A simulation study on a novel trench SJ IGBT*

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Abstract: An overall analysis of the trench superjunction insulated gate bipolar transistor (SJ IGBT) is presented and a detailed comparison between a trench SJ IGBT and a trench field stop IGBT is made by simulating with Sentaurus TCAD. More specifically, simulation results show that the trench SJ IGBT exhibits a breakdown voltage that is raised by 100 V while the on-state voltage is reduced by 0.2 V. At the same time, the turn-off loss is decreased by 50%. The effect of charge imbalance on the static and dynamic characteristics of the trench SJ IGBT is studied, and the trade-off between parameters and their sensitivity versus charge imbalance is discussed.

Key words: IGBT; superjunction; SJBT; charge imbalance; on-state voltage; breakdown voltage; turn-off loss

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1. Introduction

In the field of power semiconductor devices, the insulated gate bipolar transistor (IGBT) plays an important role, especially in medium and high voltage applications, and its application fields are continuously expanding due to the optimization of the structure.

The IGBT is developed in the following two ways. First, the gate structure is improved from planar to trench for the sake of high-density integration. Second, the withstanding voltage structure is enhanced from punch through (PT) to non-punch through (NPT), and to field stop (FS)[1]. All of these improvements depend on fabrication technology. However, the basic design idea of an IGBT is never changed. Adjusting the doping concentration and thickness of the n-drift region is still the only way to obtain a high breakdown voltage (BV).

The superjunction[2, 3] (SJ) is a great concept in the power semiconductor device field since the introduction of the IGBT in 1980s. It breaks the so-called "limit of silicon" in high voltage devices. The SJ is a special structure that replaces the n-drift region by multiple highly doped pillars. Highly doped pillars reduce the on-state voltage (V_{cesat}), and the lateral electric field formed by the pillars enhances the breakdown voltage. The SJ principle was practical for the power MOSFET devices, and the superior static and dynamic performance was demonstrated by Infineon in their CoolMOS[4] series.

The SJ bipolar transistor (SJBT[5−9]) is proposed to describe a special IGBT structure with a drift region built with alternating p- and n-pillars. It is the first attempt to combine the SJ with an IGBT. Due to the introduction of the SJ, an SJ IGBT does not rely on the conductivity modulation completely to reduce the V_{cesat}, so the turn-off loss (E_{off}) is low. As its basis, this paper shows that the use of a coupled trench and SJ technology concepts results in an IGBT with significantly superior static and dynamic performance. For an accurate comparison between devices, the 1200 V trench SJ IGBT and the 1200 V trench FS IGBT are compared under the same condition. In addition, charge imbalance is an unavoidable and serious problem for the trench SJ IGBT, so it is discussed in detail lastly.

2. Device structure and operation mechanism

Figures 1(a) and 1(b) show the 1200 V simulated device structures of a trench FS IGBT and a trench SJ IGBT, respectively. They are similar in their main structure. The only difference is the drift layer structure. It is made of alternating p- and n-doped pillars in the trench SJ IGBT [Fig. 1(b)]. The parameters of the two device structures are shown in Table 1. This structure has the following three advantages. First, when the lateral PN junction is under reverse bias, it generates a lateral electric field which reduces the net charge in the drift region, so the vertical electric field is flat and the breakdown voltage

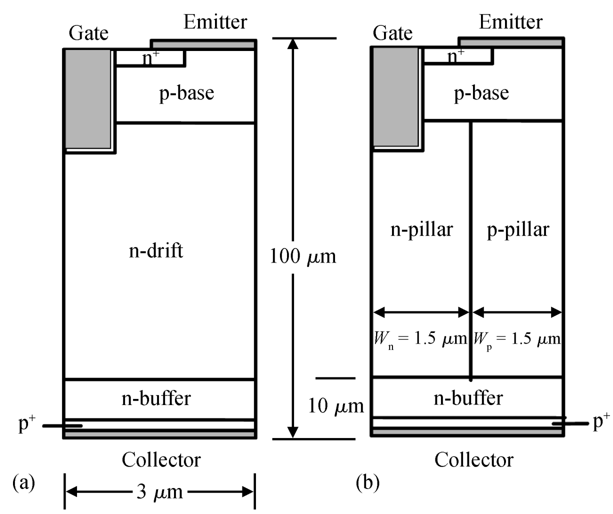

Fig. 1. The half-cell structure of a 1200 V (a) trench FS IGBT and (b) trench SJ IGBT.

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Table 1. Device specifications.

Parameter	Trench SJ IGBT	Trench FS IGBT
Half-cell width, W_{hc} (μm)	3	3
Substrate thickness, T_s (μm)	100	100
n-buffer layer thickness, T_b (μm)	10	10
Half trench width, W_{ht} (μm)	0.7	0.7
Gate oxide thickness, T_g (nm)	100	100
Channel length, L_{ch} (μm)	3	3
Pillar width, W_n, W_p (μm)	1.5	—
Pillar doping, N_d, N_a (cm^{-3})	8×10^{15}	—
n-drift doping, N_{drift} (cm^{-3})	—	8×10^{13}

is high. Second, the highly doped pillars have small on-state resistance. Moreover, according to the band theory, a hole current tends to traverse the p-pillar while an electron current tends to traverse the n-pillar, which makes the current distribute uniformly. The relationship between the on-state resistance of the SJ region (R_{onsj}) and the breakdown voltage of the SJ region (V_{bsj}) is given by[10]

$$R_{onsj} = 2.6 \times 10^{-7} b V_{bsj}^{1.23}\ \Omega \cdot cm^2, \quad (1)$$

where b is in μm. In this simulation structure, $b = (W_p + W_n)/2$, so

$$R_{onsj} = 3.9 \times 10^{-7} V_{bsj}^{1.23}\ \Omega \cdot cm^2. \quad (2)$$

Meanwhile, the on-state resistance is proportional to $V_b^{2.5}$ for the conventional n-drift structure. Thus, the SJ structure has the potential to significantly improve the trade-off between on-state resistance and the breakdown voltage. Last, but not the least, when the device is turned off, the lateral PN junction formed by deep pillars will be depleted quickly, so the turn-off time is short.

The principle of withstanding voltage around a blocking trench SJ IGBT can be found in Fig. 2. It shows the potential contours in a blocking trench SJ IGBT for different values of collector voltage (V_{ce}) at T = 300 K. The simulation results demonstrate that the depletion region spreads mostly in the lateral direction at low V_{ce}, as can be seen from the potential contour distribution in Figs. 2(a) and 2(b), and at a specific V_{ce} (in this case, slightly more than 30 V), the drift layer is fully depleted. A further increase in the V_{ce} raises the electric field only in the vertical direction, and the field profile becomes increasingly flat with the growth of V_{ce}, as seen from Fig. 2(c) for V_{ce} = 200 V. When the V_{ce} reaches the magnitude of BV, the contour becomes uniformly distributed throughout the device, as can be seen in Fig. 2(d) for V_{ce} = 1400 V, which implies a flat electric field profile.

In order to avoid the breakdown of the lateral PN junction, a trade-off between the doping level of the pillar and the width of the pillar is needed. In other words, the width of the pillar limits the maximum value of the doping level that can be used, and the relationship is given by[11]

$$Q_p = Q_n = N_d W_n \leqslant \frac{\varepsilon_s E_m}{q}, \quad (3)$$

where ε_s is the permittivity of silicon, E_m is the breakdown electric field of Si material ($E_m = 3 \times 10^5$ V/cm @ 300 K). To take full advantage of the SJ effect, the width of the pillar needs to be kept to a minimum, which is limited by the fabrication technology. For this simulation structure, N_d and N_a have to be less than 1.3×10^{16} cm^{-3} due to $W_p = W_n = 1.5\ \mu$m.

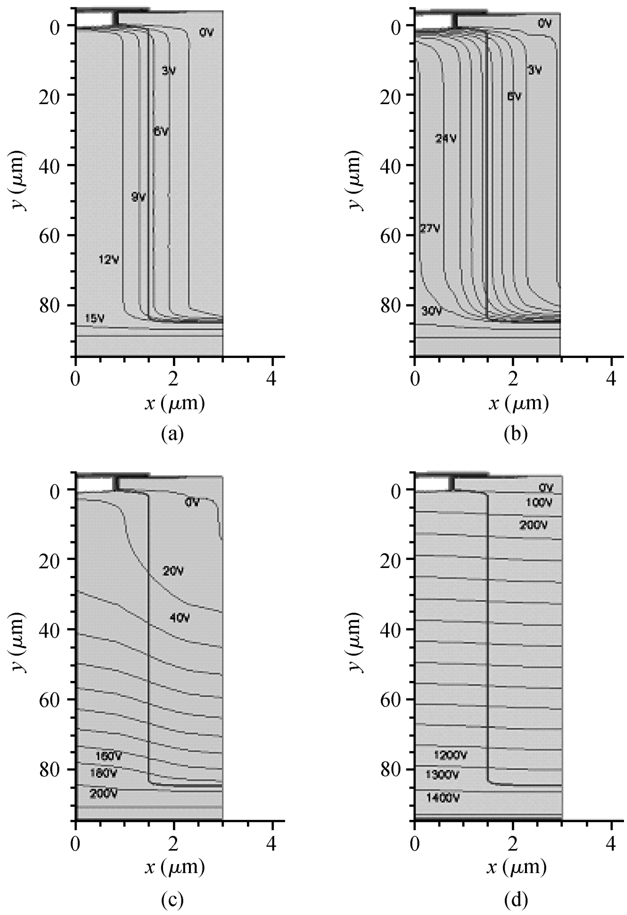

Fig. 2. Potential contours in a blocking trench SJ IGBT for (a) V_{ce} = 15 V, (b) V_{ce} = 30 V, (c) V_{ce} = 200 V, (d) V_{ce} = 1400 V at T = 300 K.

3. Static and dynamic characteristics

To investigate the impact of the SJ concept on IGBT performance, a simulation of the device with Sentaurus TCAD[12] has been performed for a 1200 V trench SJ IGBT and a trench FS IGBT, as shown in Fig. 1 at 300 K ambient temperature. The on-state voltage and switching characteristic are tested (simulations) at 100 A/cm^2 collector current in all cases. In addition, the dynamic performance of the devices is tested under inductive load.

Figure 3(b) shows a comparison of the vertical electric field distribution of the trench FS IGBT and the proposed trench SJ IGBT. As can be seen, in the blocking mode, the electric field distribution of the trench FS IGBT has a trapezoidal shape. The electric field decreases from the emitter to the collector. In the case of the trench SJ IGBT, the electric field distribution has a rectangular shape. The electric field is flat across the drift region with a small increase around the reversed biased junction near the device collector. This is due to the introduction of the SJ structure, which forms a lateral PN junction and the multiple junctions between pillars facilitate

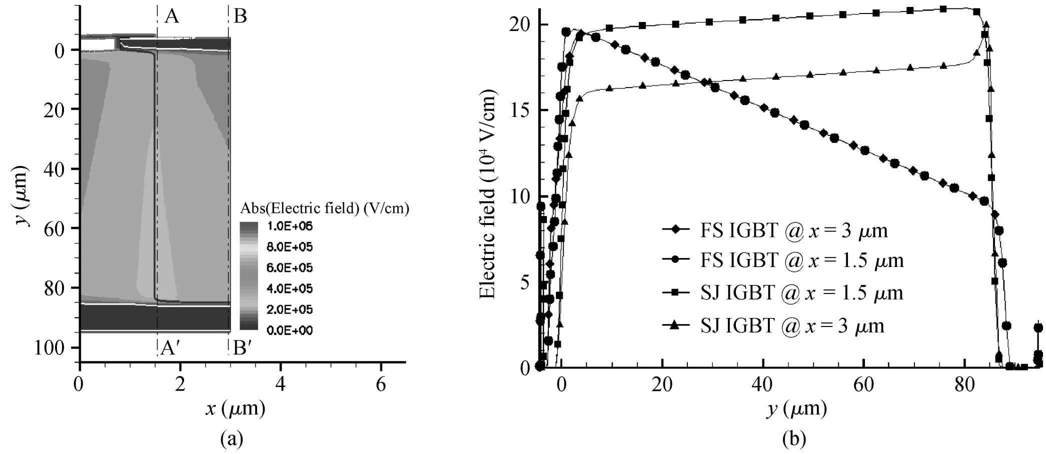

Fig. 3. (a) Electric field distribution of the trench SJ IGBT in blocking mode. (b) Vertical electric field distribution of the trench FS IGBT and trench SJ IGBT in blocking mode at $x = 1.5$ μm and $x = 3$ μm, respectively.

the depletion of the entire drift region at a lower voltage than a conventional PN junction. The breakdown voltage (which is the area enclosed by the electric field curve when the maximum electric field is equal to the avalanche field) for the trench SJ IGBT is always higher than that of the trench FS IGBT. The trench SJ IGBT demonstrates a BV of 1407 V, compared with the conventional trench FS IGBT, where the BV is increased by 100 V of the same thickness.

It can be noticed that the electric field of the trench SJ IGBT at $x = 3$ μm (the electric field distribution along the line BB' in Fig. 3(a)) is lower than that at $x = 1.5$ μm (the electric field distribution along line AA' in Fig. 3(a)). The reason is that the lateral electric field formed by the lateral PN junction is not even. The peak value of the lateral electric field is obtained at the interface of the lateral PN junction, and the interface is located just at $x = 1.5$ μm.

Generally speaking, the IGBT cannot maintain a high level of carriers in the on-state approaching the emitter because of the weak conductivity modulation in this area. This area is responsible for the largest contribution to the voltage drop across the n-drift of an IGBT. Many new IGBT structures (injection enhanced gate transistors (IEGTs)[13], high-conductivity gate transistors (HiGTs)[14], carrier store trench bipolar transistors (CSTBTs)[15], etc.) are proposed to improve carriers near the emitter, but the effect is limited. At the critical emitter side, the trench SJ IGBT can rely on its highly doped pillars (a level of 8×10^{15} cm^{-3} is used in the simulation) to provide higher than normal conductivity without the cost of having to deplete modulated charge during turn-off.

Moreover, the IGBT cannot maintain a low E_{off} because the stored carriers in the n-drift used to reduce the V_{cesat} are not swept out quickly during turn-off. With a design of the SJ region that allows for high background doping concentrations, the trench SJ IGBT employs only a small fraction of the stored charge in a conducting IGBT to achieve comparably low V_{cesat}. In addition, the deep p- and n-pillar junction helps to sweep out stored carriers to reduce the switching-off time. These excellent features of the trench SJ IGBT allow for a very low V_{cesat} with an extremely low E_{off}. Figure 4 presents simulation results highlighting a comparison of the trade-off of turn-off loss and on-state voltage between trench FS IGBT and trench SJ IGBT.

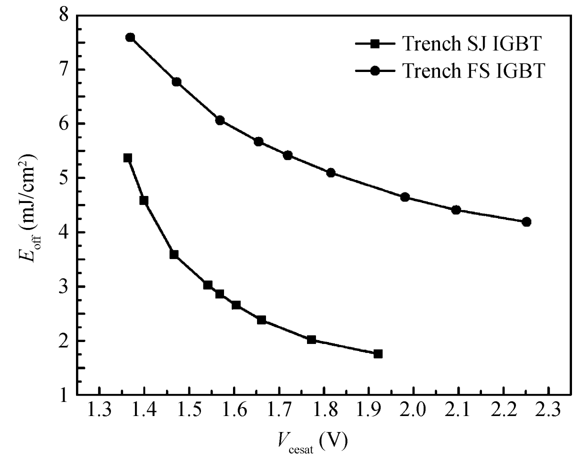

Fig. 4. Turn-off loss versus on-state voltage drop of a trench SJ IGBT and a trench FS IGBT($I_c = 100$ A/cm^2, $T = 300$ K).

At a V_{cesat} of about 1.8 V, the E_{off} of the SJ IGBT was about 60% lower than that of the FS IGBT, and at an E_{off} of about 4.6 mJ/cm^2, the V_{cesat} of the SJ IGBT was 0.5 V (30%) lower. The trench SJ IGBT has a better trade-off relationship than the trench FS IGBT evidently. To obtain these trade-off curves, the p-emitter doping concentration is varied in both devices.

4. Effect of charge imbalance on the characteristics of the trench SJ IGBT

The simulation results of the trench SJ IGBT above are all based on the hypothesis that charge in the SJ region is balanced. Perfect charge balance is difficult to achieve in a practical manufacturing situation[16], so research about the effect of charge imbalance on the characteristics of the trench SJ IGBT is meaningful and important. It is the purpose of this part to investigate, with the help of device simulation, the effect of charge imbalance in the trench SJ IGBT.

The essence of charge balance is the charge in n-pillar equals the charge in the p-pillar ($Q_p = Q_n$), for a fully depleted SJ structure, the charge in the p-pillar is $Q_p = N_a W_p$ and in the n-pillar is $Q_n = N_d W_n$. So the charge balance can

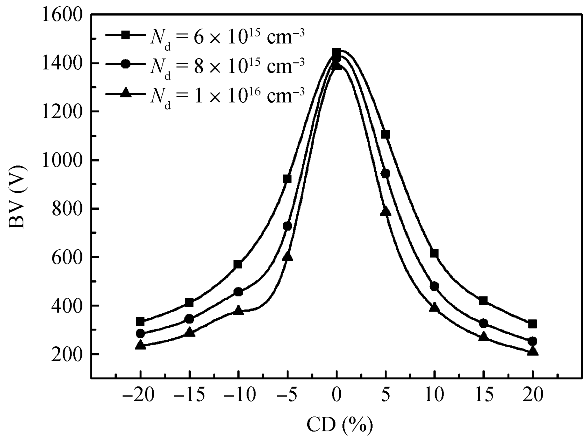

Fig. 5. Breakdown voltage versus the charge imbalance for different values of N_d.

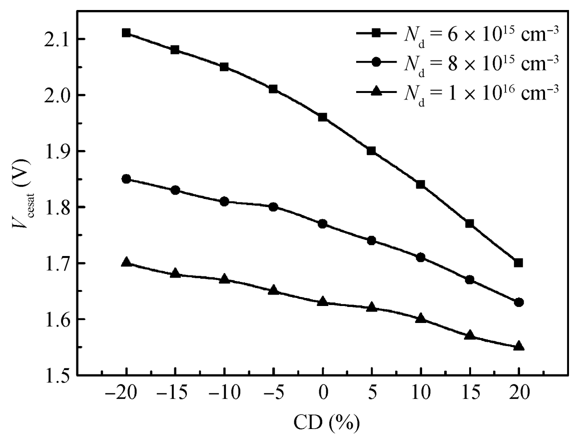

Fig. 6. On-state voltage versus the charge imbalance for different values of N_d.

be described as

$$N_a W_p = N_d W_n, \quad (4)$$

where N_a and N_d are the doping concentrations of p- and n-pillars, W_p and W_n are the widths of the p- and the n-pillars, respectively. In this simulation structure the width of pillar is determinate ($W_p = W_n = 1.5$ μm), so the charge imbalance is obtained through the changing of doping concentration. In order to facilitate the contrast, N_d is defined as the "center" value, Then, a "compensation degree" (CD) may be defined as[17]

$$CD\% = \frac{N_d - N_a}{N_d} \times 100\%. \quad (5)$$

CD is used to measure the extent of the charge imbalance. Obviously, CD equaling 0 indicates charge balance, a negative value of CD indicates $N_a > N_d$ and a positive CD indicates $N_d > N_a$.

Figures 5, 6, and 7 show the BV, V_{cesat}, and E_{off} versus the charge imbalance for different values of N_d, respectively. All devices operate at the determinate condition ($I_c = 100$ A/cm^2, $T = 300$ K). Each figure shows three curves for $N_d = 6 \times 10^{15}$ cm^{-3}, $N_d = 8 \times 10^{15}$ cm^{-3}, and $N_d = 1 \times 10^{16}$ cm^{-3}. N_a is varied to get different values of CD. In Fig. 5, the BV decreases with the growth of N_d overall. The highest BV can be obtained

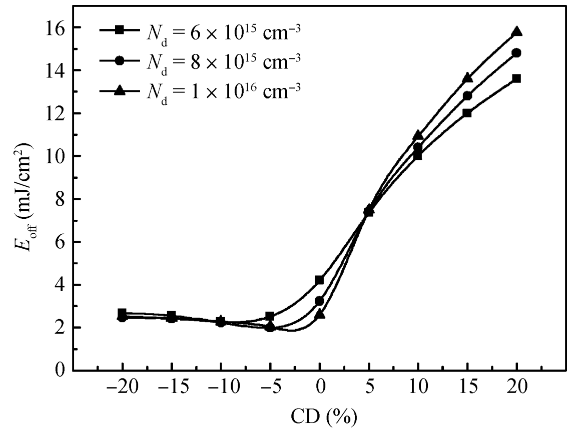

Fig. 7. Turn-off loss versus the charge imbalance for different values of N_d.

when the charge is balanced. However, when the charge balance is broken, the breakdown voltage will decline from the peak value. Furthermore, the BV sensitivity (ΔBV/ΔCD)[17] increases with the growth of N_d. This is because the degradation of BV is dependent on the absolute value of the net charge, which increases with the growth of N_d. Both the V_{cesat} and the V_{cesat} sensitivity ($\Delta V_{cesat}/\Delta$CD) decrease with the growth of N_d rapidly, as shown in Fig. 6. When CD increases from 0 to 20%, the V_{cesat} can be reduced from over 13% for N_d of 6×10^{15} cm^{-3} to just 5% by increasing N_d to 1×10^{16} cm^{-3}. In Fig. 7, the E_{off} decreases with the growth of N_d, on the contrary, the E_{off} sensitivity ($\Delta E_{off}/\Delta$CD) increases with the growth of N_d when $N_d > N_a$ (positive CD). It can also be found that the E_{off} increases with the growth of CD in the positive CD area as a result of the undepleted n region in the n-pillar.

A conclusion can be drawn from the three figures above that any imbalance in the charge affects both the static and dynamic characteristics of the trench SJ IGBT. If the trench SJ IGBT is designed for low V_{cesat} by increasing N_d, the E_{off} and the V_{cesat} sensitivity will be low, but it will also result in high sensitivity of both BV and E_{off}. Moreover, the BV will be reduced. Hence an optimum design of a trench SJ IGBT requires a trade-off between parameters and their sensitivities.

Here, it should also be noted that the simulation is only done to highlight the potential of the trench SJ IGBT, The feasibility of the fabrication technology[18] is not considered. This means that there is still further room for improvement of the trench SJ IGBT design when the process condition is considered.

5. Conclusion

In this paper, a trench SJ IGBT structure for 1200 V is designed analytically and simulated with Sentaurus TCAD tools. The trench SJ IGBT exhibits a BV of 1407 V, V_{cesat} of 1.6 V and E_{off} of 2.652 mJ/cm^2. Compared with its counterparts of the trench FS IGBT under the same condition, the trench SJ IGBT shows that the BV is enhanced by 100 V, the V_{cesat} is decreased by 0.2 V (10%) and the E_{off} is reduced by 2.44 mJ/cm^2 (50%). The physical principles of the static and dynamic behavior of this device under charge imbalance is explained with the help of simulations. Simulations predict that the trench SJ

IGBT is highly sensitive to charge imbalance if designed for low on-resistance. Hence an optimum design requires a trade-off between parameters and their sensitivity versus charge imbalance.

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