SiC gate-controlled bipolar field effect composite transistor with polysilicon region for improving on-state current

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A novel silicon carbide gate-controlled bipolar field effect composite transistor with polysilicon region (SiC GCBTP) is proposed. Different from the traditional electrode connection mode of SiC vertical diffused MOS (VDMOS), the P+ region of P-well is connected with the gate in SiC GCBTP, and the polysilicon region is added between the P+ region and the gate. By this method, additional minority carriers can be injected into the drift region at on-state, and the distribution of minority carriers in the drift region will be optimized, so the on-state current is increased. In terms of static characteristics, it has the same high breakdown voltage (811 V) as SiC VDMOS whose length of drift is 5.5 μm. The on-state current of SiC GCBTP is 2.47×10^{-3} A/μm ($V_{\rm G}=10$ V, $V_{\rm D}=10$ V) which is 5.7 times of that of SiC IGBT and 36.4 times of that of SiC VDMOS. In terms of dynamic characteristics, the turn-on time of SiC GCBTP is only 0.425 ns. And the turn-off time of SiC GCBTP is similar to that of SIC insulated gate bipolar transistor (IGBT), which is 114.72 ns.

Keywords: SiC power device, on-state current, bipolar, vertical diffused MOS (VDMOS), insulated gate bipolar transistor (IGBT)

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1. Introduction

With the constant improvement of circuit performance, the performance of silicon-based devices gradually cannot meet the requirement of the circuit, and the situation is more obvious in power semiconductor devices. In wide bandgap semiconductor materials, silicon carbide (SiC) has begun to show great advantages in power semiconductor devices by virtue of many excellent properties (high blocking voltage capability, high temperature operation and high switching frequencies).[1–3] The breakdown voltage of SiC power device has developed to several kV in recent years.[4] Insulated gate bipolar transistor (IGBT), as a substitute for bipolar junction transistor (BJT), came out in the 1980s. It combines MOSFET and BJT together and controls BJT to turn on. IGBT has lower forward voltage drop, which is generally used in medium and high power circuits.[5,6] If SiC and IGBT can be well combined, we will get device with excellent performance, such as high current conduction, low power consumption and operation at higher temperatures.[7] In recent years, we have been able to obtain SiC IGBT, which can well replace SiC MOSFET at high voltage in low-frequency switching applications.[8] And P-channel IGBT has been widely used because its performance is better than that of N-channel IGBT,[9] but the SiC P-type substrate required by P-channel SiC IGBT is very difficult to manufacture.[10,11]

Through previous studies, it can be found that this problem is solved by SiC GCBT. The P+ region of P-well is connected with the gate in SiC GCBT, which can effectively introduce two carriers into the device, achieving the characteristics of bipolar device without SiC P-type substrate.[12] Although it can improve the on-state current, the disadvantages are also very obvious. For example, the reverse current is very high, which is much larger than the on-state current at the same voltage of the gate.

In order to solve this problem and further increase the on-state current, a novel SiC gate-controlled bipolar field effect composite transistor with polysilicon region (SiC GCBTP) is proposed, which can effectively increase the on-state current and reduce the reverse current. When both $V_{\rm G}$ and $V_{\rm D}$ are 10 V, the on-state current of SiC GCBTP is 2.47×10^{-3} A/μm, which is 36.4 times of that of traditional SiC vertical diffused MOS (VDMOS) (6.78×10^{-5} A/μm) and 5.7 times of that of traditional SiC IGBT (4.37×10^{-4} A/μm). And SiC GCBTP can reduce the difficulty of process, because it does not need SiC P-type substrate. Besides, SiC GCBTP greatly optimize the reverse current by adding a suitable doped polysilicon between the gate and the P+ region of P-well, reducing the reverse current by 91% at same operating voltage of SiC GCBT (from -6.52×10^{-2} A/μm to -5.66×10^{-3} A/μm).

2. Device structure and description

The structure of SiC GCBTP is shown in Fig. 1(a), and its main structure is the same as that of SiC VDMOS. This means that SiC GCBTP can be easily manufactured by existing processes. In Fig. 1(a), the marked area of the device is different from SiC VDMOS and SiC GCBT. The cross-section

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in Fig. 1(a) shows the difference in the structure of the three devices. The electrode connection mode of SiC VDMOS is to connect the P+ region of P-well and the source, however, the electrode connection mode of SiC GCBT is to connect the P+ region of P-well and the gate. The electrode connection mode of the novel SiC GCBTP device proposed in this paper is similar to that of SiC GCBT, but the polysilicon is added between the gate and the P+ region. This polysilicon is doped, and it can play two roles. Firstly, it can reduce the large reverse current when the gate voltage is much larger than the drain voltage. Since the resistivity of polysilicon can be adjusted by adjusting the doping concentration, the increase of resistivity will lead to the decrease of base voltage, thereby reducing the reverse current. Secondly, it is used to obtain the appropriate driving ability, so that the injected hole can achieve a satisfactory trajectory and improve the effect of conductance modulation effect. Therefore, the structure provides two channels for the carrier to obtain greater current. Through the equivalent circuit diagram in Fig. 1(b), we can intuitively understand how the device works, and the two channels correspond to the VDMOS and BJT, respectively.

According to previous studies on the breakdown principle of VDMOS, we can know that when the device is breakdown, the current mainly appears in the P+ region of P-well due to the existence of PN junction between the source and P-well.[13] Because the polysilicon region in SiC GCBTP is a high-doping concentration, and the blocking effect on carrier motion is not as strong as that of PN junction, the breakdown mechanism of SiC GCBTP is the same as that of traditional SiC VDMOS. For this reason, SiC GCBTP has the same high breakdown voltage as SiC VDMOS. When the gate voltage of the device gradually increases, the BJT in the device will firstly turn on. Since the P-well region has a resistivity, a lower voltage can still be obtained below the VDMOS gate. When the gate voltage is sufficiently enough, an inversion layer can be obtained below the gate of the VDMOS to turn on the VDMOS. So SiC GCBTP can provide two channels for the carrier. The hole injected into the drift region also participate in the conduction, and the resistivity of the drift region is reduced by the conductance modulation effect, which further increases the on-state current of the device. In addition, compared with SiC IGBT, SiC GCBTP does not need the P-type substrate. Therefore, it can solve some negative effects caused by P-type substrate, and also solve the problem that it is difficult for SiC to manufacture P-type substrate.

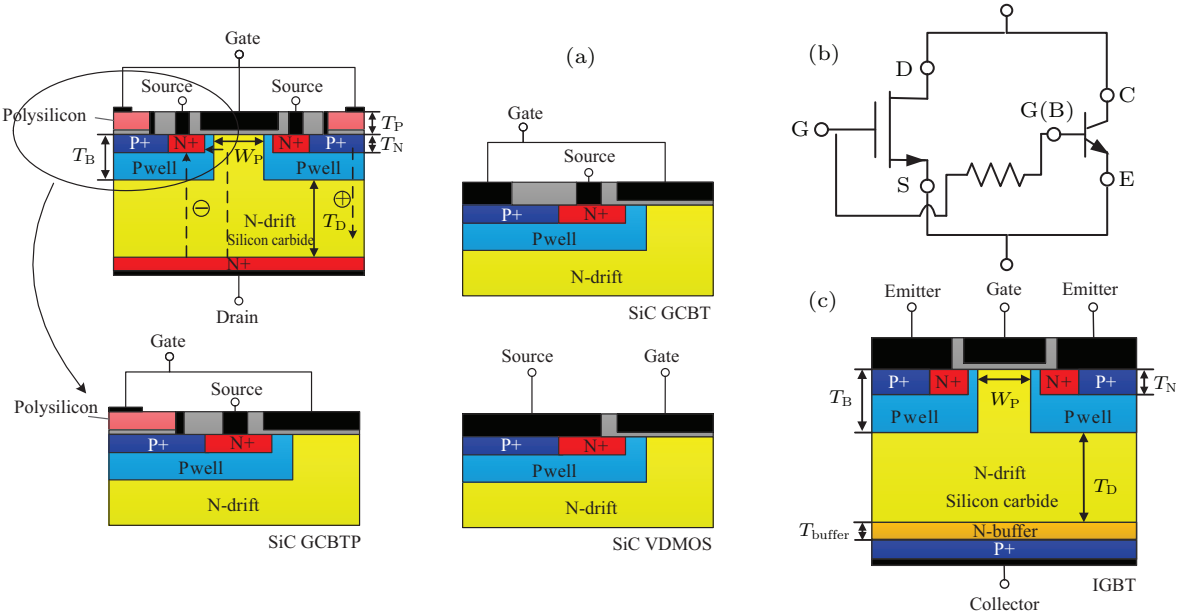


Fig. 1. (a) Schematic cross-section of the novel SiC GCBTP, SiC GCBT and the conventional SiC VDMOS. The figure also shows the flowing paths of electrons and holes. (b) The equivalent circuit diagram of the novel SiC GCBTP. (c) Schematic cross-section of the traditional SiC IGBT. $T_P = 0.1$ μm, $T_D = 4.5$ μm, $T_B = 1$ μm, $T_N = 0.3$ μm, $W_P = 5$ μm and $W_B = 4$ μm are used in the structures for simulation.

In order to study the main characteristics of SiC GCBTP, ISE TCAD was used to conduct the two-dimensional numerical simulation. Before the simulation of SiC GCBTP, ISE TCAD was used to simulate the structure in Refs. [14,15]. The main physical models are applied, including effective intrinsic density, Old Slotboom, mobility (Doping Dep High Fieldsat), Shockley–Read–Hall, and Auger avalanche (Eparal) model for recombination, *et al.* The criterion of breakdown is the break criteria {Current (Contact = "drain" Absval = 1×10^{-7})}. By comparing the simulation results with the experimental results, we found that the results are similar, indicating that the relevant model data used in this simulation is correct and can reflect the true electrical characteristics of the device. After obtaining the relevant characteristics of SiC GCBTP, this paper compares its results with those of other traditional devices and SiC GCBT. It is proved that SiC GCBTP is a device with

excellent performance. Table 1 lists the key parameters in this simulation. For ease of comparison, the common dimensions and parameters of SiC VDMOS in Ref. [16] are selected. In the simulation of IGBT as shown in Fig. 1(c), the length of drift region is kept the same as other devices used in this simulation, but the substrate becomes a P-type substrate and an N-type buffer is added at the bottom of the drift region.

Table 1. Key parameters used in simulation.

Variable	Parameter	Simulation values
N_P	concentration of P-well	4×10^{17} cm^{-3}
N_D	concentration of N-drift	1×10^{15} cm^{-3}
N_R	concentration of polysilicon	1×10^{19} cm^{-3}
N_{buffer}	concentration of N-buffer	1×10^{18} cm^{-3}
T_S	thickness of SiO_2 layer	0.052 μm
T_N	thickness of source layer	0.3 μm
T_B	thickness of P-well	1 μm
T_D	thickness of N-drift layer	4.5 μm
T_R	thickness of polysilicon	0.1 μm
T_{buffer}	thickness of N-buffer	0.5 μm
W_P	width of JEFT	5 μm
W_R	width of polysilicon	0.5 μm
L_C	length of channel	1 μm

3. Result and discussion

The comparison of breakdown voltage of several devices are shown in Fig. 2(a). By comparing the simulation results, it is found that SiC GCBTP has the same breakdown voltage value (811 V) as SiC VDMOS and SiC GCBT. It is proved that the device proposed in this paper does not have a negative impact on the breakdown voltage. SiC GCBTP has the same high breakdown voltage as SiC VDMOS, which is conducive to its work under high voltage. Through the comparison of Figs. 2(b) and 2(c), there is almost no current flowing through the source of the two devices, and the distribution of current density is the same, which can prove that the breakdown mechanism of SiC GCBTP is the same as SiC VDMOS. However, due to the existence of P-type substrate, the breakdown voltage of SiC IGBT is lower than that of SiC GCBTP with the same drift region length. Thanks to the same breakdown mechanism as SiC VDMOS, SiC GBCTP as a bipolar device can have the same high breakdown voltage as unipolar device.

The forward I–V characteristics of SiC GCBTP and SiC GCBT are shown in Fig. 3(a). SiC GCBTP has remarkable effect in reducing the reverse current. Since SiC GCBT needs to provide two carriers to participate in conducting simultaneously, holes must be injected into the drift region. However, this will generate reverse current when the drain voltage of SiC GCBT is much lower than the gate voltage, which seriously limits the working environment of the device, and the optimization of reverse current is very important for SiC GCBT. By adding appropriate polysilicon region, SiC GCBTP greatly improves the reverse current without affecting other performance of the device. By comparing Figs. 3(b) and 3(c), it can be found that the revers current density of SiC GCBT at the drain is much higher than that of SiC GCBTP. Since the reverse current is generated by the parasitic diode, the reverse current is proportional to the voltage of the base. Adding polysilicon can reduce the voltage of the base, so the reverse current is reduced. When voltage of the gate is 10 V and voltage of the drain is 0 V, the reverse current of SiC GCBT is -6.52×10^{-2} A/μm and the reverse current of SiC GCBTP is -5.66×10^{-3} A/μm, so the reverse current of SiC GCBTP is 91% lower than that of SiC GCBT. With the decrease of reverse current, the drain voltage required for SiC GCBTP is also greatly reduced when the on-state current goes up to positive. When voltage of the gate is 10 V, the drain voltage of SiC GCBT needs to rise to about 2 V to obtain a positive on-state current. Under the same gate voltage, the drain voltage of SiC GCBTP only needs 0.26 V. Such optimization facilitates the device to operate normally at low operating voltage.

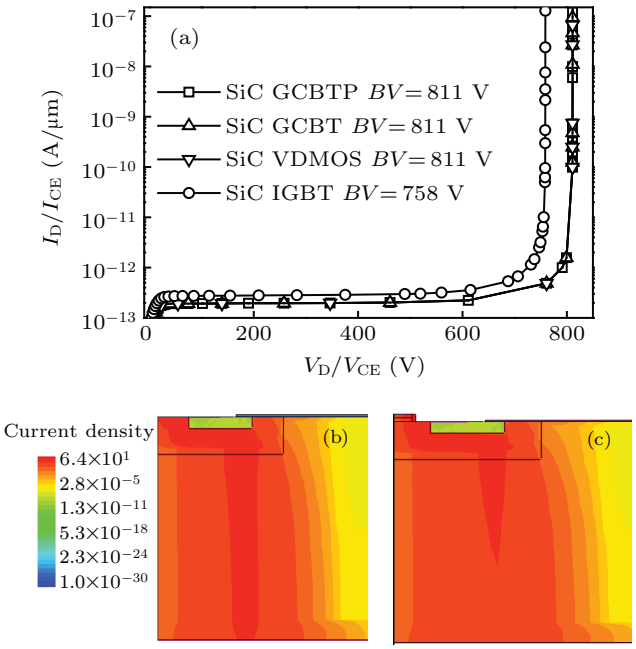


Fig. 2. (a) Simulated breakdown voltage comparison curves for SiC GCBTP and other devices. (b) Distribution of breakdown current density of conventional SiC VDMOS. (c) Distribution of breakdown current density of SiC GCBTP.

It can be proved from Fig. 3(a) that SiC GCBTP not only optimizes the reverse current, but also greatly improves the on-state current. From the comparison between Figs. 4(a) and 4(b), it can be found that when the device works (V_G = 10 V, V_D = 20 V), the distribution of hole current density in the two devices are different. The holes injected into the drift region not only move vertically, but also move horizontally. SiC GCBTP enlarges the area of lateral hole movement. The existence of conductance modulation effect can generate additional electrons in each part of the drift region, so the on-resistance of SiC GCBTP is reduced. By comparing Figs. 4(a)

with 4(b), it can be found that when the length of drift region reaches 1.8 μm, the hole current density of SiC GCBT in the middle of the horizontal becomes 0, and when the length of drift region reaches 2.5 μm, the hole current density of SiC GCBTP in the horizontal middle region becomes 0. Through the comparison between Figs. 4(c) and 4(d), it can be found that the on-state current of SiC GCBT is mainly concentrated on the edge of the device, and the current density in the horizontal middle region is small. In SiC GCBTP, the small current region is greatly reduced, and the overall on-resistance of the device is significantly reduced. Therefore, SiC GCBTP can well increase the on-state current. When voltage of the gate is 10 V, and voltage of the drain is 10 V, the on-state current of SiC GCBTP (2.47×10^{-3} A/μm) is about 1.8 times of that of SiC GCBT (1.36×10^{-3} A/μm).

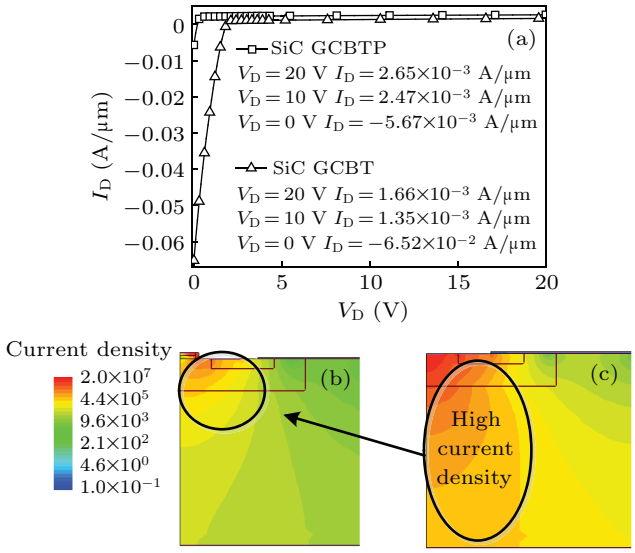


Fig. 3. (a) Simulated forward *I*–*V* characteristic for SiC GCBTP and SiC GCBT ($V_G = 10$ V). (b) The current density distribution of SiC GCBTP ($V_G = 10$ V, $V_D = 0$ V). (c) The current density distribution of SiC GCBT ($V_G = 10$ V, $V_D = 0$ V).

In addition to the comparison of the forward conductive characteristics with the structures published in Ref. [12], this paper also compares SiC GCBTP with other traditional structures. The forward *I*–*V* characteristic of device are shown in Fig. 5. It can be obviously found from the figures that the on-state current of GCBTP is much larger than that of traditional structure devices. When the working voltage is same ($V_G = 10$ V, $V_D = 20$ V), the on-state current of SiC GCBTP (2.47×10^{-3} A/μm) is 36.4 times of that of the traditional SiC VDMOS (6.78×10^{-5} A/μm) and 5.7 times of that of the traditional SiC IGBT (4.37×10^{-4} A/μm). It is proved that SiC GCBTP has excellent on-state performance. Compared with SIC VDMOS, the main structure of SiC GCBTP is the same, but the on-resistance is greatly reduced by introducing double carriers. Usually, the on-state current of bipolar devices is larger than that of unipolar devices. SiC IGBT is a traditional bipolar device, so the on-state current of SiC IGBT is large. But the on-state current of SiC GCBTP is larger than SiC IGBT. It is proved that SiC GCBTP significantly improves the on-state current by providing two current paths. At the same time, it also provides a new idea to solve the difficulty in manufacturing P-channel SiC IGBT (because it is very difficult to manufacture the SiC P-type substrate required for P-channel SiC IGBT). In addition, SiC GCBTP also solves the problem of latch-up effect in IGBT. Due to the IGBT structure, there will always be a parasitic thyristor. The latch-up effect brought by this thyristor will cause the device to fail to work normally under high voltage.[17] The working environment of the device is limited. So, SiC GCBTP as a bipolar device can solve many problems of SiC IGBT and have a higher on-state current.

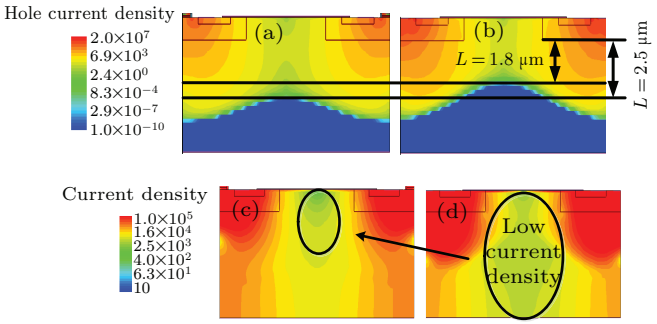


Fig. 4. (a) The hole current density distribution of SiC GCBTP ($V_G = 10$ V, $V_D = 20$ V) and (b) of SiC GCBT ($V_G = 10$ V, $V_D = 20$ V), (c) the current density distribution of SiC GCBTP ($V_G = 10$ V, $V_D = 20$ V) and (d) of SiC GCBT ($V_G = 10$ V, $V_D = 20$ V).

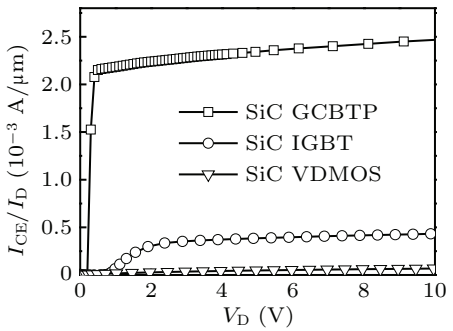


Fig. 5. Simulated forward *I*–*V* characteristic for SiC GCBTP, SiC IGBT and SiC VDMOS ($V_G = 10$ V).

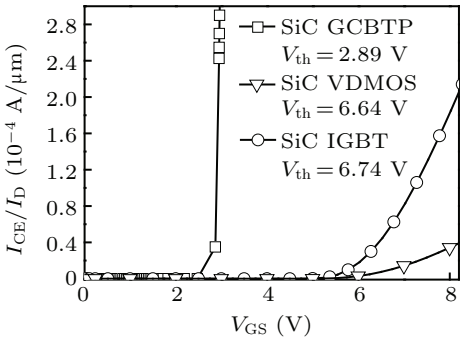


Fig. 6. Simulated threshold voltage characteristics comparison curves of the devices ($V_D = 10$ V).

Threshold voltage is an important parameter of gate control device. Figure 6 shows the comparison curves of threshold

voltage characteristics of SiC GCBTP, SiC IGBT and SiC VDMOS. Among the three devices, the threshold voltage of SiC VDMOS is the largest, which is 6.64 V. The threshold voltage of SiC IGBT is 6.74. The threshold voltage of SiC GCBTP is only 2.89 V. In order to obtain a high breakdown voltage, the doping concentration of P-well is large. If the device relies solely on the inversion layer for conduction, its threshold voltage will be high. But SiC GCBTP does not rely solely on inversion layer conduction, the threshold voltage of SiC GCBTP is small.

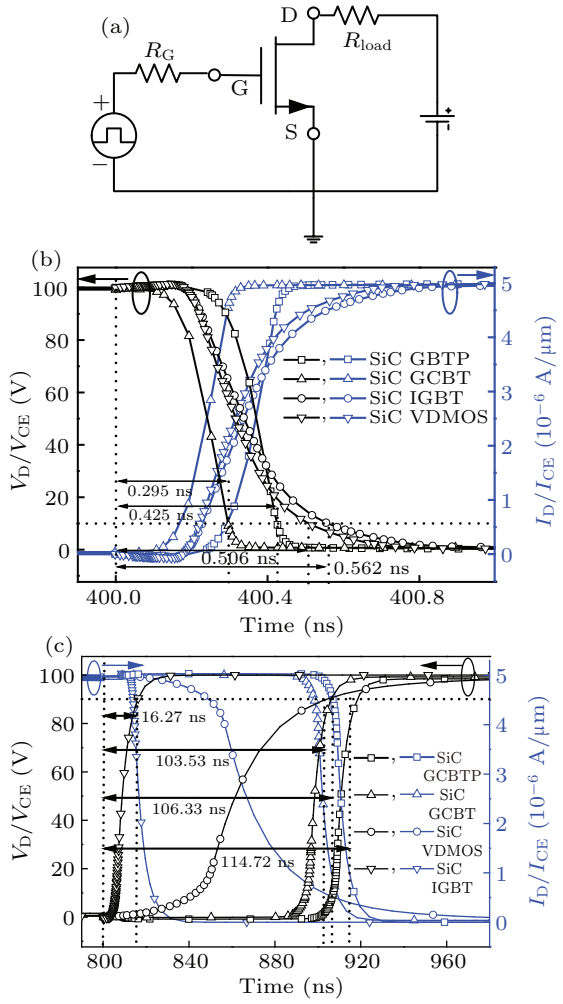


Fig. 7. (a) The switching circuit with a resistive load for the devices. (b) Simulated resistive turn-on characteristics for SiC GCBTP and other devices. (c) Simulated resistive turn-off characteristics for SiC GCBTP and other devices.

The circuit diagram with resistive load is shown in Fig. 7(a). Change the gate voltage of the device from 0 V to 10 V, and then from 10 V to 0 V to simulate the turn-on and turn-off of the device. In order to compare the dynamic characteristics of SiC GCBTP, SiC GCBT, SiC VDMOS and SiC IGBT were simulated at the same time. The simulation results of the four devices are shown in Figs. 7(b) and 7(c). It can be seen from Fig. 7(b) that the turn-on time of the four devices is very small, and the smallest turn-on time is SiC GCBT, which is 0.295 ns. The turn-on times of SiC VDMOS and SiC IGBT are 0.506 ns and 0.562 ns, respectively. The turn-on time of the device SiC GCBTP proposed in this article is 0.425 ns, which is about 80% of traditional devices. The turn-off time of bipolar devices is usually much longer than that of unipolar devices. This is because when the bipolar device is turned off, when the gate voltage drops to 0 V, there are still a large number of minority carriers in the drift region of the device. The extraction of these minority carriers takes a lot of time and generates a trailing current. It can be seen from Fig. 7(c) that the turn-off time of the SiC VDMOS as a unipolar device is the smallest, which is 16.27 ns. The turn-off time of the three bipolar devices has little difference. Among them, the turn-off time of SiC IGBT is 103.53 ns, the turn-off time of SiC GCBT is 106.33 ns, and the turn-off time of SiC GCBTP proposed in this paper is 114.72 ns. Through the comparison of simulation results, it can be concluded that while SiC GCBTP greatly optimizes the static characteristics, the dynamic characteristics are not negatively affected. Although a larger turn-off time will affect the application at high frequencies, the dynamic characteristics of bipolar devices can be improved by some methods, so that the device can work normally at high frequencies.[18]

4. Conclusion

A novel SiC GCBTP has been proposed in this article. It optimizes the on-state current and the reverse current. Besides, the main structure of SiC GCBTP is the same as that of SiC VDMOS, which reduces the manufacturing difficulty. In terms of static characteristics, the on-state current of SiC GCBTP is excellent, which is 2.47×10^{-3} A/μm ($V_G = 10$ V, $V_D = 10$ V). With the same structural parameters, the on-state current of SiC GCBTP is 1.8 times of that of SiC GCBT (1.36×10^{-3} A/μm), 36.4 times of that of traditional SiC VDMOS (6.78×10^{-5} A/μm) and 5.7 times of that of traditional SiC IGBT (4.37×10^{-4} A/μm). In addition, compared with SiC GCBT, SiC GCBTP reduces the reverse current by 91% (from -6.52×10^{-2} A/μm to -5.66×10^{-3} A/μm). In terms of dynamic characteristics, the turn-on time of the SiC GCBTP is very short, which is only 0.425 ns. The turn-off time of GCBTP is 114.72 ns, which is not significantly different from other bipolar devices. Through the analysis of the data, it can be known that SiC GCBTP has optimized the on-state current and reverse current, and has not caused other negative effects.

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