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SEMICONDUCTOR STRUCTURES, INTERFACES, AND SURFACES

Investigation of the SiC/$(SiC)_{1-x}(AlN)_x$ Heterostructures by the Method of Capacitance–Voltage Characteristics

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Abstract—Using the method of measuring and analyzing the capacitance–voltage characteristics, it is found that the *n*-6*H*-SiC/*p*-$(SiC)_{1-x}(AlN)_x$ heterostructures obtained by sublimation epitaxy of the $(SiC)_{1-x}(AlN)_x$ layers on the 6*H*-SiC substrates have abrupt heterojunctions ~10^{-4} cm thick. The basic properties of heterostructures, which depend on the epilayer composition and temperature, were determined from the capacitance–voltage characteristics. © *2001 MAIK "Nauka/Interperiodica".*

INTRODUCTION

Among the systems with SiC-based solid solutions, the $(SiC)_{1-x}(AlN)_x$ solid solution has been investigated in most detail. This solid solution forms a continuous series of compounds with a gradual variation of the band gap and unit cell parameters. Corresponding values of these quantities are 3.35 eV, a = 3.076 Å, c = 5.048 Å for x = 0 and 6.2 eV, a = 3.114 Å, c = 4.986 Å for x = 1. An indirect gap structure transforms to a direct gap structure at $x > 0.6$ [1]. The problem of controlling the composition and conduction type has already been solved for a sublimation epitaxy of these solid solutions [2]. Due to their high thermal conductivity, as well as their mechanical, chemical and radiation resistance, these solid solutions are promising materials for device structures. The unit cell parameters and thermal expansion coefficients for SiC are close to those for $(SiC)_{1-x}(AlN)_x$, and the synthesis technologies are identical. This permits one to obtain the SiC/$(SiC)_{1-x}(AlN)_x$ heterostructures with a low concentration of defects at the heterointerface.

There is a lack of published data on the electrostatic parameters for the $(SiC)_{1-x}(AlN)_x$-based *p–n* structures. This paper is devoted to investigating the properties of the *n*-SiC/*p*-$(SiC)_{1-x}(AlN)_x$ heterostructures using the method of capacitance–voltage (*C–V*) characteristics.

SAMPLES AND EXPERIMENTAL TECHNIQUE

Single-crystal epilayers of the *p*-$(SiC)_{1-x}(AlN)_x$ solid solutions were grown on 6*H*-SiC substrates by sublimation epitaxy in the temperature range of 2300–2550 K at the pressure of the N_2 + Ar mixture from 2×10^4 to 8×10^4 Pa. The sources were hot-compacted SiC–AlN pellets [3]. The substrates were of *n*-type conduction with $N_d - N_a = 6 \times 10^{17}$–$3 \times 10^{18}$ cm^{-3}. The epilayers were 10–30 μm thick, and the substrates were 400 μm thick.

The *C–V* characteristics for the *n*-SiC/*p*-$(SiC)_{1-x}(AlN)_x$ heterostructures were measured using the setup based on an E7-8 automated digital meter. The measurement procedure was based on a bridge method with phase-sensitive detectors of balancing. The bridge was powered by a GZ-49a external wide-band oscillator. The amplitude of the sinusoidal signal was no larger than 300 mV. The measurements were carried out using a parallel equivalent circuit, and the error of the capacitance measurement was no larger than 1%. The *C–V* characteristics were measured on the mesas formed by ion-plasma etching with an Al mask fabricated by high-vacuum thermal evaporation from tungsten wire. After annealing, this mask was used as the nonrectifying contact to the $(SiC)_{1-x}(AlN)_x$ epilayer. The contacts to the base layer (6*H*-SiC substrate) were formed by the fusion of In subsequent to spark treatment of the surface. Checking the metal contacts confirmed that they were adequately nonrectifying. The mesas under study were installed in a two-probe cell.

To study the *C–V* characteristics, we selected the *p–n* structures with a capacitance independent of frequency up to 50 kHz. Corresponding *C–V* curves plotted in the C^{-2}–*U* coordinates were linear in the voltage range from –10 to 0 V. The leakage current of the structures was no larger than 10^{-5} A in the above voltage range.

RESULTS AND DISCUSSION

The *C–V* characteristics for two heterostructures with a different AlN content in the epilayer, which were measured at room temperature (293 K), are shown in Fig. 1. The deviation from a straight line observed for some experimental points is apparently related to a certain nonuniformity of dopant distribution in the $(SiC)_{1-x}(AlN)_x$ epilayer. For the *n*-6*H*-SiC/*p*-$(SiC)_{0.87}(AlN)_{0.13}$ and

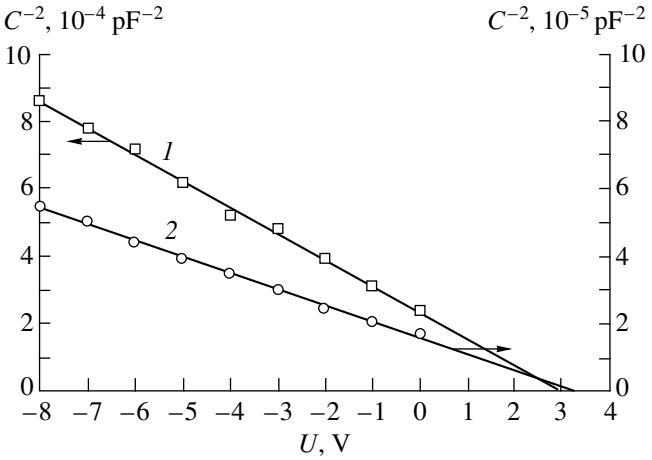

Fig. 1. Capacitance–voltage characteristics for two *n*-6*H*-SiC/*p*-$(SiC)_{1-x}(AlN)_x$ heterostructures at room temperature with the AlN content of x = (*1*) 0.13 and (*2*) 0.56.

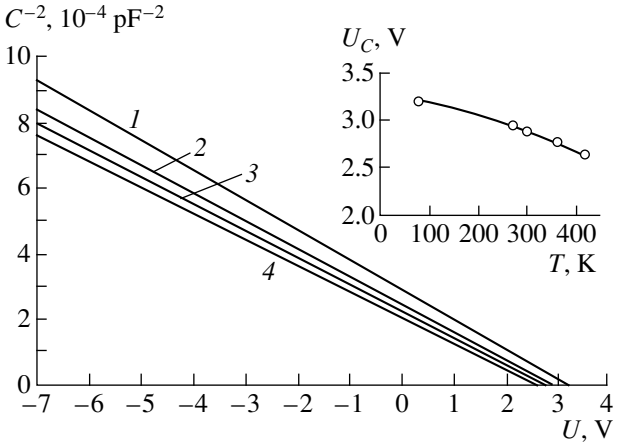

Fig. 2. Capacitance–voltage characteristics for the *n*-6*H*-SiC/*p*-$(SiC)_{0.85}(AlN)_{0.15}$ heterostructures at T = (*1*) 77, (*2*) 273, (*3*) 361, and (*4*) 418 K. The temperature dependence of the capacitance cutoff voltage U_C for this heterostructure is shown in the inset.

n-6*H*-SiC/*p*-$(SiC)_{0.44}(AlN)_{0.56}$ heterostructures, the straight lines extrapolated to $C^{-2} = 0$ intersect the voltage axis at 2.95 and 3.5 V, respectively. These voltages correspond to diffusion contact voltages U_d for the above-mentioned structures. For comparison, the value of U_d for the *p*–*n* homojunctions based on SiC, which was determined from the *C*–*V* and current–voltage characteristics, was about 2.7 V [4, 5]. It seems likely that an increase observed in U_d with increasing AlN content in the $(SiC)_{1-x}(AlN)_x$ epilayer is related to an increase in the epilayer band gap.

Using the values of U_d obtained from *C*–*V* characteristics and the expression

$$\Phi_2 = qU_d + \Phi_1,$$

we can determine the work function Φ_2 for the $(SiC)_{1-x}(AlN)_x$ layers with various AlN contents. The work function Φ_1 for the (0001) face of 6*H*-SiC is 4.5 eV at 300 K [6]. The Φ_2 value increases with increasing AlN content in the epilayer. Thus, for example, for *p*-$(SiC)_{0.87}(AlN)_{0.13}$ and *p*-$(SiC)_{0.44}(AlN)_{0.56}$, Φ_2 = 7.45 and 7.85 eV, respectively.

We determined the impurity concentrations in the $(SiC)_{1-x}(AlN)_x$ epilayer from the slope of the *C*–*V*(*U*) characteristic in the C^{-2}–*U* coordinates, using the known formula [7]

$$\frac{\partial C^{-2}}{\partial U} = \frac{2(\varepsilon_1 N_{d_1} + \varepsilon_2 N_{a_2})}{S^2 q N_{d_1} N_{a_2} \varepsilon_1 \varepsilon_2}.$$

The concentration of N impurity in the 6*H*-SiC substrate for heterostructures shown in Fig. 1 was $\sim 9 \times 10^{17}$ cm^{-3}. This concentration was preliminarily determined from the value of $N_d - N_a$ obtained from the *C*–*V* characteristics for the Schottky barriers. The low-frequency relative permittivity ε_1 of 6*H*-SiC for $E \parallel c$ and T = 300 K is equal to 10.03 [6]. The relative permittivities ε_2 for the $(SiC)_{1-x}(AlN)_x$ solid solutions were determined from photoelectric measurements for the metal–semiconductor (the $(SiC)_{1-x}(AlN)_x$ solid solution) contact. For $0.1 < x < 0.6$, $\varepsilon_2 \simeq 9.4$–9.8. In our calculations, we used the average value $\varepsilon_2 = 9.6$. The area S for *p*–*n* junctions was 2×10^{-2} cm^2. The N_{a_2} concentration determined from the slope of the *C*–*V* curves was 9.02×10^{17} cm^{-3} and 7.98×10^{16} cm^{-3} for the $(SiC)_{0.87}(AlN)_{0.13}$ and $(SiC)_{0.44}(AlN)_{0.56}$ epilayers, respectively. Along with other results, this demonstrates that the impurity concentration N_a in the $(SiC)_{1-x}(AlN)_x$ layers decreases with increasing x. This conclusion was also confirmed by the fact that the capacitance dependence on voltage was weakened at high values of AlN content in the epilayer (Fig. 1). This indicates that the epilayer grown has high resistivity, and the depletion region is located mainly in its bulk.

The temperature dependences of the *C*–*V*(*U*) characteristics for *n*-6*H*-SiC/*p*-$(SiC)_{0.85}(AlN)_{0.15}$, measured in the range of 77–418 K, are shown in Fig. 2. The capacitance cutoff voltage U_C, which was found by extrapolating the straight lines to the voltage axis, was 3.2 V at 77 K (curve *1*). With increasing temperature, the cutoff voltage initially decreases nonlinearly and then almost linearly to 2.65 V at 418 K (curve *4*). For the linear portion, $U_C(T) = U_{C0} - \alpha_C T$ (Fig. 2, inset), where U_{C0} is the voltage obtained by extrapolating $U_C(T)$ to T = 0 K, and α_C is the temperature coefficient of the capacitance cutoff voltage. For the structure under study, U = 3.46 V and $\alpha = 2.1 \times 10^{-3}$ V/K. Unfortunately, there is a lack of published data on the temperature dependence of the E_g band gap for the $(SiC)_{1-x}(AlN)_x$ solid solutions. For this reason, the

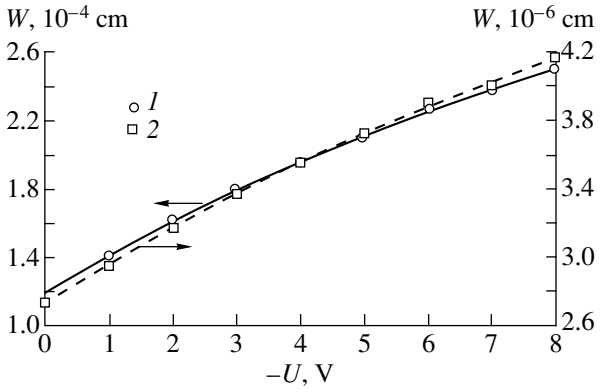

Fig. 3. Thickness W of the space charge region for the n-6H-SiC/p-$(SiC)_{0.87}(AlN)_{0.13}$ heterostructures as a function of the voltage applied to the structure: (*1*) experimental and (*2*) calculated.

nature of the U_C temperature dependence observed and, consequently, the U_d quantity cannot be determined unambiguously. However, knowing that the $U_d(T)$ dependence is more strongly pronounced than $E_g(T)$ for the 6H-SiC based structures [8], we may assume that the $U_C(T)$ dependence is caused mainly by the temperature dependence of the chemical potential in the n- and p-regions. The temperature dependence of the band gap for the components of the SiC–$(SiC)_{1-x}(AlN)_x$ heterocombination also introduces a certain contribution.

Investigation of the C–V characteristics for heterostructures enables the transition-region thickness W to be determined. The dependence $W = f(U)$ for the n-6H-SiC/p-$(SiC)_{0.87}(AlN)_{0.13}$ heterostructure is shown in Fig. 3. The p–n junction thickness determined from the capacitance value at zero bias was 1.2×10^{-4} cm. The thicknesses calculated were compared with those evaluated from the C–$V(U)$ characteristics (Fig. 3). The comparison demonstrated that the experimental values were larger than those calculated. This is apparently related to the effect of mobile charge carriers within the p–n junction and charged states at the interface on the experimental capacitance values.

To clarify the mechanism of electrical breakdown for heterostructures, which was observed at reverse biases larger than 25 V, we calculated the largest values of the electrical field $E_M(U)$ from the C–V characteristics according to the procedure reported elsewhere [9]. The value of $E_M(U)$ in n-6H-SiC/p-$(SiC)_{0.44}(AlN)_{0.56}$ heterostructure is about 5×10^4 V/cm at the prebreakdown voltage. Such an electric-field strength is inadequate to ionize the impurity via tunneling. For this reason, we assumed that the mechanism of the electrical breakdown for the structures under study is impact ionization.

CONCLUSION

Using the method of the capacitance–voltage characteristics, we found that abrupt heterojunctions were formed in the heterostructures fabricated by sublimation epitaxy of the p-$(SiC)_{1-x}(AlN)_x$ layers on the n-6H-SiC substrates. The space charge region was $0.5-2 \times 10^{-4}$ cm thick. The capacitance cutoff voltage U_C exceeded 2.9 V and increased with increasing AlN content in the epilayers. The temperature coefficient α_C of the U_C quantity is equal to $(1–3) \times 10^{-3}$ V/K.

The capacitance measurements demonstrated that the concentration of noncompensated impurities N_a in the epilayers of $(SiC)_{1-x}(AlN)_x$ solid solutions decreases with increasing AlN content. The largest values of the electric field E_M for the prebreakdown region were calculated for the n-SiC/p-$(SiC)_{1-x}(AlN)_x$ heterostructures from the capacitance–voltage characteristics. The values $E_M(U) \simeq 10^4$ V/cm obtained indicate that the mechanism of the electrical breakdown of heterostructures is an impact ionization in the space-charge region.

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