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Irradiation temperature effect on the carrier removal rate in GaN

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Fabrication of devices based on wide-band semiconductors is one of the most fast-growing modern electronics areas. The paper compares the effect of irradiation temperature on the radiation resistance of GaN exposed to proton and electron irradiation. Carrier removal rate was determined for GaN irradiated by protons and electrons at high temperatures. It is shown that, as in the case of SiC, the carrier removal rate decreases significantly at an irradiation temperature of 200 °C compare with irradiation at room temperature.

Keywords: GaN, SiC, radiation resistance, irradiation temperature, protons, electrons.

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1. Introduction

Semiconductors with large band gap are often treated as materials for creating high-temperature electronic devices [1–3]. Therefore, it is important to investigate the influence of temperature on various properties of these devices, for example, on radiation resistance.

It was shown before that an increase in temperature up to $\sim 500\,^\circ$C for silicon carbide leads to a decrease in the carrier removal rate by almost an order of magnitude [4]. The identified effect was associated with an increase in vacancy mobility with temperature leading to a significant increase in the probability of recombination of formed primary radiation-induced defects. As a result, the concentration of formed compensating radiation-induced defects decreased considerably. For GaN, dependence of the carrier removal rate on the temperature hasn't been studied before.

2. Samples and research methods

The investigations used gallium nitride layers with the thickness $d = 2\,\mu$m grown on sapphire wafers by the MOVPE method. Initial concentration $(N_d - N_a)_0$ at room temperature was equal to $1.8 \cdot 10^{17}\,\text{cm}^{-3}$. For capacitance-voltage measurements, high-temperature Schottky diodes $\sim 600\,\mu$m in diameter were formed on the epitaxial layer surface by electron-beam deposition of Pt(50 nm)/Au(150 nm). Ohmic contacts were formed by Ti/Al/Ti/Au (30/150/60/150 nm) sputtering after argon plasma surface treatment.

Irradiation was performed with 0.9 meV electrons and 15 meV protons. Irradiation temperature was 200 °C. The maximum dose was $1 \cdot 10^{15}\,\text{cm}^{-2}$ (protons) and $4 \cdot 10^{17}\,\text{cm}^{-2}$ (electrons). Capacitance-voltage and volt-ampere characteristics were measured after each irradiation dose.

3. Findings and discussion

Radiation resistance is often evaluated using such parameter as the carrier removal rate (η_e):

$$\eta_e = [(N_d - N_a)_0 - (N_d - N_a)]\,/\Delta D, \tag{1}$$

where $(N_d - N_a)_0$ is the initial concentration of uncompensated donors in a semiconductor before irradiation, $(N_d - N_a)$ is the concentration of uncompensated donors after irradiation; ΔD is the irradiation dose.

Note that a significant scatter in particular values of η_e was observed before even in the case of irradiation at room temperature [5,6]. This was probably attributable to different impurity composition of samples used in the experiments [7,8]. Therefore, our experiments used epitaxial layers grown in a single process experiment and on a single wafer. Capacitance-voltage characteristics (CVC) measured using equation (1) were used to calculate (η_e) for electron and proton irradiation in the specified experiment conditions. The values were: for proton irradiation $\eta_e = 50.3\,\text{cm}^{-1}$; for electron irradiation $\eta_e = 0.2\,\text{cm}^{-1}$ (Figures 1 and 2). In the case of proton irradiation, η_e was also evaluated from volt-ampere characteristic (VAC) measurements of the Schottky diodes. Base resistance R was determined from the VAC slope in the ohmic segment (Figures 3 and 4). Then, η_e was calculated as follows

$$\eta_e = n_0(1 - R_0/R)/\Delta D, \tag{2}$$

where n_0 is the initial concentration of carriers in the layer; R_0 is the initial forward resistance of the diode; R is the diode resistance after exposure toΔD [9,10].

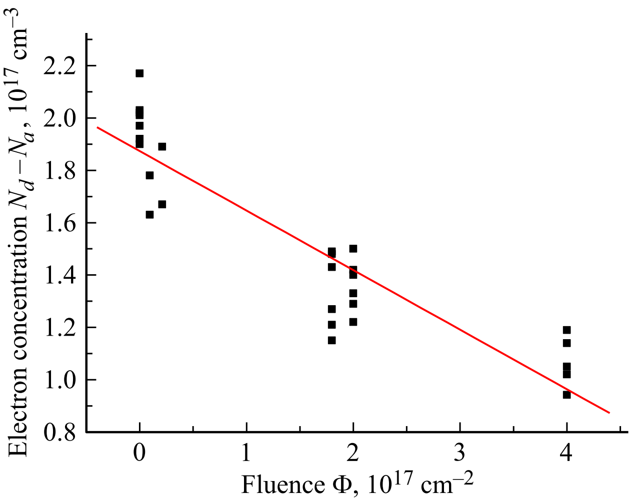

Figure 1. Dependence of the measured $N_d - N_a$ in the epitaxial GaN layers on the electron irradiation dose.

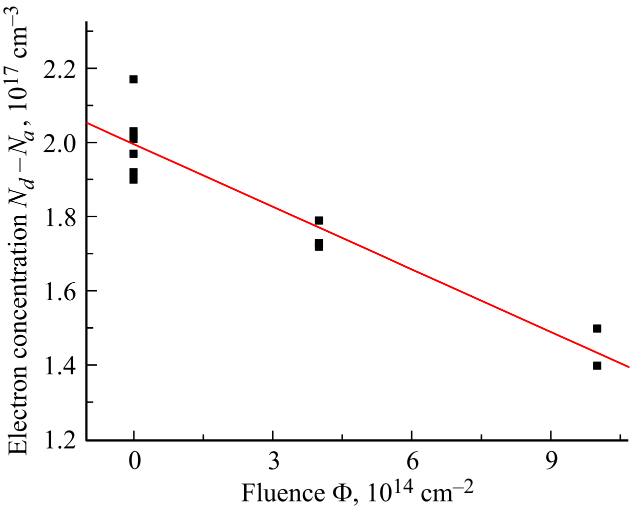

Figure 2. Dependence of the measured $N_d - N_a$ in the epitaxial GaN layers on the proton irradiation dose.

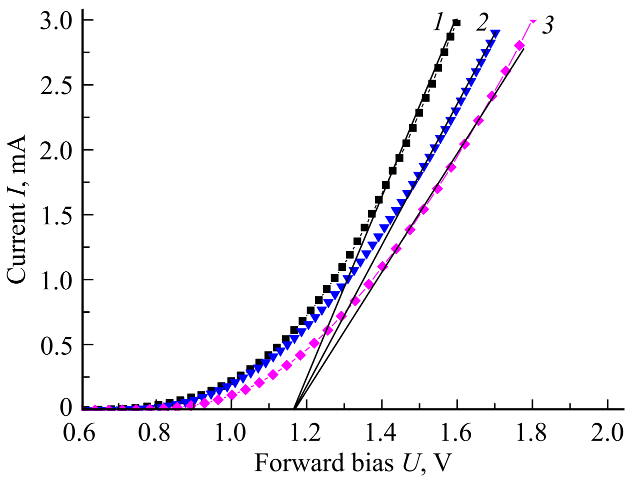

Figure 3. VAC of the samples after various proton irradiation doses cm^{-2}: *1* — 0, *2* — $5 \cdot 10^{14}$, *3* — $1 \cdot 10^{15}$. VAC in the ohmic segment is approximated by straight lines.

Dependence of the carrier removal rate on the temperature for SiC and GaN

T, K	300		500	
Material	SiC [9]	GaN [10]	SiC [9]	GaN, this study
η_e, cm^{-1}, electrons	~ 0.07	0.47	0.02	0.2
η_e, cm^{-1}, protons	~ 60	150	13	65 (CVC) 68 (VAC)

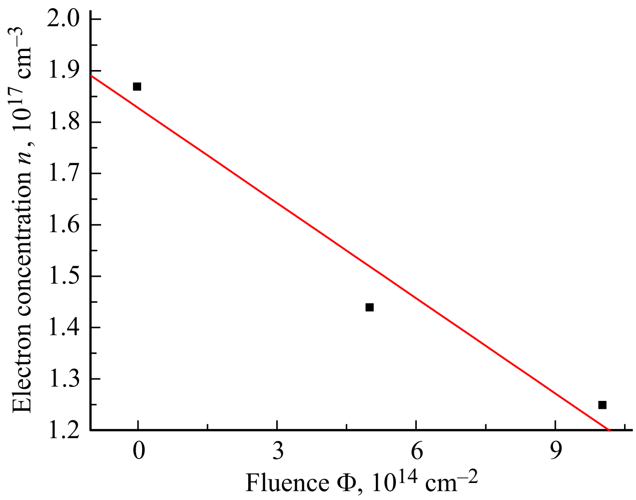

Figure 4. Dependence of the carrier concentration (n) according to the VAC data in the GaN samples on the proton irradiation dose.

All obtained experimental data and literature data concerning irradiation at room temperature and for SiC are listed in the table.

As shown in the table, the radiation resistance of GaN is a little lower than that of SiC. However, the behavior of the temperature dependence of the carrier removal rate is similar for both semiconductors — heating to 200 °C leads to a decrease in η_e by a factor of $\sim 3-4$ for SiC and by a factor of 2–3 for GaN.

4. Conclusion

Thus, the investigations showed that significant decrease in the carrier removal rate was observed in GaN and SiC exposed to irradiation at high temperatures. This result is important for GaN as a promising material for creating high-temperature electronic devices. In GaN and SiC, this effect is presumably induced by increasing vacancy mobility with temperature rise. This leads to an increase in the probability of vacancy and interstitial atom recombination, which reduces the concentration of formed radiation-induced defects. However, additional experiments are needed for final validation of this conclusion, and this will be the topic of our future research.

Conflict of interest

The authors declare no conflict of interest.

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