Optimized design of 4H-SiC floating junction power Schottky barrier diodes*

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Abstract: SiC floating junction Schottky barrier diodes were simulated with software MEDICI 4.0 and their device structures were optimized based on forward and reverse electrical characteristics. Compared with the conventional power Schottky barrier diode, the device structure is featured by a highly doped drift region and embedded floating junction region, which can ensure high breakdown voltage while keeping lower specific on-state resistance, solved the contradiction between forward voltage drop and breakdown voltage. The simulation results show that with optimized structure parameter, the breakdown voltage can reach 4 kV and the specific on-resistance is 8.3 mΩ·cm^2.

Key words: SiC; floating junction; Schottky barrier diode

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1. Introduction

With silicon carbide (SiC) wafer localization and the maturing of high quality 6H-SiC and 4H-SiC epitaxial technology, SiC power devices have seen an upsurge in study. Generally, the SiC Schottky barrier is thinner than silicon at high voltages, and further improvement of SiC Schottky barrier blocking capability will be limited by reverse barrier tunneling leakage current. In order to take advantage of the SiC high critical breakdown field character, a pn junction and Schottky barrier composite structure (JBS or MPS) was proposed to eliminate tunneling current and achieve high blocking voltage. Further study of SiC Schottky barrier diode, minimum forward specific resistance without sacrificing blocking voltage could maximize forward current. So, the conventional design idea must be inadequate. During recent years, the super-junction (SJ) structure has being proposed and realized. For SJ Schottky barrier diodes (SBD), 1000 V Si-based devices have been reported[1]. However, only the two research groups of Chow and Sheng have engaged in research of SiC SJ-SBD[2,3], and they mainly focused on the structure simulation. The reason is that the charge must be strictly controlled in SJ devices[4,5], otherwise breakdown voltage decreases rapidly. The other reason may be that it is very difficult to make deep implantation due to crystalline damage caused by the high energy implants, so there is no report about 4H-SiC SJ structure processing.

It is hoped to overcome these issues in the new structure, and to consider the feasibility of the process flow, the floating junction (FJ)[6,7] structure is used in this paper. Employing a two-dimensional physically based device simulator MEDICI 4.0[8], we have simulated the performance of FJ-SBD based on 4H-SiC. On-state resistance (R_{on}), breakdown voltage (V_R) and other character parameters are simulated, and the device structure and the related parameter are discussed and optimized based on the simulation results.

2. Device structure

The FJ structure features a floating p$^+$-buried layer embedded in the n$^-$ drift region, as shown in Fig. 1. The drift region is divided into upper and lower sections by inserting FJ. With the p$^+$-buried floating layer, the depletion layer enhances development due to a mechanism similar to that of p-guard rings in planar terminations, when the depletion region from the Schottky contact reaches the p$^+$-buried floating layer, the voltage of the layer is pinned due to punch-through between the floating layer and the anode, and then a new depletion layer develops from the bottom of the p$^+$-floating layer toward the cathode. Compared with the conventional SBD form one triangle electric field, the FJ structures form two electric field distributions, and each triangular shape is formed at both upper and lower regions. Therefore, the FJ structures are used to provide the desired device performance with designing the peak field in the FJ below the critical field of 4H-SiC. So, the V_R of the device can be improved. If we assume the critical electric field is constant and the current path (narrowed by inserting the FJ) does not affect the R_{on}, then the V_R and R_{on} become M (number of drift regions) times larger than those of single drift region. In other words, R_{on} is proportional to V_R, rather than V_R^2 for the conventional structure. So, with the

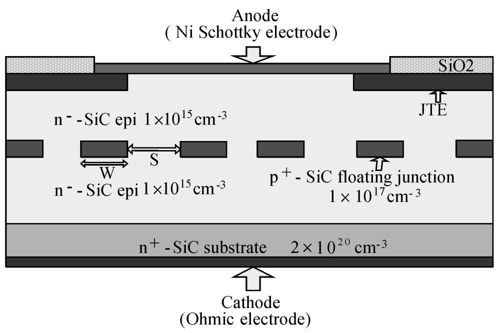

Fig. 1. Schematic drawing of FJ SBD.

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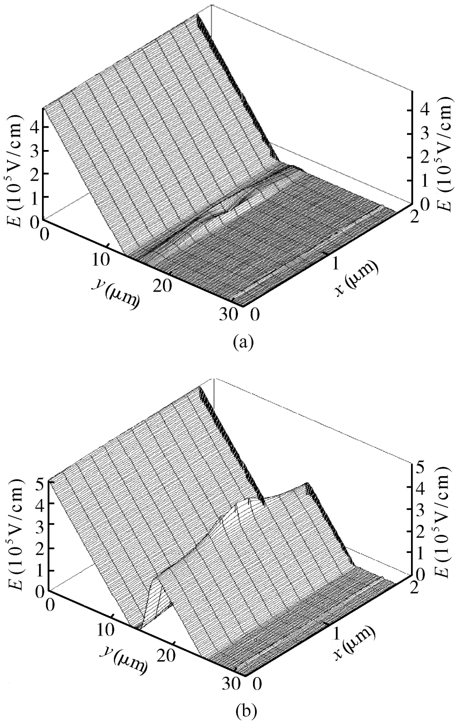

Fig. 2. Electric field distribution with different reverse bias voltages: (a) 100 V; (b) 1100 V.

same voltage-sustaining layer, it is possible to increase doping concentration for lower R_{on} and therefore maintaining the same voltage blocking capacity.

For characteristic simulation, we choose a 15 μm thick, 1×10^{15} cm^{-3} doped n-type epilayer grown on an n$^+$ 4H-SiC substrate. The floating junction was formed by Al$^+$ implantation and the designed doping concentration is 1×10^{17} cm^{-3}; then, the second epilayer with a dose of 1×10^{15} cm^{-3} and 15 μm thickness was formed. Ni is selected as Schottky electrode metal, and its barrier height is about 1.4 eV.

3. Device simulation

In order to achieve realistic results, it is imperative to use accurate SiC property models. Several important material parameters used in simulator were adjusted to obtain the closest agreement with published material data of 4H-SiC. Here the energy bandgap at room temperature was adjusted to 3.26 eV. And models used in the simulator are bandgap-narrowing effect, impact ionization, Auger recombination, SRH recombination, Fermi-Dirac statistics and incomplete ionization of impurities[9].

In order to accurately predict both the forward and reverse characteristics of 4H-SiC SBD, the simple empirical model[10] is used to estimate the barrier height lowering at Ni/SiC interface, which can be expressed as

$$\Delta\phi_B = a\,(E_{av})^{1/2} + b, \qquad (1)$$

where E_{av} is the average electric field (V/cm) at the Schottky contact, a and b are the constants. These constants are evaluated by iterating in MEDICI until the simulated reverse leakage current matches the measured data. In our study, the two parameters match well with the experimental results reported by Schoen *et al.*[11]; for Ni/SiC Schottky contact, we obtain that a and b are 1.54×10^{-4} V$^{1/2}$·cm$^{1/2}$ and 0.638 V, respectively.

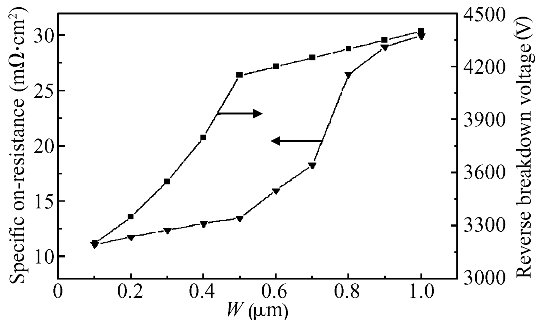

Fig. 3. Breakdown voltage and specific on-resistance with different floating widths.

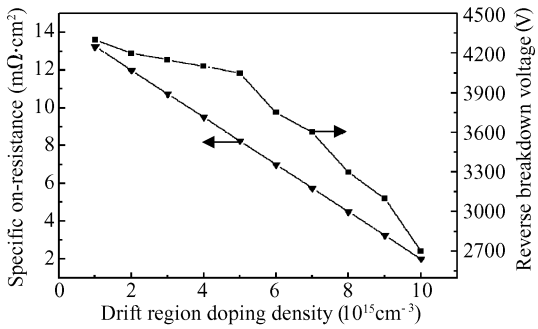

Fig. 4. Breakdown voltage and specific on-resistance with different drift region doping densities.

4. Simulation and discussion

4.1. Electric field distribution of reverse bias

The electric field distribution is shown in Fig. 2 at the cathode bias of 100 and 1000 V, in which we can see the electric field distribution in FJ location is changed and the peak electric field near Schottky interface is no longer increased and spread with reverse bias voltage increasing. This agrees with our theory analysis and reaches our demands.

4.2. Optimization of floating junction width

The junction size and its relative position are treated as parameters. In simulation, a repeat unit is selected as simulation target, and the floating junction width (W) and spacing (S) are fixed as 2 μm in number. Compared with traditional Schottky diodes, it could double the doping concentration with the same epitaxial thickness. The V_R and R_{on} dependences on W are shown in Fig. 3.

In Fig. 3, the V_R reduces at smaller W. It is because the field at upper region deforms and increases the peak field with increasing S and the peak field at the corner of floating junction increases with decreasing W. The R_{on} rises at larger W, because the depletion region extended from the p$^+$n junction with the built-in potential pinches off the channel and hence

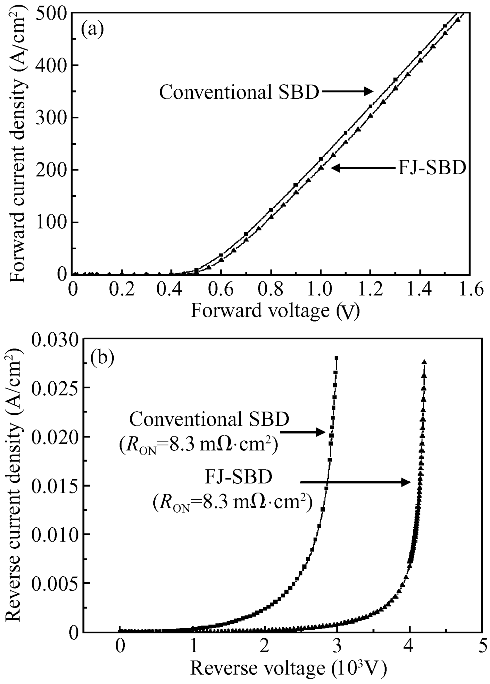

Fig. 5. *I–V* character: (a) Forward; (b) Reverse.

the current does not flow. So there must be a trade-off between R_{on} and V_R, and they are balanced when $W = 0.5$ μm.

4.3. Optimization of drift region doping

When $W = 0.5$ μm, floating junction doping of 1×17 cm^{-3}, and set drift doping concentration as parameters, the forward and reverse characteristics are shown in Fig. 4.

These simulations predict that the forward resistance and drift region doping is nearly a linear relationship. There is a turn point when the drift region doping concentration is equal to 5×15 cm^{-3}, and the breakdown voltage changes slowly lower than that. In order to guarantee lower forward on-resistance at the same breakdown voltage, set drift region doping as 5×15 cm^{-3}.

4.4. *I–V* character

When $W = 0.5$ μm and junction and drift region concentration of 1×17 and 5×15 cm^{-3}, the *I–V* characteristics of the conventional SBD and the FJ-SBD are shown in Fig. 5.

The FJ-SBD specific on-resistance was the same as the conventional SBD one. The blocking voltage of the FJ-SBD was 1000 V higher than that of the conventional SBD and the leakage current increases much more slowly than the conventional one. This shows that FJ-SBD could effectively reduce Schottky surface electric field intensity and leakage current.

SiC FJ-SBD with above optimized design parameters were simulated, and results are that the device V_R and R_{on} are 4050 V and 8.3 mΩ·cm^2, respectively.

5. Conclusion

The R_{on} and V_R of floating junction power Schottky barrier diodes optimized by 2-D commercial simulation software MEDICI. The simulation results show that when the floating junction width and spacing were 0.5 and 1.5 μm, drift region doping concentration of 5×15 cm^{-3}, its performance is excellent, and exceeds that of the conventional Schottky barrier diode. The floating junction Schottky barrier diode is an excellent performing and process-feasible 4H-SiC Schottky barrier diode.

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