A very narrow mesa biased IGBT for ultra-low on-state saturation voltage and a good short circuit ruggedness

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Abstract—**In this paper, a novel CSTBT with very narrow mesa structure is proposed by numerical simulation. The floating pwell region in the proposed structure is connected with the cathode through the very narrow mesa structure to deplete the very high dose concentration of the CS layer. Therefore, the conductivity modulation effect of the proposed structure can be enhanced significantly. It can help the proposed structure to achieve ultra-low on-state saturation voltage closed to the theoretical limit. In addition, there is no degeneration of the short-circuit behavior due to the relatively normal active cell mesa region. It can avoid the CIBL behavior induced by the very narrow conductive channel structure.**

Keywords—Insulated gate bipolar transistor (IGBT), very narrow mesa, saturation voltage, short circuit

I. INTRODUCTION

The insulated gate bipolar transistor (IGBT) is a mainstream power semiconductor device, which is widely used in various power electronic systems. The IGBTs with very narrow mesa structure have also demonstrated a useful skill to enhance the conductivity modulation. However, the poor short-circuit ability was observed in the actually fabricated very narrow mesa IGBTs due to the CIBL (Collector bias Induced Barrier Lowering) phenomenon [1-4]. Although the short-circuit performance can be improved with thin gate oxide thickness and low gate voltage bias, the poor short-circuit behavior still occurs when the mesa width below 100nm. This phenomenon may become an obstacle to pursue ultra-low $V_{ce(sat)}$ further in the very narrow mesa IGBT structure. Although some improved methods have been given, such as the CSTBT with P-ring structure [5] or the grounded floating pwell region via diode-clamped structure.[6] But, it can be known that the maximum dose concentration of CS layer in the P-ring structure still have the limitation due to the undepleted situation. And the CSTBT structure with an additional diode on the chip surface may bring a challenge to the fabrication technology and chip surface bonding process.

In this paper, a novel IGBT with very narrow mesa structure is proposed by numerical simulation. The floating pwell region in the proposed structure is connected with the cathode through the very narrow mesa structure to deplete the relatively high dose concentration CS layer. Therefore, the conductivity modulation effect of the proposed structure can be enhanced significantly. Meanwhile, the mesa width of the conductive channel region of the proposed structure is with the normal size structure, which can avoid the CIBL behavior induced by the very narrow conductive channel structure. Thus, the proposed structure can achieve ultra-low $V_{ce(sat)}$ closed to the theoretical limit without the degeneration of the short-circuit behavior. In addition, the proposed structure is completely compatible with the standard fabrication process without using additional surface diode.

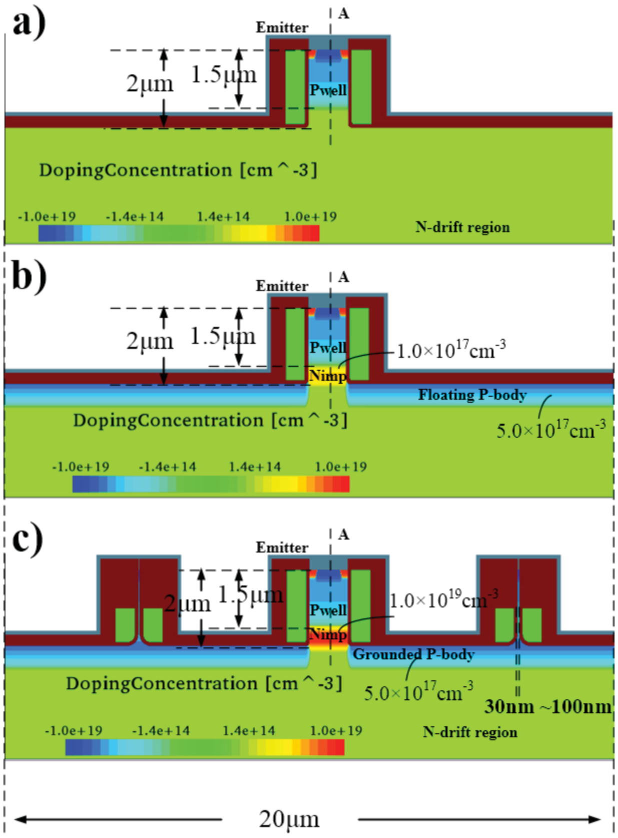

Fig. 1. Cross-sectional view of (a) the conventional IGBT, (b) the CS IGBT with P-ring structure and (c) the proposed structure with very narrow mesa biased structure.

II. DEVICE STRUCTURE AND MECHANISM

Fig. 1 shows the cross-sectional view of the conventional IGBT structure, the CS IGBT with P-ring structure and the proposed structures. The floating P-body region of the proposed structure [see Fig. 1(c)] is connected with the cathode through the very narrow mesa structure. The narrow mesa width of the proposed structure is 30nm as the baseline structure parameter. It is worth to noting that the gate polysilicon is only at the bottom part in the very narrow region to avoid the occurring of the conductivity modulation phenomenon in the whole very narrow region, which is the main reason of the CIBL phenomenon. The major structural parameters are shown in Table I. The simulations are performed by Synopsis Sentaurus Technology Computer Aided Design (TCAD) software.

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In the on-state, a very high dose concertation (~1.0×10^{19} cm^{-3}) of the CS layer can be used to block the holes carries effectively. The dose concertation of CS layer in the proposed structure is much higher than that of typical CS layer (~1.0×10^{17} cm^{-3}). Therefore, the proposed structure can achieve ultra-low on-state saturation voltage closed to the theoretical limit. In the off-state, the grounded pwell structure can help to deplete the very high dose concentration of the CS layer. So, the enough blocking ability is maintained. Moreover, there is no degeneration of the short-circuit behavior due to the relatively large mesa width in active cell compare that of the very narrow mesa IGBT. Therefore, the CIBL phenomena is avoided in the proposed structure.

TABLE I. MAJOR STRUCTURAL PARMETERS

Structural Parameters	Proposed IGBT	CS IGBT With P-ring	Conventional IGBT
Cell pitch (μm)	20	20	20
N-drift thickness (μm)	120	120	120
Gate oxide thickness (nm)	100	100	100
Gate Poly depth (μm)	2	2	2
Mesa width (μm)	1	1	1
Mesa width at very narrow region (nm)	30	-	-
N-drift doping (cm^{-3})	7.5×10^{13}	7.5×10^{13}	7.5×10^{13}
FS doping (cm^{-3})	6.44×10^{15}	6.44×10^{15}	6.44×10^{15}
P-well doping (cm^{-3})	2.8×10^{17}	2.8×10^{17}	2.8×10^{17}
N+ doping (cm^{-3})	1.0×10^{19}	1.0×10^{19}	1.0×10^{19}
P+ collector doping (cm^{-3})	5.15×10^{16}	5.15×10^{16}	5.15×10^{16}
Floating P-body doping (cm^{-3})	5×10^{17}	5×10^{17}	-
N+ CS doping (cm^{-3})	1×10^{19}	1×10^{17}	-
Lifetime τ_n (μs)	10	10	10
Lifetime τ_p (μs)	3	3	3

III. DEVICE ELECTRICAL PERFORMACE

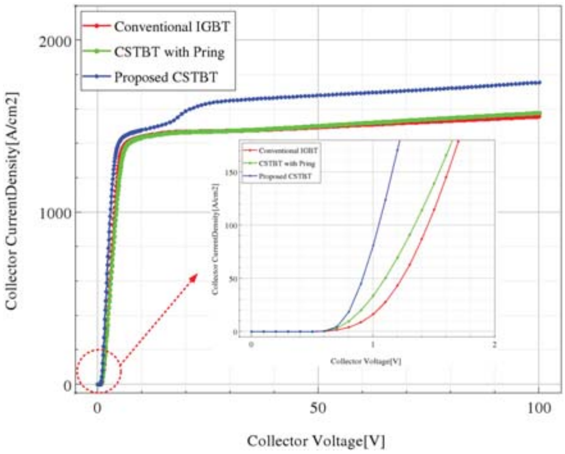

Fig. 2. Simulated gate charge and I-V characteristic for different structures. The curve of I-V characteristic is set at Vgs=15V.

Fig. 2 shows the forward I-V characteristic of all structures. At a current density of 100A/cm^2 and gate bias Vge=15V, the on-state saturation voltage $V_{ce(sat)}$ of the conventional IGBT, CS IGBT with P-ring structure, and the proposed structure are 1.57V, 1.34V and 1.06V, respectively.

Fig. 3 presents the hole density distribution along line A (at current density 150A/cm^2). It can be seen that the flowing of hole carries is blocked by the CS layer and the very narrow structure at emitter side, which helps to approach the theoretical limit. According to theoretical result of ideal 1200V IGBT theoretical limit, [1-2] the $V_{ce(sat)}$ is about 0.9V at current density 100A/cm^2. Therefore, the proposed IGBTs are very close the theoretical limit due to superior conductivity modulation effect. It can be seen that the saturation current density of the proposed structure is similar with other structure and there is no degeneration behavior, which is unlike the structure with very narrow mesa channel region. [1-4] Moreover, it can be noted that the saturation current of the proposed structure becomes a slightly higher around 20V. This phenomenon may related to the proposed structure is hard to pinch off at channel region due to the very high dose concertation of CS layer.

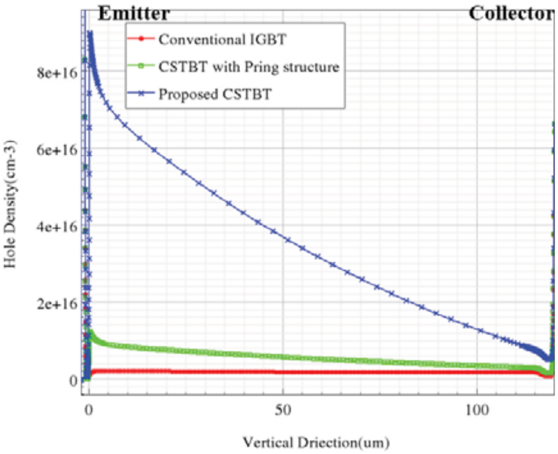

Fig. 3. The hole density distribution along line A (at current density=150A/cm^2)

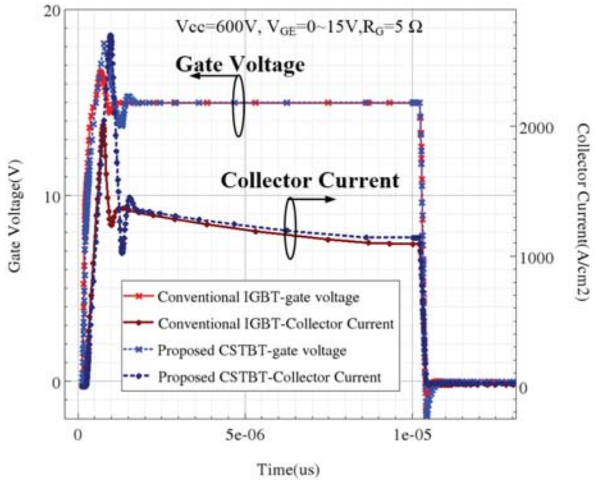

Fig. 4. Simulated short circuit waveforms of the conventional IGBT and the proposed structure. All structures can withstand 10μs short-circuit current.

The breakdown voltage of the conventional IGBT, the CS IGBT with P-ring structure and the proposed structure at 100μA/cm2 are 1.47kV, 1.51kV and 1.42kV, respectively. Obviously, The breakdown voltage of the proposed structure at high CS doping concentration is similar with the conventional structure due to the depletion effect of the grounded floating P-body. The threshold voltage of three structures at drain current of 1mA are 3.51V, 3.51V and 3.33V, respectively.

Fig. 4 shows that the conventional structure and the proposed structure can withstand 10μs short-circuit current at the same bias conditions. In the proposed structure, the adjacent conduction channel in the same active cell region is not need to shrink to the nanometer level, which can avoid the CIBL behavior effectively. In addition, it is worth to noting that the saturation current in the short circuit waveforms is lower than the saturation current of I-V characteristic given in the Fig.2. The main reason is that the degeneration effect of the mobility by using the thermal model in the short circuit simulation but not using in the I-V characteristics simulation. Thus, it brings to the relatively small saturation current phenomenon in the short circuit simulation and the similar situation also can be seen in the Ref. [2,7]

IV. CONCLUSION

A novel CSTBT by using the very narrow mesa structure in the floating pwell region to deplete the high dose concentration CS layer. Based on the structure improvement, the conductivity modulation effect of the proposed structure can be enhanced significantly. In addition, the mesa width of the conductive channel region in the proposed structure can be designed with the normal size, which can avoid the CIBL behavior induced by the very narrow conductive channel structure. Therefore, the proposed structure can achieve ultra-low on-state saturation voltage closed to the theoretical limit without the degeneration of the short-circuit behavior.

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