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# Design of edge termination on non-uniform 100-V super-junction trench power MOSFET

**Young Hwan Lho**[a)]
*Department of Railroad Electricity and Information Communications, Woosong University, 17–2 Jayang-Dong Dong-Ku, Daejeon, Rep. of Korea*
a) *yhlho@wsu.ac.kr*

**Abstract:** A design methodology for the edge termination is proposed to achieve the same breakdown voltage of the non-uniform super-junction (SJ) trench metal-oxide semiconductor field-effect transistor (TMOSFET) cell structure. A simple analytical solution for the effect of charge imbalance on the termination region is suggested, and it is satisfied with the simulation of potential distribution. The doping concentration decreases linearly in the vertical direction from the N drift region at the bottom to the channel at the top. The structure modeling and the characteristic analyses for potential distribution and electric field are simulated by using of the SILVACO TCAD 2D device simulator, Atlas. As a result, the breakdown voltage of 132 V is successfully achieved at the edge termination of non-uniform SJ TMOSFET, which has the better performance than the conventional structure in the breakdown voltage.

**Keywords:** non-uniform SJ MOSFET, trench MOSFET, power MOSFET, edge termination, blocking voltage, breakdown voltage
**Classification:** Electron devices, circuits, and systems

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## 1 Introduction

For the conventional MOSFET device structure, there exists a tradeoff relationship between specific on-state resistance and breakdown voltage (BV). 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 super-junction (SJ) trench metal-oxide semiconductor field-effect transistor (TMOSFET) structure below the ideal specific on-resistance becomes larger with increasing breakdown voltage [1, 2].

SJ TMOSFET power devices are well known for lower on-state resistance and gate charge. In the SJ TMOSFET structure, the heavily doped alternative P-N columns substitute the lightly doped drift region of the conventional power MOSFETs. A non-uniform SJ TMOSFET structure is used to overcome the specific on-resistance occurred in the drift region under the same 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 a uniform SJ TMOSFET structure to have equal amount of positive and negative charges are put at the precisely charge-balanced P and N columns. In this letter, the novel edge termination structure with different widths of P and N pillars shows higher breakdown voltage than the conventional structure with the same pillar widths. The breakdown voltage of the termination should be higher than that of the active main structure.

## 2 Structure of edge termination

The widths of P pillar and N pillar in the conventional edge termination structure are identical with those in the transition and main cell region. It is assumed that the termination region is totally depleted, and the charge in the termination region and transition is balanced as follows.

$$N_A W_P = N_D W_N \tag{1}$$

where $N_A$ and $N_D$ are the concentration of the N pillar and P pillar, and $W_N$ and $W_P$ are the widths in Fig. 1, respectively.

The electric field at each P column and N column junction in the termination region [3] of non-uniform SJ TMOSFET can be described by

$$E(x) = \int_0^x \frac{qN(x)}{\varepsilon_{Si}} dx = -\frac{qN_o}{\varepsilon_{si} g}(e^{-gx} - 1) \tag{2}$$

where $q$ is the charge, $N_o$ is the doping concentration at the top, $\varepsilon_{si}$ is the dielectric coefficient of silicon, g is a slope, and $N(x)$ is a doping concentration with exponential function in vertical direction of N drift region. Then, the electric potential maintained by the charge-balance termination region can be computed by

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$$V_R = -\int_0^{L_D} E(x)dx = \frac{qN_o}{\varepsilon_{Si}g^2}\left(-e^{-gL_D} - gL_D + 1\right) \tag{3}$$

where $L_D$ is the length of drift region. The electric potential is proportional to the length of the drift region since the quantity of $e^{-gL_D}$ is much less than $gL_D$. The drift region of the main cell consists of a total thickness of 10 $\mu$m with a doping concentration of $2 \times 10^{16}$ cm$^{-3}$ for the top 1.2 $\mu$m where the channel is formed. The applied slope parameter value of $g$ is 961 cm$^{-1}$. The breakdown voltage is obtained at 128 V, at which point the drift region is fully depleted.

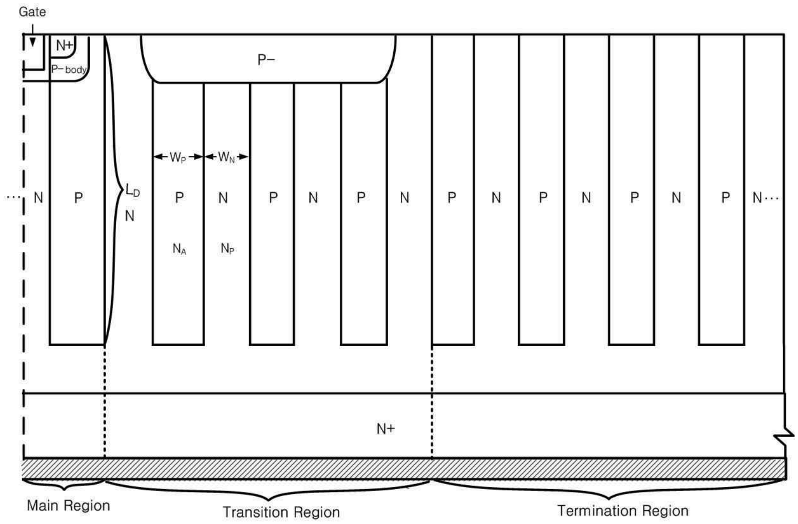


**Fig. 1.** Schematic cross-sectional structure of edge termination

## 3 Design of edge termination on non-uniform SJ TMOSFET

The linear doping gradient of the drift region toward the bottom is varied to study its impact on the breakdown characteristics. The edge termination structure is composed of main, transition, and termination. The edge termination that allows the non-uniform SJ TMOSFET structure to achieve the same breakdown voltage as the device's main structure is shown in Fig. 2 a). The edge termination trench region has a width of 40 $\mu$m and a depth of 10 $\mu$m. The breakdown voltage for the edge termination was found to be 132 V which is identical to that of the non-uniform SJ TMOSFET [2]. This shows that the breakdown voltage is occurring in the cell region and is not limited by the edge termination. The trench at the transition contains an electrode that overlaps the trench sidewalls with only the thick trench oxide. The electric field in the oxide is reduced to levels suitable for reliable operation of the non-uniform SJ TMOSFET structure. The widths of P column and N column in the termination region are identical with those in the transition region and main cell region, but the doping concentration of N drift region varies linearly for the same doping one of P column.

The current through the channel does not flow at the surface at the gate since there does not exist the source of $N^+$ in Fig. 2 a). From the active main cell, it can be observed that the P base region has a doping profile with a

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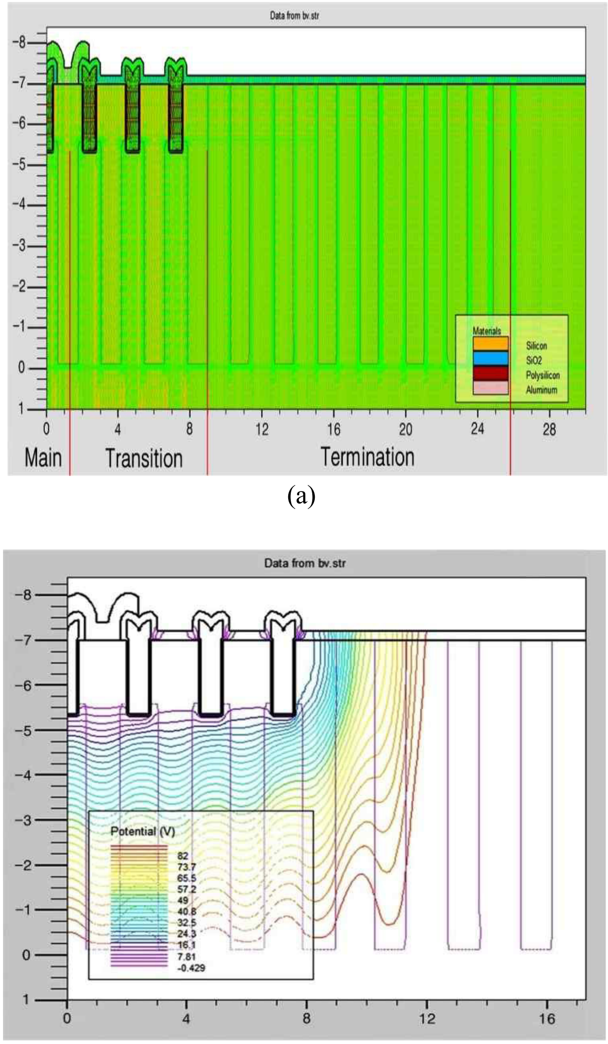
peak doping concentration of $1.5 \times 10^{17}\,\mathrm{cm}^{-3}$ to obtain the desired threshold voltage. The vertical depths of the P base and $\mathrm{N}^{+}$ source regions [4] are 1.4 and 0.1 $\mu$m, resulting in a channel length of only 1.3 $\mu$m. The drift doping concentration increases linearly from $1 \times 10^{16}\,\mathrm{cm}^{-3}$ to $2 \times 10^{16}\,\mathrm{cm}^{-3}$ at a depth of 10 $\mu$m for the upper 1.7 $\mu$m where the channel is formed.




(a)

(b)

**Fig. 2.** a) Structure of edge termination and b) potential distribution at BV ($V_{drain} = 87\,\mathrm{V}$)

## 4 Simulations and analyses

For non-uniform SJ TMOSFET, it is important to find the optimal values of minimizing the specific on-state resistance of $R_{on,sp}$ and maximizing BV. The variation of BV is relatively insensitive to the doping concentration for non-uniform SJ TMOSFET. The potential distribution in the uniform TMOSFET structure keeps constant [1], but the potential one in the non-uniform TMOSFET structure [5] increases linearly with distance in the drift region between the drain and source regions.

The specific on-state resistance of non-uniform SJ TMOSFET is obtained $0.66\,\mathrm{m\Omega \cdot cm^2}$ from the structure [2], which is mainly composed of the channel resistance and the drift region resistance since the

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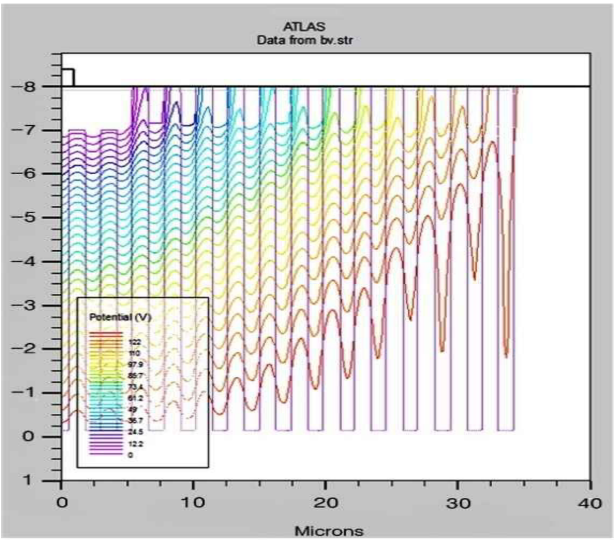
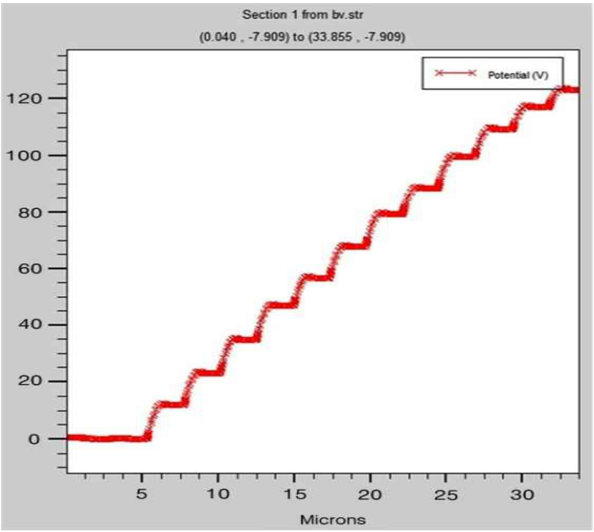
contributions from the source contact resistance, the source resistance, and the drain contact resistance are insignificantly negligible and can be ignored in this letter.

The potential distributions obtained from the simulations at the edge termination for the breakdown voltage of 87 V and 132 V are demonstrated in Fig. 2 b) and Fig. 3 a), respectively. The contour line starts at the top and ends at the bottom. The edge is consisted of 33 contour lines. A line indicates 4 V, and the total is equal to 132 V. Fig. 3 b) shows the potential distribution at horizontal direction. From the figures, it can be confirmed that the potential distribution of the cell structure at the edge termination is identical to that of the non-uniform SJ TMOSFET, proving that the charge coupling phenomenon is occurring effectively at the edge of the device.




(a)




(b)

**Fig. 3.** a) Potential distribution at BV ($V_{drain}$ = 132 V) and b) the potential distribution at horizontal direction

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## 5 Conclusions

The breakdown voltage of the proposed edge termination is simulated as 132 V, which is consistent with the outlined theory, at the class of 100-V and 100-A which is successfully optimized, showing better performance than the traditional edge termination structure. First, the breakdown voltage mainly depends on the doping concentration of N drift region and pillar width. Second, the fundamental structure of the edge termination for non-uniform SJ TMOSFET is designed, and the optimum doping gradients and profiles of the edge termination for the non-uniform SJ TMOSFET are analyzed after simulation by SILVACO TCAD [6]. It is determined that the design of the edge termination in this letter can be applied to the implementation of the non-uniform SJ TMOSFET for a chip, which requires 120 V, in a BLDC motor with enough margin when the implementation is completed.

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