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Research Article

Features of the Electrical and Optical Characteristics of the Original and Irradiated by γ-quanta Co^{60} InGaN/GaN LEDs with Quantum Wells

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Abstract

The results of studies of the electrical and optical characteristics of the original and irradiated by γ-quanta Co^{60} of high-efficiency InGaN/GaN blue light-emitting diodes with quantum wells are presented. Possible mechanisms for the appearance of singularities in current-voltage characteristics at low temperatures (T ≤ 180 °K) are discussed. It was found that the process of radiative degradation of electroluminescence is accompanied by an increase in the carrier temperature Te and an increase in the activation energy of electroluminescence.

Keywords: InGaN/GaN; Electrical and Optical Characteristics; Irradiated by γ-quanta Co^{60}

Introduction

The intensive development of communication and information networks, means of control, processing and management of information arrays contributes to the expansion of the search for more reliable and efficient light-emitting diodes (LEDs) than traditional ones grown on the basis of GaP, GaAs, or their solid solutions, which could satisfy the needs of consumers in the visible region.

Heterostructures, due to their inherent barriers at the boundaries of the contact and active layers, make it possible to keep charge carriers in the active zone of the diode; the presence of quantum wells (QWs) in it contributes to their accumulation, and then to the avoidance ofrecombination through non-radiating centers [1,2].

The defining feature of the use of the InGaN solid solution as the active region of the LED is the direct bandgap of nitride solutions, in contrast to, for example, GaAsP solutions.

Consequently, a change in the ratio between the In and Ga components does not affect the transition probability and, accordingly, the quantum yield [2-4].

The cheapest option for manufacturing a source of “white” glow as close to natural as possible is based on the use of phosphors. The principle of RGB mixing, when structures emittedat different wavelengths are combined in one LED module, faces the problem of the “green valley” of increasing the In concentration, which is necessary to shift the emission maximum to the red region, accompanied by clustering of atoms and an increase in the lattice mismatch of thesolution InGaN and GaN. Strengthening the role of the quantum-limited Stark effect leads to the separation of the wave functions of the electron and hole, and, as a result, to a drop in the quantum yield [4-8].

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But if the problem of the "green valley" in InGaN/GaN LEDs is directly related to an increase in the defect level of the bottom of the QW, then there is no unequivocal opinion in the literature regarding the reasons for the drop in the quantum yield at currents slightly higher than the nominal value (I_{nom} ≈ 20 mA) [9-16].

Therefore, the use of penetrable radiation for the purpose of controlled introduction of structural defects into the objects under study can contribute to the elucidation of their role in themechanism of degradation of device characteristics.

It is also worth noting that an artificial satellite of the Earth, passing through the Van Allen radiation belt, receives up to 25 rem per year, so the issue of radiation stability of elements of onboard optoelectronic modules currently remains quite relevant [8].

Taking into account the incomparably high (compared to cosmic) particle flux densitiesand intensities of radiation fields of modern accelerators and nuclear installations, where it is possible to use optoelectronic communication lines or devices for displaying, storing, and processing data, we also note that the study of the radiation resistance of their active elements is one of the components of ensuring the reliability of operation of the above-mentioned heavy- duty sources of penetrating radiation.

The experiment

Original blue λ_{max} = 470 nm LEDs InGaN/GaN with QWs were studied. The current- voltage characteristics (CVCs) were measured in the modes of a current generator and a voltage generator in the range of 77 ÷ 300 °K. The emission spectra were recorded by an automated system assembled on the basis of the monochromator MDR, and the change in the quantum yieldwas controlled by a device based on a silicon photodiode. Irradiation by γ - quanta was carried out in a gradient field of the Co^{60} source within doses of 0 ÷ 1.5 Mrad at room temperature.

Result and Discussion

Electrical properties

It is known that the process of the current generation in 2D objects, such as QWs of the InGaN active layer, is mainly affected by three specific nanoscale phenomena: quantum confinement at the QW - barrier interface; ballistic transport of carriers together with the interference of electron waves and tunneling of carriers through barrier layers [17-19].

The effect of their ballistic movement and interference phenomena are observed along the channels created by the QWs barriers. The low-dimensionality condition, according to which the mean free path of the carrier l must exceed the width of the QW "a" for semiconductor layers, is fulfilled, since l for them is of the order of microns, typical widths of QWs are 10 ÷ 20 nm (for example, in structures based on GaAs l ≈ 120 nm; a ≈ 10 nm) [17].

The current flow in the longitudinal direction across the barriers proceeds by tunneling, and resonance penetration is of particular importance when the level of the Fermi injector at a certain voltage coincides with the discrete level of the nearest QW. In the case when QWs are of the same type, carriers can flow through several barriers [18].

Figure 1 and Figure 2 show the CVCs of a blue LED taken in the generator current mode for various temperatures. Within the temperature range 180°K ÷ 290°K and voltages U ≤ 2.5 V, the dependence I(U) is consistent with the Shockley model [20,21]:

$$I = I_S(e^{\frac{qu}{nkT}} - 1) \qquad \text{---------(1)}$$

n is the diode ideality factor equal to 2, which indicates the predominance of the recombination-tunneling component in the total current; I_S is the reverse saturation current.

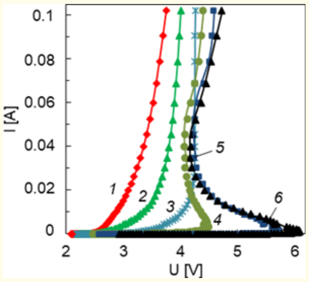

Figure 1: CVCs of the original InGaN LED (λmax = 470 nm, blue) were taken at different temperatures in the current generator mode (linear scale): 1 - 290 K; 2 - 230 K; 3 - 180 K; 4 - 130 K; 5 - 95 K; 6 - 77 K.

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It is appropriate to note that the study of the mechanism of the occurrence of a nonlinearirregularity of this type on the CVCs can give, in addition to cognitive practical results, the use of InGaN/GaN LEDs as low-temperature optoelectronic high-speed switches.

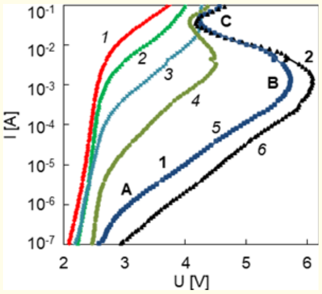

Figure 2: CVCs of the original InGaN LED (λmax = 470 nm, blue) taken at different temperatures in the current generator mode (semilogarithmic scale): 1 - 290 K; 2 - 230 K; 3 - 180 K; 4 - 130 K; 5 - 95 K; 6 - 77 K.

As can be seen from Figure 2 (section AB), after $u \approx 2.5$ V, the current growth slows down, which is especially pronounced in the low-temperature region (curves 1, 2). This trend is an obvious consequence of the effect of the series resistance of the diode. Its value can be obtained using the Shockley formula [2] modified for this case:

$$I = I_S e^{\frac{q(u-IR_S)}{nkT}} \qquad \text{---------(2)}$$

And the experimental CVCs.

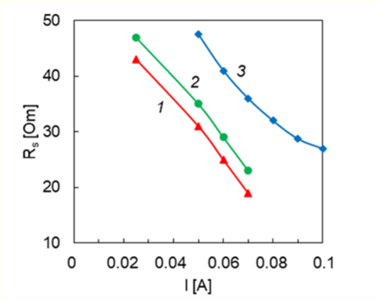

Figure 3: Dependence of the value of the series resistance of the diode Rs on the current through the diode. Original LED InGaN (λmax = 470 nm, blue): 1 - 290 °K, 2 - 77 °K, 3 - 300 °K in the area of high currents.

Figure 3 shows the similarly calculated dependences of R_s from current through the diode for temperatures T_1 = 77°K and T_2 = 290° K. It can be seen that an increase in current leads to a decrease in series resistance.

Its drop with an increase in the current through the diode can be due to the filling of QWs and the growing role of the above-barrier quasi-ballistic flow of charge carriers.

The main feature of the samples under study begins to manifest itself at T ≤ 150 °K, whena section of negative differential conductivity (NDC) of the S type appears on the CVCs (Figure 1,2), the formation of which is ensured in the general case by the existence of positive feedback in the system.

The effect of switching the diode to the "low-resistance state" is clearly demonstrated by the family of CVCs taken in the voltage generator mode (Figure 4).

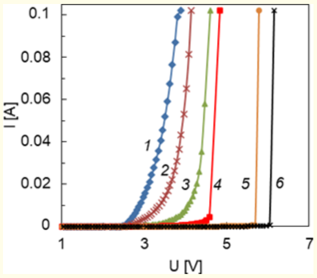

Figure 4: CVCs of InGaN LEDs (λmax= 470 nm, blue) taken at different temperatures in the voltage generator mode: 1 - 290 K; 2 - 230 K; 3 - 180 K; 4 - 130 K; 5 - 95 K; 6 - 77 K.

The dependence of the value of the negative differential resistance $\left(\frac{du}{dI}\right)$ and the dependence of the breakdown voltage on temperature are shown in figure 5.

Returning to the consideration of possible mechanisms that form individual sections of the CVC, we note that, as mentioned above, already at $I = (10^{-7} \div 10^{-3}$ A) and temperatures close to room temperature 290 °K ÷ 180 °K, within the exponential section, the tunneling effect playsa significant role in the emergence of a general current through the active region.

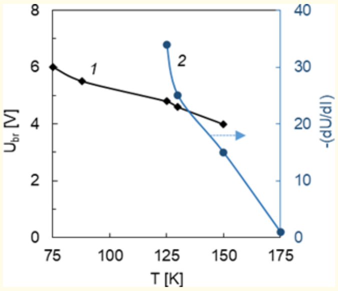

Figure 5: Breakdown voltage dependence on the CVCs on the temperature of the InGaN sample, blue N3 (1). Dependence of negative differential resistance on temperature (2).

The section of the power dependence $I(u)$ exists on all CVCs, and its length increases withdecreasing temperature. At room temperature, it has an almost linear dependence of the resistance R_S on the current, which may indicate a weakening of the effect of barriers between QWs and an enhancement of the above-barrier quasi-ballistic carrier transfer mechanism.

A further increase in the applied voltage up to $u = u_{br}$ may result in the coincidence of the Fermi level of the injector with one of the discrete levels of the QW, after which the resonant tunneling process begins.

Filling the QW promotes smoothing of the barriers and an increase in the carrier concentration in the active layer - the current continues to increase - a typical example of the effect of positive current feedback, which led to the appearance of NDC.

After the diode enters the NDC mode, due to the S-shaped specificity of the CVC, the voltage across the diode begins to decrease (section BC) and the resonance condition is violated, the diode leaves the state of resonant tunneling and returns to the quasi-ballistic charge transfer mode, however, under conditions of a higher level of filling with carriers, the value of R_s less than in section AB.

Figure 6 (a, b) shows the electroluminescence spectra of the original and irradiated(D = 1.5×10^6 rad) InGaN LEDs taken at different temperatures.

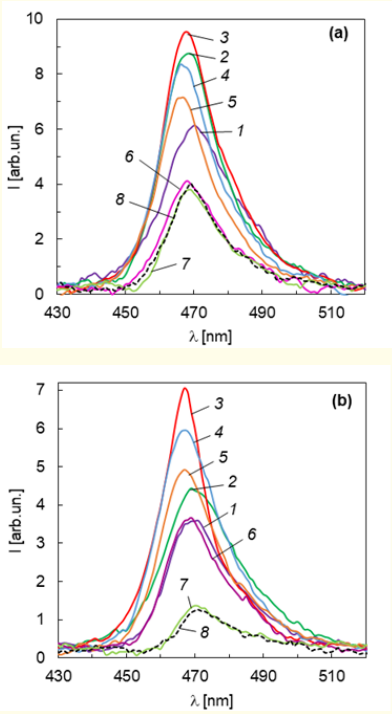

Figure 6: The electroluminescence spectra of the original (a) and irradiated (D = 1.5×10^6 rad) (b) InGaN LEDs taken at different temperatures (T), K: 1 - 290; 2 - 270; 3 - 250; 4 - 230; 5 - 190; 6 - 150; 7 - 110; 8 - 77.

The shape of the spectral curves was used to estimate the carrier temperature T_e and the activation energy of radiative recombination E_a [2]. The results of calculations for the original and irradiated diodes show that irradiation entails an increase in T_e and in E_a. It was also found that the quantum yield of samples with an absorbed dose of Co^{60} γ-quanta, D = 1.5 × 10^6 rad, decreases on average by 1.9 times in the region of the maximum.

The predominance of the non-radiative component in the recombination process and the existence of a high probability in it of the Auger mechanism for InGaN/GaN LEDs [9,22] make it possible to conclude that T_e can grow in the samples under study by direct transfer of the recombination energy directly to the carrier.

It was established in [23] that a change in the luminescence activation energy can be due to a change in the ratio between the barrier values between E_a^{irrad} and $E_a^{non-rad}$. Therefore, it is possible that in our case, the increase in E_a is precisely associated with a decrease in the value of $E_a^{non-rad}$.

Conclusions

In the temperature range 180° ÷ 290 °К and $u \leq 2.5$ V, the CVC of the diode is described by the Shockley relation, which at higher voltages is no longer valid due to the action of the series resistance of the diode R_s.

The decrease in the value of R_s with increasing current can be a consequence of the overfilling of QWs by carriers and an increase in the role of the above-barrier quasi-ballistic overflow mechanism.

After $T \leq 150$°К, a region of negative S-type differential conductivity appears on the CVCs, the existence of which is due to positive current feedback, which may be based on the effect of resonant tunneling between the levels of QWs.

Irradiation by γ-quanta Co^{60} is accompanied by a decrease in the quantum yield as a result of the introduction of deep non-radiating levels into the crystal, an increase in the temperature of current carriers, and an increase in the activation energy of the electroluminescence process.

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