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Current and temperature dependences of optical characteristics of powerful deep UV AlGaN LED (λ = 270 nm)

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Abstract. The main goal of this work was to study the energy characteristics of deep ultraviolet light-emitting diodes and to establish the physical reasons for the limiting of output optical power and conversion efficiency of such devices. The voltage-current, light-current and spectral characteristics of the AlGaN multiquantum wells flip-chip light-emitting diodes emitting at a wavelength of 270 nm were experimentally studied in a wide range of operating current densities of 0.01–2.5 kA/cm^2 and ambient temperatures of 200–350 K. Using the ABC-model, it was found that at a relatively high internal quantum efficiency of radiation of ~70–90% and a quite acceptable value of series resistance of ~1 Ω. The main factor (key obstacle) limiting the energy possibilities of devices is low light extraction efficiency. The latter is due to the strong absorption of the generated light in the chip volume and on the contacts, as well as total internal reflection on the AlGaN/sapphire and sapphire/air interfaces.

Keywords: AlGaN, deep UV, light-emitting diodes, internal quantum efficiency, light-extraction efficiency, ABC-model, light-current characteristic

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Токовые и температурные зависимости оптических характеристик мощного AlGaN светодиода глубокого УФ диапазона (λ = 270 nm)

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Аннотация. Целью данной работы было изучение энергетических характеристик светодиодов глубокого ультрафиолетового излучения и установление физических причин ограничения выходной оптической мощности и эффективности преобразования энергии в таких устройствах. В ходе работы были экспериментально исследованы электрооптические характеристики мощных AlGaN flip-chip светодиодов глубокого ультрафиолетового диапазона (λ = 270 нм) в широком диапазоне токов и температур. На основе анализа полученных зависимостей в рамках ABC-модели сделаны выводы, что при относительно высокой внутренней квантовой эффективности излучения ~70–90% и значении последовательного сопротивления ~1 Ω, основным фактором, ограничивающим энергетические возможности устройств, является низкая эффективность экстракции света. Последнее обусловлено сильным поглощением генерируемого света в объеме чипа и на контактах, а также полным внутренним отражением на границах AlGaN/сапфир и сапфир/воздух.

Ключевые слова: AlGaN, глубокий ультрафиолет, светодиод, внутренний квантовый выход, коэффициент вывода излучения, ABC-модель, ватт-амперная характеристика, ультрафиолетовый светодиод

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Introduction

Over the past decade, significant efforts have been directed to improving epitaxial technologies and designs of deep ultraviolet (DUV) light-emitting diodes (LEDs) based on AlGaN quantum-well heterostructures emitting in UV-C spectral region that spans from 100 nm to 280 nm [1, 2]. UV-C radiation covers wide range of applications including polymer curing, biochemistry and analytical systems using fluorescence, spectrometry, military fields, etc. But the main interest is attracted by the bactericidal effect of UV-C radiation, which can be used to deactivate pathogens (e.g., bacteria, spores and viruses), air and water purifiers, disinfection and sterilization of various items. Currently, one of the most effective methods for disinfecting is the use of discharge mercury lamps, for example, type DB 75. However, they have a number of well-known disadvantages, including size, power systems, insufficient service life and mercury disposal. With the replacement of lamps with LEDs, great prospects are associated, but today they are hampered by low energy parameters of DUV LEDS: output optical power (P_{out}), external quantum efficiency (η_{EQE}) and, respectively, wall-plug efficiency (WPE). So, for similar in design flip-chip blue (λ = 470 nm) LEDs based on AlInGaN multiquantum wells (MQWs) heterostructures a peak η_{EQE} of more than 80% has been attained [3]. This allows, at sufficiently high operating currents, to get P_{out} up to tens of watts at the $WPE > 40\%$ [4, 5]. At the same time, for DUV LED $\eta_{EQE} \sim 20\%$ has been achieved for record laboratory LEDs [6], while for commercial devices it is only a few percent and $P_{out} < 100$ mW [7].

Experimental details

We studied a high-power AlGaN multiquantum well DUV LEDs with a wavelength $\lambda_{peak} \sim 270$ nm. Emitting chips have "flip-chip" design with a multilevel distributed system of p- and n-contacts on the back side [9]. As is known, such LED design is the most efficient in terms of radiation output, current distribution and heat removal [10, 11]. The dimensions of the emitting chip are 1280 × 1160 μm^2, so the total area is S = 1.4 mm^2 and the active area under the p-contact is S_{act} = 0.75 mm^2 (used to calculate the current density J). The chip for contacts with additional metallization is mounted by soldering on the AlN electrode and heat-removing carrier-board.

The power and spectral characteristics of DUV LEDs at room temperature and moderate currents (up to 350 mA) were measured in continuous mode using a 6-inch integrating sphere of the OL770-LEDUV/VIS (200–780 nm) High-speed LED Test and Measurement System [12].

At high currents (units - tens of amperes), a pulsed operation mode was used, excluding self-heating (τ = 100–300 ns, F = 100 Hz). The power supply current pulses were provided by an Agillent 8114A generator with a PicoLAS LDP-V 80–100 V3.3 amplifier, the optical signal was recorded by a remote high-speed photodetector THORLABS DET02AFC and a Tektronix TDS3044B oscilloscope in relative units. The conversion to the absolute values was carried out according to the calibration obtained in the OL770-LED. The emission spectrum was recorded with an Avantes AvaSpec-2048 spectrometer. The investigated temperature range 200–350 K was set by a cryostat with an optical window CCS-450 (Janis Research Company Inc.).

Results and discussion

Fig. 1, *a* shows typical room temperature electroluminescent (EL) spectra of the DUV LED in a wide range of currents (I = 0.001–20 A), respectively, current densities (J = 0.0001–2.6 kA/cm^2). Calculated on the basis of Fig. 1, *a*, the current dependences of the peak wavelength λ_{peak} and full width at half maximum (FWHM) are presented in Fig. 1, *b*. For comparison, similar typical dependences for blue (λ ~460 nm) flip-chip AlInGaN LED are shown by dashed curves. As can be seen from Fig. 1, *a*, the emission spectra of DUV LEDs are distinguished by a very high current stability, in comparison with similar blue LEDs. The short-wavelength shift $\Delta\lambda_{peak}$ with a change in current density by 3 orders for DUV LED is only ~ 1–1.5 nm, while the FWHM remains within ~10–11 nm. For blue LEDs, the short-wavelength shift with current change within the same limits is ~25 nm, and FWHM increases from 21 nm to 32 nm. Such a difference in the spectral behavior of DUV LEDs and blue LEDs is explained by the fact that for highly polar "blue" structures containing In in the quantum well ($In_{0.16}Ga_{0.84}N$), the short-wavelength current shift λ_{peak} and the expansion FWHM are mainly affected by screening injected carriers of the internal field, which causes the quantum confined Stark effect (QCSE). In DUV LEDs, the $Al_{0.4}Ga_{0.6}N$ active quantum well does not contain In and is not strongly spontaneously polarized. A small change in the spectrum with current is associated with an increase in the carrier concentration and their energy distribution.

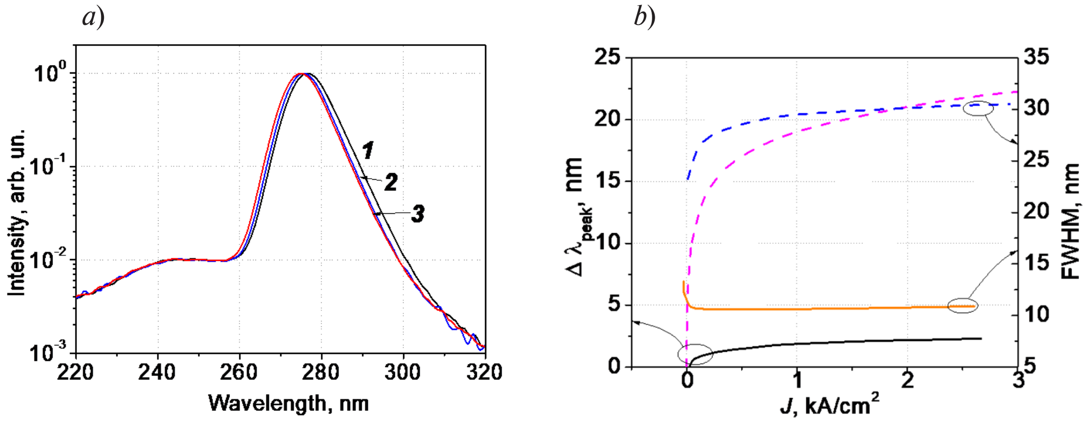

Fig. 1. Spectra of DUV LED emission at different current, T = 293 K, curve *1* corresponds to J = 0.05 kA/cm^2, curve *2* to J = 0.5 kA/cm^2, curve *3* to J = 2.5 kA/cm^2 (*a*); current dependence of $\Delta\lambda_{peak}$ and FWHM. For comparison, the same dependences for blue LED are shown by the dashed line (*b*)

Fig. 2, *a* shows the emission spectra of the DUV LED at an average current value I = 0.5 A (J ~ 70 A/cm^2) in the temperature range T = 200–350 K. It is clearly observed from Fig. 2, *a* that the changes in λ_{peak} and FWHM for DUV LEDs with temperature are within 2.0–3.0 nm, i.e., the temperature coefficient $TC\lambda_{peak}$ < 0.02 nm/K (for blue LEDs $TC\lambda_{peak}$ ~ 0.1 nm/K). Thus, both in terms of current and temperature stability of the spectrum, DUV LEDs are noticeably better than blue LEDs. Fig. 2, *a* also shows on a semi-logarithmic scale the view of the short wavelength shoulder of the emission spectrum as a function of energy ($h\nu$ [eV] = 1239.6/λ [nm]), which makes it possible to estimate the carrier temperature T_c from the slop of shoulder (based on their Boltzmann distribution) [13].

$$T_c = [-k_B \frac{\partial(\ln P)}{\partial(h\nu)}]^{-1}. \quad (1)$$

As follows from Fig. 2, *a*, there is a good correlation of the carrier temperature with the temperature of the LED package, which indicates the absence of noticeable self-heating in the pulsed operating mode. Therefore, the energy current dependences considered below have a purely electronic character.

Fig. 2, *b* shows the main energy characteristics of the DUV LED: the dependences of the external quantum efficiency η_{EQE} on the current density. As can be seen from Fig. 2, *b*, the maximum value of η_{EQE}^{max} was 3.4%, at current density J = 5 A/cm^2. For comparison, the value of η_{EQE}^{max} of the blue LED of similar design approaches to ~ 70%, and at high current η_{EQE} remains at the level of ~30%. [4] at low current densities. With such a cardinal difference in energy efficiency, it is of undoubted interest for research and applications to find out which of the factors, i.e., transport and injection of carriers, internal quantum efficiency or efficiency of radiation extraction, plays a major role in limiting possibilities of DUV LEDs.

To answer this question, in addition to the temperature dependences of emission spectra already described above, we consider the temperature dependences of η_{EQE}. Fig. 2, *b* shows the dependences of the η_{EQE} on the current on an enlarged scale in the moderate current range for temperatures set from 200 K to 350 K with a step of 10 K. Two important consequences follow from Fig. 2, *b*. First, the values of η_{EQE} gradually increase with decreasing temperature, since reducing the rate of nonradiative Shockley-Reed-Hall recombination. And, secondly, for the same reason, the current density decreases, where the value η_{EQE}^{max} is reached. It is important that at low temperatures 223–233 K, the possibility of a clear identification of the position of the η_{EQE}^{max} on the current dependences $\eta_{EQE} = f(J)$ opens up. The form of the dependence, for example, at T = 223 K, with a pronounced maximum η_{EQE}^{max} on the curve, allows us to apply *ABC*-model for estimating the internal quantum efficiency η_{IQE} [14].

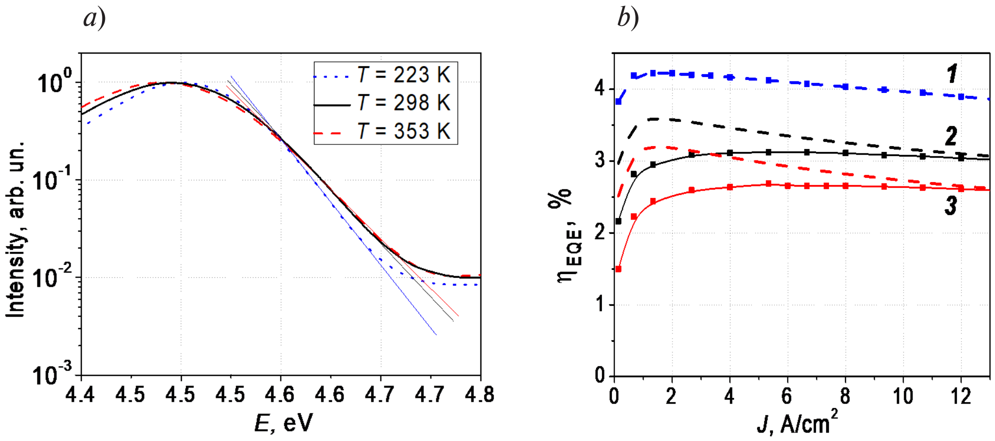

Fig. 2. Normalized DUV LED emission spectra as a function of temperature at a current density of 13 A/cm^2 and the short-wavelength shoulder of the same spectra recalculated in energy coordinates (*a*). Dependence of η_{EQE} on the current at three temperatures 223 K (*1*), 298 K (*2*); 353 K (*3*). Experimental and calculated data according to the *ABC*-model (dotted line) (*b*)

In the ABC-model, η_{IQE} is determined by the competition of three recombination mechanisms in the active region:

$$\eta_{EQE} = \eta_{ext},\ \eta_{IQE} = \eta_{ext}\frac{Bn^2}{An + Bn^2 + Cn^3}, \quad (2)$$

where A, B, C are the coefficients corresponding to the mechanisms of nonradiative Shockley-Read-Hall recombination, radiative bimolecular recombination and nonradiative Auger recombination, n is the concentration of injected carriers in the active region. Determining the parameters A, B, C separately is an experimentally difficult task, which, as a rule, gives only approximate estimates. However, using the well-known transformations [15] when plotting the experimental dependences of the $\eta_{EQE}^{max}/\eta_{EQE}$ on the sum of the roots of the powers $(p^{1/2} + p^{-1/2})$, where $p = P_{out}/P_{out}^{max}$, and P_{out}^{max} is the power at a current corresponding to η_{EQE}^{max}, we obtain an expression to determine the main parameters of radiative recombination:

$$\frac{\eta_{EQE}^{max}}{\eta_{EQE}} = \eta_{IQE}^{max} + \frac{p^{1/2} + p^{-1/2}}{Q+2}, \quad (3)$$

where the invariant $Q = B/(A \cdot C)^{1/2}$ – "quality factor" is a fundamental characteristic of the LED: $\eta_{EQE}^{max} = Q/(Q+2)$. Considering the graph based on expression (3) with the extrapolated $(p^{1/2} + p^{-1/2}) \to 0$, we can determine η_{EQE}^{max}, and Q from the slope of the curve. Taking into account

$\eta_{EQE} = \eta_{ext}\eta_{IQE}$ knowing η_{IQE}, and experimentally measured η_{EQE}, it is possible to determine η_{ext}, that is, all the main parameters of the LED. The results of corresponding calculations based on the 5th experimental dependence $\eta_{EQE} = f(J)$ in the region of moderate currents (0.01-0.1 A) at T = 223 K gave the following values: η_{IQE}^{max} = 0.87, η_{EQE}^{max} = 0.042, η_{ext} = 0.048. As the temperature rises to room T = 293 K, assuming reasonably that ηext does not depend on temperature, it follows from Fig. 2, *b* that η_{IQE}^{max}, drops to 0.68 due to an increase in nonradiative recombination.

Conclusion

The experimental dependences $\eta_{EQE} = f(J)$ for DUV LED (λ = 270 nm) are well described by the *ABC*-model, which made it possible to estimate η_{IQ}E which has a rather acceptable value of 70–90% in the temperature range T = 200–350 K. The low value of η_{EQE} ~3–4 % is due to the smallness of η_{ext}. The latter is due to the absence of the effect of 'multi-passage' of light in UV-C emitting chips because of absorption at the contacts, which occupy a large area. This is the main difference from blue LEDs, where the contacts have sufficient reflectivity. Further efforts to improve the energy parameters of DUV LEDs are primarily related to improving the design of the emitting chip: Bragg reflectors, micro mesa-reflectors etc., increasing the chance of light output.

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