The efficiency of UV LEDs based on GaN/AlGaN heterostructures

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Abstract. The UV LED GaN/AlGaN heterostructures obtained by HVPE approach were investigated. It was shown that the peak wavelength of UV LEDs was in the range of 360 - 380 nm with FWHM of 10 - 13 nm. At operating current of 20 mA, the active region temperature $T_j$ was 43°C, the output optical power and efficiency $\sim 1.14$ mW and 1.46%, respectively. It was shown that the use of HVPE method allowed to achieve a high degree of structural perfection of epitaxial structures.

1. Introduction

In modern optoelectronic industry in order to create LED structures, the compositions based on solid solutions of semiconductor nitrides are used. Their most important characteristic is the conversion efficiency of electrical energy into optical radiation. The main problems of UV LEDs are low quality of epitaxial heterostructures [1, 2], low light extraction index [3], and self-heating effect. Addressing these problems will allow us to create high-quality GaN/AlGaN heterostructures for such promising areas as photoelectrochemical hydrogen generation, photopolymerization, medicine.

The main factor limiting the light extraction from the chip and reducing the efficiency of LEDs is total internal reflection [4, 5] at the interface of materials with high and low optical density. The effective way to solve this issue is introducing into the structure the surfaces that scatter light. When creating a specific shape roughness the light extraction index increases due to a significant increase in the critical angle. At present time, the texturing of the substrates and epitaxial layers is widely used [6]. The texturing can be created using a variety of methods: the technique of wet etching in combination with the Laser-lift-off technology [7], creation of microoptical elements on a sapphire substrate [8], micromachining [9] etc.

The experimental study of the optical and electrical properties of UV LEDs based on GaN/AlGaN [10-12] heterostructures has been carried out. Special attention was paid to investigation of the electroluminescence spectra at different forward currents and temperatures and determination of optical power and luminescence efficiency.
2. Experimental results
The main objective of the experiment was to investigate the structural perfection and features of the distribution of impurities in the UV LED heterostructures grown by HVPE [13], and determine their most important operating parameters, including output optical power, the temperature of the active region and efficiency [14, 15].

The design of UV LEDs based on GaN/AlGaN heterostructures is shown in Fig. 1. Counting from the surface of the sapphire substrate (0001), the heterostructure includes the following epitaxial layers: nucleation layer, stress control layers, electron emitter, undoped active region, electron-blocking layer, p-contact layer. The total thickness of the above-mentioned layers is about 5 μm. Planar chips were fabricated with dimensions of 0.31 × 0.31 mm$^2$ and then packaged. The Ti/Al and Ni/Au metal compositions were used as n- and p-type electrodes, respectively.

Good quality of the structures was confirmed [16] by XRD method. The FWHM of the active layer peak on XRD rocking curve obtained in a symmetric reflection (0002) was less than 400 arcsec. The threading dislocation density measured by AFM varied from $8 \times 10^7$ to $9 \times 10^8$ cm$^{-2}$, which is typical for thin epitaxial nitride layers grown on sapphire substrates. The wavelength of PL maximum was in the range of 359.5–362 nm, the average PL FWHM was 11 nm. The position of the PL peak wavelength and FWHM of the main peak were almost identical for different areas on the wafer surface. The results showed that the use of rapid and low-cost HVPE method allowed us to achieve a high degree of structural perfection of epitaxial structures.

When studying the operating parameters of LEDs we focused on the investigation of spectral (Fig. 2), power-current (P-I) (Fig. 3) and I-V characteristics, the measurement of power and efficiency of the luminescence, as well as the study of the impact on them of the direct current and ambient temperature. The investigated structures demonstrated high enough output optical power. At 20 mA current it was 1.15 mW and reached a maximum of 4.2 mW at 120 mA. A deviation of the P-I characteristics from the linear dependence was observed at current values above 30 mA. The LEDs showed a working capacity in the continuous operation mode up to the values of the direct current of 140 mA.

![Figure 1. Schematic of the precise laser machining system.](image)

![Figure 2. Electroluminescence spectra of UV LEDs at different values of direct current.](image)

Depending on the wavelength of the maximum of the luminescence spectrum on the current value (Fig. 2) one can see that the shift of the spectral characteristics to long-wave region accelerates with an increase in current. This effect is due to a rapid increase in the temperature of the crystal. In general, the peak wavelength is seen to shift by 20 nm with increasing of the current from 2 mA to 140 mA.
(Fig. 4). Special attention was paid to the influence of direct current on the temperature of the active region of the structure (Fig. 5). The experimental data indicate that the p-n-junction temperature $T_j$ at 20 mA is 43°C, which is higher than the values of blue emitters based on InGaN. At the current of 60 mA $T_j$ exceeded 100°C and then the temperature continued to increase significantly. A comparison dependencies of wavelength and temperature on the current leads to a conclusion that self-heating is a one of the main process that reduces the output optical power of the structures. It was determined that the thermal resistance of the samples at $I_f$ was equal to 250°C/W.

**Figure 3.** The power-current characteristics of UV LEDs.

**Figure 4.** The dependence of the wavelength at the maximum of the spectral characteristics on the direct current.

Maximum wall-plug efficiency of packaged UV LED chips was equal to 1.5% at $I_f$ (Fig. 6). At 100 mA the efficiency decreased by about 2 times.

**Figure 5.** The dependence of the temperature of the UV LED active region on the direct current.

**Figure 6.** The dependence of the efficiency of the UV LED on the direct current active region on the direct current.

3. Conclusions

The UV LED heterostructures were grown by HVPE approach. The FWHM of the active layer peak on XRD rocking curve obtained in symmetric reflection (0002) was less than 400 arcsec. The threading dislocation density measured by AFM varied from $8 \cdot 10^7$ to $9 \cdot 10^8$ cm$^{-2}$. PL measurements revealed a uniform distribution of peak wavelength and FWHM across the wafer. The results showed
that the use of HVPE method allowed us to achieve a high degree of structural perfection of epitaxial structures.

The experiment showed that the peak wavelength of UV LEDs was in the range of 360-380 nm with FWHM of 10-13 nm. At operating current of 20 mA the active region temperature $T_j$ is 43°C, the output optical power - 1.14 mW. At 100 mA the efficiency decreased by about 2 times.

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