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Noise spectroscopy of current in ultraviolet LEDs based on InGaN/GaN quantum well structures

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Received October 10, 2025
Revised October 10, 2025
Accepted November 29, 2025

The spectral density of low-frequency current noise increases sharply and changes its frequency dependence when the temperature drops below 150 K, in the flesh to the temperature of liquid nitrogen. Explanations are proposed based on changes in the mechanisms of carrier transport and the increasing role of nonradiative recombination.

Keywords: low-frequency current noise, quantum wells, tunnel resistance.

DOI: 10.61011/TPL.2026.03.63073.20523

Thermal studies of the characteristics of solid-state LEDs (based, e.g., on InGaN) are of obvious scientific interest, since they reveal the possibilities of application of optoelectronic devices in special climatic conditions and allow one to predict the duration of uninterrupted operation of LEDs and lasers in solid-state lighting sources and various equipment used in medicine, industry, agriculture, and sanitation. Light-emitting devices are heated during operation; the variation of their characteristics under heating within the range of temperatures $T = 280-500$ K was observed in [1,2]. The processes associated with cooling of lasers and LEDs have been studied less extensively [3,4]. Stability of their operation at extremely low temperatures is crucial for aviation, astronautics, satellite communications, and imaging in outer space during flights to the planets of the Solar System [5].

Most studies note an improvement in the parameters of LEDs and lasers under cooling. An increase in luminescence and efficiency with a T reduction from 300 to 160 K was reported in [6]. The external quantum efficiency (EQE) increases due to a greater overlap of the electron and hole wave functions in quantum wells (QWs).

Cooling is used to suppress noise in semiconductor devices [7]. Noise spectroscopy provides an opportunity to predict the duration of uninterrupted operation of optoelectronic devices, identify the energy levels of localized centers, and determine the location of defects in a device structure [8,9], which affect the reliability of its operation and structural changes during degradation. The aim of the present study is to identify changes in the mechanisms of current flow and the formation of current noise under cooling by examining low-frequency noise in ultraviolet InGaN LEDs and to demonstrate that low-frequency noise is not necessarily suppressed in the process of cooling of LEDs.

Industrial ultraviolet LEDs based on InGaN/GaN structures with QWs and emission wavelength $\lambda = 375$ nm were used to study low-frequency current noise during cooling to liquid nitrogen temperature. The chosen Nichia NSPU510CS LEDs had EQE $\eta = 30\,\%$, peak emission energy $h\nu_{\mathrm{QW}} = 3.31$ eV, an active area of 10^{-3} cm^2, and a nominal current of 20 mA. A FD-7K silicon photodiode operating in short-circuit conditions was used for relative measurements of luminescence and EQE. A description of the setup and the noise measurement procedure was provided in [10,11].

Figure 1, *a* presents the dependences of low-frequency current noise density S_I on frequency f at $T = 295$ and 77.4 K. At current $I \sim 1\,\mu$A, dependences S_I are almost indistinguishable. The noise density increases significantly with increasing I at $T = 295$ K: by a factor of 30 at ~ 2 mA and by another order of magnitude at ~ 16 mA. A more profound increase in S_I is observed at 77.4 K. The frequency dependences of noise at these two temperatures differ greatly in nature. At 295 K, noise is suppressed drastically at frequencies $f < 100$ Hz with a transition to Gaussian white frequency-independent noise. At $T = 77.4$ K, dependence $S_I \propto 1/f^b$, which exceeds significantly the noise density at 295 K, is maintained throughout the entire measurement range.

Figure 1, *b* presents the variation of frequency dependence of S_I with temperature under a forward bias and a current of 2 mA. In the process of heating from $T = 77.4$ to 295 K, the noise density decreases significantly (by three orders of magnitude at $f = 1000$ Hz) within the 133–171 K interval, and the nature of the dependence changes: the noise density follows the $S_I \propto 1/f^b$ law at low temperatures, but noise at frequencies $f > 100$ Hz becomes white under heating and increases slightly with increasing temperature in accordance with traditional assumptions.

This result is confirmed by the data in Fig. 2. The temperature dependence of S_I at $I = 2$ mA for four measurement frequencies features a sharp drop at $T \approx 150$ K. Further heating has little effect on the noise density value at each frequency.

The main mechanisms of current frequency-dependent noise in InGaN LEDs are flicker noise ($1/f$ noise), which

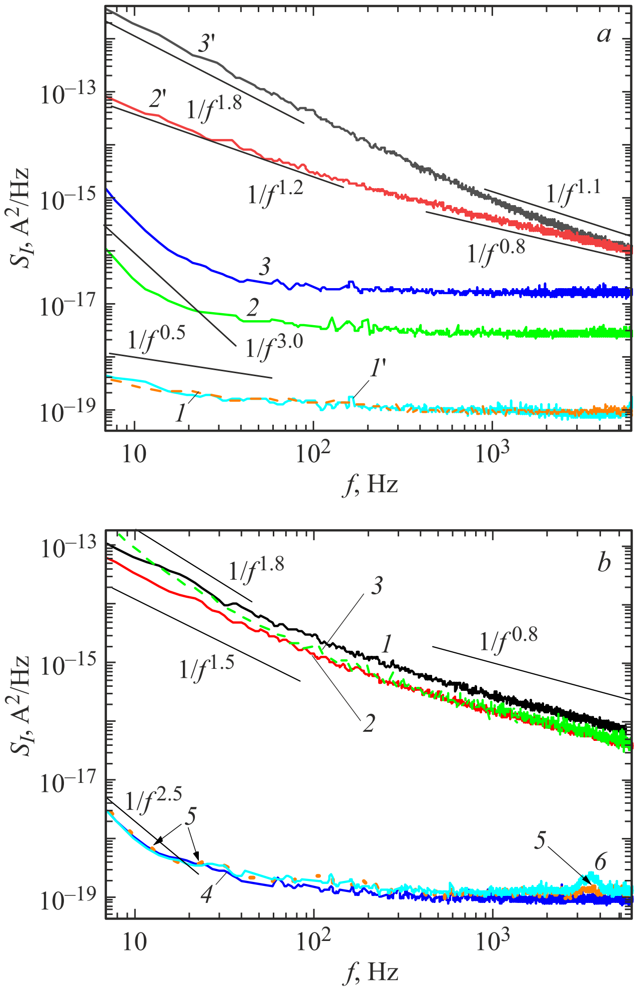

Figure 1. Frequency dependences of the spectral density of current noise at different temperatures. T, K: a — 295 (*1–3*), 77.4 (*1'–3'*); b — 77.4 (*1*), 101 (*2*), 133 (*3*), 170 (*4*), 258 (*5*), 295 (*6*). I, mA: a — 0.001 (*1*), 0.0015 (*1'*), 2.3 (*2*), 2.0 (*2'*), 15.9 (*3*), 14.4 (*3'*); b — 2 (*1–6*).

is associated with fluctuations of the number of carriers during directional motion and scattering [7]; generation-recombination noise produced by the capture and ejection of carriers from levels in the band gap (BG); and tunnel resistance noise determined by fluctuations of the number of carriers involved in hopping charge transfer to QWs:

$$S_I = S_{1/f} + S_{g\text{-}r} + S_{tun}. \qquad (1)$$

The spectral density of 1/f noise is $S_{1/f} = (\alpha I^2)/(fN)$. Here, α is Hooge's constant and N is the number of conduction electrons. The observed increase in S_I upon cooling is associated with a reduction in tunnel hopping conductivity and N.

Excess noise in semiconductor devices is caused by defects, structural imperfections, manufacturing imperfections [12], and an uneven distribution of defects in a sample. The observed frequency dependence of generation-recombination noise density $S_I \propto 1/f^b$ is attributable to the presence of a spectrum of defects in the semiconductor BG. In $1/f^b$-type semiconductor devices, fluctuations arise from a superposition of Lorentz-type spectra due to different processes of capture and emission of charge carriers in defects with a very wide distribution of relaxation times [8].

The shape of frequency spectra of the current noise density associated with fluctuations of the hopping resistance during tunneling through defects and tails of the density of states in the BG [13] is determined by Lorentzian function $S_I(f) \propto (1 + (2\pi f \tau_r)^2)^{-1}$ ($\tau_r = \varepsilon_0\varepsilon/\sigma_{hop}$ is the local time constant of dielectric relaxation, where σ_{hop} is the local hopping conductivity and ε_0 and ε are the electric constant and the relative permittivity, respectively). The hopping frequency is characterized by a wide range of local hopping times, which vary in the space charge region from nanoseconds to milliseconds [14]. The hopping conductivity increases with temperature [15,16], while the tunneling resistance and the associated noise increase with decreasing temperature.

Figure 3 shows dependences $I(V_I)$ of current flowing through an LED on the $p{-}n$-junction voltage. The dependences shift toward higher voltages as the temperature decreases. They were approximated by an exponential function. The ideality factor was calculated as $n_I = (q/kT)/(d\ln I/dV_I)$, where k is the Boltzmann constant and q is the elementary electric charge. Its dependences on current and temperature are shown in the inset in Fig. 3. At $I > 10$ mA, $n_I \leqslant 1$ and the current flow is dominated at all temperatures by above-barrier injection of carriers into QWs. The plot reveals a loose trend: n_I increases with decreasing I and T. At $n_I > 2$, the main mechanism is carrier tunneling to QWs through defects.

Figures 4, a, b present the results of relative measurements of optical power (open-circuit photodiode photocurrent I_{ph}) and EQE with the temperature varying from 77.4 to 295 K at a current of 2 and 20 mA. These dependences drop sharply at temperatures < 200 K, and this drop for

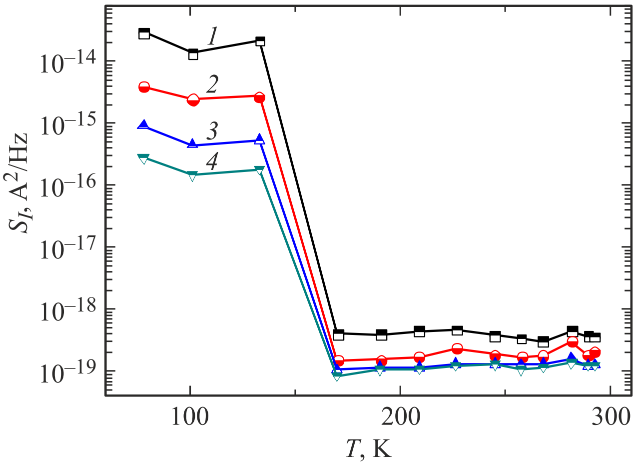

Figure 2. Temperature dependences of the spectral density of current noise for different analysis frequencies f at $I = 2$ mA. f, Hz: *1* — 20, *2* — 70, *3* — 270, *4* — 1000.

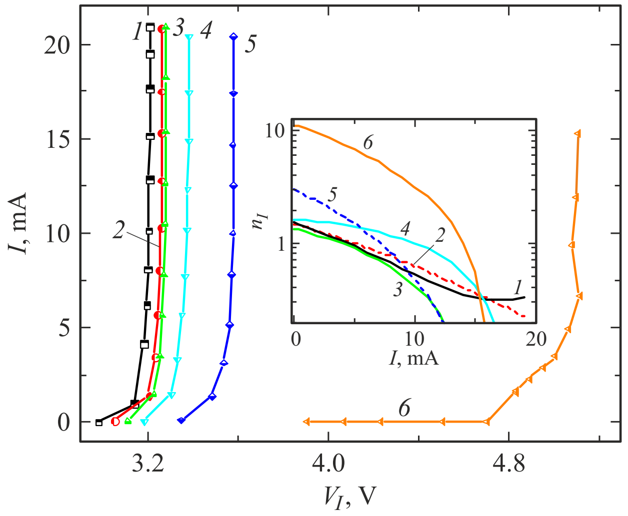

Figure 3. Dependences $I(V_I)$ of current on the $p-n$-junction voltage. The current dependence of ideality factor n_I is shown in the inset. T, K: *1* — 295, *2* — 275, *3* — 266, *4* — 240, *5* — 199, *6* — 77.4.

$I = 2$ mA is observed at lower temperatures. The temperature dependence of EQE features no regions where the efficiency increases with decreasing temperature. This behavior contradicts the established concepts [6] (the samples in this study were cooled down to 160 K). At $T < 150$ K, shallow defect (oxygen at a nitrogen site, nitrogen vacancy) levels reduce the intensity of electroluminescence by capturing injected carriers [17]. The LED emits virtually no light.

Comparing the obtained results with those published earlier, one may note that EQE and I_{ph} at 2 and 20 mA differ only slightly at liquid nitrogen temperatures. At 77.4 K, the EQE value in [10] at 20 mA is several times higher than the one at 2 mA, while the I_{ph} values differ by a factor of 15. At 295 K, I_{ph} at 20 mA is also an order of magnitude higher than the corresponding value at 2 mA. This is attributable to an increasing ratio of the densities of carriers transferred to deep and shallow QWs with decreasing temperature [3]. In [10], carriers tunneled to a deeper QW, where the number of carriers grows. In the present study with a shallower QW, nonradiative recombination current is dominant at 77.4 K: carriers mostly recombine at the barriers or tunnel below the QW. Their localization is made difficult. The leakage of carriers from a QW and possible delocalization are taken into account in the ABC model for the internal quantum efficiency [18]. The calculated barrier for electron and hole escape from a QW decreases with decreasing indium content x in $\text{In}_x\text{Ga}_{1-x}\text{N}-\text{GaN}$ QWs [19]. These phenomena are more pronounced in shallower QWs, and the currents characterizing them contribute to the formation of noise.

The noise density values at a frequency of 20 Hz and microampere currents are virtually equal (Fig. 1, *a*), and the noise density at 295 K in [10] is higher than at 77.4 K. At a current of 3 mA and 77.4 K, the noise density in [10] is an order of magnitude higher than at room temperature. In the present study, the noise density at a current of 2 mA with cooling increases by 3–5 orders of magnitude. Noise is more pronounced in currents associated with non-radiative processes.

All terms in (1) increase with decreasing temperature. In the case of above-barrier injection and tunneling of carriers to QWs with their subsequent localization and radiative recombination, the mechanisms of formation of frequency-dependent current noise are less pronounced, since random processes of photon emission lead to optical shot noise [20]. As the temperature decreases, the carrier transport across QWs may become ballistic or quasi-ballistic [3]. In addition, the current–voltage curves shift toward higher voltages under cooling (Fig. 3): field strength E increases ($J = \sigma E$, where J is the current density and σ is the specific conductivity). A significant suppression of scattering and accelerated carrier transport provide a given current density with a smaller number of charge carriers. According to Hooge, this increases S_I. In addition, the probability of tunneling to deeper QWs is higher, and a

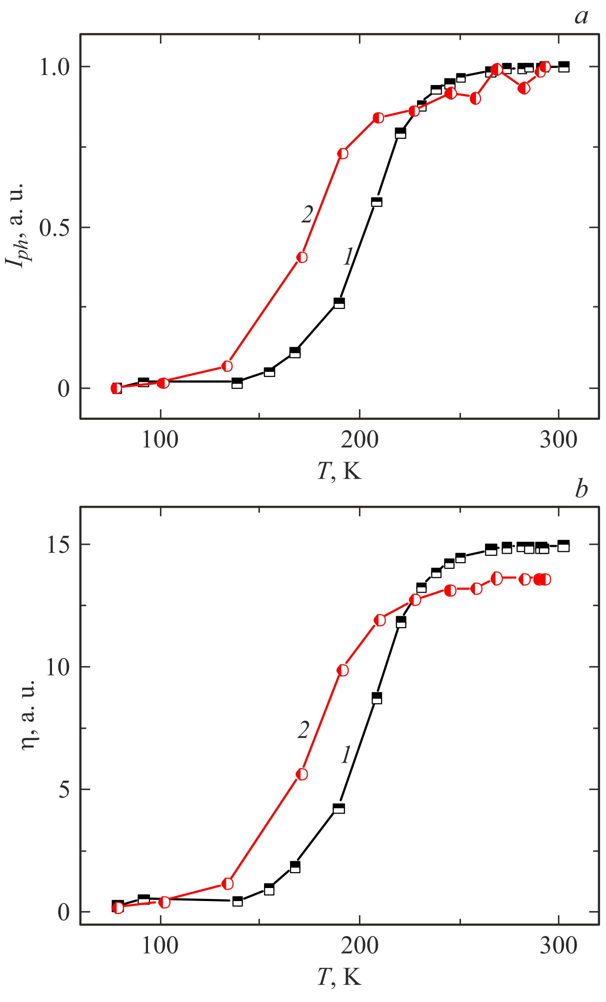

Figure 4. Temperature dependence of the photocurrent normalized to the maximum value (*a*) and the external quantum efficiency (*b*) at $I = 20$ (*1*) and 2 mA (*2*).

high noise level may be associated with defects outside QWs that contribute to leakage from the active region [9].

In general, it should be noted that the behavior of LEDs during cooling depends strongly on the indium content in InGaN structures. As the concentration of In decreases and QWs become shallower with a significant drop in temperature, the barrier for electron and hole escape from a QW becomes lower; in current under forward bias, the contribution of nonradiative recombination in barriers and through tunneling below the QW and the leakage of carriers from the QW increase. These processes provide a significant enhancement of current noise: flicker noise, generation-recombination noise, and tunnel resistance noise. The difference in QW depth is taken into account in the description of carrier transport in InGaN/GaN structures; at the same time, the mechanism of tunneling carrier transport is prioritized.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin