, and the BV is basically independent of L_{JTE} for longer L_{JTE}, as the electric field distribution is relatively uniform along the termination. The BV versus the JTE depth d is given in Fig. 3(c), which shows that the BV promptly increases with the increasing d and then begins to decrease when d is larger than 1.5 μm. We will set $d = 1$ μm in the following discussion.

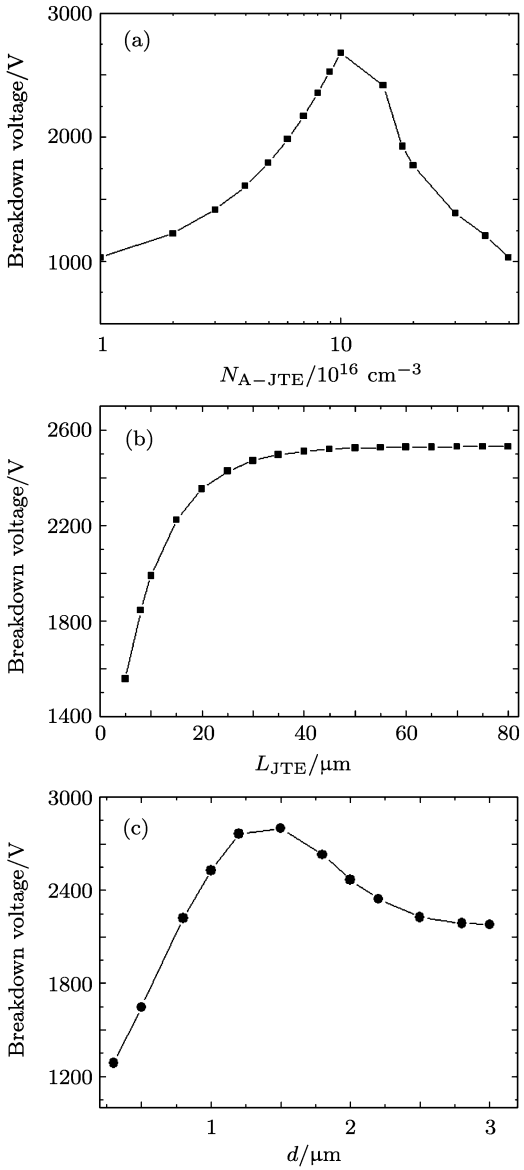


Fig. 3. Simulated BV values versus parameters of JTE: (a) doping concentration N_{A-JTE}, (b) length L_{JTE}, and (c) depth d.

Figure 4 shows the dependence of the BV on the FP length L_{FP}. As will be discussed later, when the JTE is slightly doped, the FP part plays the major role. When L_{FP} equals L_{JTE} and N_{A-JTE} reaches its optimal value, the BV will decrease remarkably,[10] so we will set L_{FP} to be 20 μm.

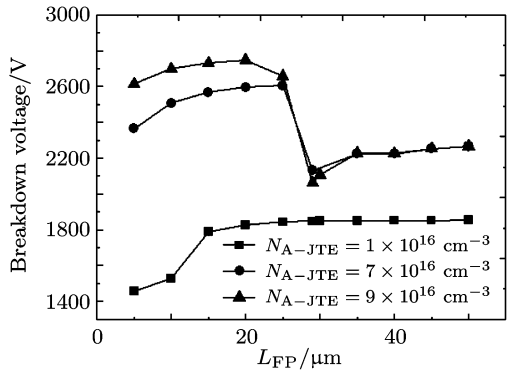


Fig. 4. FP length L_{FP} dependence of BV.

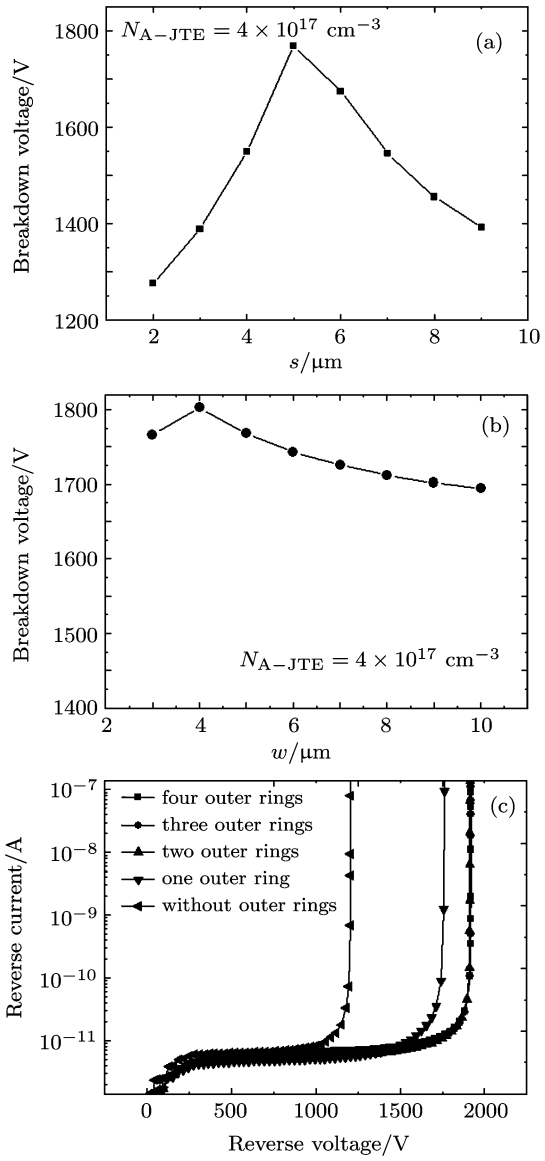


Fig. 5. Simulated BV versus parameters of outer rings: (a) spacing s, (b) width w, and (c) number.

Figure 5 shows the effect of the outer rings when the JTE is highly doped. We can clearly see that the BV is strongly dependent on spacing s between the JTE and the first outer ring and is less sensitive to ring width w, which is similar to the case in which only the guard ring is used as the edge termination. The BV will no longer increase when the number of the rings is more than two. Here w and s are both set to be 5 μm, and three rings are utilized.

3. Characteristics and discussion

Figure 6 illustrates the N_{A-JTE} dependence of the BV with different terminal structures. We can see from Fig. 7 that when N_{A-JTE} is lower than the optimal value, the FP plays an important role. The JTE and the outer rings sustain the reverse voltage simultaneously when the JTE is highly doped. This is the reason why the BV with the mixed terminal structure is less sensitive to N_{A-JTE} than that with the JTE, as shown in Fig. 6.

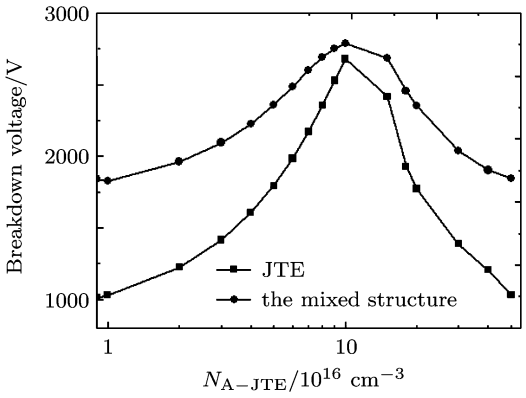


Fig. 6. The N_{A-JTE} dependence of BV with two terminal structures.

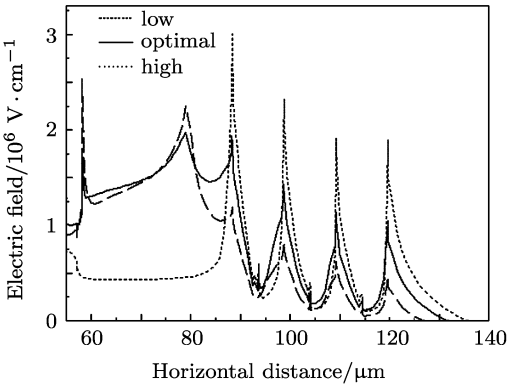


Fig. 7. Electric field distributions of the mixed structure at breakdown with different values of N_{A-JTE}.

Figure 8 shows a comparison of the effect of interface charge Q_{ss} on the BV between the JTE and the mixed terminal structure. As shown in the figure,

the BV with the JTE decreases significantly as Q_{ss} increases to exceed 1×10^{12} cm^{-2}. The mixed structure can ease the influence of the interface charge effectively.

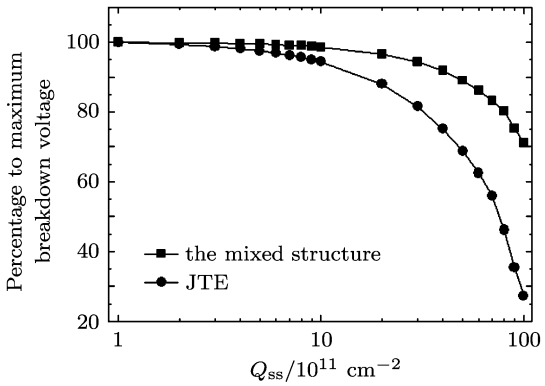


Fig. 8. Comparison of effect of interface charge on the breakdown voltage between the JTE and the mixed terminal structure.

4. Conclusion

A mixed terminal structure used in the 4H-SiC merged PiN/Schottky diode is investigated. The simulation results suggest that this structure is less sensitive to the JTE doping concentration and can relieve the influence of the surface charge effectively. A high breakdown voltage is achieved in the 4H-SiC MPS with this structure. The process of this structure is simple, since the FP is formed simultaneously with the anode and the outer guard rings are formed with the JTE.

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