Study of the characteristics of UVA LEDs grown by HVPE: active region thickness-dependent performance

E A Menkovich¹, S A Tarasov¹, I A Lamkin¹, A V Solomonov¹, S Yu Kurin²,³, A A Antipov², I S Barash², A D Roenko², A S Usikov⁴,⁵, H I Helava⁴, Yu N Makarov²,⁴

¹Saint-Petersburg Electrotechnical University “LETI”, ul. Prof. Popova 5, St. Petersburg 197376, Russia
²Nitride Crystals Ltd., pr. Engels 27, St. Petersburg 194156, Russia
³Saint-Petersburg Academic University RAS, ul. Khlopina 8/3, St. Petersburg 194021, Russia
⁴Nitride Crystals Inc., 181 E Industry Court, Site B, Deer Park, NY 11729, USA
⁵Saint-Petersburg National Research University ITMO, Kronverkskiy pr. 49, St. Petersburg 197101, Russia

E-mail: menkovichea@gmail.com

Abstract. We report on results of the performance study of UVA LEDs depending on the thickness of the active region. UVA LEDs are based on GaN/AlGaN heterostructures grown on Al₂O₃ (0001) substrates by hydride vapor phase epitaxy (HVPE). It is shown that the use of thick (> 100 nm) single layer as the active region of UVA LED is a promising concept to achieve enhanced efficiency.

1. Introduction
UV light sources are widely used in modern science, industry, medicine. In the near UV area (UVA: 320-390 nm) it is highly relevant to use UV radiation for photocatalytic purification of water and air as well as for photopolymerization processes. Nowadays mercury lamps generally serve as a source of UV radiation. Mercury lamps replacement by UVA LEDs will provide ten-fold increase of lifetime of UV devices and will lead to considerable decrease of their power consumption as well as reduce mercury pollution of the environment.

Despite the demand for UVA LEDs, they are not yet available in the world market in sufficient quantities. Currently, one of the major obstacles in the development of semiconductor UV emitters is the low luminescence efficiency in epitaxial heterostructures at high current densities, which is usually associated with self-heating of the active region that leads to a decrease in the optical emission power of the UVA LED and its lifetime [1].

In this study, we suggest a special design for an epitaxial heterostructure, which provides stable UV LED operation at high current densities.

2. Sample and experimental technique
It is known that maximum of the internal quantum efficiency (IQE) of nitride-based LED structures depends strongly on the active layer thickness [2]. In very thin active layers, thinner than 2 nm, maximum IQE is reached at relatively low current densities. In this case the electron concentration is
much higher than the hole one. As a result, the carrier recombination at threading dislocations is controlled by the hole migration to the dislocation cores, lowering non-radiative recombination rate [3, 4]. As the active region is thicker (3–5 nm) electron and hole concentrations becomes nearly equal and IQE decreases [5]. Further enlargement of the active layer results in the IQE increasing accompanied by shifting of the IQE maximum to higher current densities. IQE becomes even higher than that of LEDs with 3–5 nm quantum wells (QWs) [6].

It was also shown that multiple QW structure of the active region could be ineffective for improvement of the LED IQE because of inhomogeneity of electron and hole injection in various wells and IQE–I dependence drop as a result of heating of the active region, carrier leakage and Auger recombination [2]. At a desirable current density it could be possible to choose the active layer thickness providing the maximum IQE. LEDs with a thick single active region (more than 100 nm) are promising for high-current operation to get high output optical power.

In order to check this assumption the IQE dependence of UVA LEDs on current density at different active region thicknesses was calculated and UVA LED structures with different active region thicknesses were grown by hydride vapor phase epitaxy (HVPE) and analyzed. The growth procedure included in-situ sapphire substrate Al₂O₃ (0001) treatment followed by multilayer structure growth. UVA LED structures consisted of AlN/AlGaN buffer layer, 6–8 pairs of AlGaN/AlGaN stress control layers, Si-doped n-AlGaN barrier, (Al)GaN active region (50, 80, 120 nm thick depending on epitaxial process), and Mg-doped p-AlGaN barrier. Mg-doped p-AlGaN cover layer completed the structure.

Characterization of UVA LEDs was carried out by using an automated diagnostic complex which allows performance investigation of LEDs and LED devices [1, 7-9].

3. Calculations of UVA LED efficiency

The calculations were made by using software based on finite element method. It allows two-dimensional (2D) simulation of the band diagram, electron and hole transport inside the structure, radiative and non-radiative carrier recombination rate, electric field distribution, current-voltage (I-V) and power-current (P-I) characteristics. The software implements 2D drift-diffusion model with account for such features as elastic strain in the heterostructure layers and its effect on the valence band structure, as well as existence of spontaneous electric polarization and piezoeffect in III-nitride materials. According to the model, electrons and holes obey Fermi-Dirac statistics.

A natural way to obtain the emission wavelength of 365 nm is the use of the active layer made of GaN. To ensure, firstly, a good electron carrier confinement in the active layer and, secondly, the lack of absorption of the emitted light in the contact areas the layers surrounding the active layer should be made of a wide-bandgap material − AlGaN.

We consider here a Ga-polar fully strained UVA LED structure consisting of a thick n-AlGaN contact layer ([Si] = 1×10¹⁹ cm⁻³), an active region, a p-AlGaN contact layer ([Mg] = 5×10¹⁹ cm⁻³). The threading dislocation density was supposed to be 10⁹ cm⁻². We considered UVA LED structures operating at room temperature.

After the band diagram (figure 1) was computed, the simulator calculated the IQE. The calculations of the IQE maximum were made in a wide range of the active layer thickness and current density. Figure 2 shows that there are two main tendencies: 1) the current density at which the IQE maximum is achieved increases with the increase of the active layer thickness; 2) the absolute value of the IQE maximum also increases with the increase of the active layer thickness.
It means that UVA LEDs with a thick single active region (more than 100 nm thick) are preferable to achieve enhanced efficiency.

4. Experimental results and discussions
The UVA LED structures with 50, 80, and 120 nm thick single active regions (1, 2, and 3, respectively) were investigated. Figure 3 shows the electroluminescence (EL) spectra at the operating current of 20 mA. There is a "bend" in the long-wave region of EL in type 1 structures. Its appearance is probably caused by higher defects density in the active region of the structures of this type. It leads to the existence of band tails in the density of states that distort the energy spectrum of the crystal. This affects the electroluminescence spectra and may indicate poorer structural perfection of type 1 structures that has an impact on their operational characteristics such as efficiency and optical output power.
Studies of the I–V characteristics showed that the voltage drop across the diode at the operating current was about 3.9 V. In general, the wavelength shift in the emission maximum was approximately 20 nm upon varying the current from 2 to 125 mA.

Figures 4, 5 show dependences of efficiency and output optical power on current. The analysis of experimental data showed that all emitters had approximately the same output optical power at the operating current. Type 3 structures revealed the highest efficiency of 1.12%. The efficiency of other structures was about 1%. The structures of type 1, as might be expected, had the lowest efficiency at high current densities. The largest efficiency decline of 0.8% was observed in the structures of this type upon varying the current from 20 to 125 mA. It was caused by significant inhomogeneity of electron and hole injection into the active region in comparison with other structures. Increasing the thickness of the active region improves uniformity of electron injection and results in higher efficiency.

5. Conclusions
It was observed that wall-plug efficiency of UVA LEDs with 120-nm-thick active region was 1.12% at operating current of 20 mA and this value reduced to less than 1% with decreasing the thickness of the active region to 50 nm. The intensity of UV radiation demonstrated the same behavior. Thus, it is possible to conclude that UVA LEDs with thick single active layers are promising for achieving enhanced efficiency.

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