IOP Conf. Series: Materials Science and Engineering **363** (2018) 012010 doi:10.1088/1757-899X/363/1/012010

LEDs based upon AlGaInP heterostructures with multiple quantum wells: comparison of fast neutrons and gamma-quanta irradiation

A V Gradoboev[1], K N Orlova[2] and A V Simonova[1]
[1]National Research Tomsk Polytechnic University, Tomsk, Russia
[2]Associate Professor, Department of Life Safety, Ecology and Physical Education, Yurga Institute of Technology, TPU Affiliate, Yurga, Russia
E-mail: gradoboev1@mail.ru

Abstract. The paper presents the research results of watt and volt characteristics of LEDs based upon AlGaInP heterostructures with multiple quantum wells in the active region. The research is completed for LEDs (emission wavelengths 624 nm and 590 nm) under irradiation by fast neutron and gamma-quanta in passive powering mode. Watt-voltage characteristics in the average and high electron injection areas are described as a power function of the operating voltage. It has been revealed that the LEDs transition from average electron injection area to high electron injection area occurs by overcoming the transition area. It disappears as it get closer to the limit result of the irradiation LEDs that is low electron injection mode in the entire supply voltage range. It has been established that the gamma radiation facilitates initial defects restructuring only 42% compared to 100% when irradiation is performed by fast neutrons. Ratio between measured on the boundary between low and average electron injection areas current value and the contribution magnitude of the first stage LEDs emissive power reducing is established. It is allows to predict LEDs resistance to irradiation by fast neutrons and gamma rays.

1. Introduction

AlGaInP heterostructures with multiple quantum wells are widely used as base of light-emitting diodes (LEDs) [1–7]. The LEDs are increasingly used in electronic devices for various applications. Under operating conditions they may be influenced by different radiation factors. Therefore, determining the interest to their resistance study as introduction of radiation defects leads to deterioration of the basic LED parameters [8].

AlGaInP heterostructures with multiple quantum wells are produced by metalorganic chemical vapor deposition (MOCVD)-based gaseous epitaxy [9–15]. However, a set of technological problems in production of heterostructures has not been solved yet. These are the following: hydrogen passivation, timely oxygen removal from the case, decrease of imperfection on heteroboundaries of layers and improvement of grown layer homogeneity.

These technological problems can cause high concentration of compounds (in particular Mg-H, Mg–O and Te-O) in the layers of AlGaInP heterostructures with multiple quantum wells [10], which are the centers of non-radiative recombination and/or absorption of active region-generated radiation. Aluminum in AlGaInP heterostructures with multiple quantum wells can further generation of impurity compounds (Mg-O, Te-O) both in active and in barrier regions under ionizing irradiation, as the consequence, centers of non-radiative recombination and/or absorption of generated radiation grow

[16]. The presented facts should be taken into consideration for studying radiation-induced defects in the heterostructures and devices made of them.

Quantum wells, introduced into the core of a heterostructure, facilitate concentration growth of minor charge carriers in it due to the state of two-dimensional electronic gas; it increases internal quantum efficiency [1]. Here, elastic strain relaxation on the layers boundary arising due to the inconsistency of lattice parameters with the introduction of quantum wells in the AlGaInP heterostructures active region doesn't lead to dislocations or point defects formation, which can be centers of non-radiative recombination.

At present, the change in parameters of AlGaInP heterostructures with multiple quantum wells exposed to ionizing irradiation has not been adequately investigated [17, 18]. The issue of radiation stability of the LEDs produced on their base is gaining its urgency because they can be used in conditions of various ionizing irradiation [19, 20].

The purpose of the work is to research watt and volt characteristics changes of LEDs based upon AlGaInP heterostructures with multiple quantum wells under fast neutron irradiation and gamma-irradiation.

2. Experimental

The objects of research were red and yellow LEDs (batch LED1) produced on the base of AlGaInP heterostructures with 10 multiple quantum wells (λ = 624 nm) and yellow LEDs (batch LED2) (λ = 590 nm) made by metalorganic chemical vapour deposition method. Dimethylditelluride (DETe) and bis (cyclopentadienyl) magnesium (Cp, Mg) were used as the doping sources for *n*-type and *p*-type layers, respectively. Therefore, under investigation the LEDs were distinguished by the broad band gap, that is, composition of the active region.

At first, a *p*-layer of the structure was dielectrically SiO_2 coated (0.5 μm) and a part of the substrate was chemically and chemical-dynamically etched to obtain the total thickness of the structure (200-210 μm).

Nextly, an ohmic contact was formed towards n-GaAs substrate all over the surface of plates via magnetron-coated Au-Ge-Ni^+-Au deposition (0.15–0.2 μm). An ohmic contact was burnt into in the atmosphere of hydrogen at temperature (425–430) ^{0}C during 5 min.

To form ohmic contacts to *p*-layers of the structures photolotigraphy was carried out on the plates, SiO_2 was etched and after exposed surface of the surface had been chemically treated layers of metals Au-Zn^+-Au (about 0.2 μm) or Ti-Au (0.15–0.2 μm) were coated subsequently or into spaces in photoresist. After coating had been completed photoresist was explosively removed, followed by burning into metal layers in hydrogen atmosphere at temperature 460 ^{0}C for 5 min. In this way mesastructures – prototypes of crystals (chips) were formed. Then contacts to *n*- and *p*-layers of heterostructures were additionally Au-deposited (4–5 μm) (all over the substrate surface and photolithographically formed mesastructures over the surface of *p*-layer).

The crystals were mounted into corresponding cases via thermal-compression assembly.

Fast neutrons with effect level characterized by particle fluence F_n [n/cm^2] and gamma-rays characterized by dose $D\gamma$ [Gy] were chosen as a source of radiation action.

LEDs were irradiated in standard conditions in passive power mode that is without forward current flowing. For the purpose of research different LED sets were made, and each set included at least 20 diodes. For various LED sets exposure level was augmented via sequentially increased radiation dose.

Watt and volt characteristic was measured before and after irradiation in a sphere. In the all experiments focused on irradiation particle flux was directed perpendicularly to the substrate plane. Each experimental value of the below given dependences conforms to a mean parameter value for LED set.

We applied both one-time and sequential sets of required levels of exposure. By comparing the obtained results we can conclude that methods to measure the change in LED parameters don't cause annealing of introduced radiation defects.

3. Results and considerations

Let us consider the results of measurement, which were obtained before irradiation of LEDs. To begin our consideration we analyze the straight branch of volt-ampere characteristics shown in Figure 1. Forward branches of volt-ampere characteristics are in line with the standard LED characteristic with p-n junction at forward bias. Inaccuracy of measurements didn’t exceed 3%. Inaccuracy is depicted in Figure 1 as confidence intervals to assess measurement validity. Therefore, batches LED1 and LED2 under consideration demonstrate typical volt-ampere characteristics, which are quite similar to dependences presented in publications [10].

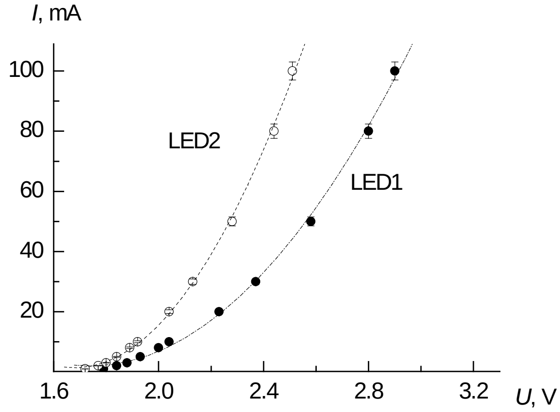

Figure 1. Volt-ampere characteristic of LED1 and LED2 in the linear scale, where symbols are experimental data; lines are identified regularities.

The higher supply voltage is observed for LED2 with identical forward current as compared with LED1 due to the ohmic contacts bad quality which has led to decrease of additional supply voltage in case of LED2.

Watt and volt characteristics are ones of main LEDs characteristics, which determine operating features of an electronic appliance. Relying on the analysis of watt and volt characteristics optimal parameters of appliance maintenance can be selected including voltage, which provides maximum external LED quantum efficiency.

At first, let us consider what the changes in watt and volt characteristics under neutron irradiation are registered. As fast neutron fluence was increased the change in watt and volt characteristics was identified (Figure 2). The light output power is shown in the figures in relative units. Therefore, the change of the results obtained by irradiation you can trace. Neutron flux values reach 1015 n/cm^2.

As one can see, three zones are highlighted for reference diodes, and there is a boundary area between them (selected triangle area patterned by touches in Figure 2). Each pronounced zone has its specific dependence of analyzed regularities.

Therefore, LED external quantum efficiency depends on the different factors as same as the manufacturing technology, chemical composition of material and rate of emitting and full recombination of charge carriers, lifetime of radiative and non-radiative recombination [21–23]. More efficient LED1 (in our case) is distinguished by shorter lifetime of minor charge carriers.

Three typical areas (I, II and area III) can be highlighted for each LED type according to obtained watt and volt characteristics. We can sum up that highlighted areas are those of average electron injection, high electron injection and low electron injection into the LEDs active region is highly pronounced. The frontier between average electron injection and high electron injection is specified by equal concentration of injected electrons and holes in p-region. Our assessment has revealed that concentration of injected electrons is really comparable with concentration of holes in p-region in conditions of the identified frontier.

The dependence of emissive power on supply voltage can be described by power function. Then power exponent in low electron injection area is approached to zero.

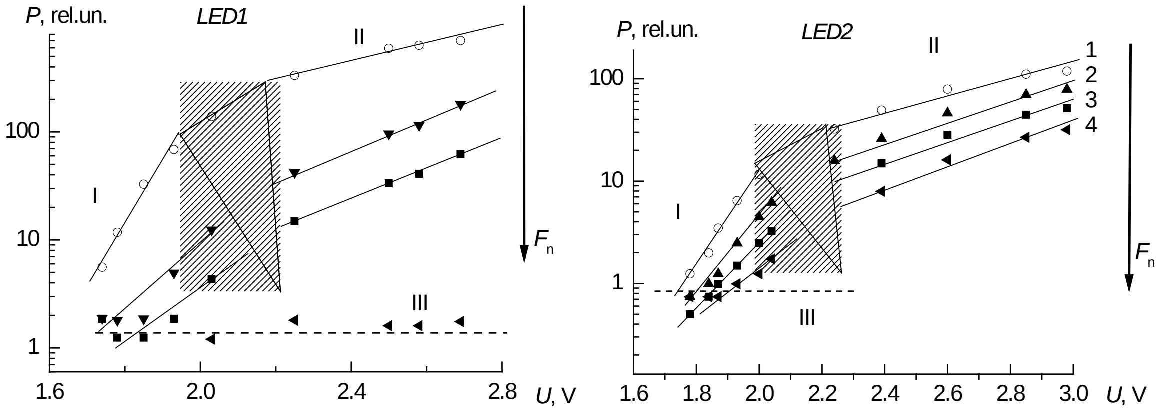

Figure 2. Watt and volt characteristic of the LEDs under irradiation by fast neutrons, where are I is average electron injection area; II is high electron injection area; III is low electron injection area; symbols are results of measurement; lines are identified regularities; *LED1*: 1 – F_n=0; 2 – F_n=1.07·10^{14} n/cm^2; 3 – F_n=2.74·10^{14} n/cm^2; 4 – F_n=2.57·10^{15} n/cm^2; *LED2:* 1 – F_n=0; 2 – F_n=9.1·10^{12} n/cm^2;
3 – F_n=2.06·10^{13} n/cm^2; 4 – F_n=3.83·10^{13} n/cm^2.

At the same time, power exponent in average electron injection zone is always greater than power exponent of high electron injection area. Perhaps this is due to appearance of thermal effects in high electron injection area, whereas noticeable crystal heating by operating current is exactly observed in this zone during taking measurement of watt-ampere characteristics. Temperature increasing of active region leads to quantum efficiency decreasing, which consequence declines power exponent reduction in the high electron injection area.

The transition field is observed between average and high electron injection areas, and it decreases with neutron fluence increasing.

LED1 power exponent is practically irrespective from neutron fluence in high electron injection area. It noticeable decreases in the average electron injection area. In the limiting case under neutron irradiation low electron injection area initially extends into the average electron injection area, and then on the high electron injection area.

Let us consider the change in watt-voltage characteristics of AlGaInP LEDs under gamma-irradiation (Figure 3).

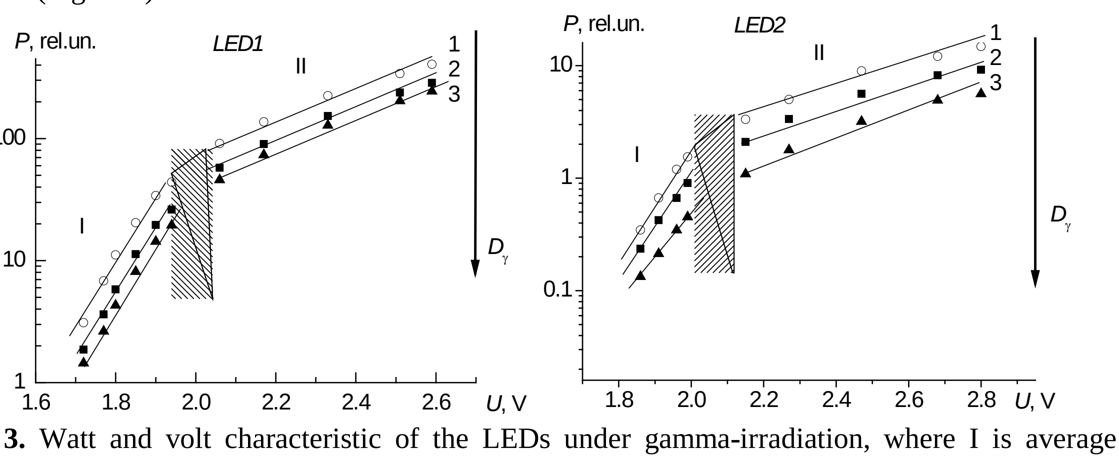

Figure 3. Watt and volt characteristic of the LEDs under gamma-irradiation, where I is average electron injection area; II is high electron injection area; III is low electron injection area; symbols are results of measurement; lines are identified regularities; *LED1*: 1 – D_γ=0; 2 – D_γ =4.18·10^7 Gy; 3 – D_γ =1.08·10^8 Gy; *LED2*: 1 – D_γ=0; 2 – D_γ =1.76·10^8 Gy; 3 – D_γ =4.68·10^8 Gy.

The change of the obtained results under irradiation by ^{60}Co gamma-rays shows a decrease in the relative power of the radiation due to increasing exposure. The gamma irradiation dose values reach

10^8 Gy. These results show that observed changes of watt and volt characteristic under gamma-irradiation are identity which is observed previously under neutron irradiation (Figure 2).

Previously [17–20], we have established that LEDs light output power at predetermined operating current has decreased as a result of ionizing radiation in three stages. On the first stage emissive power reduction is the result of radiation-enhanced existing defectiveness restructuring. Present stage characterizes by light output power decrease saturation with exposure level increase.

On the second stage emissive power decreases by exclusively radiation defects. On the third stage LEDs goes into low electron injection area. At the same time emissive power is practically independent from the operating current value with its changes in investigated current ranges. The third stage characterizes ultimate resistance of observable LEDs.

The first stage contribution of the emissive power decreasing under irradiation can be characterized at percentage ratio by value A and the second stage contribution – value B, so (A + B) = 100%.
In the analysis of available experimental data of LED1 and LED2 we have determined following ratio for fast neutrons:

$$A_{\mathrm{n}} = \left(\frac{I_{\mathrm{b}}}{I_{\mathrm{op}}}\right)^{\alpha_{\mathrm{n}}} \times 100\% , \tag{1}$$

where A_{n} is first stage contribution of the emissive power decreasing under neutron irradiation, %; I_{b} is operating current value measured on the boundary between low and average electron injection areas; I_{op} is operating current value, which is considered the changes of emissive power under irradiation; $\alpha_{\mathrm{n}} = 0.28$ is power exponent for fast neutrons.

For gamma radiation we have established similar ratio:

$$A_{\gamma} = \left(\frac{I_{\mathrm{b}}}{I_{\mathrm{op}}}\right)^{\alpha_{\gamma}} \times 42\% , \tag{2}$$

where A_{γ} is first stage contribution of the emissive power decreasing under gamma irradiation, %; $\alpha_{\gamma} = 0.11$.

To compare ratio (1) with ratio (2) we can make the conclusion that gamma-irradiation can be able to reconstruct only part (42 %) of initial defect structure in comparison with fast neutrons.

Analysis of established regularities allows to state that LEDs operating current level on the boundary between low and average electron injection areas is determined by used semiconductor material defectiveness. Also it defines resistance to fast neutrons and ^{60}Co gamma-rays irradiation.
So the correlations (1, 2) allow us to predict radiation resistance of investigated LEDs.

4. Conclusion

In conclusion main results of investigation into deterioration of watt and volt characteristics of AlGaInP LEDs based on heterostructures (λ1 = 590 nm and λ2 = 630 nm) with multiple quantum wells under fast neutron and gamma irradiation are summarized:

1. Watt-voltage characteristics of LEDs based on AlGaInP heterostructures with quantum wells in the average and high electron injection areas can be described as a power function of the operating voltage. Wherein the power exponent in average electron injection is always higher than in a high electron injection area. In the low electron injection area exponent is zero, i.e. LEDs emission power does not depend on the supply voltage.
2. Transition field is observed on the boundary between the average and high electron injection areas. It disappears as you get closer to the limit result of the irradiation LEDs - low electron injection mode in the entire supply voltage range.
3. During irradiation with the fast neutron fluence growth (with increasing gamma rays absorbed dose) exponent in the average electron injection area is reduced. It is equal to zero in the limit. While high electron injection area extends into the average electron injection area.

4. At the beginning irradiation with the fast neutron fluence growth (with gamma rays absorbed dose increasing) power exponent in the high electron injection area is practically independent of exposure level (area low impacts – the existence region of the average electron injection mode). And then it decreases and equals zero in the limit, while the low injection area extends into the high electron injection.

5. Measured on the boundary between low and average electron injection areas current value depends on the initial defectiveness of the semiconductor material. It determines first stage contribution of LEDs light output power reducing under irradiation due to radiation-enhanced initial defects restructuring in total emissive power decreasing.

6. The first stage contribution of emissive power reducing under irradiation by gamma rays lower (42%) than the observed fast neutrons contribution (100%).

7. Established ratio between measured on the boundary between low and average electron injection areas current value and the contribution magnitude of the first stage LEDs emissive power reducing allows to predict their resistance to irradiation by fast neutrons and gamma rays.

References

[1] Hodapp M W High brightness light emitting diodes 1997 *New York: NY, Academic press* 87–92 doi: 10.1016/S0080-8784(08)62407-2
[2] Plotnikova I V *et al* 2018 *IOP Conf Ser: Mater Sci Eng* **289 (1)** 012029 doi: 10.1088/1757-899X/289/1/012029
[3] Plotnikova I *et al* 2018 *MATEC Web of Conf* **155** 01052 doi: 10.1051/matecconf/201815501052
[4] Galtseva O V *et al* 2016 *IOP Conf Ser: Mater Sci Eng* **110** 012094 doi: 10.1088/1757-899X/110/1/012094
[5] Gavrilin A *et al* 2016 *MATEC Web of Conf* **79** 01078 doi: 10.1051/matecconf/20167901078
[6] Craford G M 2000 *MRS bulletin* **25(10)** 27-31 doi: 10.1557/mrs2000.200
[7] Corbett B *et al* 2003 *Proceedings of SPIE* **4876** 176-183 doi: 10.1117/12.463713
[8] Zeller H R 1995 *Solid-State Electronics* **38(12)** 2041-2046 doi: 10.1016/0038-1101(95)00082-5
[9] Sugawara H *et al* 1992 *Applied physics letters* **61(15)** 1775-1777 doi: 10.1063/1.108423
[10] Feng Z C *et al* 1999 *Journal of Applied Physics* **85(7)** 3824-3831 doi: 10.1063/1.369752
[11] Bemš J et al 2014 Radiation Physics and Chemistry **104** 398–403 doi: 10.1016/j.radphyschem.2014.02.008
[12] Kapranov B I *and* Varga V V 1999 *Proc of KORUS'1999* **2** 876255 672–676 doi: 10.1109/KORUS.1999.876255
[13] Alkhimov Yu V *et al* 2012 *Russian Journal of Nondestructive Testing* **48(4)** 238–244 doi: 10.1134/S106183091204002X
[14] Vavilova G *and* Ryumkin A 2018 *IOP Conf Ser: Mater Sci Eng* **289(1)** 012017 doi: 10.1088/1757-899X/289/1/012017
[15] Surzhikov A P *et al* 2016 *IOP Conf Ser: Mater Sci Eng* **110(1)** 012002 doi: 10.1088/1757-899X/110/1/012002
[16] Maranowski S A *et al* 2005 *Proc of SPIE* **3002/110** 110–118
[17] Gradoboev A V *and* Orlova K N 2015 *Physica Status Solidi C* **12(1-2)** 35–38 DOI: 10.1002/pssc.201400072
[18] Gradoboev A V *and* Orlova K N 2014 *Advanced Materials Research* **880** 237–241 DOI: 10.4028/www.scientific.net/AMR.880.237
[19] Orlova K N *et al* 2012 *Proc of IFOST'2012* **1** 1-4 doi: 10.1109/IFOST.2012.6357528
[20] Orlova K N *and* Gradoboev A V 2014 *Proc of CriMiCo'2014* 874-875 doi: 10.1109/CRMICO.2014.6959672
[21] Ashry M *et al* 2004 *Radiation Effects and Defects in Solids* **159(8-9)** 453-460 doi: 10.1080/10420150410001670297
[22] Suzuki M *et al* 1993 *Journal of Crystal Growth* **133(**3-4) 303-308 doi: 10.1016/0022-0248(93)90169-W
[23] Makhkamov S *et al* 2005 *Radiation Effects and Defects in Solids* **160(8)** 349–356 doi: 10.1080/10420150500415116