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Simulation Study of an Insulated Gate Bipolar Transistor With Pinched-Off N-Type Pillar

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ABSTRACT This paper proposes a novel field-stop insulated gate bipolar transistor with an N-type pillar (NP-IGBT) formed on the silicon backside, which acts as a field-stop layer to pinch off electric field in the n-drift region under forward-blocking mode. TCAD simulation indicates that the proposed IGBT offers an avalanche energy 32% and reverse-biased safe operating area 20% higher than a conventional field-stop IGBT. Therefore, the proposed IGBT provides more reliable electrical performance for high-power converters.

INDEX TERMS Avalanche energy, breakdown voltage, forward voltage drop, IGBT, reliability.

I. INTRODUCTION

The Insulated Gate Bipolar Transistor (IGBT) integrates the advantages of Bipolar Junction Transistor (BJT) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET), which is widely used in electric traction, smart grid, and other power electronic systems. However, the reliability of IGBT has not been of much consideration in electrical performance. An n-type layer under the p-base of IGBT was used as the hole barrier to enhance conductivity modulation effect [1], [2], but the n-type layer degrades the breakdown voltage and reliability of the IGBT. Nakagawa [3] predicted the theoretical limit of silicon IGBT, and proposed a fine trench structure to verify this concept. Sumitomo *et al.* [4] again experimentally validated the concept with a vase-shaped trench structure, which also degrades the reliability of the IGBT with a challenging fabrication process. Some new IGBT structures were also proposed recently [5]–[7] with various electrical performance, but their reliability has not been further studied [8]–[11].

In this letter, the authors propose a novel field-stop IGBT structure with an n-type pillar formed on the collector side, which acts as a field-stop layer to stop the electric field in the n-drift region under forward-blocking mode, preferably using a backside trench fabrication process [12]–[15]. This device concept offers larger SOA and higher avalanche energy when compared with a conventional FS-IGBT with a similar breakdown voltage, forward voltage drop, and threshold voltage.

II. DEVICE CONCEPT

Fig. 1 depicts the proposed IGBT and conventional FS-IGBT structures. The only difference between the two is that the FS layer of the conventional FS-IGBT no longer exists in the proposed IGBT, but rather an n-type pillar is formed on the silicon backside. The built-in potential between the n-pillar/n-drift junction depletes adjacent n-drift region, and its depletion region merges together to pinch-off the electric field under forward-blocking mode. Therefore, this new forward-blocking mechanism is different from the FS layer in an FS-IGBT, which may induce avalanche breakdown at the n-drift/FS-layer junction [16], [17]. Under forward-conduction mode, the major hole current flows through the p+collector/n-drift junction because the n-type pillar is so thick that it suppresses the hole injection efficiency. Under dynamic mode, the thick n-type pillar extracts electrons from the n-drift region, which accelerates dynamic turn-on and turn-off process. Furthermore, the novel forward-blocking mechanism can lead to better heat conduction. This is attributable to the lower doping concentration in the n-drift

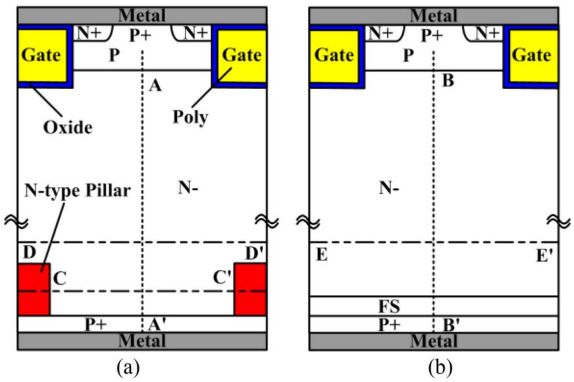

FIGURE 1. (a) Proposed IGBT and (b) conventional FS-IGBT structures. The cutlines AA′ and BB′ indicate electric field distribution, the cutlines CC′, DD′, and EE′ indicate excess hole distribution.

region between adjacent n-type pillars, which can cause lower thermal resistance when compared with an FS layer, as will be discussed in Section III. Therefore, the proposed IGBT exhibits a superior reliability.

III. SIMULATION AND DISCUSSION

The proposed IGBT concept is verified though cell simulations by TCAD tools. The simulation is based on silicon because it has reliable physical model, which includes parallel electric field dependence mobility model, concentration- and temperature-dependent mobility model, concentration-dependent recombination model, bandgap narrowing, impact ionization, and lattice self-heating model. The device parameters of the proposed IGBT and conventional FS-IGBT are summarized in Tab. 1 based on the 1200 V IGBT design in [3]–[5].

TABLE 1. Major parameters.

Parameters	NP-IGBT	FS-IGBT
Room Temperature (℃)	25	25
Cell Pitch (μm)	4	4
Wafer Thickness (μm)	120	120
Gate Oxide Thickness (nm)	50	50
Channel Length (μm)	2	2
Trench Depth (μm)	6	6
Trench Width (μm)	1	1
N-type Pillar Depth (μm)	10	-
N-type Pillar Width (μm)	0.4	-
N-drift Doping (cm^{-3})	5×10^{13}	5×10^{13}
FS Doping (cm^{-3})	-	2×10^{16}
P+ Doing (cm^{-3})	5×10^{17}	5×10^{17}
Lifetime ($\tau_n=3\tau_p$, μs)	1.2	1.2

A. FORWARD-BLOCKING CHARACTERISTICS

As a verified study, the concentration of the n-type pillar is set to be 1×10^{16}, 1×10^{17}, and 1×10^{19} cm^{-3} for comparison. Fig. 2 shows the avalanche I-V characteristics. The breakdown voltage of the proposed IGBT is 1179 V, 1268 V, and 1273 V for an n-type pillar concentration of 1×10^{16}, 1×10^{17}, and 1×10^{19} cm^{-3} at 1 mA/cm^2, respectively. In comparison, the conventional FS-IGBT exhibits

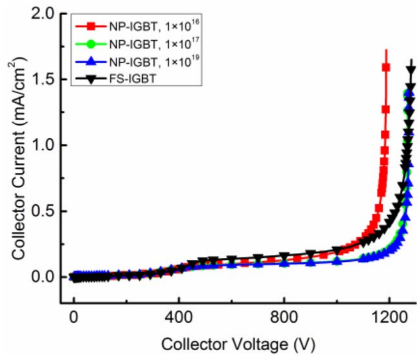

FIGURE 2. Avalanche I-V characteristics of the proposed IGBT with various n-type pillar concentration. The conventional FS-IGBT with the same cell dimensions is also included for comparison.

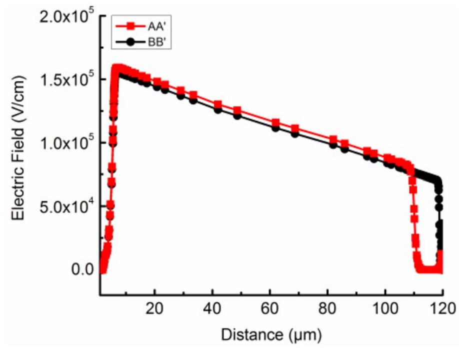

FIGURE 3. Electric field distribution along the vertical direction between the p-base, the n-drift region and/or the FS layer under breakdown conditions. The cutline AA′ is shown for the proposed IGBT at the n-type pillar concentration of 1×10^{17} cm^{-3}, the cutline BB′ is shown for the FS-IGBT, as marked in Fig. 1.

a breakdown voltage of 1268 V. It can be seen that the breakdown voltage of the proposed NP-IGBT is similar to that of the FS-IGBT, which increases with increasing n-type pillar concentration as a result of the enhanced built-in potential between n-pillar/n-drift junction. Fig. 3 shows the electric field distribution along the vertical direction between the p-base, the n-drift region, and the FS layer under breakdown conditions. It can be observed that the electric field in the n-drift region is pinched-off by the adjacent n-type pillars.

B. FORWARD-CONDUCTION CHARACTERISTICS

Fig. 4 illustrates the forward I-V characteristics. At a current density of 150 A/cm^2, the forward saturation voltage is 1.49 V, 1.54 V, and 1.75 V for an n-type pillar concentration of 1×10^{16}, 1×10^{17}, and 1×10^{19} cm^{-3}, respectively. The forward saturation voltage is 1.51 V for the conventional FS-IGBT. It can be seen that the proposed IGBT's forward saturation voltage decreases with increasing n-type pillar concentration, as a result of the enhanced built-in potential that suppresses the hole injection efficiency. It is worth noting that the current exhibits a linear distribution for the n-type pillar concentration of 1×10^{19} cm^{-3}. The conductive

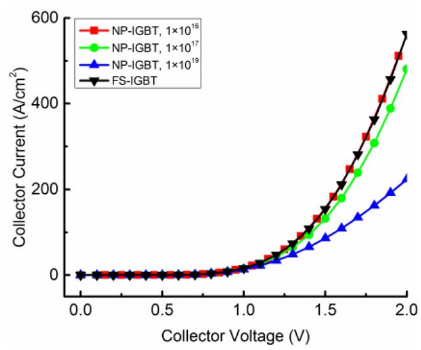

FIGURE 4. Forward I-V characteristics of the proposed IGBT with various n-type pillar concentration. The conventional FS-IGBT with the same cell dimensions is also included for comparison.

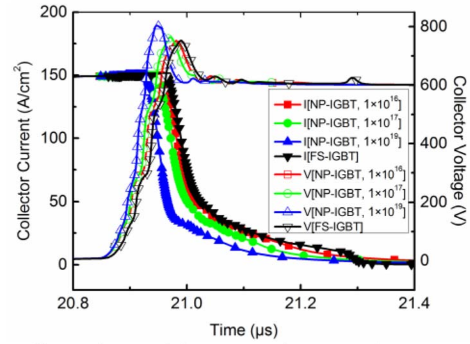

FIGURE 6. Turn-off waveforms of the proposed IGBT and FS-IGBT at a current density of 150A/cm², a bus voltage of 600V, a gate resistor of 5 ohm and a stray inductance of 60 nH.

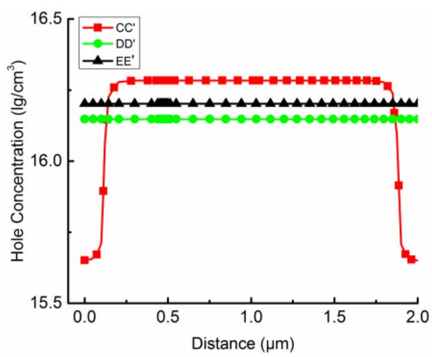

FIGURE 5. Excess hole distribution along the horizontal direction between the n-type pillar, the n-drift region and the n-type pillar at 150A/cm². The cutlines CC' and DD' are shown for the proposed IGBT at n-type pillar concentration of 1×10^{17} cm^{-3}, the cutline EE' is shown for the FS-IGBT, as marked in Fig. 1.

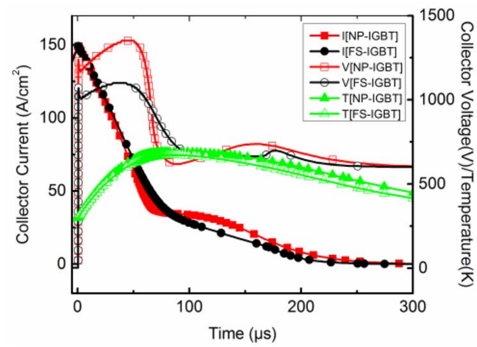

FIGURE 7. Unclamped inductive switching waveforms of the proposed IGBT and FS-IGBT at a current density of 150 A/cm², a bus voltage of 600 V, a gate resistor of 5 ohm, a thermal resistance of 20 °C/kW and a case temperature of 25 °C.

mechanism can be further observed in Fig. 5 where excess hole concentration profiles are plotted through the IGBT cell with the n-type pillar concentration of 1×10^{17} cm^{-3}. It can be observed that the major hole current flows through the p+collector/n-drift junction at the cutline CC', and the thick n-type pillar only conducts minor hole current. The hole concentration distribution shows a slight difference between the cutline DD' and EE' at the same position, as a result of the different forward-conduction mechanism. However, the optimization of the n-type pillar concentration, width, and depth should be based on the tradeoff between the breakdown voltage and the forward saturation voltage of the proposed IGBT.

The transfer characteristics have also been simulated. The threshold voltage of the NP-IGBT is 5.0 V for all n-type pillar concentrations. The conventional FS-IGBT also exhibits a threshold voltage of 5.0 V. This is because the NP-IGBT and FS-IGBT have the same surface parameters, as shown in Table 1.

C. TURN-OFF CHARACTERISTICS

Mixed-mode inductive switching characteristics have been studied by simulation. The DC bus voltage is set at 600 V, the load current density at 150 A/cm^2, the stray inductance at 60 nH, and the gate resistor at 5 ohm. Fig. 6 shows the turn-off waveforms of the NP-IGBT with a turn-off time of 879, 836, and 778 ns for an n-type pillar concentration of 1×10^{16}, 1×10^{17}, and 1×10^{19} cm^{-3}, respectively; thus, various levels of electron extraction are present in the n-drift region. For comparison, the waveforms of the conventional FS-IGBT with a turn-off time of 912 ns are also included. It can also be seen that the proposed IGBT exhibits a decreased initial delay because of the reduced diffusion capacitor.

D. UNCLAMPED INDUCTIVE SWITCHING (UIS) CHARACTERISTICS

UIS characteristics have been simulated to study ruggedness at an n-type pillar concentration of 1×10^{17} cm^{-3}. The test circuit is the same as the turn-off circuit except the freewheeling diode. Fig. 7 shows the UIS waveforms at the maximum inductance load. It can be calculated that the avalanche energy is 4.5 J for the NP-IGBT at 0.4 mF, which is 32% larger than 3.4 J for the FS-IGBT 0.3 mF, as a result of the novel forward-blocking mechanism of the NP-IGBT and its lower thermal resistance between adjacent n-type pillars.

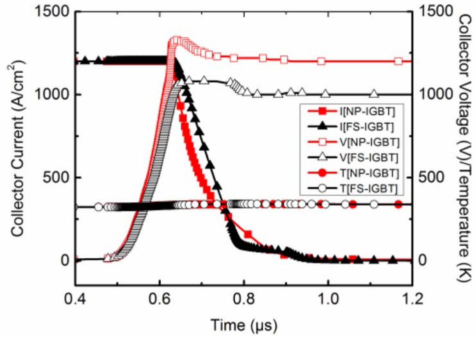

FIGURE 8. RBSOA Turn-off waveforms of the NP-IGBT and FS-IGBT at a thermal resistance of 20 °C/kW and a case temperature of 25 °C.

E. REVERSE BIASED SOA (RBSOA)

Simulations have been performed to verify the RBSOA at the n-type pillar concentration of 1×10^{17} cm^{-3}. After repeated tests, the NP-IGBT withstands a maximum current density of 1200 A/cm^2 and a bus voltage of 1200 V, compared with a maximum current density of 1200 A/cm^2 and a bus voltage of 1000 V for the NP-IGBT at 25 °C case temperatures, as shown in Fig. 8. The RBSOA of the NP-IGBT is 20% larger than that of the FS-IGBT as a result of the novel forward-blocking mechanism. It can be inferred that the novel forward-blocking mechanism is superior to the conventional FS layer.

IV. CONCLUSION

This letter presents a novel field-stop IGBT structure with n-type pillar formed on the silicon backside. Simulated results show that the NP-IGBT offers an avalanche energy 32% and RBSOA 20% higher than the FS-IGBT with a similar breakdown voltage, forward voltage drop, threshold voltage and turn-off time. Therefore, the proposed IGBT offers more reliable electrical performance for high-power converters.

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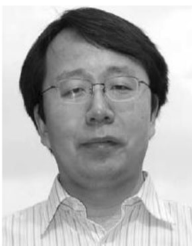

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