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Injection-Enhanced Annealing of GaAs- and GaN-based Heterostuctures Irradiated with Gamma-Quanta and Neutrons

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Injection current has been shown to fully recover gamma-irradiated GaAs and GaN heterostructures in contrast to neutron-irradiated samples. The threshold dependency of injection-enhanced annealing on current density has been revealed. The threshold current density of annealing in neutron-irradiated samples is of the order of magnitude higher than in gamma irradiation case. The results indicate different height of potential barriers created by radiation-induced defects clusters in GaN and GaAs.

Keywords: radiation-induced defects, injection-enhanced annealing, gamma radiation, neutrons, clusters, light-emitting diodes.

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The passage of injection current through an irradiated $p-n$-junction may restore its characteristics (i. e., result in injection-enhanced annealing (IEA) of radiation-induced defects). Research shows that IEA is most commonly observed in $A^{III}B^{V}$ semiconductor compounds (GaAs, InGaP, InGaAsP, etc.) [1–5]; it may proceed at liquid nitrogen temperatures [1] and be athermal [6]. This raises interest in the mechanism of IEA and in the practical application of this phenomenon. The mechanism of IEA is typically associated with a change in the charge state of defects or local energy release at a defect as a result of non-radiative capture of minority carriers [5,6]. From a practical perspective, IEA holds promise as a means for enhancing the radiation resistance of semiconductor devices. The use of thermal annealing for the same purpose requires temperatures at which the device parameters go beyond the operating range (on the order of 500 K and higher) [2,7].

IEA of point defects in GaAs, InGaP, and InGaAsP irradiated with gamma quanta, fast electrons, and protons has been examined in most detail [1–5]; specifically, potential differences in the kinetics of IEA of homo- and heterostructures were highlighted in our study [4]. Only a few studies into IEA in GaN have been published [8]; the main focus is on thermal annealing of radiation-induced defects [7]. Owing to the differences in the mechanism of injection-enhanced and thermal annealing, one should expect that the specific features of GaN-based devices, such as a relatively wide band gap, high charged dislocation density, and the presence of polarization effects [9], will have a stronger impact on IEA than on thermal annealing. In addition, there are virtually no published studies of IEA in samples irradiated with neutrons [3,8]: it is unknown whether clusters of radiation-induced defects are susceptible to IEA. Therefore, the aim of this work is to investigate injection-enhanced annealing in GaAs- and GaN-based structures irradiated with neutrons and gamma quanta.

The samples under study are commercial LEDs based on GaAs and GaN heterostructures with a quantum well. Their peak electroluminescence (EL) wavelengths are 850 nm (GaAs), 365 nm (GaN), and 440 nm (GaN), and the rated operating current is $20-40\,A/cm^2$. The samples were irradiated by gamma quanta with an average energy of 1.25 MeV at a constant exposure rate of $\sim 70\,R\cdot s^{-1}$ (a flux density of $10^{11}\,cm^{-2}\cdot s^{-1}$), by a reactor neutron pulse 2 ms in length (average energy, 1 MeV; flux density, $\sim 10^{16}\,cm^{-2}\cdot s^{-1}$), and by monochromatic neutrons with an energy of 14 MeV at a constant flux density of $\sim 10^{9}\,cm^{-2}\cdot s^{-1}$. The fluence of gamma quanta and fast neutrons was chosen so that absorbed dose D_{NIEL} in structural damage processes was the same in all cases. The EL intensity of LEDs at a current density of $0.1\,A/cm^2$ and the transmission spectrum of their lenses within the $300-1100$ nm wavelength range were measured before and after irradiation. Following irradiation, the EL intensity of LEDs decreased approximately by a factor of 10, while the change in transmittance of the LED lens did not exceed the measurement error (5 %). Injection-enhanced annealing was carried out at 300 K and constant current; the state of each sample was monitored via simultaneous measurements of voltage across the diode and the intensity of its EL. The sample temperature (< 320 K) was monitored by the change in voltage using the temperature coefficient of voltage [9],

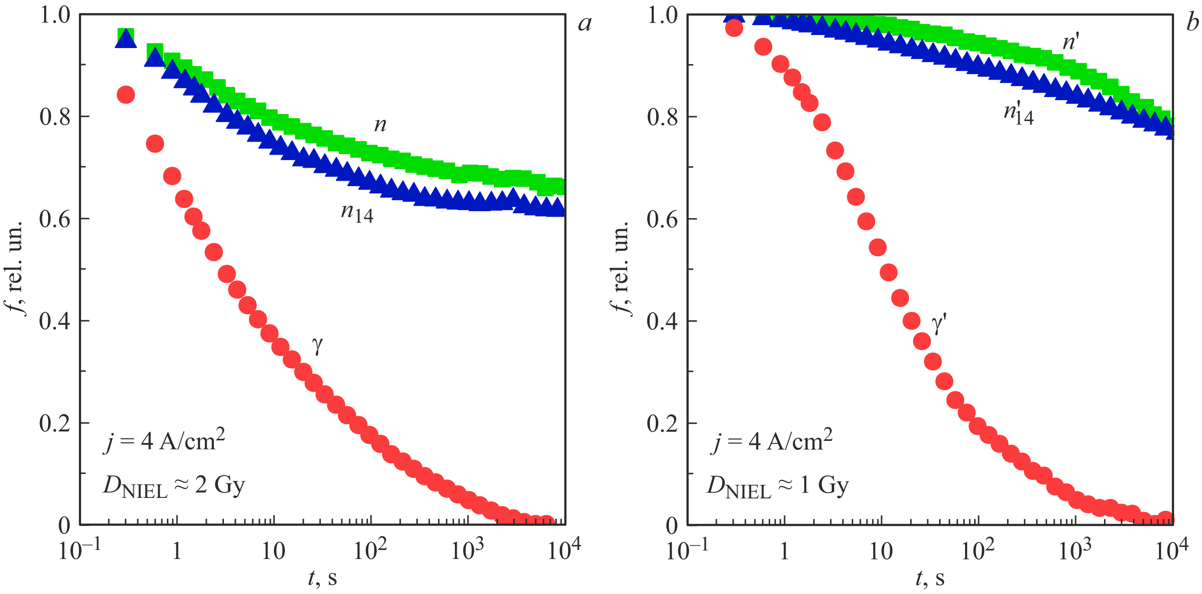

Figure 1. Dependence of unannealed fraction of radiation-induced defects f on time t of current flow through the sample. a — GaN-based LEDs (365 nm); b — GaAs-based LEDs. The samples were irradiated with reactor neutrons ($n = 3 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $n' = 1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$), 14 MeV neutrons ($n_{14} = 1.2 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $n'_{14} = 0.6 \cdot 10^{13}\,\mathrm{cm}^{-2}$), and gamma quanta ($\gamma = 2.4 \cdot 10^{17}\,\mathrm{cm}^{-2}$, $\gamma' = 0.5 \cdot 10^{17}\,\mathrm{cm}^{-2}$).

and the EL intensity was used to monitor the IEA results.

Ample experimental evidence suggests that the relation between EL intensity and fluence is nonlinear (see, e.g., [2]):

$$(I_0/I_\Phi)^n - 1 = \tau_0 K_\tau \Phi,$$

where I_0 and I_Φ are the EL intensities before and after irradiation, τ_0 is the lifetime of minority charge carriers before irradiation (hereinafter referred to as the lifetime), and K_τ is the coefficient of radiation-induced lifetime change. The variation of lifetime under irradiation is characterized by expression $\tau_\Phi^{-1} - \tau_0^{-1} = K_\tau \Phi$ [2], where τ_Φ is the lifetime after irradiation. Since the quantity inverse to the lifetime is proportional to the concentration of nonradiative recombination centers ($\tau^{-1} \propto N$) [9], the relation between the EL intensity and unannealed fraction of radiation-induced defects f takes the form

$$f = \frac{N_t - N_0}{N_\Phi - N_0} = \frac{(I_0/I_t)^n - 1}{(I_0/I_\Phi)^n - 1}, \quad (1)$$

where I_t is the EL intensity at time point t after the start of annealing and N_0, N_Φ, and N_t are the defect concentrations prior to irradiation, after irradiation, and at time point t after the start of annealing. Index n is most often set to 2/3 with the assumption that the mechanism of current flow through the sample is diffusion in nature [1,2]. The results of EL measurements confirm the applicability of $n = 2/3$ to the studied samples, since the $(I_0/I_\Phi)^{2/3} - 1$ value increases linearly with increasing fluence of gamma quanta and fast neutrons.

Figure 1 presents the results of measurements obtained in the process of annealing with a current density of $4\,\mathrm{A/cm^2}$ for 3–5 h. IEA of all radiation-induced defects is observed after irradiation with gamma quanta, while a fraction of unannealed defects (approximately 60 % for GaN and 80 % for GaAs) remains after irradiation with neutrons and IEA. Following 1 h of annealing, the kinetics reaches a plateau (GaN) or transforms into a logarithmic dependence (GaAs). The differences between samples irradiated with reactor neutrons and monochromatic 14 MeV neutrons are minor, although the neutron energy and flux density varied significantly in these experiments. The possible influence of neutron flux density on defect formation processes was discussed in [10].

It is known that the kinetic energy of knocked-on atoms formed by the impact displacement mechanism under irradiation with 1.25 MeV gamma quanta is slightly above E_d (the minimum threshold energy required to displace an atom). In the case of neutron irradiation, the kinetic energy of knocked-on atoms is much higher than E_d; therefore, only point defects are formed after irradiation with gamma quanta, while both point defects and defect clusters are produced after irradiation with neutrons. Since the dimensions of the studied samples are significantly smaller than the mean free path of neutrons and gamma quanta with an energy of ~ 1 MeV, radiation-induced defects and their clusters are distributed uniformly. Therefore, it is likely that the differences in annealing of samples irradiated with gamma quanta and neutrons are associated with the presence of clusters of radiation-induced defects in the latter. Assuming that the plateau and the logarithmic annealing component are associated with clusters, one may obtain annealing curves $f_p(t)$ of point defects in neutron-irradiated samples. This was done using expression $f_p(t) = [f(t) - f_c(t)]/[1 - f_c(0)]$, where

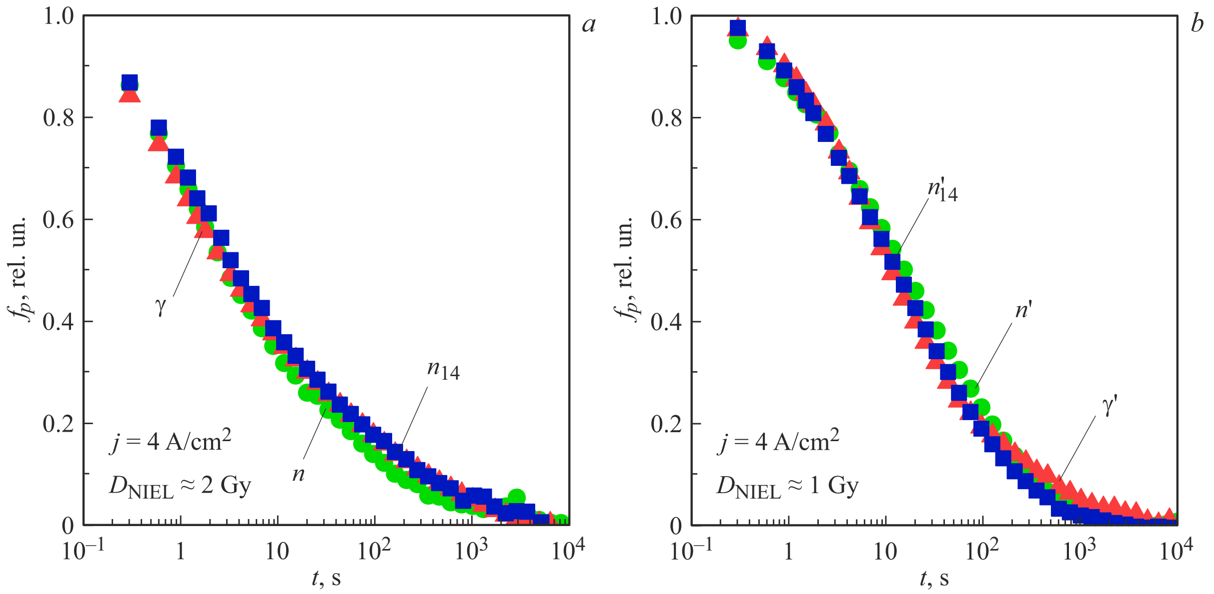

Figure 2. Dependences of unannealed fraction of point radiation-induced defects f_p on time t of current flow through the samples irradiated with neutrons and gamma quanta. a — GaN-based LEDs (365 nm); b — GaAs-based LEDs. The designations correspond to those in Fig. 1.

$f(t)$ is the annealing curve of neutron-irradiated samples; $f_c(t) = \text{const}$ (GaN) and $f_c(t) = a + b\ln(t + c)$ (GaAs); and a, b, and c are constants. Since the obtained $f_p(t)$ curves are virtually identical to the annealing curve of samples irradiated with gamma quanta (Fig. 2), it is fair to assume that point defects involved in IEA in the samples irradiated with neutrons and gamma quanta are identical.

Figure 3 shows the fractions of unannealed radiation-induced defects after 5 h of annealing at different current densities. Each point corresponds to a single sample. The solid curve is the result of approximation by an exponential function of the form $f(j) = f_{res} + (1 + f_{res})\exp(-j/j_{th})$, where f_{res} is the residual fraction of radiation-induced defects (at $j \gg j_{th}$) and j_{th} is the current density at which $f(j) - f_{res}$ decreases by a factor of e (hereinafter referred to as the annealing threshold). An increase in current density leads to an exponential (threshold) reduction in the number of radiation-induced defects after 5 h of annealing. However, unannealed defects remain in the samples irradiated with neutrons even after annealing at the highest current density (300 A/cm^2). The annealing thresholds for the samples irradiated with neutrons are 1.7 A/cm^2 (GaN) and 9 A/cm^2 (GaAs). These values are several times higher than the thresholds for the samples irradiated with gamma quanta (0.06 A/cm^2 (GaN) and 0.9 A/cm^2 (GaAs)). Note that the $f(j)$ dependence for GaAs structures does not reach saturation, and strong self-heating of the samples, which leads to their irreversible damage, makes it difficult to perform experiments at higher current densities.

Figure 3 illustrates the threshold nature of the dependence of IEA rate on current density. This threshold nature may be associated with a sharp change in the probability of trapping of minority carriers by a defect upon intersection of the quasi-Fermi level and the localized level of a defect the migration (decay) of which is activated as a result of injection. Relying on this assumption, we analyzed the electron quasi-Fermi level and determined the positions of levels of defects, which migrate under the influence of carrier injection in gamma-irradiated samples, using the expression

$$\frac{dn_0}{dt} = G^{2D} - A^{2D}n_0 - B^{2D}n_0^2 - C^{2D}n_0^3, \qquad (2)$$

where $G^{2D} = j/e$ is the generation rate and A^{2D}, B^{2D}, and C^{2D} are the coefficients of nonradiative, radiative, and Auger recombination in a 2D structure, respectively [9,11]. Typical widths of the quantum well (3 and 10 nm for GaN and GaAs heterostructures, respectively) and the stationary case ($dn_0/dt = 0$) were considered [9]. The obtained values of $E_C - 0.12$ eV for GaN structures and $E_c - 0.04$ eV for GaAs structures are close to the positions of levels of defects introduced during electron irradiation of GaN and GaAs [7,12]. The involvement of a defect with the $E_C - 0.04$ eV level in IEA of GaAs has already been reported in [1].

After neutron irradiation, the annealing threshold is higher and the obtained defect level positions are approximately 0.05 eV closer to the bottom of the conduction band. Apparently, this result should be analyzed in the context of the well-known Gossick model, which was applied successfully in the study of interaction of radiation-induced defect clusters with carriers in semiconductors [13]. This model helps reveal that the extent of the electric field produced by clusters at typical values of the dopant

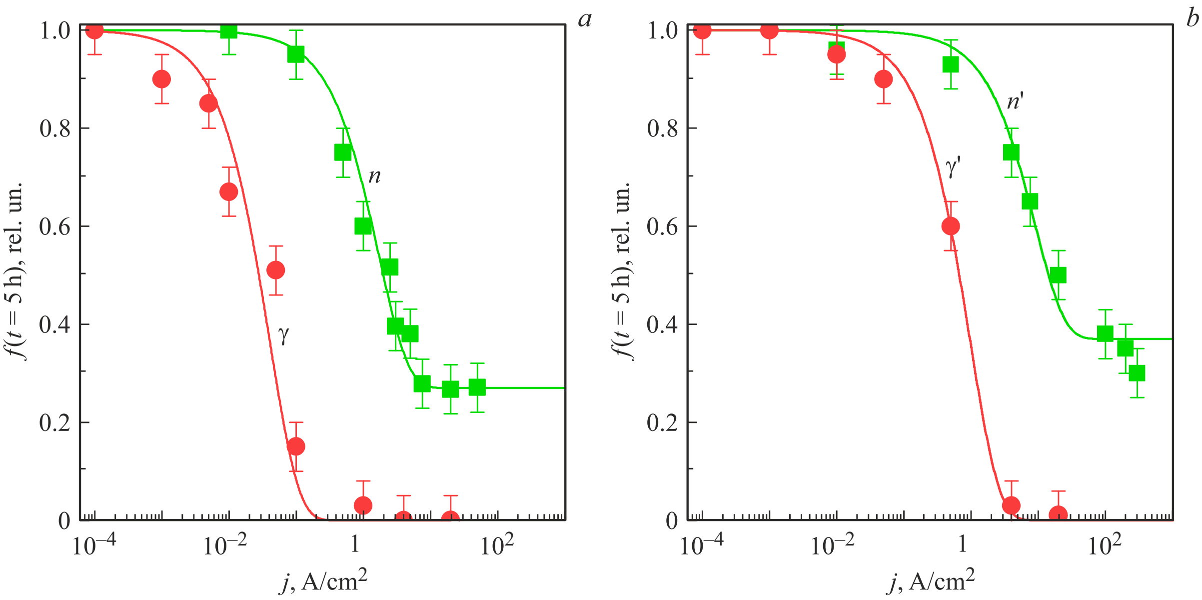

Figure 3. Unannealed fraction of radiation-induced defects after 5 h of IEA at different current densities. *a* — GaN-based LEDs (440 nm); *b* — GaAs-based LEDs. The designations correspond to those in Fig. 1.

concentration in the active region ($10^{15}-10^{16}\,\mathrm{cm}^{-3}$ [9]) is significantly greater than the dimensions of the clusters themselves. In the major part of the region occupied by the electric field, the potential is low ($\varphi(r) \leqslant k_BT/e$) and changes slowly. It may then be assumed that point defects are affected by a weak uniform electric field φ_0, which increases the distance between the quasi-Fermi level and the point defect level by $e\varphi_0 \leqslant k_BT$. Therefore, a higher current density will be required to initiate IEA of defects located within the electric field of clusters. Apparently, this is the reason why the IEA threshold in neutron-irradiated samples is higher than in gamma-irradiated ones (Fig. 3). The experimentally determined shift of defect levels, which is 0.05 eV, does not contradict the Gossick model.

Applying the Gossick model, one may clarify the reasons behind the differences in IEA of GaAs and GaN heterostructures irradiated with neutrons. The height of the potential barrier of clusters is equal to the difference between the positions of the Fermi level in the undisturbed region and in a cluster. Using the data from [14], one may find that the potential barrier of clusters in GaN (2.4 eV) is significantly higher than in GaAs (0.5 eV). It is probably more difficult for carriers to penetrate into clusters in GaN; therefore, saturation is observed in the annealing kinetics in neutron-irradiated GaN structures (Figs. 1, 3), whereas GaAs structures reveal no saturation. This assumption is supported by the logarithmic nature of annealing in GaAs structures observed after 1 h of annealing. Similar kinetics has been observed in [3,15] and attributed to the presence of a continuous distribution of activation energies of defect migration. A single value of the activation energy is observed in most cases; however, when clusters are annealed, the activation energies of defect migration in the center and at the periphery of a cluster may differ due to the interaction of defects with each other.

As a result, it was found that all radiation-induced defects are annealed after IEA in GaAs and GaN heterostructures irradiated with gamma quanta, while only a faction of defects is annealed in neutron-irradiated structures. The fraction of unannealed defects decreases with increasing current density in a threshold manner. The defect annealing thresholds in neutron-irradiated samples are 1.7 A/cm^2 (GaN) and 9 A/cm^2 (GaAs). These values are significantly higher than the thresholds for gamma-irradiated samples: 0.06 A/cm^2 (GaN) and 0.9 A/cm^2 (GaAs). It was demonstrated that the annealing kinetics of point defects in samples irradiated with neutrons and gamma quanta are the same if the doses absorbed in the processes of structural damage are equal.

The obtained results suggest the following: (1) the key differences in the annealing of samples irradiated with gamma quanta and neutrons are associated with the electric field produced by clusters; (2) the potential barrier for carriers created by clusters in GaN is significantly higher than the one in GaAs; (3) currents with a density of $\sim 10-100\,\mathrm{A/cm}^2$ are sufficient to observe the annealing of clusters in GaAs-based structures, while GaN-based structures require higher current densities. The results also demonstrate that IEA may be used not only to enhance the radiation resistance of semiconductor devices, but also to probe the characteristics of the electric field produced by clusters of radiation-induced defects.

Conflict of interest

The authors declare that they have no conflict of interest.

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