Investigations on Breakdown Voltage of Trench-gate-type Super Barrier Rectifier with Stepped Oxide

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Abstract. A novel trench-gate-type super barrier rectifier (TSBR) with stepped oxide (SO-TSBR) is proposed and researched by device simulator. As an improved TSBR structure, the proposed SO-TSBR with high breakdown voltages be effective in achieving low forward voltage drop. Simulations have demonstrated the two-dimensional charge coupling in the N-drift region resulting in an optimal electric field distribution. The 280 V SO-TSBR used for the numerical simulations decreases the on-state drop by 26.6% at the forward current density of 2.5 A/cm\textsuperscript{2} than that of the conventional TSBR. The SO-TSBR with deep trench structure reduces further the forward voltage drop by 11.0% at the forward current density of 20 A/cm\textsuperscript{2}.

1. Introduction

For high-voltage applications in modern power electronic circuits, the super barrier rectifier (SBR) without unreliable Schottky contact has excellent performance and reliability. As a majority carrier device, the main principle of SBRs is to create an adjustable potential barrier in the MOS channel (named super barrier) \cite{1-7} in order to improve the electrical characteristics. Because of its larger channel density, the trench-gate-type SBR (TSBR) removing JFET region can have ultralow forward voltages. Although some new structures for TSBRs were published to create practical devices recently \cite{8-13}, these configurations have some adverse impacts such as relatively low breakdown voltage or potential reliability issues.

In this work, a novel trench-gate-type super barrier rectifier (TSBR) with stepped oxide (SO-TSBR) is proposed and investigate by simulation method. The stepped oxide structure is similar to, yet different from the structure of the power charge-coupling MOSFET, first presented by Prof. Baliga with the key steps of the fabrication methods \cite{14-15}, and subsequently presented at alternate names \cite{16-18}, to enhance their switching performance by reducing input and gate transfer capacitances. However, the stepped oxide structure equips the SO-TSBR with reduced on-resistance. The forward conduction characteristics of SBRs and the reverse bias characteristics of TSBRs will also be discussed.

2. Device Structure and Physic

The basic SO-TSBR structure is shown in figure 1. As a special design structure of SBRs, the source, the P-base, and the gate of the MOS structure within the SO-TSBR structure are short-circuited as the anode, and the drain is considered to be the cathode. Compared to the uniform trench oxide thickness in the conventional TSBR, the oxide thickness at the top of the trench sidewall in the SO-TSBR is thinner than that at the bottom. The thinner sidewall oxide enables the SO-TSBR to have a significant
reduction of the internal resistance and a good tradeoff between the on-resistance and reverse blocking voltages.

The rectangular sharp corners of the trenches produce an enhancement of the electric field leading to a degradation of the breakdown voltage. It is customary to alleviate the electric field stress by rounding the corners, also shown in figure 1.

2.1. Forward Characteristics in the Channel
Because of the absence of Schottky contact, the super barrier improves the forward characteristics and reverse bias performance for SBRs with higher reliability. To avoid destructive failure, the channel has to work in the sub-threshold region [19]. Because of the current dominated by the diffusion, channel current continuity can apply to the total channel current, not to its individual components. Since the inversion charge density is small, only the depletion charge term needs to be kept. We obtain the channel current expression:

\[ I_{ch} = \frac{\mu_n Z}{L_{eff}} \sqrt{\frac{q N_a}{2 \varepsilon_s \kappa T}} \left( \frac{n_i}{N_a} \right)^2 \exp \left( \frac{q \phi_s}{kT} \right) \exp \left( \frac{q V_{ch}}{kT} \right) - 1 \]

where \( \mu_n \) is the electron mobility in the channel, \( Z \) is the cell length in the orthogonal direction, \( N_a \) is the P-base doping concentration, \( \phi_s \) is the channel surface potential, \( \varepsilon_s \) is the dielectric constant for the semiconductor, \( V_{ch} \) is the voltage across the channel region, and \( L_{eff} \) is the effective diffusion length for electrons in the channel and given by

\[ L_{eff} = L_n \tanh \left( L/L_n \right) \]

where \( L_n \) is the electron diffusion length in the channel and \( L \) is the channel length. In practice, \( L_n \) is much larger than \( L \), \( L_{eff} \) becomes equal to \( L \).

The surface potential, deciding the super barrier height and the channel resistance, depends on the sidewall oxide thickness, the P-base doping concentration, and the trench gate material. In addition, the channel resistance improves with decreasing \( L_{eff} \), and the short-channel effect is an important consideration in device design to make the rectifier effective.

In the blocking mode for high voltage applications, the large negative bias causes the drift current in the channel not to be negligible. However, the height between the channel and N+ region (an accumulation layer) results in the lower leakage current.

2.2. Blocking Voltage
The blocking voltage mainly supported by the charge coupling region and conventional drift region is shown in figure 1. The uniform drift doping concentration leads to a triangular electric field distribution in the conventional drift region. In the charge coupling region, depletion regions can extend both along the vertical direction and horizontal direction. This two-dimensional depletion

![Figure 1. Cross section of the SO-TSBR.](image-url)
optimizes the electric field distribution to reduce the specific on-resistance for devices with high breakdown voltage capability.

Assuming the anode potential is 0 V and ignoring the voltage drop at other regions except for the drift region and the trench oxide, the blocking voltage maintained by the charge coupling region \( V_{cc} \) is given by [20]:

\[
V_{cc} = \frac{q\lambda^2}{\varepsilon_i} N_d \left( 1 - \text{sech} \left( \frac{T}{\lambda} \right) \right)
\]  

(3)

where \( T \) is the depth of the trench gate extends into the drift region, \( N_d \) is the N-drift doping concentration, and the decay length \( \lambda \) is defined by

\[
\lambda = S \sqrt{\frac{W_m}{2} \left( \frac{W_m + \varepsilon_i T_b}{\varepsilon_i} \right)}
\]  

(4)

where \( W_m \) is the mesa width, \( T_b \) is the oxide thickness at the bottom of the trench sidewall, \( \varepsilon_i \) is dielectric constant of the insulator, and \( S \) is a step parameter evaluating the influence of the sidewall oxide structure. A step factor of 1 was used in conventional TSBRs, and \( S < 1 \) for SO-TSBRs.

From equation (3), \( V_{cc} \) rises with the increasing of \( T \), and the rate of increase descends gradually until \( V_{cc} \) is nearly saturated.

3. Parameter Optimization and Result Discussion

Two-dimensional device simulator MEDICI was used to analysis the details of the SO-TSBR. The influence of barrier lowering, SRH recombination, high-field transport with saturated drift velocity for electrons, impact ionization, and band-gap narrowing was included during the simulations.

In this work, the N+ poly-silicon is used to fill the trench regions. Aluminum is used as the electrode material. Main structural parameters and recommended values are shown in table 1. The P-base region thickness is chosen to avoid punch through of the depletion layer in the blocking mode.

| Design parameter                  | Unit    | Value       |
|-----------------------------------|---------|-------------|
| P-base thickness                  | \( D_p \) | \( \mu m \) | 1.4 |
| N+ region thickness               | \( D_a \) | \( \mu m \) | 0.3 |
| Channel length                    | \( L \)  | \( \mu m \) | 0.8 |
| Trench width                      | \( W_t \) | \( \mu m \) | 1.1 |
| Cell length in the orthogonal direction | \( Z \) | \( \mu m \) | 1 |
| Radius of rounded oxide corner    | \( R \)  | \( \mu m \) | 0.5 |
| Oxide–silicon interface charge   | \( Q \)  | \( \text{cm}^{-2} \) | \( 4.5 \times 10^{10} \) |
| N-drift doping concentration      | \( N_d \) | \( \text{cm}^{-3} \) | \( 9 \times 10^{14} \) |
| P-base doping concentration       | \( N_a \) | \( \text{cm}^{-3} \) | \( 5 \times 10^{16} \) |

3.1. Trade-off Analysis

As previously discussed, both the forward voltage drops and leakage currents for SBRs are the strong function of the super-barrier height and channel length. We choose the same value for P-base doping concentration and channel length for easy to discuss. The optimization of the barrier height can be achieved by the choice of the thinner sidewall oxide thickness \( (T_b) \). Furthermore, the simulation structure had a given mesa width \( (W_m) \) of 2 \( \mu m \), oxide thickness at the bottom of the trench sidewall \( (T_b) \) of 0.4 \( \mu m \), step depth \( (D_s) \) of 0.3 \( \mu m \), trench depth \( (D_t) \) of 3 \( \mu m \), and drift thickness \( (D_d) \) of 19 \( \mu m \).
In comparison to the case of a conventional TSBR with uniform sidewall oxide thickness of 0.4 μm, the trade-off curves for SO-TSBRs with various Tₛ to support the breakdown voltage of about 280 V are shown in figure 2. At a current density of 2.5 A/cm², even for the case of Tₛ = 0.05 μm, the reduction in the forward voltage drop is significant and this effect becomes stronger with the decrease of Tₛ. Although the reverse leakage current at a negative bias of 200 V with Tₛ = 0.025 μm is much larger than that of the conventional TSBR, it remains at a reasonable level because the reverse current density is still approximately five orders of magnitude lower than the forward current density. Furthermore, the forward voltage drop of the SO-TSBR (Tₛ = 0.04 μm) is reduced by approximately 26.6 % compared to that (0.6 V) of the conventional TSBR, while the structure still approximately keep the same reverse leakage current.

The decay length decreases with the step parameter (S) per equation (4), leading to a negative shift in the breakdown voltage predicted by equation (3). The simulation results are described to confirm the the model for the reverse blocking capability of the SO-TSBR. The vertical electric field distributions along the middle of the mesa (E-D line in figure 1) with different values of Tₛ for a given Dₛ = 0.3 μm are shown in figure 3. For comparison, the case of a conventional TSBR with uniform sidewall oxide thickness of 0.4 μm is also shown. As shown in figure 3, the step parameter decreases with the decreasing of Tₛ resulting in a slight decrease in vertical electric field in the middle of the mesa which is too subtle to be observed, and maintains almost the same reverse breakdown voltage.
Further we investigated the effects of $D_s$ in the vertical electric field and the breakdown voltage by simulation for a given $T_s = 0.04 \mu m$ as shown in figure 4. The breakdown voltage initially decreases slightly with the increasing of $D_s$, but shows sharp decrease after $D_s = 0.9 \mu m$. It was found that $D_s$ is kept to the minimum limited by the fabrication process to improve the blocking voltage capability. Considering the process margin, $D_s$ is set to 0.3 $\mu m$ for the following simulations.

3.2. Parameter Optimization
In this section, the parameters optimization and detailed operation for SO-TSBRs will be presented, except $D_s = 0.3 \mu m$ and $T_s = 0.04 \mu m$. Base on the comparison of simulation results, the influence of critical structural parameters on the electrical characteristics will be analyzed.

3.2.1. Trench depth and bottom oxide thickness
The trench depth and bottom oxide thickness influence the breakdown voltage by the charge-coupled effect. Figure 5 shows the effects of the trench depth on the breakdown voltages for five different bottom oxide thicknesses cases by simulation. Through adjusting the drift thickness, all of SO-TSBRs have a specific current density at a on-state voltage drop of 0.55 V.

Simulation results demonstrate that there exists an optimal trench depth for each bottom oxide thickness separately. $T_b = 0.4 \mu m$ and $D_t = 3 \mu m$ is an optimized choice.

For the case of the thin $T_b$, the voltage supported by the charge coupling region ($V_{cc}$) is determined by the bottom oxide thickness. The extension of the trench structure reduces the electric field at point A ($E_{Ay}$). The maximum electric field in the conventional drift region ($E_D$) determines reverse blocking capability of the conventional region. The $E_D$ decreases with the decreasing of $E_{Ay}$ leading to a negative shift of reverse blocking voltage across the conventional drift region.

For the case of big enough $T_b$ ($T_b = 0.4 \mu m$, for example), the breakdown voltage initially increases rapidly with trench depth, predicted by equation (3). But the effect is limit beyond an optimum trench depth. Although $V_{cc}$ still rises slowly with the trench depth, $E_{Ay}$ decreases with the extension of the trench structure, similar to the case of the thin bottom oxide, resulting in a low breakdown voltage.

Too large $T_b$ results in the weakened charge coupling, and contributes to a drastic reduction in the vertical electric field close to point C ($E_{Cy}$). The $E_D$ decreases with the decreasing of $E_{Cy}$ leading to a lower blocking voltage.

![Figure 5. Breakdown voltage of SO-TSBRs with various trench depths five different bottom oxide thicknesses.](image)

3.2.2. Mesa width
The mesa width ($W_m$) also has a strong impact on the charge coupling effect. The breakdown voltages and vertical electric field distributions along the middle of the mesa for various mesa widths from 1.2 $\mu m$ to 6.0 $\mu m$, with $T_b = 0.4 \mu m$, $D_t = 3 \mu m$, and $D_d = 19 \mu m$, are shown in figure 6 (a) and figure 6 (b).
Figure 6. (a) Breakdown voltage, (b) vertical electric field distributions along the middle of the mesa, and (c) forward characteristics with various mesa widths.

The simulation results shows that a narrow mesa region decrease the blocking voltage capability because of the small decay length, also predicted by equation (3). However, for the cases of too large $W_m$, although $V_{cc}$ rises with the mesa width, large $W_m$ results in loss of charge coupling, and the vertical electric field distributions along the middle of the mesa is returned to the triangular shape, as shown in figure 6 (b). The voltage handling capability across the conventional drift region decreases due to the decrease in $E_{Ay}$ and $E_D$. Simulations predict the optimum mesa width for the stable breakdown voltages in the range of 1.6 to 2.8 $\mu$m.

As an unipolar device, the channel density for the SO-TSBR with narrow mesa region can strongly improve the forward current density. Through adjusting the drift thickness, SO-TSBRs with a different $W_m$ have a specific breakdown voltage of 280 V. As shown in figure 6 (c), the forward voltages at a specific forward current density get bigger as $W_m$ increases from 1.6 $\mu$m to 3.2 $\mu$m, caused by two distinct effects: first, the forward current carrying capability increases with the MOS channel density and second, small mesa widths enhance the charge coupling effect. However, for the case of $W_m = 1.2 \mu$m, the narrow mesa region cannot support a sufficient breakdown voltage due to the poor voltage blocking capacity. Therefore, $W_m = 1.6 \mu$m is an optimized choice.

4. Optimization of the Deep Trench SO-TSBR
If the trench is deep enough with a given $T_b$, the single charge coupling region can support the needed breakdown voltage. There are two vertical component peaks of electric field: one field peak near the P-N junction created by the P-base region and the drift region, and another near the bottom of the trench.
When $D_t$ is much longer than $T_b$, $V_{cc}$ becomes saturated and therefore independent of $D_t$. For the deep trench SO-TSBR (SO-D-TSBR), the breakdown voltage depends on $T_b$ only and it is not sensitive to $D_t$. Based on the simulation results, $T_b = 2 \, \mu m$ is a suitable choice. Similar to the optimum condition for the power super-junction device [21], the optimized mesa width is approximately given by $W_m \approx 3T_b$. The mesa width is set to 5.7 $\mu m$ for the following simulations.

The vertical electric field profile is dependent on the N-drift doping concentration ($N_d$). For a low $N_d$, the field peak near the trench bottom is much bigger than that near the junction, and vice versa for a high $N_d$. Figure 7(a) shows the relationship on vertical electric field profile and $N_d$ with $D_t = 14 \, \mu m$ by simulations. For the case of $N_d = 3.0 \times 10^{15}$ cm$^{-3}$, the two electric field peaks become closer than other cases, but the specific on-state resistance degraded due to the high resistivity.

Figure 7(b) shows the forward characteristics with different $N_d$. Through adjusting trench depth, SO-D-TSBRs with different $N_d$ have almost the same breakdown voltage of 280 V. For $N_d = 4.2 \times 10^{15}$ cm$^{-3}$, there is a lowest forward voltage.

Because of the high electric field near the bottom of the trench, the drift region thickness below the trench structure ($D_n$) influences the breakdown voltage. $D_n = 2 \, \mu m$ is an optimized choice by simulation.

Figure 8 shows the comparisons for forward characteristics of shallow trench SO-TSBR (SO-S-TSBR) discussed in Section 3 and optimized SO-D-TSBR. At the forward current density of 20 A/cm$^2$, the forward voltage for SO-D-TSBR is 0.62 V, which is decreased by 11.0 % compared to that of SO-S-TSBR.
5. Conclusion
In summary, a novel SO-TSBR for high voltage applications was presented to reduce the on-resistance. The forward characteristics in the channel of SBR and the reverse blocking capabilities of the TSBR were also explained. Two dimensional numerical simulations have demonstrated coupling resulting in an advanced electric field distribution. Trade-off curves show the reduced on-resistance of SO-TSBR compared to the conventional TSBR. The influences of critical structural parameters on the electrical characteristics of the SO-TSBR have also been analyzed.

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