UV LEDs for high-current operation

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Abstract. In this paper we report on results of development of ultraviolet light-emitting diodes (UV LEDs) based on GaN/AlGaN heterostructures grown on Al₂O₃ (0001) substrates by chloride-hydride vapour phase epitaxy (CHVPE). Both UV LED heterostructures and packaged dies are investigated. UV LEDs proved performance capability at current density up to 125 A/cm² and revealed wall-plug efficiency (WPE) of 1.5% at operating current of 20 mA.

1. Introduction

UV radiation is largely used in a number of industries, medicine and measurement equipment. In the near UV area (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 UV 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.

Today the main problems preventing manufacturing of UV LED with high technical properties (low power consumption, long lifetime and high WPE) are posed by low quality of epitaxial heterostructures which are characterized by high density of structural defects as well as high prime cost of their obtaining by traditional epitaxial methods.

In order to solve some of the above-mentioned problems this paper considers a technological approach based on application of the CHVPE for the growth of UV LED heterostructures. It is a well-known method for fabrication of thick low-defect quasi-bulk or free-standing GaN materials and GaN-based templates served as substrates for device structures growth by other techniques such as molecular beam epitaxy (MBE) and metalorganic vapour phase epitaxy (MOVPE). It was also demonstrated that CHVPE can be successfully used to grow the whole device structures for application in visible and UV LEDs and power electronics. CHVPE method is convenient for mass production of semiconductor devices due to its low cost, flexibility of growth conditions, and good reproducibility.
2. Experimental technique

Nitride-based UV LEDs have some particular features compared to nitride-based LEDs of visible range which are to be taken into account for optimization of technological process of UV LED heterostructures growth.

Active region of UV LEDs with the wavelength less than 365 nm can be produced of materials not containing indium. In this case lattice constant mismatch of semiconductor materials constituting the heterostructure is relatively low that allows growing of thick active regions without stress relaxation accompanied by formation of dislocations [1].

The choice of a single layer of more than 100 nm thickness as an active region is motivated by the following assumption: the use of above-mentioned active region is promising to obtain an internal quantum efficiency (IQE) maximum at high current density (more than 100 A/cm²). The use of multiple-quantum-well (MQW) structures as active regions of UV LED heterostructures is not suitable for the work at high current density because these structures are still facing problems of inhomogeneity of electron and hole injection in various wells. Another problem of LED heterostructures with MQW is IQE−I dependence drop that is observed even at low current density as a result of heating of the active region, carrier leakage, and Auger recombination [2].

CHVPE method is considered to be optimum for growing of thick stress relief layers (SRL) and thin active region. Compared to the traditional MOVPE method it gives an opportunity to control the growth rate over a large range: from micrometer to dozens and hundreds of micrometers per hour, thus, it is possible to grow both thick (several micrometers thick) buffer layers and thin (units - dozens of nanometers) active regions within one process. In MOVPE growth rates are low (as a rule, up to 3-4 μm/hour), so it is quite a difficult task to grow thick buffer layers, and in many cases templates (AlGaN/Al₂O₃ heterostructures in which AlGaN epitaxial layer has a thickness of several micrometers) are used as a buffer. In this case the process of LED heterostructure growth is divided into two steps: a) growth of template (for instance, using CHVPE method); b) growth of heterostructure on the template by using MOVPE method. Moreover, CHVPE method provides epitaxial layers of high crystal quality with high doping level which is limited only by inversion of the type of conductivity for Mg [3]. This technique offers advantages in growth rate, simplicity, and cost as well as the ability to grow III-V compound layer directly onto a substrate without the inclusion of low temperature buffer layer. Additional advantages potentially leading to high IQE of radiative recombination in CHVPE-grown UV LED heterostructures are due to the low impurity contamination [3, 4].

Table 1 shows comparison of CHVPE and MOVPE approaches which are used for UV LEDs production.

| Parameter                  | CHVPE            | MOVPE            |
|----------------------------|------------------|------------------|
| Growth rate                | Wide range (1-150 μm/hour) | Low (a few μm/hour) |
| NH₃ consumption            | Low (< 10 slm)   | Very high (> 30 slm) |
| Costs of raw materials     | Low              | High             |
| Process pressure           | Atmospheric      | 100-250          |
| Use of H₂                  | No               | 20-50 slm        |

Epitaxial processes of the growth of UV LED heterostructures were performed in atmospheric pressure quartz hot-wall CHVPE reactor which is designed for deposition of the III group metals including GaN, AlN, InN, and their solid solutions on 2-inch diameter wafers. Ammonia (NH₃) and hydrogen chloride (HCl) were used as precursors. For GaN growth, HCl was passed over Ga source. To grow the AlGaN alloy, HCl was passed separately over the Ga and Al sources. Monosilane (SiH₄) and metallic Mg were used for n- and p-type doping, respectively. The reactor is equipped with 6-zone
resistance heater providing the required temperature profile in the reaction area. The reactor includes both a growth zone and a dwell zone. The growth temperature was 1040°C. Design of the quartz reactor allows growing multilayer structures by either variation of precursor gas flows or transferring substrate between a growth zone and a dwell zone keeping at the same temperature.

UV LED dies of 0.31×0.31 mm² were subsequently fabricated. Ti/Al and Ni/Au metal layers were used as n- and p-type electrodes, respectively. Processing and packaging were performed using outside service.

3. Experimental results and discussions
UV LED heterostructures grown on Al₂O₃ wafers were tested by X-ray diffractometry (XRD), scanning electron microscopy (SEM), secondary ion mass spectrometry (SIMS), atomic force microscopy (AFM), electroluminescence (EL), photoluminescence (PL) methods.

Al₂O₃ (0001) wafers were used for epitaxial processes of UV LED heterostructures growth. UV LED heterostructures consisted of AlN/AlGaN (x~0.6) composed buffer layer, 6-8 pairs of AlGaN (x~0.1-0.15)/AlGaN (x~0.03-0.08) SRL, Si-doped n-AlGaN (x~0.05-0.08) barrier, (Al)GaN active region, and Mg-doped p-AlGaN (x~0.12) barrier. Mg-doped p-AlGaN (x~0.05) cover layer completed the structure. Here x is a molar fraction of AlN. All these layers were clearly distinguished in cross-sectional SEM image (figure 1) and SIMS-profile (figure 2).

Figure 1. Scanning micrograph of cross-sectional view of UV LED heterostructure.
The full width at half-maximum (FWHM) of XRD peak (scan type: θ-2θ) in symmetrical reflection (0002) taken from AL of UV LED heterostructure was less than 400 arcsec. The dislocation density in the best samples measured by AFM technique varied from $9 \times 10^7$ cm$^{-2}$ to $8 \times 10^8$ cm$^{-2}$.

The results of PL measurements are shown in figures 3, 4. The wavelength of PL maximum was in the range of 359.5 – 362 nm, the average PL FWHM was 11 nm. PL measurements revealed a uniform distribution of peak wavelength and FWHM across the wafer. The variation in peak wavelength from the center of the wafer to its edge, evaluated in terms of a standard deviation, was less than 1%, the variation in FWHM was about 2.5%.

The peak wavelengths of the packaged dies were 360-365 nm at the operating current of 20 mA and the room temperature (figure 5), FWHM parameter was in the range of 10-13 nm. The output
optical power at the operating current was equal to 1.14 mW. The deviation of power-current (P-I) characteristics from linearity was observed at the current values of more than 30 mA. It was caused by a structure heating. The maximum value of output optical power – 4.2 mW – was reached at the current of 120 mA. The peak wavelength shift at the current change from 10 mA to 140 mA was about 18.5 nm.

When the ambient temperature increased there was a uniform shift of the luminescence spectrum towards the long-wave region (figure 6). At the temperature change from 30°C to 90°C the peak wavelength shift was 3.4 nm.

Figures 7, 8 show the EL spectra and WPE of UV LED die, respectively. At operating current of 20 mA peak wavelength was in the range of 360-365 nm and WPE was about 1.5%.

The output power results of our packaged dies compare favorably with the results reported by G. Smith et al. [5] on their CHVPE-grown UV LEDs at virtually the same wavelength. As for comparison with commercially available UV LEDs, the output power of our packaged dies has the same order of magnitude as Nichia’s NSSU100C UV LEDs (spectral characteristics, e.g. FWHM and spectral curve shape, are identical).
4. Conclusions
Thus, CHVPE method can be used for the growth of GaN/AlGaN heterostructures of submicron thicknesses for the UV LEDs, which proved its workability at current densities up to 125 A/cm$^2$.

UV LED heterostructures design was worked out to meet the requirement for reaching IQE maximum at high current density. For this purpose, a single layer of more than 100 nm thickness was suggested as an active layer.

The analysis of UV LEDs showed that their FWHM parameter was in the range of 10-13 nm. At operating current 20 mA the active layer temperature was 45°C, the output optical power was equal to 1.14 mW, the WPE was 1.5% (dimensions of dies: 0.31×0.31 mm$^2$).

The performed study suggests the prospects of CHVPE technology for production of nitride-based semiconductor devices such as LEDs, solar cells, photodetectors etc.

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