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Structure Modeling of 100 V Class Super-junction Trench MOSFET with Specific Low On-resistance

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Abstract

For the conventional power metal-oxide semiconductor field-effect transistor (MOSFET) device structure, there exists a tradeoff relationship between specific on-resistance ($R_{ON.SP}$) and breakdown voltage (V_{BR}). In order to overcome the tradeoff relationship, a uniform super-junction (SJ) trench metal-oxide semiconductor field-effect transistor (TMOSFET) structure is studied and designed. The structure modeling considering doping concentrations is performed, and the distributions at breakdown voltages and the electric fields in a SJ TMOSFET are analyzed. The simulations are successfully optimized by the using of the SILVACO TCAD 2D device simulator, Atlas. In this paper, the specific on-resistance of the SJ TMOSFET is successfully obtained 0.96 $m\Omega \cdot cm^2$, which is of lesser value than the required one of 1.2 $m\Omega \cdot cm^2$ at the class of 100 V and 100 A for BLDC motor.

Key words : TMOSFET, specific on-resistance, breakdown voltage, uniform super-junction, electric field

Ⅰ. Introduction

Super-junction (SJ) trench metal-oxide semiconductor field-effect transistor (TMOSFET) power devices are well known for lower on-state resistance and gate charge. However, it is difficult to fabricate the exact balanced doping profile, and the impact of imbalance results in varying breakdown voltages (V_{BR}). For the conventional MOSFET device structure, there exists a tradeoff relationship between specific on-state resistance and breakdown voltage. In this paper, a SJ TMOSFET structure is proposed to overcome the specific on-resistance occurring at the ideal silicon. The breakdown voltage is very sensitive to the doping concentration [1,2]. SJ double-diffused metal-oxide semiconductor field-effect transistor (DMOSFET) planar structure shows performance advantages only in the high voltage range above 200 V, and SJ TMOSFET structure [1] as shown in Fig. 1 is applied to that below 200 V. For high voltage power MOSFET, the portion of the specific on-resistance made from the N drift region is bigger than that from the devices with lower breakdown voltage. A much higher doping concentration of an order of $10^{16}/cm^3$ can be applied to the power SJ MOSFET structure when compared with the non-SJ structure such as trench double-diffused metal-oxide semiconductor field-effect transistor (TDMOSFET).

In this paper, the technology of lowering the specific on-resistance has been developed by using of the SJ TMOSFET with breakdown voltage of 120 V.

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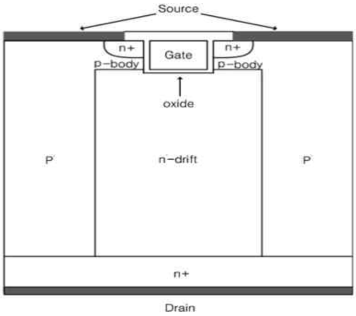

Fig. 1 SJ TMOSFET structure

The TMOSFET is made after forming P-N columns as shown in Fig. 1. The depletion region between P-N columns is formed and the charge balance is kept in the horizontal direction as the drain voltage increases continuously. Afterward, the electric fields in the drift region at P-N pillars are uniformly distributed, which make the concentration at N-pillar higher than non-SJ MOSFET, and reduce the specific on-resistance.

Ⅱ. SJ structure and design

1. SJ structure

The doping concentration of the P and N pillar has the Gaussian distribution in the ideal case, and the structure parameters are designed for achieving the required breakdown voltage. The SJ trench MOSFET structure has not widely applied in vertical power MOSFETs of breakdown voltage requiring below 200 V. It is certain that there is an optimal value of the doping concentration for the breakdown voltage of device. At the smaller value of the doping concentration, the N pillar cannot completely compensate resulting charge imbalance in the drift region. The breakdown occurs near the drain at the lower voltage comparing to that of balanced structure. Increasing doping concentration also causes the charge imbalance and the breakdown occurs near the channel region. The optimum value of the doping concentration of N/P pillar is $1\times10^{16}\,(/cm^3)$. The optimum value is considered at the maximum of figure of merit (FOM), which can be computed by the value of breakdown voltage divided by on-resistance, and makes the on-resistance minimized.

The breakdown occurs when the maximum electric field at the junction of P-N pillar reaches to the critical electric field. The charge balance of P-N column is required for maintaining the constant electric field in the horizontal direction.

The product of doping concentrations and thicknesses of the N-type and P-type drift regions are assumed to be equal. This provides the criterion for choosing the doping dose in the N-drift region to achieve the desired two dimensional charge balancing. The products are shown in Eq. (1).

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

where W_N and W_P are the widths, N_D and N_A are the doping concentrations of the N-type and P-type drift regions, respectively.

The breakdown voltage for the two dimensional charge coupled device is then given by

$$V_{BR} = E_C L_D \tag{2}$$

where E_C is the critical electric field and L_D is the length of the drift region as shown in Fig. 2.

2. On-resistance

The relationship between on-resistance (R_{ON}) and the specific on-resistance ($R_{ON,SP}$) is given by

$$R_{ON} = \rho\frac{L}{A} \qquad [\Omega] \tag{3}$$

$$R_{ON,SP} = R_{ON} \times A \qquad [\Omega\cdot cm^2] \tag{4}$$

where ρ is the resistivity $[\Omega\cdot cm]$, L is length $[cm]$, and A is area $[cm^2]$.

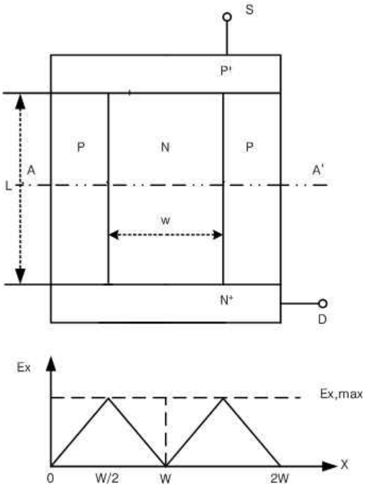

Fig. 2. SJ structure and electrical field at horizontal direction

The lower possible specific on-resistance can be obtained by TDMOSFET, which reduce the on-resistance occurring from the channel and JFET regions. The ideal specific on-resistance for the super-junction devices is given by

$$R_{ON,SP} = \frac{V_{BR}}{\epsilon_S \mu_N E_{CU}^2}\left(\frac{W_N + W_P}{2}\right) \tag{5}$$

where ϵ_S is the dielectric constant, μ_N is the electron mobility, E_{CU} is the critical electrical field, V_{BR} is the breakdown voltage, and W_N and W_P are the widths in N and P drift region, respectively. The E_{CU} [3] is given by

$$E_{CU} = 5.53 \times 10^5 V_{BR}^{-1/6} \tag{6}$$

Substituting (6) into (4) leads to

$$R_{ON,SP} = \frac{1.635 \times 10^{-12} BV^{4/3}(W_N + W_P)}{\epsilon_S \mu_N} \tag{7}$$

Since the same width for the P type and N type drift regions in SJ devices is commonly used, and the charge balance should be kept. The ideal specific on-resistance can be represented as

$$R_{ON,SP} = \frac{3.27 \times 10^{-12} V_{BR}^{4/3} W_N}{\epsilon_S \mu_N} \tag{8}$$

The ideal specific on-resistance for the drift region in one dimensional devices is computed by using of Baliga's power law [1].

$$R_{ON,SP} = \frac{1.181 \times 10^{-17} V_{BR}^{5/2}}{\epsilon_S \mu_N} \tag{9}$$

Equating (8) and (9) and neglecting the dependence of the mobility on doping concentration, we can find the cross point of breakdown voltage as

$$V_{BR} = 4.62 \times 10^4 W_N^{6/7} \tag{10}$$

The on-resistance can be obtained by currents flowing from the channel between the source and the drain electrodes as follows

$$R_{ON} = R_{CS} + R_N + R_{CH} + R_{D1} + R_{D2} + R_{CD} \tag{11}$$

where R_{CS} is the source contact resistance, R_N is the source, and R_{CD} is the contact resistance of drain, which is very small, and negligible.

The total specific on-resistance mainly occurs from the channel and the drift region as shown below.

$$R_{T.SD} = R_{CH.SD} + R_{D.SD} \tag{12}$$

At the ideal SJ TMOSFET structure, the specific on-resistance [1] in terms of breakdown voltage is also obtained as

$$R_{ON,SP} = 1.05 \times 10^{-6} V_{BR}^{1.26} \tag{13}$$

The specific on-resistance [1] with respect to breakdown voltage at SJ TMOSFET and conventional MOSFET [4] is shown in Fig. 3.

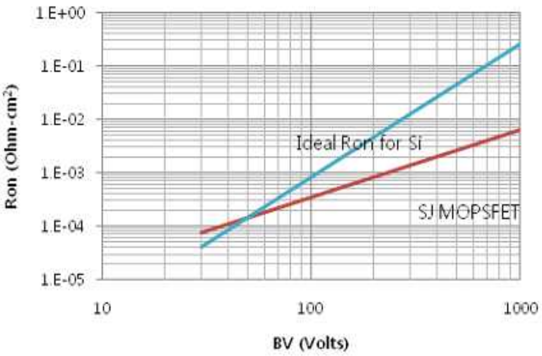

Fig. 3 The $R_{ON,SP}$ vs. V_{BR} at SJ TMOSFET and conventional MOSFET

3. Vertical SJ TDMOS Design

The fundamental structure of SJ trench MOSFET as shown in Fig. 1 is optimally designed based on the self align TDMOS developed by ETRI [5]. The specific on-resistance obtained at TDMOS is $1.4\,m\Omega{\cdot}cm^2$. The epitaxial width is $7\mu m$, the trench depth is $1.7\mu m$, and the trench width is $0.7\mu m$. The critical electric field occurring the breakdown voltage is well known as $2.5\times10^5\ V/cm$ [1]. It is checked that the minimum width of $5\mu m$ is required to have the breakdown voltage of 120 V. The doping profile at the boundary between the substrate and the drift region is determined by the out-diffusion of substrate layer during forming the P-well.

Ⅲ. Simulations

The doping concentrations for P-N columns are assumed to be equal. The doping concentration in the drift of the power SJ Trench power MOSFET structure should be optimized to obtain the desired breakdown voltage. In the manufacturing field [5], it is difficult to make the doping concentration exactly equal, and the impact of imbalance results in varying breakdown voltages.

The resistance contributions from the N^+ substrate and the contacts are neglected during the simulation. In designing the vertical SJ TDMOS, the applied parameters are the P well junction depth of $1.2\mu m$, the unit cell width of $2.4\mu m$, and each N and P pillar width of $1.2\mu m$. Here, the electric filed at the point of breakdown has to be kept below E_{CU}. The resistivity of ‘As’ doped substrate is $1\sim5m\Omega{\cdot}cm^2$, and the thickness of gate oxide is 500Å [6]. The cell density increases by reducing the trench width, which leads to a decrease in the channel resistance, and the gate capacitance is increased.

Fig. 4 shows the distributions at the breakdown phenomena. They are the electric fields, the ionization coefficients, the horizontal electric fields, and the horizontal ionization coefficients, respectively.

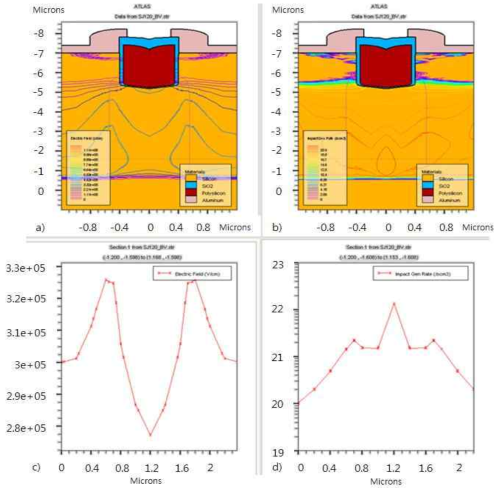

Fig. 4 Distributions at breakdown phenomena
a)Electric fields
b) Ionization coefficients
c) Horizontal electric fields
d) Horizontal ionization coefficients

The pattern of the horizontal electric fields is kept constant with minimum and maximum values within the maximum critical electric field.

The breakdown voltages decrease as the pillar doping concentration increases as shown in Fig. 5, and depend on the n-epi concentration. Here, SJ TDMOS has higher breakdown voltage than non-SJ TDMOS at the same doping concentration. Also, the specific on-resistance of SJ TDMOS is relatively lower than non-SJ TDMOS under the same breakdown voltage for higher doping concentration as shown in Fig. 5.

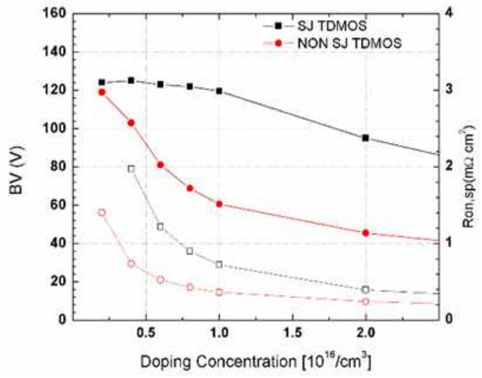

Fig. 5. The breakdown voltages and the specific on-resistances vs. pillar doping concentrations.

In Fig. 6, the potentials for 60, 80, 100, and 120 V are uniformly distributed, and the widths of potential lines become to constant as the drain voltage increases to 120 V of breakdown voltage.

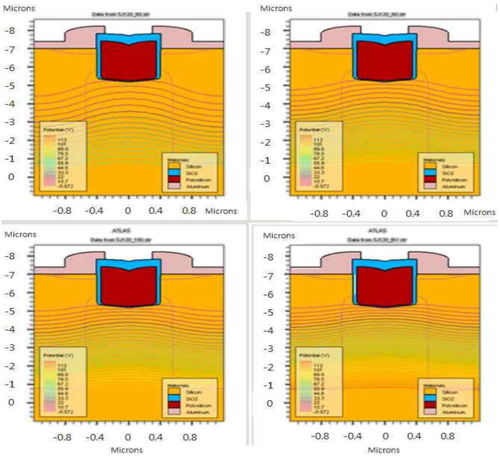

Fig. 6 Potential distributions at of 60V, 80V, 100V, and 120 V

IV. Conclusions and Discussions

The specific on-state resistance ($R_{ON,SP}$) of $0.96\,m\Omega\cdot cm^2$ for a BLDC motor at the class of 100 V and 100 A is successfully optimized and met with the ideal specific on-resistance in the super-junction trench power MOSFET, algebraically. First, the specific on-resistance mainly depends on the ideal pillar width and concentration. Second, the fundamental structure of trench gate SJ MOSFET is designed, and the doping concentration of pillar, potential distribution, ionization coefficients, and electric fields are analyzed after simulation by SILVACO TCAD [7]. It is evaluated so that the simulation results agree with the theories, and allow engineers to implement the SJ power TMOSFET.

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