A novel lateral IGBT with a controlled anode for on-off-state loss trade-off improvement*

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Abstract: A new lateral insulated-gate bipolar transistor with a controlled anode (CA-LIGBT) on silicon-on-insulator (SOI) substrate is reported. Benefiting from both the enhanced conductivity modulation effect and the high resistance controlled electron extracting path, CA-LIGBT has a faster turn-off speed and lower forward drop, and the trade-off between off-state and on-state losses is better than that of state-of-the-art 3-D NCA-LIGBT, which we presented earlier. As the simulation results show, the ratios of figure of merit (FOM) for CA-LIGBT compared to that of 3-D NCA-LIGBT and conventional LIGBT are 1.45 : 1 and 59.53 : 1, respectively. And, the new devices can be created by using additional silicon direct bonding (SDB). So, from the power efficiency point of view, the proposed CA-LIGBT is a promising device for use in power ICs.

Key words: controlled anode; turn-off time; forward drop; power IC

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1. Introduction

The lateral insulated-gate bipolar transistor (LIGBT) is a promising power device for power ICs. Conductivity modulation permits LIGBT to have low forward drop, but it also causes slow turn off due to the removal of stored electron-hole plasma in the drift region, which is strongly dependent on the recombination process of the electron–hole pairs during the turn-off period. Recently, various approaches[1] have been reported for optimization of the LIGBT structures to achieve fast turn-off speed or/and make good trade-off between on-state and off-state losses. These include passive PMOS driving LIGBT[2], shorted anode LIGBT (SA-LIGBT)[3], segmented anode LIGBT (SA-LIGBT)[4], gradual hole injection dual gate LIGBT (GHI-LIGBT)[5], segmented anode NPN controlled LIGBT[6], dual gate inversion layer emitter transistor (DG-ILET)[7] and n-region controlled anode LIGBTs[8, 9].

In this paper, a novel LIGBT with a controlled anode (CA-LIGBT) on silicon-on-insulator (SOI) substrate, of which the trade-off between off-state and on-state losses is better than that of state-of-the-art 3-D NCA-LIGBT[8], is proposed and discussed for the first time. Two-dimensional numerical simulations[10] are carried out to help with the analysis of the characteristics for the proposed CA-LIGBT.

2. Device concept and operation

The simplified schematic of the proposed CA-LIGBT is illustrated in Fig. 1(a). A trench oxide is added at the anode part for the new structure. A high resistance controlled n-region whose doping concentration is as low as that of the n-drift region is formed under anode P^+ diffusion. Figure 1(b) is for CA-LIGBT with only anode trench oxide to show the net effect of n-drift enhanced conductivity modulation because of anode trench oxide. Figures 1(c) and 1(d) are for the 3-D NCA-LIGBT and conventional LIGBT. It is noted that the new devices can be created by using additional silicon direct bonding (SDB).

For a LIGBT, the common base current gain of the inherent PNP transistor (anode P^+/N-drift/cathode P-base) is $\alpha_{PNP} = \alpha_T M \gamma_E$, where α_T is the base transport factor, which is dependent on lifetime and minority carrier diffusivity, M is the avalanche multiplication factor, which in high voltage devices can be considered as unity, γ_E is the emitter injection efficiency, which is dependent on the base and emitter Gummel numbers. For given cathode and drift region, changing the design of the anode scheme only influences the emitter Gummel number, which depends on the dimensions and doping concentration of the anode region(s).

As for our proposed CA-LIGBT, trench oxide can enhance the conductivity modulation effect in the n-drift region during the on-state. At the forward bias, the electrons diffusing toward the anode part in the proposed CA-LIGBT cannot be collected rapidly and accumulate in the n-buffer and n-drift regions, leading to an increase in electron concentration in these regions. The electrons, providing the base drive for the PNP transistor inherent in the LIGBT, in turn enhance the hole injection from the anode P^+ to maintain electrical neutrality in conductivity modulation regions. Thus, the effect of conductivity modulation in the n-drift and n-buffer regions is enhanced.

The high resistance controlled n-region affects both the forward state and the off state: during the turn-on state, according to the analysis in Ref. [8], hole injection can be initiated at a much lower applied anode voltage, which effectively suppresses snapback in the conducting state without sacrificing the high current handling capability. During the turn-off state, it acts as the electron extracting path, and the proposed CA-LIGBT has a faster switching speed and lower turn-off loss.

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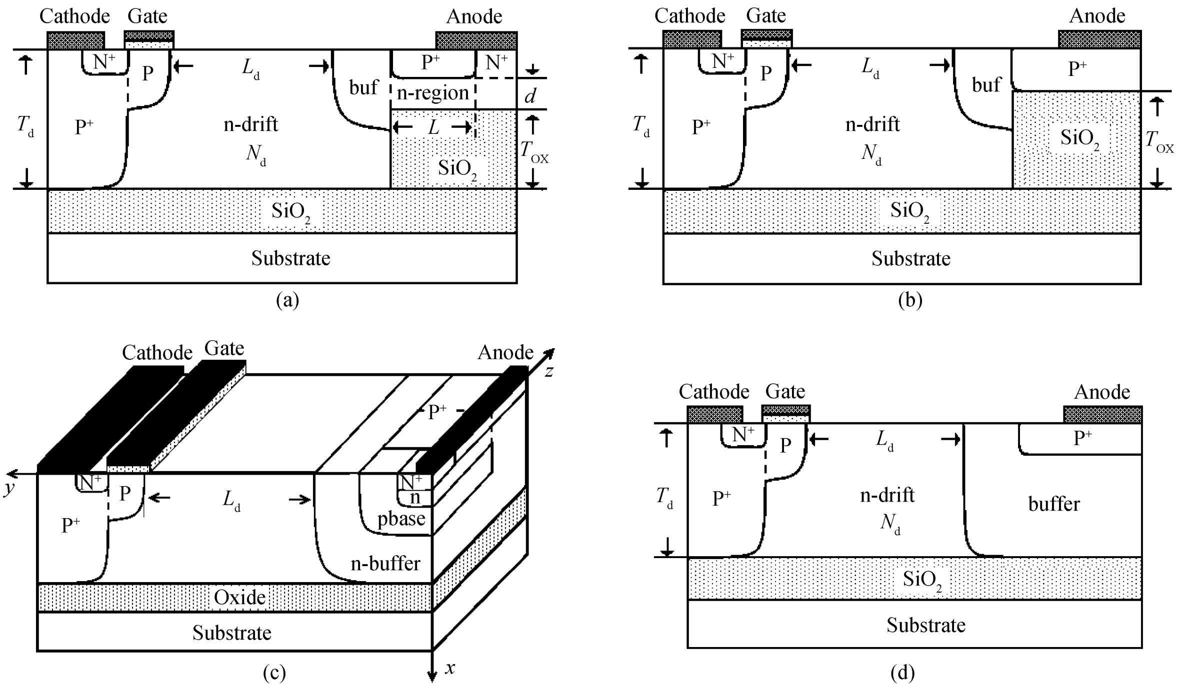

Fig. 1. Simplified schematic of (a) the proposed CA-LIGBT, (b) CA-LIGBT with only anode oxide, (c) 3-D NCA-LIGBT and (d) conventional LIGBT. n-drift thickness $T_d = 5$ μm, length $L_d = 22$ μm and doping concentration $N_d = 1.5 \times 10^{15}$ cm^{-3}; anode oxide thickness $T_{ox} = 4$ μm.

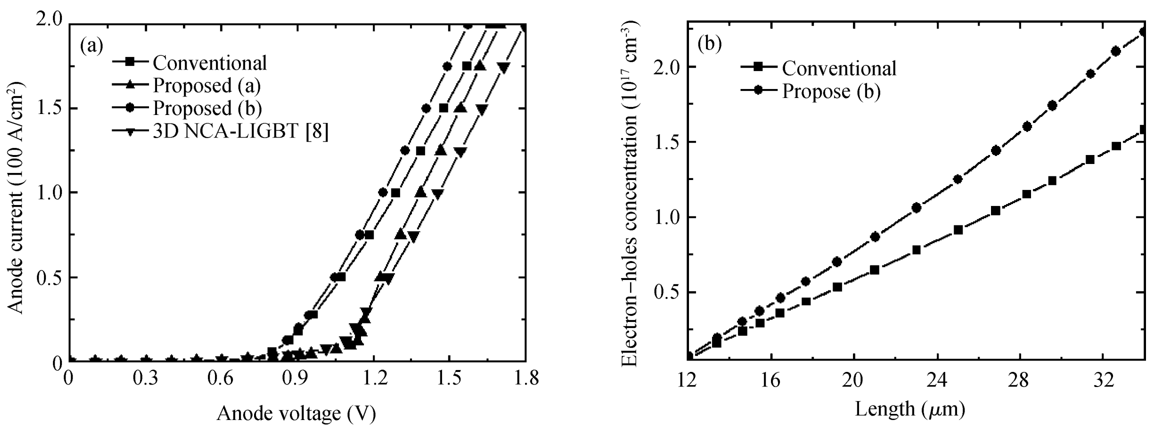

Fig. 2. I–V characteristics of (a) conventional LIGBT, CA-LIGBT, CA-LIGBT with only anode oxide and 3D NCA-LIGBT, and (b) electron–hole concentration in n-drift of conventional LIGBT and CA-LIGBT with only anode oxide at an anode current density of 100 A/cm^2. Lifetimes of carriers are 1 μs, temperature is 300 K; for CA-LIGBT, high resistance controlled n-region length, $L = 3$ μm and thickness, $d = 0.4$ μm

The novel design of the proposed CA-LIGBT inherits the advantages of both the enhanced conductivity modulation effect by the trench oxide and the high resistance controlled n-region as the electron extracting path during the turn-off state.

3. Results and discussion

Figure 2(a) shows the I–V characteristics of conventional LIGBT, CA-LIGBT, CA-LIGBT with only anode oxide and 3D NCA-LIGBT. All of these devices have the same structure and parameters except the anode part. Hole injection for CA-LIGBT is initiated at low applied anode voltage (the turn in point is about 1.15 V), and there is no snapback but holding high current handling capability. Figure 2(b), illustrating electron–hole concentration in n-drift of conventional LIGBT and CA-LIGBT with only anode oxide, shows the net effect of n-drift enhanced conductivity modulation because of anode trench oxide. It is worth noting that the forward drop of CA-LIGBT with only anode oxide is the lowest due to the net enhanced conductivity modulation effect by trench oxide at the anode part. That the forward drop of CA-LIGBT is slightly higher than that of the conventional one but lower than that of 3D NCA-LIGBT is because of both effects of trench oxide and the high resistance controlled n-region for the anode part.

Equations ((1) and (2)) show the figure of merit (FOM). For drive application, neglecting the turn-on, driving, and non-

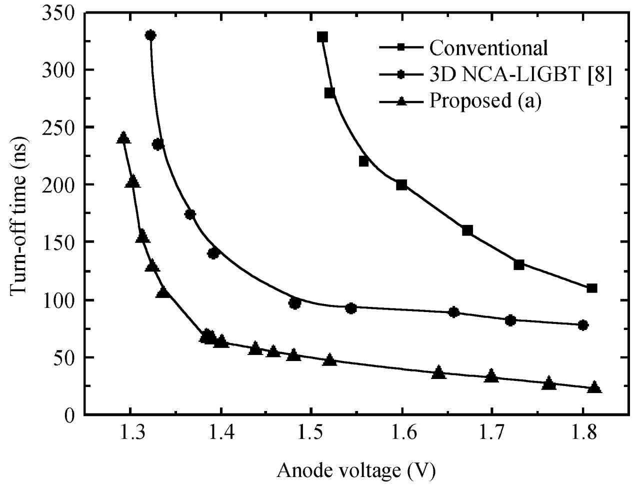

Fig. 3. Turn-off time/forward voltage drop trade-off curves obtained through control of the anode hole injection efficiency of conventional LIGBT, 3D NCA-LIGBT and CA-LIGBT.

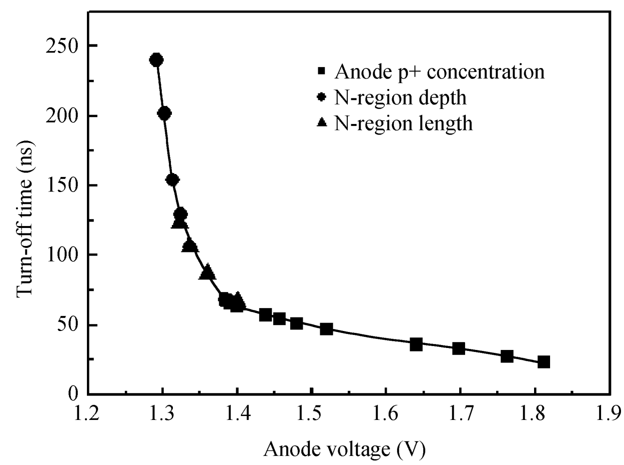

Fig. 4. Turn-off time/forward voltage drop trade-off curves obtained through control of the key parameters of the proposed CA-LIGBT: the anode P^+ concentration; high resistance controlled n-region depth and length.

conducting state losses the conducting loss and turn-off loss are the most important parts in the total loss of LIGBT[11].

$$\mathrm{FOM} = \frac{J_\mathrm{C}}{v_\mathrm{on} e_\mathrm{off}}, \quad (1)$$

$$e_\mathrm{off} = \frac{1}{6} V_\mathrm{s} J_\mathrm{C} t_\mathrm{off}, \quad (2)$$

where J_C is the current density, 100 A/cm^2; v_on is the forward drop at current density J_C; e_off is the turn-off switching energy per pulse of operation; V_s is the applied voltage, 100 V for simulation. The ratios of FOM for CA-LIGBT compared to that of 3-D NCA-LIGBT and conventional LIGBT are 1.45 : 1 and 59.53 : 1, respectively.

Also, Figure 3 shows turn-off time/forward voltage drop trade-off curves obtained through control of the anode hole injection efficiency of conventional LIGBT, 3D NCA-LIGBT and the proposed CA-LIGBT. Figure 4 shows turn-off time/forward voltage drop trade-off curves obtained through control of the key parameters of the proposed CA-LIGBT. As can be observed clearly from these two figures, the trade-off curve of the proposed CA-LIGBT lies below that of 3D NCA-LIGBT and conventional LIGBT, and all of the proposed structures with different parameters lie on the same trade-off curve. So, from a power efficiency point of view, the proposed CA-LIGBT is a promised device used in power ICs.

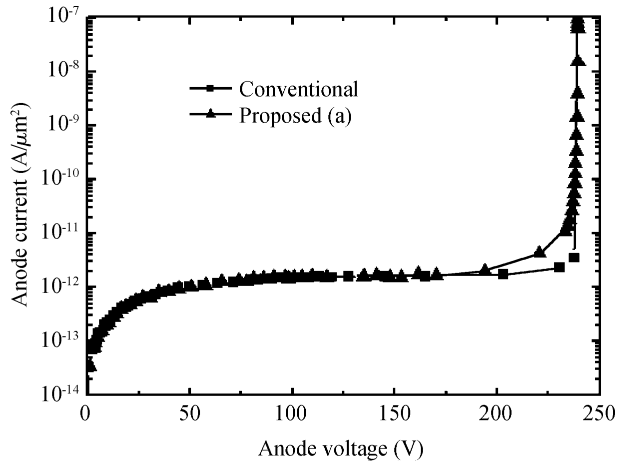

Fig. 5. Breakdown characteristics of conventional LIGBT and CA-LIGBT; lifetimes of carriers $t = 1$ μs, temperature $T = 300$ K.

Figure 5 shows breakdown characteristics of conventional LIGBT and CA-LIGBT. The proposed CA-LIGBT has the same high breakdown voltage as that of conventional one.

4. Conclusion

The operation mechanism and simulation analysis of novel fast speed LIGBT are explained in detail. The new device has higher FOM and better trade-off curves between off-state and on-state losses than that of state-of-the-art 3-D NCA-LIGBT. The proposed CA-LIGBT also has the advantages of effective snapback suppression in forward I–V characteristics and high breakdown voltage.

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