Ti/4H-SiC Schottky diode breakdown voltage with different thickness of 4H-SiC epitaxial layer

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Abstract. Breakdown voltage for Ti/4H-SiC type Schottky diode with six guard rings have been calculated theoretically and by mean of numerical simulations. It is shown that the breakdown voltage can be increase at the minimum on 100 V in case when thickness of the \(n\)-type 4H-SiC epitaxial layer increase from 18 up to 22 \(\mu\)m. It is established that the breakdown voltage value for Ti/4H-SiC type Schottky diode with guard rings calculated by mean simulation in ATLAS program and theoretically have good approximation. Thus, above approach gives the possibility for projection of diode structure with different 4H-SiC epitaxial layer thickness with higher breakdown voltage value.

1. Introduction

It is known that the silicon carbide belongs to a class of materials commonly referred to as wide-bandgap semiconductors and now silicon carbide represents an excellent candidate for high-temperature power electronic device applications because of its high breakdown voltage, low series resistance and stability under high temperature conditions [1]. Silicon carbide Schottky diodes are of special interest since these unipolar devices avoid reverse recovery effects of bipolar devices, thereby offering higher frequency operation. In particular, SiC Schottky diodes for power electronics in future must be produced by domestic company the ZAO «GRUPPA KREMNY EL» (Bryansk). It is obviously that for development of component base on the base of SiC studying and optimization of such important device as Schottky diode it is necessary.

Earlier, in our previous paper have been studied 4H-SiC type Schottky diodes with Ni and Ti Schottky anode contacts without guard rings [2-5] and 4H-SiC type MOS transistors [6]. Therefore in present paper the main goal is investigation of thickness of the epitaxial layer (4H-SiC) effect on breakdown voltage 4H-SiC Schottky diode with Ti Schottky anode contact with guard rings for increasing of breakdown voltage value.

2. Materials and methods

Figure 1 shows the schematic silicone carbide Schottky diode structure for calculation. Thus, for calculation and 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 \(N^- = 3 \times 10^{15} \text{ cm}^{-3}\), in the guard rings (boron, depth of guard about 2 \(\mu\)m) regions \(N_{p+} = 10^{18} \text{ cm}^{-3}\), anode material is Ti (titanium), the thickness \(d\) of the epitaxial layer (4H-SiC) was chosen equals 18 \(\mu\)m, 20 \(\mu\)m and 22 \(\mu\)m, the radius of the structure equals \(r=140 \mu\)m. 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 in ATLAS program.

3. Results and discussion
The breakdown voltage in classical theory depends on critical field, epilayer doping and thickness, edge termination etc [7]. For instance, in general case the breakdown voltage $V_{BV}$ of strongly asymmetric junction can be calculated by following approximation formula [1,7,8]:

$$V_{BV} = \frac{E_c W}{2},$$  \hspace{1cm} (1)

where $E_c$ – critical electric field, $W$ – the space-charge region thickness. In the limit case we can believed that the space-charge region thickness $W$ equals the thickness $d$ of the 4H-SiC epitaxial layer (18 µm, 20 µm and 22 µm in our case, respectively).

On the other hand, for a plane-parallel $p$–$n$ junction the critical breakdown field strength ($E_c$) can be determined from the condition for equality to unity of the ionization integral:

$$\int_0^d \alpha_n \exp \left[ -\int_x^d (\alpha_n - \alpha_p) dx \right] dx = 1,$$  \hspace{1cm} (2)

where $\alpha_n$ and $\alpha_p$ are the ionization coefficients for electrons and holes. In 4H-SiC, the ionization coefficients depend exponentially on the reciprocal field:

$$\alpha_n = \alpha_{n0} \exp \left( -\frac{E_n}{E} \right),$$  \hspace{1cm} (3)

$$\alpha_p = \alpha_{p0} \exp \left( -\frac{E_p}{E} \right),$$  \hspace{1cm} (4)

where $\alpha_{n0}=1.76\times10^8$ cm$^{-1}$, $\alpha_{p0}=3.41\times10^8$ cm$^{-1}$, $E_n=3.3\times10^7$ V/cm, $E_p=2.5\times10^7$ V/cm [9,10]. Then, substitute (3) and (4) into equation (1) obtain the following integral equation in $E_c$:
where \( \varepsilon_0 = 8.85 \times 10^{-12} \text{F/m} \) – the dielectric constant, \( \varepsilon_r = 9.7 \) – the dielectric relative permeability of 4H-SiC, \( N^- = 3 \times 10^{15} \text{cm}^{-3} \) – the concentration of donors in the 4H-SiC epitaxial layer, \( d=W \) – the thickness of the 4H-SiC epitaxial layer, \( q \) – the elementary charge. Further, after solving numerically Eq. (5) we can obtain the critical breakdown field strength \( E_c \) and then calculate the breakdown voltage \( V_{BV} \) value using the Eq. (1). The critical breakdown field strength \( E_c \) and breakdown voltage \( V_{BV} \) value at concentration of donors in the 4H-SiC epitaxial layer \( N^- = 3 \times 10^{15} \text{cm}^{-3} \) and various thicknesses \( d \) of the 4H-SiC epitaxial layer are generalized in Table 1.

**Table 1.** Breakdown voltage \( V_{BV} \) value calculated by Eq. (1) for various thickness \( d \) of the 4H-SiC epitaxial layer.

| \( d \), thickness of the 4H-SiC epitaxial layer (\( \mu \text{m} \)) | \( N^- \), concentration of donors in the 4H-SiC epitaxial layer (\( \text{cm}^{-3} \)) | \( E_c \), critical breakdown field calculated by Eq. (5) (V/m) | \( V_{BV} \), breakdown voltage calculated by Eq. (1) (V) |
|----------------|---------------------------------|-------------------|------------------|
| 18             | \( 3 \times 10^{15} \)          | \( 2.377220 \times 10^8 \) | \( 2.139 \times 10^3 \) |
| 20             | \( 3 \times 10^{15} \)          | \( 2.377290 \times 10^8 \) | \( 2.377 \times 10^3 \) |
| 22             | \( 3 \times 10^{15} \)          | \( 2.377217 \times 10^8 \) | \( 2.615 \times 10^3 \) |

Afterward, with aim to compare theoretically calculated breakdown voltage has been carried out numerical simulation. For simulation model of reverse current-voltage (\( I-V \)) characteristics has been used physical analytical model in ATLAS program where has been solved electrostatic Poisson’s equation in cylindrical coordinates together with drift–diffusion and continuity equations [11,12]. Above-mentioned numerical model was described in detail in previous works [2-5], but in our case the incomplete impact ionization has been taking into account. Further, for simulation of reverse current-voltage characteristics on structure of Schottky diode from Figure 1 were chosen temperature 300 K and thickness of the 4H-SiC epitaxial layer – 18 \( \mu \text{m} \), 20 \( \mu \text{m} \) and 22 \( \mu \text{m} \). Simulation results of reverse current-voltage characteristics for Ti/4H-SiC Schottky diodes with different thickness of the epitaxial layer in ATLAS program are presented in Figure 2.

As can be seen from Figure 2 the breakdown voltage value \( V_{ATLAS} \) corresponds to 2.332 kV – for thickness of the 4H-SiC epitaxial layer equals 18 \( \mu \text{m} \), 2.380 kV – for 20 \( \mu \text{m} \), 2.412 kV – for 22 \( \mu \text{m} \). In addition, in ATLAS program log also there is possibility find the critical breakdown field \( E_c \) value in case when ionization integral value exceeds unity that corresponds to diode breakdown voltage \( V_{II} \) condition.

In Table 2 are generalized the breakdown voltage \( V_{ATLAS} \) calculated in ATLAS from Figure 1, breakdown voltage \( V_{II} \) when ionization integral value in ATLAS exceeds unity and breakdown voltage \( V_{BV} \) calculated theoretically by Eq. (1). As can be seen from Table 1, theoretical value of breakdown voltage \( V_{BV} \) calculated by Eq. (1) for Ti/4H-SiC Schottky diode is in good agreement with breakdown voltage data \( V_{ATLAS} \) by simulation in ATLAS (see Figure 2) and breakdown voltage \( V_{II} \) value from ATLAS program log.
Figure 2. Reverse $I-V$ characteristics of Ti/4H-SiC Schottky diode calculated in ATLAS for various thickness of the epitaxial layer (4H-SiC) 18 µm, 20 µm and 22 µm.

Thus, it is established that the breakdown voltage value for Ti/4H-SiC type Schottky diode with guard rings can be calculated in ATLAS program with good approximation.

| d, thickness of the 4H-SiC epitaxial layer (µm) | $V_{\text{ATLAS}}$, breakdown voltage calculated in ATLAS from Figure 1 (V) | $V_{\text{BIV}}$, breakdown voltage when ionization integral value in ATLAS exceeds unity (V) | $V_{\text{BIV}}$, breakdown voltage calculated theoretically by Eq. (1) (V) |
|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 18                                           | $2.332 \times 10^3$                             | $2.302 \times 10^3$                             | $2.139 \times 10^3$                             |
| 20                                           | $2.380 \times 10^3$                             | $2.354 \times 10^3$                             | $2.377 \times 10^3$                             |
| 22                                           | $2.412 \times 10^3$                             | $2.404 \times 10^3$                             | $2.615 \times 10^3$                             |

Because of this as follows from Table 1 in case when thickness of the 4H-SiC epitaxial layer increase on 4 µm (from 18 up to 22 µm) it lead to increase of the breakdown voltage at the minimum on 100 V for Ti/4H-SiC type Schottky diode with six guard rings.

4. Conclusions

Thus, investigation of thickness of the epitaxial layer (4H-SiC) effect on breakdown voltage 4H-SiC Schottky diode with Ti Schottky anode contacts with guard rings for increasing of breakdown voltage value has been carried out. It is shown that breakdown voltage Ti/4H-SiC Schottky diode can be calculated theoretically and by mean of numerical simulation in ATLAS program. For Ti/4H-SiC type Schottky diode with six guard rings it is established that in case when thickness of the 4H-SiC epitaxial layer increase from 18 up to 22 µm it lead to increase of breakdown voltage at the minimum on ~100 V in accordance with ATLAS model numerical calculation and theoretical calculation.

Therefore, it is suggested that matches of numerical model results with theoretically obtained results indicate that the ATLAS simulation model is correct and can be used for calculation of such type SiC Schottky diode current-voltage characteristics and the optimal design of diode structure determination.

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