A comprehensive study of current-crowding effect in high power vertical AlInGaN LEDs under high pulsed current

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Abstract. The goal of the study is examination of current-crowding effect in high power AlInGaN LEDs. This effect was presented by mapping of EL (electroluminescence) near filed under high pulse current. LED chip of vertical design was study in high range of current \(10^{-9} \div 70\) A. This operating mode of LEDs are interesting for different applications, such as pumping lasers, VLC and LiFi, as well as for investigation accelerated degradation process of LEDs.

1. Introduction
The scope of application of light-emitting diodes (LEDs) keeps expanding. The study of the operation of LEDs in pulse mode to exclude self-heating at high excitation levels is interesting for establishing the injection and recombination mechanisms and identifying the reasons that limit the energy capabilities of devices [1-4]. In this work were studied the vertical design LED chip in the regime of short pulses \(\tau = 100\) ns at ultrahigh operating currents – up to 70 A.

In practice, the results of the study can be used to create special designs of AlInGaN visible-range LEDs for working with physical receivers, for example: in VLC (Visible Light Communication) systems, for pumping solid-state lasers [3]. New applications require the operation of LEDs in short pulse modes (from tens of nanoseconds to units of microseconds) when the maximum radiation power (energy per pulse) is reached.

2. Experimental
Commercial non-casted Enhanced Vertical LED chip EV-B40A produced by SemiLEDs [5] was chosen for our study. Chip peak emission wavelength \(\lambda_{\text{peak}} = 460\) nm, the emission area of 1100x1100 \(\mu m^2\) and a simple contact geometry Figure 1.

The optical parameters of the LEDs were measured in pulse regime. To ensure the predetermined pulse regime, an Agilent 8114A pulse generator was used with a PicoLAS LDP-V 80-100 V3.3 external amplifier. The pulse width and duty cycle were monitored with a Tektronix TDS3044B oscilloscope. Pulse duration was \(\tau = 100\) ns and repetition rate was \(f = 50\) Hz to avoid self-heating.

Near-field distribution of EL parameters was monitored by using Mitutoyo optical microscope with Avantes AvaSpec-2048. The minimum and maximum field of view of the optical system was 536x357 \(\mu m^2\) and 5362x3520 \(\mu m^2\), respectively, with the best spatial resolution of 25 \(\mu m\).
The optical system collected the light within the 15° cone around the normal direction. The infrared (IR) thermal imaging was used to determine the surface temperature of the LED chip. It allows measurement of the temperature directly and thereby obtaining more detailed temperature data. The IR thermal radiation in the spectral range 2.5–3.0 µm was mapped by a specially designed IR microscope [6]. The main methodological problems with thermal imaging of AlInGaN structures are the transparency epitaxial layers for IR wavelengths and a large difference in the emissivity of the materials utilized in the LED, i.e. semiconductor layers, metallic electrodes, reflective coatings, mounting elements, etc. [7]. Therefore, extraction of the correct temperature distributions from the IR images requires preliminary calibration of data for every object. Such a calibration was made with the temperature control by means of an external heater in the range 5–100 °C via recording the IR radiation from the LED chip at zero current. Using the approach mentioned above it was possible to measure the temperature with the accuracy better than 2 K. The calibration procedure is time-consuming, moreover, leads to additional errors in obtaining of temperature maps, especially at points of low emissivity [8].

3. Results and discussion
The current dependences of the power and spectral characteristics of AlInGaN LEDs of vertical design, including their distribution (mapping) over the radiating surface, were studied in a wide range of operating currents up to ~70A. As can be seen from figure 2, the dependences of the $\lambda_{\text{peak}}$ and the external efficiency ($EQE$) on the current have areas of sharp change (approximately up to 10 A) and then the tendency to saturation. We assume that the effect of current crowding under the contacts becomes the main factor in reducing the internal quantum and the radiation-extraction coefficient $\eta_{\text{ext}}$, limiting the energy capabilities of the LED. To clarify the current distribution, the dependence of the spectra on the coordinate on the chip surface at different operating currents was studied.

It is well known, that at low operating current there is a uniform distribution of LED emission, and the distribution of emission is proportional to the current density over the area of the p-n junction [9]. But at a current of 2A and above, the near field of EL confirms a significant effect of current crowding.

It should be noted that the light intensity distribution only qualitatively reflects the current density distribution. Due to the dependence of the $IQE$ on the current, and partly due to the scattering of light...
inside the LED chip, light distribution is more smoothed compared to the current density distribution. To further refine the current distribution, as well as the temperature over the crystal area, we used spectral distribution mapping, shown at figures 3-4.

![Figure 2](image)

**Figure 2.** Measured EQE (1) $\lambda_{\text{peak}}$ (2) dependencies on current.

![Figure 3](image)

**Figure 3.** Distribution of $\lambda_{\text{peak}}$ as a function of the coordinate in cross section A.

![Figure 4](image)

**Figure 4.** Distribution of $\lambda_{\text{peak}}$ as a function of the coordinate in cross section B (1) and C (2).

Noticeable short-wave shift of the spectrum emitted near the left contact pad ($x = 100$) compared to the spectrum emitted near the center of chip ($x = 600$) $\lambda_{\text{peak}} = (445 - 442) = 3$ nm, is a direct confirmation of the difference in current densities. The gradient was observed both along and transverse the metal strip contacts. The gradient transverse the contacts (figure 4) is associated with poor current flow along the GaN p-layer, and the gradient along the contacts indicates a high resistance of the strip contacts.

Since another parameter – temperature can effect on the peak wavelength the heating of the chip was monitored using IR microscopy, shown at figure 5. The graph shows that there is no increase in the intensity of infrared radiation, even at the highest pulse current used. The slight mismatch of the curves is due to the influence of noise.

In addition, the analysis of the LED radiation spectrum showed no shift in the short-wave arm, which also indicates no increase of the temperature of the active region.
Figure 5. Profile of IR intensity in cross section C (insert in figure 3).

The study of the distribution pattern of the peak wavelength as a function of the coordinate on the chip allowed us to identify the presence of regions with different current densities. It is assumed that the addition to the research methodology of studying the dependence of full width at half maximum of the spectrum.

4. Conclusion
A vertical 1x1 mm² LED chip was studied in the current range $I = 10^9 \div 70$ A.

There is a sharp change in $EQE$ and $\lambda_{peak}$ in the current range up to 10A, then a saturation of the dependence of these parameters on the current. The explanation for this can be the uneven current flow, as a result of most of the current flows under the strip contacts and increases only non-radiative recombination.

The near-field mapping of the $\lambda_{peak}$ showed noticeable gradients both across and along the metal strip contacts. Since the $\lambda_{peak}$ is a current-sensitive parameter. Consequently, the gradient of across the contacts is associated with poor current flow along the GaN n-layer, and the gradient along the contacts indicates a high resistance of the strip contacts.

To explain the type of dependence of the spectral parameters on the current, it is necessary to take into account the above-mentioned inhomogeneity of the current distribution.

The mapping of the position of the peak wavelength is the clearest indicator of the current density distribution, since $\lambda_{peak}$ is not subject to mixing, in contrast to the radiation intensity.

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