

Design of non-uniform 100-V super-junction trench power MOSFET with low on-resistance

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Abstract: The specific on-resistance of non-uniform super-junction (SJ) trench metal-oxide semiconductor field-effect transistor (TMOSFET) is superior to that of uniform SJ TMOSFET under the same breakdown voltage. For the desired blocking voltage with 100-V, the electric field varies exponentially with distance between the drain and the source regions. The idea with a linearly graded doping profile is proposed to achieve a much better electric field distribution in the drift region. The doping concentration linearly decreases in the vertical direction from the N drift region at the bottom to the channel one at the upper. The structure modeling and the characteristic analyses for doping density, potential distribution, and electric field are simulated by using of the SILVACO TCAD 2D device simulator, Atlas. As a result, the specific on-resistance of $0.66 \text{ m}\Omega \cdot \text{cm}^2$ at the class of 100 V and 100 A is successfully optimized in the non-uniform SJ TMOSFET, which has the better performance than the uniform SJ TMOSFET in the specific on-resistance.

Keywords: non-uniform SJ MOSFET, trench MOSFET, power MOSFET, on-resistance, specific on-resistance, blocking voltage, breakdown voltage

Classification: Electron devices, circuits, and systems

References

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1 Introduction

Super-junction (SJ) metal-oxide semiconductor field-effect transistor (MOSFET) power devices are well known for lower on-state resistance and gate charge. In the SJ power MOSFET structure, the heavily doped alternative P-N columns substitute the lightly doped drift region of the conventional power MOSFETs. However, it is difficult to fabricate the exact balanced profile, and the impact of imbalance results in varying breakdown voltages (BVs). For the conventional MOSFET device structure, there exists a trade-off relationship between specific on-state resistance and BV. The BV of the SJ device is proportional to the drift length but independent of the doping concentration at the N drift region. Thus, the N drift region can afford to be doped at a much higher concentration to reduce the on-state resistance of the drift region below that of the conventional structure without affecting the BV. In order to obtain the best performance in the SJ structure, the same doping concentrations for an uniform SJ trench MOSFET (TMOSFET) structure to have equal amount of positive and negative charges are put at the precisely charge-balanced P and N columns. In this paper, a non-uniform SJ TMOSFET structure is proposed to overcome the specific on-resistance occurred in the drift region under the same BV.

The doping profile required in the drift region to achieve a uniform electric field along the y-direction is determined by two dimensional charge coupling for the non-uniform SJ TMOSFET structure. The critical electric field at which breakdown occurs can be determined for the field distribution by using the criterion [1] that the ionization integral becomes unity as follows.

$$\int_0^{L_D} \alpha dx = 1 \quad (1)$$

where L_D is the length of N drift region.

2 On-resistance non-uniform TMOSFET

The components of the on-resistance for the power non-uniform TMOSFET [2] are similar as those described for the power uniform one [3]. However, the drift region resistance in the power non-uniform TMOSFET structure is much lower than that for the power uniform one due to the higher doping concentration in the drift region and an improved electric field distribution. The total on-resistance for the power non-uniform TMOSFET structure is computed by combining the seven resistances [3] in the current path between

the source and the drain electrodes. The contributions from the source contact resistance, the source resistance, and the drain contact resistance are insignificantly negligible and can be ignored in this paper.

2.1 Channel resistance ($R_{CH,SP}$)

The contribution to the specific on-resistance ($R_{on,sp}$) from the channel in the non-uniform TMOSFET structure is the same as that for the uniform one. The $R_{on,sp}$ [1] made by the channel in the non-uniform TMOSFET structure is

$$R_{CH,SP} = \frac{L_{CH}W_{cell}}{2\mu_{ni}C_{OX}(V_G - V_{TH})} \quad (2)$$

where L_{CH} is the channel length, W_{cell} is the width of unit cell, μ_{ni} is the channel electron mobility, C_{OX} is the channel gate capacitance, V_G is the gate voltage, and V_{TH} is the threshold voltage. The $R_{on,sp}$ for the channel in the non-uniform TMOSFET is $0.0184 \text{ m}\Omega \cdot \text{cm}^2$ when the gate bias is 10 V.

2.2 Drift region resistance (R_D)

The resistance contributed by the drift region in the non-uniform TMOSFET structure is reduced due to the high doping concentration in the drift region [4]. The resistances in the drift region consist of $R_{D1,SP}$ and $R_{D2,SP}$. The analytical modeling of the drift region resistance is complicated by the non-uniform doping profile with an electron mobility that also varies with doping concentration. The drift region resistance contribution from the mesa region can be obtained by considering a small segment (dy) of the drift region at a depth y from the bottom of the gate electrode. The specific resistance of the drift region for the mesa portion is computed by.

$$R_{D1,SP} = \left(\frac{W_{cell}}{W_M} \right) \int_0^{L_D} \rho_D(y) dy \quad (3)$$

where W_M is the width of N pillar, and the resistivity $\rho_D(y)$ is a function of the position in the drift region. The resistivity of the drift region is given by.

$$\rho_D(y) = \frac{1}{q\mu_n(y)N_D(y)} \quad (4)$$

where q is the charge, $\mu_n(y)$ is the channel electron mobility, and $N_D(y)$ is the doping density of the drift region.

An additional resistance contribution ($R_{D2,SP}$) in the non-uniform TMOSFET structure is related to the buffer layer located below the bottom of the trenches. In this portion of the structure, the current density is uniform and current flow occurs across the entire cell width. The specific resistance can be obtained from (4).

$$\begin{aligned} R_{D2,SP} &= \left(\frac{W_{cell}}{W_M} \right) \int_0^{L_D} \frac{1}{q\mu_n(y)N_o e^{-gy}} dy \\ &= \left(\frac{W_{cell}}{W_M} \right) \frac{1}{q\mu_n(y)N_o g} (e^{gL_D} - 1) \end{aligned} \quad (5)$$

where N_o is the doping concentration at the top of N-pillar, g is the exponential gradient doping profile with coefficient of G , and L_D is the drift length of N-pillar.

The doping profile at N-drift decreases exponentially with the coefficient of G at exponent, in which the concentration at the top of N-pillar is $1 \times 10^{16} \text{ cm}^{-3}$ and that at the bottom is $2 \times 10^{16} \text{ cm}^{-3}$. The specific on-resistance for the drift region in the non-uniform TMOSFET is theoretically calculated as $0.67 \text{ m}\Omega \cdot \text{cm}^2$ when the gate bias is 10 V.

3 Design of non-uniform SJ TMOSFET

The linear doping gradient for the rest of the drift region is varied in order to study its impact on the breakdown characteristics. The doping profile [5] taken along the surface of the trench is shown in Fig. 1 for the case of the 120 V non-uniform SJ TMOSFET structure with a doping gradient of $2.75 \times 10^3 / \text{cm}$.

From the structure, it can be observed that the P base region has a doping profile with a peak doping concentration of $1.5 \times 10^{17} \text{ cm}^{-3}$ to obtain the desired threshold voltage. The vertical depths of the P base and N⁺ source regions are 1.4 and 0.1 μm resulting in a channel length of only 1.3 μm . The drift doping concentration increases linearly from $1 \times 10^{16} \text{ cm}^{-3}$ to $2 \times 10^{16} \text{ cm}^{-3}$ at a depth of 7 μm for the upper 0.4 μm where the channel is formed.

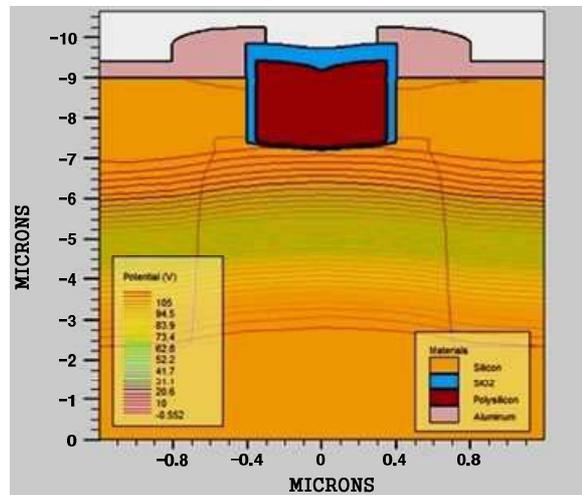


Fig. 1. Electric potential distribution at BV ($V_{\text{drain}} = 120 \text{ V}$)

The potential distribution in log scale for the uniform TMOSFET structure [3] keeps constant, but the potential one in the non-uniform TMOSFET structure decreases exponentially with distance in the P pillar and increases in the N pillar between the drain and source regions. The relationship between the doping concentration of $D_N(y)$ and the distance of y from the top

of unit cell toward substrate can be written as

$$D_N(y) = A \cdot 10^{G \cdot y} \quad (6)$$

where A is a constant and G is a parameter for slope.

Using the doping concentrations for different depths at the N pillar, the parameter of G can be obtained as

$$G = \frac{\log 2}{5 \times 10^{-4}} \quad (7)$$

Substituting (7) into (6), the equation of doping concentration in terms of potential distribution can be derived and the value of A is computed as $10^{15.88}$ by using both $D_N(y)$ and y .

4 Simulations and analyses

It is important to find the optimal values of minimizing $R_{on,sp}$ and maximizing BV. For non-uniform SJ TMOSFET, the variation of BV is relatively insensitive to the doping concentration. The $R_{on,sp}$ at BV of 118.0 V for uniform SJ TMOSFET is $0.96 \text{ m}\Omega \cdot \text{cm}^2$ when the doping concentrations at the top and bottom of the N drift region are uniform as $1.5 \times 10^{16} \text{ cm}^{-3}$ since the doping concentration of P pillar is subtracted from that of N pillar.

For non-uniform SJ TMOSFET, the doping concentration of N pillar varies from $2.0 \times 10^{16} \text{ cm}^{-3}$ to $1.0 \times 10^{16} \text{ cm}^{-3}$ and is illustrated in Table I. Then, the specific on-resistance decreases to $0.66 \text{ m}\Omega \cdot \text{cm}^2$ for BV 120.8 V. Fig. 2 shows the maximum BV occurs at about 120 V for the drain currents versus the drain voltages with different G values. The drain voltage increases as G becomes larger.

Table I. BV and $R_{on,sp}$ for non-uniform SJ TMOSFET

P pillar	N pillar	P drift at top	P drift at bottom	BV(V)	$g(\times 10^3/\text{cm})$	$R_{on,sp}(\text{m}\Omega \cdot \text{cm}^2)$
2.5	1.0 ↑ 2.0	0.5	1.5	111.6	2.70	0.64
3.0		1.0	2.0	120.8	1.73	0.66
3.5		1.5	2.5	109.3	1.28	0.69
4.0		2.0	3.0	90.9	1.01	0.70

Note: the doping concentration is multiplied by 10^{16} .

An interesting trade-off curve between the specific on-resistance and the breakdown voltage capability can be created by using the doping gradient in the drift region as a parametric variable. The reduction of the specific on-resistance for the non-uniform SJ TMOSFET structure below the ideal specific on-resistance becomes larger with increasing breakdown voltage.

5 Conclusions

The specific on-state resistance of $0.66 \text{ m}\Omega \cdot \text{cm}^2$, which is consistent with the outlined theory, at the class of 100-V and 100-A is successfully optimized by

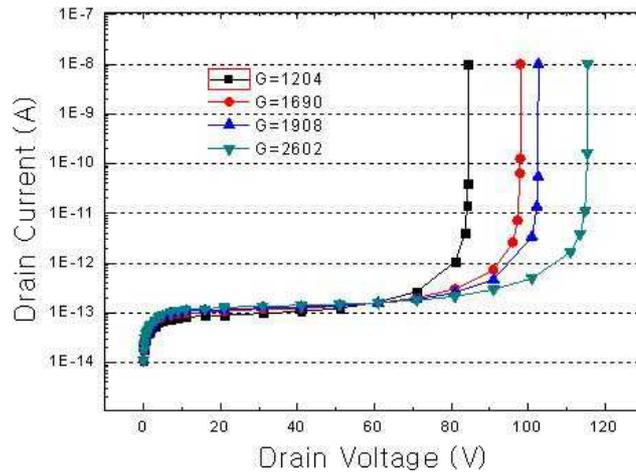


Fig. 2. Drain current vs. voltage for different G values

using non-uniform SJ TMOSEFET, showing better performance than uniform SJ TMOSEFET. First, the specific on-state resistance mainly depends on the doping concentration of N drift region and pillar width. Second, the fundamental structure of non-uniform SJ TMOSEFET is designed, and the optimum doping gradients and profiles for the non-uniform SJ TMOSEFET are analyzed after simulation by SILVACO TCAD [6]. It is determined that the design of the unit cell in this paper can be applied to the implementation of the non-uniform SJ TMOSEFET for a chip, which requires $1.2 \text{ m}\Omega \cdot \text{cm}^2$ of $R_{on,sp}$, in a BLDC motor with enough margin when the implementation is completed.

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