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Forward current-voltage characteristics simulation of 4H-SiC silicon carbide Schottky diode for power electronics

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Abstract

Forward current-voltage characteristics of 4H-SiC Schottky diode with Ni Schottky contact have been simulated based on in the physical analytical models based on Poisson's equation, drift-diffusion and continuity equations. On the base of analysis of current-voltage characteristics in terms of classical thermionic emission theory it is established that the proposed simulation model of Schottky diode corresponds to the "ideal" diode with average ideality factor $n \approx 1.1$ at low temperature ~300 K. It is determined that effective Schottky barrier height equals 1.1 eV for Ni/4H-SiC Schottky diode.

Keywords: *4H-SiC; Schottky Diode; Silicon Carbide; Thermionic Emission; Simulation.*

1. Introduction

Studying of silicon carbide (SiC) as material for semiconductor electronics has been made at first in Leningrad (St. Petersburg) by the O.V. Losev's at the A.F. Ioffe Institute at the beginning of the 1930s [1]. Now silicon carbide represents an excellent candidate for high-temperature electronic device applications because of its high breakdown voltage, low series resistance, and stability under harsh chemical and high temperature conditions. SiC Schottky diodes are of special interest since these unipolar devices avoid reverse recovery effects of bipolar devices, thereby offering higher frequency operation [2,3].

It is very perspective silicon carbide type material for manufacturing of Schottky diodes is 4H-SiC-type which is more preferable to power semiconductors electronics before high mobility of electrons in this silicon carbide type [3]. In particular, similar 4H-SiC Schottky diodes for power electronics were made in A.F. Ioffe Institute and in future may be produced by the «GROUP KREMNY L» company (Bryansk, Russia). It is obviously that for development of component base on the base of SiC studying and optimisation of such important device as Schottky diode it is necessary. Earlier simulation of current-voltage (*I-V*) characteristics in 4H-SiC Schottky diode with Ti Schottky contact has been made [4]. Therefore in the present work the main goal was the simulation of current-voltage characteristics in 4H-SiC Schottky diode with Ni Schottky contact has been made.

2. Materials and methods

The materials parameters for simulation were following: the concentration of donors (nitrogen) in the substrate equals $N_D^+ = 10^{18}$ cm^{-3}, in the epitaxial layer equals 8×10^{15}, anode material is Ni (nickel) and Ti (titanium), thickness of the epitaxial layer (4H-SiC) equals z=15 μm, radius of the structure equals r=200 μm. For simulation model of current-voltage characteristics has been solved electrostatic Poisson's equation in cylindrical coordinates together with continuity equations for electrons and holes. Because of this for calculation current-voltage characteristics in Schottky diode was applied of the thermionic emission theory which taking into account of the electron-phonon interaction, quantum-mechanical tunneling through barrier and reduction of barrier height under influence of image force effect [2].

3. Results and discussion

For simulation model of current-voltage characteristics has been solved electrostatic Poisson's equation in cylindrical coordinates together with drift–diffusion and continuity equations. In particular, we assumed that and mobility and diffusion coefficients can be described by Einstein's equations. Finally the system of the basic equations for simulation model of Schottky diode must be given by expressions of the form [2,5]:

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

$$\frac{dn}{dt}=-\frac{1}{q}div(\boldsymbol{J}_n)+(G-R), \quad (2)$$

$$\frac{dp}{dt}=-\frac{1}{q}div(\boldsymbol{J}_p)+(G-R), \quad (3)$$

$$\boldsymbol{J}_n=q\mu_n n\boldsymbol{E}_n+qD_n\nabla n, \quad (4)$$

$$\boldsymbol{J}_p=q\mu_p p\boldsymbol{E}_p+qD_p\nabla p, \quad (5)$$

where r – the radius of diode, z – the height of diode, q – the elementary charge, n and p – the concentration of electron's and holes, φ – the electrostatic potential, ε_r – the dielectric relative permeability of SiC epitaxial layer, N^+_D – the donor impurity concentration, N_A^- – the ionised acceptors concentration, $\boldsymbol{J}_n$ and $\boldsymbol{J}_p$ – the electron's and holes electric current density, G and R – the generation and recombination rates for both electrons and holes, μ_n and μ_p – the electron and hole mobilities, $D_n = \frac{k_B T}{q}\mu_n$ and $D_p = \frac{k_B T}{q}\mu_p$ – the electron and hole diffusivities according to Einstein's relationship, k_B – the Boltzmann constant, T – the temperature, $\boldsymbol{E}_n$ and $\boldsymbol{E}_p$ – the effective driving electrical field to electrons and holes, which related to with local band diagram. In the presented model also were included Shockley-Read-Hall model recombination, Auger recombination and anisotropic impact ionization [5]. Boundary conditions between Ni metal contacts for 4H-SiC layer on a lateral surface of the cylinder were used as standard for Schottky diode [2,5]. For simulation forward current-voltage characteristics were chosen the following temperature: 300, 400, 500 and 600 *K*. Anode potential has been varied from 0 *V* to 2 *V* for calculation of forward *I-V* characteristics. Materials parameters data of 4H-SiC [3] used for simulation are shown in Table 1.

Table 1. Materials parameters data for simulation.

Parameter	4H-SiC
Band-gap energy, E_g (eV)	3.23
Dielectric relative permeability, ε_r	9.7
Donor impurity concentration, N_D^+ (cm^{-3})	10^{18}
Density of state in conduction band, N_C (cm^{-3})	1.7×10^{19}
Density of state in valence band, N_V (cm^{-3})	2.5×10^{19}
Electron affinity, χ(V)	3.7
Electron mobility, μ_n (cm^2/(V·s))	800
Mobility of holes, μ_p (cm^2/(V·s))	115

For simulation forward current-voltage characteristics were chosen the following temperature: 300, 400, 500, 600 and 700 *K*. Obtained simulation results of forward current-voltage characteristics for Ni/4H-SiC Schottky diode in TCAD program are presented in Fig. 1.

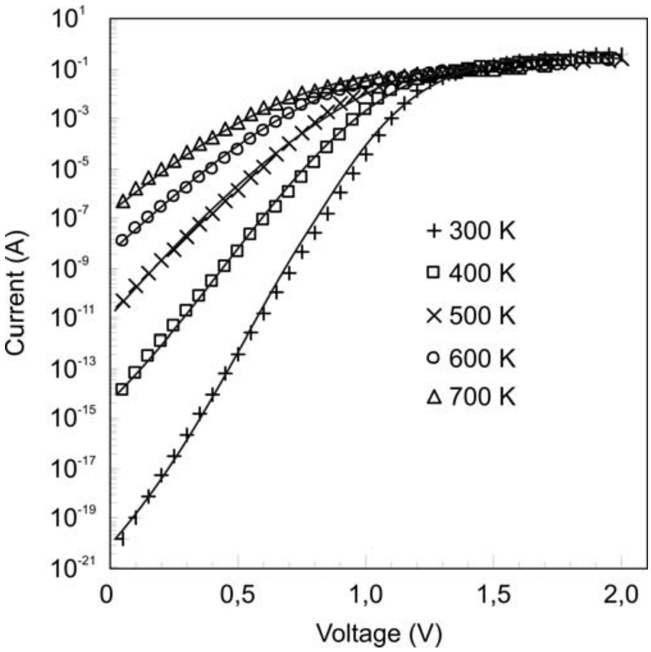

Fig. 1: The forward *I-V* characteristics of the Ni/4H-SiC Schottky diode.

Then results of forward current-voltage characteristics for Ni/4H-SiC Schottky diode was analyzed in framework of classical diode theory. According to the thermionic emission classical diode theory [2,6] current-voltage characteristics the dependence of forward current I on voltage V for semiconductors can be described by the following equation:

$$I = I_o\, exp\left(\frac{qV}{nk_B T}\right)\left(1 - exp\left(-\frac{qV}{k_B T}\right)\right) \qquad (6)$$

where I_o – the saturation current [A]; T – the absolute temperature, [K]; V – the voltage, [V]; q – the elementary charge, [C]; k_B – Boltzmann constant, [J/K]; n – the Schottky diode ideality factor. It is possible to obtain [2,6] the saturation current I_o and the ideality coefficient n if plots dependence of ln$I$ on voltage V. Data for ideality coefficient n and saturation current I_o for different temperatures ant type of diode are presented in Table 2.

Table 2. The ideality coefficient and saturation current value.

Ideality coefficient, n	Saturation current, I_o (A)	Temperature (K)
1.12	2.8×10^{-21}	300
1.39	4.5×10^{-15}	400
1.78	2.5×10^{-11}	500
2.26	8.9×10^{-9}	600
2.95	6.7×10^{-7}	700

As can be seen from Table 2 the average ideality coefficient n equals ~1.9 for Ni/4H-SiC Schottky diode. From the value of the coefficient n, it is used to estimate the Schottky diode quality which for good Schottky diode is equal ~1.0÷1.1. In our case the obtained ideality coefficients n at low temperatures (300, 400 K) are close to good Schottky diode. Thus, the forward *I–V* characteristics in the low temperatures range proved to be reasonably close to the ideal ones.

On the other hand the forward current equation (6) can be rewritten in general case by following equation [2,6]:

$$I = I_o\left[exp\left(\frac{qV}{nk_B T}\right) - 1\right], \qquad (7)$$

where I_o is the saturation current and n the ideality coefficient [5]. In this case if plots the dependence of ln(I_o/T^2) on 1/($nk_B T$) (the Richardson plot) it is possible to obtain the effective barrier height for Schottky diode [2,6]. In Fig. 2 from the slope of line was determined the effective barrier height φ_B for Ni/4H-SiC Schottky diode that equals ~1.1 *eV*. Thus, above-mentioned parameters are very good agreements with experimental data for such type of Ni/4H-SiC silicon carbide Schottky diode where effective barrier height φ_B=1.1÷1.4 *eV* [3,7,8].

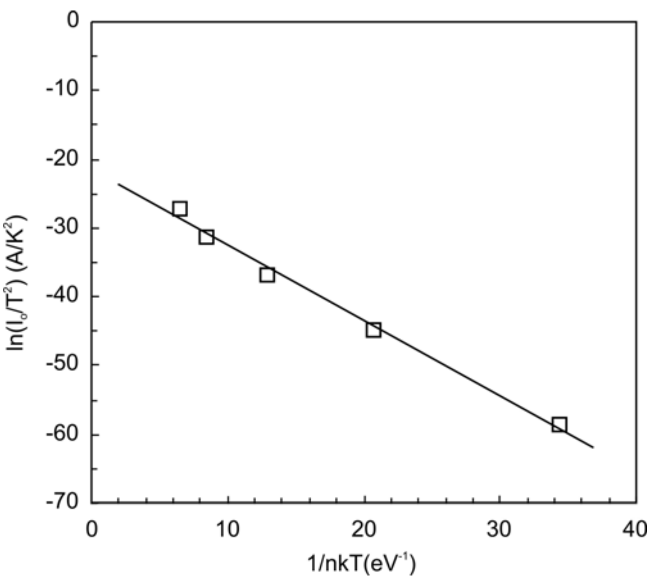

Figure 2. ln(I_o/T^2) dependence on $1/nk_BT$ for Ni/4H-SiC Schottky diode.

4. Conclusion

The forward current-voltage (*I-V*) characteristics in 4H-SiC Schottky diode with Ni Schottky contact has been calculated on the base of simulation model in TCAD in framework of the physical analytical models based on Poisson's equation, drift–diffusion and continuity equations. It is shown that forward current–voltage characteristics in terms of the Schottky diode simulation model corresponds to the almost "ideal" Schottky diode describes in framework of the classical thermionic emission theory with the ideality factor of Schottky diodes $n \approx 1.1$ is close to good Schottky diode at low temperatures near 300-400 *K*. In addition, it is established that for Ni/4H-SiC Schottky diode effective Schottky barrier height $\varphi_B = 1.1$ *eV*. Finally, using a similar approach, this model can be adapted for Schottky diode simulation with another type structure.

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