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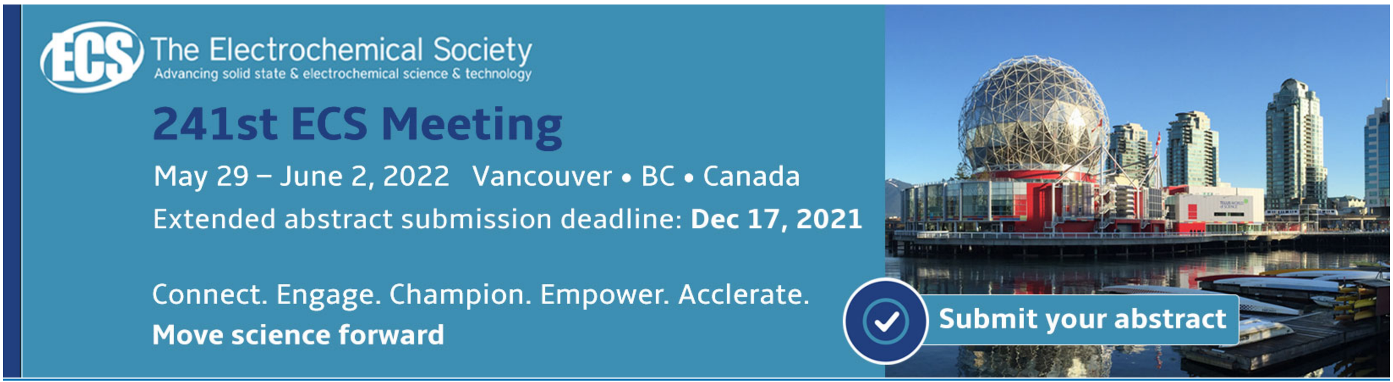

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Silicon carbide of 4H-SiC type Schottky diode current-voltage characteristics in small-sized type metal-polymeric package SOT-89

S V Sedykh, S B Rybalka, A A Demidov and E A Kulchenkov

Bryansk State Technical University, Bryansk, 50 let Oktyabrya 7, Russia

Abstract. The forward and reverse current–voltage characteristics of Ti/Al/4H-SiC Schottky diode type DDSH411A91 in modern small-sized (SOT-89) type metal-polymeric package have been obtained. In forward direction (current up to 2 A) on the basis of analysis it is shown that Schottky diode corresponds to the "ideal" diode with ideality factor n=1.12 and effective Schottky barrier height φ_B=1.2 eV. It is shown that reverse current-voltage characteristics (breakdown voltage 1200 V) can be well approximated by mechanism of field dependence of barrier height lowering by the presence of the intermediate layer in the form of oxide on the 4H-SiC surface.

1. Introduction

It is known that the silicon carbide (SiC) Schottky diodes are key component of power semiconductor electronics devices for high-temperature device applications because of its high breakdown voltage, low series resistance and stability under high temperature conditions [1]. Now modern power electronic industry comes down to use of small type of metalpolymeric package such as SOT (Small Outline Transistor), QFN (Quad Flat No-leads) and others [2], but in Russia manufacture of the main electronic components earlier was produced in standard large-sized package (DIP (Dual In-line Package), TO (Transistor Outline) and others) type. Therefore, recently by electronic company the «GRUPPA KREMNY EL» (Bryansk, Russia) the production of SiC Schottky diodes for power electronics began within the framework of import substitution program. In our previous studies were investigated some characteristics of the SiC Schottky type diodes made in small type of metalpolymeric packages [3]. In this study the main goal is establish current-voltage characteristics of Ti/Al/4H-SiC Schottky diode [4] made in small-sized (SOT-89) type of metalpolymeric package.

2. Materials and methods

In experiments was tested the following Ti/Al/4H-SiC type Schottky diode DDSH411A91 [4] produced by JSC «GRUPPA KREMNY EL» (Bryansk, Russia) in small-sized SOT package type (SOT-89, package dimensions – 4.6×2.6 mm). The main parameters for Ti/Al/4H-SiC type Schottky diode were calculated in our previous works [5-7] with using of TCAD modelling methods. The parameters of Ti/Al/4H-SiC type Schottky diode were the following: the concentration of donors (nitrogen) in the substrate equals 10^{18} cm^{-3} (thickness of substrate is 300 μm), concentration of donors in the n-type epitaxial layer (nitrogen) equals 4.75×10^{15} cm^{-3}, concentration of p+ donors in the guard rings (boron, depth of guard about 2 μm) regions equals 1×10^{18} cm^{-3}, the guard p+ rings consist from one of big guard ring with width of 30 μm and five small guard rings with width of 5 μm (the distance between guard rings was 5 μm), JTE (Junction Terminate Extension) layer formed by boron implantation with p+ concentration 1×10^{17} cm^{-3} (extending 15 µm beyond the edge of the last p+ guard ring), anode material is Ti/Al (titanium/aluminum), the thickness of the epitaxial layer (4H-SiC) equals 14 µm, the radius of the diode equals r=680 µm. For measuring the direct and reverse current-voltage characteristic were used a programmable source AKIP 1144-160-40, Tektronix MDO3102 two-channel oscillograph (bandwidth 1 GHz, refresh rate 5 GS/s) and Fluke 8845A digital multimeter.

3. Results and discussion

Figure 1 presents the photo of Ti/Al/4H-SiC type Schottky diode DDSH411A91 in small-sized SOT-89 type of metalpolymeric package produced by «GRUPPA KREMNY EL» [4].

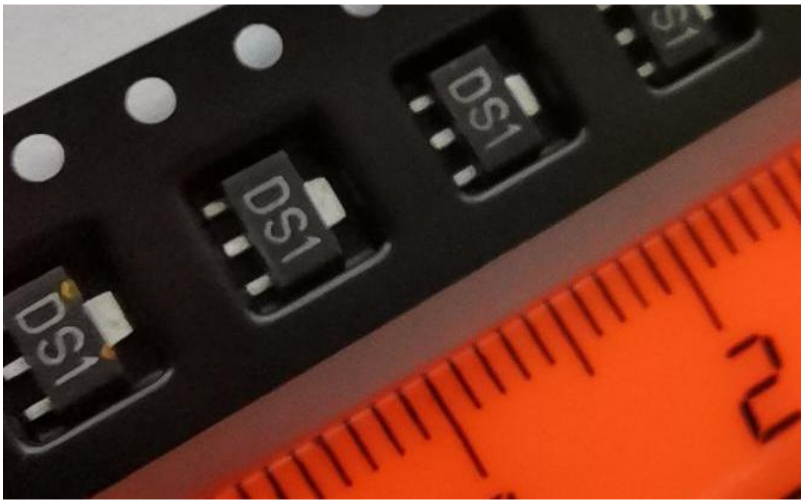
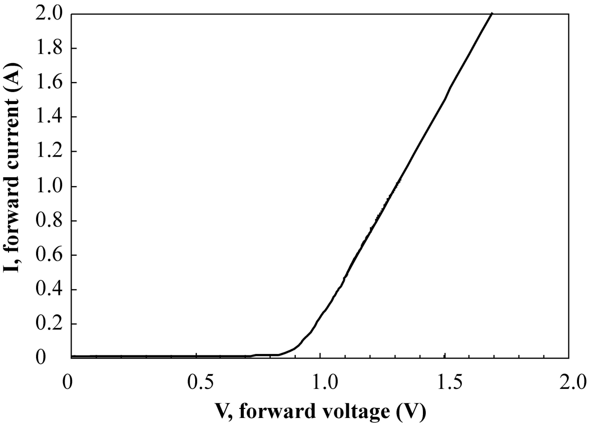


Figure 1. Photo of Ti/Al/4H-SiC type Schottky diode DDSH411A91 in small-sized SOT-89 type package [4].

In Figure 2 is shown the forward current-voltage characteristic for DDSH411A91 Schottky diode in small-sized SOT-89 type package obtained at temperature of 293 K. Further, in Figure 3 presents the reverse current-voltage characteristics for DDSH411A91 Schottky diode (293 K). As follows from current-voltage characteristic the fabricated DDSH411A91 Schottky diode in small-sized package operate with forward current up to 2 A and breakdown voltage 1200 V in reverse direction mode.



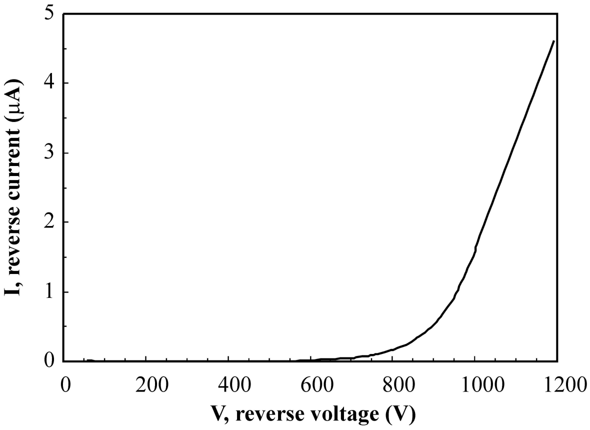


Figure 2. Ti/Al/4H-SiC Schottky diode DDSH411A91 in small-sized SOT-89 type package forward current-voltage characteristic.

Figure 3. Ti/Al/4H-SiC Schottky diode DDSH411A91 in small-sized SOT-89 type package reverse current-voltage characteristics.

Further, the obtained experimental forward current-voltage characteristics of the DDSH411A91 diode were approximated on the basis of the model of thermionic emission from a semiconductor into metal [1,8] with taking into account the effect of the series resistance R_s (0.35 Ω) of the diode, according to which the diode current in the forward direction can be described by the equations:

$$I = SA^*T^2 \exp\left(-\frac{\varphi_B}{kT}\right)\exp\left(\frac{qV_{SCR}}{nkT}\right), \tag{1}$$

$$V = V_{SCR} + IR_s, \tag{2}$$

where S is the total area of the Schottky regions ($S \approx 0.615$ cm^2), q is the elementary charge, A^* is the effective Richardson constant ($A^*=35$ A·K^{-2}·cm^{-2}) [9]), φ_B is the Schottky barrier height, V_{SCR} is the voltage drop across the depleted layer of the Schottky contact, k is the Boltzmann constant, T is the absolute temperature and n is the ideality factor of diode.

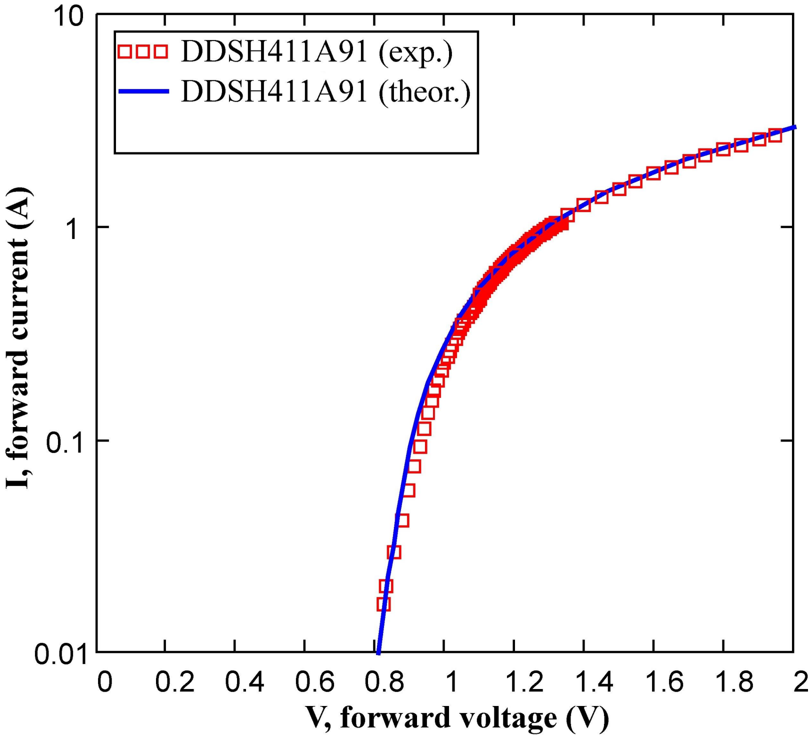


Figure 4. The forward current-voltage characteristic for Ti/Al/4H-SiC Schottky diode DDSH411A91 (T=293 K) in small-sized SOT-89 type package: experimental data (points) and calculated (solid line) by equations (1) and (2) with taken into account the effect of the series resistance R_s (0.35 Ω) and barrier height φ_B (1.2 eV).

It is established that well approximation yielded the following values of the adjustable parameters: barrier height φ_B=1.2 eV and the ideality factor n=1.12 as can be seen from Figure 4. It should also be noted that [10] obtained the barrier height is similar with experimental barrier height for Ti/Al/4H-SiC type Schottky contact (1.2 eV).

In case of the reverse current-voltage characteristic description for Schottky diode type [11] there are the following mechanisms: electron-tunnel transmission from metal to semiconductor; thermal generation of carriers; field dependence of barrier height. For mechanism of field dependence of barrier height the first mechanism is the effect of image forces on the shape and height of the potential barrier (the Schottky effect [12]) and second mechanism is the presence of a thin intermediate insulator layer between metal and semiconductor, across which there is a low voltage drop decreasing the barrier height [11,13]. In particular, as it was established experimentally in RhSi, $ZrSi_2$ and PtSi Schottky diodes [14] formed in n-type silicon the reverse characteristics can be well described by second mechanism where there is the presence of a thin intermediate insulator layer between metal and semiconductor. The above-mentioned mechanism also takes place in case of 4H-SiC type power diodes [15].

Thus, taking into account the field dependence of the barrier height, the approximating formula for the reverse current I_R can be written [11,14,15] in the following form:

$$I_R = I_S \exp\left[\frac{\Delta\varphi_B(V_R)}{kT}\right]\left[1-\exp\left(-\frac{qV_R}{kT}\right)\right], \tag{3}$$

where I_S is the saturation current, $\Delta\varphi_B$ is the barrier lowering caused by the presence of the intermediate layer, V_R is the reverse voltage, q is the elementary charge, k is the Boltzmann constant, T is the absolute temperature.

The saturation current I_S can be written by following equation:

$$I_S = SA^*T^2 \exp\left[-\frac{\varphi_B}{kT}\right], \tag{4}$$

where S is the total area of the Schottky regions ($S \approx 0.615$ cm^2), q is the elementary charge, A^* is the effective Richardson constant ($A^*=35$ A·K^{-2}·cm^{-2}) [9]), φ_B is the Schottky barrier height (1.2 eV).

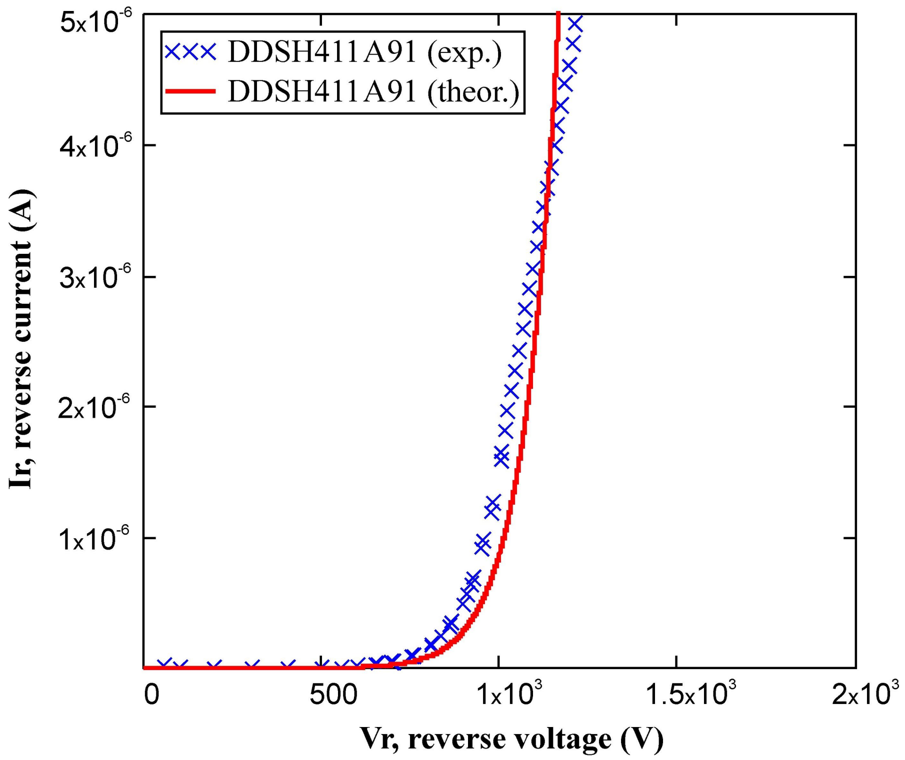


Figure 5. The reverse current-voltage characteristic for Ti/Al/4H-SiC Schottky diode DDSH411A91 (T=293 K) in small-sized SOT-89 type package: experimental data (points) and calculated (solid line) by equations (3)-(7).

Then, the barrier lowering caused by the presence of the intermediate layer $\Delta\varphi_B$ can be written [11,14,15] in the following form:

$$\Delta\varphi_B = \sqrt{\frac{qE_m}{4\pi\varepsilon_o\varepsilon_r}} + \alpha E_m, \tag{5}$$

where ε_r is the relative permittivity (ε_r =9.7 for 4H-SiC [1,16]), ε_0 is the permittivity in vacuum (8.85×10^{-12} F/m), E_m is the maximum electric field existing at the metal-semiconductor interface, α is the adjustable empirical parameter. In accordance with [11,14,15] parameter α can be defined:

$$\alpha = \frac{\delta\varepsilon_o\varepsilon_r}{\varepsilon_o\varepsilon_{ir} + q\delta D_s}, \tag{6}$$

where ε_r is the relative permittivity for 4H-SiC (ε_r =9.7), ε_{ir} is the relative permittivity for the SiO_x layer (ε_{ir} =2 [12]), δ is the thicknesses of SiO_x layer, D_s is the energy density of surface states at the Fermi level in metal.

Further, for case when the reverse voltage substantially exceeding the band bending in the semiconductor at the zero bias, the electric field E_m can be expressed in terms of the reverse voltage V_r in the following form:

$$E_m = \sqrt{\frac{2qN_D V_r}{\varepsilon_o\varepsilon_r}}, \tag{7}$$

where N_D is the doping concentration (4.75×10^{21} m^{-3}).

In Figure 5 is presented the reverse current-voltage characteristic for Ti/Al/4H-SiC Schottky diode DDSH411A91 in small-sized SOT-89 type package calculated at 293 K by equations (3)-(7).

As can be seen from Figure 5, the experimental results are very well described by equation (3) for adjustable empirical parameter $\alpha=3.159\times10^{-9}$ m. Then, for the SiO_x layer with ε_{ir}=2 and the thicknesses of SiO_x layer δ=3 nm (equal to real our diode structure) we can calculate by equation (6) the energy density of surface states at the Fermi level in metal $D_s=1.33\times10^{17}$ $V^{-1}\cdot m^{-2}$. It should be noted that above-mentioned natural oxide thicknesses δ and the values of density of states D_s not only are quite reasonable for the 4H-SiC real surface, but also very similar with values for such type of experimental high voltage 4H-SiC Schottky diode [15]. Because of this, it can be noticed that package's size miniaturization not lead to current-voltage characteristic degradation, moreover in respect of the *dV/dt* and *dI/dt* characteristics for DDSH411A91 Schottky diode [3,17] above-mentioned characteristics are comparable with same values for 4H-SiC Schottky diodes in large-sized (TO-220-F2) package type.

4. Conclusions

Forward and reverse current-voltage characteristic for DDSH411A91 (Ti/Al/4H-SiC) Schottky type diode in small-sized SOT-89 metalpolymeric package (JSC «GRUPPA KREMNY EL», Bryansk, Russia) were obtained. It is shown that fabricated Ti/Al/4H-SiC Schottky diode demonstrate current up to 2 A in forward direction and breakdown voltage 1200 V.

Analysis of experimental results in framework of classical diode theory shows that ideality factor of DDSH411A91 diode equals 1.12 that is close to good Schottky "ideal" diode and effective Schottky barrier height φ_B=1.2 eV.

For the reverse characteristics it is shown that current-voltage characteristics can be well approximated by mechanism of field dependence of barrier height lowering by the presence of the intermediate layer in the form of natural oxide on the 4H-SiC surface.

Thus, on the basis of investigation of forward and reverse current-voltage characteristics for DDSH411A91 (Ti/Al/4H-SiC) Schottky type diode in small-sized SOT-89 metalpolymeric package (JSC «GRUPPA KREMNY EL», Bryansk) it is established that miniaturization of package not lead to current-voltage characteristic degradation and small-sized package of this type can be used in Russian electronic industry.

Acknowledgements

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