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Degradation of voltage-current characteristics of gallium phosphide diodes due to radiation-induced defects

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The GaP diode radiation-induced degradation has been established to be caused mainly by the reduction of the current carrier lifetime resulting from introduction of non-radiative deep levels of the radiation-induced defects. A thin structure has been revealed in the voltage-current characteristics (VAC) at temperatures lower than 90 K. The existence of oscillations are associated with the capturing of non-equilibrium current carriers by traps followed by thermal destruction thereof. A characteristic VAC feature of the neutron-irradiated samples is the occurrence of an N-like of negative differential resistance. This deviation from the VAC monotonicity is explained by thermally-induced transformations of the disorder areas.

Установлено, что главной причиной радиационной деградации GaP-диодов является уменьшение времени жизни носителей тока в результате введения безызлучательных глубоких уровней радиационных эффектов. Выявлено тонкую структуру вольт-амперной характеристики (ВАХ) диодов в области температур ниже 90 К. Существование осцилляций связывается с захватом неравновесных носителей тока ловушками и их последующим термическим опустошением. Характерной особенностью ВАХ образцов, облученных нейтронами, есть возникновение N-образного участка отрицательного дифференциального сопротивления. Наличие таких отклонений от монотонности ВАХ объясняется термическими преобразованиями областей разупорядочення.

The wide-band gallium phosphide is among few binary compounds that are used effectively in optoelectronics as direct electricity-to-light energy converters. The main advantages of the GaP emitters include the visible region emission, the simple spectral composition variation by doping with the green (N) or red (ZnO) band activators, the possibility to regulate smoothly the free carrier concentration, the relatively low preparation temperature of the single-crystal epitaxial films (1050 to 1180°) [1, 2]. As the quantum yield of the light emitting diodes (LED) is increased, the application field thereof is widened continuously from the multicolor state indicators to large-size flat display screens. Almost all the devices mentioned can be used under strong radiation field action. Some types of the solid-state light sources of good promise can be prepared using the modern doping techniques and the desired profile construction within a crystal volume basing on the use of accelerated particle beams.

Therefore, the purpose of this work is to provide information on the influence of radiation-induced damage on the electrooptical properties of p-n junctions in gallium phosphide and to reveal the main factors causing the degradation thereof. The diode GaP structures were studied grown by the double liquid epitaxy technique and doped

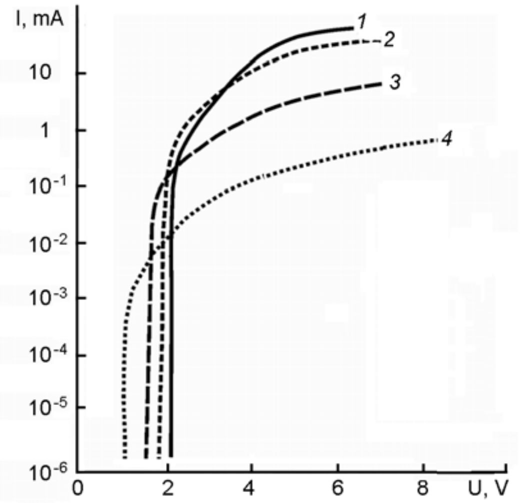

Fig. 1. VAC initial sections of GaP LED: initial (*1*) and $E = 1$ MeV electron irradiated at integral electron flows (cm^{-2}): $1.5{\cdot}10^{16}$ (*2*), $4.5{\cdot}10^{16}$ (*3*), $1.5{\cdot}10^{17}$ (*4*).

with Zn and O (red, p-area) and N (green, n-area). The voltage-current characteristics (VACs) were measured in the 77 to 300 K temperature range in the current generator and voltage generator modes using a setup comprising a high-stability current source and a precision combined measuring device. The VAC region where the diode passes to the low-resistance state was studied in detail. To that end, a current pulse generator was used allowing to vary the current across the p-n junction at 1 mA steps, thus making it possible to reveal a thin structure of VAC in the NDR region. For each VAC point, the measurements were done during one pulse of 20 to 100 ms duration.

It is known that the introduction of radiation defects into the base area of a *p–n* structure is accompanied by trapping of the free charge carriers at the deep levels of radiation defects and by the mobility reduction thereof. Simultaneously with the base material conductance reduction, the potential barrier height of the *p–n* junction is reduced.The dependence of the total voltage drop across the diode, U, on the irradiation dose, Φ, shows a minimum [3]. The current across the p-n junction being constant, the voltage on the diode is first reduced during the irradiation, and then, after passing the minimum, increases at high doses due to increasing base resistance. In [4], the influence of deep levels on the current flowing across a p-n junction has been considered in detail and an expression has been obtained for the differential variation of the voltage across the diode as a function of the irradiation dose. The current I_0 across the p-n junction has been found to decrease at zero rate of the radiation-induced voltage variation, as the dose Φ increases. Thus, the intersection point of VACs for the initial diode and irradiated ones should "slide down" along the current axis. We have proved the latter conclusion for gallium phosphide diodes.

Electrons with $E = 1$ MeV were used to introduce the point defects. Fig. 1 shows the VAC for the initial diode and for that irradiated by various integral electron flows (Φ varying from $2.65{\cdot}10^{14}$ to $1{\cdot}10^{15}$ cm^{-2}). The $I(U)$ dependence in the area of currents not limited by the base resistance is seen to be exponential. In this case, $m = 2$, thus evidencing the predominating recombination component of the forward current. The irradiation dose increase causes an increase of the forward currents at small biases and that of the diode differential resistance at high voltages ($U > 2–3$ V). As the dose increases, the VAC intersection point for the unirradiated and irradiated sample goes down to the area of lower currents and voltages.

The good agreement between the calculated results with the experimental data confirms obviously the validity of a GaP *p–n* structure model where the degradation of the electric characteristics under irradiation must be due mainly to the charge carrier lifetime reduction. The main feature of the GaP diode VACs taken in the current and voltage stabilization modes consists in the existence of negative differential resistance sections of the *S* and *N* types in the temperature range near the liquid nitrogen one. Such deviations from monotonicity are known to arise in the $I(U)$ dependences as a result of the additional positive feedback between the device input and output. In radio engineering devices, such as a non-damping oscillator, the positive feedback is provided by an external link. In contrast, it is internal in the solid state device where it it realized due to the base conductance modulation by the injected carriers [5, 6]. The transition to the negative resistance may be realized in various mechanisms. In [7–9], it is shown that the most probable cause of the *S*-section NDR existence in GaP diode structures at 77 K consists in the presence of deep levels associated with the oxygen impurity and the diode heating due to a high current running through the *p–n* junction.

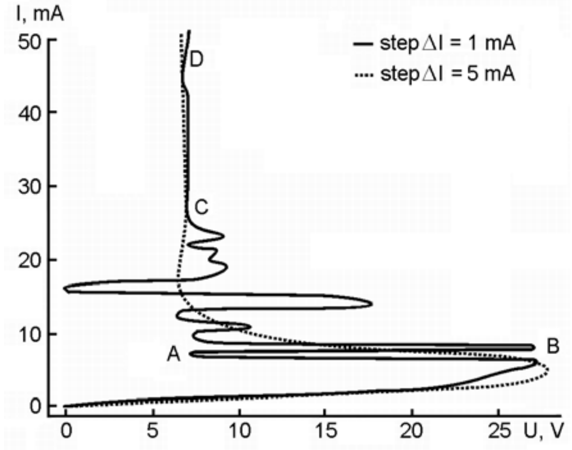

Fig. 2. VAC of a GaP LED at T = 77 K taken at the current change step of 1 mA and 5 mA.

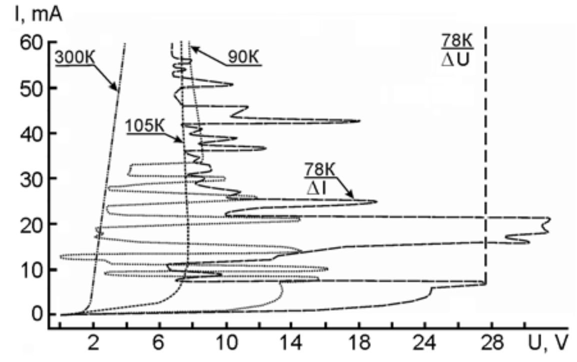

Fig. 3. VACs of GaP:N LED irradiated with neutrons at different temperatures.

Fig. 2 shows the VAC of a green diode at T = 77 K, the current through the p–n junction being set at $\Delta I > 1$ mA and $\Delta I =$ 1 mA. At the step of 5 mA, the $I(U)$ is smooth and similar to the VAC presented in [8]. But when the current increase step is decreased down to 1 mA, oscillations are appeared in the VAC instead of the smooth NDR section. If the curve taken at $\Delta I = 1$ mA is averaged within the oscillation zone, the VAC becomes identical to that at $\Delta I =$ 5mA. As the temperature decreases starting from $T \approx 110$ K, the GaP diodes show a transition into the negative differential resistance (NDR) state.

It is obvious that the NDR existence in the GaP diode VAC evidences the presence of recombination levels in the depleted area of the p–n junction, these levels defining the minor carrier lifetime. The diode transition into the low-resistance state within limits of one oscillation (Fig. 2, point A) is due to filling of those levels as the forward current increases. This rather high current causes instantly the diode heating followed by emptying of the recombination levels and return of the diode to the initial state (Fig. 2, point B). Increase of the current (the injection level increase) provides a multiple repetition of the process. The oscillation stop when the amount of the injected carriers exceeds considerably the number of the existing recombination levels. In fact, as the current is increased, e.g., up to I = 25 mA, the number of introduced carriers is so large as compared to that of recombination centers that the change in the filling thereof cannot already effect substantially the current carrier lifetime, τ_0 takes an unlimited large value and the current increases sharply, almost vertically (Fig. 2, the CD section).

Irradiation by ^{60}Co γ-quanta results in a vertical extension of the VAC oscillation area that is associated directly with the increased recombination center concentration in the device. Such levels are known to be generated in GaP by V_P, V_{Ga}, and combinations thereof [10]. It is to note also that the VACs of red GaP(Zn:O) diodes differ from those of green ones by a considerably smaller oscillation amplitude. That difference evidences obviously a lower concentration of initial defects in the "green" structure as compared to the "red" ones.

The samples irradiated with neutrons (E = 2 MeV, $\Phi = 2.65 \cdot 10^{14}$ cm^{-2}) show a N-like NDR area along with that of S type. The N-area exists only when the measuring setup is operated in the voltage generator mode. The ΔU pulse application time exceeds that of the ΔI one. It is seen in Fig. 3 that in VAC where the power $I(U)$ dependence predominates, a specific irregularity is observed as a sharp current increase (point N) followed by its sharp drop. Superposing the VACs taken at different modes (current and voltage), it is possible to observe the oscillation areas. The dependences are reproduced at a sufficient precision even at the current or voltage increase followed by decrease thereof. In [7], where deep levels in neutron irradiated GaP samples have been studied, it has been found that the wide non-structured area in spectrum of deep levels non-stationary spectroscopy is due to the presence of disordered areas in the diode.

The absence of the N-like NDR section in initial homogeneous GAP diodes and in the samples irradiated by ^{60}Co γ-quanta allows to state that such an anomaly is due to defects specific for the neutron irradiation, namely, to disorder areas (DA). The sharp current increase within the VAC N-like anomaly may be due to heating of the DA peripheral areas and thermal emission of an additional charge carriers. Its subsequent decrease is a result of the increasing concentration of the scattering centers (ionized traps) as well as of the carrier absorption by large-scale potential wells associated genetically with the DA. The possibility of such a process was considered in [8]. The absence of the sharp increase section in the VAC within the N-like anomaly area at the current generator mode is a result of slow current pulse formation during the time τ_i as compared to the voltage pulse formation time τ_u. As τ_i is longer than τ_u, the thermally generated carriers have time to be trapped by the above-mentioned potential wells so that the oscillation processes will not be revealed.

Thus, it has been shown that the GaP diode irradiation with $E = 1$ MeV electrons must result in a decreased differential resistance in the low current area and its increase at high currents. The calculation results agree well with experimental data obtained at epitaxial GaP p–n structures. The radiation-induced degradation of GaP diodes is caused mainly by shortening of the current carrier lifetime due to introduction of deep levels of radiation defects. A thin structure has been revealed in the diode VAC at temperatures lower than 90 K. The oscillations are ascribed to trapping of the non-equilibrium current carriers by the traps followed by emptying thereof due to heat release. A specific feature of the neutron irradiated samples consists in the presence of an N-like section of negative differential resistance in the VAC. This deviation from the $I(U)$ monotonicity may be caused by increased heat release in the peripheral DA areas due to thermal ionization of the traps localized near those defects as well as to the possible trapping of the non-equilibrium current carriers by the large-scale potential wells of the technological and radiation origin.

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Деградація вольт-амперних характеристик фосфідо-галієвих діодів, що обумовлена радіаційними дефектами

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Встановлено, що головна причина радіаційної деградації GaP-діодів — зменшення часу життя носіїв струму в результаті уведення безвипромінювальних глибоких рівнів радіаційних дефектів. Виявлено тонку структуру вольт-амперних характеристик (ВАХ) діодів в області температур нижче 90 К. Існування осциляцій пов'язується із захватом нерівноважних носіїв струму пастками та їх наступним термічним спустошенням. Характерною особливістю ВАХ зразків, опромінених нейтронами, є виникнення N-подібної ділянки від'ємного диференціального опору. Існування цього відхилення від монотонності ВАХ пояснюється термічними перетвореннями областей розупорядкування.