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Research paper

Calculation of 4H-SiC Schottky Diode with Breakdown Voltage Up to 3 KV

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Abstract

The current-voltage characteristic of the 4H-SiC Schottky diode for forward and reverse current direction was calculated and simulated on the base of the theory of thermionic emission and a physical analytical model based on the Poisson equation, the diffusive and continuity equations. It is shown that as follows from the theoretical calculations and calculations carried out in ATLAS that breakdown voltage of Schottky diode more than 2 kV is provided at a thickness of 4H-SiC of epitaxial layer from 18 μm. It is established that thickness of epitaxial layer from 20 μm will provide breakdown voltage of Schottky diode more than 2 kV. In addition the current-vltage characteristic for perspective Schottky diode (with breakdown voltage ~3 kV) with thickness of 4H-SiC epitaxial layer of 20 μm, *p*+ ring of 30 microns wide and five rings of 5 μm wide with a gap width of 2.5 μm, JTE layer of 80 μm wide. It is shown that the diode with the above specified structure can stand breakdown voltage up to ~3 kV

Keywords: *silicon carbide, Schottky diode, thermionic emission, simulation.*

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 of research

In this paper, we used a physical model of Schottky diode [2] which solved the Poisson equation taking into account the concentration of free charge carriers, the continuity equation for electrons and holes, taking into account the dependence of the mobility of charge carriers on the impurity concentration and the electric field strength, and also the avalanche multiplication of charge carriers was taken into account [2]. The final system of equations in spherical coordinates for the computer model of Schottky diode had the following form:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\varepsilon_r r\frac{\partial\varphi}{\partial r}\right)+\frac{\partial}{\partial z}\left(\varepsilon\frac{\partial\varphi}{\partial z}\right)=-q\left(p-n+N_D^+-N_A^-\right) \tag{1}$$

$$q^{-1}\nabla\cdot\boldsymbol{j}_n=-U_n \tag{2}$$

$$q^{-1}\nabla\cdot\boldsymbol{j}_p=-U_p \tag{3}$$

$$\boldsymbol{j}_n=n\mu_n\nabla E_c+\mu_n k_B T_l\nabla n \tag{4}$$

$$\boldsymbol{j}_p=p\mu_p\nabla E_V+\mu_p k_B T_l\nabla p \tag{5}$$

$$E_c=-q(\varphi+\chi) \tag{6}$$

$$E_V=-q(\varphi+\chi+E_g) \tag{7}$$

where r – the diode radius,   – the relative dielectric permittivity,   – the electrostatic potential, q – the elementary electric charge,   и   – the concentration of electrons and holes,   – the donor impurity concentration, – the ionized acceptors concentration, и – the electron’s and holes electric current density, – the thermodynamic temperature of crystal lattice, и – the voltage applied to anode and cathode of diode, – the electron mobility, – the holes mobility, kB – the Boltzmann constant, и – the energy of conduction band and valence band of semiconductor, – the band gap of silicon carbide 4H-SiC, – the electron affinity, and in addition it has been taken into account that – the density of states in the conduction band, – density of states in the valence band in accordance with the data of works [1,6–7]. In the presented model also were included Shockley-Read-Hall model recombination, Auger recombination and anisotropic impact ionization. The physical simulation process has been carried out in ATLAS program with using of the Newton’s iterative method.

3. Results and discussion

3.1. Calculation of the temperature effect directly on CVC Schottky diode with six guard rings

In Fig. 1 the detailed structure of the simulated Schottky diode with six guard rings is shown: a wide ring with a width of 35 µm and five rings with a width of 5 µm with a gap width of 5 µm, an epitaxial layer thickness of 14 µm and a substrate thickness of 6 µm. The concentration of n-impurity in the epitaxial layer 4H-SiC is 4.75×1015 cm-3, the concentration in p+ areas is 1.0×1018 cm-3.

Simulation of the current-voltage characteristic (CVC) in the forward direction was carried out in the ATLAS program using the Newton's iterative method for wide temperature range from 63 oC up to 427 oC.

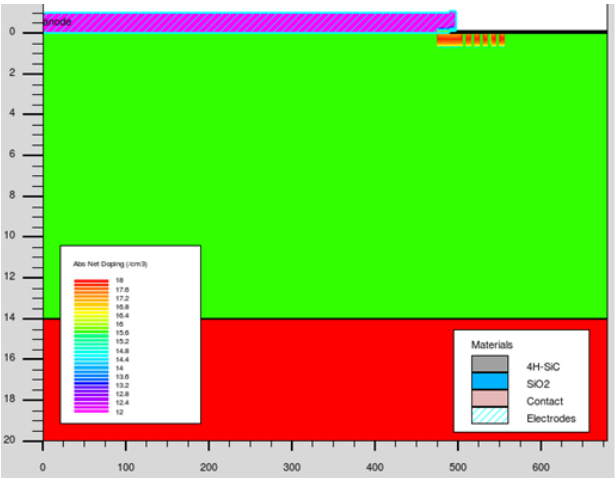


Fig. 1: The structure of the simulated Schottky diode with six guard rings: a wide ring with a width of 35 µm and five rings with a width of 5 µm with a gap width of 5 µm, the epitaxial layer thickness of 14 µm and the substrate thickness of 6 µm. The concentration of n-impurity in the epitaxial layer 4H-SiC 4.75×1015 cm-3, the concentration in p+ areas 1.0×1018 cm-3.

The simulation results of CVC straight lines in the temperature range T = 63 427 oC are shown in the following Fig. 2. The obtained CVC qualitatively demonstrate the dependence similar, for example, to the same type of CREE diode (Wolfspeed) close in class C4D02120A (1200V, 2A [8]) or the diode of the firm Infineon (IDH02SG120 1200V, 2A [9]), i.e. with temperature increase the current across the diode in the forward direction decreases.

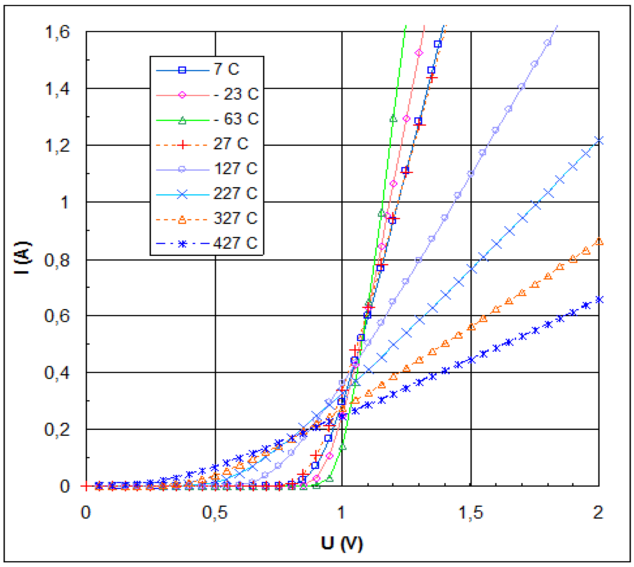


Fig. 2: CVC of the simulated Schottky diode in the forward direction at T = 63 oC до 427 oC.

3.2. Calculation of the effect of epitaxial layer thickness 4H-SiC on the breakdown voltage of Schottky diode

Schottky diode with six guard rings and donor concentration in the epitaxial layer 4H-SiC ND = 3×1015 cm−3 was taken as the object of simulation.

Previously, to calculate the breakdown voltage (BVm) of the Schottky diode in a plane-parallel p-n junction, we first determined the critical breakdown field strength (Ec) from the condition of equality to the unit of the ionization integral [10]:

$$\int_0^d \alpha_n \exp\left[-\int_x^d \left(\alpha_n-\alpha_p\right)dx'\right]dx=1, \tag{8}$$

where αn and αp – 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:

$$\alpha_n=\alpha_{n0}\exp\left(-\frac{E_n}{E}\right), \tag{9}$$

$$\alpha_p=\alpha_{p0}\exp\left(-\frac{E_p}{E}\right), \tag{10}$$

where αn0 = 1.76×108 cm−1, αp0 = 3.41×108 cm−1, En = 3.3×107 V/cm, Ep = 2.5×107 V/cm [11].

By substituting expressions (9) and (10) into formula (8), we obtain the following integral equation with respect to Ec:

$$\int_0^d \alpha_{n0}\exp\left(-\frac{En}{Ec-\frac{q}{\varepsilon_s}N_D x}\right)\exp\left[-\int_0^d\left[\alpha_{n0}\exp\left(-\frac{En}{Ec-\frac{q}{\varepsilon_s}N_D x}\right)-\alpha_{p0}\exp\left(-\frac{Ep}{Ec-\frac{q}{\varepsilon_s}N_D x}\right)\right]dx'\right]dx=1, \tag{11}$$

where □s – 4H-SiC dielectric permittivity, ND –the donor concentration in the 4H-SiC epitaxial layer, q – the elementary charge.

After the numerical solution of equation (11) and determination of the critical breakdown field strength, the breakdown voltage can be estimated by the following formula [10,11].

$$BV_m = \frac{E_c W}{2} \tag{12}$$

where Ec – the critical breakdown field strength, determined from the integral equation (11), W – the thickness of the space charge area (SCA).

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 [11]. A calculated value of the critical breakdown field strength Ec and the breakdown voltage of BVm with donor concentration ND = 3×1015 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 (11) and (12).

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

As it can be seen from Table 1 breakdown voltage of more than 2 kV is provided at a layer thickness of 18 μm. With this in mind, the breakdown voltage was simulated for the 4H-SiC epitaxial layer thickness of 18, 20 and 22 μm. The Schottky diode with six guard rings was taken as the object of modeling. The structure of the simulated Schottky diode is shown in the following Fig. 3.

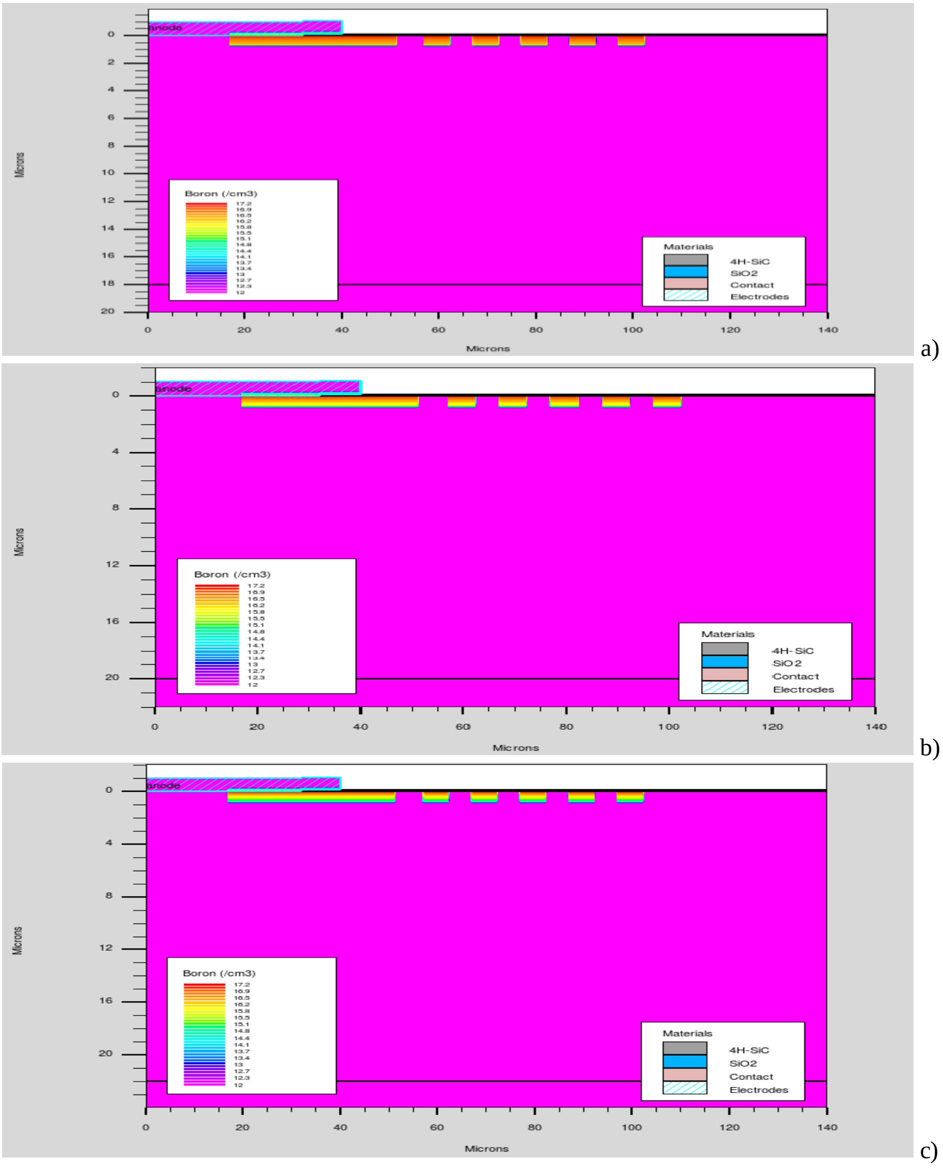


Fig. 3: The structure of the simulated Schottky diode with 4H-SiC epitaxial layer thickness of 18 μm (a), 20 μm (b) and 22 μm (c).

Simulation of the reverse CVC of Schottky diodes referred to above in Fig. 3 was carried out in the ATLAS program taking into account near-reality incomplete shock ionization and anisotropy in the direction (0001) by the Hummel-Newton method. The simulation results of reverse CVC of Schottky diodes are shown in Fig. 4.

As it shown in Fig. 4 the breakdown voltage BVexp is 2.332×103 V for 4H-SiC epitaxial layer thickness 18 µm, 2.380×103 V for 20 µm and 2.412×103 V for 22 µm, respectively. In fact, the breakdown begins somewhat earlier and more accurately the breakdown voltage can be determined from the ATLAS program log file where the ionization integral is also calculated during the iterations.

The values of the voltage BVioniz for the case when the values of the ionization integral from the ATLAS log file exceed 1, the values of the breakdown voltage BVexp calculated in ATLAS and the breakdown voltage BVm calculated by the equation (12) for different thicknesses d of the 4H-SiC epitaxial layer are summarized in Table 2.

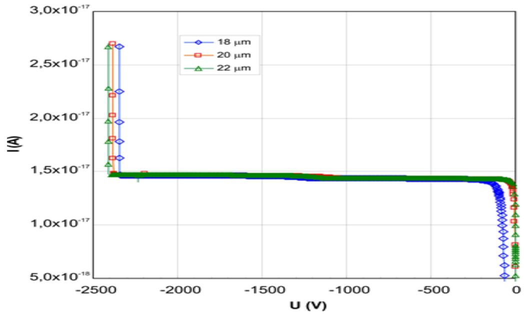


Fig. 4: Reverse CVC of Schottky diodes with 4H-SiC epitaxial layer thickness of 18 µm,20 µm and 22 µm.

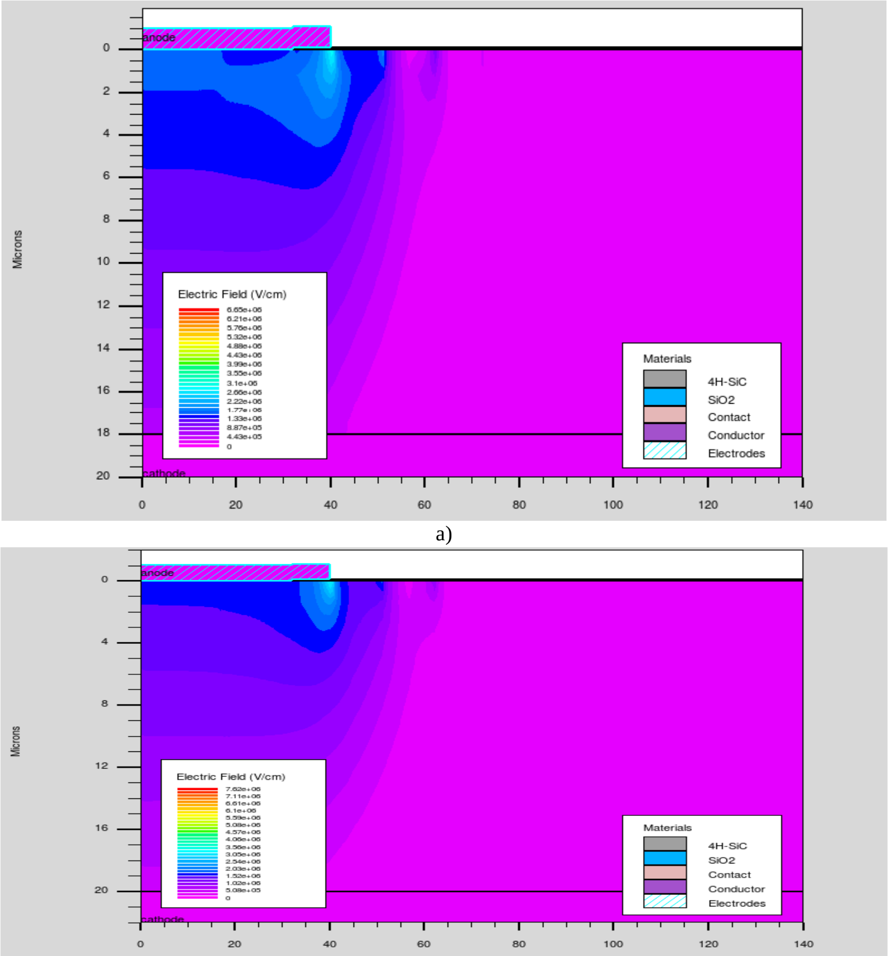
Table 2: The values of breakdown voltage for different thicknesses *d* of the 4H-SiC epitaxial layer.

d, 4H-SiC epitaxial layer thickness (µm)	BV_{exp}, the breakdown voltage calculated in ATLAS from Fig. 1 (V)	BV_{ioniz}, voltage when the values of the ionization integral in ATLAS exceed 1 (V)	BV_m, 4H-SiC breakdown voltage calculated from the equation (12) (V)
18	2.332×10^3	2.302×10^3	2.139×10^3
20	2.380×10^3	2.354×10^3	2.377×10^3
22	2.412×10^3	2.404×10^3	2.615×10^3

As it can be seen from Table 2, the breakdown voltage values determined by the simulation in ATLAS and calculated from equations (11) and (12) show very good agreement.

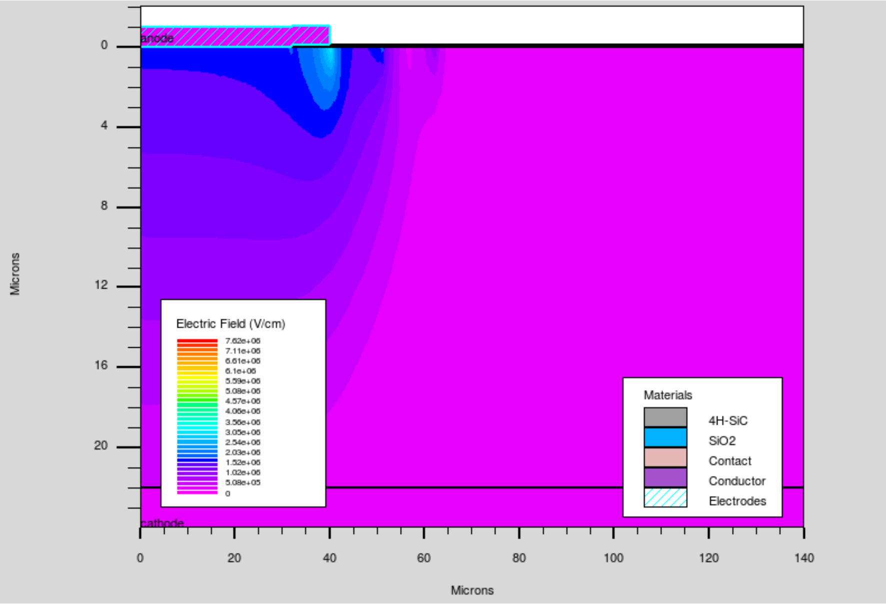
3.3 The study of the distribution of the electric field in the Schottky diode

In order to clarify the breakdown voltage conditions, the distribution pattern of the electrostatic field in the diode at the reverse voltage of 2000 V, shown in Fig. 5 was made.



a)

b)



c)

Fig. 5: The distribution of the electrostatic field of the simulated Schottky diode with the 4H-SiC epitaxial layer thickness of 18 µm (a), 20 µm (b) and 22 µm (c).

From Fig. 5 it can be seen that at the reverse voltage of 2000 V there is no excess of the electric field of the critical value for all the epitaxial layer thicknesses of 18 µm, 20 µm and 22 µm, i.e. at 2000 V the diode breakdown does not occur yet.

3.4. Calculation of parameters of perspective 4H-SiC Schottky diode with breakdown voltage ~3 kV

Taking into account the results obtained above, we have attempted to construct a Schottky diode with an increased breakdown voltage. For this purpose:

- the 4H-SiC epitaxial layer thickness was increased to 20 µm,
- the width of the gap between the guard rings was reduced to 2.5 µm and
- JTE (Junction Terminate Extension) layer with a width of 80 µm was added.

Finally, the structure of the simulated Schottky diode with six guard rings were the following: a wide ring with a width of 30 µm and five rings with a width of 5 µm with a gap of 2.5 µm and a JTE layer with a width of 80 µm, the thickness of the epitaxial layer was 20 µm and the thickness of the substrate 2 µm (Fig. 6). N-impurity concentration in 4H-SiC epitaxial layer was 4.75×1015 cm-3, concentration in p+ areas 1.0×1018 cm-3, concentration in JTE layer 1.0×1017 cm-3.

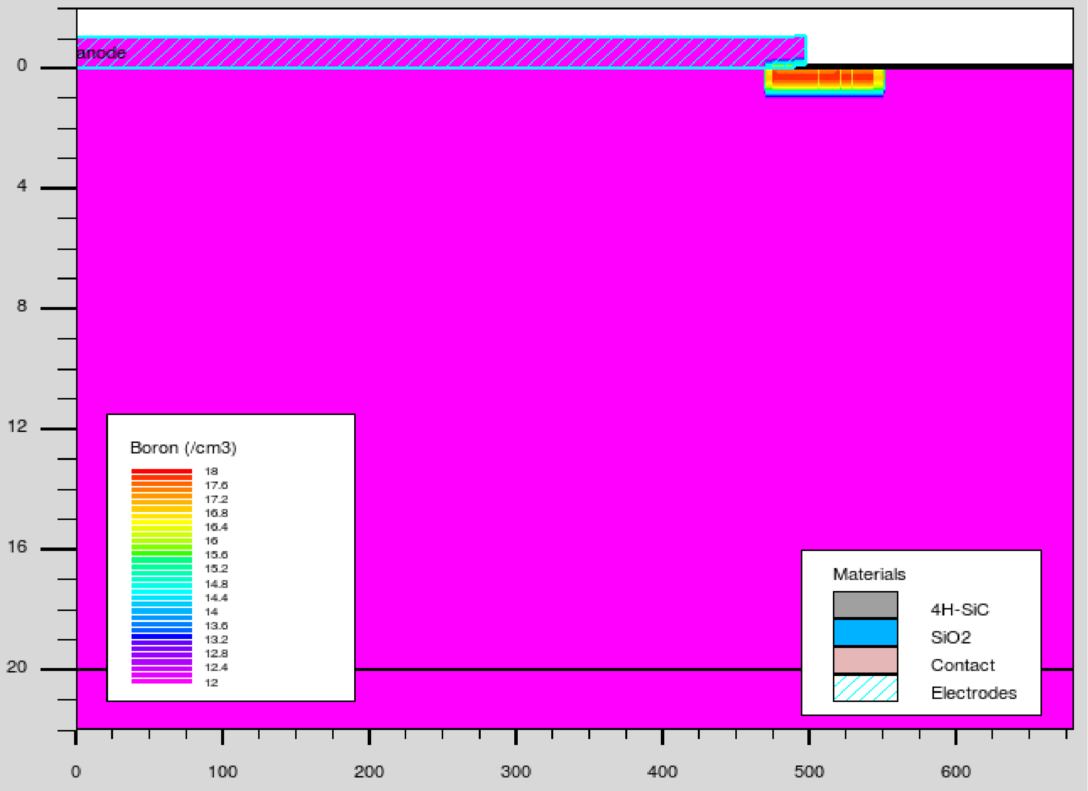


Fig. 6: The structure of the simulated Schottky diode: a wide ring with a width of 30 µm, and five rings with a width of 5 µm with a gap of 2.5 µm, the width of the JTE layer 80 µm, the thickness of the epitaxial layer 20 µm, substrate thickness of 2 µm. *N*-impurity concentration in 4H-SiC epitaxial layer 4.75×1015 cm^{-3}, concentration in p+ areas 1.0×1018 cm^{-3}, concentration in JTE layer 1.0×1017 cm^{-3}.

Further, the simulation of the direct CVC was carried out in the ATLAS program using the Newton's iterative method at temperature of 300 K. The results of the simulation of the CVC dependence (6r+JTE) are shown in Fig. 7. There for comparison the CVC dependence of diode with the thickness of the epitaxial layer 14 µm and without JTE layer (6r-JTE) is shown. Fig. 7 shows that the simulated diode with the supply voltage 4V can work in the mode of carrying current to ~12 A. To calculate the ideality factor of the diode the dependence lnI from the applied voltage U, shown in Fig.8 was further created.

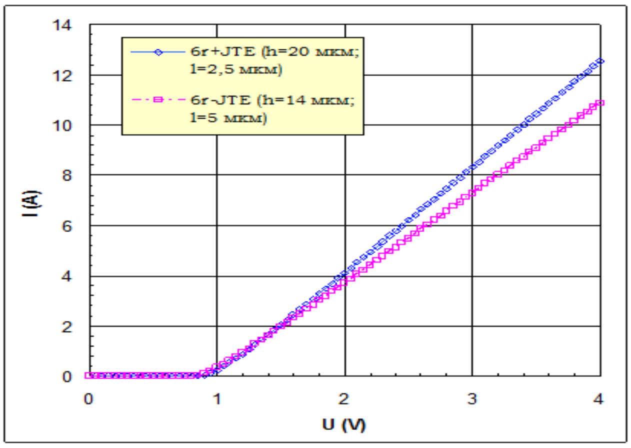


Fig. 7: CVC of the simulated Schottky diode (6r+JTE) in the forward direction at T = 300 K.

The calculation made it possible to establish that the simulated diode has an ideal coefficient close to one – n = 1.082, i.e. close to the "ideal" diode.

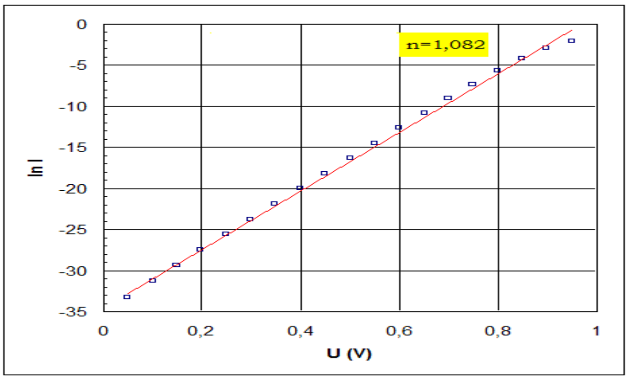


Fig. 8: Dependence of lnI on the applied voltage U for the simulated Schottky diode in the forward direction.

Further, the simulation of the reverse CVC of Schottky diode with the structure shown in Fig. 6 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. The simulation results of the reverse CVC are shown in Fig. 9. It can be seen that the voltage at which the breakdown of the diode with a similar structure is ~2870 V and further, with an increase in the voltage to 3000 V, the diode does not break through yet. Because of this, in Fig. 9, for comparison, the reverse CVC of the diode with the epitaxial layer thickness of 14 µm and without JTE layer is shown, from which it is seen that the diode of such a design breaks at voltages ~1900 V.

Thus, an increase in the 4H-SiC epitaxial layer thickness from 14 up to 20 µm and a decrease in the width of the gap between the guard rings from 5 to 2.5 µm and the addition of the JTE layer leads to a significant increase of the breakdown voltage of the diode on ~ 900 V.

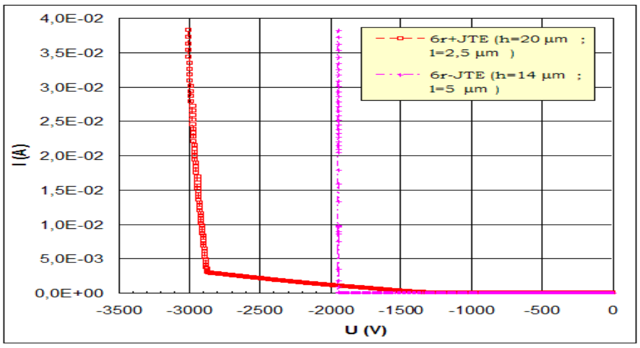
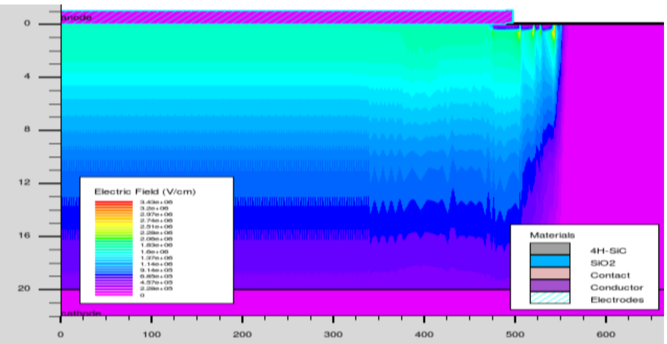


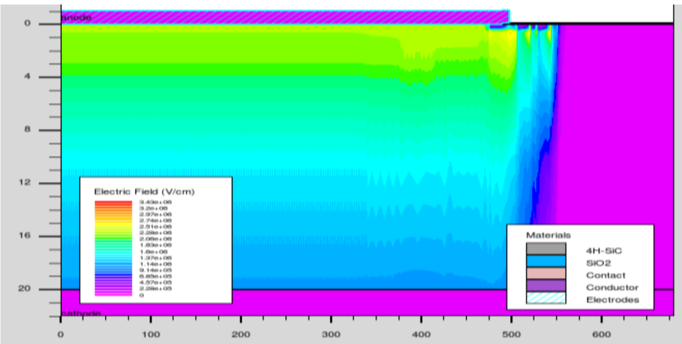
Fig. 9: Reverse CVC of Schottky diode (6r+JTE) with 4H-SiC epitaxial layer thickness of 20 µm p+ wide ring with a width of 30 µm and five rings with a width of 5 µm with a gap of 2.5 µm, JTE layer with a width of 80 µm. For comparison, the reverse CVC of the diode (6r-JTE) with the epitaxial layer thickness of 14 µm and without the JTE layer.

3.5. The study of the distribution of the electric field in the prospective Schottky diode

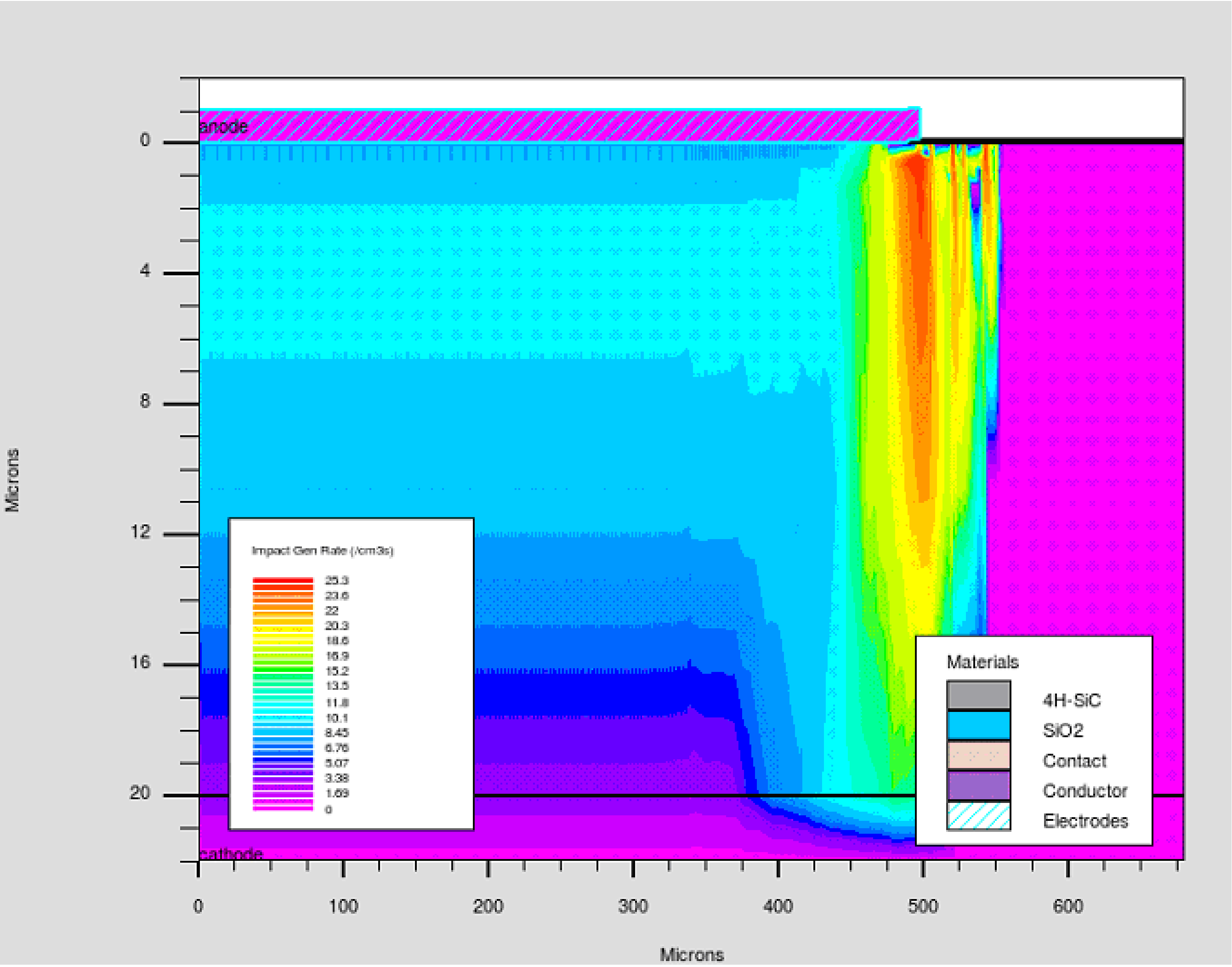
Further, in order to verify the previous fact, namely that according to the calculations (see Fig. 9) the diode does not break through, we made a picture of the distribution of the electric field E and the shock ionization rate for the above Schottky diode, shown in Fig. 10. From Fig. 10a it follows that when the reverse voltage is applied Urev. = 1900 V the maximum values of the electric field E □ 2.3□106 V/cm in the diode are observed in the area located at the interface of the anode and guard rings. A similar pattern occurs when the reverse voltage Urev. = 3000 V is applied (see Fig. 10b), where the electric field is E □ 2.7□106 V/cm but also does not exceed the critical value, i.e. when applying 3 kV diode has not broken through yet.



a) the distribution of the electric field E in the diode when the reverse voltage $U_{rev.}$ = 1900 V;



b) the distribution of the electric field E in the diode when the reverse voltage $U_{rev.}$ = 3000 V;



c) the velocity distribution of impact ionization (Impact Generation Rate – IGR) in diode when applying a reverse voltage $U_{rev.}$ = 3000 V.

Fig. 10: The distribution of electric field intensity and velocity of impact ionization of Schottky diode (6r+JTE) with 4H-SiC epitaxial layer thickness of 20 µm, *p+* wide ring with a width of 30 µm and five rings with a width of 5 µm with a gap of 2.5 µm, JTE layer with a width of 80 µm.

In order to clarify the areas of possible breakdown, we further made a picture of the distribution of the shock ionization rate of the diode IGR (Impact Gen Rate) when the reverse voltage Urev. = 3000 V. Fig. 2.10b shows that the maximum values of the velocity of impact ionization IGR □ 23□25 cm-3□s-1 are achieved in the area at the interface of the first and second guard rings. Therefore, this area is the most likely to break.

In order to prevent a breakdown at a given location, it is possible, for example, to increase the depth of the JTE layer at a given location, which can reduce the probability of a breakdown.

4. Conclusions

1. CVC of Schottky diode with six guard rings was calculated: a wide ring with a width of 35 µm and five rings with a width of 5 µm with a gap width of 5 µm, an epitaxial layer thickness of 14 µm and a substrate thickness of 6 µm. The concentration of n-impurity in the epitaxial layer 4H-SiC is 4.75×1015 cm-3, the concentration in p+ areas 1.0×1018 cm-3. The obtained CVC qualitatively demonstrate the dependence similar for the same type diodes, i.e. with increasing temperature the current across the diode in the forward direction decreases.
2. It is established, based on 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 µm. 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 µm, which can provide the required breakdown voltage of the Schottky diode more than 2 kV.
3. CVC of perspective Schottky diode (breakdown ~3 kV) with the 4H-SiC epitaxial layer thickness of 20 µm, p+ wide ring with a width of 30 µm and five rings with a width of 5 µm with a gap of 2.5 µm, JTE layer with a width of 80 µm were calculated. It is shown that the diode with this structure can stand the work with breakdown voltage up to ~ 3 kV.

Acknowledgements

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