Recovery of LED Emission Power under the Exposure to γ-n-Pulse

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Abstract. The article presents results of the study of the effect of LED power modes based on AlGaAs heterostructures (short-circuit, open circuit, and active mode with the passage of operating current during irradiation) on the resistance to γ-n-pulse exposure. Reduction of LED emission power under the influence of γ-n-pulse occurs in two stages irrespective of irradiation power mode, with each stage characterized by its own regularity and its own factor. Built-in electric field of p-n-junction does not contribute significantly to the degradation of LED power when exposed to γ-n-pulse. At irradiation of LED in active power mode after exposure to γ-n-pulse (Fn ≤ 1.5·10¹²n/cm², Dγ ≤ 20 Gy (Si)) a recovery of LED power by the value of ΔР is observed. Recovery of ΔР power leads to reduction of the damage factor at the first stage, to increase of the LED resistance, and to shift of the boundary between the stages to the area of higher neutron fluences. It is supposed, that the observed jump-like increase of ΔР radiation power under the influence of γ-n-pulse is caused by radiation-stimulated annealing of local mechanical stresses that is generated under the condition of passing of operating current through LED.

1. Introduction
Light-emitting diodes (LED) are now actively used in almost all fields of science and technology, including for fiber-optic communication, integrated optoelectronic devices, open channel optical communication systems, medical instrumentation, etc. At the same time, various LED-based devices are often operated in harsh environments [1-3]. In particular, LED-based devices are exposed to a complex impact of various types of ionizing radiation and operating factors in space conditions and at nuclear power facilities. The high responsibility and harsh operating conditions of LED-based devices are the main reasons for the special interest in the research of the related degradation processes.

It has been found that when semiconductor devices are exposed to ionizing radiation, the rate of insertion of radiation defects in the separation of generated electron-hole pairs can differ markedly from the rate observed in the absence of electron-hole pair separation [4, 5]. Thus, the resistance of LEDs to ionizing radiation may depend on the power mode.

In addition, the direct current flowing during LED operation in continuous mode leads to an increase in the temperature of its active layer, the consequence of which can be thermal or radiation annealing of the introduced defects [6].
At present, a wide variety of semiconductor structures are used for the production of LEDs in industrial and laboratory environments, with the most researched LEDs being, in our opinion, those based on AlGaAs heterostructures [7-9].

The aim of this work is to investigate the effect of the power mode of IR-wavelength LEDs fabricated on the basis of AlGaAs heterostructures on their resistance to γ-n- pulse.

2. Objects and research methods

Industrial LEDs with wavelength $\lambda = (0.82 - 0.90) \ \mu m$, which were produced on AlGaAs double heterostructures with active layer thickness about 2 µm obtained by liquid-phase epitaxy using single-crystal n+-GaAs as a substrate were used as research objects. The structural diagram of the used heterostructure is presented in sufficient detail in [10].

LEDs were manufactured using standard sandwich technology using deposition and metallisation layer formation techniques to create ohmic connections; photolithography and chemical etching techniques to form crystals (chips) and laser scribing to separate the wafers into individual chips. The crystal area was 450x450 µm². Ohmic contact to n-GaAs has been made on the (Au-Ge-Ni) basis, and for AlGaAs- p-layer on the (Au-Zn) basis.

The fabricated crystals were mounted in a plastic case made of an optical compound, which had a lens for forming a directed LED radiation beam. Since the results of preliminary studies have shown that the optical compound used does not change its optical properties upon irradiation with neutrons up to $F_n = 5 \cdot 10^{15}$ neutron/cm², then all changes in LED characteristics as a result of irradiation can only be explained by changes in the optical properties of the LED active element (crystal).

We used the watt-ampere characteristic (hereinafter referred to as WAC) as the main lighting characteristic of LED in this work, which determines the dependence of the LED radiation power from the operating current, as well as the change in the radiation power at a given operating current depending on the level of exposure. To measure the WAC of LEDs, an automated measuring complex based on a photometric sphere was used. The measuring complex allows measuring the forward voltage of LED in the range from 0 to 5 V for the range of direct currents (1 – 500) mA in increments of at least 1 mA. In this case, the error in setting the direct current from the set level is ± 3%, and the error in measuring the radiation power of the LED is ± 5%.

The pulse solid-core dual-zone reactor on fast neutrons BARS-4 was used to produce γ-n-pulse under natural climate conditions. The pulse duration was 60 μc and the average neutron energy was 1.4 MeV [11]. The exposure level was described by neutron fluence $F_n \ [n/cm^2]$ and the absorbed dose of the accompanying gamma-radiation $D\gamma \ [Gy(Si)]$.

A special cassette was made to supply bias voltage during irradiation in order to perform irradiation with different LED power modes. A separate sample of at least 5 LEDs was used for each power mode. The following LED power modes were used in this study: short-circuit, open circuit, and active mode with an operating current of 5 mA to 200 mA.

The results of LED measurements before and after irradiation were statistically processed and presented in graphics using Origin software.

3. Results and discussion

Results analysis of LEDs investigation exposed to γ-n-pulse in short-circuit and open circuit modes has shown their complete identity. All observed differences are fully explained by the measurement error; therefore, we will not separate these two modes in the further analysis and will use short-circuit and open circuit LED as one mode.

Figure 1 shows the variation of LED emission power when exposed to γ-n-pulse in the short-circuit and open circuit LED and LED 200 power mode. In this case, the emission power measured at the operating current of 50 mA after irradiation in the indicated power modes is normalized to its value before irradiation.
It can be seen from Figure 1 that in describing changes in the radiation power it is possible to distinguish obviously two common stages of power reduction each of which is described by its own regularity. For the first stage we obtain:

\[
\frac{P_F(50\,mA)}{P_0(50\,mA)}_{\text{stage I}} = \frac{1}{1 + (k_I(\text{short and open circuit}) \cdot F_n)^\beta}, \quad \text{if} \quad F_n \leq F_n^{\text{th (short and open circuit)}}
\]

and for the second stage:

\[
\frac{P_F(50\,mA)}{P_0(50\,mA)}_{\text{stage II}} = B \exp(k_{II}(\text{short and open circuit}) \cdot F_n), \quad \text{if} \quad F_n \geq F_n^{\text{th (short and open circuit)}}
\]

where \(P_F(50\,mA), P_0(50\,mA)\) is radiation power measured at 50 mA operating current; 
\(k_I(\text{short and open circuit}) = 5.6 \times 10^{-13} \, \text{cm}^2\), \(k_{II}(\text{short and open circuit}) = 2.94 \times 10^{-14} \, \text{cm}^2\) are damage factors at the first and second stages; 
\(\beta = 1.2\) is power coefficient; \(B = 0.15\) is proportionality ratio.

The results obtained allow to establish the neutron fluence which determines the boundary between the selected stages \(F_n^{\text{th (short and open circuit)}} = 8.5 \times 10^{12} \, \text{n/cm}^2\). It should be noted that the value \(F_n^{\text{th (short and open circuit)}}\) does not depend on the operating current at which the emission power of the LED is measured. We have previously distinguished similar stages of LED power reduction under the influence of various external factors [12-14]. Thus, it is found that virtually identical regularities of the radiation power decrease under the influence of \(\gamma\)-\(n\) pulse in short-circuit LED and open circuit LED modes are observed in the whole range of operating currents (in our case from 1 mA to 200 mA), and the observed differences are fully described by the measurement error.

These results allow to conclude that the embedded electric field of the p-n junction does not contribute significantly to the degradation of the LED power based on AlGaAs heterostructures during irradiation with fast neutrons.

The decrease of LED radiation power occurs in two stages, each of which is described by its own regularity.

Further we will consider the variation of LED emission power during neutron irradiation in the operating mode shown in Fig.2 and will compare the results with the short-circuit and open circuit LED irradiation modes.
From the results presented, it can be seen that there are also two characteristic stages of power reduction distinguished. In the first stage, the power reduction is described by proportionality similar to (1):

$$\frac{P_f(50\text{mA})}{P_0(50\text{mA})} = \frac{C}{1 + (k_{1200} \cdot F_n)^\beta}, \text{ if } F_n \leq F_{n\text{ th} 200}$$

where $C = 1.15$; $k_{1200} = 8.3 \cdot 10^{-14}$ cm$^2$; $F_{n\text{ th} 200} = 2 \cdot 10^{13}$ n/cm$^2$; $\beta = 1.2$.

The formula (3) with account of (1) may be converted as follows:

$$\frac{P_f(50\text{mA})}{P_0(50\text{mA})} = \frac{1 + \Delta P}{1 + (k_{1200} \cdot F_n)^\beta}, \text{ if } F_n \leq F_{n\text{ th} 200}$$

where $C = 1 + \Delta P$; $\Delta P = 0.15$ is recovery of LED radiation power after irradiation with the lowest neutron fluence.

The second stage of power reduction is described by formula (2). But, in this case, there is a threshold shift between the selected stages due to $\Delta P$.

Analysis of the determined regularities (1-4) allows us to conclude that a recovery of power by the value of $\Delta P$ is observed after exposure to a minimum neutron fluence during LED irradiation in the active mode. Upon further irradiation, there is a decrease in power according to the regularity established for short-circuit and open circuit LED irradiation modes. The emergence of power recovery $\Delta P$ leads to a decrease in the damage factor $k_1$ and, consequently, to an increase in the resistance of the LED in the first stage, as well as to the shift of the boundary between stages to the area of higher neutron fluences.

What is the reason for the observed power recovery $\Delta P$? We have already noted earlier that the passing of operating current during irradiation may lead to a partial annealing of injected defects due to an increase in the temperature of the LED active layer, and consequently to speed-down of degradation processes.

Figure 2 shows the variation of LED radiation power in selected WAC areas at different irradiation modes $I_{op,n}$. Here, the radiation power after irradiation is normalized to its value before irradiation. Further we consider the obtained results in more detail.

For the stage I there is the following correlation:

$$\frac{P_f}{P_0} = D + K \cdot I_{op,n}$$

where $D$ is a proportional coefficient, the value of which depends on the neutron fluence; $K = 0.282$ A$^{-1}$ is a coefficient, the value of which describes the speed-down of degradation of the radiation power due to the increase of the LED active layer temperature.
The ratio (5) describes the variation of radiation power before and after neutron irradiation in active mode and at other values of operating current in the range from 1 mA to 200 mA which were used to control the radiation power before and after irradiation.

The dependence of $D_F$ coefficient on neutron fluence is shown in Figure 3.

This dependence in the first stage can be described by the following correlation:

$$D_I = \Delta P - \exp(-k_3 \cdot F_{n^\text{th}})$$

where $\Delta P = 0.15$ is a recovery of LED radiation power after irradiation with the lowest neutron fluence (4); $k_3 = 3.6 \times 10^{-13}$ cm$^2$ is a damage factor which is quite close to $k_1$ (1).

For the second stage the following correlation is obtained:

$$D_{II} = N - k_4 \cdot F_n$$

where $N = 0.30$ is proportionality ratio; $k_4 = 1.18 \times 10^{-14}$ cm$^2$ is damage factor.

The presented results allow us to draw the following conclusions. During LED irradiation with neutrons in active mode an increase of resistance is observed due to partial thermal annealing of injected defects. At the same time the thermal annealing established does not allow to explain the appearance of power jump $\Delta P$ (4).

It is known by now [15, 16] that irradiation of different items with quite small doses of gamma rays leads to relaxation of local mechanical stresses, which results in improvement of physical-mechanical properties. In particular, for semiconductor devices an increase of mobility of charge carriers is observed [16]. This phenomenon was also observed under high energy proton irradiation of Gunn diodes with local mechanical stresses [16, 17]. In [17] it was found that upon irradiation with minimum proton fluence of Gunn diodes with local mechanical voltages a jump-like increase of the operating current is observed, caused by the increase of electron mobility in its active layer. With further irradiation, the decrease of the operating current is fully described by the pattern established for Gunn diodes without local mechanical stresses. A similar LED behaviour is observed in our case. We would like to recall that almost always the obtained neutron fluences are accompanied by accompanying gamma radiation, which we additionally recorded in each experiment. For the minimum neutron fluence in the active irradiation mode $1.5 \times 10^{12}$ n/cm$^2$ corresponded to an absorbed dose of 20 Gy (Si).

Thus, we can assume that the observed spike in the LED emission power when exposed to $\gamma$-n-pulse ($F_n \leq 1.5 \times 10^{12}$ n/cm$^2$; $D_I \leq 20$ Gy (Si)) is caused by radiation-induced annealing of local mechanical stresses that is introduced under the condition of passing operating current through the
LED. In the absence of separation of electron pairs generated by irradiation there is no spike in the radiation power.

It is of interest to compare the effect of the static neutron fluence with that of the $\gamma$-n -pulse, since the recovery of $\Delta P$ may be due to the high dose rate of the $\gamma$-n -pulse.

4. Summary

In conclusion, we summarize the main results presented in this paper.

- The study results of the effect of power modes of LEDs based on AlGaAs heterostructures (short-circuit, open circuit, and active mode with operating current passing during irradiation) on the resistance to $\gamma$-n-pulse were presented.
- Power reduction of LED emission at exposure of $\gamma$-n-pulse occurs in two stages irrespective of a power mode during irradiation, thus each stage is characterized by own regularity and own damage factor.
- Built-in electric field of p-n-junction does not contribute significantly to the degradation of LED power under the influence of $\gamma$-n – pulse.
- A recovery of LED power by the value of $\Delta P$ is observed under irradiation of LEDs in active power mode after exposure to $\gamma$-n-pulse ($F_n \leq 1.5 \cdot 10^{12} \text{cm}^{-2}$, $D_\gamma \leq 20 \text{ Gy (Si)}$). In this case, reduction of radiation power of LED during further irradiation occurs according to regularities that have been established for short-circuit LED and open circuit LED modes with account of $\Delta P$. The recovery of $\Delta P$ power leads to a decrease in the damage factor at the first stage, to an increase in the LED resistance, and to a shift of the boundary between the stages to the area of higher neutron fluences.
- At influence of $\gamma$-n-pulse in an active mode of LED the increase of resistance is observed owing to the partial radiation-stimulated thermal annealing of injected defects.
- It is supposed, that the observed jump-like increase of radiation power $\Delta P$ at influence of $\gamma$-n-pulse ($F_n \leq 1.5 \cdot 10^{12} \text{cm}^{-2}$, $D_\gamma \leq 20 \text{ Gy (Si)}$) is caused by radiation-stimulated annealing of local mechanical stresses, which is carried out under condition of passing of operating current through LED. In the absence of separation of electron pairs generated by irradiation there is no spike in the radiation power.

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