Study and optimal simulation of 4H–SiC floating junction Schottky barrier diodes' structures and electric properties*

Nan Ya-Gong(南雅公)[a)b)†], Pu Hong-Bin(蒲红斌)[a)], Cao Lin(曹 琳)[a)], and Ren Jie(任 杰)[a)]

[a)] *Department of Electric Engineering, Faculty of Automation and Information Engineering, Xi'an University of Technology, Xi'an* 710048, *China*

[b)] *Department of Physics and Electronics, Hexi University, Zhangye* 734000, *Gansu Province, China*

(Received 16 July 2009; revised manuscript received 5 April 2010)

This paper stuides the structures of 4H–SiC floating junction Schottky barrier diodes. Some structure parameters of devices are optimized with commercial simulator based on forward and reverse electrical characteristics. Compared with conventional power Schottky barrier diodes, the devices are featured by highly doped drift region and embedded floating junction layers, which can ensure high breakdown voltage while keeping lower specific on-state resistance, and solve the contradiction between forward voltage drop and breakdown voltage. The simulation results show that with optimized structure parameter, the breakdown voltage can reach 4.36 kV and the specific on-resistance is 5.8 m$\Omega\cdot$cm^2 when the Baliga figure of merit value of 13.1 GW/cm^2 is achieved.

Keywords: 4H–SiC, floating junction, Schottky barrier diode, optimization

PACC: 7340L, 7330, 7340S

1. Introduction

With silicon carbide (SiC) wafer production localization and the increasing maturity of high quality 4H–SiC and 6H–SiC epitaxial technology, SiC power devices ignite an upsurge in research. And the SiC Schottky barrier diodes (SBDs), as promising technical devices due to the potential for low forward voltage drop, high breakdown voltage and fast switching speed, have become key components in switching mode power supply circuit. Low on-resistance SBDs are desired for the reduction of power loss in such a system. However, it is known that, not only for silicon device but also for that of SiC, the on-resistance has been limited theoretically by the material limit.[1] Having been exploited in Si devices, we find that a super-junction (SJ) structure proposed previously cannot be used in SiC SBDs due to the extremely low diffusion rate of dopant impurities and the difficulties in achieving charge compensation between heavily doped n- and p-type pillars. To overcome this issue of SiC power devices,[2−5] based on the SJ concept,[6,7] a floating junction (FJ) structure was put forward. And the 4H–SiC SBDs have been examined to realize the FJ structure by using epitaxial overgrowth process.[7,8] But for the desired performance, the doping concentrations of drift region and p-type floating layers with the right pattern need to be precisely designed.

Although it was reported that the numerical simulation has confirmed the effectiveness of applying the FJ structure to SiC power devices,[7−13] there is no report about detailed optimization of the 4H–SiC floating junction Schottky barrier diodes (FJ-SBDs). For this purpose, exploiting the commercial device simulator, we have simulated the performance of FJ-SBDs on the basis of 4H–SiC and obtained on-state resistance ($R_{\rm ON}$), breakdown voltage ($V_{\rm BR}$) and other characteristic parameters. Furthermore, the device structure and the related parameters are also discussed and optimized based on the results.

2. Device structure

The conventional structure of SBD, as shown in Fig. 1(a), requires a lower carrier concentration in the n-type drift region to make the blocking voltage higher. This results in an increasing on-resistance.

*Project supported by the Open Fund of Key Laboratory of Wide Bandgap Semiconductor Materials and Devices, Ministry of Education of China.

†Corresponding author. E-mail: nyg2@163.com

© 2010 Chinese Physical Society and IOP Publishing Ltd

Deriving from SBD, we find that the FJ-SBD is characterized by the p^+-buried layers embedded in the n^- drift region, as shown in Fig. 1(b). And the drift region is accordingly divided into upper and lower parts by inserted layers.

When reverse bias is applied to the device, the depletion layer will expand from Schottky barrier contact above through upper drift region to the surface of p^+-buried layers. Once this layer is depleted, it continues to expand from the bottom of the p^+-buried layer to the lower drift layer. As for the distribution pattern of electrical field, it is noted that the conventional SBD has only single triangle, and the FJ-SBD's is divided into two triangles. Although they own the same value of voltage for the same sum area of the triangles, the slope of the triangle of FJ-SBD, which corresponds to the carrier concentration of the n-type drift layer, is 2 times as large as that of SBD. This leads to the reduction of the drift layer resistance.

Therefore, the FJ structures are used to satisfy the desired performance when we design the peak field in FJ-SBD while keep below the critical breakdown electrical field of 4H–SiC. And the $V_{\rm BR}$ can be improved. If we assume that the critical electrical field is constant and the current path (narrowed by inserting the FJ layers) does not affect the $R_{\rm ON}$, then the $V_{\rm BR}$ and $R_{\rm ON}$ become K (number of drift regions) times larger than those of single drift region.[5] In other words, with the same voltage-sustaining layer,[10,11] it is possible to enhance doping concentration for lower $R_{\rm ON}$ and maintain the same voltage blocking capability.

From the viewpoint of the fabrication process, we choose an n-type epi layer grown on a 4H–SiC n^+ substrate, which is 15-μm thick and 1.0×10^{15} cm^{-3} doped. The floating p^+-type layers designed doping concentration of 1.0×10^{18} cm^{-3} were formed by Al^+ implantation, and then second epitaxial layer with the same doping concentration and thickness was formed. The metal Ni is adopted as Schottky electrode and 4.6 eV for its work function. The pattern opted for the floating layers in the active region has a constant spacing, as shown in Fig. 1(b). The "w" and "$2s$"express the width and the lateral spacing of the p-type buried layers, and the depth of the p-type buried layer is 2 μm. During the course of characteristic simulation, one unit cell of FJ-SBD has been always utilized, as shown in Fig. 1(c).

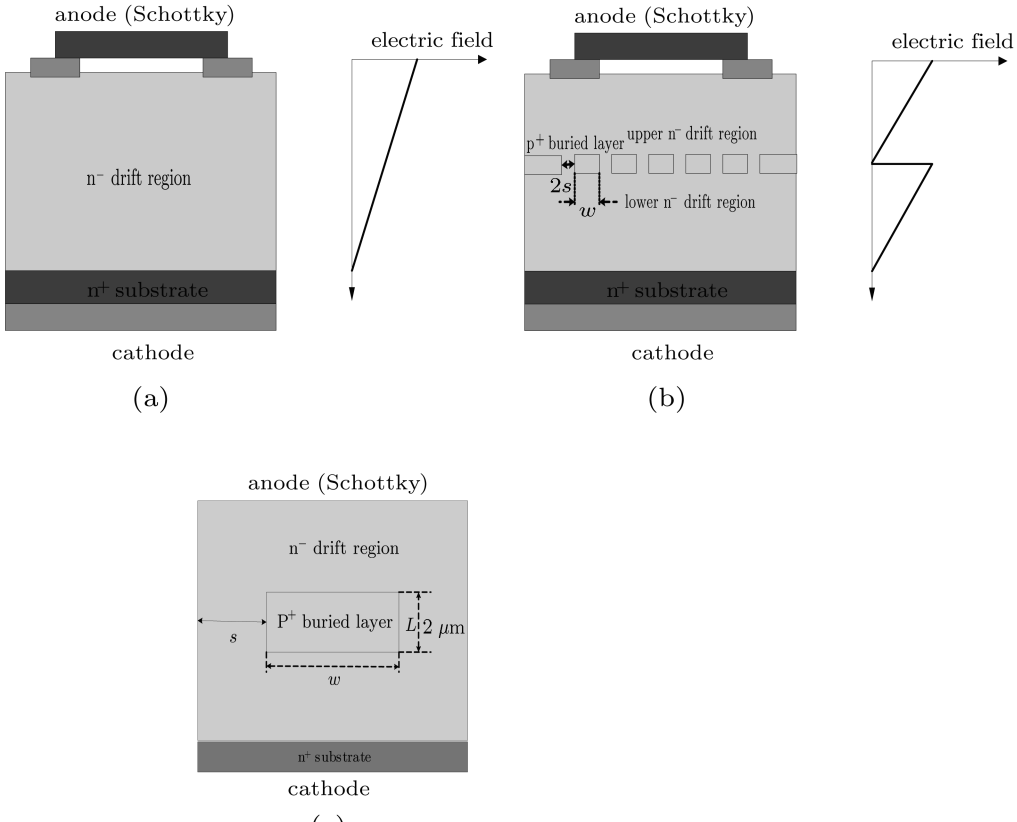


Fig. 1. Schematic diagrams of conventional SBD and FJ-SBD: (a) conventional SBD structure; (b) FJ-SBD structure; (c) unit cell structure of simulation (14 μm×35 μm).

3. Optimization results and discussion

There are some key factors, such as the dimensions of device structure, doping concentrations of drift region and p^+ floating layers, etc., which can be significant to V_{BR} and R_{ON}. Given the unchanging doping concentration of p^+ floating layers, others were considered as variables. After applied bias voltage, some electric properties of FJ-SBD, including electrical field, forward I–V characteristic and reverse blocking characteristic, could be severally acquired through simulation.

3.1. Electric field distribution

The three-dimensional (3D) drawing of electric field distribution along y axis direction, shown in Fig. 2, indicates two-triangle figurations of FJ-SBD while y changes from 0 to 35 μm and x value is 7 μm (z axis standing for the electric field intensity). Compared with that of SBD (Fig. 2(a)), the electric field of FJ-SBD is apparently stronger in the central region with the FJ layer. There is one peak value near the lower edge of the floating buried layer, because that the depletion layers mainly distribute in the drift region and the inner thickness in the p^+-type buried layer is rather narrow. And the negative acceptor ions density of the inner depleted area is specially large. With the electrical field distribution, the device is prone to breakdown at higher voltage and capability properties are improved.

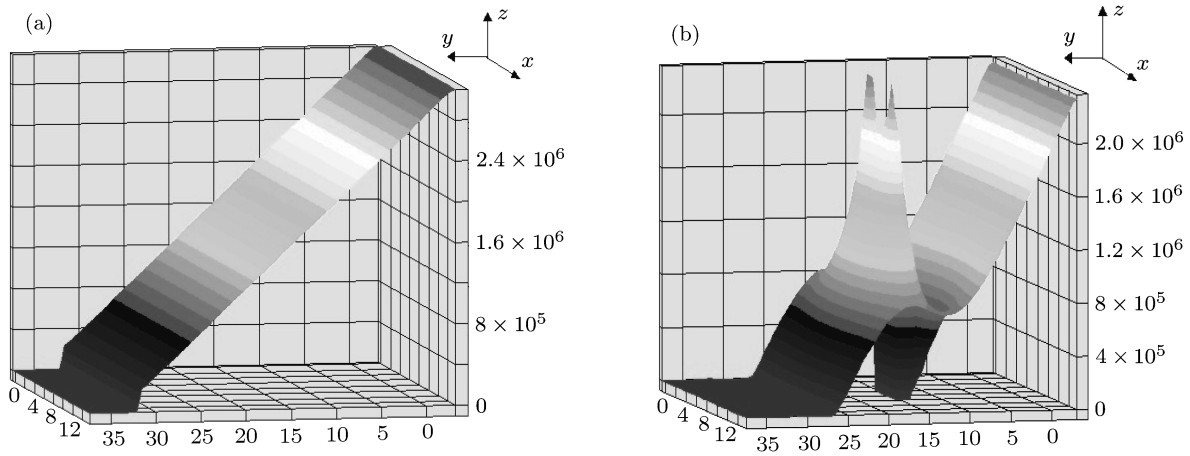


Fig. 2. The 3D drawing of electric field distribution at reverse applied voltage: (a) conventional SBD; (b) FJ-SBD.

3.2. Forward and reverse I–V characteristics

It is seen from the drawing, Fig. 3, that the device owns a better current transport capacity under forward bias condition in spite of existing difference from that of SBD. Furthermore, as the improved reverse breakdown characteristic (Fig. 4) and a lower reverse leakage current, the blocking voltage of 4.36 kV is higher than that of SBD, when other conditions kept unchanged. So, it is the floating buried layers that they have changed the current path in the drift region and benefit the electrical properties due to a certain range increased specific on-resistance and obtaining a higher V_{BR}.

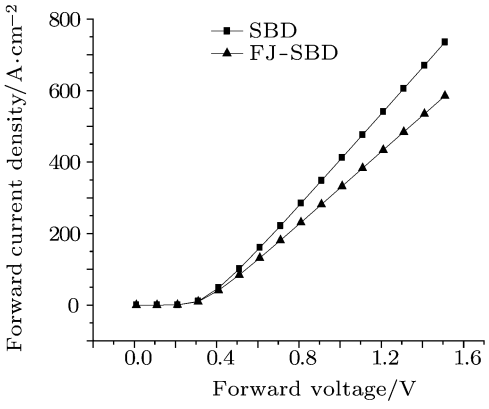


Fig. 3. The FJ-SBD forward I–V property by contrast to SBD.

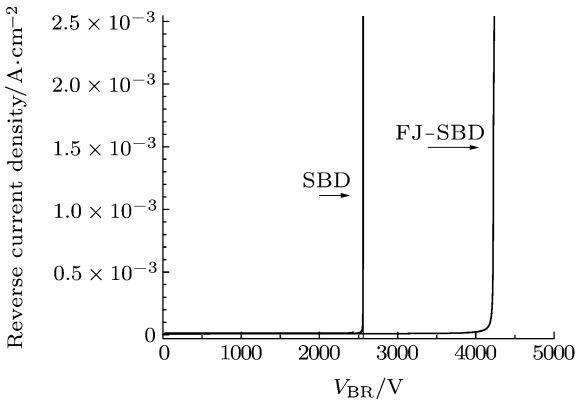


Fig. 4. The FJ-SBD reverse breakdown property compared to SBD.

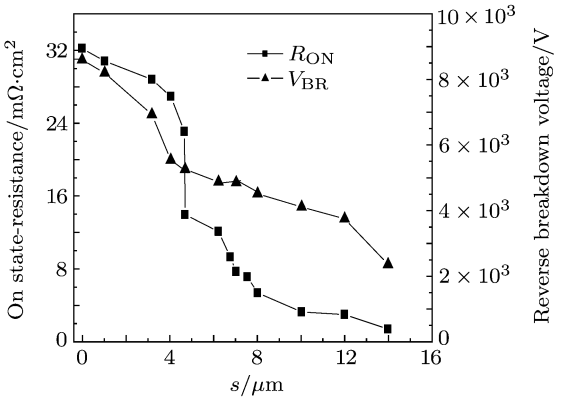


Fig. 6. The R_{ON} and V_{BR} dependence on separation (s).

3.3. Optimization and improvement of FJ-SBD electrical properties

The width or separation (s) of the floating layer is treated as a significant parameter, the effect of it on R_{ON} and V_{BR} is simulated, as shown in Figs. 5 and 6.

In Fig. 5, with the increase of n$^-$ drift region doping concentration (N_d), the R_{ON} and V_{BR} begin to reduce. They vary slightly before N_d equals the concentration value of 1.0×10^{14} cm^{-3}, and then begin to decrease sharply. When the concentration gets to 1.0×10^{15} cm^{-3}, the R_{ON} and V_{BR} are 5.8 mΩ·cm^2 and 4.36 kV, respectively.

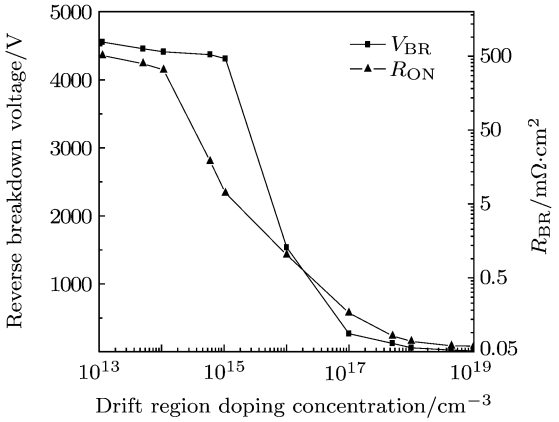


Fig. 5. The R_{ON} and V_{BR} dependence on n$^-$ drift region doping concentration.

From Fig. 6, it can be seen that, with the increase of s value, the R_{ON} and V_{BR} decrease. And the changing situation of them is not identical in the form. When the value of s is 8 μm, R_{ON} and V_{BR} in turn equal 5.8 mΩ·cm^2 and 4.36 kV.

Based on the above fact, we can find that there is a trade-off between R_{ON} and V_{BR}, and when N_d corresponds to 1.0×10^{15} cm^{-3} and s equals 8 μm, the device attains a higher reverse breakdown voltage value of 4.36 kV. At the same time, compared with others, the on-resistance for 5.8 mΩ·cm^2 is lower. Moreover, with the results, the BFOM (Baliga Figure of Merit) value of 13.1 GW/cm^2 is obtained. And simulating test has shown that the device is in good working order and meets our initial requirements.

4. Summary

In short, we have investigated the FJ-SBDs and made some progress in the simulation and optimization of their structures and properties, especially reverse blocking property. The trade-off between the specific on-resistance and breakdown voltage was considered and their values of 5.8 mΩ·cm^2 and 4.36 kV were achieved respectively with the optimized device structure parameters. The value of BFOM could reach 13.1 GW/cm^2.

References

[1] Yu L C and Sheng K 2008 *IEEE Trans. Electron Devices* **55** 1961

[2] Adachi K, Omura I, Ono R, Nishio J, Shinohe T, Ohashi H and Arai K 2003 *Mater. Sci. Forum* **433–436** 887

[3] Hatakeyamaa T, Nishiob J and Shinohec T 2005 *Mater. Sci. Forum* **483–485** 921

[4] Ota C, Nishio J, Hatakeyama T, Shinohe T, Kojima K, Nishizawa S and Ohashi H 2006 *Mater. Sci. Forum* **527–529** 1175

[5] Ota C, Nishio J, Hatakeyama T, Shinohe T, Kojima K, Nishizawa S and Ohashi H 2007 *Mater. Sci. Forum* **556–557** 881

[6] Saitoh W, Omura I, Tokano K, Ogura T and Ohashi H 2002 *Proc. ISPSD'02* pp. 34–36

[7] Saitoh W, Omura I, Tokano K, Ogura T and Ohashi H 2004 *IEEE Trans. Electron Devices* **51** 797

[8] Nishio J, Ota C, Hatakeyama T, Shinohe T, Kojima K, Nishizawa S and Ohashi H 2008 *IEEE Trans. Electron Devices* **55** 1955

[9] Pu H B, Cao L, Chen Z M and Ren J 2009 *J. Semicond.* **30** 1

[10] Ma L and Gao Y 2009 *Acta Phys. Sin.* **58** 530 (in Chinese)

[11] Yang Y T, Geng Z H, Duan B X, Jia H J, Yu C and Ren L L 2010 *Acta Phys. Sin.* **59** 567 (in Chinese)

[12] Wang C L and Sun J 2009 *Chin. Phys.* B **18** 1232

[13] Song Q W, Zhang Y M, Zhang Y M, Lü H L, Chen F P and Zheng Q L 2009 *Chin. Phys.* B **18** 5474