Novel lateral IGBT with n-region controlled anode on SOI substrate

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Abstract: A new lateral insulated-gate bipolar transistor (LIGBT) structure on SOI substrate, called an n-region controlled anode LIGBT (NCA-LIGBT), is proposed and discussed. The n-region controlled anode concept results in fast switch speeds, efficient area usage and effective suppression NDR in forward *I–V* characteristics. Simulation results of the key parameters (n-region doping concentration, length, thickness and p-base doping concentration) show that the NCA-LIGBT has a good tradeoff between turn-off time and on-state voltage drop. The proposed LIGBT is a novel device for power ICs such as PDP scan driver ICs.

Key words: turn-off time; on-state voltage drop; NDR; power ICs
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1. Introduction

The lateral insulated-gate bipolar transistor (LIGBT) is a promising power device for power ICs due to its combination of the high input impedance of the MOS gate and the conductivity modulation effect of the bipolar transistor. The conductivity modulation permits the LIGBT to have a low on-state voltage 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[1, 2]. Various approaches have been reported in the literature to improve the switching performance or to make a good tradeoff between on-state voltage drop and turn-off time for the LIGBT. These include the shorted anode LIGBT (SA-LIGBT)[2, 3], NPN controlled anode structure[4], the segmented anode concept[5, 6], multi-gate devices[7–10] and lifetime control engineering[11, 12]. The use of lifetime control engineering to reduce carrier lifetime increases cost due to the addition of a further process step. The NPN controlled anode structure suffers from large forward voltage drop because of its low current gain. The asymmetric anode structure allows the segmented anode structures to suffer from disadvantages such as asymmetrical current flow in the n-drift region. Multi-gate devices require complex control circuitry to switch the gates at the anode (high voltage) end. The shorted anode concept offers the simplest solution but introduces undesirable voltage snapback or negative differential resistance (NDR) into the forward current–voltage (*I–V*) characteristics due to the change-over from unipolar to bipolar current conduction, which can lead to system instability[13]. Furthermore, to prevent punch-through breakdown, a highly conductive n-buffer region should be employed in the anode region. Therefore, a very long p injector is required to suppress the NDR regime. This makes the device less area-efficient, especially for the middle breakdown voltage (above 200 V) power devices because of the small n-drift length. In this paper, a novel fast switching speed n-region controlled anode LIGBT on silicon-on-insulator (SOI) substrate is proposed and discussed. SOI substrates overcome the deep plasma injection into the substrate for junction-isolation substrates[14, 15].

2. Device structure and operation

2.1. Device structure

A schematic cross section of the proposed LIGBT on SOI substrate is illustrated in Fig. 1.

Distinct from the conventional LIGBT anode structure only including a P+ region, the NCA-LIGBT anode has a special design including a P+ region, N+ region, p-base region and n-region. The anode n-region, which can be formed by high energy phosphorus implantation after p-base region formation, is a key concept for the NCA-LIGBT to have fast turn-off speeds and efficient area usage. The n-drift region doping concentration was optimized to fulfil the RESURF condition[16]. Table 1 shows the device parameters used in the numerical simulation.

2.2. Operation

When a voltage above the threshold is applied to the gate, the proposed device is turned on. At a low forward bias, electrons that flow from the channel through the drift region are collected by the anode n+ region, and the transistor operates

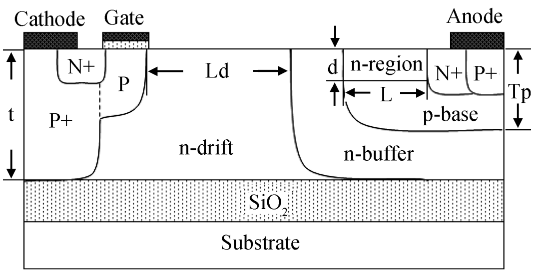

Fig. 1. Schematic cross-sectional view of the proposed LIGBT.

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Table 1. Device parameters used in the simulation.

Device parameter	Value	Unit
N-drift region length, L_d	21	μm
N-drift region doping concentration	1.5×10^{15}	cm^{-3}
N-drift region thickness, t	5	μm
SiO_2 layer thickness	3	μm
N-region length, L	3.0–6.0	μm
N-region thickness, d	0.22–0.38	μm
N-region doping concentration, N_n	0.2×10^{16}–1.2×10^{16}	cm^{-3}
P-base region thickness, T_p	2	μm
P-base doping concentration, $N_{p\text{-base}}$	2×10^{17}–8×10^{17}	μm
Gate voltage	15	V
Cathode voltage	0	V
Substrate voltage	0	V

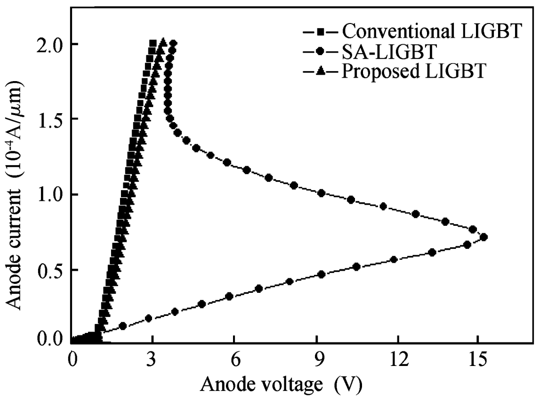

Fig. 2. Forward I–V characteristics of the conventional LIGBT, SA-LIGBT and proposed LIGBT.

like a lateral double-diffused MOS transistor (LDMOS). As the anode voltage increases, the electron current increases, so does the voltage drop across the anode n-region. When the anode p-base/n-buffer junction is forward biased, holes injecting from the anode modulate the conductivity of the highly resistive n-drift region, resulting in rapid increase of the anode current with anode voltage increase. Here, it should be noted that for the proposed LIGBT, due to the thin anode n-region (small d value in the structure), hole injection from anode is initiated even under low anode voltage. This allows the proposed device to have a shorter anode length (efficient area usage) but effectively suppress NDR in the forward I–V characteristics compared to the SA-LIGBT. Figure 2 shows the I–V characteristics of the conventional LIGBT, SA-LIGBT and proposed LIGBT. With the same anode length, the SA-LIGBT has bad voltage snapback, but the proposed device does not.

When the gate voltage falls down below the threshold voltage, the device is switched from the ON state to the OFF state; the electron–hole plasma existing in the drift region must be removed prior to device turn-off. In the case of the conventional LIGBT, removal of the electron–hole plasma during device turn-off relies on electron–hole recombination. Depending on the lifetime of the minority carriers, the recombination process is lengthy, which results in slow device turn-off. However, in the case of the proposed LIGBT, due to the existence of the electron conduction path, the electron–hole plasma present in the drift region can be removed with the electrons extracted through the anode n-region and holes extracted through the cathode. This results in significant improvement in device turn-off time.

3. Simulation results and discussion

In numerical simulation with a Silvaco simulator[17], the conventional and proposed LIGBTs have the same structure except for the anode part. For the NCA-LIGBT, the anode n-region is the key concept. Equations (1a, 1b) show the relationship of the key parameters (N_n, L, d) for initiating hole injection from the anode into the n-drift region:

$$V_{\text{n-region}} = \frac{I_{\text{MOS}} L}{q u_n N_n d w}, \tag{1a}$$

$$V_{\text{anode}} = V_{\text{n-region}} + V_{\text{others}}, \tag{1b}$$

where $V_{\text{n-region}}$ is the lowest voltage drop across the anode n-region for initiating hole injection (unchangeable for special n-buffer and p-base doping concentrations), I_{MOS} is the current flow of the MOS channel, q is the basic charge, u_n is the electron mobility, w is the third dimension device length and in our two-dimension simulation w = 1 μm, V_{anode} is the applied anode voltage, and V_{others} includes the voltage drops of the MOS channel, n-drift region and n-buffer region.

Figure 3 shows the turn-off and forward I–V characteristics of the conventional LIGBT, SA-LIGBT and NCA-LIGBT. The conventional LIGBT and NCA-LIGBT both have 10 μm anode length, but the SA-LIGBT has 30 μm anode length and is without the n-buffer region to suppress the NDR region in I–V characteristics. This makes the SA-LIGBT less efficient in area usage.

For NCA-LIGBT and SA-LIGBT anode structures, with access to the electrons, the electron–hole plasma present in the drift region can be removed with the electrons extracted through the electron path and holes extracted through the cathode. Therefore, from Fig. 3, the turn-off times of the

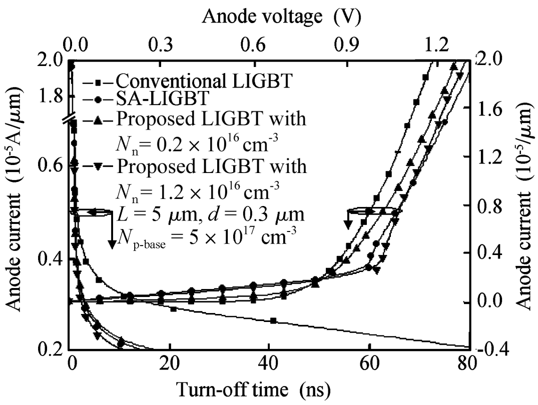

Fig. 3. Turn-off and forward *I–V* characteristics of the conventional LIGBT, SA-LIGBT and NCA-LIGBT.

proposed LIGBT and SA-LIGBT are both much smaller than that of the conventional one. For NCA-LIGBT forward *I–V* characteristics, according to Eqs. (1a, 1b), the anode voltage (V_{anode}) for initiating hole injection from the anode into the n-drift region increases as N_n increases. Furthermore, the higher N_n, the lower current gain of PNP (anode P-base region/n-drift/cathode P region), and the higher on-state voltage drop at the same current level. Due to the presence of the anode n+/n region which acts as the electron conduction path during the turn-off period, hole injection from the anode into the n-drift region is weakened, and therefore, at the same current level, the on-state voltage drops of NCA-LIGBT and SA-LIGBT are both slightly larger than that of the conventional one.

To quantitatively explain the advantages of the NCA-LIGBT, we define the turn-off time increment ratio R_{time} and on-state voltage drop increment ratio $R_{voltage}$ as follows:

$$\begin{cases} R_{time} = \dfrac{t - t_0}{t_0} \times 100\%, \\ R_{voltage} = \dfrac{V - V_0}{V_0} \times 100\%, \end{cases} \quad (2)$$

where t, t_0 and V, V_0 are the turn-off times and on-state voltage drops for the proposed and conventional LIGBT, respectively. In our two-dimension simulation, the on-state voltage drop is defined as the applied anode voltage when the applied anode current is 2.0×10^{-5} A/μm during the on state; the turn-off time is defined as the time during which the anode current falls from 1.8×10^{-5} A/μm (90% applied anode current) to 0.2×10^{-5} A/μm (10% applied anode current) during the off state.

With L = 5 μm, d = 0.3 μm and $N_{p\text{-base}} = 5.0 \times 10^{17}$ cm^{-3}, Figure 4 illustrates the turn-off time increment ratio and on-state voltage drop increment ratio of the proposed LIGBT with different n-region doping concentrations (from 0.2×10^{16} to 1.2×10^{16} cm^{-3}). The on-state voltage drop increment is less than 9%, but the turn-off time decrement is from 81.1% to 88.7%, compared to that of the conventional LIGBT.

Figure 5 shows the tradeoffs between turn-off times and on-state voltage drops with different L and $N_{p\text{-base}}$. With $N_n = 0.4 \times 10^{16}$ cm^{-3}, d = 0.3 μm and $N_{p\text{-base}} = 5.0 \times 10^{17}$ cm^{-3}, for the n-region length changing from L = 6.0 μm to L = 3.0 μm, the on-state voltage drop increment is from 5% to 13%, and

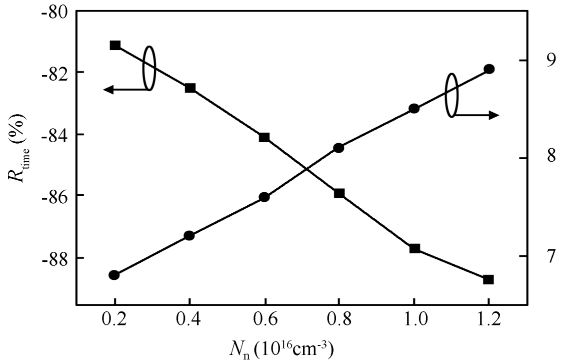

Fig. 4. R_{time} and $R_{voltage}$ with different N_n for the proposed LIGBT.

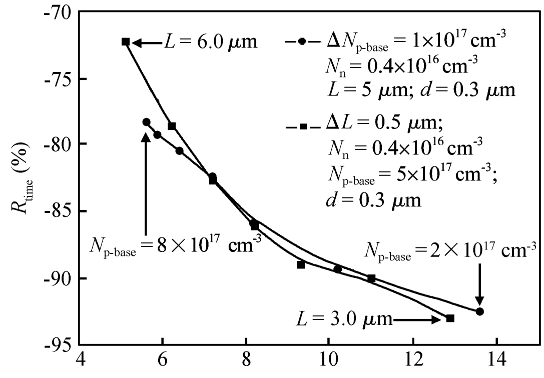

Fig. 5. Tradeoffs between turn-off times and on-state voltage drops with different L and $N_{p\text{-base}}$.

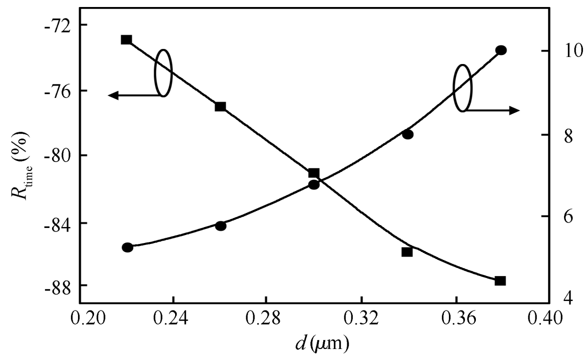

Fig. 6. R_{time} and $R_{voltage}$ with different d of the proposed LIGBT.

the turn-off time decrement is from 73% to 93%, compared to that of the conventional LIGBT. For L = 3.0 μm, the on-state voltage drop increment is 12.9%, and the turn-off time decrement is 93.1%. This can be explained similar to Figs. 2 and 3 for the N_n variable. The p-base doping concentration is one of the parameters for initiating hole injection from the anode into the n-drift region and the current gain of PNP. The higher $N_{p\text{-base}}$ is, the larger the current gain of PNP, the smaller the on-state voltage drop and the longer the turn-off time obtained are. The R_{time} and $R_{voltage}$ characteristics with different $N_{p\text{-base}}$ are also illustrated in Fig. 5, too.

With L = 5 μm, $N_n = 0.2 \times 10^{16}$ cm^{-3} and $N_{p\text{-base}} = 5.0 \times 10^{17}$ cm^{-3}, Figure 6 illustrates the turn-off time increment ratio and on-state voltage drop increment ratio of the proposed LIGBT with different d (from 0.22 to 0.38 μm). The on-state voltage drop increments are very small (less than 10%), but the turn-off time decrements are prominent (about 72% to

85%), compared to that of the conventional LIGBT. It should be noted that for the n-region controlled anode concept, the thickness of the n-region is much smaller than that of the n-drift region. That is why the proposed LIGBT has efficient area usage, fast turn-off speed and is different from shorted anode structures.

4. Conclusion

In this paper, a novel SOI n-region controlled anode LIGBT has been proposed and discussed. The influences of the key parameters, the n-region doping concentration, length, thickness and p-base doping concentration, on the operation of the proposed LIGBT have been numerically simulated by a Silvaco simulator and discussed. Numerical simulation results show that by choosing reasonable parameters, the proposed LIGBT has fast switch speeds and efficient area usage. Furthermore, the operation characteristics are not very sensitive to the key parameters, so there is a large scope of fabrication parameter difference. This n-region controlled anode concept also has the advantages of effective suppression NDR in the forward *I–V* characteristics and not requiring any additional control circuit. So, the proposed LIGBT is a promising device used in middle frequency, middle power high voltage power ICs, such as PDP scan driver ICs[18].

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