

Investigation of temperature characteristics of UV-LEDs with different GaN/AlGaN heterostructures

A S Evseenkov¹, S Yu Kurin², P O Tadtayev¹, S A Tarasov¹, A V Solomonov¹

¹St. Petersburg Electrotechnical University “LETI”, 5 Prof. Popova Street,
St. Petersburg 197376, Russia.

²GaN-Crystals Ltd., 27 Engels Ave, St. Petersburg 194156, Russia,

E-mail: as.evseenkov@gmail.com

Abstract. The quantum efficiency of AlInGaN-based LED structures with different active region thickness at different temperatures and biases was studied. The strong influence of the thickness of the active region on the characteristics of the samples was observed. Through the decrease of the active region thickness not only the emissive power dwindled but also thermodynamic properties tended to deteriorate and low temperature stability of the active region was observed. It was shown that the decrease in internal quantum efficiency through the increase of the current density was caused by charge leak from the quantum well. The heating of the active region due to the higher Auger recombination frequency led to the shift in the peak wavelength of the emission spectrum and lower emission power.

1. Introduction

At the present time, one of the main problems in development of LEDs and gallium nitride based lamps [1,2] is the decrease of the emission power of a single led in the matrix composition. Using a smaller number of LEDs in the lamp reduces its size, allows for easier electrical circuitry development and reduces the overall cost of the product. Watt-ampere characteristic is the most important characteristic of the emitters. It describes the change of radiation power with the increase in the values of direct current. Ideally, this dependence is linear. Unfortunately, in real emitters the increase of the power slows down and then goes into decline as the current grows. This limits the maximum achievable power. Such nonlinearity may be explained by self-heating of the crystal and the decrease in the efficiency of LEDs with increasing current density. The reasons for the low efficiency might be the lack of high-quality epitaxial heterostructures [3-6], low light extraction ratio [7], the influence of embedded piezoelectric fields in quantum well, charge leaks, structural defects and Auger recombination processes. A short wavelength ultraviolet emission requires an increase in the aluminum nitride concentration in a solid solution of the active region. This leads to additional technological complexity and increases the number of structural defects. In addition, in the ultraviolet range of wavelengths the absorption coefficient of epitaxial layers increases dramatically. This leads to the stronger influence of the thermal effects on the device's characteristics. What is more, the processes of self-heating depend on the device's emitting crystal properties and its package.

In order to study the processes of self-heating in the test-system [8], a new patented method of determining the temperature of the active region is used. It is based on a detailed analysis of the spectral characteristics of electroluminescence and Van-Rusbreka-Shockley theory, which considers the effect



of impurities and defects on the structure's performance. The method is quick, non-contact and allows for investigation of the individual emitters included in the composition of the LED lamp or other LED-based products with no need for unsoldering. What is more, the technique allows to determine the temperature of the active region of the chip directly on the substrate surface. Thus, the method is applicable for carrying out quick temperature diagnostics of the structures at all stages of production of LEDs and LED-based products.

However, studies have shown that in case of light emitting structures with one substrate the difference in temperature parameters can sometimes reach considerable values, which is caused by the features of integrated grouped technique used in chips production. This leads to the necessity to control the quality of the structures within the substrate. Conventional methods based on determining the power and some other parameters of the structures do not always provide researchers with data for valid conclusions about structures' quality. Fast non-contact temperature measurements solve this problem. The diagnostic technique to evaluate the emitting chip temperature in the composition of the substrate was developed, followed by an automatic analysis of the obtained characteristics and valid conclusions about the quality of the structure. Time required for testing one single chip does not exceed 1 second. The technique is completely ready for the infusion to the production process.

In this paper an experimental investigation of the optical and electrical properties of ultraviolet light-emitting diodes based on GaN/AlGaIn heterostructures was carried out, electroluminescence spectra, current-voltage characteristics and other important characteristics were investigated. Special attention is paid to the study of the influence of thermal processes on the spectral characteristics, optical power and emission efficiency of the structures. What is more, the temperature of the active region was determined and the effects of the composition on the values of these temperatures were studied.

2. Samples and Experimental techniques

In this paper UV-LEDs with emission wavelengths in the range from 355 to 385 nm were investigated. The method of chloride-hydride vapour phase epitaxy (CHVPE) was used to create light-emitting heterostructures. The means of reducing the mismatch of lattice parameters of semiconductor materials included growing a thick (over 100 nm) active region without the formation of dislocations and other defects.

The construction of UV LED heterostructure consisted of the following layers (starting from the substrate): AlN seed layer with a thickness of 200 nm; buffer area of alternating layers of AlGaIn of variable composition with a total thickness of 3.5 μm ; n-AlGaIn hole-blocking layer (dopant - Si) with a thickness of 800 nm; AlGaIn active region with a thickness of 80-150 nm; p-AlGaIn electron-blocking layer (dopant - Mg) with a thickness of 200 nm; p-GaN upper contact layer 100 nm thick. The composition of the electron-blocking layer was selected so that, on the one hand, the electron leakage into the p region was suppressed and, on the other hand, the necessary hole injection level into the Al was retained. In this work the electron-blocking layer with a gradual decrease of Al concentration from 15% to 6% was used (counting from the active layer). The linearly decreasing gradient Al concentration in the electron-blocking layer is known to significantly improve structure's efficiency. Active zones contain 1-2% of aluminum. Two types of LED structures were made: ones with a crystal size of 1×1 mm without package and ones with the crystal size 0.31×0.31 mm packaged. Metal compositions of Ti/Al and Ni/Al were used for N-type and p-type electrodes respectively. Processing and packing of samples was performed using an external service.

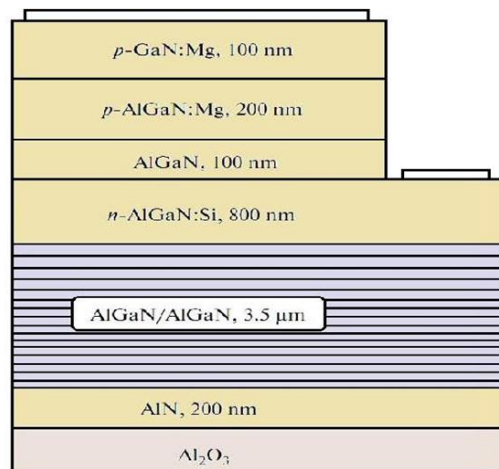


Figure 1. The structure of the ultraviolet light-emitting diode

3. Results and Discussion

In this paper an experimental study of the characteristics of a significant number of ultraviolet light emitting diodes based on different types of heterostructures and GaN/AlGaIn is presented. The study of heterostructures was performed using the test set developed by the authors [2, 9, 10]. The main tasks were the study of the thermal processes which take place in these structures, identification of their ground and evaluation of the possibility of the application of thermal parameters analysis in estimating the structures' quality. For further analysis of the obtained data two samples were selected and, being characterized by their best performance parameters - power and efficiency, are hereinafter referred to as a sample of the first type (first sample) and a sample of the second type (second sample).

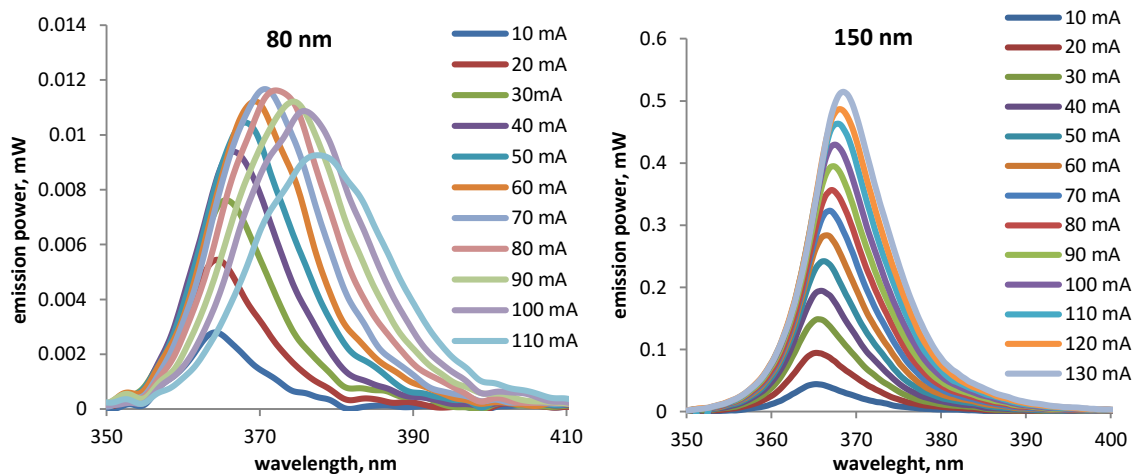


Figure 2. Electroluminescence spectra of UV LEDs with the active region thickness of 80 nm and 150 nm

The main characteristic of any light emitting diode is its emission spectrum. For a full investigation of the features of the samples, the spectral characteristics measurement must be performed within the whole operational range of currents. The emission spectra of the investigated samples are shown in Fig. 2. A very significant difference in all spectra parameters is observed, including the peak's shift and the change of the area under the curve through the increase of the direct current. The results may be also presented as the dependences of the emission power (Fig. 3), efficiency (Fig. 4) and the emission

wavelength at the maximum (Fig. 5) on the direct current. The analysis of the characteristics shows that for the samples of the second type not only significantly higher values of the power (up to 5 mW) are achieved, but also that the emission power grows almost linearly. For a sample of the first type a significant deviation from the straight dependence occurs at 24 mA already; at 80 mA the power saturation is observed and it the curve starts to decline with a further increase in the current. This limits the achievable values of the emission power by more than an order of magnitude. Similar processes are observed for the efficiency - for the sample of the second type it exceeded 6% and saturated at higher currents (40 mA).

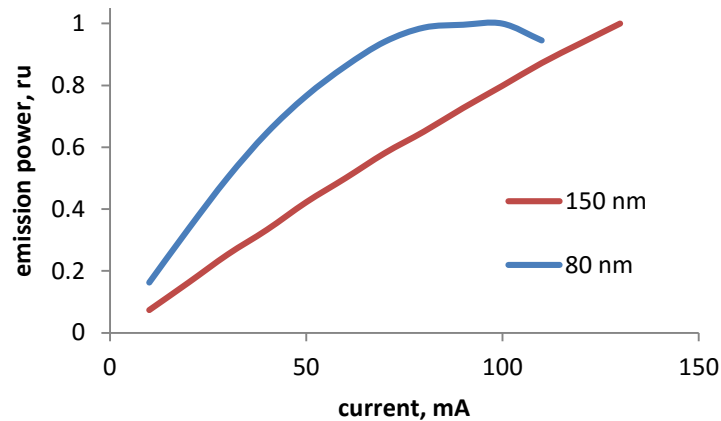


Figure 3. Power versus current for the samples with an active region thickness of 80 nm and 150 nm

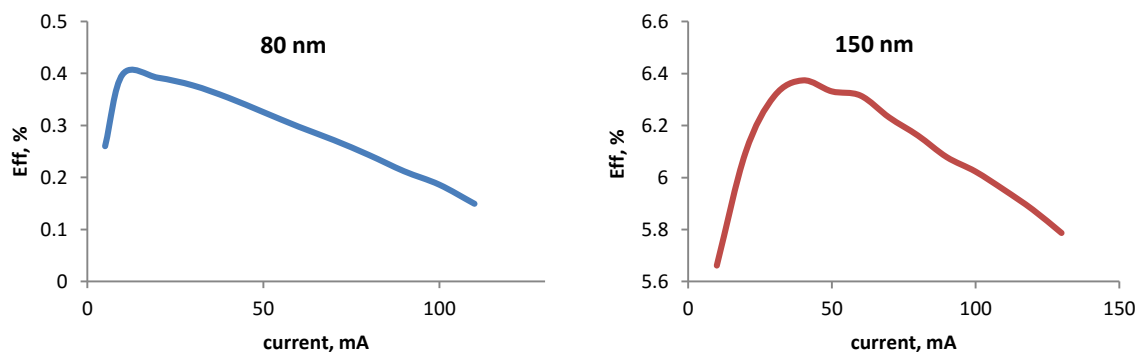


Figure 4. The dependence of the efficiency on the current for the samples with an active region thickness of 80 nm and 150 nm

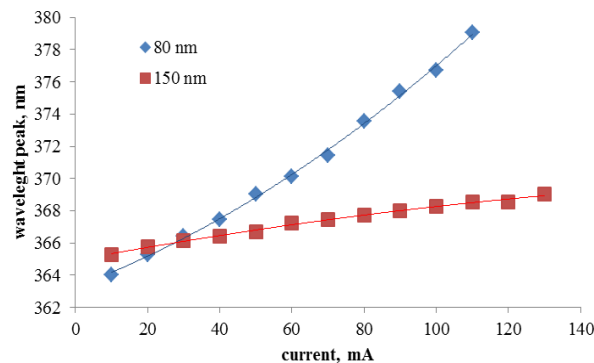


Figure 5. The dependence of the emission wavelength at the maximum on the current for the samples with an active region thickness of 80 nm and 150 nm

Preliminary information about the processes allows us to analyze the dependence of the peak wavelength of spectral characteristics on the direct current (Fig. 5). It is shown that in both cases there is a shift towards the longer wavelengths and for the first sample equals 14 nm while raising the current up to 110 mA, while for the second one the peak is shifted by only 3 nm. It is known that a shift towards longer wavelength is determined by self-heating processes in the structure, and that was further confirmed by the measurements of the spectral characteristics of the LED at a constant current and increasing the ambient temperature. In order to study these processes we analyzed the influence of the temperature on the structures' performance (Fig.6).

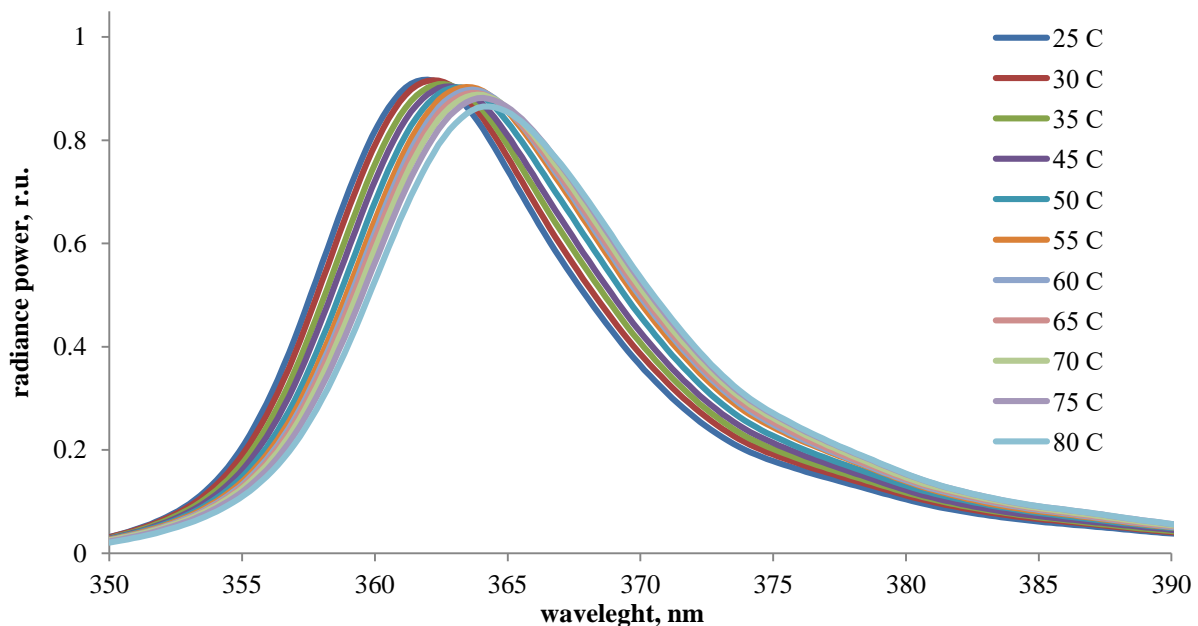


Figure 6. The emission spectra for the sample with an active region thickness of 80 nm at various temperatures

It is shown that the intensity of self-heating processes of the sample of the second type at 100 mA is more than 2.5 times lower than that of the samples of the first type for which the local temperature may exceed 200 degrees Celsius. This may be due to the following facts. Samples of the first type are characterized by a much higher density of the defects, which is associated with the non-optimized compositions of buffer layers and a smaller thickness of the active region. The features of these structures in terms of defects presence were investigated previously by the methods of secondary ion mass spectrometry, luminescence spectroscopy, atomic force microscopy and X-ray analysis; the research results confirmed these conclusions. Increasing the density of the defects increases the probability of non-radiative recombination, which leads to the additional heating of the structures. Therefore, temperature diagnostics allow for a high precision estimation of the presence of defects in the emitting region of the LEDs.

4. Conclusions

The study of the spectral and temperature characteristics of UV LEDs, created by CHVPE, was done. The experiment showed that the peak wavelength of the investigated samples was in the range of 363-367 nm at an operating current, the half-width of the emission spectrum didn't exceed 10-15 nm. At the operating current of 20 mA the temperature of the active region of the first sample was 36 degrees Celsius, but at 100 mA it raised up to 246 degrees Celsius; the optical output power and efficiency were equal to 0.29 mW and 0.4% respectively.

The second sample showed the best performance. At the operating current of 20 mA the temperature of the active region was equal to 36 degrees Celsius, at 100 mA it raised to 119 degrees Celsius. Optical output power and efficiency at an operating current were equal to 3.9 mW and 6.1% respectively.

The results can be explained by the main difference between the samples - the thickness of the active region. Small area dissipates heat worse and the study confirms that passing the current through such a small volume of the semiconductor leads to a sharp deterioration in its power characteristics. What is more, a smaller area of photon generation at the same current results in the lower intensity of the emission.

There is another phenomenon which influences the LEDs' parameters. Achieving ultraviolet emission requires higher concentration of the aluminum in the solid solution which, in turn, leads to the bigger lattice mismatch between the substrate and the grown layers. This complicates the production process significantly as the quality of the heterostructures becomes more crucial. Results obtained during this study may prove that production technique is not defectless enough. Thus, the method used in this study may be used for the analysis of the quality of the created structures.

Acknowledgments

The work was supported by the Ministry of Education and Science of the Russian Federation in the framework of the project of the state task in the field of scientific activity, project number 16.1307.2014K.

References

- [1] Panfeng J, Naixin L, Tongboo W 2011 *Journal of Semiconductors* Vol. **32** 11
- [2] Menkovich E A, Tarasov S A, Lamkin I A, Kurin S Yu, Antipov A A, Roenkov A D, Barash I S, Helava H I, Makarov Yu N 2013 *Journal of Physics: Conference Series* **461** 012027
- [3] Kim J K, Alhmed N, Frank W. 2008 *Appl Phys Lett* **93** 221111
- [4] Evseenkov A S, Tarasov S A, Lamkin I A, Solomonov A V, Kurin S Y. 2015 IEEE North West Russia Section Young Researchers In Electrical And Electronic Engineering Conference, ELCONRUSNW 2015 27-29
- [5] Kurin S, Antipov A, Barash I, Roenkov A, Makarov Y, Usikov A, Helava H, Solomonov A, Tarasov S, Evseenkov A, Lamkin I. 2015 *Physica Status Solidi (C) Current Topics in Solid State Physics* **12** № 4-5 369-371
- [6] Evseenkov A S, Tarasov S A, et al 2015 *IOP Publishing Journal of Physics: Conference Series* **643** 012033
- [7] Son J H, Jong U K, Yang Hee Song 2012 *Advanced Materials* **24** 2259-2262
- [8] Gu Y, Narendran N. 2004 *Proceedings of SPIE* **5187**: 107-114
- [9] Solomonov A V, Tarasov S A, Men'kovich E A, Lamkin I A, Kurin S Yu, Antipov A A, Barash I S, Roenkov A D, Helava H I, Makarov Yu N 2014 *Semiconductors* **48** 245-250
- [10] Menkovich E A, Solomonov A V, Tarasov S A, Yurgin P A 2014 *Functional materials* **21** 186-189