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SEMICONDUCTOR STRUCTURES, LOW-DIMENSIONAL SYSTEMS, AND QUANTUM PHENOMENA

Radiation Hardness of *n*-GaN Schottky Diodes

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Abstract—Schottky-barrier diodes with a diameter of ~10 μm are fabricated on *n*-GaN epitaxial films grown by hydride vapor-phase epitaxy (HVPE) on sapphire substrates. The changes in the parameters of the diodes under irradiation with 15 MeV protons are studied. The carrier removal rate was found to be 130–145 cm^{-1}. The linear nature of the dependence $N = f(D)$ (N is the carrier concentration, and D, the irradiation dose) shows that compensation of the material is associated with transitions of electrons from shallow donors to deep acceptor levels which are related to primary radiation defects.

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1. INTRODUCTION

The search for wide-gap semiconductors that could replace silicon in various typical power devices has a rather long history [1]. Recent advances in the technology of GaN and solid solutions on its basis enable a fresh look at this problem. Although GaN is inferior to SiC in terms of heat conductivity (table) and the structural perfection of epitaxial layers, GaN is grown at lower temperatures from less expensive materials on a variety of substrates. Thus, GaN Schottky diodes can compete well with similar SiC-based devices at voltages of up to 1000 V [3–5].

The goal of the present study is to fabricate GaN Schottky diodes and examine their radiation hardness.

2. RESULTS

The *n*-GaN epitaxial layers under study with a thickness of ~10 μm were grown by hydride vapor-phase epitaxy (HVPE) at a temperature of 1020–1050°C on sapphire substrates (Al_2O_3) [6]. The uncompensated donor concentration $N_D - N_A$ in the as-grown epitaxial layers was determined by the method of capacitance–voltage characteristics with a mercury probe. It can be seen in Fig. 1 that a layer with a concentration of $N_D - N_A \approx 4 \times 10^{16}$ cm^{-3} and thickness of 0.8–0.9 μm is present near the surface. Field-plate Schottky diodes [7] were fabricated on these layers by standard photolithographic procedures, with the deposition of metal films forming the barrier and ohmic contacts. A silicon dioxide (SiO_2) insulator coating with a thickness of 0.4 μm served as the field plate of the barrier contact formed on the basis of the Au films. The barrier contacts to GaN were formed in windows with a diameter of d = 10–50 μm, opened in the SiO_2 film. As a result of repeated deposition, the area of the contacts increased due to the formation of a 10–15-μm overlap with the insulator (Fig. 2). The ohmic contact was fabricated on the front side of the GaN/Al_2O_3 epitaxial structures in the form of a wide (5 mm) strip at the wafer edge. To form the ohmic contact, nickel (Ni) layers with a thickness of 0.3 μm were deposited over 30-nm-thick titanium (Ti) films. Further, the thus fabricated contacts were annealed in vacuum at a temperature of 850°C for 90 s.

The resulting Schottky diodes had a rectifying current–voltage (*I*–*V*) characteristic. Together with a certain spread of the *I*–*V* characteristics of diodes hav-

Electrical parameters of Si, 4*H*-SiC, and GaN [2]

Parameters	Si	4*H*-SiC	GaN
Band-gap width, eV	1.1	3.2	3.4
Breakdown-field strength, 10^6 V/cm	0.3	3	3.5
Electron mobility, cm^2/(V s)	1450	900	2000
Electron saturation rate, 10^6 cm/s	0	22	25
Heat conductivity, W/(cm K)	1.5	5	1.3
Average dislocation density in the epitaxial layer, cm^{-2}	10^0	10^3	10^8

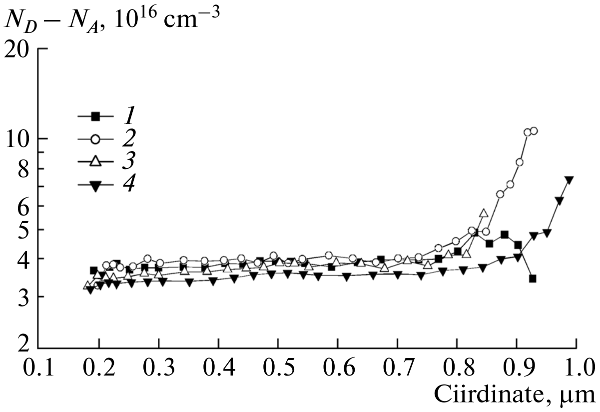

Fig. 1. Distribution profile of the uncompensated donor impurity at various points of sample nos. 1–4.

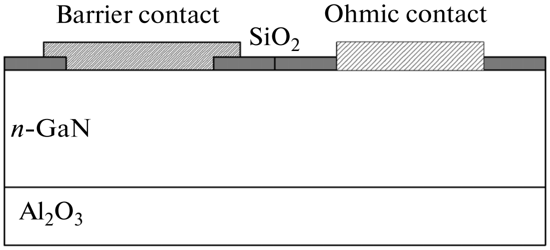

Fig. 2. Schematic of the GaN Schottky diodes under study.

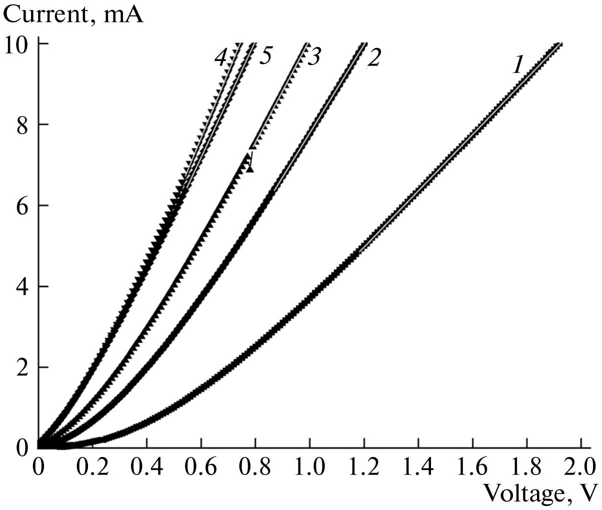

Fig. 3. Forward *I*–*V* characteristics of Schottky diodes with various diameters: (*1*) 10, (*2*) 20, (*3*) 30, (*4*) 40, and (*5*) 50 μm.

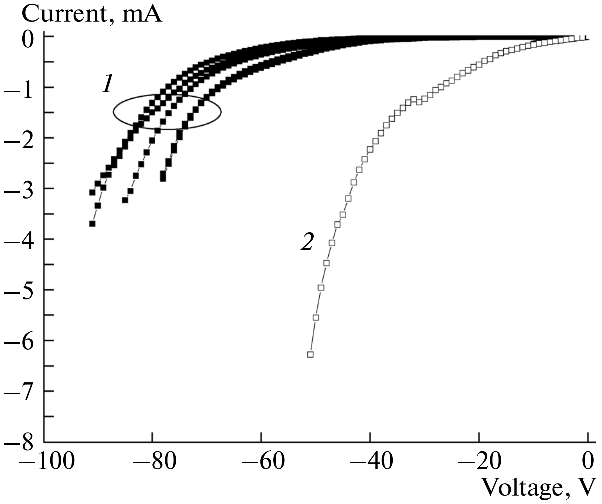

Fig. 4. *I*–*V* characteristics of reverse-biased Schottky diodes with diameters of (*1*) 10 and (*2*) 50 μm.

ing the same area, a clearly pronounced dependence of the characteristics on the diode area was observed: under forward bias, the differential resistance of the diode varies from 150 Ω at $d = 10$ μm (surface resistance $R_s = 1 \times 10^{-4}$ Ω cm^2) to 60–70 Ω at $d = 40$–50 μm ($R_s \approx 1 \times 10^{-3}$ Ω cm^2) (Fig. 3). For a reverse-biased structure, the breakdown voltage varied from 60–80 V (diameter 50 μm) to 100–120 V (diameter 10 μm) (Fig. 4). If we assume that the breakdown voltage ($U_{\rm br}$) of the Schottky diodes under study is determined by the lightly doped film lying at the layer surface, the theoretical value of $U_{\rm br}$ would be 300–350 V, i.e., the $U_{\rm br}$ obtained in the present study is 25–30% of the theoretical value. Presumably, this is due to the simple protection scheme of the periphery of a Schottky diode and to the insufficient crystal perfection of the epitaxial layer.

Proton irradiation was performed on an MGTs-20 cyclotron. Protons with energies of 15 MeV were used at irradiation doses (D) of 1.0×10^{13} cm^{-2} to 4.0×10^{14} cm^{-2}. Figure 5 shows how $1/R$ depends on the irradiation dose (where R is the resistance of a forward-biased Schottky diode). Based on the dependences presented in Fig. 5, we can estimate the carrier removal rate (V_d) by the known formula $V_d = (N_0 - N)/D$, where N_0 and N are the carrier concentrations before and after irradiation, respectively.

Disregarding the dependence of the carrier mobility on irradiation and assuming that $N_D - N_A \approx N_0$, we can write: $1/R \propto eN\mu \propto N$ (where e is elementary charge and μ is mobility). Then, V_d can be estimated as $V_d \le N_0/D_{\max}$, where $D_{\max}$ is the irradiation dose at which complete compensation of a sample is observed. In our case, we can estimate V_d to be 130–145 cm^{-1}. It should be noted that this estimate is in all probability overstated because we disregarded a decrease in the

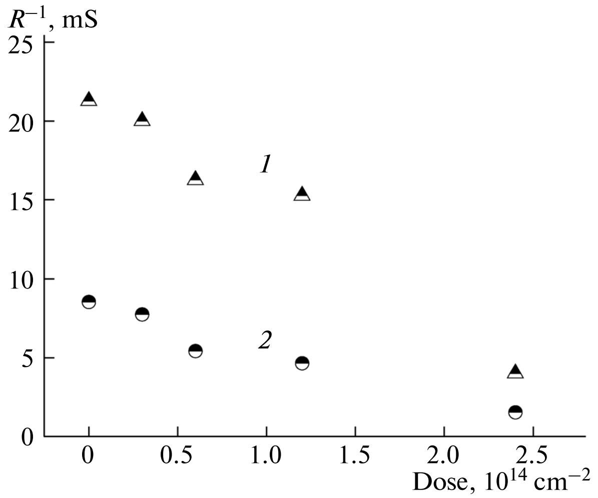

Fig. 5. Conductance of forward-biased GaN Schottky diodes with diameters of (*1*) 10 and (*2*) 50 μm vs. the dose of irradiation with 15 MeV protons.

carrier mobility under irradiation. The value we obtained is close to the value $V_d = 110–130$ cm^{-1} for SiC irradiated with 8-MeV protons [8].

It can be seen in Fig. 5 that the dependence $1/R = f(D)$, or $N = f(D)$] is linear. This indicates that the material is compensated due to the formation of deep acceptor centers to which electrons from shallow donor levels pass [9]. At the same time, it has been noted previously that the compensation of GaN epitaxial layers grown by MOCVD (metal-organic chemical vapor deposition) is due to the formation of complexes constituted by a radiation defect and a shallow donor [10–11]. Possibly, this is due to the different compositions of the background impurity in *n*-GaN layers grown by different techniques.

3. CONCLUSIONS

In the study, prototype Schottky barriers were fabricated on the basis of HVPE-grown *n*-GaN epitaxial layers. The carrier removal rate under irradiation with protons was found to be close to that for SiC epitaxial layers. The devices can be further optimized by using SiC substrates for growth and by improving the structural perfection of *n*-GaN layers.

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