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Numerical Study of a Thyristor Injection Insulated Gate Bipolar Transistor (TI-IGBT) Using P-N-P Collector

Mengxuan Jiang, Member, IEEE, and Yulei Wang

Abstract—A new thyristor injection concept is proposed to decrease conductivity modulation effects in an Insulated Gate Bipolar Transistor (TI-IGBT), which adds a floating p-type layer and an n-type layer at the collector side. The additional p-layer and n-layer form a parasitic n-p-n transistor to reduce the hole injection efficiency though the potential difference between the floating p-type layer and the field stop (FS) layer, as well as decrease hole concentration near the collector, turn-OFF fall time and turn-OFF loss. TACD simulations shows, a 24% and a 10% reduction in turn-OFF fall time and turn-OFF loss are respectively obtained in the proposed TI-IGBT with the similar breakdown voltage and threshold voltage compared to a conventional FS-IGBT by the potential difference with the various floating p-layer doping. Therefore, the TI-IGBT offers a competitive option for high power converter applications.

Index Terms—Conductivity Modulation, Thyristor Injection, P-N-P Collector, Saturation Voltage Drop, IGBT.

I. INTRODUCTION

THE Insulated Gate Bipolar Transistor (IGBT) still exhibit huge potential in high voltage and high current power conversion systems [1]-[5]. Over the past years, innovative IGBT structures and power semiconductor devices have been investigated by researchers. Takahashi et al. designed a charge storage IGBT (CS-IGBT) with an n-type layer beneath the p-base as a hole barrier to improve carrier concentration and reduce saturation voltage drop [6]. Sumitomo et al. experimented a partially narrow mesa IGBT (PNM-IGBT) through challenging trench fabrication process [7]. We proposed an emitter Schottky barrier IGBT that accumulates holes in the upper n-drift region and decreases the saturation voltage drop [8]. These designs provide hole concentration enhancement at the top side of the IGBT, then lower saturation voltage drop and turn-OFF loss. J. K. O. Sin explored a lateral Schottky injection field effect transistor (SINFET) with an n-drift/collector Schottky contact to raise hole concentration at the collector side [9], resulting in longer turn-OFF time and more turn-OFF loss. Other related outcomes have been published in the literature [10]-[15].

In this paper, we propose a new thyristor injection IGBT, which degrades conductivity modulation effect by a parasitic n-p-n transistor at the collector side, as described in Fig.1 (a). The transparent p-collector design in the FS-IGBT can lower hole concentration on the collector side, but it may be difficult to form a good ohmic contact between the light doping p-collector (i.e., 5×10^{16} cm^{-3}) and collector metal [10]. Based on hole injection control and manufacturing difficulty considerations, we designed a p-n-p collector IGBT to reduce hole concentration at the bottom side by varying the floating p-layer doping concentration, and to accelerate turn-OFF and decrease turn-OFF loss, which is studied in section III.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>6e17 TI-IGBT</th>
<th>1e17 TI-IGBT</th>
<th>1e16 TI-IGBT</th>
<th>FS-IGBT</th>
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</table>

II. DEVICE CONCEPT

Fig. 1 (a) presents the schematic cross section of the above-mentioned TI-IGBT. The floating p-type layer lies below the FS layer and above the added n-type layer, which is on the p+ collector region. The p-n-p collector structure is used as a

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Manxian Jiang and Y. Wang are with the School of Electrical Engineering, Chongqing University, Chongqing 400044, China (e-mail: mxuanjiang@gmail.com)
minority carrier source to supply hole conduction to the n-drift region. The parasitic n-p-n transistor can be designed for degrading conductivity modulation effects by lowering the floating p-type layer doping concentration. Therefore, the p-n-p collector and the parasitic n-p-n transistor form a pnpn thyristor structure, as shown in Fig. 1 (b).

Under ON-state conditions, with low doping concentration in the floating p-type layer, the potential difference between the floating p-type layer and the FS layer remains small, hence the parasitic n-p-n transistor suppresses hole injection to decrease conductivity modulation effects. The potential difference decreases with lowering of the doping concentration in the floating p-type layer, degrading the conductive level of the parasitic n-p-n transistor and the hole injection efficiency of the p-n-p collector, as discussed below in Forward-conduction Characteristics. In the OFF-state mode, the p-n-p collector structure produces smaller common-base current gain [16] than the conventional FS-IGBT, thus its breakdown voltage shows a slightly higher. In comparison with the conventional FS-IGBT, the pnpn thyristor structure includes a hole injection path and a hole barrier to reduce carrier concentration at the collector side of the TI-IGBT. Note that the floating p-type layer and the added n-type layer can be further optimized but is beyond the scope of this study.

III. SIMULATION AND DISCUSSION

TCAD simulation has been performed to compare the proposed TI-IGBT and the conventional FS-IGBT. The doping concentration of $1 \times 10^{16}$ cm$^{-3}$, $1 \times 10^{17}$ cm$^{-3}$ and $6 \times 10^{17}$ cm$^{-3}$ in the floating p-type layer are initially chosen for comparative study with the n-type layer doping concentration of $1 \times 10^{16}$ cm$^{-3}$ and depth of 0.5 μm in the TI-IGBT. The critical parameters listed in Tab. I are extracted and optimized from the 1200 V FS-IGBT in [10].

A. Breakdown Characteristics

The p-n-p collector and the parasitic n-p-n transistor are connected in darlington configuration to form the positive feedback structure, the equivalent circuit model of the TI-IGBT is shown in Fig. 1 (b). The simulated breakdown voltages are 1312 V, 1301 V and 1277 V for the TI-IGBT with the floating p-layer doping of $1 \times 10^{16}$ cm$^{-3}$, $1 \times 10^{17}$ cm$^{-3}$ and $6 \times 10^{17}$ cm$^{-3}$ at a leakage current of $1 \text{ mA/cm}^2$, respectively. The breakdown voltage of the FS-IGBT is 1266 V for reference. The common-base current gain decreases with the lowering of the floating p-layer doping [16], the TI-IGBT demonstrates a higher breakdown voltage and a lower leakage current, as presented in Fig. 2.

![Fig. 2. Breakdown characteristics of the proposed IGBT with the floating p-layer doping of $1 \times 10^{16}$ cm$^{-3}$, $1 \times 10^{17}$ cm$^{-3}$ and $6 \times 10^{17}$ cm$^{-3}$ at a gate voltage of 0 V, respectively. The reference FS-IGBT is included for comparative study.](image1)

![Fig. 3. Forward-conduction characteristics of the TI-IGBT with a floating p-layer doping of $1 \times 10^{16}$ cm$^{-3}$, $1 \times 10^{17}$ cm$^{-3}$ and $6 \times 10^{17}$ cm$^{-3}$ at a gate voltage of 15 V, respectively. The results of the FS-IGBT is included for comparison.](image2)

![Fig. 4. Hole concentration distributions along the cutline AA’ of the proposed IGBT with the corresponding doping concentration at a forward current of 150 A/cm$^2$, respectively. The FS-IGBT is included for comparison.](image3)

![Fig. 5. Quasi-Fermi potential distributions along the cutline AA’ of the proposed IGBT with the corresponding doping at a collector current of 150 A/cm$^2$, respectively. The results of the FS-IGBT is included for comparison.](image4)
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B. Forward-conduction Characteristics

Since holes injected from the p-n-p collector are limited by the conductivity of the parasitic n-p-n transistor in the ON-state mode, the conductivity modulation effect can be adjusted by changing the potential difference between the floating p-type layer and the field stop (FS) layer using different floating p-layer doping in the TI-IGBT. The forward conduction currents are 117 A/cm², 139 A/cm² and 211 A/cm² for the TI-IGBT with the floating p-layer doping of 1×10¹⁹ cm⁻³, 1×10¹⁷ cm⁻³ and 6×10¹⁷ cm⁻³ at a collector voltage of 1.7 V, respectively. The forward conduction current of the FS-IGBT is 150 A/cm² for comparison. The saturation voltage drops are 1.78 V, 1.72 V, 1.59 V and 1.70 V for the corresponding floating p-layer TI-IGBT and the FS-IGBT, respectively, as shown in Fig. 3. The decrease in forward conduction current or increase in saturation voltage drop is attributed to the degraded conductivity modulation effect of the TI-IGBT by the reduced potential difference, which reduces the hole concentration near the collector side in Fig. 4. The quasi-Fermi potential distributions in Fig. 5 also confirm this degraded effect by the potential difference between the floating p-type layer and the FS layer.

Furthermore, the p-n-p collector performs the dual role of controlling hole injection and serving as a barrier to hole flow. The short circuit current isn’t improved because the hole injection efficiency tends to the same approximate value as the FS-IGBT under short circuit conditions discussed in Fig. 9. The short circuit current increase with an increase in hole concentration at the emitter side in CS-IGBT [6], PNM-IGBT [7], HiGT [11], IEGT [12].

C. Transfer Characteristics

The trench and the p-base doping are set to be identical parameters for comparative study, as seen in Tab. I. The threshold voltages are simulated to be 5.2 V for both the TI-IGBT and FS-IGBT at a collector current of 10 mA/cm², as can be seen from Fig. 6. This similarity occurs because the gate structures are exactly the same for the TI-IGBT with the corresponding floating p-layer doping and for the FS-IGBT, as shown in Fig. 1 (a).

D. Turn-OFF Characteristics

Fig. 7 demonstrates turn-OFF waveforms under inductive load conditions at a forward conduction current of 150 A/cm². The turn-OFF fall times are 42 ns, 54 ns, 82 ns for the TI-IGBT with the corresponding floating p-layer doping, and 52 ns for the FS-IGBT. The TI-IGBT demonstrates a reduced turn-OFF fall time with decreased floating p-layer doping because the lower potential difference between the floating p-type layer and the FS layer in the parasitic n-p-n transistor decreases the hole the electron Devices Society
injection efficiency of the p-n-p collector. It can be calculated that the TI-IGBT provides a 24% reduction in turn-OFF fall time compared with the FS-IGBT at the floating p-layer doping of $1\times10^{16}$ cm$^{-3}$. However, the shorter turn-OFF fall time may induce slight oscillations in Fig. 7, thus the floating p-layer doping of the TI-IGBT can be also further optimized for high power and high switching frequency applications.

### E. Switching-OFF Loss Characteristics

Fig. 8 shows the switching-OFF loss characteristics with carrier lifetimes of 0.2 μs, 0.4 μs, 1 μs, 2 μs, 4 μs. Better switching-OFF loss tradeoffs are obtained for the TI-IGBT with the lower floating p-layer doping by reason of the shorter turn-OFF time. The TI-IGBT offers a 10% decrease in switching-OFF loss in contrast to the FS-IGBT at a floating p-layer doping of $1\times10^{16}$ cm$^{-3}$. It can be inferred that reduced doping concentration of the floating p-layer results in less switching-OFF loss for the TI-IGBT.

### F. Short Circuit Characteristics

Fig. 9 illustrates the short circuit characteristics with a stray inductance of 10nH, stray resistance of 0.01 ohm and thermal resistance of 100 °C/cm$^2$·K. It can be seen that both the TI-IGBT and the FS-IGBT failure at approximately 4 μs after short circuit occurs at 25 °C ambient temperature. Since the reduced potential difference between the floating p-type layer and the FS layer decreases the conductivity of the parasitic n-p-n transistor and the hole injection efficiency, this new p-n-p collector almost doesn’t affect heat dissipation and short circuit characteristics. It must be mentioned that the ideal short circuit currents with above parameters in simulations are applied to validate the internal failure mechanisms.

### IV. CONCLUSION

In this paper, we report a pmn thyristor injection IGBT (TI-IGBT) concept, which adopts a p-n-p collector to inject holes and a parasitic p-n-p transistor to restrict hole injection efficiency. TCAD numerical simulations confirm that the TI-IGBT offers a 24%, 10% decrease in turn-OFF fall time and turn-OFF loss in contrast to a conventional FS-IGBT with almost the same breakdown voltage and threshold voltage at a floating p-layer doping of $1\times10^{16}$ cm$^{-3}$, respectively. The advantage of this concept is to decrease the turn-OFF fall time and the turn-OFF loss instead of dealing with the fabrication difficulty in forming a good ohmic contact on the light doping p-collector for the transparent p-collector design [10].

### REFERENCES


### Mengxuan Jiang

Mengxuan Jiang received the Ph.D. degree in electrical engineering from Hunan University, Changsha, China, in 2016. He also awarded Scholarship to study at Illinois Tech., Chicago, USA, from 2014 to 2015. He is currently an Assistant Professor with the School of Electrical Engineering, Chongqing University, China. His research interests include power semiconductor devices and power electronics applications.

### Yulei Wang

Yulei Wang received the B. S. degree in electrical engineering from China University of Mining and Technology, Xuzhou, China. He is currently pursuing the M.S. degree in electrical engineering from the School of Electrical Engineering, Chongqing University, China. His research interests include power electronics systems, power semiconductor devices, etc.