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## Ti/4H-SiC Schottky diode with breakdown voltage up to 3 kV

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**Abstract.** In this study the breakdown voltage for Ti/4H-SiC type Schottky diode with six guard rings and JTE layer has been calculated by mean of numerical simulations. It is established that increase of the n-type 4H-SiC epitaxial layer from 14 up to 20  $\mu\text{m}$  and addition of JTE layer lead to increase of breakdown voltage value on  $\sim 900$  V in contrast to the same diode without JTE. The above-mentioned diode's structure gives the possibility for designing and production of diode with higher breakdown voltage value up to 3 kV.

### 1. Introduction

It is known that semiconductor material silicon carbide (SiC) is promising for the development of power electronics, microelectronics and optoelectronics devices. This is due to the large band gap of the semiconductor SiC ( $>3$  eV), high thermal conductivity, high breakdown fields and the rate of electron saturation, as well as significant radiation and thermal stability [1]. One of the simplest devices based on SiC, but at the same time important for microelectronics, is Schottky diode. For example, Schottky diodes for power electronics based on 4H-SiC have already been manufactured by the domestic industry, in particular, by the "GRUPPA KREMNY EL" domestic company (Bryansk). It is obvious that for the further development of the domestic component base based on SiC it is necessary to study in detail the influence of the diode structure parameters on its current-voltage characteristics to optimize the Schottky diode operation in power electronics, which can be done using physical simulation [2]. Earlier, in our previous paper [3-5] have been studied of 4H-SiC type Schottky diodes with Ni and Ti Schottky anode contacts without guard rings. Therefore, the main goal of this study was to design a perspective SiC Schottky diode with guard rings using physical simulation methods in the ATLAS software program and to study its electrical characteristics.

### 2. Materials and methods

The following Schottky diode with six guard rings and donor concentration in the epitaxial layer 4H-SiC  $N_D = 3 \times 10^{15} \text{ cm}^{-3}$  was taken as the object of simulation in program.

As can be seen earlier, to calculate the breakdown voltage ( $BV_m$ ) of the Schottky diode in a plane-parallel  $p$ - $n$  junction, we first determined the critical breakdown field strength ( $E_c$ ) from the condition of equality to the unit of the ionization integral [6]:

$$\int_0^d \alpha_n \exp \left[ - \int_x^d (\alpha_n - \alpha_p) dx' \right] dx = 1, \quad (1)$$

where  $\alpha_n$  and  $\alpha_p$  – the ionization coefficients of electrons and holes,  $d$  – the epitaxial layer thickness.

In 4H-SiC, the ionization coefficients of the exponential dependence on the reverse field:

$$\alpha_n = \alpha_{n0} \exp \left( - \frac{E_n}{E} \right), \quad (2)$$



$$\alpha_p = \alpha_{p0} \exp\left(-\frac{E_p}{E}\right), \quad (3)$$

where  $\alpha_{n0} = 1.76 \times 10^8 \text{ cm}^{-1}$ ,  $\alpha_{p0} = 3.41 \times 10^8 \text{ cm}^{-1}$ ,  $E_n = 3.3 \times 10^7 \text{ V/cm}$ ,  $E_p = 2.5 \times 10^7 \text{ V/cm}$  [7].

By substituting expressions (2) and (3) into formula (1), we obtain the following integral equation with respect to  $E_c$ :

$$\int_0^d \alpha_{n0} \exp\left(-\frac{E_n}{E_c - \frac{q}{\varepsilon_s} N_D x}\right) \exp\left[-\int_0^d \alpha_{n0} \exp\left(-\frac{E_n}{E_c - \frac{q}{\varepsilon_s} N_D x}\right) - \alpha_{p0} \exp\left(-\frac{E_p}{E_c - \frac{q}{\varepsilon_s} N_D x}\right) dx'\right] dx = 1, \quad (4)$$

where  $\varepsilon_s$  – 4H-SiC dielectric permittivity,  $N_D$  – the donor concentration in the 4H-SiC epitaxial layer,  $q$  – the elementary charge.

Then, after the numerical solution of equation (4) and determination of the critical breakdown field strength, the breakdown voltage can be estimated by the following formula [6, 7]

$$BV_m = \frac{E_c W}{2} \quad (5)$$

where  $E_c$  – the critical breakdown field strength, determined from the integral equation (4),  $W$  – the thickness of the space charge area (SCA).

Further, in the approximation, it can be assumed that the breakdown occurs at a time when the thickness of the SCA is equal to the thickness of the epitaxial layer  $d$  [7]. A calculated value of the critical breakdown field strength  $E_c$  and the breakdown voltage of  $BV_m$  with donor concentration  $N_D = 3 \times 10^{15} \text{ cm}^{-3}$  and different values of the thickness  $d$  of the 4H-SiC epitaxial layer are shown in Table 1.

**Table 1.** The values of breakdown voltage  $BV_m$  with different 4H-SiC epitaxial layer thicknesses calculated from equations (4) and (5).

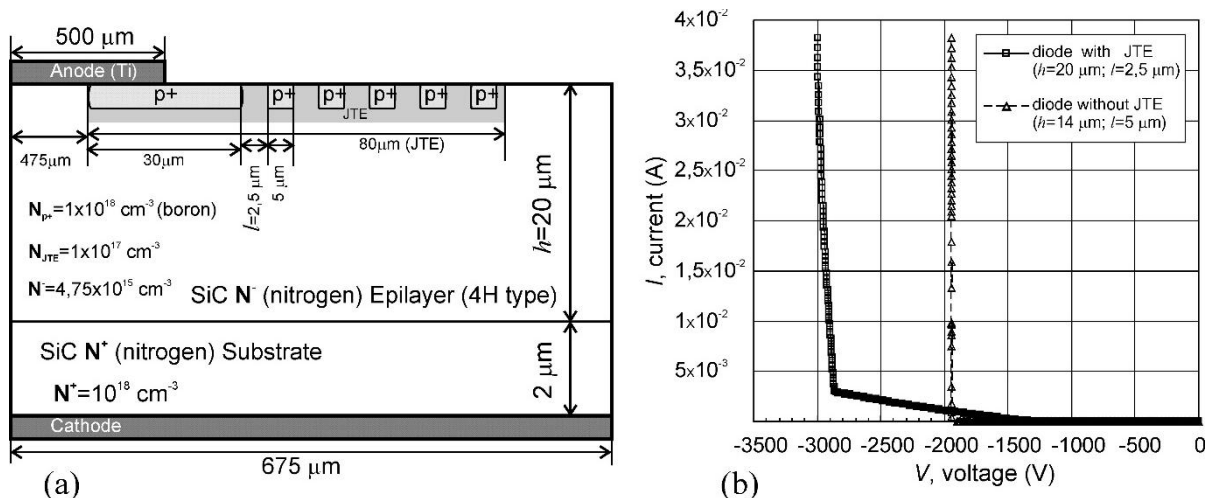
$d$ , 4H-SiC epitaxial layer thickness ( $\mu\text{m}$ )	$N_D$ , donor concentration in the 4H-SiC epitaxial layer ( $\text{cm}^{-3}$ )	$E_c$ , critical breakdown field strength calculated from the equation (4) ( $\text{V} \times \text{m}^{-1}$ )	$BV_m$ , 4H-SiC breakdown voltage calculated from the equation (5) (V)
14	$3 \times 10^{15}$	$2.37801 \times 10^8$	$1.665 \times 10^3$
16	$3 \times 10^{15}$	$2.37759 \times 10^8$	$1.902 \times 10^3$
18	$3 \times 10^{15}$	$2.37722 \times 10^8$	$2.139 \times 10^3$
20	$3 \times 10^{15}$	$2.37729 \times 10^8$	$2.377 \times 10^3$
22	$3 \times 10^{15}$	$2.377217 \times 10^8$	$2.615 \times 10^3$

As it can be seen from Table 1 breakdown voltage of more than 2 kV is provided at a layer thickness of 18  $\mu\text{m}$ . With this in mind, the breakdown voltage was simulated for the 4H-SiC epitaxial layer thickness of 18, 20 and 22  $\mu\text{m}$ . The Schottky diode with six guard rings was taken as the object of modeling. In Fig. 1a shown the simulated schematic silicone carbide Schottky diode structure for calculation. For numerical simulation were chosen the following the Schottky diode parameters: the concentration of donors (nitrogen) in the substrate equals  $N^+ = 10^{18} \text{ cm}^{-3}$ , in the  $n$ -type epitaxial layer (nitrogen) equals  $N^- = 4.75 \times 10^{15} \text{ cm}^{-3}$ , in the guard rings (boron, depth of guard about 2  $\mu\text{m}$ ) regions  $N_{p+} = 10^{18} \text{ cm}^{-3}$ , in the JTE layer concentration  $N_{JTE} = 10^{17} \text{ cm}^{-3}$ , anode material is Ti (titanium), the thickness of the epitaxial layer (4H-SiC) was chosen equals 14 and 20  $\mu\text{m}$ , the radius of the structure equals  $r = 675 \mu\text{m}$ . The simulation of the reverse current-voltage ( $I$ - $V$ ) characteristics has

been carried out in the ATLAS program, with taking into account close to reality situation the incomplete impact ionization and anisotropy in the direction (0001) by the Hummel-Newton method.

### 3. Results and discussion

Fig. 1b shows the reverse  $I$ - $V$  characteristics of Schottky diode with thickness of the epitaxial layer ( $h$ ) and distance between rings ( $l$ ) calculated in ATLAS for diode with JTE ( $h=20\ \mu\text{m}$ ,  $l=2,5\ \mu\text{m}$ ). As follows from Fig. 1b the diode breakdown starts at 2,87 kV i.e. breakdown voltage value equals  $\sim 3$  kV. For comparison in Fig. 1b also presented  $I$ - $V$  characteristics of Ti/4H-SiC Schottky diodes with reduced thickness of the epitaxial layer ( $h=14\ \mu\text{m}$ ) and increased distance between guard rings ( $l=5\ \mu\text{m}$ ) and without JTE layer. In this case the value of breakdown voltage value equals 1,94 kV.



**Figure 1.** (a) Ti/4H-SiC silicone carbide Schottky diode schematic structure in cylindrical coordinates for calculation; (b) reverse  $I$ - $V$  characteristics of Ti/4H-SiC Schottky diodes with different of thickness of the epitaxial layer ( $h$ ) and distance between rings ( $l$ ) calculated in ATLAS for diode with JTE ( $h=20\ \mu\text{m}$ ,  $l=2,5\ \mu\text{m}$ ) and without JTE ( $h=14\ \mu\text{m}$ ,  $l=5\ \mu\text{m}$ ).

Thus, the increase of the 4H-SiC epitaxial layer thickness from 14 up to 20  $\mu\text{m}$  and a decrease of the distance between the guard rings from 5 to 2.5  $\mu\text{m}$  and also the addition of the JTE layer leads to a significant increase of the breakdown voltage of the diode on  $\sim 900\ \text{V}$ . In addition, on the basis of analysis of the distribution of the impact ionization rate it is established that the maximum values of the velocity of impact ionization rate ( $23\div 25\ \text{cm}^3\cdot\text{s}^{-1}$ ) are reached in the area between first and second guard rings. Therefore, with aim to reduce the probability of breakdown in this place the depth of the JTE layer must be increase.

### 4. Conclusions.

1. It is shown, on the basis of the theoretical calculations and calculations performed in ATLAS, the required breakdown voltage of the Schottky diode of more than 2 kV is provided at a thickness of 4H-SiC epitaxial layer of 18  $\mu\text{m}$ . At the same time, taking into account the very likely possible defects in the structures of real diodes, the most preferred option from the calculations is the thickness of the epitaxial layer of 20  $\mu\text{m}$ , which can provide the required breakdown voltage of the Schottky diode more than 2 kV.

2. The reverse  $I$ - $V$  characteristics of perspective Ti/4H-SiC Schottky diode with the 4H-SiC epitaxial layer thickness of 20  $\mu\text{m}$ ,  $p+$  wide ring with a width of 30  $\mu\text{m}$  and five rings with a width of 5  $\mu\text{m}$  with a gap of 2.5  $\mu\text{m}$ , JTE layer with a width of 80  $\mu\text{m}$  was calculated. In accordance with calculation the Ti/4H-SiC type Schottky diode with above-described structure demonstrate the very high breakdown voltage value up to 3 kV and can be used in power electronics.

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