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Current Transport Mechanisms and Electrophysical Characteristics of the 4H-SiC p-n Junctions Formed by Aluminum Diffusion

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In this paper, the electrophysical characteristics of the 4H-SiC p-n junction created by low-temperature diffusion of aluminum were studied. Current-voltage (I-V) characteristics are analysed, and the current transport mechanisms in 4H-SiC p-n junctions are discussed. It is shown that at low forward bias voltages, the generation–recombination mechanism dominates, and the I-V characteristics at voltages U > 3.0 V obey the linear law. At reverse biases, the dominant mechanism of current transfer is limited by the space charge.

Keywords: 4H-SiC, aluminum diffusion, p-n junction, I-V characteristic, C-V characteristic.

1. INTRODUCTION

Silicon carbide is a promising material for application in various fields of modern electronics due to its wide band gap, high critical avalanche breakdown field, thermal conductivity, and chemical and radiation stability. Based on SiC, new devices for microwave, power, and high-current electronics, semiconductor detectors of nuclear particles, and UV LEDs have been manufactured [1 – 3].

Typically, the p-region in SiC is formed by ion implantation or thermal diffusion of boron (B) or aluminum (Al). Diffusion of these impurities in SiC occurs at high (over 2000 °C) temperatures and follows a complex mechanism. In this case, impurities move along both carbon (C) and silicon (Si) sublattices. It is known that the solubility and diffusion coefficient of impurities in different SiC sublattices differ significantly, which leads to the appearance of defects of various types [4 – 15]. Therefore, low-temperature (1150 – 1300°C) diffusion of Al in SiC can greatly reduce the number of defects in the structures created by this method [4 – 15].

To assess the quality of the obtained p-n structures, it is necessary to study the current transport mechanisms in the diode structures. In Refs. [16 – 18], the current-voltage characteristics and current transfer mechanisms in p-n-4H-SiC structures fabricated by the vapour-phase epitaxy method were investigated. It has been shown that at bias voltages up to 2.5 – 2.6 V, recombination currents dominate [16], and in the voltage range of 2.6 – 2.8 V, mixed conductivity with diffusion and recombination components is observed [16, 17]. In Ref [18], it has been shown that the recombination process in the temperature range of 25 – 275°C occurs mainly according to the Shockley-Reed-Hall mechanism. The mechanisms of current transport in diodes fabricated on the basis of SiC by ion implantation were studied in Refs. [19 – 24]. Studies of their I-V characteristics have shown that the ideality factor of diodes exceeds 2 and traps appear in the space charge region [19]. Studies of the I-V characteristics of diode structures based on 4H-SiC have also shown that at low forward voltages, the recombination mechanism of current transfer is dominant [20]. Analysis of the I-V characteristics of planar p-n-diodes based on 4H-SiC [21], which have a high breakdown voltage (1400 V) and ideality factors of 1.05 and 1.93, showed that the recombination and diffusion mechanisms of current transport dominate. Recently, the characteristics of high-voltage diodes based on 4H-SiC were studied, and two parts of the I-V characteristics (η = 2 and η = 1.2) with different current transport mechanisms were identified [24]. The investigation of the I-V characteristics of the 6H-SiC(Be) p-n^+-junctions showed the existence of three regions with different current conductivities: a flat low-current region, a conduction region, and a region of high saturation current [22]. In the second conduction region, the current increases linearly within 2 – 3 V. Similar results were also obtained for the 4H-SiC and 6H-SiC diodes fabricated by thermal diffusion [25], where three regions are also present. The authors of [22, 25] argue that the Shockley-Read-Hall current transfer mechanism is dominant in these structures. Additionally, in Refs [25, 26], the mechanisms of current transport in diodes obtained by the thermal diffusion method were studied. The coefficient of ideality determined based on the I-V characteristics has a value of 1.97, which indicates the Shockley-Read-Hall recombination mechanism, which is dominant in the conduction region [26].

Despite the large amount of research in this area, the mechanisms of current transport in p-n diodes obtained by

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the low-temperature diffusion method have not been studied.

This paper presents the results of studies of the electrical properties of p-n junctions fabricated by low-temperature diffusion of aluminum in *n*-4H-SiC.

2. MATERIALS AND METHODS

Samples of the p-n-4H-SiC structures were created on the basis of the 4H-SiC wafers by low-temperature diffusion of Al at temperatures of 1150 – 1300°C for 30 min in an air atmosphere.

In this work, we used n-type single-crystal 4H-SiC plates of n-type conductivity with a specific resistance (300 K) of ~4.5 Ω cm grown by the sublimation method with a low concentration of growth defects (dislocation concentration 10^4 cm^{-2}) and a concentration of micropipes up to $10 – 10^2$ cm^{-2}. The substrate thicknesses were 408 μm.

The starting parameters of the samples were measured on the HMS-7000 Hall Effect Measurement System (Ecopia) by the Van der Pauw method.

To form the *p*-type layer, aluminum atoms were diffused from a thin layer of Al_2O_3 deposited in a vacuum (10^{-5} Torr) at a temperature of 650 °C for 30 min. The diffusion process was carried out in an open air atmosphere at temperatures of 1150 – 1300 °C for 30 min. Thus, a diode p-n-4H-SiC <Al> structure was formed.

Ohmic contacts to the structures were formed by vacuum thermal deposition of Al and Ni/Al to the p+- and n- regions of the structure, respectively, followed by annealing at temperatures of 950 – 1000 °C for 2 min. The ohmic contact area was 2 mm^2.

Measurements of I-V characteristics of p-n structures were performed on the Keithley SMU 2400 device.

The capacitance-voltage characteristics were measured on E7-12 digital LCR meter at a frequency of 1 MHz.

3. RESULTS AND DISCUSSION

The I-V characteristics of the p-n-4H-SiC<Al>- diode structure were measured at room temperature, the results of which are shown in Fig. 1. As shown in Fig. 1, the I-V characteristics of the diode structure have a form typical of a conventional p-n-junction. The forward bias current at 60 V is 0.5 A, and the reverse bias is 0.1 mA at 60 V. Consequently, the rectification factor is $k = 5 \times 10^3$, which is considered sufficient for the structures under study.

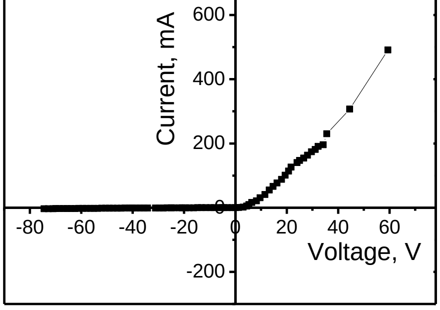

Fig. 1. I-V characteristics of the p-n-4H-SiC<Al>-structures at 300 K

The heights of the potential barrier of the structure were determined by extrapolating the linear section of the I-V characteristics to the intersection with the voltage axis U. It has been established that the barrier height for the investigated p-n-4H-SiC<Al>-structure is 2.1 – 2.4 eV.

To establish the mechanisms of current transfer, the I-V characteristics of the p-n-4*H*-SiC<Al>-structures were plotted on a semilogarithmic scale (Fig. 2). It can be seen from Fig. 2 that the direct branch of the I-V characteristics (curve 1) can be separated into two sections. In the first region, at voltage U < 1.0 V, the current increases according to the well-known diode law:

$$I = I_0 (e^{qU/nkT} - 1), \quad (1)$$

where I_0 is the saturation current; *n* is the diode ideality factor. Calculations have shown that the values of *I* and *n* are $I_0 = (2.0 – 3.5)\ 10^{-8}$ A and $n = 1.67 – 1.97$, respectively, at T = 300 K.

An analysis of these values shows the generation-recombination mechanism of current in the p-n-4H-SiC<Al>-structure in the voltage range 3kT/e < U < 1.0 V. It can be seen from Fig. 2 that the direct branch of the I-V characteristics of the p-n-4H-SiC<Al>-structure at voltage U > 3.0 V is described by a linear dependence:

$$U = U_0 + I \cdot R_{Б}. \quad (2)$$

The evaluation of cut-off voltages and base resistance yielded the following results: $U_0 \approx 2.1$ V and $R_B = 180$ Ω.

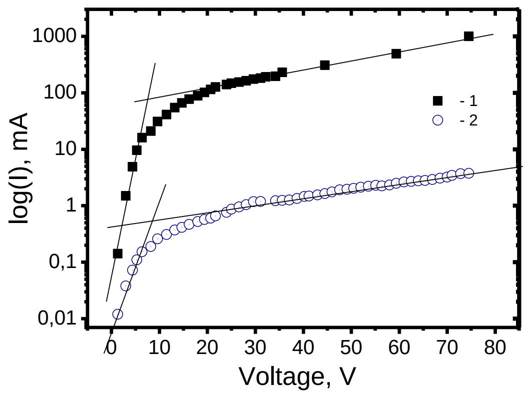

Fig. 2. I-V characteristics of the p-n-4H-SiC<Al>-structure on a semilogarithmic scale at 300 K: direct branch (1) and reverse branch (2)

As shown in Fig. 2 (curve 2), the reverse currents in the p-n-4H-SiC<Al>-structure in the voltage region $U_{rev} < 5$ V are described by Eq. 1. At reverse bias voltages $U_{rev} > 5.5$ V, I-V characteristics obey the power law $I \sim U^m$ with the value of the exponent $m = 2.2 – 2.6$. As a suggestion to ref [27], this indicates that the dominant current is limited by the space charge in the mobility regime (trapless quadratic law). At voltage U > -80 V (Fig. 1), a soft breakdown of the p-n junction begins.

It is known that it is possible to determine the dependences of the thickness W of the transition region, the width of the SCR, the sharpness of the p–n junction, and the concentration gradient of ionized centers in the region by measurements of the capacitance–voltage (C-V) characteristic of a p–n junction. Therefore, the C-V characteristics of the p-n-4H-SiC<Al> structures with a sharp asymmetric *p-n* junction were studied. Fig. 3 shows the C-V characteristics of the p-n-4H-SiC<Al> junction fabricated by low-temperature aluminum diffusion. The slope of the dependence $S^2/C^2(V)$ is proportional to the impurity concentration. As seen from the inset in Fig. 3, there is a certain nonuniform impurity distribution in the sample. Extrapolation of the curve to the voltage axis shows that the height of the potential barrier for the p-n-4H-SiC<Al> structure is 2.5 V, which agrees satisfactorily with the results of the I-V characteristics.

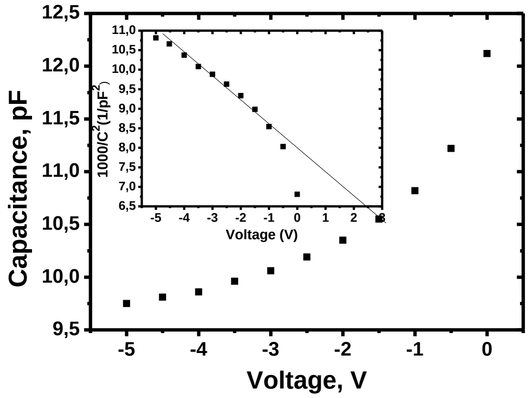

Fig. 3. C-V characteristics of the p-n-4*H*-SiC<Al> junction, measured at frequencies of 1 MHz. The inset shows the dependence of $1/C^2$ on the voltage across the p-n junction

According to Ref [28], the capacitance of the p-n-4*H*-SiC<Al> junction can be found as the capacitance of a flat capacitor, the distance between the plates of which is equal to the width W of the space charge region (SCR). The relative permittivity at a frequency of 1 MHz for 4H-SiC at room temperature is 9.76 [29].

$$C = S\sqrt{\frac{qN_d\,\varepsilon\varepsilon_0}{2(U_0+U)}} = \frac{\varepsilon\varepsilon_0 S}{W}. \quad (3)$$

Fig. 4 shows the results of calculating the thickness W of the SCR in the 4H-SiC-p-n junction according to the C-V characteristics of the sample.

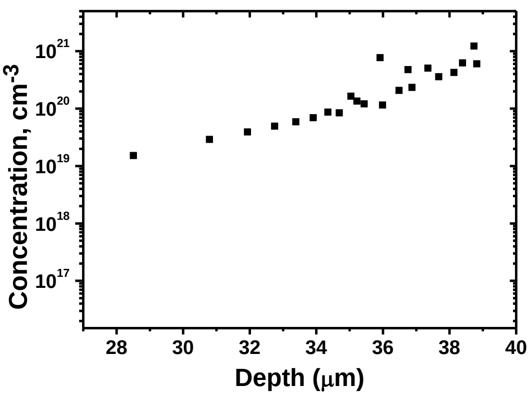

Fig. 4. Distribution of aluminum concentration as a function of W(V) according to C-V data in the doped 4H-SiC<Al> layer

The p-n junction thickness, determined from the capacitance value at zero mixing, is 28 μm. Impurity concentration can be calculated using the following formula [30] based on the slope of the C-V characteristics in the coordinates $C^{-2}(U)$:

$$N(x) = \frac{2}{q\varepsilon\varepsilon_0 S^2}\frac{(U_2-U_1)}{1/C_2^2-1/C_1^2}. \quad (4)$$

The calculation results are shown in Fig. 4. A certain impurity concentration is high $N_{Al}(W)$, which for the 4H-SiC<Al> layer ranges from 1.5×10^{19} cm^{-3} to 6×10^{20} cm^{-3}.

4. CONCLUSIONS

Thus, by studying the I-V characteristics of the p-n-4H-SiC<Al> structures, the mechanisms of current transfer have been established. It has been established that at low values of the forward bias, the generation-recombination mechanism of current transfer dominates. At voltages $U > 3$ V, the I-V characteristic obeys a linear law. At low reverse biases, the passage of current is associated with the limiting mechanism of the space charge, and at $U_{rev} > -80$ V, a soft breakdown of the junction begins. The concentration of impurities in the 4H-SiC<Al> layer was also calculated, which ranges from 1.5×10^{19} cm^{-3} to 6×10^{20} cm^{-3}.

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