INFLUENCE OF NEUTRON IRRADIATION ON REVERSE CURRENTS IN GALLIUM-PHOSPHIDE LIGHT-EMITTING DIODES

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The results of electrophysical researches of gallium-phosphide (GaP) light-emitting diodes (LEDs) irradiated with fast neutrons and annealed at various temperatures are reported. The deep levels of radiation-induced defects of $E_{t1} = 1.13$ eV and $E_{t2} = 1.17$ eV have been revealed. The stage of low-temperature annealing of defects within the temperature range 50–120 °C has been studied. A gradual recovery of luminescence, caused by the reconstruction of radiation-induced damages, was observed for specimens, which were irradiated and partially annealed first, and then kept at $T = 300$ K for a long time.

1. Introduction

Light sources based on LEDs, which are widely used in computers, novel communication facilities, control and diagnostic devices, as well as in household appliances, are simple enough, convenient in service, and economical owing to their diminutiveness, small power consumption, and low cost prices. At the same time, despite the considerable progress in the technology of the LED growing, the quantum yield of such emitters does not remain constant but monotonously decreases in the course of their exploitation [1, 2]. Especially challenging for all radiation sources is the problem of enhancing their radiation resistance.

The radiation resistance is low, to the same extent, for GaP, GaAsP, and AlGaAs structures [3, 4]. It is also known that the introduction of radiation-induced defects into such specimens is accompanied by the emergence of long-term relaxation processes [5]. Just the deep traps induced by radiation may turn out responsible for the reduction of the luminous efficacy of GaP-based LEDs [6, 7].

Radiation-induced damages actively influence the electric characteristics of diodes. The analysis of the radiation-induced changes in current-voltage characteristics (CVCs) makes it possible to obtain information concerning the depth of trap levels, to determine the limits of thermal stability of introduced defects, to obtain data which characterize the mechanisms of current flowing through a junction, and so on.

2. Experimental Part

In this work, we report the results of our researches of the commercial samples of GaP diodes subjected to irradiation with fast ($\bar{E} = 2$ MeV) neutrons produced by a reactor. The CVCs were measured by an automatic computer-assisted installation which operated in two modes — as a current or a voltage generator. The isochronous annealing was carried out with the period $t = 20$ min. The temperature dependences of the CVC were measured in the range 77—300 K. The maximal neutron flux was $\Phi = 10^{16}$ neutron/cm^2.

3. Results and Their Discussion

The total reverse current at $|V| = 3kT/q$ and $p_0 \gg n_0$ can be represented as a sum of the diffusion current in the neutral region and the generation current in the depletion one [8]:

$$I_R = \sqrt{\frac{D_p}{\tau_p}} \frac{q n_i^2}{N_D} + \frac{q n_i W}{\tau_e},$$

where W is the width of the depletion layer. The estimations carried out according to the relation

$$n_i = (N_C N_V)^{1/2} e^{-E_g/(2kT)}$$

show that the concentration of intrinsic current carriers in a wide-band-gap GaP is low even at room temperature, being close to unity. Therefore, the augend in the expression for I_S is small, so that the current of

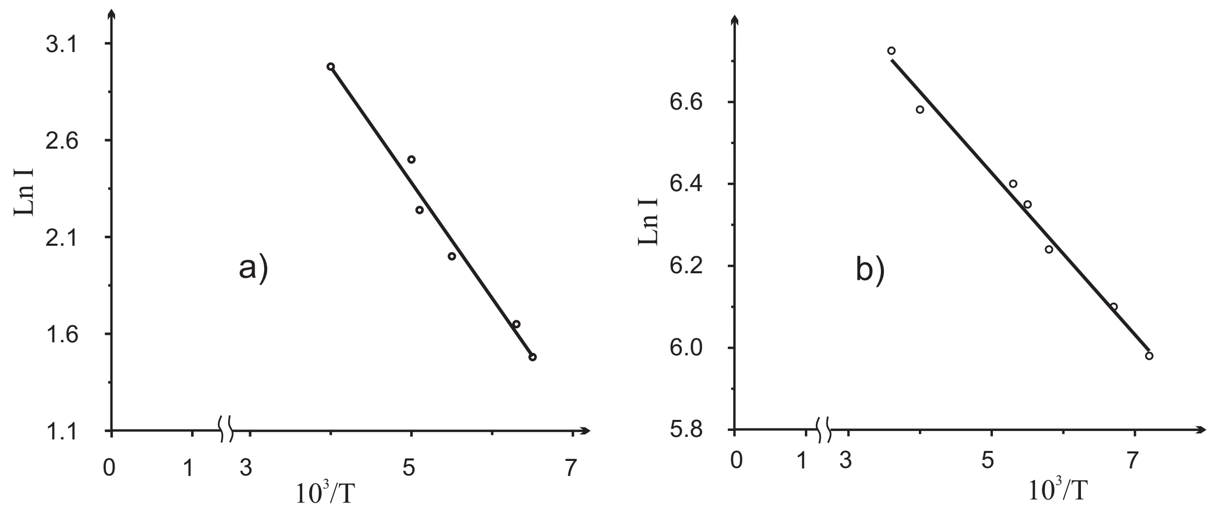

Fig. 1. Temperature dependences of the reverse current in green (a) and red (b) LEDs irradiated with neutrons to the dose $\Phi = 5 \times 10^{15}$ neutron/cm^2

the predominantly generation origin

$$I_{\text{gen}} = \int_0^W q|U|dx \approx q|U|W = \frac{qn_iW}{\tau_e},$$

where $|U|$ is the generation rate, runs through the p—n-junction. Making use of the expression for the current carrier lifetime τ_e with respect to a trap with the energy depth E_t [9],

$$\tau_e = \frac{\exp[(E_i - E_t)/(kT)]}{\sigma_p v_p N_t} = \tau_{p_0} e^{-E_t/(kT)},$$

we obtain

$$I_{\text{gen}} = \frac{qn_iW}{\tau_e} =$$

$$= \frac{qW(N_C N_V)^{1/2} e^{-E_g/(2kT)}}{\tau_{p_0} e^{-E_t/(kT)}} \Rightarrow A e^{(2E_t - E_g)/(2kT)},$$

where A is the multiplier, which depends weakly, in comparison with the following exponent, on the temperature; and N_C and N_V are the densities of states in the conduction and valence bands, respectively. Taking the logarithm, we obtain an expression for evaluating the energy depth of the trap level:

$$E_t = \frac{1}{2}\left[E_g + \frac{2k\Delta \ln I}{T_2^{-1} - T_1^{-1}}\right].$$

Our estimations, which used the data presented in Fig. 1, showed that the level depth is equal to $E_{t1} = 1.13$ eV in the case of green GaP:N diodes irradiated with neutrons to the dose $\Phi = 5 \times 10^{15}$ neutron/cm^2, and to $E_{t2} = 1.17$ eV in the case of red GaP:(Zn,O) diodes irradiated to the dose $\Phi = 10^{15}$ neutron/cm^2.

Therefore, in both cases, the levels of radiation-induced defects (RIDs) are deep. The annealing of neutron-irradiated diodes, in the course of which the magnitude of the reverse current was monitored, is illustrated in Fig. 2. It should be emphasized that it is rather difficult to obtain an integrated picture of the isochronous annealing of defects by monitoring a variation of the luminescence intensity as a function of temperature, because the optical transmittance of the lens material changes, while the diode is being heated.

The magnitude of the reverse current turned out more sensitive to the changes in the depletion region of the p—n-junction than the radiative recombination intensity. It is evident from Fig. 2,b that the annealing of irradiated specimens starts at a temperature of 50—70 °C; and, in the case of red GaP:(Zn,O) diodes, there appears a stage of negative annealing (up to 150 °C), which has not been detected earlier neither when annealing Hall specimens, nor when measuring optical spectra.

In the GaP:N specimens, the stage of negative annealing is absent. Most probably, such a difference is caused by the formation of impurity complexes RID+Zn or RID+O in a specimen heated up to 150 °C. Above this temperature, the stage of normal annealing begins, which is associated with the annealing of phosphorus vacancies (at 150—180 °C) and gallium ones (at 250—300 °C) [9,10]. One can see that, provided the irradiation

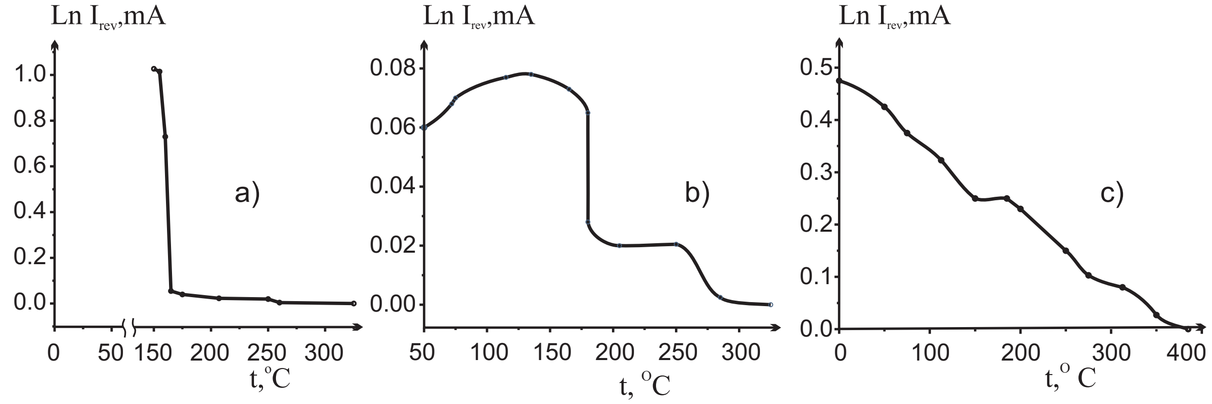

Fig. 2. Annealing of the diodes irradiated with neutrons: (*a*) GaP:(Zn,O), $\Phi = 5 \times 10^{15}$ neutron/cm^2; (*b*) GaP:(Zn,O), $\Phi = 5 \times 10^{14}$ neutron/cm^2; and (*c*) GaP:N, $\Phi = 5 \times 10^{14}$ neutron/cm^2

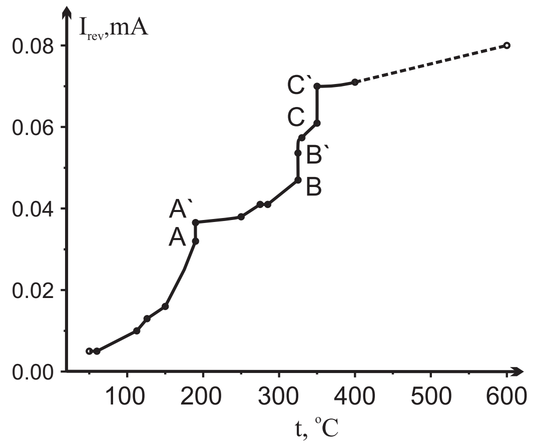

Fig. 3. Annealing of a GaP(Zn,O) diode irradiated to the dose $\Phi = 10^{16}$ neutron/cm^2. Measurements were carried out next day (A, A'), 2 weeks (B, B'), and 3 weeks (C, C') after irradiation

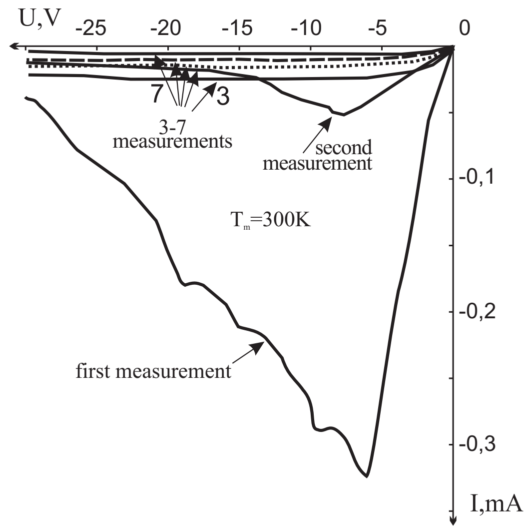

Fig. 4. Reverse CVC branches of a green GaP light-emitting diode, measured in succession one after another at $T = 300$ K

dose is lower than 5×10^{14} neutron/cm^2, those stages are well separated for a red diode and undistinguished for a green one irradiated to the same dose. The growth of the irradiation dose gives rise to the expansion of both stages, so that, at $\Phi = 5 \times 10^{15}$ neutron/cm^2, they can hardly be separated; both stages overlap, and the recovery process gets a monotonous character in the wide temperature interval 100—300 °C.

The annealing of a diode irradiated to the dose $\Phi = 10^{16}$ neutron/cm^2 reveals — besides the features indicated above — the existence of one more stage at temperatures above 450 °C, which is known to be related to the decay of the disordered regions in gallium phosphide [11]. In the specimens irradiated to a lower neutron dose, the stage of the annealing of disordered regions does not manifest itself owing to a low concentration of the latter (Fig. 3).

An important feature of the isochronous annealing of diodes irradiated to the dose $\Phi = 10^{16}$ neutron/cm^2 is a partial recovery of the reverse current, if the specimens are held at room temperature. In Fig. 3, points A and A' correspond to the reverse currents measured just after annealing (A) and on next day (A') (accordingly, points B, B' and C, C'). Figure 3 demonstrates that, if the annealing temperature grows and the time of specimen storage at 300 K becomes longer, the amplitude of the recovery jump increases. It is obvious that the high-temperature annealing is accompanied by long-term relaxation phenomena, which were discovered as early as in works [12,13] and which the large-scale traps for current carriers are responsible for.

In the case where the current passed through the diodes for the first time after their fabrication, in the negative-bias branches of the relevant CVCs measured in the voltage-generator mode, there appeared the characteristic N-shaped sections of negative differential resistance (NDR). In the vicinity of such an anomaly, the reverse current drastically increased first; then, at some reverse voltage, its absolute value became maximal; afterwards, its amplitude fell down as the negative bias continued to grow. A reduction of the specimen temperature from 300 to 77 K shifted such an N-section by tens of volts towards the negative voltage range.

If the diode was energized in the forward direction during the intervals between the measurements of the reverse CVC branches, the amplitude of the reverse current became reduced considerably, down to the complete disappearance of the anomaly (Fig. 4). Therefore, if the emergence of the NDR section in the negative-bias branch of the CVC can be attributed to the existence of initial, technologically induced defects which are concentrated, most probably, in the high-resistance depletion region of the p—n-junction, its total disappearance is obviously a result of the injection annealing mechanism.

For some diodes irradiated with neutrons and especially for those underwent the ultrasound treatment ($\nu = 1 \div 3$ MHz, $P = 1$ W/cm^2), a number of irregularities of the N-type emerged in the ordinary dependence of the saturation current on the reverse voltage at $T = 77$ K, in addition to the deviations described above. From Fig. 5, one can see that, as the annealing temperature of a specimen $T_{\rm ann}$ grew, these irregularities became shifted along the CVC towards larger negative voltages. For every specimen, for which we managed to register such anomalies, the latter remained well reproducible at repeated measurements, surviving at least up to 130 °C.

The revealed deviations from the classical dependences $I(V)$ constitute only preliminary results. The elucidation of the nature of corresponding defects demands additional researches. Now, we may only point out that the mechanism of formation of the N-shaped NDR sections of two types considered above can be based on the tunneling of current carriers to the region of deep quantum wells formed by either the initial technological defects (defects of the first type) or the acoustically induced defects (defects of the second type). Changing the position of the N-section with temperature can be a consequence of the temperature shift of the band edges with respect to the level of tunneling in the quantum well; the shift of the N-section towards negative voltages at isochronous annealings can be caused by the modification of the energy configuration

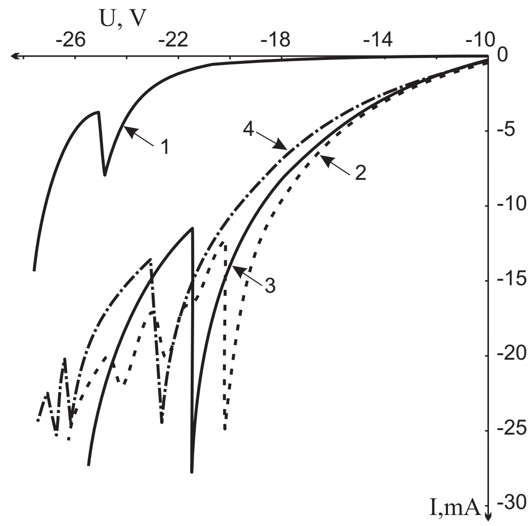

Fig. 5. Reverse CVC branches of a GaP:(Zn,O) diode for various annealing temperatures $T_{\rm ann}$: initial specimen (*1*), $T_{\rm ann} = 80$ (*2*), 110 (*3*), and 130 °C (*4*)

of defects in the quantum well and by the corresponding redistribution of fluxes of tunneling carriers.

4. Conclusions

Neutron irradiation of light-emitting diodes has been demonstrated to bring about the emergence of deep levels with $E_{t1} = 1.13$ eV and $E_{t2} = 1.17$ eV. A stage of the low-temperature annealing of radiation-induced defects has been found within the temperature interval 50—120 °C. Provided that the specimens, irradiated and partially annealed, had been kept at $T = 300$ K for a rather prolonged time interval, their luminescence recovery caused by the reconstruction of radiation-induced damages was observed. The emergence of the N-shaped sections of negative differential resistance in the CVC may be a consequence of the existence of the aggregations of defects of the quantum-well type in the specimen and the tunneling of current carriers onto the levels belonging to those defects.

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ВПЛИВ НЕЙТРОННОГО ОПРОМІНЕННЯ НА ЗВОРОТНІ СТРУМИ ФОСФІДО-ГАЛІЄВИХ СВІТЛОДІОДІВ

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Р е з ю м е

Наведено результати електрофізичних досліджень фосфідо-галієвих світлодіодів, опромінених швидкими нейтронами при різних температурах. Було виявлено глибокі рівні радіаційних дефектів (E_{t1}=1,13 еВ, E_{t2}=1,17 еВ). Досліджено стадію низькотемпературного відпалу радіаційних дефектів при температурах 50 — 120 °C. У процесі тривалого зберігання при T=300 К опромінених і частково відпалених зразків спостерігається поступове відновлення свічення, зумовлене перебудовою радіаційних пошкоджень.