Effect of growth temperature of GaN:Mg layer on internal quantum efficiency of LED structures with InGaN/GaN quantum wells

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Abstract. The results of studies of quantum efficiencies for photoluminescence and electroluminescence regimes of blue light-emitting diode structures with InGaN/GaN quantum wells are presented. Experimental samples differed in growth temperature of p-GaN emitter layer. It is shown that increasing of growth temperature of p-GaN layer in temperature range 940–1060 °C leads to decreasing of internal quantum efficiency due to diffusion of magnesium atoms from p-GaN into quantum wells. At the electroluminescence regime quantum efficiency of samples with low temperature p-GaN is limited by insufficient crystal quality or low solubility of magnesium in emitter layer.

1. Introduction
Magnesium is the most commonly used acceptor impurity to form p-conductivity layers in growth process of nitride semiconductors by metal organic chemical vapor deposition (MOCVD). In gallium nitride the Mg initiates level with sufficiently large ionization energy (about 150 meV \cite{1}) what is greater than average thermal energy of carriers at room temperature. As a result a small portion of acceptors are ionized, contributing holes to valence band. Furthermore during epitaxial growth the chemical compensation of Mg acceptors by hydrogen atoms occurs. As a rule to decompose chemical bonds of Mg-H complexes thermal annealing of light-emitting diode (LED) structures in inert gas is used.

In LED structures p-GaN layer usually is grown immediately after active region which consist of InGaN/GaN multiple quantum wells (MQWs). Therefore growth parameters of p-GaN layer effect on crystal quality of active region and characteristics of whole LED structure. In the present work blue LED structures with InGaN/GaN MQW with different p-GaN layers are investigated. The purpose of this paper is to establish general patterns of temperature growth influence on efficiency of InGaN/GaN LED structures.

2. Experimental details
The InGaN/GaN MQW LED samples were grown on (0001) sapphire substrate by a MOCVD method. As precursors of III-group elements the following metal organic compounds were used: trimethylindium In(CH\textsubscript{3})\textsubscript{3}, trimethylgallium Ga(CH\textsubscript{3})\textsubscript{3}, triethylgallium Ga(C\textsubscript{2}H\textsubscript{5})\textsubscript{3}. As nitrogen
precursor an ammonia (NH$_3$) was used. For acceptor dopant (magnesium) bis(cyclopentadienyl)magnesium was used. For donor dopant (silicon) silicomethane was used. The LED structures consisted of a low temperature (LT) nucleation layer, a 2 µm unintentionally doped GaN layer, a 2 µm Si-doped GaN layer, five InGaN/GaN QWs (3/10 nm), and a 140 nm Mg-doped GaN. Figure 1 shows schematic cross-section of the epitaxial layers for investigated InGaN/GaN MQW LED structures. All experimental samples were grown under the same conditions except growth temperature of p-GaN emitter layer, which varied for different samples in the range T = 940–1060 °C.

| Mg-doped GaN, 140 nm |
|----------------------|
| 5 MQW InGaN/GaN, 3/10 nm |
| Si-doped GaN, 2 µm |
| Buffer layer n-GaN, 2 µm |
| LT nucleation layer GaN |
| Substrate Al$_2$O$_3$ |

Figure 1. Schematic cross-section of the epitaxial layers for investigated InGaN/GaN MQW LED structures.

In experiment we measured internal quantum efficiency for photoluminescence and external quantum efficiency (EQE) for electroluminescence regimes. The internal quantum efficiency (IQE) were measured by photoluminescence (PL) method at different excitation power and temperatures [2]. The dependence of IQE on excitation power were measured in temperature range 10–300 K. Pulse YAG laser with wavelength 355 nm were used as a pumping source. Detailed description of the measurement condition are presented in [3,4]. EQE was measured at current density 1 A/cm$^2$. The samples for EQE measurements were made with indium contacts fused in LED structures in inert gas at temperature T = 350 °C.

3. Experimental results

Figure 2 shows dependence of normalized PL intensity on excitation power for samples with different growth temperature of p-GaN layer: 940, 990 and 1060 °C. The obtained dependences qualitatively the same for all samples and can be explained by the ABC-model of recombination:

$$IQE = \frac{B \cdot n^2}{A \cdot n + B \cdot n^2 + C \cdot n^3},$$  \hspace{1cm} (1)

where A, B, and C are the temperature dependent Shockley-Read, radiative, and Auger recombination coefficients, respectively, and n is the concentration of non-equilibrium carriers in the MQW (n is proportional to excitation power for linear recombination regime).

At a low excitation level, the quantum efficiency drastically decreases with increasing T due to the temperature dependence of the nonradiative recombination rate. At a high excitation level, the Auger recombination rate starts to play a significant role leading to a decrease in IQE with increasing excitation power. A characteristic feature of the dependences IQE on temperature is the shift of the maximum to higher excitation intensities with increasing T.
Increasing of growth temperature of p-GaN layer from 940 to 1060 °C leads to reduction of IQE of LED structures (figure 3, left axes). Decreasing of IQE for sample with growth temperature of p-GaN layer 1060 °C was about 50 % relative to the sample with growth temperature of p-GaN layer 940 °C. Probably this is due to Mg diffusion into the active region with increasing of growth temperature of p-GaN layer. An additional argument for this assumption is broadening of PL spectra (figure 3, right axes) with increasing of growth temperature of p-GaN layer. In [5] it is shown that Mg diffusion leads to interdiffusion of In-Ga atoms in InGaN layers, which should leads to an increase of full width at half maximum (FWHM) of PL spectra.

Figure 3 shows dependence of EQE on growth temperature of p-GaN layer for investigated InGaN/GaN MQW LED structures. The maximum EQE is observed at the temperature 990 °C. Lower value of EQE at the growth temperature 940 °C of p-GaN can be explained by worse crystal quality in comparison to samples grown at temperature 990 °C. On the other hand it can be explained by low
injection efficiency. The external quantum efficiency of electroluminescence can be written as the product

$$\eta = \gamma \cdot \eta_i \cdot \eta_{\text{ext}},$$

(2)

where $\gamma$ is the injection coefficient, $\eta_i$ is the internal quantum efficiency, and $\eta_{\text{ext}}$ is the extraction efficiency. Injection coefficient is a complex parameter which is depend on structure design, and in particular it is determined by doping level of p-GaN emitter. It is well known that solubility of impurities in solids decreases at the lower temperatures. Probably in our case temperature lowering leads to reduction of $\gamma$ due to Mg solubility decrease.

Also it should be noted that for growth temperature of p-GaN $T = 1060$ °C the lower EQE is observed in comparison to samples grown at temperature 990 °C. This fact can be explained by faster diffusion of Mg from p-GaN into quantum wells at higher temperatures. Obviously Mg atoms initiate the centers of nonradiative recombination in quantum wells what leads to lowering of EQE.

4. Conclusion

Thus, according to the results of this study, increasing of growth temperature of p-GaN layer from 940 to 1060 °C leads to reduction of IQE of blue LED structures with InGaN/GaN MQW. This fact can be explained by Mg diffusion into active region of LED structures. The investigation of electroluminescence have shown that dependence of EQE on growth temperature is described by curve with a maximum. At the low growth temperature EQE is limited by low crystal quality or low Mg solubility which cause insufficiently injection coefficient of holes from p-GaN into MQWs. At the higher temperatures EQE is limited by diffusion of Mg from p-GaN into quantum wells of active region.

Acknowledgements

This study was supported by the Russian Foundation for Basic Research, project No. 14-02-31180.

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