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A Novel Approach to Suppress the Collector Induced Barrier Lowering (CIBL) Effect in Narrow Mesa IGBTs

Peng Luo, Hong Yao Long, and E. M. S. Narayanan, *Senior Member*, *IEEE*

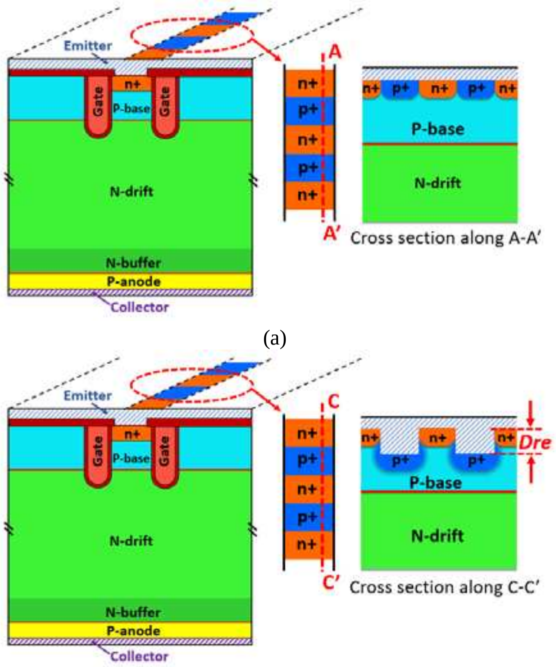
***Abstract*— A recessed p$^+$-cathode IGBT (RP-IGBT) structure with very narrow mesa is analysed through 3-D simulations in 1.2-kV, field stop technology. Compared to a conventional narrow mesa IGBTs, the RP-IGBT can effectively restrain the collector-induced barrier lowering (CIBL) effect and hence, two-thirds reduction in saturation current can be achieved. As a result, more than 10μs short circuit capability is enabled at a junction temperature of 400K. Most importantly, the proposed RP-IGBT structure has no influence upon on-state performance and its forward voltage drop remains at 1.1V at a current density of 200A/cm^2 at 400K.**

***Index Terms*—IGBT, RP-IGBT, recessed p$^+$-cathode, narrow mesa, collector induced barrier lowering (CIBL), short circuit capability.**

I. INTRODUCTION

IMPROVING efficiency in power conversion is essential to counter the significant increase in demand for worldwide electrical energy, as 25-40% of wasted energy can be saved by using state-of-the-art power semiconductor technologies [1]. For medium to high power conversion applications, silicon based IGBTs play a crucial role and the theoretical limit of on-state performance has yet to be reached even after ~40 years of continuous technology advancement [2]. Most recent developments on trench gated IGBTs are focussed upon scaling down mesa regions sandwiched between the gates to reduce on-state losses by enhancing the injection enhancement (IE) effect [3-6]. However, the IGBTs with very narrow mesa suffer from poor short circuit robustness because of the collector induced barrier lowering (CIBL) effect [7, 8], which occurs at the P-base/n$^+$-cathode junction caused by the conductivity modulation in the channel inversion layers [9].

In this letter, a recessed p$^+$-cathode IGBT (RP-IGBT) structure is suggested to restrain the CIBL effect of the very narrow mesa IGBTs without degrading on-state performance. 3-D TCAD tools in Synopsys Sentaurus Device are used to investigate the electrical characteristics of the 1.2-kV Field Stop RP-IGBT [10] with models calibrated against the simulated data in [9].



(a)

(b)

Fig. 1. Schematic cross-sections of (a) the conventional narrow mesa IGBT and (b) the proposed RP-IGBT structure.

II. DEVICE STRUCTURE AND STATIC CHARACTERISTICS

The single cell schematic cross-sections of the conventional narrow mesa IGBT and the proposed RP-IGBT structure are shown in Fig. 1(a) and (b), respectively. It can be seen from the top view that both structures feature ladder design of the mesa regions and trench gates run across the active areas. Major structural parameters are kept identical for comparison and summarized in Table I. The cell pitch is 10μm and the mesa width is 400nm. A carrier lifetime of 10μs is set as default. Both conventional IGBT-A and IGBT-B are benchmarks while the P-base peak doping concentration of IGBT-B is significantly increased to lower its J_{sat} to ~1100A/cm^2 at T_j=300K. In the

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TABLE I
MAJOR STRUCTURAL PARAMETERS

Parameters (Unit:μm)	***Conv. IGBT-A***	***Conv. IGBT-B***	***RP-IGBT***
Cell Pitch	10	10	10
Mesa width	0.4	0.4	0.4
Gate oxide thickness	0.03	0.03	0.03
n^+ cathode length	1	1	1
p^+ cathode length	1	1	1
P-base depth	1.3	1.3	1.3
n^+ cathode depth	0.3	0.3	0.3
p^+ cathode depth	0.3	0.3	0.3
Trench depth	2.5	2.5	2.5
Recess depth (D_{re})	N.A.	N.A.	0.5
P-base peak doping (cm^{-3})	7e17	1.1e18	7e17

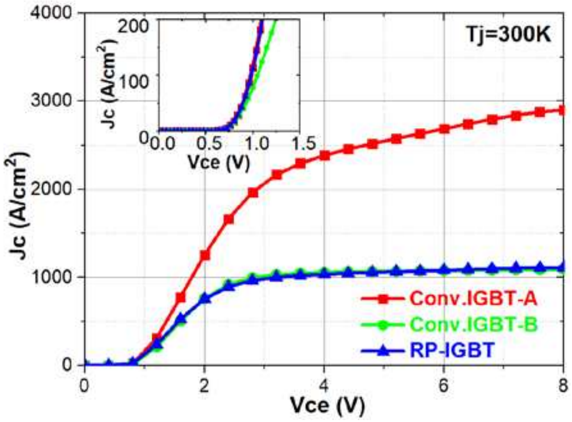
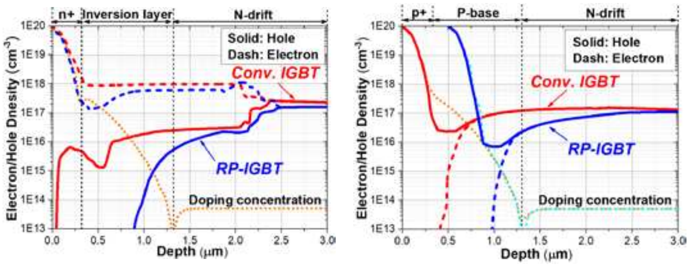


Fig. 2. J_c-V_{ce} characteristics of conventional IGBTs and RP-IGBT. (V_g=5V)

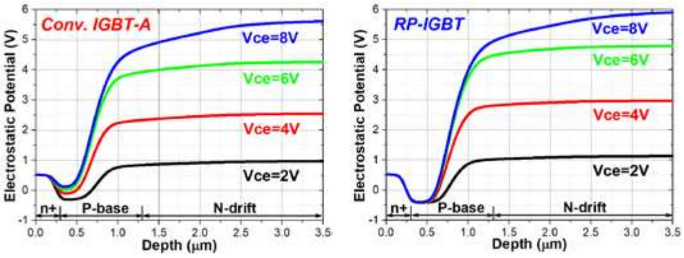
RP-IGBT structure, after the implantation of n^+-cathode, 0.5μm of silicon is etched prior to the implantation of the recessed p^+-cathode. The lateral diffusion of the recessed p^+-cathode moves into the P-base region below n^+-cathode regions, which helps to maintain the P-base/n^+-cathode junction barrier and suppresses the CIBL effect. More importantly, as the P-base region is not penetrated by the p^+-cathodes, there is no influence upon threshold voltage as well as on-state voltage.

Fig.2 depicts the J_c-V_{ce} characteristics of the conventional and proposed devices, while Fig. 3 and Fig. 4 compare the carrier distributions and on-state potential distributions within the mesa regions between the conventional IGBT-A device and the RP-IGBT device, respectively. It can be observed from Fig. 2 that the conventional IGBT-A shows non-saturated tendency of the J_c-V_{ce} characteristics due to CIBL effect [7]. The CIBL mechanism can be explained as follows: during forward conduction, the whole mesa region becomes conductivity modulated, which is caused by the hole current flowing into the inversion layers and n^+-cathode, as shown in Fig. 3(a). As a result, it can be seen from Fig. 4(a) that the P-base/n^+-cathode junction barrier reduces significantly with increased collector voltage resulting in the non-saturation behaviour of the collector current, which will cause premature latch-up and degrade the short circuit capability. Increasing P-base doping concentration is a potential solution to lower J_{sat} at the expense of increase in the threshold voltage, which will influence the on-state performance, as illustrated in Fig. 5(a). Moreover, it can be observed from Fig. 5(b) that the CIBL effect continues to exist to cause conductivity modulation in the P-base region of the conventional IGBT-B device.



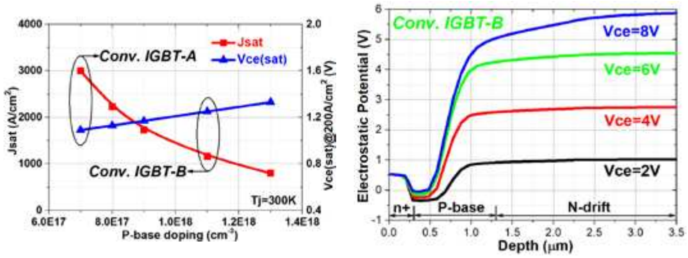
(a) (b)

Fig. 3. Comparison of carrier distributions within mesa regions between conventional IGBT-A and RP-IGBT. (a) Across n^+-cathode/inversion layer/ N-drift, (b) across p^+-cathode/P-base/N-drift. (V_g=5V, J_c=500A/cm^2)



(a) (b)

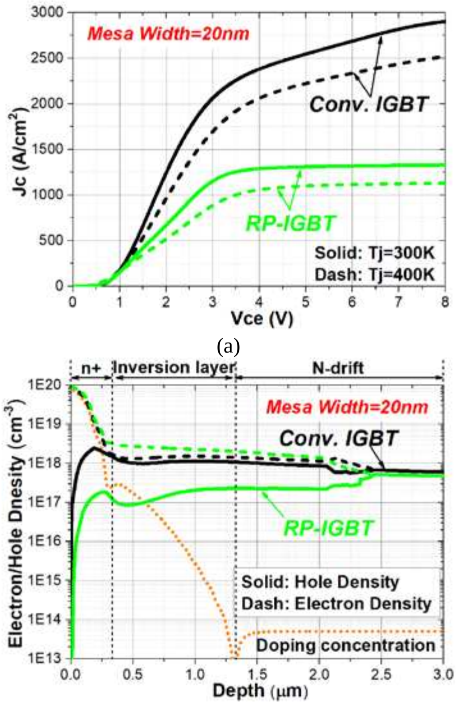
Fig. 4. Comparison of potential distributions within the middle of mesa regions between (a) conventional IGBT-A and (b) RP-IGBT. (V_g=5V)



(a) (b)

Fig. 5. (a) Dependence of P-base doping concentration upon $V_{ce(sat)}$ and J_{sat} of the conventional narrow mesa IGBT. (b) Potential distributions within the mesa region of the conventional IGBT-B device. (V_g=5V)

In contrast, it should be noted from Fig. 2 that the proposed RP-IGBT can reduce the J_{sat} to ~1100A/cm^2 at T_j=300K without increase of P-base doping concentration. Significant reduction in J_{sat} can be explained by the fact that the recessed p^+-cathode diverts the flow of holes into the p^+-cathode rather than the channel inversion layers. It is evident from Fig. 3(a) that the hole density in the inversion layer of the RP-IGBT is significantly reduced compared to that of conventional IGBT. Therefore, the conductivity modulation is effectively suppressed in the P-base region, as shown in Fig. 3(b). Furthermore, the lateral diffusion of the p^+-cathode increases the acceptor concentration beneath the P-base/n^+-cathode junction and contributes to maintain the P-base/n^+-cathode junction barrier during conduction. Due to the suppression of conductivity modulation in the mesa region, the P-base/ n^+-cathode junction barrier does not decrease with increased collector voltage, as illustrated in Fig. 4(b). Consequently, the current saturation characteristics are significantly improved compared to that of the conventional narrow mesa IGBT.



(a)

(b)

Fig. 6. Comparison of (a) J_c-V_{ce} characteristics and (b) carrier distributions within mesa regions for the case of 20nm mesa structures. (V_g=1.2V)

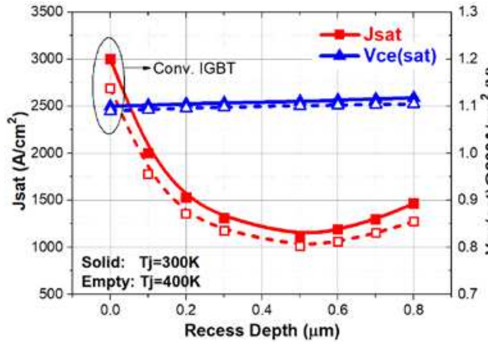


Fig.7. Influence of recess depth upon $V_{ce(sat)}$ and J_{sat}. (V_g=5V)

Moreover, note that RP-IGBT structure can suppress the conductivity modulation in the channels and enable current saturation behaviour even though the mesa width is reduced to 20nm, as shown in Fig. 6.

Fig. 7 shows the influence of the recess depth of the p$^+$-cathode upon the $V_{ce(sat)}$ and J_{sat} of RP-IGBT. As shown, the recess depth does not affect the on-state performance. This is because the lateral diffusion of the p$^+$-cathode does not affect the threshold voltage as well as the channel resistance of the RP-IGBT. However, its saturation current density shows significant reduction as the recessed depth increases and tends to increase when the recessed depth exceeds 0.5μm. This is because the lateral diffusion of the p$^+$-cathode has less influence on the P-base/n$^+$-cathode junction barrier when the recessed depth is deeper and away from this junction.

III. SHORT-CIRCUIT CHARACTERISTICS

The short-circuit withstand capability of the proposed RP-IGBT structure is investigated in Fig. 8. The DC bias is 800V, the rated current is 100A at a current density of 200A/cm^2. In addition, self-heating effect is considered herein and the initial junction temperature is set as 400K. Unlike the conventional IGBT-A device which fails immediately after the device turns ON, the RP-IGBT device clearly shows more than 10μs short-circuit withstand capability, which is also superior to that of the conventional IGBT-B device. This short-circuit robustness is contributed by the recessed p$^+$-cathode which suppresses the CIBL effect and maintains the saturation current level.

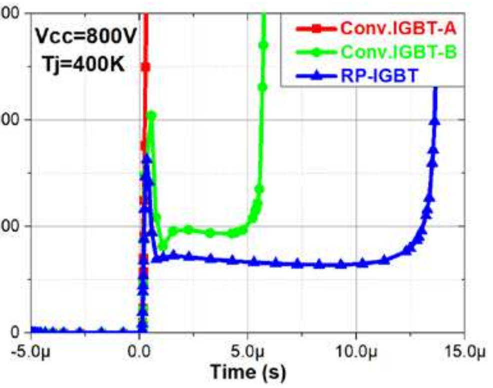
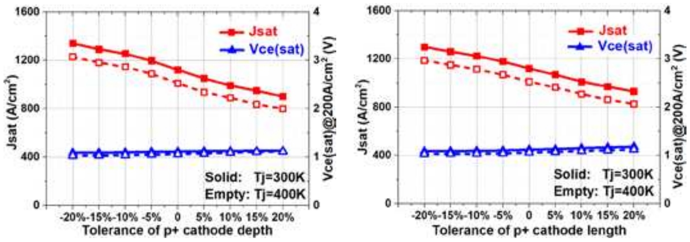


Fig. 8. Comparison of short-circuit characteristics between the conventional devices and the RP-IGBT device. (V_g=5V, R_g=22Ω)



(a) (b)

Fig. 9. Influence of the tolerance of (a) p$^+$-cathode depth and (b) p$^+$-cathode length upon $V_{ce(sat)}$ and J_{sat}. (V_g=5V)

IV. SENSITIVITY ANALYSIS

From a fabrication point of view, a robust process compatibility is essential to meet the commercially available technologies. The sensitivity of the recessed trench depth is shown in Fig.7, while Fig. 9 shows the sensitivity analysis of the recessed p$^+$-cathode. As shown, even with a tolerance of plus or minus 20%, there is no significant influence upon electrical characteristics. Therefore, RP-IGBT structure is fully compatible with narrow mesa IGBT processing technologies.

V. CONCLUSION

A method to suppress the CIBL effect in a narrow mesa IGBT is proposed and analysed. Compared with the conventional narrow mesa IGBT, the 3-D simulation results show that the recessed p$^+$-cathode in an IGBT can significantly reduce the saturation current level while maintaining the on-state performance. Due to the suppression of CIBL effect, the short-circuit capability is enabled. Therefore, the RP-IGBT structure can provide a much wider short circuit safe operating area (SCSOA) than the conventional narrow mesa IGBTs.

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