Optimization of Schottky-contact process on 4H-SiC Junction Barrier Schottky (JBS) Diodes

Qingling Li1, 2, *, Tao Zhu1, 2, Jialing Li1, 2 and Hailiang Yan1, 2

1State Key Laboratory of Advanced Power Transmission Technology, Beijing 102209, China
2ChinaGlobal Energy Interconnection Research Institute Co., Ltd., Beijing 102209, China

*Corresponding author: liqingling@geiri.sgcc.com.cn

Abstract. SiC Junction Barrier Schottky (JBS) Rectifier is a kind of unipolar power diode with low threshold voltage and high reverse blocking voltage. And the Schottky barrier $\Phi_{BN}$ is a main technology parameter, which could greatly affect the forward conduction power and reverse leakage current in the JBS rectifiers. Therefore, it is necessary to balance the influence of $\Phi_{BN}$ on the electrical characteristics of JBS rectifiers. In this paper, physical properties at the metal-semiconductor at the Schottky-contact could be optimized by the improvement of Schottky-contact process. And this optimization could significantly decrease $\Phi_{BN}$ to reduce the on-state voltage drop $V_F$ and minimize negative impact on its reverse characteristics. After the completion of Silicon carbide JBS diodes, the static parameter electrical test was carried out on the wafer by using Keysight B1505A Power Device Analyzer/Curve Tracer. The test results show that the Schottky barrier height $\Phi_{BN}$ of JBS Schottky rectifier manufactured by the modified Schottky foundation technology decreased from 1.19eV to 0.99eV and $I_R$ increased from 1.08μA to 3.73μA (reverse blocking voltage $V_R$=1200V). It indicated that the power consumption of Schottky barrier junction in JBS rectifiers could be significantly reduced by about 25%, and $I_R$ could effectively be limited to less than 10μA.

Keywords: 4H-SiC, Schottky contact process, JBS Schottky rectifier, Schottky barrier height $\Phi_{BN}$, reverse leakage current

1. Introduction
Power semiconductor device is the core of power electronic technology, which plays an important role in the development of power electronic technology towards high power density [1]. At present, power devices based on Silicon (Si) material are limited by the characteristics of its material, which limits the development space of high frequency and high density power. And Silicon Carbide (SiC) material has a band gap of 3 times that of Si and a critical breakdown field strength of 10 times that of Si [1]. Therefore, SiC power devices are suitable for high frequency and high voltage applications, helping to improve the efficiency and power density of power electronic systems.
SiC power Schottky diode is a typical SiC power device that has been widely used in commercial applications. There are three main types: Schottky Barrier Diode (SBD), Junction Barrier Controlled Schottky (JBS) Rectifier and the merged P-i-N Schottky (MPS) Rectifier [2] shown as in fig. 1. And due to the large reverse leakage current of SBD structure and the difficulty of process realization of MPS structure, the mainstream commercial Schottky diodes all adopt JBS structure at present.

![Fig 1. The diagram of three types of silicon carbide diode structure.](image)

In this paper, the influence of Schottky barrier $\Phi_{BN}$ on the forward pass characteristics and reverse blocking characteristics of SiC JBS diode is analyzed, and an effective process optimization scheme to reduce the forward pass pressure drop is proposed.

2. The optimization process of SiC JBS diode

2.1. The device structure of SiC JBS diode

Fig. 2 shows the profile structure of a typical commercial SiC JBS diode, including the device active region and terminal region structure. The width of P$^+$ injection zone in the active region of the device is (p-s), and the width of the cell is P. An equipotential ring is set between the active region and the terminal region. The terminal region adopts a non-equipotential ring spacing floating empty field ring terminal structure, above which the field oxygen and passivation layer are coverd [2].

![Fig 2. The sectional structure of silicon carbide JBS diode.](image)
The working principle of JBS diode relies on Schottky-barrier to achieve rectifying action. On the forward conduction, the forward voltage drop $V_F$ of SiC JBS diode is mainly determined by the voltage drop $V_{FS}$ of the Schottky junction and the voltage drop $V_{Re}$ at both ends of the specific conduction impedance, as shown in equation (1),

$$V_F = V_{FS} + V_{Re} = \frac{kT}{q} \ln \left( \frac{J_F}{J_0} \right) + R_{S,SP}J_F$$  \hspace{1cm} (1)$$

Where $J_F$ is the forward current density, $J_0$ is the saturation current density, $R_{S,SP}$ is the total series resistance. On the condition of reverse blocking, the saturation leakage current $J_0$ of JBS diode is mainly determined by the Schottky barrier $\Phi_{bn}$ and the reverse blocking electric fields at the metal-semiconductor interface[3], as shown in equation (2),

$$J_0 = AT^2 \exp \left(- \frac{q\Phi_{bn}}{kT} \right)$$  \hspace{1cm} (2)$$

Where $A$ is effective Richardson’s constant, $T$ is the thermodynamic temperature and $k$ is the Boltzmann constant. When the JBS diode is in the reverse blocking state, a depletion barrier region is formed between the P$^+$ region and the N-epitaxial layer to shield the high electric field on the surface of the Schottky barrier, effectively reducing the electric field intensity at the metal-semiconductor interface.

Therefore, Schottky barrier height $\Phi_{bn}$ is an important parameter affecting the electrical performance of JBS diodes, especially electrical parameters $V_F$ and $J_0$.

2.2. The scheme of optimization

The design and process optimization of SiC JBS diodes mainly focus on the Schottky barrier height $\Phi_{bn}$. It is necessary to compromise between reducing the forward voltage drop and minimizing the leakage current.

![Image of Schottky reduction effect and tunneling effect on reverse leakage current of silicon carbide Schottky diodes][4].

Fig 3. The influence of schottky reduction effect and tunneling effect on reverse leakage current of silicon carbide Schottky diodes [4].
The saturation leakage current $J_0$ of JBS diode has an exponential relationship with the height of Schottky barrier $\Phi_{bn}$. If $\Phi_{bn}$ decreases by 0.2eV, $J_0$ will increase by about 2190 times. Actually, the reverse leakage current $J_L$ of SiC JBS diode is not only affected by barrier lowering, but also affected by tunnel current[4], as shown in equation (3),

$$ J_L = AT^2 \exp\left(-\frac{q\Phi_{bn}}{kT}\right) \exp\left(\frac{q\Delta\Phi_{bn}}{kT}\right) \exp\left(CT^2E_M^2\right) $$

(3)

Where $C_T$ is a tunneling coefficient and $\Delta\Phi_{bn}$ is the barrier lowering, determined by the electric field $E_M$ at the Schottky contact interface[5], as shown in equation (4),

$$ \Delta\Phi_{bn} = \sqrt{\frac{qE_M}{4\pi\varepsilon_S}} $$

(4)

Where $\varepsilon_S$ is the dielectric contact at the metal-semiconductor interface. If the influence of the barrier lowering and tunneling on the reverse leakage current can be reduced, as shown in fig. 3, the negative influence caused by the height of the barrier can be effectively reduced.

Therefore, the process optimization strategy will focus on the metal-semiconductor contact at the Schottky barrier to change the physical properties at the metal-semiconductor compound interface, such as tunneling coefficient $C_T$ and dielectric coefficient $\varepsilon_S$. This way could not only reduce $\Phi_{bn}$, but also minimize the negative impact on the $J_L$.

The expected goal of this optimization is to reduce the barrier height $\Delta\Phi_{bn}$ of 1200V/20A JBS diode by 0.15eV~0.25eV based on the improvement of the process of Schottky contact. And at the meanwhile, the reverse leakage current $J_L$ increase less than 5 times at the reverse blocking voltage $V_R$ of 1200V.

2.3. The design of optimization process experiment

For SiC JBS diode, the relationship between the doping concentration $N_d$ and the epitaxial thickness $W_{PP}$ of the N-epitaxial layer and the reverse blocking voltage $BV_{PP}$ of the device is shown in equation (5) and (6)[4],

$$ BV_{PP}(4H – SiC) = 3.0 \times 10^{15} N_D^{-3/4} $$

(5)

$$ W_{PP}(4H – SiC) = 1.82 \times 10^{11} N_D^{-7/8} $$

(6)

Considering that the cylindrical junction and spherical junction region of the actual device will reduce the effective utilization rate of the plane junction termination [3]. So, the parameters of SiC wafer were as follows: the epitaxial thickness $W_{PP}$ was 12μm, the epitaxial doping concentration $N_d$ was about $1 \times 10^{16}$ cm$^{-3}$, and the substrate thickness was about 350μm.

In this optimization-process experiment, two silicon carbide epitaxial wafers were selected to fabricate JBS diode, including structure-1 based on the unoptimized process as the control group and structure-2 based on the optimized process as the experimental group.
Fig 4. Process flow to fabricate JBS diodes of structure-1 and structure-2.

Fig 4 shows the fabrication process of this experiment and the different process for structure-1 and structure-2 mainly display on the process of Schottky contact. And Schottky-annealing temperature of structure-2 is 50℃ higher than that of structure-1, as shown fig 4. The other process steps adopt the manufacturing process of the conventional silicon carbide JBS diode manufacturing process.

3. Experimental results and discussion

3.1. The performance of SiC JBS diode wafer
The finished silicon carbide JBS diode wafer is shown in fig. 5, where the effective chip area of the sub-chip is about 0.0767cm$^2$. These electrical characteristics of structure-1 and structure-2, such as Schottky-barrier $\Phi_{BN}$, reverse leakage current $I_R$ and on-state voltage drop $V_F$, were compared to evaluate the optimization of SiC JBS diodes.

Fig 5. The diagram of finished JBS diode wafer.
3.2. The comparison of Schottky barrier height of SiC JBS diode

I-V method is used to test the Schottky barrier, and $\phi_{BN}$ at the metal-semiconductor interface is obtained through forward I-V test data, as shown in equation (7). Fig 6 shows a comparison of the Schottky barrier test curves of structure-1 and structure-2 wafer neutron chips.

$$\ln J = \frac{q}{kT} \left[ \ln \left( \frac{AT^2}{q} \right) + V \right] - \phi_{BN}$$

(7)

Fig 6. Comparison of Schottky barrier test curves.

As shown in fig 6, by changing the Schottky contact process conditions, the typical value of $\phi_{BN}$ of structure-2 is about 0.99eV, which is about 0.2eV smaller than its value of structure-1.

3.3. The comparison of reverse leakage current of SiC JBS diode

Fig 7 shows the reverse leakage current $I_R$ comparison of silicon carbide JBS diode under the reverse blocking voltage drop $V_R$ at 1200V. It can be seen that the reverse leakage current $I_R$ of structure-2 is about 2.6μA larger than that of structure-1 and the curve $I_R$ of structure-2 is little softer.

As the reverse leakage current density $J_L$ of SiC JBS diode is affected by the barrier lowering and tunnel current, it is shown in equation (8)[5], where $C_T$ represents the tunnelling coefficient at the interface of metal-semiconductor. As shown in fig. 8, with the increase of reverse voltage $V_R$, reverse leakage current $I_R$ also increases gradually.

Fig 7. Comparison of reverse leakage current curves.
Although the optimization of metal-semiconductor interface inevitably caused the enhancement of reverse leakage current, the increase factor of $I_R$ is much less than the theoretical analysis value. This result turns out that the optimization process change also changed physical properties of Schottky-contact interface and it reduced disadvantageous effect of Schottky barrier lowering and tunnelling on reverse leakage current.

3.4. The comparison of forward conduction characteristics of SiC JBS diode

Fig. 10 shows a comparison of the forward voltage curves of structure-1 and structure-2.

![Comparison diagram of forward guide voltage drop curve.](image)

As shown in fig 10, when the forward current density $J_F$ is 260A/cm², the forward voltage $V_F$ of bare die on the structure-2 is smaller than that of structure-1. It can be seen from the slope of the I-V curve that the specific conduction impedance $R_{SSP}$ is 1.87 mΩ·cm², indicating that the reduction voltage at the Schottky barrier junction decreases by about 0.2V, which effectively reduce the conduction loss of the junction.

By optimizing the front metal-semiconductor interface of SiC JBS diode based on the Schottky contact process, the on-state threshold voltage of the device is reduced from 0.8V to 0.6V, and the conduction power loss at the Schottky junction barrier is reduced by 25%. When the forward conduction current $I_F$ is at 20A, the on-state voltage drop $V_F$ is reduced by about 0.17V. in addition, the total power consumption $P_L$ (total) of SiC JBS diode is mainly composed of the conduction power consumption $P_L$ (on) and the reverse blocking loss $P_L$ (off), as shown in equation (8),

$$ P_L \text{ (total)} = P_L \text{ (on)} + P_L \text{ (off)} = \delta J_F V_F + (1 - \delta) J_L V_R $$

$$ \delta = t_{ON} / T $$

Where $T$ represents the working period and $\delta$ represents the duty cycle.

4. Conclusions

The optimized SiC JBS diode is proposed in this paper, which is suitable for the application with large duty ratio and dominant power consumption. It can effectively reduce the power consumption at the Schottky junction and alleviate the influence of Schottky junction temperature on the device performance to a certain extent.
Acknowledgments
This work is supported by Science and Technology Project of State Grid corporation of China (Research on key process technology of 1700V SiC MOSFET device, No. 5500-202058403A-0-0-00).

References
[1] Sheng Kuang, Ren Na, Xu Hongyi. A Recent Review on Silicon Carbide Power Devices Technologies[J]. Proceedings of The Chinese Society for Electrical Engineering, 2020(6).
[2] Kang I H, Seok O, Moon J H, et al. Design and Fabrication of 1.2 kV/10A 4H-SiC Junction Barrier Schottky Diodes with High Current Density[J]. Transactions on Electrical and Electronic Materials, 2021.
[3] Baliga B J. Fundamentals of Power Semiconductor Devices || Introduction[J]. 2019, 10.1007/978-3-319-93988-9(Chapter 1):1-22. P.G. Clem, M. Rodriguez, J.A. Voigt and C.S. Ashley, U.S. Patent 6,231,666. (2001)
[4] Chante J P, Locatelli M L, D Planson, et al. Silicon carbide power devices[C]// International Semiconductor Conference. IEEE, 2006.
[5] Baliga B J. Advanced Power Rectifier Concepts[M]. Springer US, 2009.