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Study and Optimization of Field Limiting Rings for 10kV SiC Insulated Gate Bipolar Transistor

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Abstract

A 10kV-level silicon carbide (SiC) insulated gate bipolar transistor (IGBT) with field limiting rings (FLRs) is designed and simulated with Sentaurus TCAD, the detailed optimization method and comparisons are presented in this paper. Linearly varying spacing between rings is introduced to SiC IGBT and adjustment is performed on width of rings, the final structure achieves a breakdown voltage over 12kV with a termination length of **164.5 μ m**, which is 69.93% lower than that of conventional structure with a fixed ring spacing. Moreover, the final design can decrease the sensitivity to the interface charges, the tolerance to positive surface charges exceeds **8 $\times$ 10¹¹cm⁻²**, which is 3.5 times that of the conventional structure. Besides, double pulse measurements prove no degradation of conduction and switching characteristics.

Keywords: silicon carbide (SiC), insulated gate bipolar transistor (IGBT), field limiting ring (FLR), breakdown voltage, interface charge.

1 Introduction

SiC material is considered as an ideal substitute for silicon material because of large breakdown field, high thermal conductivity, and low permittivity, and SiC products can be used in high-temperature, high-frequency and high-power applications. Among all SiC power devices, SiC IGBT has attracted much attention in recent years due to its low on-resistance, easy gated control and fast switching, it is a suitable choice for ultra-high voltage switch [1, 2].

To reduce electric field crowding at the corners and make full use of the blocking capability of SiC materials, edge terminations should be carefully designed for SiC devices [3]. To date, junction termination extension (JTE) and field limiting ring (FLR) are two main termination technologies for SiC IGBT, and the latter is considered more suitable because rings are formed by ion implantation together with the P-well, larger fabrication margin of doses can be achieved and no additional process steps are required. However, to ensure high breakdown voltage, the width and spacing of each ring need to be carefully selected so that the electric field is uniformly distributed on the different rings, the design of the FLR termination is complex and few literatures are for the FLR of SiC IGBT [4–6].

To obtain IGBT for ultra-high voltage ($> 10\text{kV}$) power system, the design of the FLR termination is carried out in this paper, Sentaurus TCAD software is used for numerical simulations [7]. To resist process variations and interface charges, the design goal is set to 12kV , and the length of termination region is carefully optimized for small area consumption. Besides, the influence of termination structure on switching characteristics and conduction characteristics is also studied.

2 Device Description and Simulation Setup

The schematic cross-sectional view of SiC IGBT with FLR termination is shown in Fig. 1, device parameters are also given in the figure. The n-channel structure with P-type substrate is selected to achieve low switching loss [8], $100\mu\text{m}$ drift layer is doped to $1 \times 10^{15}\text{cm}^{-3}$ on the substrate for a breakdown voltage of 10kV , the implant dose of rings and P-well is $4 \times 10^{13}\text{cm}^{-2}$. The number of rings is denoted as n , the width of the i -th ring is denoted as W_i , and the spacing between the i -th ring and the $(i-1)$ -th ring is denoted as S_i .

All simulations are completed in Sentaurus TCAD simulator. The simulation of the recombination process includes Shockley-Read-Hall (SRH) mechanism and Auger mechanism, carrier lifetimes are affected by temperature and doping. The Okuto-Crowell model is used to describe the dependence of the impact ionization coefficients on the avalanche generation. For carrier mobility, the Masetti model describes the effect of doping and the Canali model describes the effect of temperature, the velocity saturation effect and interface degradation effect are also considered. The influence of temperature and doping on the energy bandgap and the incomplete ionization effect of dopants are also added [9].

Fig. 1 The cross-section of SiC IGBT with FLR termination.

3 Results and Analysis

For the FLR termination, increasing the number of rings can increase the number of electric field peaks, thereby increasing the breakdown voltage, but it will also consume more chip area, so it is important to improve the efficiency of each ring. Ring-by-ring adjustment was proposed for FLRs in power diodes [10], but this method is not suitable for high-power SiC IGBT. To reduce the number of parameters, W_i and S_i usually remain the same for FLRs in SiC IGBTs, and this simplest FLR termination is called the conventional filed limiting rings (Con-FLRs) [11]. In order to study the area utilization efficiency of this design, the ring width is fixed to $5 \mu\text{m}$ and the ring spacing is fixed to $3 \mu\text{m}$, the relationship between n and breakdown voltage is shown in Fig. 2.

When the number of rings is close to 50, increasing n cannot continue to improve the breakdown voltage, and the maximum breakdown voltage is lower than 12kV, the blocking capability of the drift layer is not fully utilized. In order to further study the dependence of blocking characteristics on W_i and S_i , the dependence of maximum breakdown voltage on ring spacing is plotted in Fig. 3 for three ring widths, and it can be seen that the maximum breakdown voltage will first increase and then decrease with the increase of the ring spacing. To explain this trend and further explore the influence of structure parameters on electric field distribution, two devices with different Con-FLRs (IGBT A: $W_i \equiv 5 \mu\text{m}$, $S_i \equiv 2.6 \mu\text{m}$ and IGBT B: $W_i \equiv 5 \mu\text{m}$, $S_i \equiv 3 \mu\text{m}$) are selected, and the surface electric field distribution (along dashed line AA' in Fig. 1) at breakdown is shown in Fig. 4. When n increases from 60 to 80, the breakdown voltage of IGBT B remains at 11650V, and the breakdown voltage of IGBT A rises from 10290V to 12160V. From Fig. 4(a), at $n = 60$, the breakdown voltage of IGBT B is higher because the electric field near the main junction is higher. From Fig. 4(b), at $n = 80$, the breakdown voltage

Fig. 2 Changes of the breakdown voltage as a function of the number of rings for SiC IGBTs with Con-FLRs ($W_i \equiv 5\mu\text{m}$, $S_i \equiv 3\mu\text{m}$).

of IGBT A is higher because the electric field decreases more slowly from the inside to the outside and the distribution is more uniform.

Fig. 3 Changes of the maximum breakdown voltage as a function of the ring spacing for SiC IGBTs with different Con-FLRs designs.

It can be concluded that the electric field distribution has a strong dependence on the ring width and ring spacing, so the breakdown voltage of SiC IGBT with Con-FLRs is very sensitive to size. And from Fig. 3, to obtain a high breakdown voltage and a wide tolerance to variations, the ring

Fig. 4 Surface electric field distribution of two SiC IGBTs with different Con-FLRs at breakdown, (a) $n = 60$, (b) $n = 80$.

width needs to be large enough, which means long termination region. Take $W_i \equiv 5\mu\text{m}$, $S_i \equiv 2.6\mu\text{m}$ as an example, at least 72 rings are needed to achieve a breakdown voltage over 12kV, and the total length of the termination region is $547\mu\text{m}$, which is more than 5 times the thickness of the drift layer.

When n-channel SiC IGBT with FLRs is biased, the depletion region extends from the main junction to the termination region, negative charges are left in the rings. These negative charges can attract positive charges and repel negative charges, which helps to widen the space charge region laterally and reduce the electric field at the main junction [12]. According to semiconductor physics analysis, the electric field near the main junction is the electric field generated by the collector-emitter voltage minus the electric field generated

by the negative charges, and electric field in the outermost region is only generated by the negative charges. So in order to obtain a uniformly distributed electric field, it is desirable to embed more charges near the main junction and fewer charges in the outermost region [13]. And for Con-FLRs, it can be seen from Fig. 4 that the electric field on the two sides is much higher than that of the middle ring, which limits the optimization of electric field distribution. One way to improve the charge distribution is linearly varying FLRs (LV-FLRs), W_i still remains the same, and S_i increases linearly from the inner side to the outer side. This idea is common in SiC power diodes, this article introduces it to SiC IGBTs and the equation description is

$$S_i = S_1 + \Delta \times (i - 1) \quad (\Delta > 0) \quad (1)$$

Similarly, the number of rings needs to be optimized for LV-FLRs to balance the chip area and breakdown voltage. Considering the lateral straggle effect of P+ implants [14], S_1 is set to $1\mu\text{m}$, Δ is set to $0.1\mu\text{m}$ in this paper, and the breakdown voltage versus the number of rings under different ring widths is shown in Fig. 5.

Fig. 5 Changes of the breakdown voltage as a function of the number of rings for SiC IGBTs with LV-FLRs ($S_1 \equiv 1\mu\text{m}$, $\Delta \equiv 0.1\mu\text{m}$).

Increasing W_i can improve the optimal blocking capability, but it will also result in more rings required to reach the target breakdown voltage, and the maximum breakdown voltage of SiC IGBT with LV-FLRs and the minimum number of rings required to achieve a breakdown voltage of 12kV versus ring width are plotted in Fig. 6. To achieve a breakdown voltage of 12kV, the minimum W_i is $2\mu\text{m}$, and when W_i is reduced from $5\mu\text{m}$ to $2\mu\text{m}$, the shortest length of the termination region is reduced from $318\mu\text{m}$ to $164.5\mu\text{m}$, which is

48.27% optimized. And compared with Con-FLRs, the length is optimized by 69.93% and the number of rings is optimized by 51.39%.

Fig. 6 Changes of the blocking characteristics as a function of the ring width for SiC IGBTs with LV-FLRs.

The surface electric field distribution of different structure at breakdown is shown in Fig. 7. The electric field distribution of SiC IGBTs with LV-FLRs is more uniform as expected, so fewer rings are required to withstand the same voltage. As with the Con-FLRs, reducing the ring width can reduce the charge density, so the electric field generated by the negative charge in the junction termination region will be reduced, which means that the electric field near the main junction is less suppressed. The inner rings of the termination region is more efficient, but the high electric field near the main junction will also cause the maximum breakdown voltage to decrease.

For SiC power devices, passivation is usually implemented by thermal oxidation and SiO₂ deposition, and fixed charges can be introduced into the SiC/SiO₂ interface during the fabrication process [15]. Fig. 8 compares the blocking capability of SiC IGBTs with different edge terminations under the effect of interface charge. The positive charges can cancel the depleted acceptors in the termination region, resulting in a significant drop in breakdown voltage. To achieve a breakdown voltage over 10kV, the tolerance to positive surface charge is $2.4 \times 10^{11} \text{ cm}^{-2}$ for IGBT with Con-FLRs and $8.3 \times 10^{11} \text{ cm}^{-2}$, $4.9 \times 10^{11} \text{ cm}^{-2}$, $5.5 \times 10^{11} \text{ cm}^{-2}$, $4.6 \times 10^{11} \text{ cm}^{-2}$ for LV-FLRs with the ring width of 2 – 5 μm . The sensitivity to interface charges is greatly reduced by adopting LV-FLRs, and smaller W_i can achieve a higher tolerance due to the lower embedded negative charge density.

To fully evaluate the performance of field limiting rings, the circuit for double pulse measurement is shown in Fig. 9(a), the turn-on waveforms and turn-off waveforms are given in Fig. 9(b) and Fig. 9(c) respectively. The difference in switching time and on-voltage drop of different structures is negligible due to the conductivity modulation effect, so the optimization of the

Fig. 7 Surface electric field distribution of SiC IGBT with different termination structures at breakdown.

Fig. 8 Dependence of breakdown voltage on interface charge density.

blocking capability will not affect the conduction characteristics and dynamic characteristics.

4 Conclusion

SiC IGBT with high blocking voltage (10kV for 100 μ m drift layer) is proposed and designed in this paper. Field limiting ring technique is applied, the novel linearly varying FLRs is introduced and compared with conventional FLRs, and the new termination structure can increase the tolerance to positive interface charges by 3.5 times and reduce the termination length by 69.93%. Finally, the total length is only 164.5 μ m to achieve a breakdown voltage over

Fig. 9 (a) Circuit for measuring dynamic characteristics of SiC IGBT. (b) Simulated turn-on waveforms. (c) Simulated turn-off waveforms.

12kV and the tolerance to positive surface charges is $8.3 \times 10^{11} \text{ cm}^{-2}$ to ensure a breakdown voltage over 10kV. Double pulse measurements prove that the optimization of edge termination will have little effect on the conduction characteristics and switching characteristics, so linearly varying FLRs is attractive and promising for high-voltage SiC IGBTs.

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