NPN aided fast switching insulated gate bipolar transistor with a p-buffer layer

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Abstract: A novel insulated gate bipolar transistor (IGBT) entitled NPN aided fast switching IGBT (NFS-IGBT) with a P-buffer layer is presented, which enhances the switching speed greatly. Compared with the conventional IGBT, double sided NPN structure is incorporated into the anode to facilitate the turn-off process. The proposed structure is verified by two-dimensional mixed device-circuit simulation, which indicates that the turn-off time is drastically reduced to one third of the conventional value at the expense of acceptable increase of on-state voltage drop. The tradeoff performance also shows great improvement for the new structure.

Keywords: IGBT, NFS-IGBT, NPN aided, Fast switching, P-buffer

Classification: Electron devices

References

1 Introduction

Because of the advantages of bipolar current conduction with MOS-gated control, the insulated gate bipolar transistor (IGBT) has gained wide acceptance in low and medium voltage applications [1]. Various approaches and schemes have been proposed to improve the overall performance of IGBT, with which minimizing and optimizing a device cell structure are mainly concerned [2]. To have features of low on-state voltage drop ($V_{on}$) and fast switching speed, the anode injection of minority carriers should be enhanced during on-state and weakened or ideally eliminated during turn-off [3]. The on-state/switching trade-off performance of the IGBT is strongly dependent on the anode injection efficiency [4]. Significant effort has been placed in anode engineering for the IGBT as a method to enhance the on-state/switching loss tradeoff [5]. Segmented Anode IGBT (SA-IGBT) [6,7] is one of the most efficient approaches to enhance the switching speed, but the concept is based on lateral IGBT. Its counterpart with vertical structure is difficult to fabricate and shows inferior tradeoff performance to the proposed structure. In this paper, an improved IGBT entitled NPN aided fast switching IGBT (NFS-IGBT) with a P-buffer layer is proposed and analyzed. Results of mixed device-circuit simulation demonstrate the novel structure has higher switching speed and better trade-off relation between $V_{on}$ and turn-off time ($t_{off}$) than the conventional IGBT.

2 Device structure and analysis

The cross-sectional views of conventional IGBT and NFS-IGBT are illustrated in Fig. 1(a) and (b) respectively. For comparison with the segmented anode concept later, the equivalent vertical SA-IGBT structure is also shown in Fig.1(c). The NFS-IGBT is similar with the conventional one except the embedded NPN structure and a P-buffer layer in the anode. N-buffer, P-buffer and $P+$ anode are formed by sequent backside ion implantations, and then double sided N+ region is plugged into the anode to constitute the NPN structure.

When IGBT is turned on, heavily doped $P+$ anode begins to inject holes into the n base region. This injection causes conductivity modulation which greatly reduces the on-state voltage drop. During device turn-off, the MOSFET current diminishes rapidly, while the bipolar transistor collector current falls off with time as the stored excess carriers in the open base bipolar transistor decay by sweep-out and recombination. For the NFS-IGBT, the shrunk $P+$ anode portion and reduced doping level of p-buffer degrade the anode injection efficiency, thus a moderately higher on-state voltage. On the other hand, due to the low level conductivity modulation in the n drift region, there are less stored minority carriers which can be extracted faster in turn-off. The incorporated NPN also lends a hand to create an easy path for the minority carriers to be swept out, and that’s where the NPN aided fast switching IGBT come from.
Results and discuss

2-D mixed device-circuit simulation is carried out by MEDICI to investigate the operation and performance of the NFS-IGBT. The doping levels of N-buffer, P-buffer, P+ anode and N+ anode are in the range of $1 \times 10^{16}$ cm$^{-3}$, $1 \times 10^{17}$ cm$^{-3}$, $1 \times 10^{19}$ cm$^{-3}$ and $1 \times 10^{20}$ cm$^{-3}$, respectively, with junction depths range from 10 $\mu$m to 2.5 $\mu$m. The n+ anode locates symmetrically in both sides consuming around half of the entire anode. The doping profiles along the A-A’ and B-B’ lines in Fig. 1 (b) are shown in Fig. 2.

The Forward I-V characteristics of the NFS-IGBT and conventional IGBT are shown in Fig. 3. As expected, the I-V curve of NFS-IGBT is similar with the conventional one except an increased $V_{on}$. At 100A/cm$^2$, the on-state voltage drop of the NFS-IGBT is 2.05V, while that of the conventional one is 1.58V. With a p-buffer layer inserted between P+ anode and N-buffer, the hole concentration gradient at the interface is reduced, leading to a lower anode injection efficiency.
Meanwhile, the flow of electrons into the N+ anode also results in the reduction of the current gain [8]. Fewer electrons are required to obtain the charge neutrality in N-drift region under high level injection, which weakens the conductivity modulation and leads to a higher on-state voltage. As a result, the on-state voltage drop only ends up with a moderately higher value, which is acceptable in typical applications.

Fig. 4 shows the simulated turn-off wave forms for conventional IGBT and NFS-IGBT. It can be seen that the turn-off times of NFS-IGBT and the conventional one are 0.22 $\mu$s and 0.70 $\mu$s respectively. In other words, NFS-IGBT turns off more than three times as fast as the conventional IGBT.

The fast switching quality of NFS-IGBT mainly attributes to two factors. Firstly, the suppressed anode injection efficiency reduces the excess minority carriers in n drift region, and therefore less time is needed to evacuate them during turn-off. Secondly, the plugged NPN structure plays an important role in introducing the
electrons from n drift region into n+ anode. In the conventional IGBT, the stored carriers are removed only by the recombination process. While in the NFS-IGBT, electrons are easily extracted into n+ anode by swept-out. In addition, the p-buffer layer acts as the base of the NPN with lowered doping level, which further increases the back injection of electrons. The electron concentration variation during turn-off along the A-A’ lines in Fig. 1(a, b) for conventional IGBT and NFS-IGBT is shown in Fig. 5. Both devices are in the turn-off period from 0.002 μs to 0.3 μs. In consistent with the previous analysis, the initial electron concentration of NFS-IGBT is lower, but the tail current is highly diminished in the turn-off period.

![Electron Concentration Variation](image1)

**Fig. 5.** Simulation results of electron concentration variation during turn-off process along the A-A’ lines of the conventional IGBT and NFS-IGBT.

![Turn-off Time](image2)

**Fig. 6.** Simulation results of tradeoff relations between on-state voltage drop and turn-off time for conventional IGBT, equivalent segmented anode IGBT and NFS-IGBT.

By adjusting the carrier lifetimes, the tradeoff relations between forward voltage drop and turn-off time for conventional IGBT, equivalent SA-IGBT depicted in
Fig. 1(c) and NFS-IGBT are shown in Fig. 6. It is obvious that NFS-IGBT has a better tradeoff relation than the conventional IGBT and equivalent SA-IGBT. With the same on-state voltage drop at 1.7V, the turn-off time of NFS-IGBT is only about half that of the conventional IGBT and 92% that of the equivalent SA-IGBT, which definitely validates the fast switching quality of NFS-IGBT. Besides, NFS-IGBT is more suitable for vertical structure than SA-IGBT in consideration of fabrication availability and compatibility.

4 Conclusion

A novel IGBT structure entitled NPN aided Fast Switching IGBT (NFS-IGBT) is proposed and verified by two dimensional device simulation. The embedded NPN in anode structure helps to eliminate the excess minority carriers from n drift region during turn-off. Besides, an inbuilt P-buffer layer as the base of the NPN degrades the anode injection efficiency and promotes the back injection of electrons to further accelerate the turn-off speed. Simulation results indicate that the turn-off time of NFS-IGBT is considerably reduced to one third that of the conventional IGBT with only moderate increase of on-state voltage drop. Variations of the parameters for the P-buffer layer are made to investigate the influence on device performance, and it turns out to be in accordance with the mechanism of device operation. NFS-IGBT has visibly better trade-off relationship than the conventional IGBT, and it is especially promising in fast switching oriented applications.