LETTER

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A novel high-voltage trench gate insulated gate bipolar transistor with diffusion remnant layer

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Abstract: A novel high-voltage trench gate insulated gate bipolar transistor with diffusion remnant (DR) layer (DR-IGBT) is proposed in this letter. The DR layer in the emitter side which is formed by grinding after ultra-deep N^+ diffusion helps to stored the carrier and improves the on-state voltage drop ($V_{ce(SAT)}$). The DR-IGBT has a better trade-off between the breakdown voltage (BV) and $V_{ce(SAT)}$ than the carrier stored trench bipolar transistor (CSTBT). The doping profile of diffusion remnant layer makes the junction of the p-base/DR layer nearly linearly graded junction, which does not decline the BV too much. The depth of the diffusion remnant layer and N^+ diffusion layer less impacts BV and $V_{ce(SAT)}$ unless the diffusion depth is reduced.

Keywords: IGBT, DR-IGBT, diffusion remnant layer, breakdown voltage, light punch-through

Classification: Electron devices, circuits, and systems

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1 Introduction

For the past few years, the performance of Insulated Gate Bipolar

Transistor (IGBT) has been significantly improved, owing to the appearance of some new technologies, such as trench gate, carrier stored (CS) [1], and enhanced planer (EP) [2], for the emitter side and field stop (FS) [3], Soft Punch-Through (SPT) [4], and Light Punch-Through (LPT) [5] for the collector side. As an advanced trench gate IGBT, the CSTBT with LPT structure incorporates many innovations and demonstrates excellent overall performance [6]. The LPT structure makes it possible to realize a thinner N^- drift layer, which results in a lower $V_{ce(SAT)}$. The CS layer act as the hole barrier to improve the conductivity modulation, hence realizing a low $V_{ce(SAT)}$. However, the BV of the device is degraded severely due to strong electric field curvature at the junction of the P base/CS layer. In this letter, a high-voltage IGBT with a Diffusion Remnant (DR) layer (DR-IGBT) is proposed. The DR layer, which is formed by grinding the N^+ high temperature deep junction diffusion layer, replaces CS layer and can be used to overcome or mitigate the unfavorable factor. Furthermore, the new structure is easy to realize with no additional processes.

2 Devices structure and analysis

Figure 1 shows schematic cross-section of the proposed cell structure of high voltage trench gate IGBT. It can be seen, compared with the case of CSTBT, the structure of proposed IGBT is completely the same. However, the doping profile of the emitter side carrier stored layer is much different because of their different forming method.

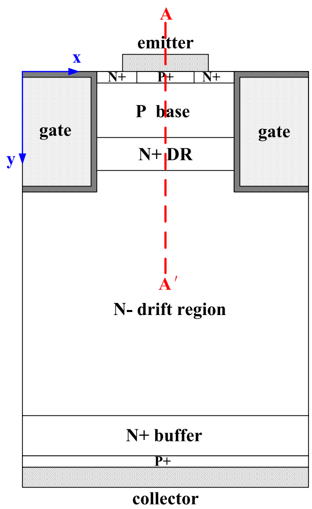

Fig. 1. Schematic cross-section of the proposed IGBT structure.

The DR-IGBT starts from the high temperature ultra-deep phosphorus diffusion at the both sides of the wafer. The topside diffusion layer is ground to retain a few microns as the DR layer and the trench gate MOSFET cells are fabricated. Then, the wafer is ground at the back side and residual part of the diffused layer is well controlled to form the N^+ buffer. At last, the transparent P^+ collector is fabricated.

The junction of P base layer/DR layer can be regarded as linearly graded junction. And its doping concentration is slightly higher than that of the N^- drift layer, which acts as the CS layer and is used to reduce the

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on-state resistance. While the CS layer of CSTBT is formed by ion implantation and diffusion, the junction of P base layer/CS layer can be regarded as the abrupt junction. The buffer layer is also a residual part of the diffused layer formed by the ultra-deep diffusion at the beginning of the process. The depth of topside DR layer and back side N^+ buffer is easy to control through grinding and polishing. No additional implantation and diffusion process will enable the total process simple and low cost.

3 Results and discuss

The main structural dimensions of the two structures are same except the concentration of CS (or DR) layers. In the numerical simulations, the trench depth of the two structures and the interval of the trenches are both 6 μm. The peak doping concentration of CS layer of CSTBT is set to be 5E15 cm^{-3}, 1E16 cm^{-3}, and 5E16 cm^{-3}, respectively. But after the topside structures are finished, the doping profiles along A-A′ line are shown in Fig. 2. The doping profile along A-A′ line of DR-IGBT with the 80 μm N^+ diffusion layer is also shown in Fig. 2. The lifetimes of electron and hole are both set to be 10 μs.

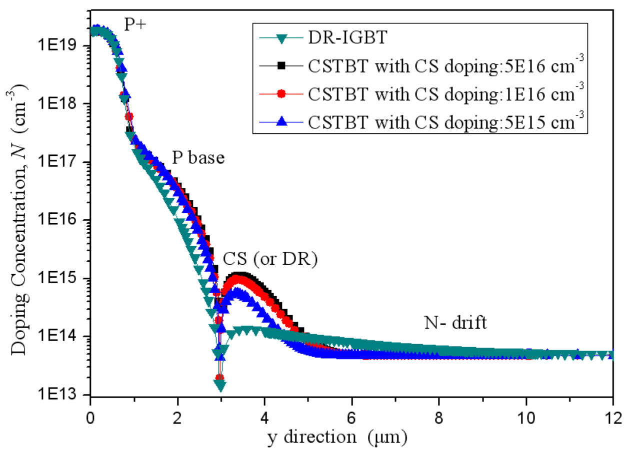

Fig. 2. The doping profiles along A-A′ line of DR-IGBT and CSTBT in Fig. 1.

Figure 3 shows the simulation results of forward conduction I-V characteristics at V_{ge}=15 V for the DR-IGBT and CSTBT. Under the collector current density J_{ce}=100 A/cm^2, the $V_{ce(SAT)}$ of the DR-IGBT equals to 1.54 V. The $V_{ce(SAT)}$ of CSTBT are 1.4 V, 1.50 V and 1.62 V with the CS layer doping varying from 5E15 cm^{-3} to 5E16 cm^{-3}. When the J_{ce}=200 A/cm^2, the $V_{ce(SAT)}$ of the CSTBT increase to 1.78 V, 1.90 V and 2.06 V, respectively. However, the $V_{ce(SAT)}$ of the DR-IGBT is only 1.87 V under this collector current density. Under the high collector current density, the slope rate of the I-V curve for the DR-IGBT is larger than that of CSTBT.

The optimizing doping profile of DR layer leads to lower $V_{ce(SAT)}$ under the high current density. As can be seen from Fig. 2, comparison of the doping profile of CS layers, because of the ultra-deep diffusion, the peak doping concentration of DR layer is less than any of the CS layers, but the total N^+ carrier numbers of DR layer which distributed in a longer range between P base and N^- drift region are not less than those of CS layers. So

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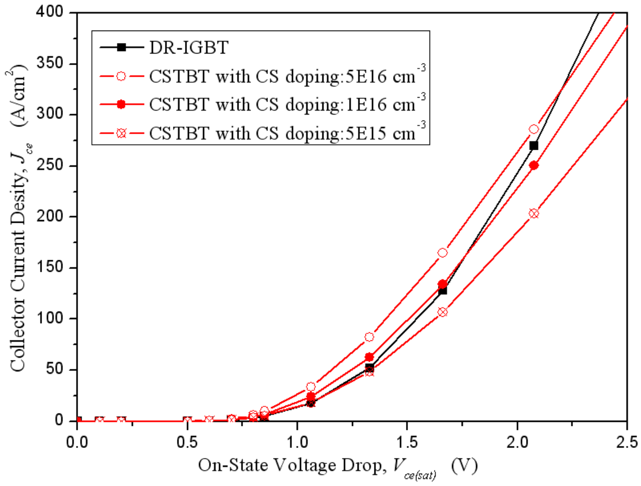

Fig. 3. Simulation result of forward voltage drop of DR-IGBT and CSTBTs.

the DR layers can restrict the movement of more holes to P base, and be "stored" in the DR layer, which lower the $V_{ce(SAT)}$ under the high collector current density [1].

The simulation results of forward blocking I-V characteristics for DR-IGBT and CSTBTs are shown in Fig. 3. The BV value of DR-IGBT is 2054 V. And the BV values of CSTBTs are 2019 V, 1962 V, 1862 V, respectively. The BV of the DR-IGBT has a distinct advantage compared with the CSTBTs. Fig. 3 and Fig. 4 indicate that the DR-IGBT has a better trade-off between BV and $V_{ce(SAT)}$.

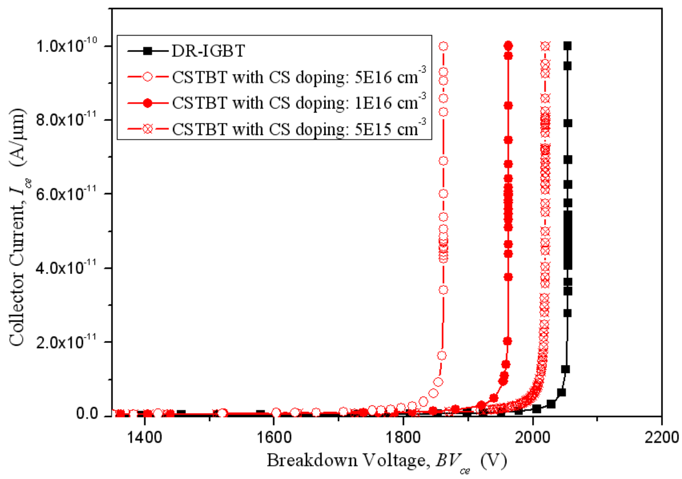

Fig. 4. Simulation results of forward blocking I-V characteristics of DR-IGBT and CSTBTs.

The BV of an IGBT is mainly determined by the reverse biased characteristics of the junction that consists of the p-base and the n-drift junction. For the DR-IGBT and CSTBTs, the reverse junction consists of the P-base and the CS layer (or DR layer). The doping profile of the CS layer and DR layer inevitably lead to the BV drop.

The electrical field and potential for abrupt and linearly graded junctions are determined from the solution of Poisson's equation. The BV for linearly graded junction can be expressed as [7]:

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$$V_B = 2E_m W/3 = \frac{4E_m^{3/2}}{3}\sqrt{\frac{2\varepsilon}{q}}\left(\frac{1}{\sqrt{a}}\right) \tag{1}$$

Where E_m is the maximum field. And is the impurity gradient.

While the BV for abrupt junction can be expressed as [7]:

$$V_B = E_m W/2 = \left(\frac{\varepsilon E_m^2}{2q}\right)\left(\frac{1}{N_B}\right) \tag{2}$$

Where N_B is the doping concentration.

The E_m has a fixed value. Then we obtain from equation (1) and (2) that $V_B \sim N_B^{-1}$ for abrupt junctions and $V_B \sim a^{-0.5}$ for linearly graded junctions. The reverse bias junction of CSTBT resembles abrupt junction while the junction of DR-IGBT is just like linearly graded junction. The impurity gradient of the junction is very small and has little effect on the BV. Therefore, the higher BV is obtained from the DR-IGBT.

Figure 5 shows the simulation results of the depth of DR layer on the BV of the DR-IGBT with the depth of the N^+ diffusion layer varying from 80 μm to 170 μm. It can be seen that the higher the depth of the N^+ diffusion layer, the higher the BV of DR-IGBT get. Moreover, the BV hardly declined even the DR layer increased for the structure with higher depth of diffusion layer. On the other hand, the BV little decreases as long as the depth of the DR layer is not more than 8 μm. But with the decreasing of the depth of the N^+ diffusion layer, the BV decline much faster along with the increasing of the depth of the DR layer. This indicates the impurity gradient of DR layer increases with the decreasing of the depth of the N^+ diffusion layer.

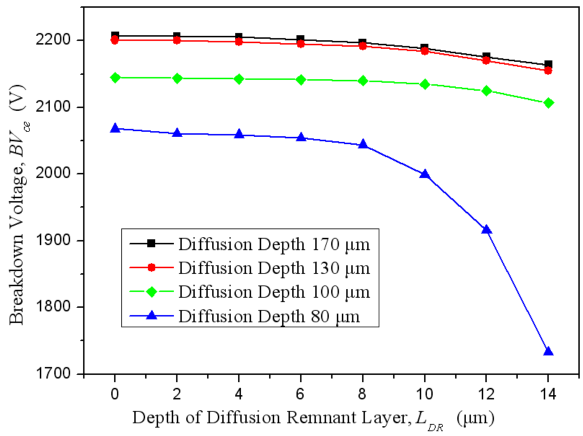

Fig. 5. The influences of the DR layer on the BV of DR-IGBT.

Figure 6 shows the simulation results of the depth of DR layer on the $V_{ce(SAT)}$ of the DR-IGBT with the depth of the N^+ diffusion layer varying from 80 μm to 170 μm. It can be observed that with the depth of N^+ diffusion layer decreasing from 170 μm to 80 μm, the $V_{ce(SAT)}$ significantly decline and under the same N^+ diffusion layer condition, the $V_{ce(SAT)}$ also decline with the increase of the DR layer. For the structure of lower N^+ diffusion layer, the $V_{ce(SAT)}$ declines more remarkably with the increase of the DR layer. The Fig. 5 and Fig. 6 indicate that the curves of $V_{ce(SAT)}$ versus the depth of DR layer have trends similar to those of BV.

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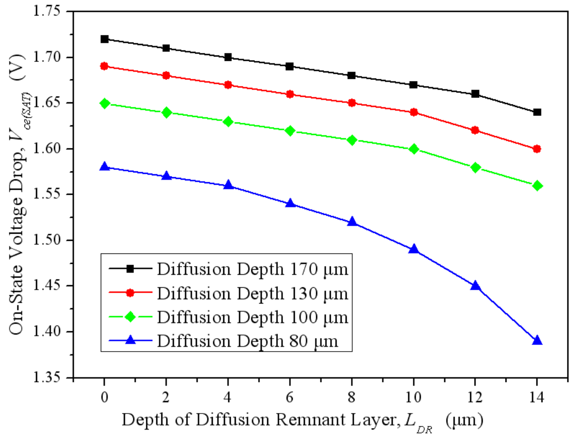

Fig. 6. The influences of the DR layer on the $V_{ce(SAT)}$ of DR-IGBT.

4 Conclusion

A high-voltage trench gate DR-IGBT is proposed in this letter. The diffusion remnant layer in the emitter side which is formed by grinding after ultra-deep N^+ diffusion helps to stored the carrier and improve the $V_{ce(SAT)}$. The DR-IGBT has a better trade-off between the BV and $V_{ce(SAT)}$ than the CSTBT. The doping profile of remnant layer make the junction that consists of the p-base and the diffusion remnant layer just like linearly graded junction, which does not decline the BV too much compared with the CSTBT. The BV and $V_{ce(SAT)}$ decline faster along with the decreasing of the depth of the N^+ diffusion layer or increasing of the depth of the DR layer.

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