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Drop in external quantum efficiency during cooling and noise density during heating in InGaN ultraviolet LEDs

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It has been shown that for ultraviolet InGaN/GaN industrial LEDs in a practical temperature range from −74 to 84°C, a decrease in the density of low-frequency noise during heating and a drop in the external quantum efficiency during cooling can occur. The observed features of the experimental dependences are explained on the basis of the physical mechanisms of carrier transport, primarily tunneling along defects and tails of the density of states in the band gap of a semiconductor.

Keywords: low-frequency noise, quantum efficiency, carrier transport, hopping tunnel conduction.

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Studies into the possibility of slowing down the degradation of solid-state radiation sources (due, e.g., to the formation of nonradiative recombination centers in active regions of heterostructures [1], degradation of ohmic contacts or LED lenses [2], or encapsulation [3]) are important for ultraviolet (UV) LEDs and lasers, since they age faster than devices operating in the visible range. The adjustment of morphology of nitride nanostructures is a feasible way to improve the characteristics of devices based on them and slow down their aging.

It is known that the density of low-frequency noise decreases, aging processes slow down, and the contribution of tunneling along defects [4] and impurities [5] to carrier transport becomes more significant as the temperature decreases. The luminescence intensity and the external quantum efficiency decrease during heating. It should be stressed that the examination of electrophysical characteristics of LEDs and lasers (in particular, the physical mechanisms inducing their variation during heating (280−500 K) [6–8] and cooling [9]) may help improve their electrophysical performance and slow down the aging of devices. It was demonstrated in [10] that the above regularities may be violated at low temperatures (77.4 K).

In the present study, the characteristics of UV InGaN LEDs were examined within the temperature range from −74 to 84°C with the aim of establishing the physical mechanisms responsible for their variation. Industrial UV LEDs with InGaN/GaN quantum wells (QWs) produced by Nichia (NSPU510CS with peak emission energy $h\nu_{QW} = 3.31$ eV, wavelength $\lambda = 375$ nm, external quantum efficiency $\eta \leqslant 30\%$, a power of 8200 μW, and a „T1 3/4“ package) were used. Their active area is $\sim 10^{-3}$ cm^2. At nominal current $I = 20$ mA, the increase in temperature of the active LED region is $\sim 10^\circ$C [11]. The setup for measuring spectral density S_I of low-frequency current noise and determining the external quantum efficiency was described in detail in [10].

Figure 1, *a* presents the dependences of photocurrent I_{ph} of an FD-7K photodiode (positioned at a distance of 4 cm from an LED) on current through the UV LED under forward bias for four temperatures (27, 2, −34, and −74°C). At currents $I < 1$ mA, the emission intensity increases gradually with decreasing temperature. At $I = 20$ mA, the ratio of dependences changes under cooling, and the photocurrent reduction at $T = -74^\circ$C is 30% of its magnitude at $T = 27^\circ$C. The value of η in Fig. 1, *b* increases during cooling at $I < 1$ mA, which agrees with earlier data. At $I > 1$ mA and $T = -34^\circ$C, the η value of UV LEDs starts decreasing. At $I = 20$ mA and $T = -34$, -74°C, the efficiency is 5 and 25% lower, respectively, than the one at 27°C. This contradicts the existing notion that the quantum efficiency and luminescence intensity should grow during cooling in this temperature range [9,12].

The internal quantum efficiency is $\eta_{int} = Bn^2/[An + Bn^2 + Cn^3 + k(n - n_0)^2 + \alpha I^p]$, where A, B, and C are the coefficients of nonradiative Shockley−Read−Hall recombination and radiative and nonradiatve Auger recombination, respectively, and the last two terms characterize the delocalization of carriers in QWs and their probable leakage [13]. The *ABC* model does not explain the observed drop in photocurrent and external quantum efficiency (Fig. 1), since radiative recombination coefficient B decreases with increasing temperature [7]. It disregards the assumption that hopping conduction along defects and tails of the density of states in the band gap may produce a significant contribution to carrier transport at such currents. Hopping conductivity $\sigma \propto \exp[-W_2/kT]$ (W_2 is the hopping activation energy) increases with temperature [14], facilitating the tunnel transport of carriers. This may explain the increase in efficiency observed when the temperature changes from −74 to 27°C. Carriers

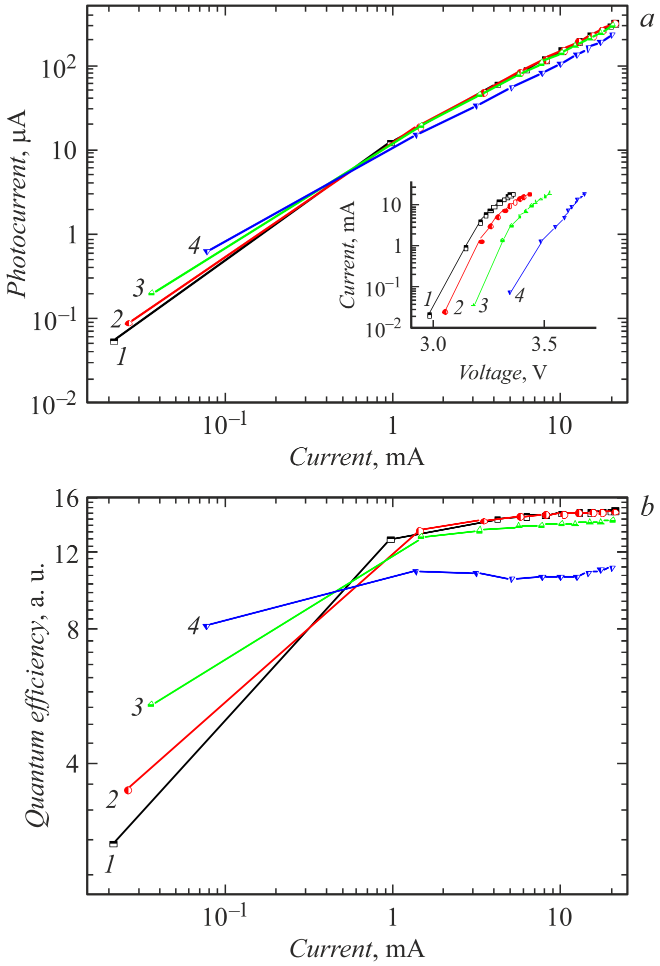

Figure 1. Dependences of the photocurrent of the measurement photodiode (a) and the external quantum efficiency (b) of the UV LED on current under forward bias and cooling. The inset shows the dependence of current on forward bias that increases monotonically during cooling. $T = 27$ (*1*), 2 (*2*), -34 (*3*), and -74°C (*4*).

tunneling from barriers into QWs along levels in the band gap are localized faster, which reduces the probability of tunnel leakage from QWs. The contribution of the last two terms in the denominator of the *ABC* model formula in carrier tunneling is reduced compared to the mechanism of over-barrier injection of carriers into QWs. The growth of tunnel conductivity with temperature prevents a local increase in current density associated with the redistribution of carriers and the unevenness of current flow in the LED, which would lead to an enhancement of nonradiative recombination and a drop in quantum efficiency.

The value of ideality factor m_I (calculated based on the data in Fig. 2, a) [10] may serve as an indicator of dominant current flow mechanisms in LEDs. At $I < 30\,\mu$A, $m_I(I) \geqslant 2$ (Fig. 2, b), indicating that tunneling along defects and tails of the density of states of allowed bands is dominant [15]. As the temperature rises from 27 to 84°C, the tunnel conductivity increases, which is evidenced by an increase in $m_I(I)$ (dependences *1–3* in Fig. 2, b).

With further growth of current, $m_I(I) \leqslant 2$, and the over-barrier injection current becomes dominant. However, the growth of current with bias voltage slows down at $I \geqslant 10$ mA (Fig. 2, a), and m_I starts increasing, while still remaining below 2 (Fig. 2, b). This implies an enhancement of the contribution of tunneling and reflects a change in the series resistance in the $p-n$ junction circuit, which slows down the growth of current and cannot be regarded as a constant resistor [1].

Noise density S_I decreases at all frequencies in Fig. 3 at $I < 100\,\mu$A during heating to 84°C (for voltage fluctuation density S_U at $I < 500$ nA and $40\,\mu\text{A} < I < 1$ mA). The carrier transport in QWs within this section is associated with tunneling along defects. According to the Hooge formula, the spectral density of $1/f$ current noise is $S_I = (\alpha I^2)/(fN)$, where N is the number of electrons involved in conduction, f is the frequency, and α is the Hooge constant. The reduction in noise density during heating is associated with an increase in tunnel hopping

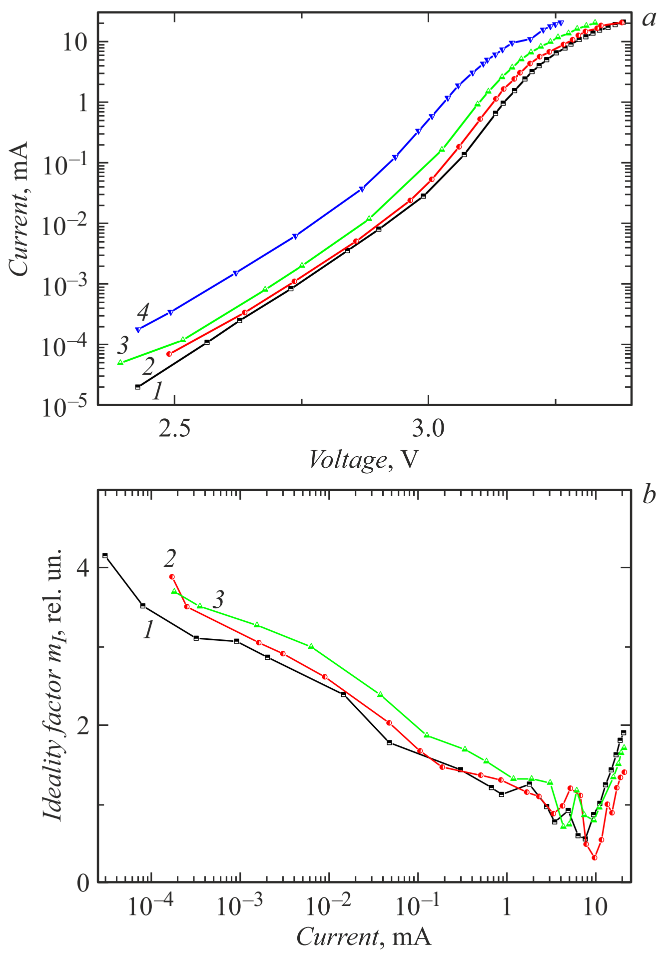

Figure 2. Dependences measured during heating of the UV LED: a — current versus forward bias at $T = 27$ (*1*), 40 (*2*), 50 (*3*), and 84°C (*4*); b — ideality factor m_I versus current at $T = 27$ (*1*), 40 (*2*), and 84°C (*3*).

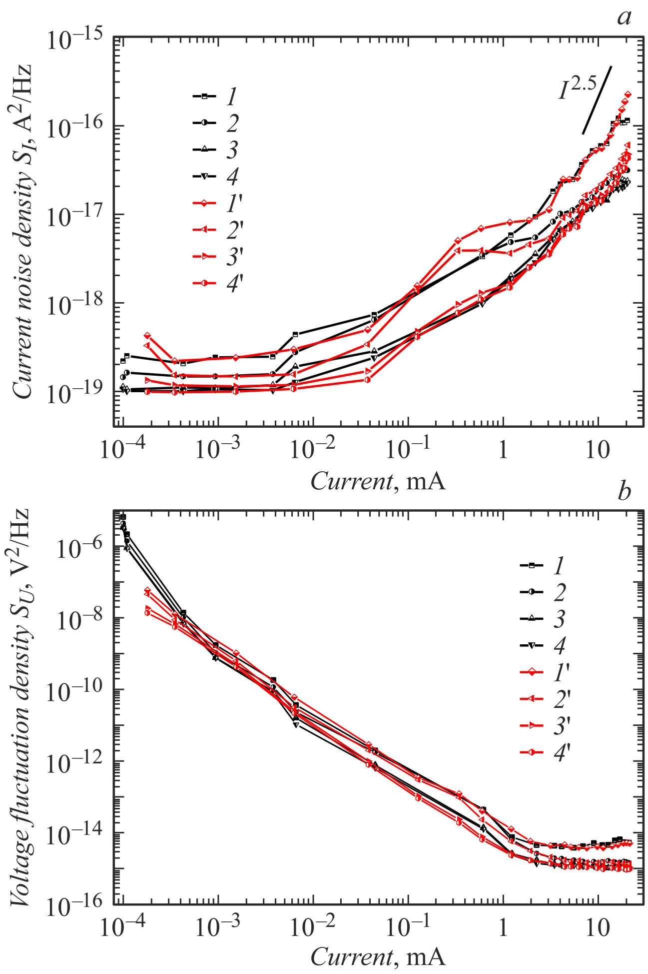

Figure 3. Dependences of spectral density S_I of current noise (a) and voltage fluctuation density S_U (b) on current for analysis frequencies $f = 20$ (*1*, *1*'), 70 (*2*,*2*'), 270 (*3*,*3*'), and 1000 Hz (*4*, *4*') at $T = 27$ (*1*–*4*) and 84°C (*1*'–*4*') for the UV LED.

conductivity and the value of N. At $I \sim 20$ mA and four measurement frequencies, current noise density S_I increases by a factor of approximately 2 as the temperature rises from 27 to 84°C (Fig. 3, a). As for S_U, the noise densities corresponding to all measurement frequencies remain approximately equal as the temperature rises to 84°C at this current. With such current values, over-barrier injection and recombination in barriers play a significant role in the transport of carriers across the cross section of LEDs with QWs. At $I < 100\,\mu$A, the tunnel resistance noise, which is associated with uneven filling of tunneling levels in the band gap [4], produces a significant contribution to low-frequency noise. This noise gets suppressed when the temperature increases. As the current grows, the contribution of this noise becomes less significant. Other mechanisms, such as generation-recombination noise or shot noise associated with photon emission, produce a greater contribution [16].

At $I > 10$ mA and a temperature of 84°C, spectral density of current noise $S_I \propto I^{2.5}$ for frequencies of 20, 70, 270, and 1000 Hz (Fig. 3, a). Such a dependence may be indicative of restructuring or formation of point defects in the light-emitting structure [17]. Forming defects may play a dual role in light-emitting structures with QWs. Their accumulation is manifested in an increased rate of nonradiative recombination and a reduction in quantum efficiency. At the same time, they establish hopping tunnel conduction, supporting carrier transport in QWs.

We note in conclusion that the examination of industrial UV LEDs revealed that, in contrast to long-held beliefs, the external quantum efficiency increased during cooling only at low currents; at nominal currents and negative temperatures, the efficiency started decreasing. A slight increase in the density of low-frequency noise was observed under heating to 84°C at $I > 10$ mA; at low currents ($I < 100\,\mu$A), this density decreased. The observed changes were explained by appealing to tunneling along defects as a carrier transport mechanism, which is a scientific novelty in interpreting the nature of observed features.

Conflict of interest

The authors declare that they have no conflict of interest.

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