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A comprehensive study of electroluminescence and temperature distribution of “UX:3” AlInGaN LED

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Abstract. Comprehensive analysis of current spreading, temperature distribution and near-field electroluminescence of high-power “UX:3” AlInGaN emitting chips with a distributed system of reflective contacts, located on the back of the chip, has been performed by combination of different experimental methods. Current dependences of power and spectral characteristics, including their distribution (mapping) over the emitting surface, were studied in a wide range of operating currents. A thermal resistance evaluation was based on transient electrical processes under heating by direct current and analysis of thermal equivalent circuit (the Cauer’s model). The high resolution mapping of electroluminance and thermal radiation was obtained by optical microscope and infrared images technique. It has been established distribution pattern of light and temperature at different levels of excitation. The conclusions were drawn about the degree of uniformity of the current and light spreading and their influence on the power characteristics of devices.

Keywords: LED, light and temperature mapping, light-current characteristic, external quantum efficiency

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Комплексное исследование распределения светового и температурного полей в мощных AlInGaN светодиодах конструкции «UX:3»

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Аннотация. Исследованы токовые зависимости светового и температурного распределения (мэппинг) в наиболее совершенных на сегодняшний день AlInGaN светодиодах конструкции «UX:3» с распределенной системой отражающих контактов. Анализ ближнего поля собственного излучения совместно с ИК тепловым излучением выявил высокую однородность распределения тока по площади кристалла при всех уровнях возбуждения.

Ключевые слова: светодиод, световой и температурный мэппинг, характеристика свет-ток, внешний квантовый выход

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Introduction

To date, AlInGaN LEDs from leading manufacturers, primarily OSRAM Opto Semiconductors, Cree, Philips Lumileds and some others, are great performance by a high level of design excellence and emitting characteristics. An optimized Multiple Quantum Well (MQW) heterostructure, a system of distributed reflective contacts, low values of electrical and thermal resistance ensured the achievement of watt optical powers per square millimeter at a high, more than 50% efficiency [1]. Most of the research on AlInGaN LEDs refers to continuous operation used in lighting. At the same time, interest has recently increased for the use of AlInGaN LEDs in the visible blue-green range of the spectrum, not only "for the eye", but also in working with physical receivers, in particular, for pumping solid-state lasers [2] or in open Visible Light Communication (VLC) [3]. New applications require the use of LEDs in pulse mode with duration from tens of nanoseconds to units of milliseconds upon reaching the maximum possible radiation power (or energy per pulse). In this regard, of particular scientific and practical interest is the task of identifying the main factors limiting the energy capabilities of the LED. They are either thermal or electrical in nature. The latter can be associated both with "external" design factors: (current crowding under the contact, shadowing of light by contacts), and with "internal" processes: "efficiency droop" determined by the transport and recombination of carriers in the active region [4].

In this work, we aim to reveal the main factors limiting the performance of LEDs at high levels of excitation, using as an object of study the best to date emitting chips of the "UX:3"design. An important advantage of "UX:3" chip is a multi-point geometry of reflective n-contacts, which, thanks to a special "isolated well" technology, are transferred and distributed evenly over the p-contact area on the back of the chip. The complexity of the technology pays off with ideal conditions for uniform current distribution and light output without loss due to shading.

Experiment: Object and Methods

The object of the study is the most advanced AlInGaN LEDs OSRAM OSTAR LE B Q8WP [5] based on the emitting chip "UX:3" [6] with a distributed system of reflective p- and n-contacts located on the back side of device (Fig. 1). The implementation of the design required the development of a complex technology of isolated "wells" crossing the p-n-junction, with metal "columns" inside forming a multipoint n-contact Thereby chip had a unilateral arrangement of contacts and the light output through the n-area without shadow effect. LEDs had 1500×1200 μm^2 chip mounted by "flip-chip" method on the AlN substrate.

As has been shown previously, the near field of own electroluminance (EL), as a first approximation, correlated with the current density distribution in the active region [7]. The uniformity of the current distribution can be estimated by the uniformity of the near field EL.

The near field EL was mapped by a Mitutoyo optical microscope equipped with a digital camera (12 Mpxl CMOS matrix) and Avantes AvaSpec-2048 spectrometer. Profiles of EL intensity are shown in Fig. 2, *b*. In addition, for revealing the mechanisms of current redistribution with an excitation, the dependence light output and thermal resistances on current was measured. General light-current characteristics (optical power dependence, external quantum efficiency and emission spectrum from the current) at direct current were obtained using the automated OL 770-LED Test and Measurement System [8].

To obtain the temperature distribution across the area of chip (temperature mapping), the

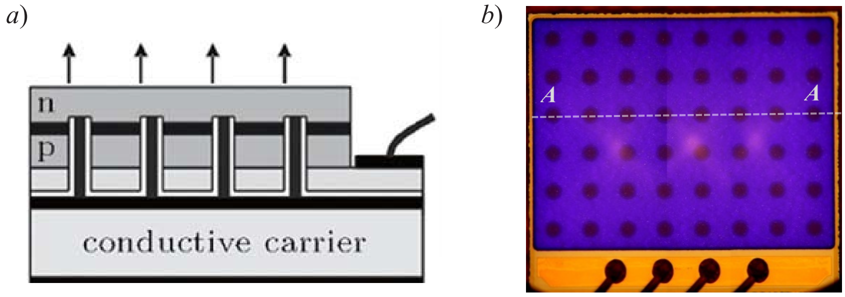

Fig. 1. The emitting chip “UX:3”: cross-section with a diagram of the formation of distributed n-contacts (*a*); photo of the emitting surface, dark dots correspond to the location of the n-contacts (*b*)

infrared (IR) micro-thermography was used, which allows to estimate not only device average heating, but also to establish the temperature distribution over the area with the detection of overheat spots and temperature gradients. Thermal radiation in the spectral range of 2.5–3 μm was mapped by a specially designed IR microscope. The use of short wavelength IR radiation as compared to conventional radiation (8–12 μm) made it possible to reduce the diffraction blurring and, consequently, to improve of the spatial IR mapping resolution to ~ 3 μm at a temperature resolution of about 1 degree [9].

In addition, the total thermal resistance of the LED $R_{th\Sigma}$ and the thermal resistance of the individual elements of the thermal circuit (chip layers, soldering, heat sink) R_{thi} were measured using temperature-sensitive parameters, namely the forward-voltage relaxation method with a Thermal tester T3Ster [10].

Results and Discussion

In Fig. 2, *a* the current dependences of emitting power Popt and external quantum efficiency EQE in a wide range of currents from units of milliamps to 3 A are presented. As it can be seen from Fig. 2 the above dependences have a characteristic typical for AlInGaN LEDs: deviation from the linearity of the light-current dependence due to the “efficiency droop” from EQE = 70% to EQE = 50% (drop in conversion efficiency to ~ 40%). It should be noted high absolute magnitudes the above-mentioned values, which indicates the high structure perfection of devices.

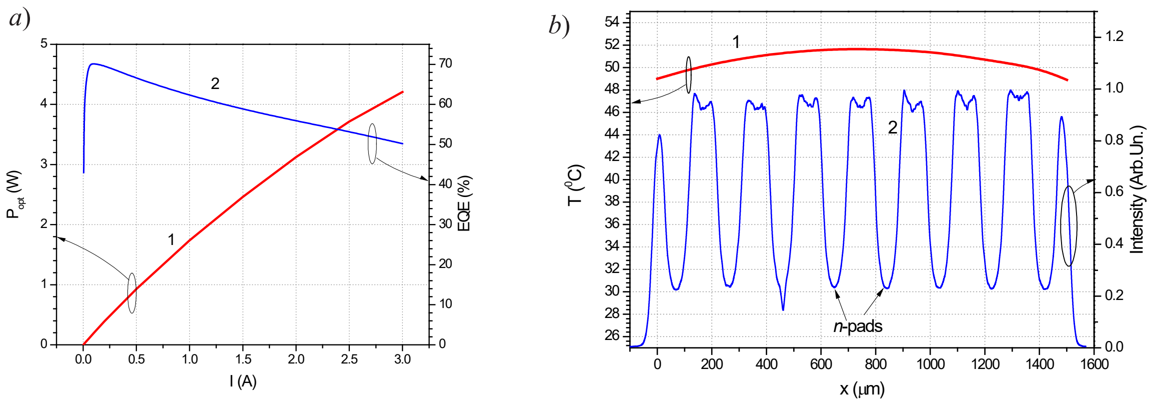

Fig. 2. LED optical power Popt (curve 1) and external quantum efficiency EQE (curve 2) dependences on current (*a*); temperature distributions (curve 1) and EL intensity profile (curve 2) in the cross-section AA at I = 3 A (*b*)

The question is whether this drop is “purely” electronic in nature or the effects of self-heating and the occurrence of temperature and current density gradients over the area of the p-n junction are added and enhance efficiency loss [11]. To clarify this issue the temperature distribution over the chip area in cross section AA (Fig. 1, *b*) was obtained by mapping the IR thermal radiation at different operating current.

In Fig. 2, *b*, curve 1 shows temperature distribution in the cross-section AA at maximum direct current of I = 3 A (input power P_{in} ~ 10.5 W). As can be seen in Fig. 2, *b* the temperature distribution remains almost uniform over the area of the chip and is not related to the location of the n-contacts (there is no local overheating near the contacts as it could be assumed from the current crowding near them). On the other hand, there is some tendency to a concave temperature profile can be recognized in the distributions. It can be explained by the fact that the heat transfer from the center of the chip to the ambient environment is worse than at the periphery. The absolute overheating of the active region is about $\Delta T \approx 30$ °C (the temperature of heat-sink is 20 °C) which, taking into account the input power of 10.5 W and "optical cooling" at high conversion efficiency of 40% gives the value of the total real thermal resistance $R_{th\Sigma} \approx 4.1$ K/W, which coincides with the thermal resistance measurement data obtained using the T3Ster.

The map of distribution near field EL intensity on the chip surface at I = 3 A was obtained by optical microscopy and shown in Fig. 2, *b*, curve 2. It can be seen that there is a uniform distribution of itself emission takes place. The minimum of curve indicates the n-contact pads, which pass through the *p-n*-junction and, accordingly, there is no radiation generation. At the same time, the light background of ~ 20% of the maximum indicates the multiple pass of radiation through the chip and the reflective properties of the n-contacts.

The results of the thermal resistance measurement of the LED are presented as cumulative structure functions in Fig. 3. In the figure, the horizontal axis shows thermal resistance Rth measured from the *p-n* – junction towards the heatsink. The vertical axis represents thermal capacity C_{th} from the heat source to the heatsink, shown in logarithmic scale. The total thermal resistance $R_{th\Sigma} = R_{chip}+R_{case}+R_{substrate}$ obtained at the current I = 3 A. From the Fig. 3 it can be seen that the values of "electrical" thermal resistance (without "optical cooling") amount: junction/bottom of chip $R_{j\text{-}chip}$ = 0.5K/W, junction/solderpoint $R_{j\text{-}sp}$ = 0.9 K/W and junction/heat-sink $R_{j\text{-}hs}$ = 2.9 K/W.

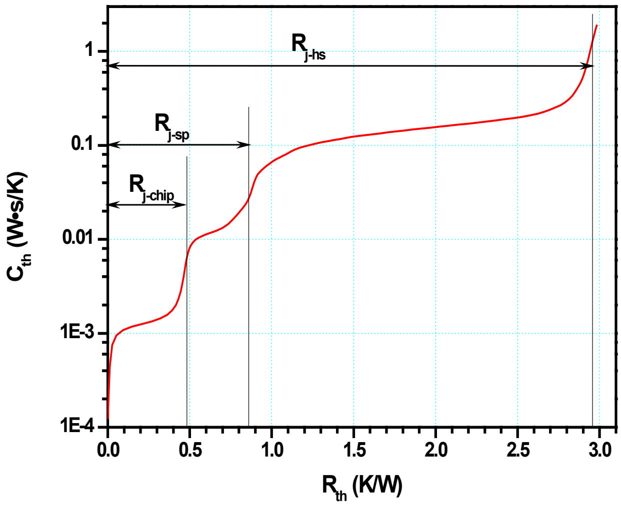

Fig. 3. Cumulative structure functions of the LED at the current I = 3 A

Conclusion

High-power AlInGaN blue LED of "UX:3" design were studied by advanced experimental techniques including measurement of optical power and external quantum efficiency dependences on current, high-resolution mapping of EL and IR radiation and transient thermal analysis.

EL variation and temperature distribution were studied as well as thermal resistance for high-power LED with the driving current. For LED chip was established uniform temperature distribution of the central. The little temperature gradient ΔT ~ 3 K of distribution in the cross-section was associated with the deterioration of the conditions of heat removal from the center to the periphery. The real material thermal resistance of the LED taking into account that part of the heat is carried away by light is ~ 4 K/W.

It is concluded that in "UX:3" there are no significant current density and temperature gradients over the area up to currents ~ 3 A, and the behavior of the optical characteristics is due to internal processes in the active region.

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