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Field effects in electron-irradiated GaP LEDs

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Abstract. The paper presents the results of the study of field effects in non-irradiated and irradiated by electrons ($E = 2$ MeV, $F = 8.2 \cdot 10^{16}$ cm^{-2}) gallium phosphide (GaP) light emitting diodes (LEDs) under reverse bias. The avalanche multiplication of charge carriers and tunneling breakdown in the space charge region has been considered. An increase of breakdown voltage after electron irradiation has been revealed. The effects of the annealing of non-irradiated and irradiated diodes in the temperature range of 20 to 500 °C have been analyzed.

Keywords: GaP, LED, field effects, electron irradiation, current-voltage characteristics.

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1. Introduction

Commercial production and large-scale studies of the properties of gallium phosphide structures began in the early 70s of the last century. However, a professional interest to these structures still remains invariably high due to almost all the types of radiative recombination observed in them, from exciton to donor-acceptor one. There is a steady tendency to expand the area of the practical application of both GaP single crystals and *p-n* junctions based on them [1–7].

As evidenced by the results of the work [1], frequency mixing can be realized using GaP structures, and growth of modern active nanostructured elements for photonics becomes possible. This is achieved due to the high thermal conductivity of GaP, its minimum nonlinear absorption and the large band gap value ($E_g^{300°K} = 2.26$ eV), which provides a wide transparency window (from 550 µm to the IR region).

The authors of [2] report on the possibility of obtaining direct-gap GaP–$Al_{0.4}Ga_{0.6}P$ nanowires with wurtzite crystal structure and a short carrier lifetime ($\tau = 0.78$ ns) as compared to the typical value for GaP ($\tau = 254$ ns). Incorporation of Al and As in such nanowires allows to shift the radiation wavelengths to 555…690 nm.

It was shown in [3] that formation of a relief on the surface of indirect-gap GaP using metallic (Au, Ag) nanoparticles enables to increase the photosensitivity of this material. These results can be also used to improve the characteristics of other materials as well as the devices with low quantum efficiency, including GaP LEDs.

The possibility of increasing the radiation energy of GaP homojunctions above the band gap ($\hbar\nu_{max} = 2.32$ eV) and the luminescence intensity (up to 550%) by using the combined annealing of diodes was considered in [4].

The authors of [6] proposed a method for correction of a typical model of the partial avalanche breakdown of *p-n* junction, which is applicable to increase the security of confidential information in optoelectronic communication lines, where GaP LEDs may be used.

In [7, 8], the results of the studies of the mechanisms of current flow in non-irradiated and irradiated *p-n* structures of GaP are presented. It is noted that, along with the processes of the avalanche multiplication of carriers under reverse bias, tunneling effects also play an important role.

The efficiency of silicon solar cells is limited by the low optical transparency and electrical conductivity of amorphous Si entrance windows. In order to increase these characteristics, the authors of [5] proposed to replace the α-Si (H) emitter with a wide-gap crystalline GaP one. It was found that the optical response of resulting cells was improved due to the lower optical absorption by GaP in the UV region as compared to Si.

In this work, we consider the breakdown processes in GaP LEDs at large reverse voltages, when the internal fields reach the values of $10^5 \ldots 10^6$ V/cm, as well as their degradation-reduction features accompanying the introduction of radiation defects and annealing.

At the extreme values of reverse fields, surface streamline currents and tunnel currents caused by the interband Zener effect and involving defect states in the depletion region, avalanche or microplasma breakdown currents as well as currents due to the field-induced ionization of impurity atoms in the space charge region (SCR) can flow through the diode in addition to thermal and generation currents.

Any uncontrolled growth of even one of the listed components of reverse current in a separate link of an optoelectronic module can disable the entire unit. Emission of light by a separate microplasma during a pulse of reverse polarity can cause parasitic operation of optocoupler.

The factors and circumstances mentioned above have extremely negative effects on the operation of electronic equipment and require a detailed study.

2. Samples and experiment

We investigated commercial GaP LEDs, the red emission of which originated from the simultaneous doping with Zn and O. The *n*-GaP substrate prepared using the Czochralski method had the concentration of charge carriers close to $(5 \ldots 7) \cdot 10^{17}$ cm^{-3}. The size of the samples was 1 mm^2.

Current-voltage characteristics (CVCs) were measured using the automated complex in the modes of a current generator and a voltage generator within the temperature range 77…300 K [9]. Irradiation by electrons with $E = 2$ MeV and $F = 8.2 \cdot 10^{16}$ cm^{-2} took place at room temperature in a pulsed mode by using the pulsed plasma accelerator (IPP-6). The electron beam current was $I = 4$ mA. Isochronous annealings were carried out in the temperature range $T = 20 \ldots 500$ °C during 20 min.

3. Results and discussion

At the values of reverse bias sufficient to generate a field $E \sim 10^5$ V/cm in a narrow layer of SCR, the temperature of carriers can exceed the lattice temperature. This increases the probability of ionization and, hence, the development of avalanche multiplication process.

In Fig. 1, reverse branches of CVCs of red GaP LED recorded at $T = 300$ K and $T = 77$ K are shown. The temperature shift of the region to higher voltages indicates the avalanche nature of discharge current [6]. The specificity of breakdown process in the objects under study is especially apparent at low temperatures (77 K) and high currents ($I = 10^{-2} \ldots 10^{-1}$ A) [7]. As can be seen from Fig. 2, the avalanche of carriers starts at $I = 10^{-2}$ A and continues up to $I = 5 \cdot 10^{-2}$ A. After this, the dependence $I(U)$ becomes close to the linear one, corresponding to the current limited by only the series resistance of the base [8].

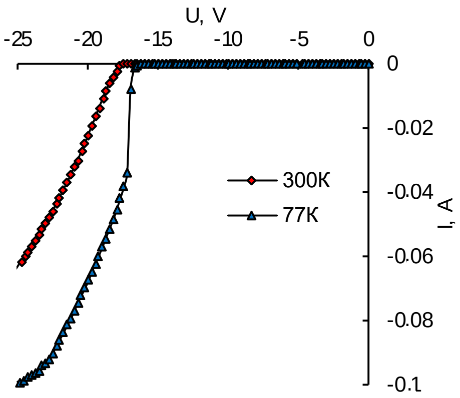

Fig. 1. Reverse branches of CVCs of red GaP LED measured at different temperatures.

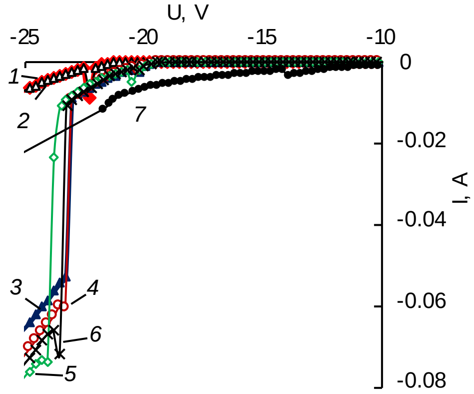

Fig. 2. Reverse branches of CVCs of GaP (Zn, O) LED irradiated by electrons ($E = 2$ MeV, $F = 8.2 \cdot 10^{16}$ cm^{-2}), measured at 77 K after isochronous annealings at different temperatures: *1* – irradiated, *2* – 50, *3* – 170, *4* – 270, *5* – 390, *6* – 450, *7* – 500 °C.

The value of the ionization coefficient α(ε) of GaP (ε is the electric field strength), which characterizes the rate of the increase of carrier concentration, can be obtained using the theoretical Baraff curves [10]. However, it is more convenient to extract it from experimental data using the following approximate expression:

$$\alpha(\varepsilon) = A \exp\left[-\left(\frac{b}{\varepsilon}\right)^m\right], \tag{1}$$

where A and b are the constants fitted for each semiconductor. For GaP, $A = 0.4 \cdot 10^{-6}$ cm^{-1} and $b = 1.18 \cdot 10^6$ V/cm, respectively.

Shown in Fig. 3 are the dependences α(ε) for GaP obtained using the Baraff theory as well as the expression (1). It can be seen from this figure that there is significant disagreement between the two curves at $\varepsilon > 1.6 \cdot 10^5$ V/cm. The field stress values did not exceed $\varepsilon = 1.5 \cdot 10^6$ V/cm in our work. Therefore, use of expression (1) is justified. The breakdown voltage U_{BR},

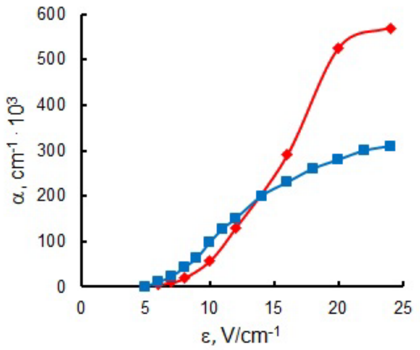

Fig. 3. Dependence of the ionization coefficient of GaP (Zn, O) LEDs on the electric field strength: *1* – obtained according to Baraff's theory, *2* – calculated by relation (1).

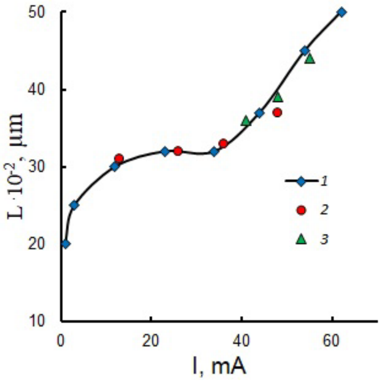

Fig. 4. Dependence of SCR width on the breakdown current for the sample annealed at different temperatures: *1* – output, *2* – 20…210 °C, *3* – 290…490 °C.

equal to the sum of the barrier potential U_B and the applied bias, can be estimated by the Miller relation. It should be noted, however, that it will be correct only in some cases even for Si diodes. Regarding GaP LED structures to be used in variable load circuits, there is no simple relationship for evaluation of this important operational parameter necessary for planning the operation of an optoelectronic pair. Therefore, its value must be obtained experimentally.

Using a predetermined value of U_{BR}, the width L of SCR of a *p*-*n* junction can be calculated.

The results of calculations for the reverse branches of CVCs show (Fig. 4) that an increase of SCR thickness is accompanied by an increase of breakdown current. At this, the value of L remains practically unchanged during the heat treatment of sample.

Increase of the breakdown voltage of a heated diode results from additional scattering of charge carriers by thermal vibrations of lattice (Fig. 5a).

Increase of the temperature of isochronous annealing of the GaP output diode leads to a drop of breakdown voltage (Fig. 5b). The irradiation increases U_{BR} and stabilizes its value in the temperature range of 20 to 300 °C.

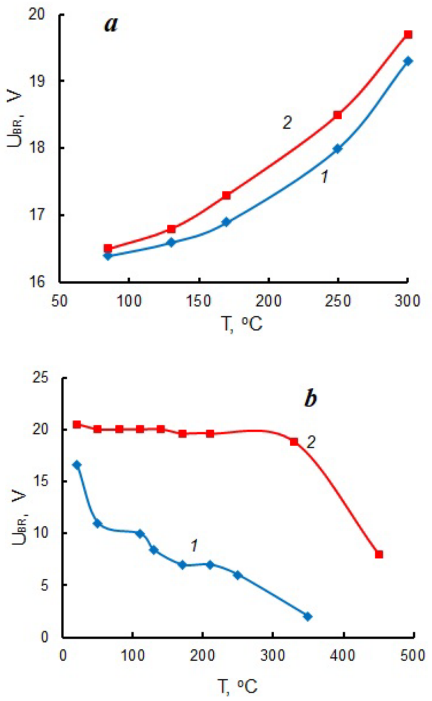

Fig. 5. Dependence of breakdown voltage on the temperature of sample (*a*) and the temperature of isochronous annealing (*b*) of GaP (Zn, O) LED: *1* – output; *2* – irradiated by electrons with $E = 2$ MeV and $F = 8.2 \cdot 10^{16}$ cm^{-2}.

Decrease of the breakdown voltage of the output sample with the increase of annealing temperature as well as its partial "radiation strengthening" as a result of irradiation (Fig. 5b) are obvious consequences of the increase of the mean free path of charge carriers.

It is known that the main role in the appearance of the prior-to-breakdown part of reverse saturation current I_s in wide-gap semiconductors is played by the recombination component.

$$I_s = \frac{qn_iL}{\tau_{eff}}, \qquad (2)$$

where n_i is the intrinsic concentration of charge carriers and L is the width of depleted region [10], respectively.

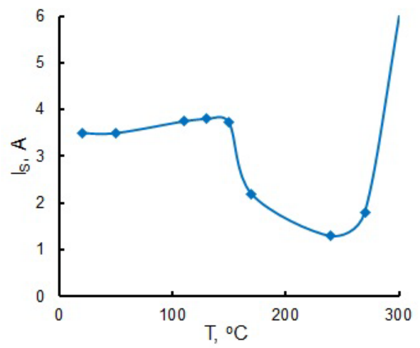

Fig. 6. Dependence of the saturation current I_s of red GaP LED irradiated by electrons ($E = 2$ MeV, $F = 8.2 \cdot 10^{16}$ cm^{-2}) on the temperature of isochronous annealing.

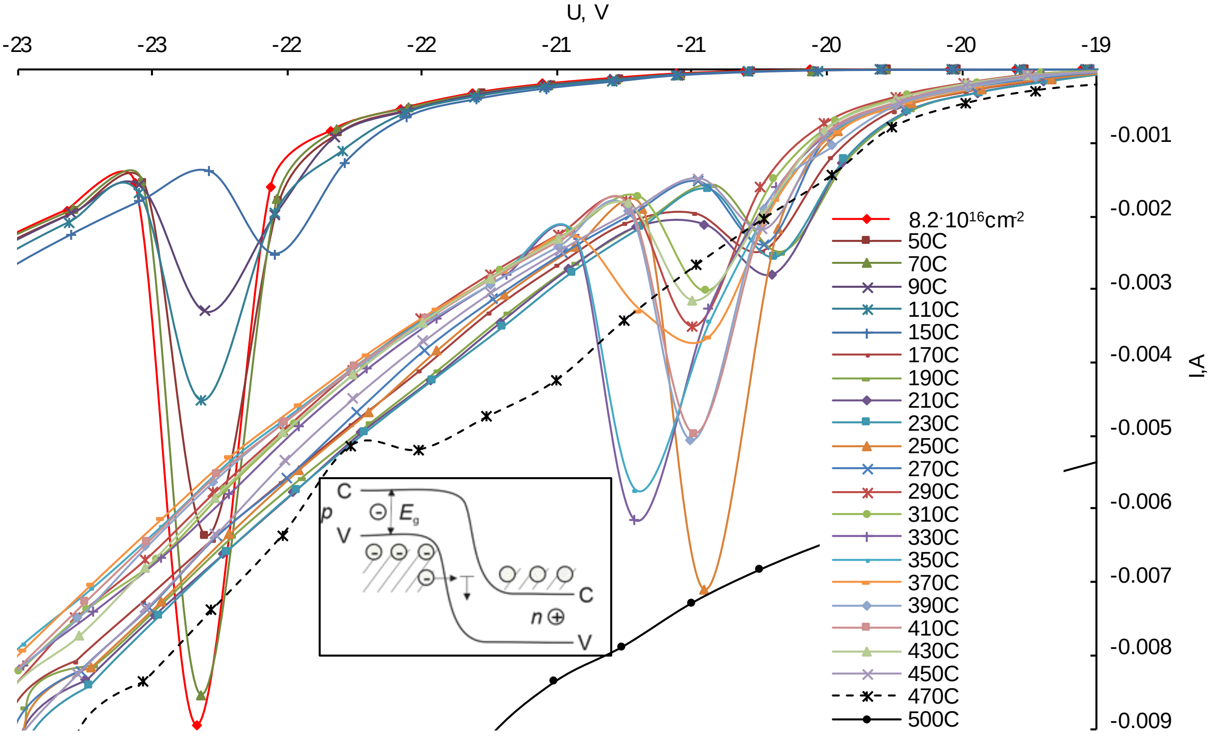

Fig. 7. Reverse branches of CVCs of red GaP LEDs irradiated by electrons (E = 2 MeV, $F = 8.2 \cdot 10^{16}$ cm^{-2}), measured during isochronous annealing. Measurement temperature is 77 K. Inset shows a diagram of a possible process of carrier tunneling, which leads to the appearance of minima. (Color online)

In the GaP diodes under study, irradiation leads to the increase of I_s. It can be seen from the relation (2) that such a tendency is a consequence of the influence of two factors, namely: the expansion of SCR caused by the compensation of the electrical conductivity of both parts of the transition by the levels of radiation effects and the decrease of the effective lifetime of charge carriers.

Isochronous annealing of the irradiated sample (Fig. 6) begins at T = 150 °C. During the first stage of annealing (T = 150…250 °C), I_s reaches a minimum value and then sharply increases at the stage II. Probably, the defects of technological origin present in SCR, which take part in the compensation of the electrical conductivity of crystal, being activated by irradiation, are annealed at the stage I, thereby contributing to both narrowing of depletion region and increase of the effective lifetime of charge carriers.

A sharp increase of I_s at the second stage of annealing is an indication of the development of destructive phenomena in the irradiated diode at high temperatures.

Decrease of the reverse current of the diode as a result of radiation-heat treatment is an undoubtedly positive effect from the point of view of its practical application. It should be noted, however, that because of the narrow temperature range inherent to this effect and significant variation of parameters observed in commercial LEDs, researches in this direction should be continued and expanded.

At low temperatures (77 K), the monotonicity of $I(U)$ curves in the prior-to-breakdown region of irradiated red GaP diodes is broken by two deep minima (Fig. 7). Taking into account the narrow voltage intervals and significant field strengths ($\varepsilon = 5.48 \cdot 10^5$ V/cm at L = 0.42 µm and U = 23 V), we can make a preliminary conclusion that the revealed deviations from the typical $I(U)$ dependence are caused by local tunneling breakdowns, this tunneling occurs due to the transitions of the “band-defect-band” type (see inset in Fig. 7). Emission of carriers within each minimum is a consequence of the displacement of band edges when the voltage changes and the edge of corresponding band coincides with the defect level (Fig. 7). It can be seen from the annealing curves of the latter two minima that the recovery of the first minimum is completed at the temperatures up to 150 °C, which coincides with the temperature range of the annealing of phosphorus vacancies in n-type GaP single crystals. The temperature range for the annealing of the second minimum (T = 250…300 °C) is close to the one for the diffusion of gallium vacancies to sinks. The minimum appears in the curves at T = 330…350 °C. It is annealed in narrow temperature ranges and can be associated with structural damage that recovers at lower temperatures.

4. Conclusion

It is found that the breakdown region in CVCs of GaP LEDs corresponds to the avalanche multiplication of carriers. Increase of the annealing temperature of non-irradiated samples leads to a decrease of breakdown voltage, while irradiation causes its growth.

The revealed increase of saturation current I_s after irradiation results from the expansion of space charge region and the decrease of effective carrier lifetime. The initial value of I_s is restored during the stage of annealing at 150…250 °C.

Deviation of $I(U)$ from the monotonic dependence by formation of individual minima can be associated with the band-defect-band carrier tunneling.

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Konoreva O.V.: software, validation, investigation, data curation, visualization.
Olikh Ya.M.: methodology, resources.
Radkevych O.I.: resources, supervision, funding acquisition.
Stratilat D.P.: methodology, investigation, project administration.
Tartachnyk V.P.: conceptualization, formal analysis, investigation, writing – review & editing, supervision, project administration.

Польові ефекти в опромінених електронами світлодіодах GaP

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Анотація. Наведено результати досліджень польових ефектів, які спостерігаються у вихідних та опромінених електронами з $E = 2$ МеВ, $F = 8.2\cdot10^{16}$ см$^{-2}$ світлодіодах фосфіду галію (GaP) при зворотному зміщенні. Розглянуто процеси лавинного множення носіїв струму та тунельного пробою у межах області просторового заряду. Виявлено зростання пробійної напруги після електронного опромінення. Проаналізовано наслідки відпалу вихідних та опромінених діодів у інтервалі температур 20…500 °C.

Ключові слова: GaP, світлодіод, польові ефекти, електронне опромінення, вольт-амперні характеристики.