RADIATION DEFECTS IN GaP, GaAsP, InGaN LEDs

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Abstract. The results of the effect of irradiation by electrons with $E = 2 \text{ MeV}$, $F = 2.6 \cdot 10^{16} \text{ cm}^{-2}$ on LEDs grown on the basis of GaP and GaAsP homojunctions, as well as on InGaN/GaN heterojunction structures with quantum wells are presented. The consequences of irradiation with γ -quanta from Co^{60} from an absorbed dose of 1.5 Mrad are analyzed. It is revealed that the introduction of radiation defects is accompanied by a decrease in the glow intensity due to the capture of charge carriers by deep levels of defects, an increase in the differential resistance, and a decrease in the reverse currents of p-n junctions. Isochronism annealing of irradiated samples is multistage and proceeds within the range ($20 \div 300^\circ\text{C}$, for GaP LEDs) and ($20 \div 450^\circ\text{C}$, for GaAsP LEDs). The maximum quantum output of InGaN LEDs has been 32 %, irradiated with $\gamma\text{-Co}^{60}$ with an absorbed dose of 1.5 Mrad – 17 %.

Key words: Current-voltage characteristics (CVCs), light emitting diode (LED), negative differential resistance (NDR), radiation defects.

1. INTRODUCTION

LED light sources have now taken their rightful place both in the most modern computing and communication systems and in everyday life. Possessing undoubted advantages over emitters of previous generations, light-emitting diodes (LEDs) quickly ousted them from optical communication networks, storage systems, processing, and display of information.

In addition to low cost, significant mechanical strength, and long service life, LEDs stand out among other sources with high efficiency, low inertia, and a narrow luminescence spectrum; the coefficient of conversion of electrical energy into light energy of specific products is close to unity [1].

It is also worth noting that photons are neutral particles that do not interact with electromagnetic fields, as a result of which optical communication lines do not react to external obstacles and provide a wide range of operating frequencies (up to 1 GHz). This makes it possible to simultaneously transmit 1010 telephone conversations or 106 TV programs with one cable. Refusal of means of shielding of on-board equipment gives winning by mass by 3-5 times.

The optical cable does not radiate into the surrounding area, which is important for maintaining the confidentiality of communication. Replacing non-ferrous metals with glass, quartz, polymers gives a tangible economic effect [2, 3]. Diodes with negative differential resistance (NDR), which include LEDs

based on GaP, GaAsP, and InGaN, are distinguished by wide functionality and high efficiency [4]. Investigation of the mechanisms underlying the emergence of such sections of current-voltage characteristics (CVCs) contributes to the establishment of the general prerequisites for their formation in solid-state objects and the further use of such devices.

The use of permeable radiation makes it possible to change the characteristics of materials and devices in a directed manner - to increase the speed of the elements of microelectronic technology by reducing the lifetime of minority charge carriers, to create n -layers and superlattices, to reduce the voltage level in heterostructures, to reduce the flow currents, etc. [5-9].

Determination of the coefficients of their radiation resistance is also an urgent task. In addition, LEDs based on GaP and GaAsP, as relatively simple structures, can be used as model objects for studying the effect of radiation on the processes of charge transfer in samples with p-n junction and radiative recombination. In recent years, the number of works devoted to the technology of growing and researching the latest high-performance LED nanostructures with quantum wells has been rapidly increasing; what has been said especially concerns InGaN diodes [10-18].

The main goal of our work was to reveal the effect of radiation on the optical and electrophysical characteristics of LED structures of GaP, GaAsP, and InGaN and to determine the regions of thermal stability of introduced damages, which affect the CVCs of diodes.

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2. THE EXPERIMENT

Commercial red and green GaP LEDs, the emission regions of which were filled with Zn, O, and N - respectively, with electron concentrations $\sim 2 \cdot 10^{17} \text{ cm}^{-3}$, $(4 \div 5) \cdot 10^{16} \text{ cm}^{-3}$ - holes were studied. The GaP substrate was grown by the Czochralski method with a carrier concentration of $(5 \div 7) \cdot 10^{16} \text{ cm}^{-3}$. The sample size is 1 mm^2 . LEDs grown on the basis of $\text{GaAs}_{1-x}\text{P}_x$ solid solutions belonged to yellow ($x = 0.85$) and orange ($x = 0.45$) diodes. Blue diodes with quantum wells (QWs) were obtained on the basis of the InGaN solid solution.

Irradiation by electrons with $E = 2 \text{ MeV}$, $F = 3 \cdot 10^{14} \div 2,6 \cdot 10^{16} \text{ cm}^{-2}$ took place in a pulsed mode on a pulsed plasma accelerator (IPP-6) with an electron beam current $I = 4 \text{ mA}$ and γ -quanta of Co^{60} absorbed dose 1.5 Mrad at room temperature.

Electroluminescence spectra were obtained using a system assembled on the basis of an MDR spectrometer; the CVCs were measured by an automated device in the modes of a voltage generator and a current generator in the range of $77 \div 300 \text{ K}$ under conditions of pulsed diode power supply.

Isochronous annealing of the irradiated samples was carried out with a period of 20 min.

3. RESULTS AND DISCUSSION

It was found that irradiation electrons with $E = 2 \text{ MeV}$, of all three groups of LEDs, leads to a monotonic decrease in the intensity of their luminescence; in this case, the damage factor of the carrier lifetime for GaP LEDs is $k_t^{\text{GaP}} = 10^{-7} \text{ cm}^2 \text{ s}^{-1}$.

In the case of GaP diodes, the destructive effect of radiation is due to the destruction by the fields of radiation defects of excitons bound to the isoelectronic impurity N or to Zn-O vapors, as well as the introduction of irradiation of deep nonradiative levels into the bandgap of the crystal [19].

On the CVCs of all three groups of LEDs at low temperatures ($90 \div 70 \text{ K}$), regions of negative differential resistance (HDR) of the S-type appear; GaP diodes also have N-type HDR (Fig. 1).

S-type regions are typical for systems with positive feedback, in which when a certain breakdown voltage U_b is reached, the current value rises rapidly. Therefore, to build the CVCs, it is necessary to limit current using the current generator mode. With a sufficient discreteness level, the experimental points form an S-shaped curve, the main feature of which is the existence of a section with a negative slope - a section of NDR (Fig. 1).

The appearance of S-similarity in GaP LEDs caused by the peculiarities of the C-band structure; the formation of the N-region is associated with the tunneling transitions of carriers band-defect-band [20].

At the significant reverse voltages ($U_{\text{rev}} = 15 \div 20 \text{ V}$), an avalanche-like increase in current is observed on the CVCs of GaP diodes, which is characteristic of the breakdown of the p - n -structure; an increase in the sample temperature decreases the

breakdown voltage, indicating the predominance of the tunneling mechanism of breakdown.

Figure 1. CVCs of LEDs were taken at different temperatures in the current generator mode: *a* – GaP (1 – 300, 2 – 245, 3 – 180, 4 – 135, 5 – 95, 6 – 77 K); *b* – GaAsP (1 – 300, 2 – 250, 3 – 200, 4 – 160, 5 – 145, 6 – 125, 7 – 77 K); *c* – InGaN (1 – 300, 2 – 230, 3 – 180, 4 – 150, 5 – 130, 6 – 95, 7 – 77 K). The inset to Fig. 1 (a) shows a section of the characteristic taken at a temperature of 77 K in the voltage generator mode, which makes it possible to detect the existence of a section of N-type negative resistance on it.

Irradiation also leads to an increase in the differential resistance of the diodes and, in most cases, a decrease in reverse currents. A decrease in the reverse currents can be a consequence of a drop in the value of the flow currents caused by a change in the charge state of surface defects and the rate of surface recombination [5].

The value of the nonideality coefficient of the GaP LED is in the range $n = 1.6 \div 1.7$, which indicates the main role of the tunneling-recombination component of the full current.

The restoration of the electrophysical characteristics of the irradiated diode can be traced by monitoring the change in voltage on the CVCs as a function of the isochronous annealing temperature at a fixed value of the current through the sample.

Fig. 2 shows that the $U(T_{\text{anneal}})$ curve can be divided into stages $20 \div 100$ °C and $160 \div 300$ °C.

Figure 2. Dependence of the voltage drop across the irradiated diode GaP:N ($E_e = 2$ MeV, $F = 2.2 \cdot 10^{16}$ cm $^{-2}$, $T = 300$ K) on the annealing temperature at constant current $I = 6 \cdot 10^{-2}$ A: 1 - current generator mode; 2 - voltage generator mode.

The emergence of the first stage can be interpreted as a process of decay of unstable defect formations localized near large-scale structural disturbances, such as dislocations or dislocation networks. Annealing in the range of $150 \div 350$ °C, where the diffuse fluxes V_P and V_{Ga} coincide [21], are the main ones in terms of the scale of restoration of the CVCs of the irradiated samples. A decrease in the breakdown voltage after $T_{\text{anneal}} = 300$ °C (Fig. 3) is a direct consequence of an increase in the carrier concentration in the base of the diode during its high-temperature annealing.

The decisive advantage of LEDs based on GaAs $_{1-x}$ P $_x$ solid solution is the possibility of reducing the emitting lifetime of carriers by changing the composition: an increase in the percentage contribution of As relative to P brings the solution closer to direct-gap GaAs, increasing the probability of radiative transitions.

Doping of the isoelectronic impurity with N further enhances the effect of the "band structure effect" on recombination, and upon reaching $x \approx 50\%$, when the extrema of the C - and V -bands are equalized, the intensity becomes maximum [22].

Figure 3. Dependence of the breakdown voltage of the irradiated diode GaP:Zn,O ($E = 2$ MeV, $F = 8 \cdot 10^{16}$ cm $^{-2}$, $T = 300$ K) on the annealing temperature.

It has been found that irradiation with fast electrons with $E = 2$ MeV, the emission intensity of GaAsP LEDs monotonically decreases as a result of the introduction of deep nonradiative levels of radiation defects into the sample. The broadening of the spectral lines is also observed due to the influence of the defect fields.

Fig. 4 shows the dependence of the luminescence intensity of GaAsP LEDs on the injection current for the original and irradiated with electrons ($E = 2$ MeV, $F = 3 \cdot 10^{14}$ cm $^{-2}$ and $F = 5.9 \cdot 10^{14}$ cm $^{-2}$).

Figure 4. Dependence of the luminescence intensity of the original (1) and irradiated by electrons with $E = 2$ MeV, $F = 3 \cdot 10^{14}$ cm $^{-2}$ (2) and $F = 5.9 \cdot 10^{14}$ cm $^{-2}$ (3) yellow LED GaAsP on the excitation current at $T = 300$ K.

At high currents ($I > 0.06$ A), the process of saturation of the recombinant channel obviously begins to influence the heating of the sample.

The damage coefficient of the lifetime of minority charge carriers K_τ , determined from the dose dependence of the glow intensity of the GaAsP LED, is

$K_r = 1.2 \cdot 10^{-10} \text{ cm}^2 \text{ s}^{-1}$. It has been also revealed that the radiative component of the current of the original and irradiated by electrons with $E = 2 \text{ MeV}$, $F = 5.7 \cdot 10^{17} \text{ cm}^{-2}$ of the diode is controlled by diffusion (nonideality coefficient equal to 1.045).

The restoration of the electrophysical characteristics during isochronous annealing is shown in Fig. 5

Figure 5. CVCs of an orange GaAsP LEDs, measured in the mode of a current generator at $T = 77 \text{ K}$: 1 - original; 2 - irradiated by electrons ($E = 2 \text{ MeV}$, $F = 5.7 \cdot 10^{15} \text{ cm}^{-2}$) after annealing: 3 - $50 \text{ }^\circ\text{C}$; 4 - $90 \text{ }^\circ\text{C}$; 5 - $120 \text{ }^\circ\text{C}$

The main feature of the CVCs, as can be seen from Fig. 5, is the existence of the NDR region, the nature of which for GaP diodes was discussed in [20]. In the samples under study, its occurrence is obviously associated with the presence of GaP in the GaAsP solution. The size of the NDR, equal to $\sim 540 \Omega$, practically does not change upon annealing of the samples, which may indicate the thermal stability of the mechanism of its formation.

The position of the transition point from the positive differential resistance in the NDR (point A) is the limit, after which a sharp increase in current is observed on the CVCs measured in the voltage generator mode (Fig. 5) (breakpoint). It changes during annealing and reflects its character. It can be seen (Fig. 5, inset) that almost complete restoration of the CVCs of the diode occurs in the range $20 \div 120 \text{ }^\circ\text{C}$, coinciding with the stage of V_P annealing in GaP [21].

InGaN LEDs are characterized by high efficiency due to the possibility of accumulation of current carriers in quantum wells; the probability of nonradiative recombination decreases. The internal quantum yield of such structures can approach 90% due to their direct-gap; by changing the QW width, it is possible to obtain sources with different radiation wavelengths, creating conditions for obtaining a "white" glow.

We have been studying the blue LEDs, the spectra of which are shown in (Fig. 6).

In the samples under study, the temperature shift of the maximum radiation intensity, as can be seen

from (Fig. 6), falls within the measurement error, which indicates the temperature independence of the degree of filling of the dimensional quantization levels of the active region of the LED within $77 \div 300 \text{ K}$.

Figure 6. Emission spectra of the LED InGaN, obtained at a constant current $I = 24 \text{ mA}$ and at different T : 1 - 300 K ; 2 - 230 K ; 3 - 170 K ; 4 - 150 K ; 5 - 130 K ; 6 - 77 K .

The influence of temperature on the value of $I_{\max}$ is sufficient non-trivial, up to $T = 250 \text{ K}$, the maximum glow intensity increases; after passing through the maximum at $T = 250 \text{ K}$, it decreases (Fig. 7).

Figure 7. Dependence of the luminescence intensity of the InGaN LEDs on the temperature of the irradiated sample: 1 - original; 2 - irradiated with γ -quanta of Co^{60} , absorbed dose 1.5 Mrad

The absence of a temperature shift of the maximum of the main spectral band and the nature of the change in its value should obviously indicate the participation of only one optically active level of quantum wells in the process of radiative recombination up to $T_{\max} = 250 \text{ }^\circ\text{C}$ and the activation of a nonradiative center at $T > T_{\max}$.

The shape of the spectral curve $I(\lambda)$ can be used to estimate the temperature of the carriers and the

activation energy of the luminescence process; at $T_{\text{sample}} = 230 \text{ K}$ and 300 K ; the corresponding values turned out to be equal $T_{e^{230 \text{ K}}} = 653 \text{ K}$; $T_{e^{300 \text{ K}}} = 651 \text{ K}$; $E_{a^{230 \text{ K}}} = E_{a^{300 \text{ K}}} = 0.08 \text{ eV}$.

The value of the quantum yield of the diodes under study is significantly higher than that of similar samples based on homojunctions. If, for example, for GaP $Q_{\text{max}} < 1 \%$; for GaAsP $Q_{\text{max}} \sim 1 \%$; then for the InGaN LEDs we used, the maximum external quantum efficiency is 35 % (Fig. 8).

Figure 8. Dependence of the quantum yield of the InGaN diode on the injection current. 1 - original LED, 2 - irradiated with γ -quanta of Co^{60} ; absorbed dose 1.5 Mrad.

The decrease in the value of Q with increasing current through the diode (Fig. 8) can be considered as a result of a change in the population of the upper levels of the quantum wells upon heating the sample. In an irradiated diode, the thermal effect is weaker in comparison; the reason for this may be the redistribution of charge carriers between the levels of quantum wells and deep nonradiative levels of radiation defects in favor of the latter.

4. CONCLUSION

The introduction of radiation defects into LEDs of GaP and GaAsP is accompanied by an increase in their differential resistance, a decrease in the reverse current, and a drop in the luminescence intensity due to the introduction of deep levels in the bandgap of crystals.

The restoration of the electrophysical characteristics of GaP, GaAsP diodes upon isochronous annealing is multistage and covers the intervals ($20 \div 300 \text{ }^\circ\text{C}$) (GaP) and ($20 \div 450 \text{ }^\circ\text{C}$) (GaAsP), during which the diffusion fluxes of point defects V_p and V_{Ga} are superimposed. The reason for the decrease in the quantum yield of InGaN LEDs after $I = 0.002 \text{ A}$ may be the thermal depletion of the upper levels of the quantum wells. The introduction of deep traps by radiation defects contributes to an additional decrease in the population of these levels and manifests itself as radiation degradation, which accordingly flattens the

dependence of the quantum efficiency on the current flowing through the diode.

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