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Comprehensive study of the power capabilities of UV-C LEDs in pulsed and continuous modes

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Abstract. Data is reported on study of light-current characteristics and thermal properties of flip-chip AlGaN UV-C LED over a wide range of excitation levels: up to 2 kA/cm^2 in pulse mode. The tailor-made microscope based on InAs matrix with photosensitivity in 2.5–3.1 μm range was employed for getting IR-intensity maps and revealing of temperature distribution across the emitting chips. The work is aimed at detailed study the factors limiting the energy capabilities of UV-C LEDs.

Keywords: power UV-C LED, thermal resistance, temperature mapping

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Комплексное исследование энергетических возможностей светодиодов UV-C в импульсном и непрерывном режимах

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Аннотация. Представлены данные по исследованию электрооптических характеристик и тепловых свойств «флип-чип» AlGaN светодиодов UV-C в широком диапазоне токов: до 2 кА/см^2 в импульсном режиме. С помощью ИК-микроскопа получены карты распределения температуры по СД чипу. Работа направлена на детальное изучение факторов, ограничивающих энергетические возможности светодиодов UV-C.

Ключевые слова: мощные UV-C светодиоды, тепловое сопротивление, температурный мэппинг

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Introduction

UV-C light emitting diodes (LEDs) are environmentally friendly, mercury free, and nonpolluting sources of UV radiation in contrast to traditional mercury sources. The sterilization wavelength is concentrated between 260 and 280 nm. Studies have documented the wide use of UV-C LEDs in medical phototherapy and in the disinfection and sterilization of water, food, and medicine for safe consumption [1–3]. Traditional mercury UV lamps are disadvantaged by their long warm-up times, short lifetime, risk of exploding and environmental pollution; UV-C LEDs are superior in all aforementioned aspects [4].

The driving current, chip area of UV-C LEDs and the level of integration of LED matrixes are continuously increased to provide ever higher output light flux. The new developments require pay more attention to achieving the maximum possible radiation power while maintaining an acceptable efficiency. In other words, elucidation of the main factors of an electronic or thermal nature that limit the power of devices [5, 6].

Experimental Setup

1. Test sample

The investigated LED chips produced by Bolb Inc. had a peak emission wavelength λ_{peak} = 280 nm. The flip-chip LED (Fig. 1, *a*) had the emission area of 1280×1160 μm^2 and simple multi-strip interdigital contact pad topology (Fig. 1, *b*). For high current operation the chip was soldered on AlN plate, which was then mounted on bulky heat sinks.

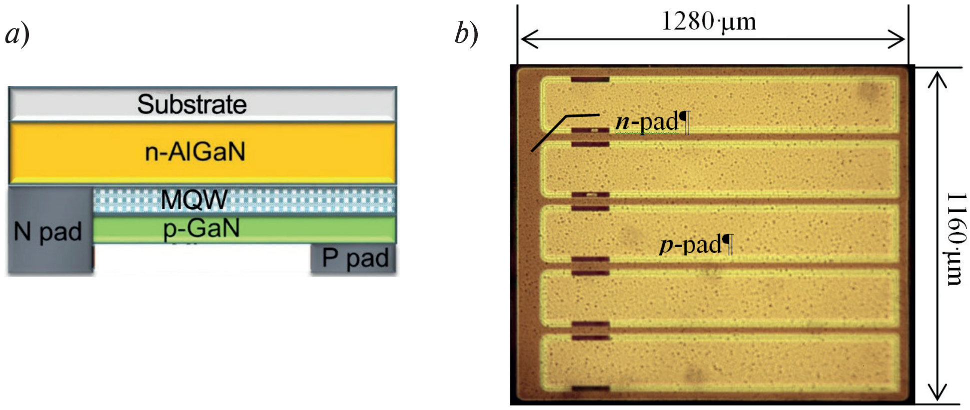

Fig. 1. Structure scheme of the flip-chip LED (*a*) and image of the test sample (*b*)

2. Current-voltage and light-current characteristics of LEDs

The studies were carried out up to I = 350 mA in continuous mode and up to I = 20 A in pulsed mode (τ ~ 100 ns). In Fig. 2 the current dependences of radiation power P_{opt} and external quantum efficiency η_{EQE} are presented, while Fig. 3 shows the temperature dependences of spectrum. The entire range of current changes during measurements covered five orders of magnitude from fractions of a milliamp to 20 A. The pulse mode during measurements (τ = 100 ns, f = 100 Hz) was provided by an Agilent 8114A generator with a PicoLAS LDPV 80-100 V3.3 amplifier. Optical power and emission spectra were recorded using the OL 770-LED Highspeed LED Test and Measurement System [7].

3. IR thermal imaging

The determining the surface temperature distribution is based on the application of thermal imaging equipment. It allows one to measure the temperature directly and thus to obtain more detailed information on the temperature distribution. To obtain the temperature distribution over the chip, the IR thermal radiation in the spectral range of 2.5–3.1 μm was mapped by a specially designed IR microscope. We would like to emphasize that using a relatively short wavelength IR radiation (compared to an 5–12 μm range utilized in conventional thermal-imaging systems) allowed us to reduce diffraction blurring and thus to improve the spatial resolution of the IR mapping down to 3 μm.

The main methodological problems of thermal imaging of AlGaN structures are: (i) the transparency of the sapphire substrate and epitaxial layers for IR radiation and (ii) a large difference in the emissivity of the materials utilized in the LED, i.e., semiconductor layers, metallic electrodes, reflective coatings, mounting elements, etc. [8]. So, extraction of correct temperature distributions from the IR images requires preliminary calibration of data for every particular object. Such a calibration was made with the temperature control by external heater in the range of 20–100 °C and recording the IR radiation from the LED chip at zero current. The calibrated relationship between the IR radiation intensity and temperature was then used to determine the absolute temperature under operation current (I = 350 mA).

4. Thermal resistances

The total thermal resistance R_{th} and thermal resistance R_i of internal elements of the LED an equivalent thermal circuit were determined via operating voltage relaxation method [9], using the Thermal Transient Tester T3Ster by MicRed, Ltd. For this purpose, a relationship between the voltage and temperature was determined from preliminary calibration of every LED.

The 1D heat transfer through the active region and AlN substrate was considered similarly to the current flow in an equivalent electrical circuit. Generally, there are two conventional models for building up the equivalent circuit; we used Cauer's one combines all the capacitances to a common bus.

Results and Discussion

The current dependences of the emitted power and spectral characteristics of investigated AlGaN LEDs, including their distribution (mapping) over the radiating surface, were studied in a wide range of operating currents from milliamp currents up to 350 mA in continuous mode and 20 A in pulsed mode.

In Fig. 2, the current dependences of radiation power P_{opt} and external quantum efficiency η_{EQE} are presented. As can be seen from Fig. 2, the sharp changes of EQE (approximately up to 4–5 A) and then the tendency to saturation take place. That dependence is in good correlation with the conventional ABC-model. The value of η_{EQE} is only 3 % in maximum and decreases to 1 % at current 20 A. The low value of efficiency can be explained by low extraction radiation coefficient due to the large area of non-reflective contacts. Despite this fact, the output optical power density reaches level of ~ 1 W/mm^2.

The spectral analysis of emission (Fig. 3) showed low dependence on temperature. The peak wavelength at operating current 350 mA is = 279.5 nm without heating and λ_{peak} = 280 nm at the external heating up to 90 °C. Thus, the temperature coefficient of the peak wavelength is only TKλ_{peak} = 0.08 Å/K.

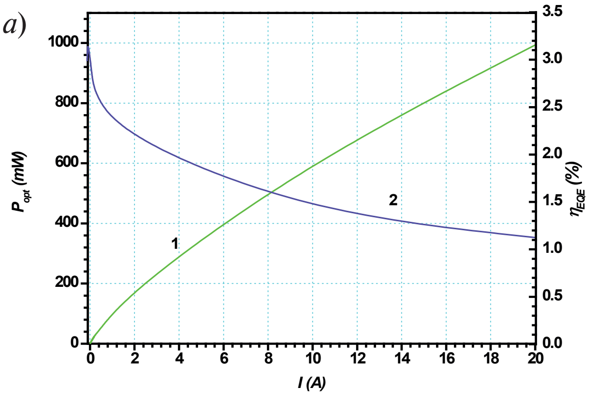

Fig. 2. Optical output power P_{opt} (1) and external quantum efficiency η_{EQE} (2) of the LED dependences on current

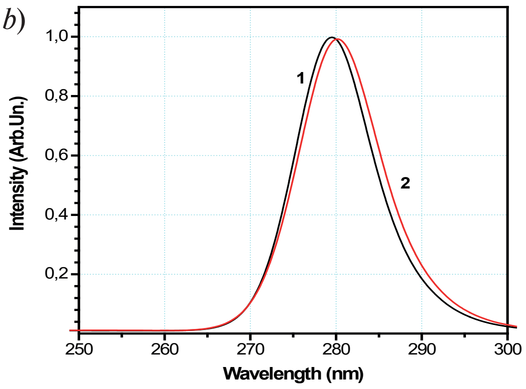

Fig. 3. Peak wavelength λ_{peak} dependences on wavelength at operating current I =350 mA and temperature of 25 °C (1), 90 °C (2)

Figure 4 shows a map of temperature distributions over the area of LED chip at the continuous operating current 350 mA. At the current of 350 mA, the temperature distributions remain to be nearly uniform, indicating good lateral heat spreading inside the LED chip. And the temperature of surface is 60 °C with temperature of ambient 25 °C, consequently the overheating is 35 °C.

The latter conclusion is also supported by the cumulative structure functions (CSFs) measured by the T3Ster tester (see Fig. 5). The sum of the thermal resistances R_{th} = 25 K/W is associated the overheating of chip relatively ambient. It can be noted much more thermal resistances of the UV LED in comparison with similar blue LEDs (~ 5 K/W) which requires additional consideration.

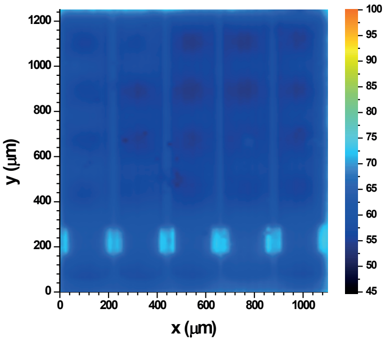

Fig. 4. The IR thermal image of chip at the current 350 mA

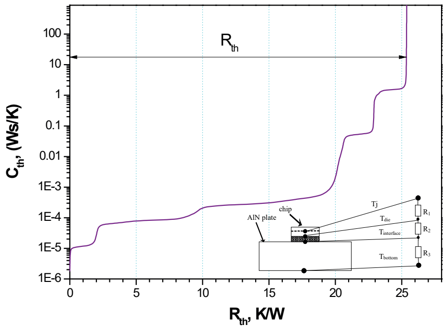

Fig. 5. The cumulative structure functions of the LED at the current 350 mA

Conclusion

Optical, electrical and thermal characteristics of high-power AlGaN UV-C LEDs of “flip-chip” design have been studied over a wide range of excitation levels in continuous and pulsed modes. The temperature and current dependences of conversion efficiency and output power, as well as the drift of spectral parameters λ_{peak} and FWHM have been determined. The operation capacity of LEDs in pulse mode up to current ~ 20A with an output power ~ 1 W has been established.

The thermal properties of UV-C LEDs were investigated both by infrared microscopy techniques (temperature mapping) and by analysis of the equivalent thermal circuit by voltage relaxation method, using the Thermal Transient Tester T3Ster. The uniformity of the temperature distribution over the entire area of the chip was established for all operating currents, that is, the absence of the effects of current crowding and the occurrence of temperature gradients. The quantum efficiency droop with increasing current is determined by recombination processes, apparently the growth of nonradiative Auger recombination.

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