Technical Physics Letters, 2024, Vol. 50, No. 7

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Injection-enhanced annealing kinetics of GaAs-based gamma-irradiated homo- and heterostructures

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Received February 19, 2024
Revised March 20, 2024
Accepted March 23, 2024

The injection-enhanced annealing kinetics of radiation-induced defects has been studied by electroluminescence intensity measurements for quantum-sized GaAs/AlGaAs heterostructures irradiated with ^{60}Co gamma-quanta. The comparison of the obtained results with the available literature data for GaAs homostructures has revealed that in transition from homostructures to heterostructures the current density, needed for radiation-induced defects annealing, decreases by 2-4 orders and a different mechanism of defect annihilation comes out. The results indicate higher injection-enhanced annealing efficiency in devices containing quantum-sized heterostructures.

Keywords: injection-enhanced annealing, recombination-enhanced annealing, radiation resistance, radiation-induced defects.

DOI: 10.61011/TPL.2024.07.58721.19899

Injection current may restore the characteristics of an irradiated $p-n$ junction. This phenomenon is called the injection-enhanced annealing (IEA) of radiation-induced defects. In practical terms, it is a promising method for enhancing the radiation hardness of optoelectronic devices [1,2]. One significant advantage of IEA over conventional thermal annealing is that it may proceed at temperatures of 223−323 K typical of the on-board equipment of spacecraft. Thermal annealing requires higher temperatures (~ 570 K and above) [1,3]. The mechanisms of IEA and thermal annealing are also different. IEA is associated with a change in the charge state of defects and local energy release at a defect as a result of non-radiative capture of non-equilibrium carriers [4]. One can say that IEA is initiated by the charge carriers, while thermal annealing is initiated by the lattice.

The IEA phenomenon has been studied since the 1960s [5]. Since then, homostructures (especially those fabricated from GaAs) have been analyzed in most detail [5–9]. Heterostructures are examined more often in current research [10–12]. These structures have widely different dimensions and structures of the active region where carrier recombination occurs. Active regions of heterostructures are characterized by high densities of injected carriers and the presence of interfaces and solid solutions. All this suggests that IEA processes in homo- and heterostructures should differ significantly. However, as far as we know, these differences have not been addressed in studies published to date. A comparison of the kinetics of IEA in homo- and heterostructures based on the same material may be the key to clarifying this issue. This is the reason why the present study was aimed at comparing the kinetics of IEA in GaAs homostructures and GaAs/AlGaAs-based heterostructures.

The samples under study are commercial GaAs/AlGaAs-based heterostructure LEDs with an electroluminescence (EL) wavelength of 850 nm. A typical active region of such LEDs contains one quantum well formed by an undoped GaAs layer ~ 10 nm in thickness and wide-gap p-Al$_{0.3}$Ga$_{0.7}$As layers [13]. According to the results of measurement of capacitance-voltage characteristics, the approximate acceptor density in Al$_{0.3}$Ga$_{0.7}$As layers is $5 \cdot 10^{16}\,\mathrm{cm}^{-3}$. The samples were irradiated with γ-quanta of the ^{60}Co isotope to create radiation-induced defects. Following irradiation, the EL intensity of LEDs decreased by a factor no greater than 5; the fluence of γ-quanta in these experiments was $2.5 \cdot 10^{16}-2.5 \cdot 10^{17}\,\mathrm{cm}^{-2}$. The EL intensity reduction due to radiation-induced absorption in the LED lens did not exceed the measurement error (5%). Annealing was carried out at 300 K under constant current with density $j = 4\,\mathrm{A/cm}^2$. The magnitude of heating of samples induced by the flow of current did not exceed 2°C; therefore, the influence of thermal annealing on the obtained results could be excluded. The process was monitored by measuring the dependence of the EL intensity of LEDs on the current flow time. Unannealed fraction of radiation-induced defects f [7,10] was the quantity used to characterize the measured dependences:

$$f = \frac{I_t^{-2/3} - I_0^{-2/3}}{I_\Phi^{-2/3} - I_0^{-2/3}} = \frac{N_t - N_0}{N_\Phi - N_0},$$

where I_0, I_Φ, and I_t are the EL intensities of a LED prior to irradiation, after irradiation, and time point t in the process of annealing. A similar notation (N_0, N_Φ, and N_t) was used for defect density.

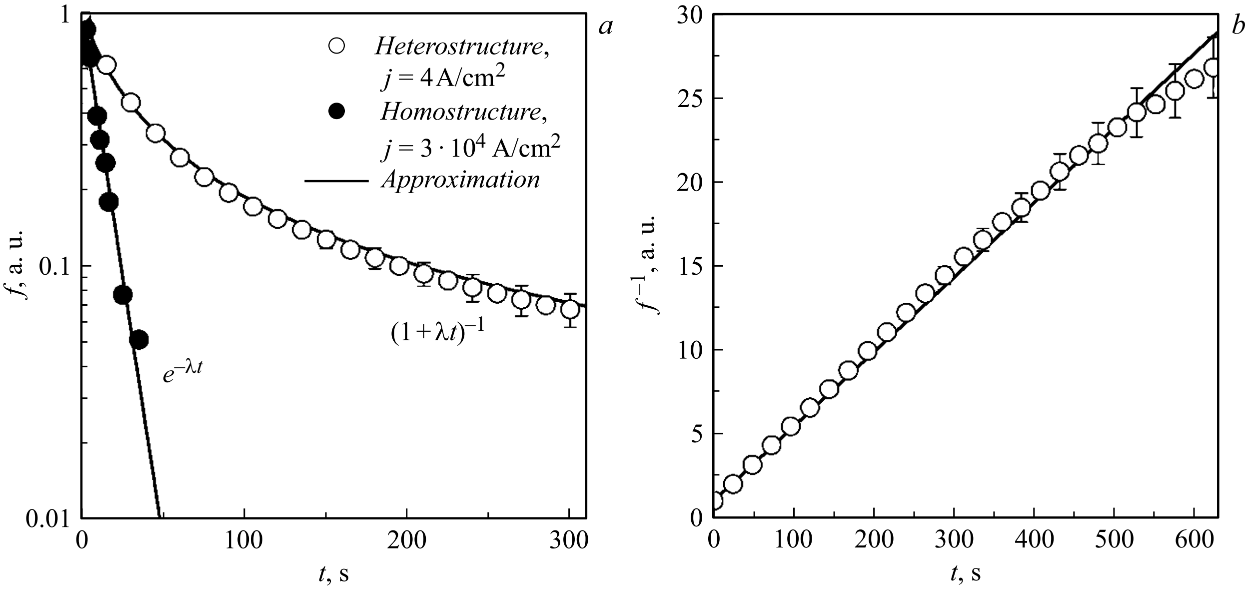

Figure 1. *a* — Comparison of the curves of injection-enhanced annealing of radiation-induced defects in a GaAs homostructure [6] and a GaAs/AlGaAs-based heterostructure in the $\ln f - t$ coordinates; *b* — injection-enhanced annealing curve for the GaAs/AlGaAs-based heterostructure in the $f^{-1} - t$ coordinates.

Figure 1, *a* presents the measurement results corresponding to the GaAs/AlGaAs heterostructure and literature data corresponding to the GaAs homostructure [6]. The samples were irradiated with approximately equal fluences of γ-quanta ($2.5 \cdot 10^{17}$ and $4 \cdot 10^{17}\,\text{cm}^{-2}$, respectively; the absorbed dose is 1.1 and 1.75 MGy). One may note that almost all radiation-induced defects were subject to IEA in both cases. However, in the case of homostructures, this result is observed only at relatively high current densities $j \approx 2 \cdot 10^2\,\text{A/cm}^2$ [7] and $j \approx 2 \cdot 10^4\,\text{A/cm}^2$ [6]. The current density for the studied heterostructures is 2–4 orders of magnitude lower ($4\,\text{A/cm}^2$). Note that current pulses $2\,\mu$s in width were used in [6] to reach the indicated high j values. In heterostructures with quantum wells, IEA may be performed at a constant current with a relatively low density, which makes it much easier to apply this phenomenon in practice.

The observed differences in current density at which all radiation-induced defects are annealed are probably related to restrictions on the size of the active region in heterostructures with a quantum well. A high density Δn of injected carriers may thus be obtained in a heterostructure at significantly lower current densities. For example, $\Delta n \approx 3 \cdot 10^{17}\,\text{cm}^{-3}$ [6] for a GaAs homostructure at 300 K and $j = 3 \cdot 10^4\,\text{A/cm}^2$. With Δn estimated as $\Delta n = j\tau/(de)$, a current density j on the order of $1\,\text{A/cm}^2$, which agrees with experimental data, is needed to achieve the same carrier density in the examined heterostructure. In the above formula, d is the quantum well width, τ is the minority carrier lifetime, and e is the electron charge. The values of $\tau = 10\,\text{ns}$ [14] and $d = 10\,\text{nm}$ were used to obtain an estimate.

Figure 1, *a* also reveals a qualitative difference in the kinetics of IEA of the homo- and heterostructures under consideration. According to [6,7], $f(t)$ for GaAs homostructures is linear in semilogarithmic coordinates; thus,

$$f = \exp(-\lambda t),$$

where λ is the IEA rate constant. In the case of GaAs/AlGaAs heterostructures, the $f(t)$ dependence in the same coordinates is significantly nonlinear. However, since this dependence remains linear in the $f^{-1} - t$ coordinates throughout almost the entire annealing process (Fig. 1, *b*), the kinetics is characterized by a hyperbolic dependence. This is indicative of a significant difference in the mechanisms of annihilation of radiation-induced defects in homo- and heterostructures.

In homostructures, exponential IEA kinetics is observed within a wide range of materials and for various doping impurities [6,8,9]. The same kinetics is typical of solar cells based on the GaInP/GaAs/Ge heterostructure [10]. However, lasers based on quantum-sized GaAs/AlGaAs heterostructures are characterized by IEA kinetics following a hyperbolic law. Therefore, it is fair to assume that the difference in IEA kinetics and, consequently, the mechanism of annihilation of radiation-induced defects is associated with a restriction on the size of the active region.

It should be noted that an energy exceeding slightly the threshold displacement one is transferred to GaAs atoms irradiated with ^{60}Co γ-quanta with an average energy of 1.25 MeV. In view of this, the primary radiation-induced defects are Frenkel pairs, and both annihilation due to the sinking of defects to dislocations and the decay of a complex consisting of an interstitial atom and a chemical impurity

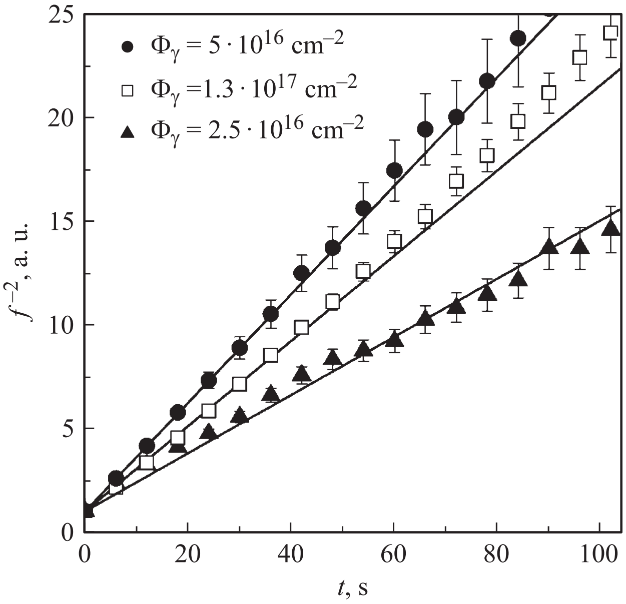

Figure 2. Curves of injection-enhanced annealing of radiation-induced defects in GaAs/AlGaAs heterostructures at fluence $\Phi_\gamma < 2.5\cdot10^{17}\,\mathrm{cm}^{-2}$ of γ-quanta.

with subsequent annihilation of the interstitial atom may be the reasons why exponential annealing kinetics is observed in homostructures [7]. In the case of heterostructures, the region in which recombination-enhanced migration of defects is possible is likely to be confined within the boundaries of a quantum well. Therefore, the observation of a hyperbolic dependence of the annealing kinetics instead of an exponential one may be associated with a reduction in the probability of interaction of radiation-induced defects with dislocations and the high chemical purity of an undoped quantum well.

Figure 2 presents the annealing kinetics of GaAs/AlGaAs heterostructures irradiated with fluence $\Phi_\gamma < 2.5\cdot10^{17}\,\mathrm{cm}^{-2}$ of γ-quanta. It was found that the annealing curve is linear in the f^{-2}–t coordinates (Fig. 2); i.e., annealing kinetics $f(t) \propto t^{-1/2}$. Thus, a transition from $f(t) \propto t^{-1}$ to $f(t) \propto t^{-1/2}$ occurs when the fluence of γ-quanta decreases. This result is consistent with theoretical data on the annihilation of correlated Frenkel pairs (see [15] and references therein). Therefore, the following conclusions may be made: IEA in heterostructures proceeds via direct recombination of Frenkel pairs; the change in annealing kinetics with a reduction in the fluence of γ-quanta is associated with an increase in the probability of annihilation of homologous Frenkel pairs.

A qualitative difference between the kinetics of IEA of radiation-induced defects in homo- and heterostructures based on GaAs was found at similar levels of exposure to ^{60}Co γ-quanta. In heterostructures, the law may change from $\propto t^{-1}$ to $\propto t^{-1/2}$ as the fluence of γ-quanta decreases. It was demonstrated that the current density at which all radiation-induced defects are annealed in heterostructures irradiated with γ-quanta is approximately 2–4 orders of magnitude lower than the corresponding current density in homostructures.

The observed differences are likely to be attributable to restrictions on the size of the active region and the specifics of its structure. This makes it much easier to produce high densities of injected carriers, reduces the size of the region in which recombination-enhanced migration of radiation-induced defects is possible, and confines these defects within a GaAs layer with high chemical purity.

On the one hand, the obtained results indicate that IEA is efficient in terms of enhancing the radiation hardness of heterostructures. On the other hand, the increased sensitivity of heterostructures to this effect makes it necessary to take it into account in radiation-hardness assurance. Notably, the results of experiments with homostructures should not be extended to modern optoelectronic and bipolar devices containing quantum-sized heterostructures.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin