St. Petersburg Polytechnic University Journal. Physics and Mathematics. 2023 Vol. 16. No. 1.3
Научно-технические ведомости СПбГПУ. Физико-математические науки. 16 (1.3) 2023

Conference materials
UDC 621.382.2
DOI: https://doi.org/10.18721/JPM.161.314

Peculiarities of low frequency noise and non-radiative recombination in AlGaN QWs emitting at 280 nm

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Abstract. A prominent source of charge carrier losses due to non-radiative recombination in AlGaN QWs, caused by the presence of charged centers localized at disordered hetero interfaces, has been experimentally revealed. It was found out that the spectral density of current low-frequency noise, which carries integral information about single defects and a defect system, is an order of magnitude higher in AlGaN QWs than in effective blue InGaN/GaN QWs. Thus, non-radiative recombination losses are still the source responsible for the low quantum efficiency of ultraviolet LEDs.

Keywords: AlGaN/GaN, LEDs, UV LEDs, EQE, low-frequency noise, non-radiative recombination, QWs

Citation: Talnishnikh N.A., Ivanov A.E., Shabunina E.I., Shmidt N.M., Peculiarities of low frequency noise and non-radiative recombination in AlGaN QWs emitting at 280 nm, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.3) (2023) 85–89. DOI: https://doi.org/10.18721/JPM.161.314

Материалы конференции
УДК 621.382.2
DOI: https://doi.org/10.18721/JPM.161.314

Особенности низкочастотного шума и безызлучательной рекомбинации в MQW AlGaN/GaN, излучающих на длине волны 280 нм

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Аннотация. Экспериментально выявлен значительный источник потерь носителей заряда на безызлучательную рекомбинацию в AlGaN QWs, вызванный присутствием заряженных центров, локализованных на разупорядоченных гетеро границах. Выяснено, что спектральная плотность токового низкочастотного шума, несущая интегральную информацию о единичных дефектах и дефектной системе, на порядок выше в AlGaN QWs, чем в эффективных голубых InGaN/GaN QWs. Таким образом, потери на безызлучательную рекомбинацию по-прежнему являются источником, ответственным за низкую квантовую эффективность ультрафиолетовых светодиодов.

Ключевые слова: AlGaN/GaN, светодиоды, УФ светодиоды, внешняя квантовая эффективность, низкочастотный шум, безызлучательная рекомбинация, квантовые ямы

Ссылка при цитировании: Тальнишних Н.А., Иванов А.Е., Шабунина Е.И., Шмидт Н.М. Особенности низкочастотного шума и безызлучательной рекомбинации в MQW AlGaN/GaN, излучающих на длине волны 280 нм // Научно-технические ведомости

СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.3. С. 85–89. DOI: https://doi.org/10.18721/ JPM.161.314

Introduction

AlGaN QWs are the foundation for deep ultraviolet light-emitting diodes (DUV LEDs). DUV LEDs have been widely explored for their potential applications in a variety of areas including air/water purification, disinfection, bio-medical detection [1, 2]. However, as of today DUV LEDs still demonstrate low light output external quantum efficiency (*EQE*) < 10% and life time < 1500 hours [1–3]. The efficiency of AlGaN-based DUV LEDs is found to decrease drastically with decreasing emission wavelength. There are several factors that limit *EQE* values such as high dislocation density, insufficient carrier injection, and quantum confined Stark effect (QCSE) in MQWs. Some works also point out a number of contributions related to the epitaxial growth and chip fabrication technologies of DUV LEDs that have to be overcome [1]. The conductivity is limited not only by the increasing dopant ionization energy and formation of a stable DX center but also by the potential formation of cation vacancy defects VIII that are known to act as compensating acceptors in n-type AlN [3]. The latter issue derives mainly from the series of total internal reflections of photons at the interface between high-refraction epitaxial layers/substrate and the ambient medium [4]. It should be noted that the majority of works rarely consider the influence of the quality of hetero interfaces on the decrease in *EQE* at the maximum of DUV LEDs.

The studies carried out in this work were aimed at showing the contribution of non-radiative recombination of charge carriers in a system of defects and at the hetero interfaces to a decrease in *EQE* values at the maximum in DUV LEDs and assessing this contribution compared to more efficient blue InGaN/GaN LEDs. To achieve this, we employed the study of the low-frequency noise (LFN) alongside the conventional techniques. LFN is known to contain the integral information on the properties of extended defect system as well as single defects.

Materials and Methods

The study was carried out a comparative investigations on commercial DUV LEDs emitting at 278–280 nm whose *EQE* is about 4% and blue LEDs with 70% *EQE* emitting at 445 nm. Electroluminescence spectra and *EQE* dependences versus current density were examined at the direct current and in pulse mode (at pulse widths of 5 μs up to 2 A and 100 ns up to 20 A and repetition rates of 50 Hz) by OL 770-LED System (Optronic Laboratories Inc.) in integrated sphere. Optical power was determined by photodetector THORLABS DET02AFC/M. I-U characteristics were measured by the KEITHLEY 6487 power source. The noise spectra were measured within frequency range of 1 Hz to 50 kHz. The studied LEDs were connected in series with a low-noise load resistor R whose resistance varied from 100 Ω to 13.8 kΩ, depending on the current passing through the LEDs. The voltage fluctuations S_U at the resistors R were amplified by a low noise preamplifier SR 560 (Stanford Research Systems, Sunnyvale, CA, USA) and subsequently measured by an SR 770 FET NETWORK Analyzer (Stanford Research Systems, Sunnyvale, CA, USA). The background noise of the preamplifier did not exceed 4nV/√Hz at 1 kHz, which is approximately equivalent to the Johnson-Nyquist noise of a 1000-Ω resistance.

Results and Discussion

The maximum *IQE* in LEDs based on nitrides is determined by tunneling radiative recombination in MQW, located in the space charge region (SCR) around *p-n* junction [5, 6].

Thus, we considered the processes of non-radiative recombination (NR) at current values corresponding to the voltage range up to the *p-n* junction opening, i.e. up to threshold voltage (U_{th}). The U_{th} values were derived from forward *I-U* characteristics in DUV AlGaN and blue InGaN/GaN LEDs (Fig. 1).

Currents $I < 20$ mA correspond to this voltage range. Fig. 2, *a*, *b*) shows typical low-frequency noise spectra (i.e. dependences of power spectral density of current noise S_I versus frequency) in this current range for the same LEDs. The shape of the noise spectra is observed to be $S_I(f) \sim 1/f$ in the entire frequency range, which means the $1/f$ noise dominates at all currents (Fig. 2, *a*).

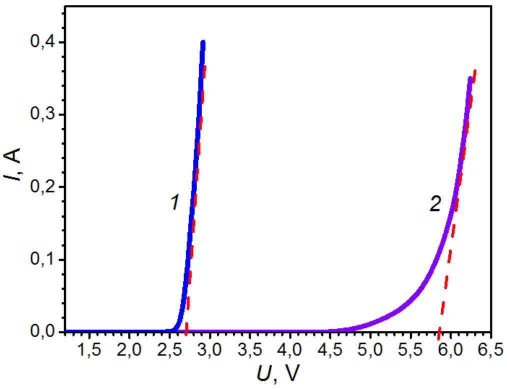

Fig. 1. Linear I–U characteristics of InGaN/GaN (curve *1*) and AlGaN (curve *2*) LEDs

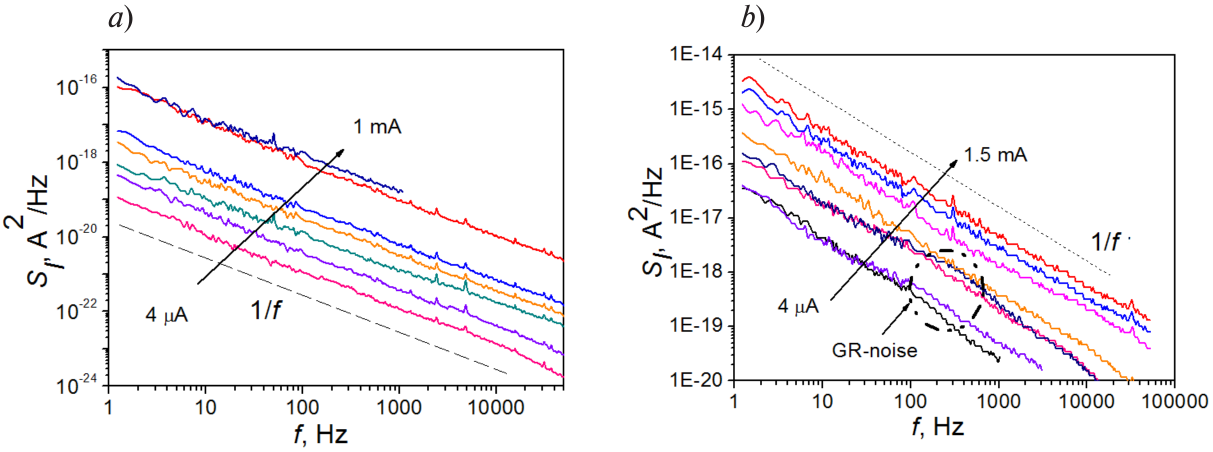

Fig. 2. Noise spectra in blue InGaN/GaN (*a*) and DUV AlGaN/GaN (*b*) LEDs

According to [7], this indicates the predominant contribution of the system of defects to NR in blue InGaN/GaN LEDs.

For the DUV LEDs, the values of spectral density of current fluctuations S_I is observed to be at least an order of magnitude higher than that in blue InGaN/GaN LEDs (Fig. 2, *b*). Moreover, the noise spectra of current fluctuations at high currents were close to the $1/f$ noise. However, the noise spectra at low currents were a superposition of the $1/f$ and generation-recombination (GR) noise caused by the presence of Shockley-Read-Hall (SRH) centers. The GR noise has a form of Lorentzian that typically doesn't depend on frequency at low frequencies and follows the law of ~ $1/f^2$ at high frequencies. The contribution of GR noise to the spectra is shown in a deviation from the shape of $1/f$ noise at $f > 100$ Hz. In our case, however, the contribution of GR noise and, thus, SRH centers is insignificant because there is little change in the slope of the noise spectra (Fig. 2, *b*). Additionally, for both types of LEDs, the dependence of spectral density of voltage fluctuations (S_U) on the current deviates remarkably from the classic shape characterized by $S_U(j) \sim I^{-1}$ that, according to [8], is typical for semiconductor devices with uniform current distribution in SCR (Fig. 3). Thus, this deviation shows identifies the non-uniform current distribution in SCR for both types of LEDs. Moreover, the inhomogeneity of the current distribution is more prominent in DUV LEDs than that in blue LEDs (Fig. 3, curve *2*).

The obtained results correlate with peculiarities of I–U characteristics such as non-ideality factor n being significantly higher than 2 at $U < 5$ V, strong dependence of reverse current on U, and poor rectifying properties of p-n junction in DUV LEDs. (Fig. 4, curve *2*).

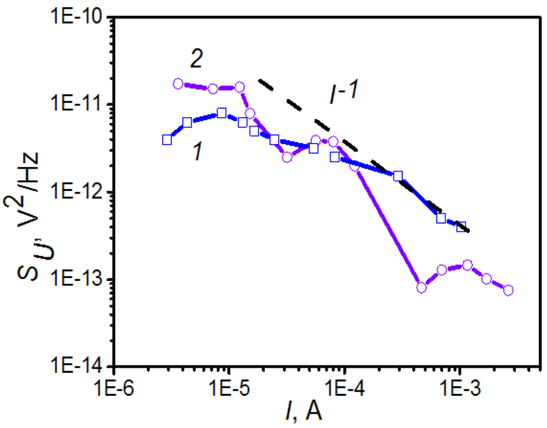

Fig. 3. Dependences of the spectral density of voltage fluctuations (S_U) on the current in InGaN/GaN (curve *1*) and AlGaN/GaN (curve *2*) LEDs

According to [9, 10], such peculiarities of I–U characteristics are related to the presence of charged centers in abrupt p-n junction. In our case, the presence of charged centers in SCR around p-n junction can be associated with imperfect hetero interfaces caused by random fluctuations in the AlGaN alloy composition, small thickness, less than 3 nm quantum wells, and Ga segregation.

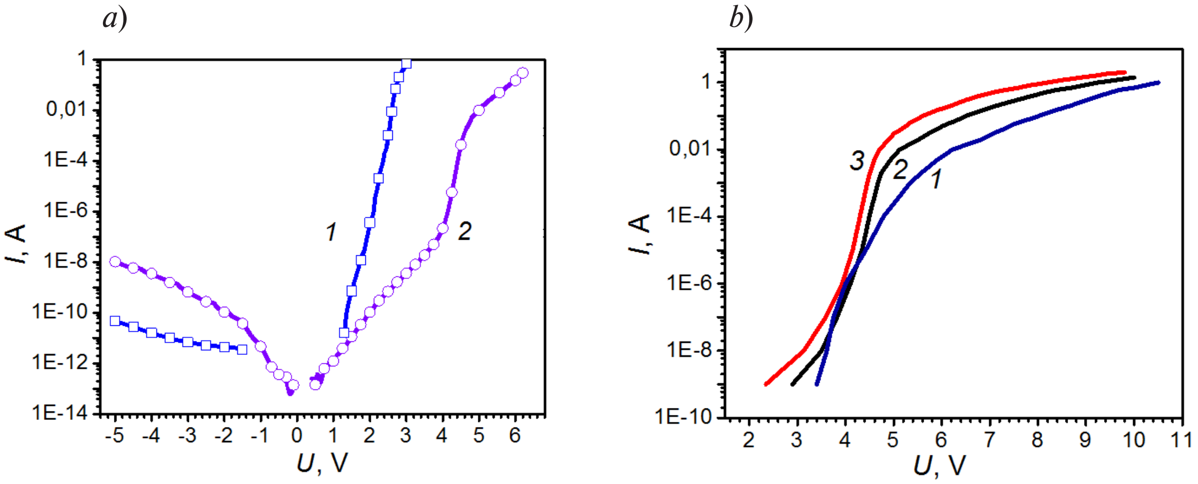

Fig. 4. I–U characteristics of blue (*1*) and DUV (*2*) LEDs (*a*); change in I–U characteristics of DUV LED over the temperature range (*b*): *1* – 200 K, *2* – 300 K, *3* – 350 K

The disordered hetero interface is indicated by the large difference (1.3 V) between $U_{th} = 5.8$ V (Fig. 1, curve *2*) and the voltage of 4.46 V corresponding to the emission wavelength of 280 nm. A similar difference in voltage values is observed in green InGaN/GaN LEDs with low *EQE* ~ 10%. Moreover, in these LEDs, the disordered of hetero interfaces caused by indium segregation was experimentally observed in [11]. At the same time, in effective blue LEDs, the difference in the values of these voltages is less than 0.1 V (Fig. 1, curve *1*). As a result, the charged centers localized at disordered hetero interfaces take part in NR and reduce *EQE* values at maximum in AlGaN QWs situated in SCR around p-n junction. To reduce these losses, it is necessary to avoid Ga segregation and to provide a step-flow growth mode during. The change in forward characteristics of DUV LEDs in the temperature range 200–350 K (Fig. 4, *b*) at $U < 5$ V differs significantly from that when single SRH centers determine NR mechanisms. It should be noted that the weak temperature dependence of forward I–U characteristics, tunneling transport of charge carriers and the a shape of the characteristics themselves at the temperature range 200 – 350 K are closest to the characteristics calculated for nitride-based LEDs by the multi-phonon-elastic trap assisted tunneling model. Thus, in addition to the loss of charge carriers on NR, the loss of charge carriers in multi-phonon emission is also possible.

Conclusion

A comparative investigation of low-frequency noise features and I–U characteristics in AlGaN and efficient blue InGaN QWs in commercially-available LEDs shows that the loss of charge carriers in non-radiative recombination is much more prominent in AlGaN QWs. The sources of these losses are charged centers localized at disordered hetero-interfaces, a system of defects including donor-acceptor pairs, extended defects, local regions with a random fluctuations in AlGaN composition, and, to a lesser extent, single SRH centers. Thus, the losses due to non-radiative recombination are still responsible for the low quantum efficiency in ultraviolet LEDs. To increase the efficiency of DUV LEDs, it is necessary to improve the growth conditions of AlGaN alloy, to prevent the segregation of gallium at hetero-interfaces, and to ensure layer growth in the step-flow growth mode.

Acknowledgments

This work was carried out at the Center of Multi-User Facilities “Element Base of Microwave Photonics and Nanoelectronics: Technology, Diagnostics, and Metrology”.

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Received 14.12.2022. Approved after reviewing 03.02.2023. Accepted 19.02.2023.