00

Participation of defects localized at heterointerfaces and extended defects in the degradation of nitride-based light-emitting devices

© N.A. Talnishnikh[1], A.E. Ivanov[1], E.I. Shabunina[2], N.M. Shmidt[2]

[1] Submicron Heterostructures for Microelectronics, Research & Engineering Center, RAS, Saint-Petersburg, Russia
[2] Ioffe Institute, St. Petersburg, Russia

e-mail: nadya.fel@mail.ru

Received May 19, 2023
Revised September 29, 2023
Accepted October 30, 2023.

A decrease in external quantum efficiency (EQE) of commercial LEDs based on MQW InGaN/GaN at wavelengths of 445, 530 and MQW AlGaN/GaN at 280 nm was experimentally studied in the standard aging mode at direct current. The decrease in EQE (regardless of the radiation wavelength) is found out to occur due to cooperative phenomena developing in 1-2 quantum wells (QWs) located in the space charge region (SCR) around the *p-n* junction, as well as in most of the QWs outside of SCR. It is shown that the inhomogeneous flow of current in these regions leads not only to the transformation of defects localized at heteroboundaries in the SCR and in lateral inhomogeneities in the alloy composition outside of SCR as well as in the extended defects, but also to a change in the alloy composition.

Keywords: InGaN/GaN, defects, LED, AlGaN/GaN.

DOI: 10.61011/EOS.2023.11.58031.5209-23

Despite the impressive advances in nitride-based LED and laser technology, the problem of low service life of green and especially ultraviolet lasers and LEDs has not been resolved. As noted in the review [1], this is largely due to the fact that the mechanism of defect generation under the influence of injection current has not been clarified and there is no consensus on in which part of emitting quantum-sized structures this process develops. In lots of studies, Auger recombination is used as the main mechanism, as well as the generation of Shockley-Read-Hall point defects in the active region or in dislocations and grain boundaries.

In this work, the role of heterointerface disorder in the development of the degradation process in nitride-based LED is experimentally clarified.

The studies were carried out on commercial LED with an area of $1\,\mathrm{mm}^2$ with radiation wavelengths of 280, 450 and 530 nm. The VCE values of the studied diodes were 3, 70 and 37%, correspondingly. The current-voltage curves (CVC) of LED, electroluminescence (EL) spectra, VCE dependences at half maximum (FWHM) on current density, the VCE distribution over wavelengths, and the dependence of the spectral density of low-frequency noise on frequency have been studied. The standard aging mode [1,2] was used at constant current density $j = 35\,\mathrm{A/cm}^2$ without heating for AlGaN/GaN LEDs and $j = 80\,\mathrm{A/cm}^2$ with heating up to 80°C.

An analysis of the experimental data obtained in this work and in numerous published works [1,3,4] showed that a decrease in the values of the VCE at the maximum of nitride-based LED (regardless of the radiation wavelength) is almost always accompanied by a characteristic change form CVC (Fig. 1, *a, b*) with increasing aging time.

In this case, the main difference lies in the significant difference in the aging time, during which the VCE falls by a factor of 2, in the value of the VCE before and after aging, as well as in the opening voltage of the *p-n* junction (U_{th}) LED before aging. For the LED studied in the work, U_{th} has the following values: 2.7 V for blue, 2.8 V for green and 5.8 V for ultraviolet LED. The excess of the experimental value U_{th}, in comparison with U_{th}, corresponding to the maximum wavelength of LED radiation, is known [5] to be caused by fluctuations in the composition of the solid solution. Thus, there are maximum fluctuations in the composition of the solid solution for ultraviolet LED. Previously, in our work [6] it was shown that the U_{th} values increase on LED with the same radiation wavelength, but with different degrees of ordering of heterointerfaces and solid solution composition. It should be noted that changes in the CVC during aging are observed at a voltage less than U_{th}, i.e. in quantum wells (QW) located in the SCR of the *p-n*-transition, and the transport of charge carriers is tunneling. The evolution of the reverse branch reflects the growth of charged centers with increasing aging time (Fig. 1), and the increase in the ideality factor of the forward branch ($n > 2$) and the deterioration of the rectifying properties of the *p-n* junction suggest the participation of defects localized at heterointerfaces and in composition fluctuations solid solution, in a reduction VCE. This assumption is confirmed by the experimental facts presented in our work [6]. It shows that the CVC have the same characteristic form as in Fig. 1, *a* (curve *3*) for LED with poorly ordered heterointerfaces before degradation and low VCE values at the maximum before degradation. Distributions of VCE values over wavelengths in the range

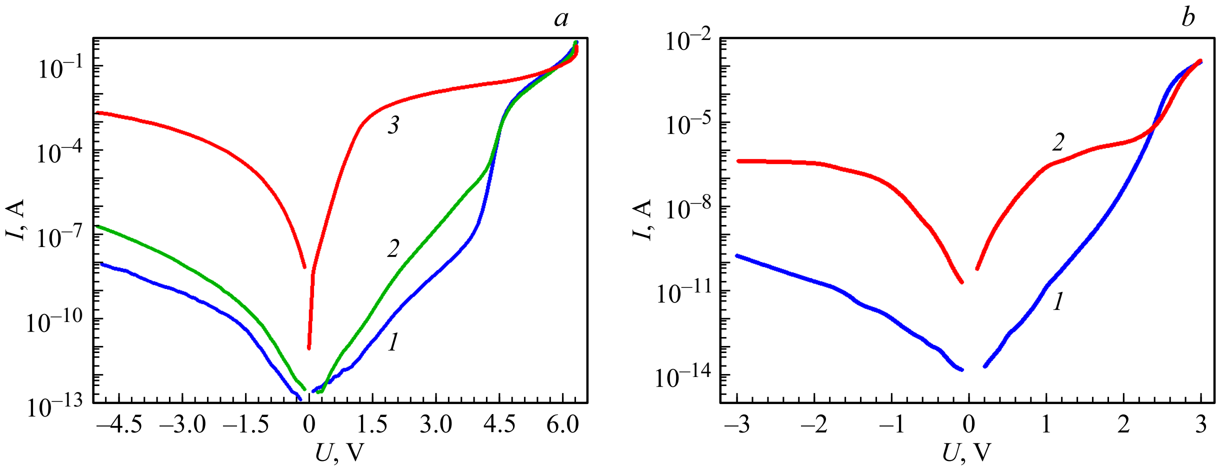

Figure 1. Current-voltage curves before and after aging for (*a*)AlGaN/GaN-LED: *1* — before aging, VCE — 3.2%; *2* — after 10 h aging, VCE — 2.7%; *3* — after 25 h aging at constant current, VCE — 1.8% and (*b*) InGaN/GaN LED: *1* — before aging, VCE — 60%; *2* — 10000 h aging at constant current, VCE — 40%.

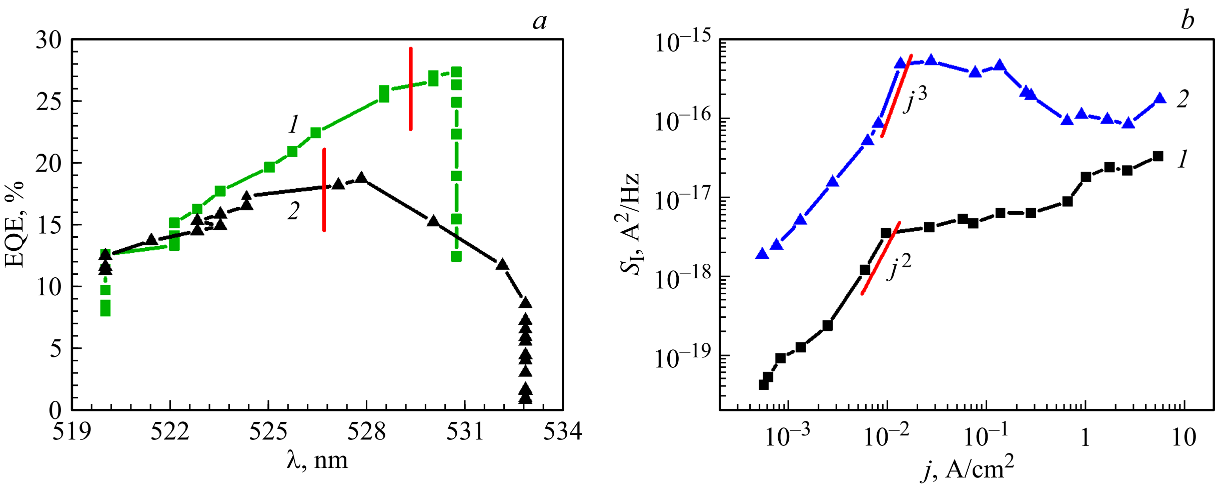

Figure 2. (*a*) Distribution of VCE values by wavelength for green LED: *1* — before aging, *2* — after 3000 h. (*b*) Dependence of the spectral density of low-frequency current noise on the current density in a blue LED: *1* — before degradation, *2* — after 3000 h aging . There is a decrease in the VCE without a change in wavelength at direct current and in pulsed mode at current densities of more than 40 A/cm^2, presumably caused by heating as a result of recombination-stimulated defect reactions [7].

of currents$I = 4-1000$ mA and voltages, before and after aging using the example of a green LED (Fig. 2, *a*) reflect the changes occurring in QW located in the SCR (the area to the right of the red line in Fig. 2, *a*) and in the QW outside the SCR under the influence of current. Previously [6] it was found that a vertical straight line at a fixed wavelength (curve *1* in Fig. 2, *a*) visualizes the growth of the effective radiative recombination (IR) from QW located in the SCR of the *p-n*-junction, and the areas of decrease in the VCE at $U > U_{\text{th}}$ (to the left of the red line) visualize the process of non-equilibrium filling with carriers of lateral fluctuations in the solid solution composition (SSC) in (QW) outside SCR. After aging (Fig. 2, *a*, the curve *2*) shifts the maximum to a shorter wavelength region and a weak IR appears in the longer wavelength region, and the lateral fluctuations SCR are practically filled with carriers. These changes after aging (Fig. 2, *a*, curve *2*) essentially visualize the change in SCR in the QW, which allows to assume not only the transformation and generation of defects, but also the local migration of indium or gallium. The assumption of local migration of indium or gallium is based on the mechanism of recombination-stimulated diffusion of defects, discovered in light-emitting devices based on GaAs, GaP, InP and developing with increasing level of injection of non-equilibrium charge carriers. This mechanism is described in many theoretical and experimental works, summarized in the review [7].

The observed phenomena can be explained within the framework of the microscopic theory of heating of local vibrations during multiphonon recombination [7,8]. Experimentally revealed increase in heterogeneous current flow during aging (change in the slope in the section of the $S_I(j)$ dependence in LED, Fig. 2, *b*, curve *2*), heating of LED at $U > U_{th}$, non-equilibrium filling of lateral fluctuations in the composition of the solid solution by tunneling charge carriers, the local nature of metal release at the contacts at the final stage of degradation are strong arguments in favor of the participation of recombination-stimulated defect reactions in the development of degradation. The interaction of charge carriers with lateral composition fluctuations leads to a decrease in the fluctuation band potential. As a result, the mechanism of transport of charge carriers changes from tunneling to diffusion, from lateral to vertical along conducting channels outside the SCR. The heterogeneous flow of current is confirmed by the experimental distributions of power and spectral characteristics over the emitting surface [9,10]. As a result, the local current density in conducting channels, such as stacking faults, grain boundaries, and dislocations, increases, and the process of multiphonon recombination of charge carriers in extended defects with local energy transfer sufficient for configuration rearrangement and migration of defects becomes possible. This mechanism leads not only to a decrease in the VCE values, but also to the failure of light-emitting devices. Experimental confirmation is the local release of gallium or indium in degraded devices [10].

The studies carried out made it possible to find out that the decrease in the VCE of nitride-based LED during aging is caused not only by the transformation of defects localized at the heterointerfaces of the QW located in the space charge region (SLC) of the *p-n* junction, but also by a change in the composition of the solid solution in its lateral heterogeneities. The transformation of defects is accompanied by a characteristic change in the appearance of the CVC of the LED and a deterioration in their rectifying properties. Moreover, these changes in the type of CVC are practically independent of the composition of the LED solid solution and the test mode for service life. However, the time to achieve these changes may differ by orders of magnitude for LED with different solid solution compositions.

Acknowledgments

Measurements of light parameters were carried out at the common use center „Hardware Components of Radio Photonics and Nanoelectronics: Technology, Diagnostics, Metrology".

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] J. Rusche, J. Glaab, M. Brendel, J. Rass, C. Stolmacker, N. Lobo-Ploch, T. Kolbe, T. Wernicke, F. Mehnke, J. Enslin, S. Einfeldt, M. Weyers, M. Kneissl, J. Appl. Phys., **124** (8), 084504 (2018). DOI: 10.1063/1.5028047

[2] Y-F. Su, S-Y. Yang, T-Y. Hung, C-C. Lee, K.-N. Chiang, Microelectronics Reliability **52** (5), 794−803 (2012). DOI: 10.1016/j.microrel.2011.07.059

[3] N. Renso, C. De Santi, A. Caria, F. Dalla Torre, L. Zecchin, G. Meneghesso, E. Zanoni, M. Meneghini, J. Appl. Phys., **127** (18), 185701 (2020). DOI: 10.1063/1.5135633

[4] F.I. Manyakhin, FTP, **52** (3), 378−384 (2018). (in Russian). DOI: 10.21883/FTP.2018.03.45625.8341

[5] F.E. Schubert, *Light-emitting diodes*, 2nd ed. Cambridge University Press, Cambridge, UK, 2006), p.415

[6] E.I. Shabunina, A.E. Chernyakov, A.E. Ivanov, A.P. Kartashova, V.I. Kuchinsky, D.S. Poloskin, N.A. Talnishnikh, N M. Schmidt, A.L. Zackheim, Prikladnaya spektroskopiya, **90** (1), 29 (2023). (in Russian). DOI: 10.47612/0514-7506-2023-90-1-29-34

[7] V.N. Abakumov, A.A. Pakhomov, I.N. Yassievich, FTP, **25** (9), 1489 − 1515 (1991). (in Russian).

[8] S.V. Bulyarskiy, N.S. Grushko. *Generatsionno-rekombinatsionnyye protsessy v aktivnykh elementakh* (Izdatel'stvo Moskovskogo universiteta, M., 1995). (in Russian).

[9] A.L. Zakgeim, A.E. Ivanov, A.E. Chernyakov, Pisma v ZhTF, **47** (16), 32−35 (2021). DOI: 10.21883/PJTF.2021.16.51326.18795

[10] K.N. Tu, Yingxia Liu, Menglu Li. Appl. Phys. Rev., **4** (1), 011101 (2017). DOI: 10.1063/1.4974168

Translated by E.Potapova