Development of >10kv 4H-SiC SBD junction extension termination

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Abstract. 10kV 4H-SiC JBS diodes with various junction extension terminations have been experimentally realized. The protection efficiencies of single JTE and modulation JTE terminations were investigated by means of numerical simulations. The JTE dose window to achieve the high protection efficiency has been enlarged, which indicates the robustness to the deviation of effective JTE dose and SiO_2/SiC interface charge. The samples with the single JTE, two-zone JTE, three-zone JTE and improved three-zone JTE terminations were fabricated. With the modulation JTE, the typical breakdown voltage of 13.5 kV corresponding to protection efficiency of 95% has been achieved, and the various JTE terminations were compared and discussed.

Keywords: 4H-SiC; power device; termination; JTE.

1 Introduction

Because of the superior material properties, 4H silicon carbide (4H-SiC) are regarded as an ideal semiconductor for high temperature, high power, high radiation conditions. It is a better candidate for high power applications. In ultrahigh voltage power converter system, PiN diode is a good choice because of its lower leakage current and higher conduction current density, but the forward voltage of PiN diode is higher than SBD (Schottky Barrier Diode) diode, and it also be limited by forward voltage degradation due to the material quality. SBD diode has been commercialized before PiN diode because of lower forward voltage, and the reliability of Schottky diode is not limited by the forward voltage drift.

In most of the high voltage SiC SBD, the termination of floating guard ring termination (FGR) was widely used because that FGR can be formed together with active region [1]. However the protection efficiency of FGR is not enough for the ultrahigh voltage SiC power devices [2,3]. Junction termination extension (JTE) was widely used because of high termination efficiency, however the protection efficiency of JTE is limited by interface charge [4,5]. To eliminate the negative influence of interface charge to the protection efficiency, multiple implantations must be done [6,7,8].

In our previous research, a SiC SBD diode with a breakdown voltage higher than 10kV has been reported [1]. In this paper, we will report a 10 kV 4H-SiC diode with JTE termination. The conduction current more than 10A has been reached by the technology and epitaxial growth process optimization. The simulations by finite elements method have been performed to study the optimization of single

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JTE and modulation JTE termination, the protection efficiency have been compared [9,10]. After a brief description of implantation mask design and technological process, single JTE, modulation JTE, two-zone JTE, three-zone JTE and three-zone JTE with rings between JTEs have been fabricated, and all the diode characterizations will be presented for both forward and reverse modes. The relationships between the design of JTE and protection efficiency have been discussed.

2 Simulation

Simulations by finite elements method using SILVACO ATLAS TCAD software [11] have been performed to determine parameters of the drift region such as thickness and doping without considering the termination. The models of Shockley-Read-Hall (SRH) and Auger recombination model, avalanche generation, bandgap narrowing, impact ionization, incomplete ionization have been used for breakdown analysis of 4H-SiC JTE termination. For a theoretical blocking voltage of 14300V, the parameters: W_{n-}= 120 µm and N_d= 6×10^{14} cm^{-3} have been chosen.

The JTE termination performs a higher efficiency than FGR termination, but the electric field distribution is sensitive to the JTE dose. In this work, the 2-D device simulation was performed. A SBD with a single zone JTE and length of 600 µm was simulated. In the Fig.1 SBD protected by single zone JTE has been presented, and the electric field distribution of the termination has been simulated. Fig.3 shows the simulated breakdown voltage of the SBD diodes with the single zone JTE as a function of JTE dose. The maximum breakdown voltage of 12 kV corresponding to efficiency of 84% has been reached with the JTE dose of $8\times10^{12}cm^{-2}$. There is not enough tolerance to the deviation of the effective JTE dose, considering the influence of interface state density on the protection efficiency, the single JTE protection is not the best solution.

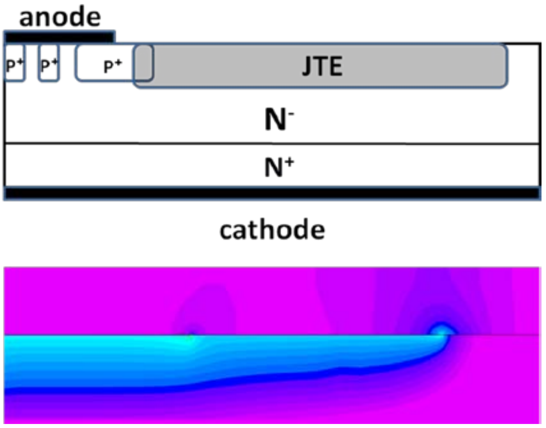

Figure 1. Distribution of electric field for reverse bias 10 kV for single JTE termination.

The modulation JTE termination was also simulated to determine the implantation doses and mask parameters(fig.2). The JTE2 dose is modulated by JTE1 dose, and the JTE1 dose has been fixed to $5.8\times10^{12}cm^{-2}$, and 20 JTE1 rings has been used to modulate the JTE2 dose. The V_{br} as a function of JTE2 dose was simulated, and the results were compared with single JTE in Fig.3. The maximum V_{br} is 14kV corresponding to efficiency of 98%, and at the JTE dose between 4×10^{12} cm^{-2} and 8×10^{12} cm^{-2} the V_{br} is higher than 12 kV. The modulation JTE provides a wider optimum JTE doping window than single zone JTE.

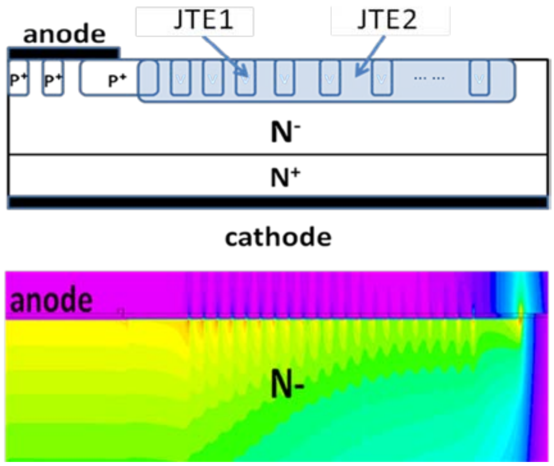

Figure 2. Electric field distribution for reverse bias 10 kV for modulation JTE termination.

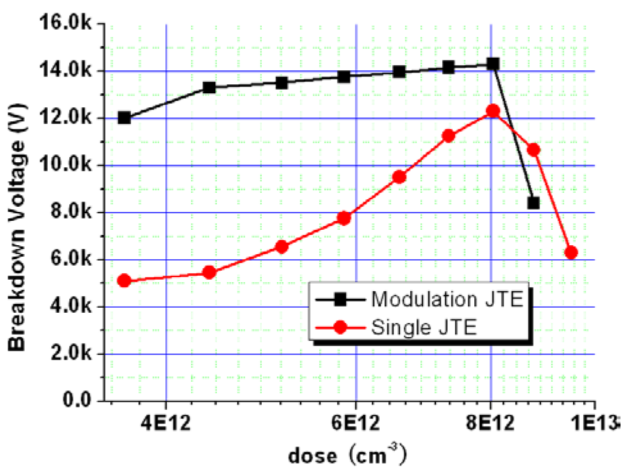

Figure 3. Comparison of the JTE dose optimization of single JTE and modulation JTE termination.

3 Fabrication

The 10 kV 4H-SiC JBS diodes were fabricated on n^+ type conductivity 4H-SiC substrates. An epitaxial N^- drift layer was grown on n-type substrates with a doping concentration of 6×10^{14} cm^{-3}, and the epitaxial thickness was 120 μm to obtain a high breakdown voltage. Six different termination structures with length of 600 μm have been designed as shown in Fig.4. The termination T1 and T2 are single JTE termination with different JTE doses. The termination T3 is modulation JTE termination. 40 rings has been used, and by adjusting the width and spacing of rings the dose of JTE termination is modulated. Termination T4 is double-zone JTE structure with JTE1 and JTE2 doses, and termination T5 is three-zone JTE structure with JTE1+JTE2, JTE1 and JTE2 doses. For the termination T6 several rings have been used at the junction of each JTE on the base of termination T5.

The 4H-SiC JBS diodes were fabricated on n^+ type 4H-SiC substrates with a 120μm low doped epitaxy (fig.5). In this research, our technology and epitaxial growth process has been optimized to realize the large SBD diode with active area of 0.5 cm^2, and a series of small diodes were fabricated to determine the optimal termination parameters. The active JBS P^+ grids, JTE1 and JTE2 were implemented by multiple Al implantations with a maximum energy of 320 keV. The doses of JTE1 and JTE2 implantation were 6.0×10^{12} cm^{-2} and 9.0×10^{12} cm^{-2} respectively. The ion implantation activation annealing was performed at 1650^{o}C for 30 min in Ar. After that 200 nm thick field SiO_2 and 300 nm thick SiN were deposited on the surface as the passivation layer. After the etching of the passivation layer, the anode and cathode contacts were formed by Ni. The Schottky contact annealing was carried out at 600^{o}C for 10 min.

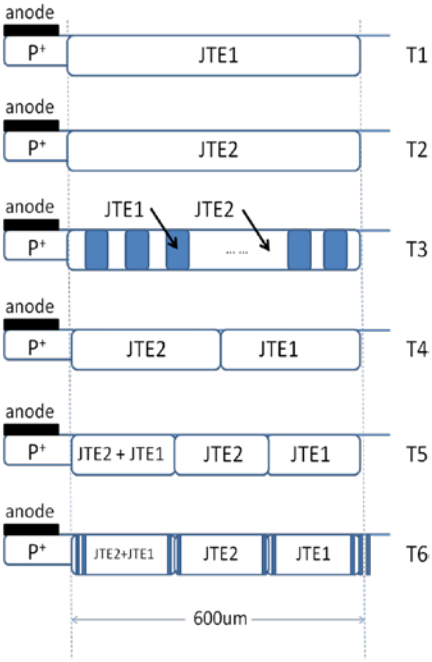

Figure 4. JTE terminations design of 10 kV JBS diode on 4H-SiC.

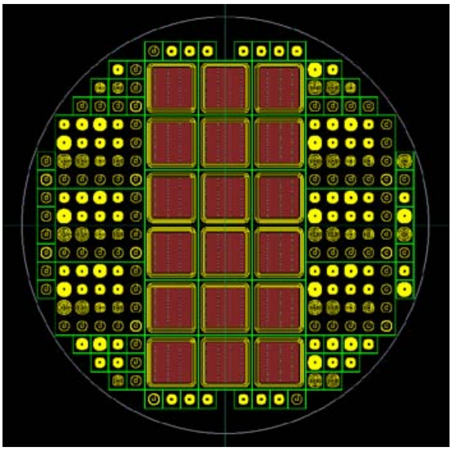

Figure 5. Fabricated 10 kV 4H-SiC JBS diodes

4 Characterization

4.1 Reverse characteristics

Diode reverse performance has been characterized up to a leakage current of 100 µA. Table.1 shows the typical breakdown voltages for the different terminations. For the single JTE termination, the V_{br}

of T1 and T2 are 10 kV and 7 kV which agree well with the simulation results. The V_{br} of T3 is 13.5kV corresponding to efficiency of 94%. The protection efficiency of modulation JTE termination is higher than single JTE termination. The protection efficiency of single JTE is not enough for the protection higher than 10 kV, and the protection efficiency is sensitive to the JTE dose and the interface state density. The optimum JTE doping window of modulation JTE is wider than single JTE, this means that modulation JTE is advantageous when it comes to device, the drawback is that it requires two separate implantations which require extra mask and higher cost. The breakdown voltage of two-zone JTE T4 and three-zone JTE termination are 11 kV and 12 kV. The protection efficiency of T5 is higher than T4, and with several rings at the junction of JTEs, the protection efficiency of T6 is higher than T5. In this design, the three-zone JTE termination is achieved by ion implantation superposition, the implantation conditions were not optimal. If three-zone JTE termination was chieved by three time implantations, the protection efficiency will increase, but the fabrication cost will increase too. The rings between zones of JTE can decrease electric field peak, therefore the breakdown voltage has been increased to 13 kV.

Table 1. Typical breakdown voltage for different termination

termination	T1	T2	T3	T4	T5	T6
Typical breakdown voltage (V)	10 k	7 k	13.5 k	11 k	12 k	13 k
Protection efficiency	70%	50%	95%	77%	84%	91%

4.2 Forward characteristics

The diode has been forward characterized in room temperature. To limit the device auto-heating, these characteristics have been obtained in pulse mode with a pulse width of 200 µs. At 10 A, the voltage drop is lower than 4.0 V. A threshold voltage lower than 1.2 V has been achieved. Fig.6 shows the typical forward characteristics.

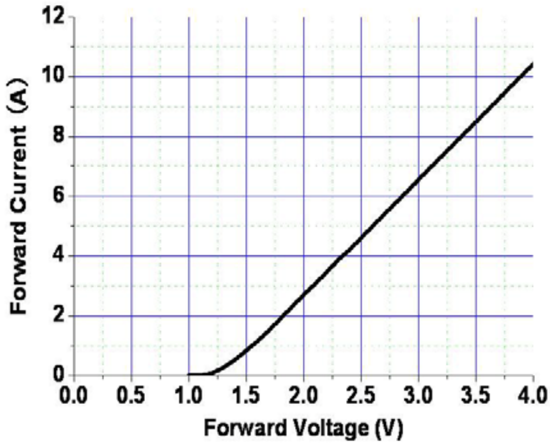

Figure 6. Measured forward I-V characteristic for 10 kV 4H-SiC JBS diodes (active area = 0.5 cm^{-2})

5 Conclusion

The protection efficiencies of the single JTE and modulation JTE terminations have been simulated. The modulation JTE performs a higher JTE dose windows to achieve a ultrahigh voltage than the single JTE. 10 kV 4H-SiC JBS diodes have been fabricated. According to the simulation results an epitaxial N^- drift layer (120 µm, 6×10^{14} cm^{-3}) was grown on n^+ type conductivity 4H-SiC substrates. The diodes protected by single JTE, modulation JTE, two-zone JTE, three-zone JTE and three-zone JTE with rings between JTEs have been fabricated with two implantations. Reverse and forward characterizations were performed at room temperature. With modulation JTE the breakdown voltage can exceeds 13.5kV corresponding to a protection efficiency of 95%, and the rings added between JTE zones can improve the protection efficiency of three-zone JTE termination. The forward voltage drop at a current of 10A is less than 4.0 V. The threshold voltage is lower than 1.2 V.

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