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Change of radiative and low-frequency noise characteristics of UV LEDs based on InGaN/GaN quantum wells at liquid nitrogen temperature

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Abstract. The results of temperature studies of UV-band LEDs based structures with InGaN/GaN quantum wells are presented. At room temperature and liquid nitrogen temperature, volt-ampere characteristics, frequency dependences of low-frequency noise density, external quantum efficiency, and optical power were measured. The performed studies showed differences in the characteristics of UV LEDs at temperatures $T = 77.4$ K from those at $T = 295$ K. The possible physical mechanisms of the formation of low-frequency current noise, carrier transport, and the effect on the external quantum efficiency of the processes of radiative and non-radiative recombination at two temperatures are considered.

Keywords: external quantum efficiency, density of current noise, tunneling current

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Материалы конференции
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Изменение излучательных и низкочастотных шумовых характеристик УФ светодиодов на основе InGaN/GaN квантовых ям при температуре жидкого азота

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Аннотация. Представлены результаты температурных исследований светодиодов УФ диапазона на основе структур с InGaN/GaN квантовыми ямами. При комнатной температуре и температуре жидкого азота измерялись вольт-амперные характеристики, частотные зависимости плотности низкочастотного шума, внешней квантовой эффективности, оптической мощности. Рассмотрены возможные физические механизмы формирования низкочастотного токового шума, транспорта носителей, и влияние на внешнюю квантовую эффективность процессов излучательной и безызлучательной рекомбинации при двух температурах.

Ключевые слова: внешняя квантовая эффективность, плотность токового шума, туннельный ток

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Introduction

Optoelectronic devices based on nitride materials are currently widely used in various manufacturing industries. A significant increase in the production of UV LEDs (and lasers) based on InGaN/GaN and AlGaN/GaN is associated with the areas of application of light-emitting devices in this range. UV LEDs and lasers are used in industrial and agricultural production, as well as in criminology, banking and solid-state lighting. Of particular importance is the use of these optoelectronic devices in medicine, biology and sanitation.

The modern literature presents works aimed at improving the light-emitting characteristics (often only in the form of mathematical modeling), operability and reliability of semiconductor optoelectronic devices. Temperature measurements more affect the region of elevated temperatures [1–3]. Therefore, the change at reduced temperatures of radiative and noise characteristics [4–7] is of research interest.

With a decrease in temperature, the optical power increases and the degradation of LEDs slows down; the noise density of semiconductor diodes decreases. It has been experimentally established that external quantum efficiency in the range of low pumping current densities (less than 30 A/cm^2) increases monotonically with temperature decrease [8]. The radiative recombination increases due to an improvement in the distribution of carriers in the phase space.

Studies of noise density, its spectral composition are used to study degradation processes and forecast service life [9], for comparative studies of UV LEDs and LEDs in visible range [10, 11], improve the reliability of designed optoelectronic, semiconductor devices, and improve their production technology.

Comparative studies performed in this work at room temperature and nitrogen temperature were aimed at identifying differences in the operation of UV LEDs and the possibility of improving their characteristics under conditions of reduced temperatures. Mechanisms of formation of low-frequency current noise and recombination, transport of carriers to active area of InGaN/GaN quantum structures are considered.

Experimental

The experiments were carried out on commercially manufactured UV (UV-A) LEDs from Betlux with InGaN/GaN quantum well (X: BL-L563VC with peak radiation energy h_{QW} = 3.06 eV or radiation wavelength λ = 405 nm, nominal current I = 20 mA, luminous intensity of 100 mcd and Y: BL-L522VC with the same parameters and luminous intensity of 180 mcd). The actual area of LEDs is ~ 10^{-3} cm^2. Also, control measurements were carried out on blue indicator LEDs from Nichia NSPB300, h_{QW} = 2.36 eV, λ = 465 nm, external quantum efficiency η = 15%, luminous intensity is 2300 mcd. Measurements of current, photocurrent and density of low frequency current noise were made at room (T = 295 K) and nitrogen temperatures (T = 77.4 K). The silicon photodiode FD-24K was located at a strictly fixed distance from the LED and was used to measure only relative changes in the emission intensity (photocurrent) and external quantum efficiency. The power source was a GPS-4303 DC device; the voltage was set using a high-precision Agilent 34401A multivoltmeter. The photocurrent in the short-circuit mode was measured by a digital ammeter.

The time dependence of voltage deviations at the load resistance R_L = 100 Ω in the range of three decades of frequency (with a maximum frequency of 7.3 kHz) was measured using an analog-to-digital converter (own noise level 1 μV). The semi-automatic installation was used to measure the density of low-frequency current noise (in four bands with central frequencies of 20, 70, 270 and 1000 Hz) and its frequency dependence. The computer program remembered $2\cdot10^6$ samples with a sampling frequency of 16 kHz. A detailed description of the experimental setup is given in [12].

Results and Discussion

Fig. 1, *a* shows the results of measuring the optical power (photodiode current) as a function of the current at forward bias I for LED X. At $T = 295$ K, the dependence of the photocurrent has the character of $I_{ph} \infty I^{1.5}$ at $I \leq 100$ μA, at $I \geq 1$ mA it is close to $I_{ph} \infty I$. At $T = 77.4$ K at $0.1 \leq I \leq 1$ mA, there is a significant slowdown in the growth of the photocurrent, followed by its acceleration at high currents. The dependence of the photocurrent at low temperature first exceeds the photocurrent at room temperature, and after the deceleration section becomes less than it.

Fig. 1, *b* represents the dependences of the external quantum efficiency of LED X on the current $\eta(I)$ for two temperatures. At $T = 295$ K, the curve has a traditional character with saturation and a slight drop at nominal current. At $T = 77.4$ K at $I \leq 0.1$ mA, the quantum efficiency greatly exceeds the efficiency at room temperature. A significant decrease in efficiency coincides with the region of currents slowing down the growth of photocurrent. The subsequent increase in the efficiency at $I \geq 4$ mA corresponds to the region of a rapid increase in the photocurrent (at $T = 77.4$ K) and saturation and an insignificant drop in the quantum efficiency (at $T = 295$ K).

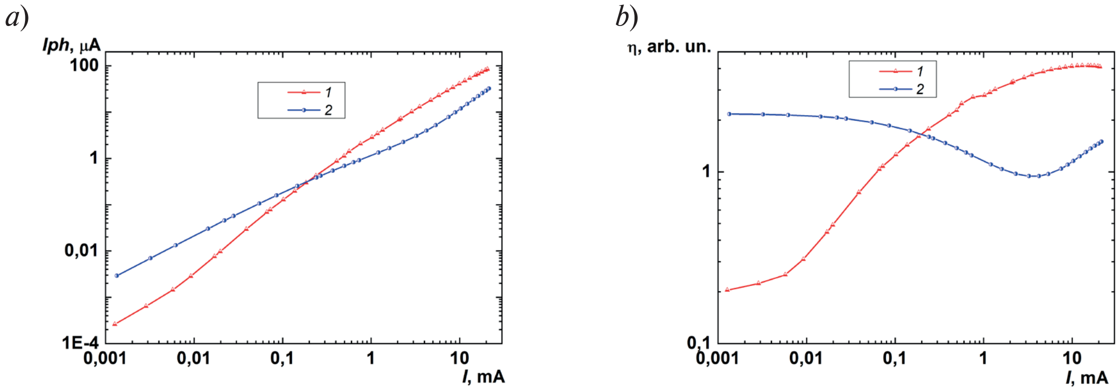

Fig. 1. Photocurrent (*a*), external quantum efficiency (*b*) of UV LED at $T = 295$ (1) and 77.4 (2) K at forward bias for LED X

For comparative studies, measurements of photocurrent and external quantum efficiency in blue LEDs were carried out. Fig. 2, *a* shows the dependence of the optical power on the current at forward bias. At $T = 295$ K, the dependence is close to $I_{ph} \infty I$. And at $T = 77.4$ K, the threshold current $I_{th} = 0.24$ μA; at $I = 0.1 \div 2.0$ mA, the growth of the photocurrent slows down (sublinear dependence) and it becomes less than at $T = 295$ K. Fig. 2, *b* represents graphs of current dependences $\eta(I)$ of a blue LED. Dependencies qualitatively repeat the picture of Fig. 1, *b*. The efficiency of the blue LED at $T = 77.4$ K at $I \geq 0.04$ mA begins to decrease and becomes less than the efficiency at $T = 295$ K. At nominal current, a slight increase in η is manifested, which was not observed before [13].

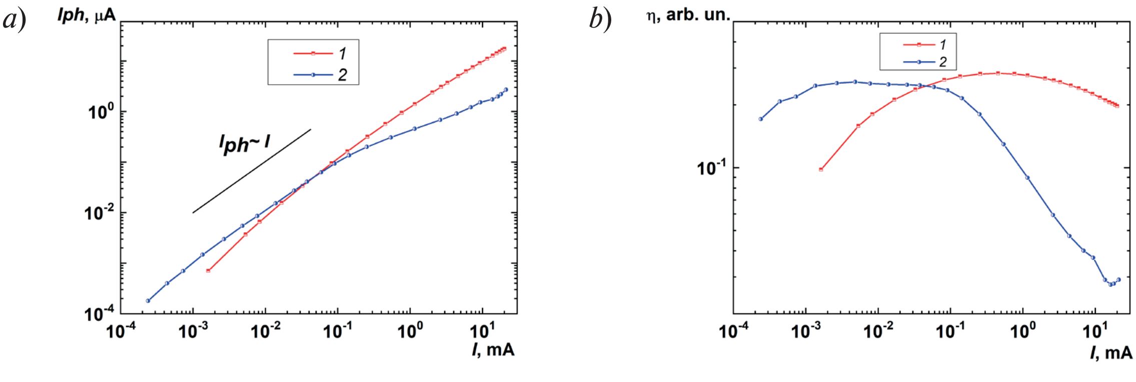

Fig. 2. Photocurrent (*a*) and external quantum efficiency (*b*) of blue LED at T = 295 (1) and 77.4 (2) K at forward bias

When the temperature drops below room temperature, the external quantum efficiency increases (in the case of UV LEDs at $I \leq 0.2$ mA), which is explained by *a*) a decrease in the rate of non-radiative recombination; *b*) an increase in the rate of radiative recombination due to greater overlap of the wave functions of the electron and the hole. The change in the filling of the phase dk space with a decrease in temperature contributes to this, because the number of carriers per interval dk in k-space decreases with an increase in temperature [14] and increases with a decrease in temperature. *c*) At low temperatures ($T < 80$ K), the movement of carriers into quantum wells QWs becomes ballistic or quasi-ballistic [5]. In general, the transport of electrons and holes to the active zones is improving; d) tunnel leakages of charge carriers from QWs to the space charge region are reduced [15, 16].

In the studies performed with a slowdown in the growth of photocurrent at liquid nitrogen temperature, a significant drop in the external quantum efficiency at this temperature is observed. In contrast to [8], where a monotonous increase in efficiency was observed with a decrease in temperature to $T = 160$ K in the same current range, in the presented work the quantum efficiency at $T = 77.4$ K becomes less than the efficiency at $T = 295$ K (for $I \geq 0.2$ mA).

In the ABC model [17], the internal quantum efficiency is $\eta_{int} = Bn^2/\{\mathrm{A}n + Bn^2 + Cn^3 + F(n)\}$, where n is the carrier concentration, A, B, C are the coefficients of non-radiative Shockley-Reed-Hall recombination, radiative recombination and non-radiative Auger recombination, respectively. The fourth term in the denominator $F(n)$ is added to take into account the possible outflow of carriers from the QW to the barriers [18]. The temperature dependences of A, B, C are presented in [2], and in [19] the current dependences of recombination rates are given for various mechanisms. Based on these articles, it can be concluded that *a*) as the temperature decreases, B and C coefficients decrease; *b*) as the current increases, the concentration of n increases, which leads to an increase in A and a decrease in B. The coefficient C (Auger recombination) seems to change little in this range of currents. Associated with these changes is the decreasing part of the current dependence of the quantum efficiency at $T = 77.4$ K (Fig. 1, *b*). The subsequent increase in efficiency ($I > 4$ mA) is determined by the superiority of the rate of radiative recombination over the rates of non-radiative recombination [19].

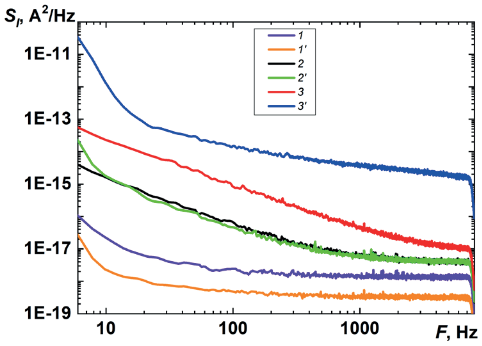

Fig. 3. Frequency dependence of the spectral density of current noise for LEDs X – 1,2, 1',2'; Y – 3, 3' at $T = 295$ (1, 2, 3) and 77.4 (1', 2', 3') K at a current of 2.2 (1), 2.0 (1'), 20.7 (2), 20.3 (2'), 21.0 (3), 20.0 (3') mA

Fig. 3 shows the frequency dependences of the current noise density for the UV LEDs X and Y. These dependences have a sharper slope ($\infty 1/f^{\alpha}$) in the low-frequency part of the spectrum, $1 < \alpha \leq 4$. This is most clearly manifested for the dependences at $T = 77.4$ K, where both LEDs X and Y have the highest α value. This may be due to the addition of two or more low-frequency noise mechanisms. An increase in noise density with an increase in the magnitude of the current (dependence 1, 1', 2, 2') at frequencies > 3000 Hz indicates an increase in frequency independent noise. Noise with a "white" spectrum at these frequencies is associated with shot noise due to random photon radiation [9] and increases with current growth at forward bias to the value ~ 10^{15} A/Hz.

The observed increase in noise density in the low frequency region suggests the participation of several types of noise in the formation of frequency dependencies. These can be flicker noise, telegraph noise, generation recombination noise, and noise related with the defect-assisted tunneling.

The high density of defects in InGaN/GaN-based LEDs provides tunneling transport of charge carriers (trap-assisted tunneling (TAT), model [20]) to the active region through potential barriers. In the TAT mechanism, the determining factor is the distance between the centers, since tunneling in the space charge region SCR occurs along deep centers and tails of the density of states of the bands. Near the QW, their density is minimal. At low temperatures, this type of carrier transport becomes predominant [21]. The dual role of defects in the SCR is manifested in the provision of carrier transport and participation in recombination processes.

The low-frequency tunnel resistance noise associated with charge fluctuations at the levels during horizontal jumps (model [12]) is represented by the same mathematical description as the generation-recombination noise [22]. The latter is determined by vertical transitions between centers and free bands. In tunneling transport, the low-frequency current noise is determined by the random distribution of centers over the SCR at the tunneling level. The hopping frequency depends exponentially on the distance between the centers, which is determined by their density [23]. An increase in the tunneling transport of carriers through barriers in a QW is possible due to a change in the spectrum of defects during the flow of current, unevenly distributed over the cross section of the LED [7, 24]. These changes can be caused by non-radiative recombination processes. The amount of energy released in them is close to the semiconductor band gap [19, 25].

The calculated dependences of current on voltage at the *p*-*n*-junction $I(V_I)$ were approximated by the exponential function $I = I_0 \exp(qV_I/n_I(V_I)kT)$, where kT is the thermal energy, q is the elementary charge, and $n_I(V_I)$ is the ideality factor, which determines the features of the current flow, was calculated as $n_I = (q/kT)/(\mathrm{d}lnI/\mathrm{d}V_I)$. The obtained values $n_I(I) \geq 2$ (for $T = 295$ K) only for $I \leq 10$ μA. In the rest of the current range, the values $n_I(I) < 2$. This suggests that the above-barrier injection of carriers into the QW is dominant in almost the entire measured range of currents, while the fraction of the tunneling current is insignificant. At liquid nitrogen temperature, $n_I > 2$ in the current range $I \leq 3$ mA, i.e. hopping conductivity (tunneling) through defects predominates. Consequently, at $T = 77.4$ K, the contribution of noise associated with tunneling through defects is significant, while at $T = 295$ K, other types of noise are mainly manifested.

Conclusion

The performed studies showed differences in the characteristics of UV LEDs at low temperatures ($T = 77.4$ K) from room temperatures. Despite the increase in the external quantum efficiency at low currents (< 0.2 mA) at $T = 77.4$ K, at high currents there was a drop in efficiency compared to the external quantum efficiency at room temperature. At the temperature of liquid nitrogen in the transport of carriers the role of tunneling by defects increases. The spectrum of defects can change due to the energy released during recombination. A manifestation of this is a sharp increase in noise at the lowest frequencies ≤ 20 Hz, which is due to the addition of several noise mechanisms. The behavior of the external quantum efficiency and density of low-frequency current noise at intermediate temperatures is interesting.

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