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Comparison of the Irradiation Temperature Effect of on the Carrier Removal Rates in GaN and SiC

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Abstract. In this paper, the radiation resistance of GaN and SiC is compared. The effect of the irradiation temperature on the carrier removal rate in both semiconductors during proton irradiation is considered. It was found that in GaN, as well as in SiC, the rate of carrier removal decreases with increasing irradiation temperature. The dependence of the GaN sample resistance on the radiation dose was also calculated based on a model previously proposed to describe a similar dependence for SiC. Based on the experimental data obtained, it is concluded that the processes of radiation compensation in GaN and SiC are similar.

Introduction

It is known that, like SiC, GaN is considered a promising material for manufacturing power semiconductor devices [1-3]. Compared with silicon carbide, gallium nitride has a larger forbidden gap, greater mobility, and a larger critical breakdown electric field. However, it has less structural perfection and worse thermal conductivity. From our point of view, it is also necessary to compare the radiation resistance of these two materials. While a large amount of work has already been done on this topic for SiC, many issues remain unclear for GaN. For example, the effect of irradiation temperature on the rate of carrier removal or the mechanism of radiation compensation. The purpose of this study was to partially fill the existing knowledge gap about GaN.

Samples and Research Methods

For the research, gallium nitride layers with a thickness of d = 2 microns grown on sapphire substrates using the MOVPE method were used. The initial concentration of $(Nd\text{-}Na)_0$ at room temperature was 1.8×10^{17} cm^{-3}. To carry out volt-farad measurements on the surface of the epitaxial layers, high-temperature Schottky diodes with a diameter of ~600 microns were formed using electron beam sputtering of Pt (50 nm)/Au (150 nm). Ohmic contacts were formed by spraying Ti/Al/Ti/Au metals (30nm/150nm/60nm/150nm) after surface treatment in argon plasma. The irradiation was carried out with protons with an energy of 15 MeV with a maximum dose of 1 x 10^{15} cm^{-2}. The irradiation temperature is 200 ^{0}C. After each radiation dose, the volt-farad and volt-ampere characteristics were measured.

Results and Discussions

Effect of irradiation temperature on the rate of carrier removal in GaN

The parameter carrier removal rate η_e is often used to assess radiation resistance.

$$\eta_e = [(\mathrm{Nd\text{-}Na})_0 - (\mathrm{Nd\text{-}Na})]\Delta D, \tag{1}$$

Where $(\mathrm{Nd\text{-}Na})_0$ is the initial concentration of uncompensated donors in the semiconductor before irradiation, (Nd–Na) is the concentration of uncompensated donors after irradiation; ΔD is the radiation dose. Based on the measurements of the capacitance-voltage characteristics (CVC) using formula (1), the values (ηe) for irradiation with protons under the specified experimental conditions were calculated. All obtained experimental data, as well as literature data for irradiation at room temperature and for SiC are presented in the table 1.

Table 1. Temperature dependence of the carrier removal rate for SiC and GaN.

T, K	300		500	
Material	SiC [4]	GaN [5]	SiC [4]	GaN, current work
η_e, см$^{-1}$, protons	~ 60	150	13	~ 70

As can be seen from the Table, the radiation resistance of GaN is some what inferior to the radiation resistance of SiC. At the same time, the nature of the temperature dependence of the carrier removal rate is similar for both semiconductors – heating to 200^0C leads to a decrease in the values of η_e by about 3-4 times for SiC and 2-4 for GaN . Thus, the conducted studies have shown that in GaN, as well as in SiC, there is a significant decrease in the rate of carrier removal in the case of irradiation at elevated temperatures. This result is important for GaN as a promising material for creating high-temperature electronics devices.

Analysis of the temperature dependence of the GaN resistance on the radiation dose

Let us now consider the effect of the radiation dose on the resistance of the sample base. We will use the model that we previously developed for SiC analysis [6].

Table 2. Parameters and concentrations of DL arising in n-GaN after proton irradiation [7-10].

Energy level position	Fluence, cm^{-2}				
	0	1.0×10^{12}	3.9×10^{12}	7.2×10^{12}	1.1×10^{13}
	Deep level concentration, cm^{-3}				
$E_c - 0.13$ eV	0	2.9×10^{14}	9.0×10^{14}	1.7×10^{15}	2.5×10^{15}
$E_c - 0.16$ eV	0	2.5×10^{14}	1.0×10^{15}	1.5×10^{15}	3.0×10^{15}
$E_c - 0.25$ eV	1.7×10^{14}	2.7×10^{14}	5.4×10^{14}	6.9×10^{14}	1.3×10^{15}
$E_c - 0.6$ eV	2.8×10^{15}	3.0×10^{15}	3.7×10^{15}	4.0×10^{15}	3.6×10^{15}
$E_c - 0.72$ eV	6.2×10^{14}	1.0×10^{15}	2.3×10^{15}	2.4×10^{15}	3.9×10^{15}
$E_c - 1.25$ eV	3.9×10^{14}	5.1×10^{14}	5.9×10^{14}	7.1×10^{14}	7.7×10^{14}

There are a number of studies where the parameters of the deep levels (DL) that occur when n-GaN is irradiated with protons have been determined. The results are presented in table 2.

Consider n-GaN, doped with Si, which is most often used to produce n-type conductivity in gallium nitride. Silicon donor levels have an activation energy of 15 MeV [11]. We will assume that all radiation defects formed after irradiation are acceptors. Then levels with an energy of 0.13 – 0.25 MeV will not affect the concentration of electrons in the base at room temperature, since all charge carriers captured by them will be ionized almost instantly into the conduction gap. The remaining GU levels can be conditionally divided into two groups, according to the ratio of the probability of capture and ionization of the carrier at this level.

1) Acceptor A1, which is an average of Ec – 0.6 eV and Ec – 0.72 eV levels. This level will capture electrons from the conduction zone, which will be partially ejected back into the zone.

2) Acceptor A2 with an activation energy equal to 1.25 eV. This level will only capture electrons, and there will be no reverse ionization from it at room temperature.

The schematic arrangement of these levels in the GaN forbidden gap is shown in Fig. 1. The parameters of deep acceptors A1 and A2 and the rate of their introduction are summarized in Table 3.

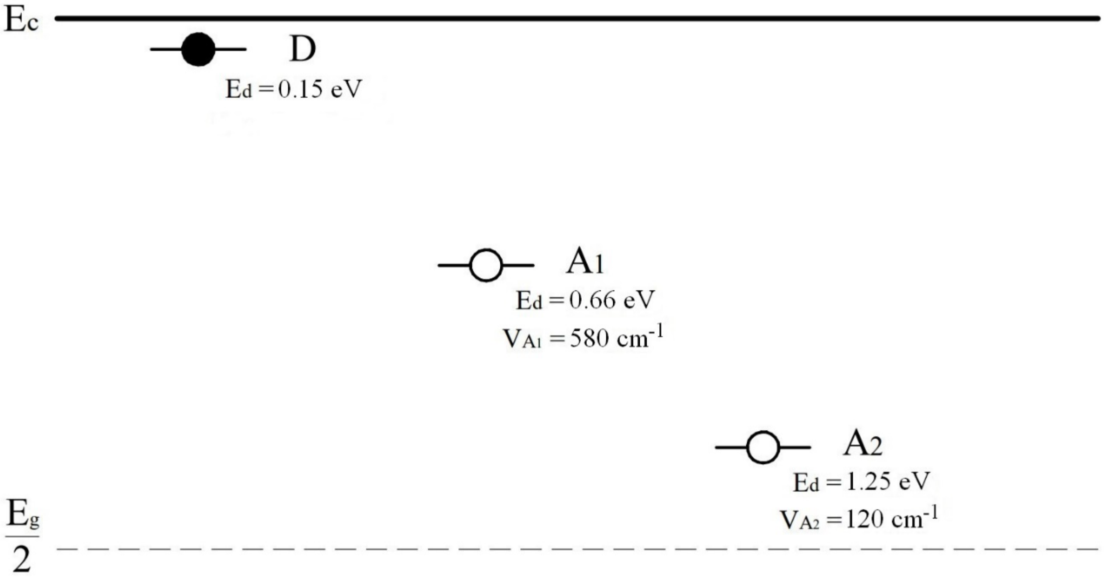

Fig. 1. Diagram of the location of the main types of levels in the upper half of the GaN forbidden gap during proton irradiation.

Table 3. Parameters of deep levels in case of proton irradiation.

Level	Ionization energy, eV	Concentration before irradiation, cm^{-3}	Concentration after irradiation, cm^{-3}	Carrier removal rate, cm^{-1}
A1	0.66	$3.42 \cdot 10^{15}$	$4 \cdot 10^{15}$	580
A2	1.25	$3.9 \cdot 10^{14}$	$5.1 \cdot 10^{14}$	120

The total concentration of electrons in the conduction band will be considered as the sum of the contributions of levels D and A1. The calculation for each level was performed according to (2) [12]:

$$n = \frac{2(N_d - N_a)}{1 + \frac{gN_a}{N_c} \cdot e^{\varepsilon_d} + \left[\left(1 + \frac{gN_a}{N_c} \cdot e^{\varepsilon_d}\right)^2 + \frac{4g(N_d - N_a)e^{\varepsilon_d}}{N_c}\right]^{1/2}} \tag{2}$$

where N_c is the effective density of states in the conduction band, $g = 1$ is the level degeneracy factor, E_d is the activation energy of the level, and ε_d is the reduced value of the activation energy calculated by formula (3):

$$\varepsilon_d = \frac{E_d}{kT} \tag{3}$$

$$R = \frac{L}{e \cdot n \cdot \mu \cdot S} \tag{4}$$

where L is the length of the diode base, e is the electron charge, μ is the mobility of charge carriers, and S is the contact area.

As the radiation dose increases, electrons from the donor level D will move to the acceptor levels A1 and A2. After full compensation of the donor level, the residual conductivity of the sample will be due to the electrons ionized from the A1 level. The dependence calculated by formulas (2) – (4), as well as experimental data from [13] are shown in Fig. 2.

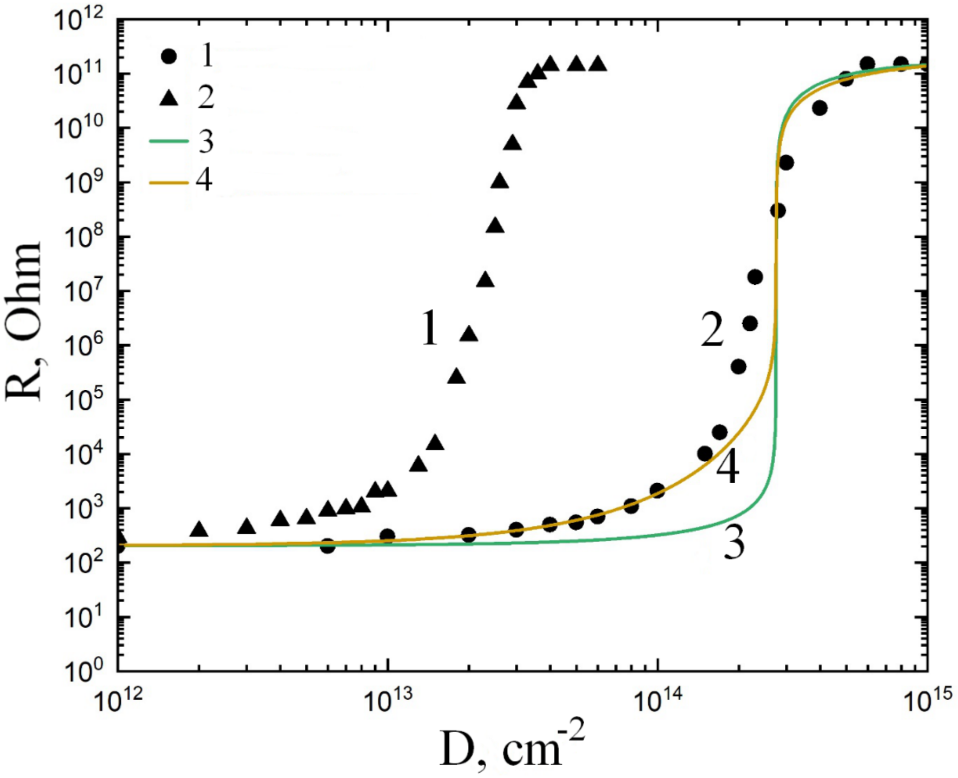

Fig. 2. Dependence of GaN resistance on the dose of proton irradiation at a temperature of T = 300 K: experiment [13]: 1-Irradiation 0.6 MeV H; 2- Irradiation of 3 MeV 7Li; Calculated dependences 3 – without taking into account changes in mobility; 4 – taking into account changes in mobility.

When irradiated with protons with an energy of 0.6 MeV, the dependence practically coincides with the experiment, however, there are inconsistencies at intermediate radiation doses of $\sim 10^{14}$cm^{-2}. The values of GaN resistance at low and high doses of proton irradiation practically coincide with the experiment.

A parameter that can affect the angle of inclination of the resistance curve depending on the radiation dose may be the mobility of charge carriers, which decreases with increasing radiation dose due to the introduction of defects in the crystal structure. There are no direct experimental data on this dependence, but in [14] the authors investigated the change in the mobility of gallium nitride charge carriers after irradiation during isochronous annealing. As the annealing temperature increased, the mobility of the irradiated gallium nitride sample increased, therefore, the mobility of charge carriers decreases during irradiation. Using the values of the mobility of the n-GaN sample carriers after irradiation, as well as after isochronous annealing, the curve of the resistance dependence on the dose of proton irradiation was calculated, taking into account the change in mobility.

The calculation results are also shown in Fig. 2.

Taking into account the change in carrier mobility, the coincidence with the course of experimental dependence becomes more satisfactory and has only small deviations at intermediate doses.

Conclusion

The conducted studies have shown the similarity of radiation compensation processes in SiC and GaN. In both materials, a decrease in the rate of carrier removal is observed with an increase in the irradiation temperature. It was shown in SiC that this is due to an increase in the mobility of primary radiation defects with increasing temperature and an increase in the probability of their recombination. It can be assumed that a similar process takes place in GaN.

It was also shown that the dependence of GaN resistance on radiation dose is well described by the model developed for SiC. This model assumed that radiation compensation is caused by the transition of electrons to deep acceptor levels. Thus, it is obvious that such a compensation mechanism is also implemented for GaN.

Conflict of Interest

The authors declare that they have no conflict of interest.

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