Photoelectric diagnostics of InGaN-based LEDs in static and dynamic modes

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Abstract. The method and measuring installation for diagnostics of light-emitting heterostructures (HS) with the quantum well (QW) by registration of the photocurrent arising in case of radiation of HS the narrow-band optical radiation of different wavelength in the static and dynamic modes are described. On the example of commercial InGaN-based LEDs it is shown that offset of a maximum of photocurrent spectrum concerning a maximum of electroluminescence spectrum is defined by QW depth. The steepness of photocurrent spectrum on the section corresponding to absorption in QW is defined by structural perfection of heteroboundaries. In case of harmonic modulation of a luminous flux on all probed wavelengths amplitude of a photocurrent of blue LEDs monotonically falls down with growth of modulation frequency with the steepness 0.2 dB for a decade, and at green LEDs to the frequency of 200 kHz the plateau and then recession with the steepness 8 dB for a decade is watched.

1. Introduction

For the non-destructive diagnostic of the InGaN-based LEDs with quantum well (QW) developed various methods, including photoelectric, based on the measurement of parameters and characteristics of the LED during irradiation with monochromatic radiation [1, 2]. The purpose of this operation to show communication of amplitude and frequency responses of the photocurrent arising in an external circuit of a LED in case of radiation by its narrow-band optical radiation with parameters and quality of LED HS.

If energy of the falling photons is more than width $E_{g}^{QW}$ of the forbidden band of material QW, but it is less than width $E_{g}^{GaN}$ of the forbidden band of GaN-barriers, then light absorption and generation of excess charge carriers happens only in QW (figure 1a). At the same time the charge carriers generated by light by means of thermal burst, a tunnel effect and photoexcitation [3] can pass from QW into barrier areas and move freely in the direction, perpendicular to the interface (figure 1b), as leads to appearance of a photocurrent in case of switching on of the LED in a closed circuit. The excess charge carriers arising when lighting create a photocurrent if it is generated in the space-charge region (SCR) or at distance of no more diffusion length from its boundaries. Level of a photocurrent is defined by the speed of activation of charge carriers, that is speed of their burst from QW: where $\eta$ – share of the activated charge carriers forming photocurrent. Speed of activation is defined by different mechanisms and can be found (is estimated) from an equilibrium condition of processes of generation and disappearance of charge carriers at QW:
\[
\frac{dn}{dt} = G - R - A,
\]

where \( G = kW\beta F \) – the speed of photogeneration of charge carriers in QW, \( k \) – a radiation absorption coefficient in material QW, \( W \) - thickness QW, \( \beta \) – quantum yield, \( F \) – density of the luminous flux density falling on QW, \( R \) – the full speed of a recombination representing the amount of speeds of a radiant and nonradiative recombination.

Precisely it isn't possible to describe all processes happening in HS in case of its radiation by light, but in the stationary mode \( (dn/dt = 0) \) from (1) follows that \( A = G - R \), and for qualitative analysis it is possible to use expression:

\[
I_\Phi = \eta(G - R).
\]

Figure 1. Generation of a photocurrent in heterostructure with a quantum hole (schematically).

When training structure radiation with the energy of photons exceeding width of the forbidden band of a barrier layer, optical radiation is absorbed both in QW, and in barrier layers (figure 1a), and the equilibrium condition will have more difficult appearance, than (1). With a further growth of energy of photons the main part of radiation will be absorbed near a surface of structure, at the distance considerably exceeding the diffusion length of charge carriers, and the photocurrent will decrease.

In the dynamic mode in case of switching on and switching off of a flare of HS LED the photocurrent will rise and fall down not instantaneous, and with growth of modulation frequency of a luminous flux the amplitude of a photocurrent will decrease. The steepness of this recession is defined by effective times of a recombination and activation of charge carriers in QW HS. Qualitative analysis shows that constants of time of rise and recession of a photocurrent shall differ, and on a waveform of a relaxation it is possible to judge the speed of the specified processes.

2. Experimental setup for the study of photocurrent spectra
Measurement of a photocurrent and photovoltage of LEDs was carried out in case of radiation them by narrow-band radiation, the close to monochromatic, created on an output of the spectrophotometer SF-46 with a width of output slot of 6,5 nm, in the range of lengths of waves 350…530 nm and the range of flux density of radiation 0,03…5000 uW/cm² (figure 2). Photocurrent spectrum of LEDs was calculated by normalizing the measured spectrum to the spectrum of the radiation source. The central wavelength and width of narrow-band radiation was in addition controlled by OceanOptics USB2000 spectrometer. Emissive power was measured by the integrating sphere of TKA-KK1. As a source of radiation the 100 W glow lamp was used. A photocurrent and photovoltage depending on the diagram of switching on of the researched LED the registered the universal B7-21A voltmeter. The electroluminescence spectrum of the LEDs was measured by the Ocean Optics USB2000 spectrometer.
3. Measurement and analysis of a photocurrent spectrum of LEDs

We investigated commercial InGaN-based LEDs of two types: blue LEDs C503B-BAN-GY0461 produced by Cree (central wavelength of the EL spectrum 470 nm) and green LEDs ARL-5213 PGC produced by Arlight (central wavelength of the EL spectrum 525 nm).

Figure 3 shows the PC spectrum and EL spectrum of blue LEDs measured at a current of 1 mA. The maximum of photocurrent spectra corresponds to energy of the falling radiation 2.92 eV, and a LED electroluminescence spectrum maximum – 2.64 eV. Stokes’s shift characterizing losses in structure makes 0.28 eV. From figure 3 it is visible that the photocurrent spectra plotted in half-logarithmic scale has several line (exponential) sections of different steepness, and, the more steep the spectral characteristic of a photocurrent, the is higher homogeneity of HS [4]. The most steep section is watched in the range from 2.6 eV to 2.68 eV that testifies to homogeneity of the interface of heteroboundaries of QW. Fractures on a photocurrent spectra demonstrate change of a contribution of different energy levels in QW in the general photocurrent. In case of the radiant energy corresponding to an electroluminescence spectra maximum, the photocurrent decreases more than much, and in case of energy less than 2.58 eV photogeneration of charge carriers almost completely stops.

Figure 4 shows the PC spectrum and EL spectrum of green LEDs. Stokes’s shift makes 0.56 eV. The left wing of a spectral characteristic in the range of energies 2.35…2.5 eV confirms losses on band-gap absorption of radiation in structure. The steepness of recession of the right wing of a spectral characteristic characterizes parameters of "tails" of frequency curve of statuses in the forbidden band and is evaluated by E₀ parameter value. The low level of orderliness of structure is confirmed by rather great values of the E₀ parameter.

As a result of measurement of a photocurrent and photovoltage of the LED in case of different flux density of the falling radiation it is set that value of a photocurrent of the LED linearly depends on flux density of the falling radiation within the probed range of intensity (figure 5). The photovoltage has the linear dependence from the level of the falling radiation in the range of small flux densities of radi-
ation and experiences saturation in the field of big flux densities in case of 1.9...2.1 Century. The same tension in case of live broadcast of a LED corresponds to threshold voltage of the beginning of a glow of a LED.

![Graph showing photocurrent and photovoltage vs radiation power density curves measured on green LED when irradiated with light at λ = 470 nm.](image1)

**Figure 5.** Photocurrent and photovoltage vs radiation power density curves measured on green LED when irradiated with light at λ = 470 nm.

**4. Measurement and analysis of dynamic characteristics of a photocurrent**

Figure 6 shows the photocurrent frequency dependences of the blue LED when irradiated with alternating luminous flux in the frequency range from 170 Hz to 7 MHz. Two LEDs with central wavelengths of 410 nm (UV) and 470 nm (blue) used as the source of variable optical signal. Register photocurrent was carried out on the collector resistor of 25 Ω. The alternating LED photocurrent was determined by measurement of alternating voltage on collector resistor by selective nanovoltmeter. The amplitude of the alternating optical signal is maintained constant over the entire frequency range. The measuring unit bandwidth is 100 MHz. The level of the photocurrent in the case of illumination of the blue LED is about 6 times less than when illuminated with UV LED, at the same time, in both cases the form of the frequency dependence of the photocurrent is almost identical.

For comparing the frequency dependences of a photocurrent of green and blue LEDs of the specified type are given in figure 7. In case of harmonic modulation of a luminous flux on all probed lengths of waves amplitude of a photocurrent of blue LEDs monotonically falls down with growth of modulation frequency with the steepness 0.2 dB for a decade, and at green LEDs to the frequency of 200 kHz the plateau and then sharp recession with the steepness 8 dB for a decade is watched.

![Dependences of the photocurrent of green and blue LEDs on the frequency of the incident radiation with λ = 470 nm.](image2)

**Figure 6.** Dependences of the photocurrent blue LED on the frequency of the incident radiation. **Figure 7.** Dependences of the photocurrent of green and blue LEDs on the frequency of the incident radiation with λ = 470 nm.
5. Conclusions

1) Photocurrent level in case of photoexcitation of light-emitting HS low-energy photons decides on QW by the sizes and zonal structure of QW.

2) Value of offset of a maximum of photocurrent spectra in relation to electroluminescence spectra of InGaN/GaN of LEDs is defined by QW depth.

3) Character of photocurrent spectra and in particular the steepness of dependence of value of a photocurrent on energy of photons on different sections of spectrum characterizes homogeneity of HS. The steepness of recession of a photocurrent of blue InGaN/GaN of the LED in the range 460…475 nm is defined by homogeneity of the interface of heteroboundary of QW.

4) In case of harmonic modulation of the falling radiant flux the level of a photocurrent of blue InGaN/GaN of the LED monotonically falls down with the steepness 0,2 dB for a decade of frequency, and at green InGaN/GaN of the LED to the frequency of 200 kHz the plateau, and at frequencies more than 200 kHz recession with the steepness 8 dB for a decade is watched.

Acknowledgments
The reported study was funded by RFBR and Government of Ulyanovsk Region according to research project № 16-47-732159.

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