10

Near-field radiation and the effect of non-uniformity of current density distribution in AlInGaN micro-LEDs

© A.L. Zakgeim[1], A.E. Ivanov[1,2], A.E. Chernyakov[1], L.A. Alexanyan[3], A.Ya. Polyakov[3]

[1] Submicron Heterostructures for Microelectronics, Research & Engineering Center, RAS, Saint-Petersburg, Russia
[2] St. Petersburg State Electrotechnical University „LETI", St. Petersburg, Russia
[3] National University of Science and Technology MISiS, Moscow, Russia

e-mail: zakgeim@mail.ioffe.ru

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The object of study in this work was the rapidly developing micro-LEDs based on AlGaInN nanoheterostructures, which have high electroluminescent characteristics and open up new application possibilities. A study of near-field radiation with high spatial resolution (mapping) revealed high current density inhomogeneity over a wide range of excitation levels, namely, the concentration of light and current in the annular region adjacent to the side surface of the mesa. Taking this effect into account, the concept of "effective" current density is introduced, and the current dependences of energy characteristics are analyzed, including optical power saturation and efficiency droop.

Keywords: AlInGaN, mesostructure, micro-LED, electroluminescence, near-field radiation, quantum efficacy.

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Micro-LEDs based on quantum-sized MQW (Multiple Quantum Well) heterostructures AlInGaN with typical dimensions of the emitting area determined by the diameter of mesostructure $D = 10-100\,\mu$m, have been sparking great interest recently for use in high brightness and high resolution displays, light-diode projectors, specialized light sources for medicine, biosensors etc. [1,2].

While the potential advantages of microLEDs that expand their applications are known, new problems arise both in the technology of instrument development and in their operation. First of all, these are higher densities of operating currents, growth of values of serial resistance and direct voltage, which directly impacts the quantum yield and efficiency. Besides, the growth in the ratio of the active area perimeter to its surface area increases the role of radiationless surface recombination, changes the conditions of current spreading, radiation coupling, heat removal etc. These issues are currently the center of attention of a wide circle of researchers [3–5].

The object of research in this paper were blue ($\lambda \approx 450$ nm) micro-LEDs InGaN with the structure presented in fig. 1, *a*, grown by method of metal-organic gas-phase epitaxy (MO GPE) on a sapphire substrate. The structure contains a bottom contact layer *n*-GaN ($\sim 3\,\mu$m), MQW active area of four quantum wells $In_xGa_{1-x}N$ (~ 2.75 nm), separated by barriers GaN (~ 8.0 nm), a top contact *p*-GaN-layer (~ 500 nm). Mesastructures with diameter from 20 to $100\,\mu$m and depth of $\sim 1\,\mu$m (up to *n*-GaN contact layer) were formed by methods of photolithography and reactive ion etching. Side slopes of the mesa were cleaned by dielectric Al_2O_3, *p*- and *n*-contacts (Cr/Au/Ni and Cr/Au accordingly) were made by sputtering, Cr/Au metallization also provides for current feed and assembly. Schematically the cross section of micro-LED and photograph of the top view are shown in fig. 1, *b, c*.

To explain the type of the main „physical" characteristic of LED — dependence of the outer quantum yield η_{EQE} on current — ABC-model is widely used, which takes into account the competition of the biomolecular radiative recombination and two mechanisms of radiationless recombination: Shockley–Rida–Hall and Auger [6]. The basis for the analysis of the LED energy characteristics and contribution of various recombination mechanisms within the ABC-model is experimental dependence of the output optical power on current $P_{\mathrm{opt}} = f(I)$ in the wide range of currents with further recalculation into dependence of the external quantum yield η_{EQE} on current density j: $\eta_{\mathrm{EQE}} = f(j)$. Precise measurement P_{opt} in the state-of-the-art equipment using an integrating sphere causes no problems [7], and the current density is usually calculated as medium $j = I/S$, where I — current, S — surface area of crystal ($p-n$-transition). The latter, generally speaking, is not correct, since the homogeneous distribution of current density is implemented only in special cases: of relatively low currents and with proper geometry of bond sites. The operating modes always include current crowding effects near (under) contacts [9–11].

In the previous papers we studied experimentally and by modeling the patterns of current density, brightness and temperature distribution (mapping) for a wide circle of LEDs „of macro"-sizes ($> 300\,\mu$m). At the same time we used the methods of scanning and photometry of the emitting surface in the range of the internal electroluminescence (EL) (300–800 nm) [12,13]. This paper applies the similar approaches to micro-LEDs, which required

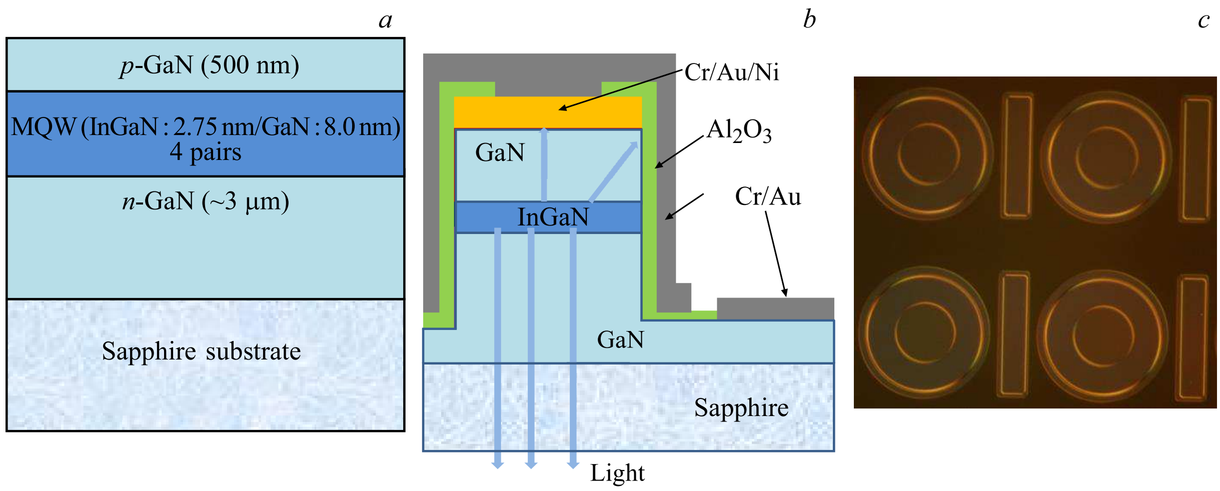

Figure 1. Schematic section of MQW InGaN epitaxial structure on a sapphire substrate for micro-LED (a); cross section of micro-LED with schematic image of contact and dielectric layers: arrows show the paths of light spreading — exiting and blocked by contacts (b); photograph of the top view of the plate with micro-LED (c). Borrowed from [8].

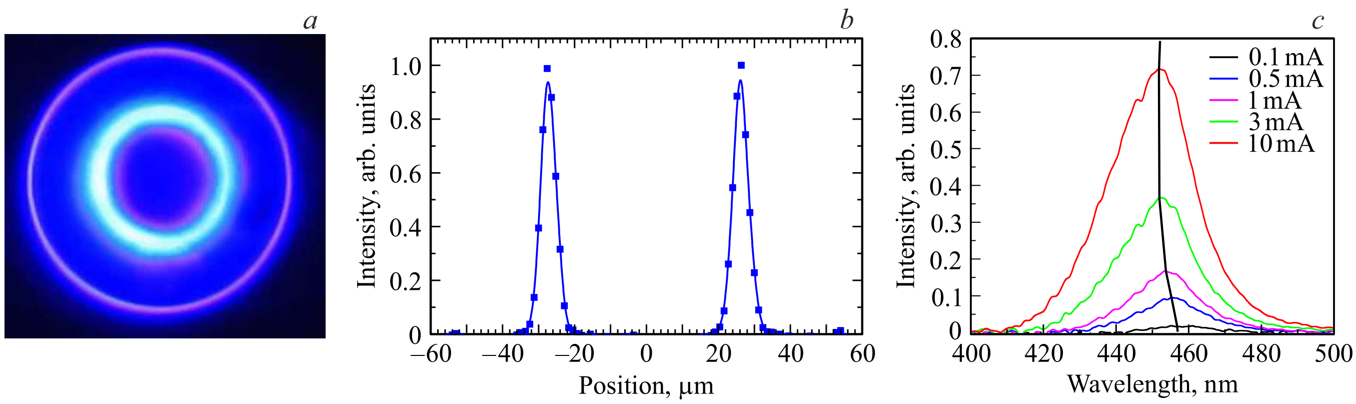

Figure 2. The near field pattern of EL ($I = 300\,\mu$A), where the increase in the luminescence intensity is shown by transition from blue to white color (a). Profile of intensity in diametral cross section (b) and spectrum of micro-LED radiation (c) at currents of 0.1−10 mA.

maximum increase of sensitivity and spatial resolution of the measurement equipment.

EL characteristics of micro-LEDs were studied from the side of the transparent sapphire substrate (at the bottom) with the installation of the substrate with the specimens in probe station Suss PM-5 with optical microscope Mitutoyo and spectrometer Avantes 2048. To record the spatial distribution of EL intensity, camera Canon EOS 5D with 12 Mpxl CMOS was used. Electrical modes were set and controlled by source Keithley 2400. Optical power and radiation spectra were recorded by complex „OL 770-LED High-speed LED Test and Measurement System" (Optronic Lab).

The near field of radiation of the internal EL were studied (in other words, mapping of the emitting surface brightness) for micro-LED with diameters 50 and 100 μm with spatial resolution $\sim 1.5\,\mu$m, as well as integral dependences P_{opt}, η_{EQE} on the current in the range of values 0.003−5 mA. It is necessary to note the important difference in the conditions of light and current spreading in macro- and micro-LEDs with mesastructure. In macro-LED (with the free side surface of the mesa with sufficient depth) the complete internal reflection of the light from the side surface is provided, with the reflection from the partially reflecting metal contacts usually added. This helps to achieve multiple passes and internal focusing of the radiation causing higher EQE and the difference in the distributions of light intensity and pumping current density in the crystal surface area [14,15]. In our case of micro-LEDs (fig. 1, b) the mesastructure geometry is close to „a flat" cylinder (with diameter of 10 − 100 μm and height of $\sim 1\,\mu$m), the top and side surfaces are closed with the Cr/Au ($R < 30\%$) contact layer absorbing the blue radiation, which means the absence of the conditions for the multiple passes of light. Therefore, the near field of EL in the first approximation is compliant with the distribution of the current density (in certain cases of strong dependence of the quantum yield from current this factor must be taken into account as well).

Fig. 2, a presents the photograph of the near field of EL in a micro-LED with diameter of $100\,\mu$m at current $300\,\mu$A (bottom view, on the side of the sapphire substrate, where the luminescence intensity increase is reflected by change in the color from dark blue to white). Fig. 2, b, corresponding to the photo in fig. 2, a, shows the profile of luminescence intensity in the cross section by diameter.

The analysis of the near field pattern with current increase shows the strong localization of EL so much so that already at current $300\,\mu$A 90% of the total radiation is concentrated in a ring with width of $\sim 7-10\,\mu$m, located at the distance of $\sim 30\,\mu$m from the mesastructure center. Such result may be obtained from the current spreading model in an equivalent electric circuit of the mesa-structure LED at certain ratio of the contact and layer resistances [16].

The observed strong heterogeneity of the current distribution in the area of $p-n$-transition (somewhat unexpected at such small dimensions and low currents) should be first taken into account for interpretation of the main current dependences of the micro-LED parameters. As you know, the internal quantum yield η_{IQE}, the output power P_{opt}, and the spectrum of InGaN LED radiation strongly depend on the current density (concentration of injected carriers in the active area). Accordingly, to analyze the behavior of the specified characteristics, including within the ABC-model, one should address the real or effective current density, which, as our research shows, may greatly exceed the average one. As it appears from fig. 2, b, at $I = 300\,\mu$A ($U = 4.2$ V) the average current density for micro-LED is $j_{\text{med}} \approx 4\,\text{A/cm}^2$ ($S = 7.9 \cdot 10^{-4}\,\text{cm}^2$), and the effective one — for the ring with diameter $\sim 50\,\mu$m and width $\sim 7\,\mu$m ($S_{\text{ef}} = 9.4 \cdot 10^{-6}\,\text{cm}^2$) $j_{\text{ef}} \approx 33\,\text{A/cm}^2$, i.e. nearly an order higher, however, it meets the nominal values of serial powerful LEDs.

This should manifest itself in „steeper“ current dependences of reduction η_{EQE} (efficiency droop), and in significant drifts of radiation spectra (first blue shift — screening of active area polarity, then red one — heating, fig. 2, c). Note that for macro-LED AlInGaN it is usually not possible to achieve the thermal red shift at the implemented currents. The effect of current crowding and its displacement with the current towards the mesastructure perimeter must also be taken into account when analyzing the surface recombination and heat removal conditions [10].

The result of the experimental study of the near field of InGaN micro-LED radiation with round mesastructure (with diameter of $\leq 100\,\mu$m) was the detection of strong ring-shaped current crowding even at its low values. Developed gradients in the distribution of the current density by area of $p-n$-transition are higher than in LEDs of large sizes with optimal contact geometry [17]. The difference of the real current density distribution, its effective value j_{ef} from the average j_{med}, produced by division of current into surface area, must be taken into account when analyzing all electric-optic and thermal characteristics.

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Conflict of interest

The authors declare that they have no conflict of interest.

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