Study of characteristics of LEDs based on InGaN/GaN quantum wells under short electric impacts accompanied by joule heating

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Abstract. Results are presented of a study of commercial blue and UV light-emitting diodes based on structures with InGaN/GaN quantum wells. An accelerated aging was provided by currents of 80–190 mA under a forward bias with duration not exceeding 3 h. The study demonstrated the possible rise in the external quantum efficiency by 20% relative to that in the starting samples. The possible physical mechanisms responsible for the rise in the quantum efficiency and for the formation of a low-frequency current noise are presented.

I. Introduction
Light-emitting (LEDs) and laser diodes based on InGaN and AlGaN quantum-sized structures are widely used in medicine, biology, industrial manufacture, instrument making, forensic science, banking and serve for disinfection of air and medical instruments. Despite the multitude of modern studies [1–4], there is no commonly accepted concept of the mechanisms of degradation and failure of LEDs based on nitride materials. The mechanisms of aging of GaN LEDs and lasers and the possibility of mitigating this aging are of researchers interest. The understanding of the nature of the occurring changes will make it possible to make more reliable the operation of GaN LEDs by improving their fabrication technology.

At present, most of researchers believe that the degradation of GaN LEDs is associated with changes in the concentration of doping impurities in the p and n regions [1,4] and the formation of point defects, with this occurring both within the active region itself [3] and in barrier regions adjacent to the active region [5,6]. The increase in the concentration of point defects leads to higher the rate of the nonradiative Shockley–Read–Hall (SRH) recombination. An increase in the number of defects in barriers can facilitate the flow of charge carriers from quantum wells (QWs), which decreases the time of nonradiative recombination at high injection levels [2].

The increase in the concentration of intrinsic defects in the InGaN active region may possibly be responsible for the nonradiative SRH recombination in this region. First, the $V_{Ga3H}$ and $V_{Ga2H}$ complexes in InGaN act as effective SRH recombination centers [1], resulting in degradation of the internal quantum efficiency. Moreover, a long-term degradation of LEDs occurs due to the migration of Mg and H into the active region [7] or toward it [6], electromigration of contact metals [8], their interaction with p-type layer [9], degradation of the phosphor [10], and oxidation of the sheath material. A catastrophic failure is observed at extremely high currents (260 A/cm$^2$) due to formation of shunts, nonuniform power scattering, and current filamentation [11].
Noise level measurements are a good nondestructive tool for diagnostics of degradation processes in semiconductors. Measurements of the noise power and spectral composition can be used to predict the reliability of solid-state devices.

It has been known previously that the external quantum efficiency grows upon short current impacts [12].

In this study we examine a comparative changes in UV and blue LED parameters with InGaN/GaN QWs with a possible rise in the external quantum efficiency. We used the accelerated-aging special mode under short (not more than 3 h) test with currents (80 to 190 mA) under a forward bias. These currents strongly surpass the nominal currents of the studied indicator LEDs. The possible mechanisms of the observed changes, the formation of low-frequency current noise, and technological solutions aimed at improving the characteristics of GaN-based LEDs are presented.

2. Experiment
Experiments were performed with Nichia’s indicator UV LED, NSPU510CS and blue LED, NSPB-300 with InGaN/GaN QWs emitting at 3.31 and 2.70 eV, respectively, at the nominal current J=20 mA (the actual area is ~10^(-3) cm^2). The silicon photodiode FD-24K was used to estimate relative changes in the emission intensity and external quantum efficiency. The photocurrent was measured in the short-circuit mode with a digital ammeter. To study the transformation of LED parameters we used a sequence of short tests of accelerated degradation: under a forward bias, currents in the range 80 – 190 mA were passed through a LED at ambient room temperature. The duration of separate stages of the tests was varied from 10 min to 3 h. The stages of the test were applied sequentially from lower to higher currents for all samples.

The frequency and noise characteristics were measured on a semi-automated installation. Current fluctuations that appeared on passing a permanent forward current through a LED were measured. An analog-to-digital converter with its own noise level of 1 μV made it possible to record the time dependence of the voltage fluctuations on a load resistor \( R_t = 100 \, \Omega \) in the frequency range from 10 Hz to 7.3 kHz. 2·10^6 samples with sampling frequency of 16 kHz were recorded in the measurements. From these samples, the average noise spectrum was calculated using the fast Fourier transform. The noise power in each band was calculated by integrating in four bands of equal width - 17.6 Hz, with central frequencies of 20, 70, 270, 1000 Hz.

3. Results and discussion
The aging of LEDs involves several mechanisms that may cause opposite results [13,5], i.e., to compete with each other [14]. The changes occurring in modern commercial LEDs under accelerated aging are associated with changes in doping impurities and the deep-level spectrum in the energy gap of a nitride material, for which mostly point defects are responsible. According to the simplest \( ABC \) model \( I = qV_r(An+Bn^2+Cn^3) \), where \( I \) is the current, \( n \) is the carrier concentration, \( q \) is elementary charge, \( V_r \) is the recombination volume, i.e. the volume of the active region with intensive carrier recombination, and \( ABC \) are the coefficients of nonradiative, radiative and non-radiative Auger recombination [13]. \( A \) is proportional to the defect density, capture cross-section, and thermal velocity of carriers and associated with the defectiveness in the active region [3,4]. Changes in the concentration and spectrum of point defects make it possible to affect the value of the emission energy.

Figure 1 (a) presents the results of six successive tests on accelerated degradation of UV LEDs under the action of a current at a forward bias. The efficiency dependences characteristically have a plateau at medium voltages and hardly exhibit a pronounced maximum and efficiency droop at higher voltages. That is, the efficiency droop effect was negligible. On the contrary, a fast rise in the quantum efficiency was observed after test no. 1 (80 mA/1.2 h). However, this effect being insignificant after test no. 2 (120 mA/3 h). The total increase of the efficiency was 19% relative to the initial value at the nominal current. However, the efficiency dropped in the subsequent tests [no. 3 (150 mA/2 h) and no. 4 (170 mA/0.5 h), but especially in tests no. 5 (180 mA/0.5 h) and no. 6 (190 mA/1.5 h)]. This is
associated (i) with the high currents, when the rise in the concentration of defects responsible for the nonradiative recombination; (ii) with negative changes involving the migration of doping Mg impurity atoms from p-regions and the formation of other acceptor defects (a carbon atom serves as a compensating center in n-GaN if it substitutes nitrogen (C$_N$) [7]) leads to compensation of donors in n regions and to an increase in their resistance.

Figure 1 (b) shows current–voltage ($I(V)$) characteristics for a UV LED before and after six accelerated-aging tests. Several portions with different slopes of these characteristics can be distinguished. In the first portion ($V \leq 2.9$ V) a rise in current is observed in successive current action (test nos. 1 – 6) because of the activation of Mg in the p region and increase in its conductivity due to the disintegration of the Mg-H complex and to a rise in the hole concentration. Simultaneously grows the concentration of defects involved in the recombination in the active region [15] and within barriers. Defects associated with Mg in various substitution positions can also pretend to play their role (by analogy with [16]). To this rise is related the increase in the trap-assisted tunneling (TAT) and hopping across potential barriers in the active region [17,18], which occurs in nitride LEDs. The defect spectrum can change with action current and Joule heating of the forward-biased diodes. As a result, the decrease in the concentration of shallow centers and the increase in the concentration of deeper centers lead to degradation of InGaN LEDs [15]. However, we previously showed that the contribution of these factors, which enhance nonradiative recombination, is smaller than the simultaneous increase in the efficiency [19].

![Figure 1](image1.png)

**Figure 1.** Voltage dependences before and after six successive tests with currents under a forward bias: (a) external quantum efficiency and (b) current.

At $3.05 \, V \geq V \geq 2.9$ V the tunneling transparency of the barriers increases and the $I(V)$ characteristics becomes steeper, which is accompanied by an increase in the emission intensity, efficiency, and current associated with trap-assisted tunneling [8]. This is manifested in an increase in the contribution of the current associated with radiative recombination to the total current.

In the portion corresponding to large currents $\geq 0.1$ mA, the overbarrier injection of currents prevails, the increase in current after tests with short actions with currents being less noticeable. The dependences of the external quantum efficiency on voltage (figure 1 (a)) level-off. The nonradiative recombination processes become more pronounced.

The $I(V)$ characteristics were used to calculate the dependences of the current on voltage across the p-n-junction $I(V_i)$, $V_i = V - I r_s$. The series resistance $r_s$ was estimated from the linear portion of the $I(V)$ characteristic. The dependences $I(V_i)$ can be approximated with an exponential function $I \propto \exp(qV_i/n_s(V_i)kT)$, where $n_s(V_i)$ is the ideality factor (reveals differences in the current transport), and $kT$ is the thermal energy. Figure 2 plots the ideality factor $n_s(I) = (q/kT)(d\ln I/dV_i)$ against current, produced from the $I(V_i)$ for the starting blue LED sample. It can be seen in figure 2 that, as the current...
increases, \( n_f(I) \) grows to a value \( n_f \approx 3.7 \); then, at \( I > 3 \) mA, it starts to decrease, remaining larger than 2 at \( I < 10 \) mA, which points to the contribution of the trap-assisted tunneling \[20,21\]. The nature of the \( n_f(I) \) dependence remained unchanged after the test at a current of \( I = 150 \) mA for 2.5 h.

The external quantum efficiency of blue LEDs remained at the level of the starting samples before exposure to currents of \( \geq 150 \) mA. Under such the action, the active region overheated at > 100°C (105°C at a current of \( I = 150 \) mA, 118°C at \( I = 160 \) mA and 133°C at \( I = 170 \) mA) and the maximum increase in efficiency was 20% at the nominal current \[19\]. Blue Nichia LEDs showed a significantly higher resistance to action by current compared to UV LEDs from the same company. In them, the changes began at \( I = 80 \) mA.

Figure 3 (a) presents the results of measurements of the spectral density of the current noise \( S_f(I) \) for the frequencies \( f = 20, 70, \) and 270 Hz for a blue LED before and after the action with \( I = 150 \) mA for 2.5 h. The frequency of 270 Hz was used as the extreme point of the transition of the measured noise to white noise, the frequency dependence is still evident. The rise in efficiency after the action was accompanied by changes in the spectrum of defects and an increase in the low-frequency current density, which manifests itself for all measurement frequencies. The sharp increase in the noise density at high currents caused by the nonuniformity of the carrier flow and appearance of new centers of nonradiative recombination \[22\].

Figure 3 (b) presents the spectral dependences of the noise density \( S_f(I) \) for the starting UV LED, measured at \( I = 86 \) \( \mu \)A, 7 and 20 mA. It can be seen that both the dependences at the higher current are of Lorentzian nature with a steeper slope \( \propto 1/f^2 \) at low frequencies. This indicates the addition of
several mechanisms of noise formation. As possible noises may be the generation-recombination [23],
or telegraph, either flicker noises, as well as the fluctuations of the hopping resistance in the defect-assisted tunneling [24]. At the same time, the increase in the pedestal at frequencies $\geq 1000$ Hz indicates that the Gaussian noise becomes stronger. The increase in efficiency is accompanied by an increase in the density of low-frequency noise. The emerging shallower centers increase the rate of radiative recombination. But at the same time they participate in the formation of noise.

In the model [24] for the tunneling current limited by the density of states in the energy gap, the frequency spectra of the current noise density are governed by the Lorentzian function: $S(f) \propto (1+(2\pi f \tau)^2)^{-1}$ ($\tau$ is the local time constant of the dielectric relaxation $\tau = \epsilon_0 \epsilon/\sigma_{\text{hop}}$, here $\sigma_{\text{hop}}$ is the local hopping conductivity, and $\epsilon_0$ and $\epsilon$ are the electric constant and the relative dielectric permeability, respectively). The carrier hopping frequency exponentially depends on the distance between the centers. It is characterized by a wide spectrum of values of the local hopping times, which vary within the space-charge region (SCR) from nanoseconds to milliseconds [25]. In a thin layer at the interface with the active region, the hopping time is large (because of the low density of the centers) and $2\pi f \tau > 1$ is valid for the lowest frequencies. At frequencies lower than 100 Hz, the current noise density decreases by the law $S(f) \propto 1/f^2$ (figure 3 (b), dependences for $I = 7$ and $20$ mA), and at frequencies $>1000$ Hz it levels off and becomes frequency-independent. Away from the boundary of the active region, $\tau$ decreases and SCRs with higher density of centers more weakly limit the tunneling current and, consequently, make a substantially smaller contribution to the formation of a low-frequency noise.

The study of the observed changes is aimed at possible improvements in characteristics and an increase in the LED service life based on structures with InGaN / GaN quantum wells. The improvements at increasing injection of holes into the active region because of the activation of Mg in p-type layers enables use of technological approaches aimed to produce the same positive changes. The carrier concentration in QWs must increase due to the use of reservoir, blocking layers and special barrier designs [26]. These provide a better injection into the active region, and smaller current leakage from this region. For the same purpose serves the decrease in polarization fields in quantum structures [27]. However, the high concentration of Mg (more than $2\cdot 10^{19}$ cm$^{-3}$) leads to a decrease in the concentration of holes and in the p-type conductivity due to of the self compensation of the Mg impurity [28]. In the competition between radiative and nonradiative recombination processes an increase in the indium concentration and stronger localization of charge carriers with increasing QW width in blue-violet light emitting InGaN/GaN structures makes larger the number of carriers associated with the radiative recombination, thereby slowing down the efficiency degradation [29].

4. Conclusion
The study of the accelerated aging of LEDs in the proposed modes by passing a current of $80–190$ mA, accompanied by a Joule heating, for not longer than 3 h demonstrated a possible improvement of the characteristics of LEDs. Changes in UV LEDs started at significantly lower currents (at $I = 80$ mA versus $I = 150$ mA in blue LEDs). In the initial stages (in contrast to the decrease in the external quantum efficiency observed in most cases upon degradation) the emission intensity and the quantum efficiency increased and the operating voltage at the nominal current decreased as compared with the initial levels. This is due to the activation of the doping impurity in the $p$-barrier and to changes in the defect spectrum, with increasing share of shallower transport centers in the band gap semiconductor, involved in the carrier tunneling into the QW and the formation of low-frequency current noise. Activation of Mg in p-layers and improvement of carrier transport into QW can contribute to slowing down aging and improving the characteristics of LED based on structures with InGaN/GAN QW. In subsequent tests with increasing currents the concentration of SRH recombination centers increased, and a gradual LED’s degradation is observed, accompanied by a decrease in the optical power and quantum efficiency.
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