Novel low loss and snapback-free SOI LIGBT controlled by anode junction self-built potential
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\textbf{Abstract} In this work, we evaluated a novel low loss and snapback-free silicon-on-insulator lateral insulated gate bipolar transistor (SOI LIGBT) by numerical simulation, which utilizes the inherent junction self-built potential (JSBP) to form depletion region at the anode. When the anode voltage ($V\text{\textsubscript{an}}$) is less than built-in potential ($V\text{\textsubscript{bi}}$), the introduced electron flow channel between P-anode pillars is occupied by the depletion region, which hinders electron current from flowing into N-anode and limits the device to working in MOS mode. Furthermore, due to the offset effect for the JSBP by higher $V\text{\textsubscript{an}}$, the depletion region disappears and the anode PN junction turns on, which makes the device work in IGBT mode forming normal electron and hole current. At the same forward voltage drop ($V\text{\textsubscript{F}}$) of 1.64V, extra electron flow channel makes the turn-off loss ($E\text{\textsubscript{off}}$) of proposed JSBP LIGBT 22.1% lower than that of conventional (Conv.) LIGBT. Moreover, considering to the same $E\text{\textsubscript{off}}$ of 0.3mJ/cm\textsuperscript{2}, the depletion region with low $V\text{\textsubscript{an}}$ contributes to relatively enhanced conductivity modulation, which makes $V\text{\textsubscript{F}}$ of proposed JSBP LIGBT reduce by 19.6% compared to separated shorted-anode (SSA) LIGBT, while also completely eliminates snapback effect. Therefore, the proposed JSBP LIGBT gains the best trade-off performance between $V\text{\textsubscript{F}}$ and $E\text{\textsubscript{off}}$.

\textbf{key words:} SOI LIGBT, depletion region, self-built potential, snapback, turn-off loss, forward voltage drop

\textbf{Classification:} Power devices and circuits

1. Introduction

The silicon-on-insulator lateral insulated gate bipolar transistor (SOI LIGBT) is suitable for power integrated circuits (PIC) as a kind of conductivity modulated power device, which has numerous consumer and industrial applications\textsuperscript{[1,2,3,4,5,6]}. Compared with currently used vertical design for IGBT, lateral design with flip-chip technique can lower the cost of the assembly while enable advanced embedding and stacking\textsuperscript{[7]}. Moreover, the SOI LIGBTs can achieve significantly lower leakage currents and better dielectric-isolation (DI) capability, which reduce power consumption during normal operation\textsuperscript{[8,9,10,11,12]}. Different from the fastfing turn-off capability of unipolar devices, LIGBT devices are limited by the minority carrier extraction, so it is necessary to optimize the tradeoff between forward voltage drop ($V\text{\textsubscript{F}}$) and turn-off loss ($E\text{\textsubscript{off}}$). The initial shorted-anode (SA) structure enhances the extraction of excess electrons to accelerate the turn-off process\textsuperscript{[13,14]}, but also results in the formation of negative differential resistance regime (NDR)\textsuperscript{[15]}. In order to avoid voltage snapback and keep the advantage of SA structure, the high fixed anode resistance can be obtained by extending or compressing the electron flow path, which ensures the normal hole injection process. For example, the further proposed separated shorted-anode (SSA) structure\textsuperscript{[16,17,18,19,20]}, and the trench barriers and shorted anode (TBSA) structure\textsuperscript{[21,22]} realize the suppression of voltage snapback phenomenon, but also brings higher drift resistance and larger chip area. After that, the NPN controlled anode (SA NPN) structure\textsuperscript{[23,24,25]}, and the trench/planar gate and integrated Schottky barrier diode (TP-SBD) structure\textsuperscript{[26,27]} have achieved completely snapback-free ability by introducing extra fixed turn-on voltage for SA structure, but it also leads to the weakening of the conductivity modulation ability of the device. Moreover, the multiple current P-plugs (MCP) structure\textsuperscript{[28]} is proposed based on the method of SA structure, which can form the electron channel under the N-anode region and improve the turn-off speed on the basis of restraining snapback phenomenon.

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but the disadvantage is that MCP structure needs complex process steps of multiple epitaxy and ion implantation. therefore, compared with fixed anode resistance and fixed anode turn-on voltage, the variable anode resistance has many advantages to meet the needs of eliminating snapback at the beginning of on-state and promoting electron extraction at the off-state.

In this paper, we proposed and analyzed the novel low loss and snapback-free SOI LIGBT controlled by anode junction self-built potential (JSBP). Through the depletion region formed by the JSBP between anode PN junction, the variable anode resistance can be gained in the anode region with the variation of anode voltage \((V_{AC})\), so the normal hole injection process can be ensured with high anode resistance, while the electron extraction process can be maintained with low anode resistance. The simulated results demonstrate that proposed JSBP LIGBT with complete snapback-free have achieved improved tradeoff performance between \(V_F\) and \(E_{off}\).

2. Device Structure and Mechanism

Figure 1 mainly shows the schematic cross-section of the proposed JSBP LIGBT and the conventional (Conv.) LIGBT. The anode region of proposed LIGBT can be equivalent to a three-layer structure. The innermost layer contains the P-anode region and extra introduced shorted N-anode region. And the middle layer is the lowly doped N-well region, which ensures that the depletion region formed by the JSBP can completely hinder electron current flowing into N-anode under low \(V_{AC}\). Meanwhile, as can be seen in Figure 1(a), the simplified equivalent circuit illustrates that anode PN junction is turned on when the voltage across PN junction \((V_{PN})\) is higher than the built-in potential \((V_{bi})\), thus the electron flowing channel resistance \((R_{fc})\) within the N-well region is greatly reduced due to the carrier accumulation instead of the depletion region. The outermost layer is the N-buffer region, which plays the buffer role for electric field to ensure breakdown ability.

In addition to the structural parameters given in table 1. At anode region of proposed LIGBT, the width and length of electron flowing channel are set as \(W_p\) and \(L_p\), respectively. Furthermore, the simulated results are implemented by two-dimensional numerical simulation tools (Sentaurus TCAD) [29] in this work. The used physical models including the doping-dependent Massetti model, the Carneli model for High-Field Saturation, Philips unified mobility, Auger recombination, Enhanced Lombardi mobility model, the recombination theory of Shockley–Read–Hall recombination, and Lackner avalanche generation [30].

When the anode PN junction is in the state of thermal equilibrium and zero-bias, due to the different doping concentrations and types on both sides, the \(V_{bi}\) is generated by the diffusion process of carriers, as shown in Figure 2. From [1], we can gain the expression of \(V_{bi}\) in equation (1):
depletion region width by solving the integral of equation (2).

Owing to the high value of \( N_d \), the depletion region width in P-anode \( (W_d) \) is almost negligible, while the depletion region width in N-well \( (W_d) \) can be written as equation (3) for \( N_d = N_d^c \):

\[
W_d = \frac{2 \varepsilon_F}{qN_d} (V_{bi} - V_{AC}), \quad V_{bi} \geq V_{AC}
\] (3)

Through equation (1) and (3), we can know that the value of \( W_d \) is mainly related to the \( N_d \) and \( V_{AC} \). It shows that when \( V_{AC} \) is less than \( V_{bi} \), the anode PN junction is not turned on, and the electron flowing channel occupied by the depletion region also has high \( R_{dc} \), so both the hole and electron current density are very low. With the increase of \( V_{AC} \), the anode PN is turned on and \( R_{dc} \) is greatly decreased, the hole and electron current density are increased at the same time, which is conducive to achieve completely snapback-free without seriously affecting the conductivity modulation ability.

In order to make the depletion region in the zero-bias state fully occupy the electron flowing channel and obtain a higher \( R_{dc} \), we first need to make the inequality (4) satisfied:

\[
W_p \leq 2W_d = \frac{2 \varepsilon_F}{qN_d} \left[ \frac{kT}{q} \ln \left( \frac{N_d D_a}{n_i^2} \right) - V_{AC} \right]
\] (4)

Finally, the maximum value of \( W_p \) can be increased by reducing \( N_d \) to obtain improved process tolerance. Therefore, the three-layer anode structure with lowly doped N-well and highly doped N-buffer is introduced to enhance the channel control ability of the depletion region.

3. Results and Discussion

Figure 3 shows the simulated breakdown characteristics for all the devices in this paper. The highly doped N-buffer still has the function of preventing the electric field line from punching through, thus ensuring that the breakdown capability of the proposed device does not degrade. It can be seen from Figure 3 that the BVs of the three devices are almost equal of about 250V under the same drift region parameters. Furthermore, the formation of lowly doped N-well embraced by the N-buffer can make depletion region formed by self-built potential easier to occupy the whole electron flowing channel, which plays a role in enhancing the channel control ability of the JSBP.

Figure 4 shows the simulated forward \( I-V \) characteristic curves of the Conv. LIGBT, the SSA LIGBT, and the proposed JSBP LIGBT. The inherent self-built potential of proposed LIGBT can realize the complete elimination of snapback phenomenon, while the electrons flowing channel will be formed as the anode PN junction is turned on, which also slightly weakens the capability of drift conductivity modulation. Therefore, under the same key structural parameters, the JSBP LIGBT gains \( V_f=1.64V \) at the anode current density \( J_{AC}=100A/cm^2 \), which is slightly higher than that of Conv. LIGBT \( (V_f=1.42V) \). However, even anode region length is high as 15µm, the SSA LIGBT still suffers from snapback phenomenon and greatly improves \( V_f \) because of higher drift resistance.

With increasing \( V_{AC} \) for the proposed JSBP LIGBT, Figure 5 shows the schematic variation of depletion region and electron flowing between P-anode pillars. When \( V_{AC} \) is less than \( V_{bi} \), the anode PN junction is at off-state, while electron flowing channel is completely occupied by the depletion region due to the JSBP under N-anode, which hinders electron current flowing into the N-anode, so as to limit the device working in MOS mode. When \( V_{AC} \) is high, due to the offset effect for the JSBP, the anode PN junction is at on-state and depletion region disappears, which makes the device working in IGBT mode forming normal electron and hole current. Obviously, the JSBP LIGBT makes use of the variable \( R_{dc} \), that is, high depletion region resistance and low carriers accumulation region resistance, which ensures the normal injection of anode holes before the extensive extraction of anode electrons. Thus, it is the reason that the proposed structure can finally prevent the NDR phenomenon formed on the forward \( I-V \) characteristic curves, which is caused by the sudden change of device total resistance for the conventional SA structure.
depletion region on the channel can be maintained until the anode PN junction is turned on.

Figure 8 compares the switching characteristic curves for the Conv. LIGBT and the proposed JSBP LIGBT. The inset is the inductive load circuit diagram. Under the same $V_F$ of 1.64V, the JSBP LIGBT shows a shorter current tailing phenomenon by additional electron extraction channel, and its turn-off time is 27.2% lower than that of Conv. LIGBT. The variation of hole density at surface from t1 to t4 in Figure 8(a) is shown in Figure 8(b). According to the principle of charge balance, accelerating the extraction of electrons is also conducive to the removal of excess holes, so the recombinination process at anode region can be completed earlier.

Figure 9 compares the simulated tradeoff curves of $V_F$ versus $E_{off}$ for the Conv. LIGBT, the SSA LIGBT, and the proposed JSBP LIGBT. The hole injection efficiency is controlled by changing doping concentration of P-anode, and the $E_{off}$ values under different $V_F$ conditions are obtained by simulation. As the simulation results show that, extra electron flowing channel makes $E_{off}$ of JSBP LIGBT lower 22.1% than that of Conv. LIGBT.

Figure 6 shows the simulated variation of electron density along the cut line MN (shown in Figure 2) with different $W_p$ for the proposed JSBP LIGBT. In Figure 6(a), when $V_{AC}$ is low from 0V to 0.6V, it shows that electron density along electron flowing channel remains at a low value, indicating that the electron current is blocked out of the channel. Moreover, with the increase of $W_p$, the control ability of depletion region on channel is gradually weakened, and the electron density is always maintained at a high value with $W_p$ of 0.5μm. Meanwhile, when $V_{AC}$ is high from 1.4V to 2.0V in Figure 6(b), the anode PN junction has been fully turned on for $W_p$ less than 0.5μm. Because the formation of hole current has promoted the increase of electron current, which has occupied electron flowing channel completely and shows higher electron density compared with the case for $W_p$=0.5μm in the figure.

Figure 7 shows the simulated dependence of $\Delta V_{th}$, $V_F$, and $E_{off}$ on the $W_p$ for the proposed JSBP LIGBT with different $L_p$. A lower $W_p$ or higher $L_p$ means that the JSBP has a stronger ability to occupy electron flowing channel, that is, the harder it is for electrons to reach the N-anode through the channel. Therefore, when device is at on-state, the less likely it is to bring snapback and the weaker it is to affect the drift conductivity modulation. Moreover, when device turns off, the extra extraction ability of excess electrons is also weaker. Furthermore, when $W_p$ is no more than 0.3μm, the change of $L_p$ only affects $V_F$ and $E_{off}$, but does not affect snapback-free ability, which indicates that the pinch-off effect of

Figure 8 (a) Simulated switching characteristic curves with inductive load circuit diagram, and (b) variation of hole density at surface from t1 to t4 (a) for the Conv. LIGBT and the proposed JSBP LIGBT.

Figure 9 Simulated tradeoff curves of $V_F$ versus $E_{off}$ for the Conv. LIGBT, the SSA LIGBT, and the proposed JSBP LIGBT.

with the same $V_F$ of 1.64V. Moreover, the depletion region under low $V_{AC}$ hinders electron current flowing into the N-anode, under the same $E_{off}$ of 0.3mJ/cm², which makes $V_F$ of proposed JSBP LIGBT reduce by 19.6% compared to SSA LIGBT while completely eliminates snapback effect.
Figure 10 shows the short-circuit characteristics for the proposed JSBP LIGBT and the Conv. LIGBT. And the circuit diagram for short circuit simulation is also given in inset. In which, the initial junction temperature is set as 400K and the thermal resistor is set as 0.1K·cm²/W at circuit parameters of $V_D=100V$, $R_G=5\Omega$, $L_S=10nH$. Since the mainly optimization in this work focuses on the anode region, the temperature characteristic of the proposed structure will not be affected. It can be seen that the proposed LIGBT sustains almost the same time ($T_{sc}=6.11\mu s$) as that of the Conv. LIGBT ($T_{sc}=5.67\mu s$) to happen thermal runaway, which shows almost the same capability of short-circuit withstand under the same external condition for both of structures.

Figure 11 shows the key fabrication process for the special anode region of the proposed JSBP LIGBT. Based on the SOI substrate in Figure 11(a), the highly doped N-buffer can be formed successively by ion implantation in Figure 11(b). As shown in Figure 11(c-d), the lowly doped N-well can be implanted by deep reactive ion etching and selective epitaxial growth technology. With the formation of P-cathode (not shown in the figure), the dual vertically parallel P-anode can also be formed by boron ion implantation annealing in Figure 11(e). Similarly, the N-cathode (not shown in the figure) and N-anode can be formed by phosphorus ion implantation annealing at the same time in Figure 11(f). The following process steps are consistent with the conventional LIGBT process, that is, the formation of anode electrode by contact hole etching on gate oxide and metal deposition. According to the conventional BCD process for proposed LIGBT devices, the additional process steps of the proposed structure are the formation of extra lowly doped N-well, and the formation of P-anode with specific depth by adjusting the temperature and time of the drive process. Furthermore, compared with the fabrication process in [15], the complex process steps of multiple epitaxy and ion implantation are no longer needed. Therefore, on the premise of retaining the advantages of SA structure and snapback-free, the proposed JSBP structure in this work is promising to achieve simple, flexible and low-cost fabrication process.

![Figure 10 Simulated short-circuit characteristics for the proposed JSBP LIGBT and the Conv. LIGBT. The short circuit diagram is given in inset.](image)

**4. Conclusion**

As a conclusion, the novel low loss and snapback-free SOI LIGBT is reported and analyzed, which utilizes the inherent junction self-built potential between anode PN junctions to form depletion region with variable anode resistance. The additional electron flowing channel between P-anode pillars makes $E_{off}$ of the proposed JSBP LIGBT 22.1% lower than that of Conv. LIGBT with the same $V_F$ of 1.64V. Moreover, at low $V_{AC}$, the channel occupied by depletion region contributes to relatively enhanced conductivity modulation compared to SSA LIGBT, so as to completely eliminate snapback effect, which makes $V_F$ of proposed JSBP LIGBT reduce by 19.6% with the same $E_{off}$ of 0.3mJ/cm². The simulated results demonstrate that the proposed JSBP LIGBT with complete snapback-free have achieved the best trade-off performance between $V_F$ and $E_{off}$, while it is promising to achieve simple, flexible and low-cost fabrication process base on the conventional BCD process.

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