Self-heating process influence on efficiency of luminescence of nitride-based heterostructures

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Abstract. In this paper we report on dependence of the temperature of active layers (ALs) of heterostructures of light-emitting diodes (LEDs) based on AlGaN (UV LEDs) and InGaN (blue LEDs) on various current values (up to 150 mA). It is shown that the heating of the heterostructures is directly related to the concentration of defects. UV LEDs are characterized by a higher temperature than blue LEDs, they also demonstrate a lower wall-plug efficiency (WPE) (about 1.5% at 20 mA). The WPE of blue LEDs with and without the superlattice are 15% and 18%, respectively. To verify the accuracy of the performed measurements the theoretical calculation of the AL temperature according to Van Roosbroeck-Shockley theory and the model of 2D-combined density of states is carried out.

1. Introduction

Due to the unique properties of LEDs based on InGaN alloy they will soon replace conventional lighting. Their operation does not require high voltage, they are safe and low-cost. Their luminous efficacy is significantly higher than that of incandescent lamps. LEDs based on AlGaN alloy can be used as the sources of UV radiation that is also promising. These emitters can be applied in electrical engineering, medicine, science, and industry. They do not contain mercury and other poisonous substances, their recycling do not require special conditions and equipment. Therefore, large-scale application of LEDs based on nitride semiconductors allows reducing energy consumption costs as well as enhancing the state of the environment. Hence, the development of the production technology of nitride-based LEDs is an important goal.

Unfortunately, nowadays there are a number of limiting technological and other factors which decrease efficiency of luminescence of nitride-based LEDs. Self-heating of the LED AL which occurs at high current density is the most critical factor. When the temperature rises the amount of phonons increases that results in high probability of non-radiative recombination and low output power. Moreover, it leads to impurity cluster delocalization that decreases the lifetime of device. These limiting factors are especially relevant in AlGaN-based UV LED heterostructures.

The study of the influence of self-heating processes in AL on efficiency of nitride-based LED heterostructures allows us to find the reasons of this decrease. Moreover, p-n-junction temperature monitoring gives an opportunity to identify a structure defectiveness.

2. Sample and experimental technique

The paper analyzes the process of self-heating and its influence on luminescence efficiency in LED heterostructures based on solid solutions of AlGaN (peak wavelength is 362 nm) and InGaN (peak wavelength is 460 nm). The blue LED heterostructures were grown by metalorganic vapour phase epitaxy (MOVPE) (hereinafter referred to as type 1 crystals), the UV LED heterostructures (type 2 crystals) were obtained by chloride-hydride vapour phase epitaxy (CHVPE). Sapphire was used as a substrate for both types.

Type 1 crystals had a 2 μm thick GaN buffer layer grown on substrate to protect the AL from threading dislocations (TDs) which are formed because of lattice mismatch of substrate and epitaxial layers. Then a 2 μm thick n-GaN contact layer (CL) was grown. The LED AL contained a set of 5-10 InGaN quantum wells having a width of 4-5 nm. The wells were separated from each other by 25-50 nm thick GaN barriers. Then a 100 nm thick p-GaN top layer (TL) was grown. Part of LED heterostructures contained AlGaN/GaN superlattice with the lattice period of 20 nm between the p-GaN TL and the AL. The crystals containing the superlattice are called type 1A thereafter, those that do not contain − type 1B.

The design of the heterostructures of type 2 was worked out to take into account the requirement for acheiving of internal quantum efficiency maximum at high current densities. To meet this requirement a planar heterostructure (n+-n-p) was grown and a 100 nm thick single layer was used as the AL. In order to reduce the density of TDs stress relief layers were grown. Then n-type AlGaN hole-blocking layer, AlGaN, AL, p-type AlGaN electron-blocking layer, p-type GaN CL were subsequently grown. The total thickness of all epitaxial layers grown on substrate was about 6 μm.

For characterization of LED dies we used our invention – a state-of-the-art diagnostic complex which allows investigation of optical and electrical characteristics of both LEDs and laser diodes according to the international standard CIE 127:2007 and the Russian GOST 17616-82. The diagnostic complex employs a new method for determination of LED AL temperature which is based on the detailed analysis of electroluminescence spectra. The effects of noise including those induced by interference are considerably suppressed. The diagnostic complex is designed to investigate both separate and built-in LEDs and other devices based on them.

The developed diagnostic complex includes the following components: power supply system for measurements in constant- and pulsed-mode operation; measuring block which includes thermostat (cryostat) and probe station; optical subsystem; PC. Measurements can be carried out in automatized regime under control of the specialized software worked out on the basis of LabView. The diagnostic complex allows accurate measurements of any LEDs and devices based on them in the following ranges: emission wavelength: 200-1100 nm; direct current: 10^{-8}-10 A; voltage: 0-250 V; temperature: 10-500 K.

3. Experimental results and discussions

In order to evaluate self-heating processes influence on efficiency of luminescence of nitride-based LED heterostructures the main attention was paid to the study of spectral, power-current (P-I) and current-voltage (I-V) characteristics.

To calculate the dependence of self-heating on current density the investigation of the dependence of luminescence spectra on temperature was conducted (figures 1, 2). The temperature of the AL was determined by analysis of external heating influence on luminescence spectra and the impact of direct current on the shape and location of luminescence spectra (figure 1, 2).

Figure 2 shows that self-heating in type 2 LEDs (45^{o}C at operating current (I_f) of 20 mA) is more intensive than in type 1 LEDs (30^{o}C). This difference can be explained by a higher dislocation density in epitaxial heterostructures of type 2. When the direct current rised to 50 mA the temperature was equal to 90°C. Even at lower current than I_f the crystal temperature was higher than room temperature.

Theoretical calculation of the AL temperature was implemented to assess the experimental results. For this goal the theory of Van Roosbroeck-Shockley was applied with account of the model of 2D-combined density of states [1]. Amendments were made to the equations which allowed us to take into account potential fluctuations caused by the Coulomb field of impurities, variations of the composition of solid solutions, and rough heterointerfaces. Quasi-band-to-band transitions were considered in calculations. The model of 2D-combined density of states was used to take into account effects of dimensional quantization.

The results of calculation were compared with normalized experimental spectra. In this case the value of the band-gap used for the calculation was obtained from experimental data. Evaluation of the AL temperature was performed by using mathematical programs based on spectral properties obtained experimentally. Figure 2 shows theoretically calculated and experimentally obtained dependencies of the AL temperature. One can see that the discrepancy of experimental and theoretical data does not exceed 5% that proves the correctness of the proposed methods for determination of the AL temperature and reliable work of the diagnostic test-system.

Optical and electrical properties of the samples were studied. The following dependencies were obtained (figures 3, 4):

- Dependence of emission wavelength on current and temperature;
- Dependence of output power on current;
- Dependence of WPE on current;
- I-V characteristics.

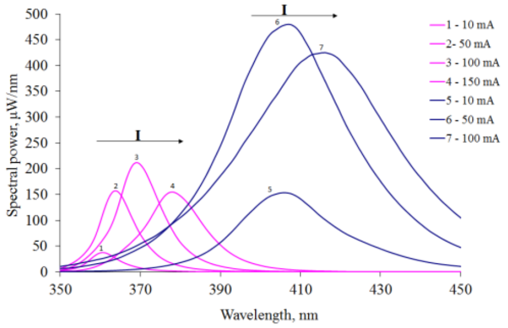

Figure 1. Dependence of spectral power on wavelength at different currents.

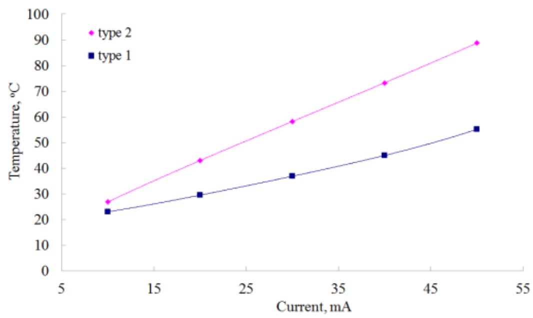

Figure 2. Dependence of temperature of active layer on current.

The analysis of these experimental data showed that the wavelengths of the type 1 LEDs were in the range of 460-462 nm, spectral full width at half-maximum (FWHM) − 30-40 nm at I_f and room temperature, while the LEDs of type 2 revealed 360-365 nm and 10-13 nm, respectively. The output power at I_f was equal to 9.5 and 1.15 mW for type 1 and type 2 LEDs, respectively. P-I characteristics deviation from linearity was observed in the samples of both type at currents higher than 30 mA. The maximum value of 23.1 mW was reached at the current of 90 mA for type 1 LEDs and 4.2 mW at 120 mA for type 2 LEDs. Output power reduction of LEDs of type 1 was negligible as compared with LEDs of type 2. Deviation of P-I characteristics from the linear dependence was caused by the structure heating that led to a higher non-radiative recombination rate and decrease of the emission intensity. When the ambient temperature increases there is a uniform shift of luminescence spectrum towards long-wave region by 0.5 nm for LEDs of type 1 and 1 nm for LEDs of type 2. Generally, wavelength shift of emission maximum caused by the current was 7 nm for the blue LEDs when the current changed from 10 mA to 100 mA, caused by the temperature (30-90°C) – 3 nm, for UV LEDs – 9.7 nm (10-100 mA) and 3.5 nm, respectively.

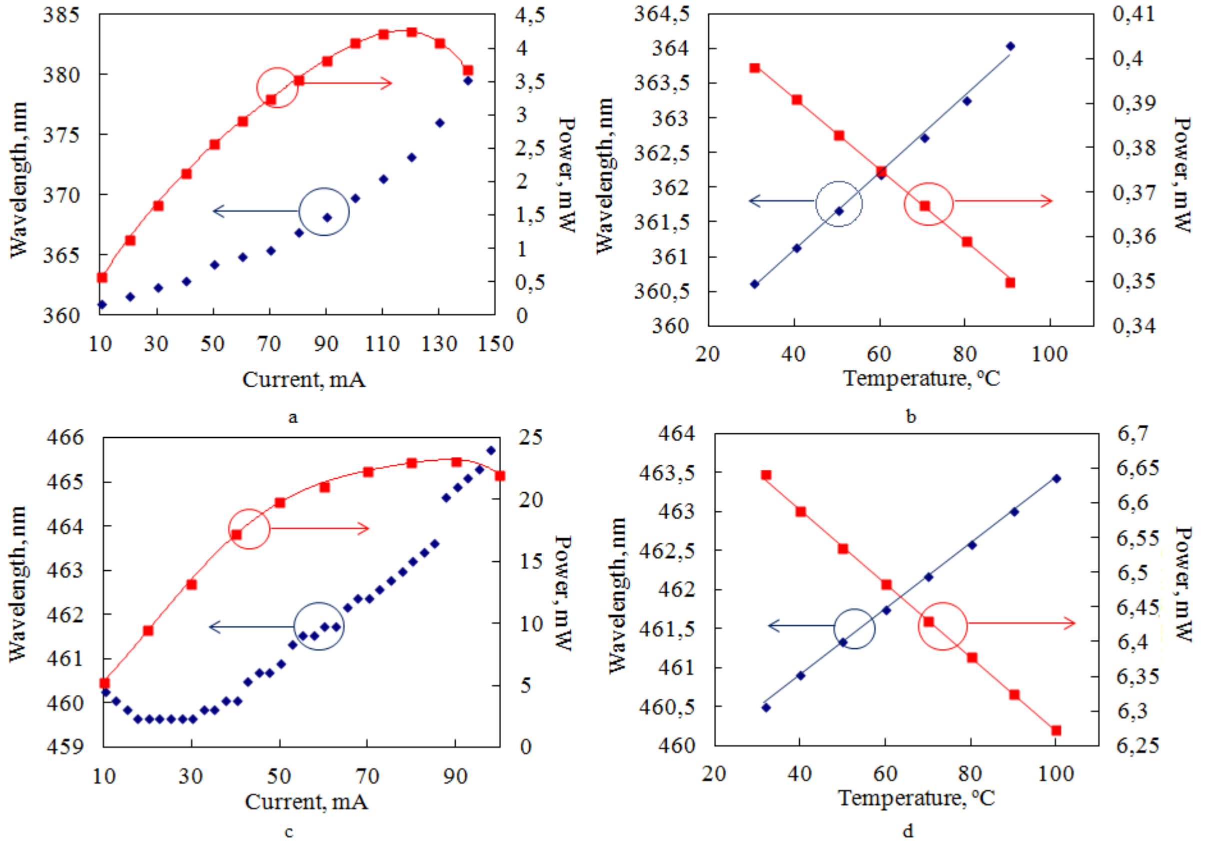

Figure 3. (a) Dependence of emission wavelength of UV LEDs on current and temperature. (b) Dependence of output power of UV LEDs on current. (c) Dependence of emission wavelength of blue LEDs on current and temperature. (d) Dependence of output power of blue LEDs on current.

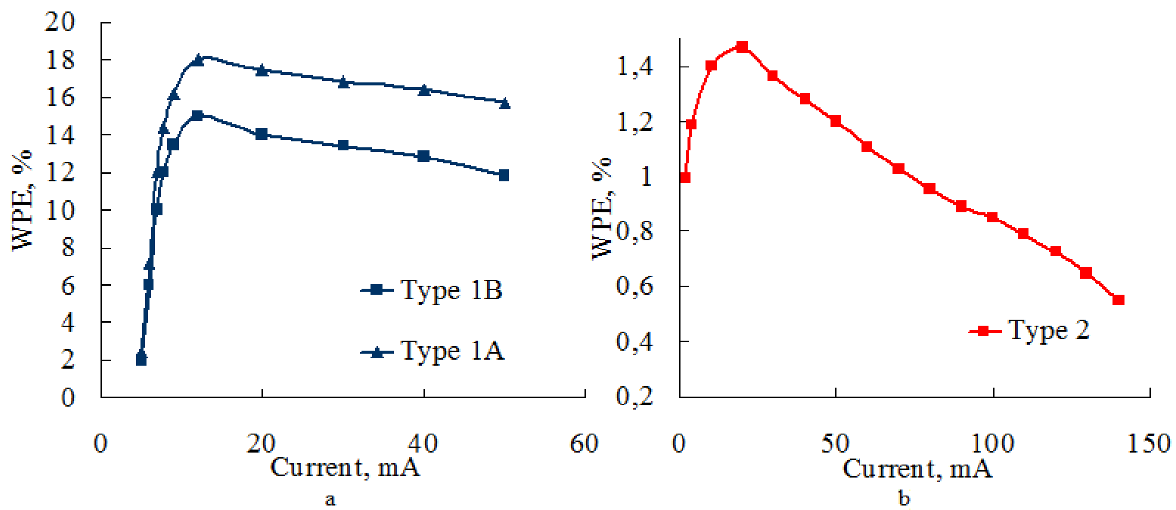

Figure 4. (a) Dependence of WPE of LED of type 1 on current. (b) Dependence of wall-plug efficiency of LED of type 2 on current.

The calculation showed that the LEDs of type 2 revealed the WPE as low as 1.5% at low currents. It can be caused by relatively high density of defects. The WPE of the LEDs of type 1B reached 15% and decreased to 12% at 50 mA, the LEDs of type 1A had the WPE as high as 18%, their maximum achievable power was 23.1 mW (figure 5).

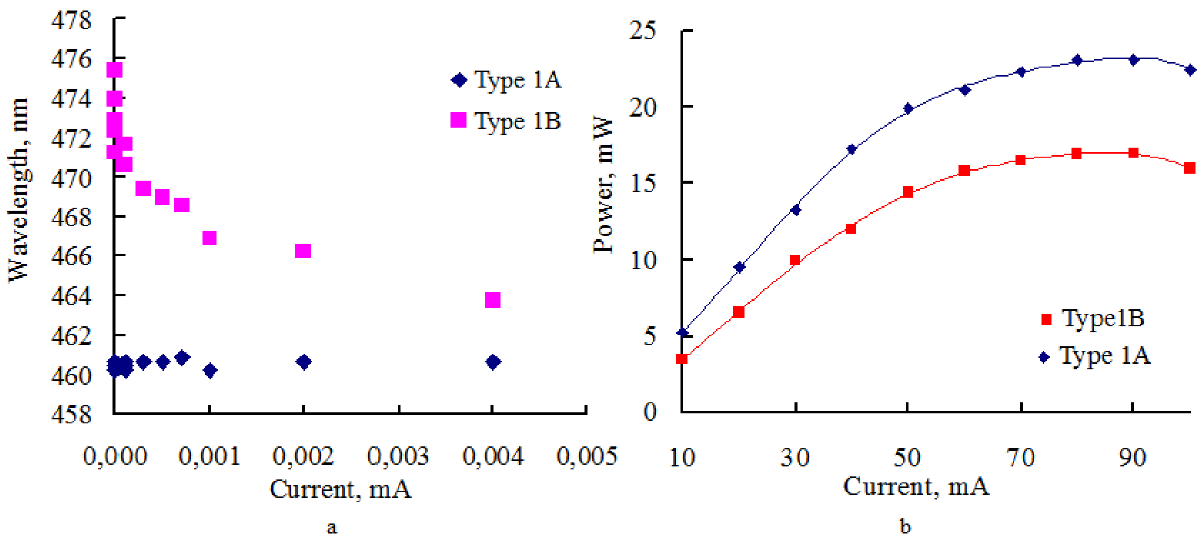

Figure 5. (a) Dependence of wavelength on low currents. (b) Dependence of output power on high currents.

The analysis demonstrated the considerable decline in density of defects in ALs of such heterostructures. It can be caused by lower values of elastic stresses. The analysis of emission wavelength maximum evolution at low currents showed that there was no wavelength shift in the structures of type 1A while it was considerable in the structures of type B. We assume that the shift of electroluminescence spectrum at low currents in the structures of type B is caused by the impact of elastic stresses and piezoelectric fields at the heterointerfaces. At low currents in the background of small stresses applied to the AL of the structures the contribution of piezoelectric fields is significant. Therefore, the well shape is considerably distorted under their influence. It results in a significant decrease of the distance between the layers constituting the heterostructure. When the external stress increases piezoelectric fields impact is compensated and the shift declines. Superlattice heterostructures demonstrate the absence of spectral maximum shift. We suppose it is caused by compensation of tensile and compressive elastic stresses due to the superlattice. Thus, the structure of type A demonstrates considerably higher stability of emission wavelength. Moreover, elastic stresses may relax during the LED operation by forming dislocations in the AL. Stress compensation caused by the superlattice should reduce formation of dislocations in type A LEDs. Therefore, this structure shows a better performance and has a longer lifetime.

4. Conclusions

The study determined the values of the LED AL temperatures for the structures based on AlGaN and InGaN alloys at different currents (up to 150 mA). It was shown that in case of structures with high density of defects the temperature can reach the value of 200°C and higher, i.e. the heating of the structures is directly related to the defect concentration.

To verify the accuracy of the performed measurement theoretical calculation of the AL temperature according to Van Roosbroeck-Shockley theory and the model of 2D-combined density of states was carried out. The calculation was made with account of potential fluctuations caused by Coulomb field of impurities, variations of the composition of solid solutions and rough heterointerfaces. The discrepancy of temperature values obtained by theoretical and experimental approaches was less than 5%. It proves the correctness of the developed method.

The direct interconnection of self-heating processes and luminescence efficiency was shown for the the above-mentioned structures. UV LED heterostructures were characterized by a higher temperature than the visible LEDs, they also demonstrated a lower efficiency (up to 1.5% at low currents). The WPE of blue LEDs without the superlattice reached 15% and decreased only to 12% at 50 mA. The structures with the superlattice revealed a better performance and showed the WPE of 18% and 1.5-fold higher maximum achievable output power. It proves a significant reduction of the density of defects in the ALs of studied structures. Moreover, considerably smaller influence of current values on emission wavelength was observed. It can be attributed to the compensation of elastic stresses.

References

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Acknowledgments

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