The contribution of 3D nanoscale indium fluctuations into the efficiency droop in the green and blue InGaN/GaN LEDs

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Abstract. It was shown that the contribution of 3D nanoscale indium fluctuations into the efficiency droop at $j < 50$ A/cm$^2$ can be very high and results in different shapes of the efficiency dependency on current $\eta(j)$ in blue and green LEDs. Reducing 3D nanoscale indium fluctuations can decrease the efficiency droop in these LEDs. The contribution of delocalized carriers is predominant at $j > 50$ A/cm$^2$ and the current dependences of efficiency, approximated by as $\eta(j) \propto j^{-b}$ where $0.2 < b < 0.3$, are alike in both green and blue LEDs.

1. Introduction

The efficiency droop is currently one of the most popular research topics for GaN-based light-emitting diodes (LEDs). The reduction in the external quantum efficiency in green and blue InGaN/GaN light emitting diodes (LEDs) with increasing current injection, the so-called droop, is a definite limitation for the future improvement of the light output in these LEDs including the white lamps [1]. The physical mechanisms behind the droop have been discussed intensely during the last decade, as reviewed by several authors [1-3]. In the majority of papers, the analysis of the efficiency droop is based on the assumption that these LEDs have homogeneous nanomaterial properties [2, 3]. However, it is known that the complicated nanomaterial arrangement of nitrides [4-6] includes 3D nanoscale indium fluctuations and extended defects, piercing device active layers, that are both incorporated into InGaN/GaN heterostructure. This leads to the existence of the vast variety of nanomaterial arrangements in nitride based compounds, the inhomogeneity of properties and the current crowding effect. These peculiarities result in numerous NA forms with different forms of nanomaterial disordering which are governed by crystallites’ coalescence of near 3D growth mode to near 2D one. It is known that nanomaterial disordering causes crowding current effect, the local Joule heating and degradation effect in light emitting devices based on III-N nano materials [7], the percolation paths in InGaN layers [5] and the conductive paths localized in extended defects [8], Yet, not many papers consider the contribution of extended defects [4, 6] and 3D nanoscale indium fluctuations [5] into the efficiency droop in the blue and green InGaN/GaN LEDs.

The aim is to clarify the contribution of 3D nanoscale indium fluctuations into the external quantum efficiency ($\eta$) droop in blue and green commercial LEDs, using the approach based on the concept that the nitrides have the complicated NA.
2. Experimental Details

Commercially available LEDs from several leading manufactures had maximum values of external quantum efficiency (η) in the range of 40 – 50 % for blue and 15 – 30 % for green LEDs. The maximum of radiation emission was observed at wavelength 450 – 460 nm for blue LEDs and 527 – 530 nm for green ones. The current–voltage (I–V) characteristics in the region of 10^{-13} – 1 A were determined. I–V characteristics at the voltage less than 1.5 V were used to reveal the conductive paths (and identify the values of their conductivity) localized at the extended defects. The shape of the η (j) dependences was used to separate the contribution in radiative recombination of localized and delocalized carriers and to determine the external quantum efficiency droop. The peak wavelength at each voltage step (at fixed the current value) during the η (j) dependences measure of LEDs was determined carefully. The distribution of carriers in MQW and the MQW position in depleted layer of p-n junction were clarified from C-V profiling.

3. Results and Discussion

I–V characteristics of blue and green InGaN/GaN LEDs at the voltage lower than 1.5 V allow us to distinguish two groups of LEDs differing by a several order of magnitude in the conductivity values of shunts (conductive paths) and the shape of the η (j) dependences Figure 1a. The η values of blue (Figure 1a, curves 1, 2) and green (Figure 1a, curves 3, 4) InGaN/GaN LEDs differ noticeably. However, the shape of the η (j) dependences of all LEDs Figure 1a have common properties are determined by the competitive contribution of localized and delocalized carriers into radiative recombination for both green and blue LEDs with low value of the paths’ conductivity (j < 10^{-9} A/cm² at the voltage less than 1.5 V) Figure 1a, curves 1, 3. The contribution of localized carriers is predominant at j < 50 A/cm². Both green and blue LEDs with high value of paths’ conductivity (j > 10^{-6} A/cm² at < 1.5 V) Fig.1a, curves 2 demonstrate a shift of maximal η values to the higher injection current region, which is observed on the η (j) Fig.1a, curves 1, 3. The shift is caused by the carrier transport along the conductive paths localized at the extended defect. This process prevents the carriers localization in MQW and leads to a decrease in η values. This, however, is not the only mechanism behind the droop.

Figure 1 (a, b). The external quantum efficiency dependences on current density of blue (curves 1, 2) and green (curve 3, 4) LEDs with different values of path conductivity at the voltage less than 1.5 V: j < 10^{-9} A/cm² – 1, 3, 4; j >10^{-6} A/cm² – 2 (a). The distribution of peak wave lengths on current density for green LEDs curves 1 and 2 for LEDs with the η (j) dependences are presented at Fig. 1a, accordingly curves 3 and 4 (b). The insert shows the distribution of peak wave lengths on current density for blue LEDs.
The study of the peak wavelength distribution on current densities Fig. 1b allows us to reveal another cause of low $\eta$ values in the green LEDs without prominent conductivity paths (Fig. 1a, curve 4). It is shown that the low $\eta$ values in LEDs Fig.1a curve 4 is due to the losses related to the radiative recombination at local regions enriched by In. According to the peak wavelength distribution on current densities Fig.1b curve 2 the radiative recombination begins approximately at 0.02 A/cm$^2$ at 542.2 nm, while the peak wavelength at current densities corresponding to the maximum value of quantum efficiency (15 A/cm$^2$) is 527.1 nm. The low $\eta$ values at 542.2 nm allow us to assume that the InGaN composition in these In enriched local regions is highly irregular. Moreover, another feature in 3D nanoscale indium fluctuations leading to a large $\eta$ droop (~ 50 %) in green LEDs is observed (Fig.1a, curve 3). The similar peculiarities were observed in blue LEDs earlier, but now the more typical $\eta(j)$ dependence is shown at figure 1a, curve 1 [8].

In green LEDs (Figure 1a, curve 3) the radiative recombination of localized carriers begins at low current density $j< 0.03$ A/cm$^2$ until 0.1 A/cm$^2$ at the peak wavelength 532.8 nm, at $j > 0.15$ A/cm$^2$ the continuous change of the peak wavelength until 520 nm (Figure 1b, curve 1) correlating with the huge $\eta$ droop by approximately 50% is observed (Figure 1a, curve 3). The 3D nanoscale indium fluctuations in such LEDs is also confirmed by C-V profiling (Figure 2a). The distribution of carriers in MQW in green LED differs drastically from that in blue LED (Figure 2b) as well as the shape of the peak wavelength distribution (the insert on Figure 1b).

Figure 2. The distribution of carriers in MQW of green (a) and blue (b) LEDs. The MQW position in depleted region under zero bias in green (a) and blue (b) LEDs.

For blue LEDs in the region of the maximal efficiency droop (at $j < 15$ A/cm$^2$) the indium fluctuations are significantly lower according to the peak wavelength distribution (Figure 1b, on the insert). The position of first well at the depletion region of this green LED provides a good localization for carriers. However, other wells are distorted by In fluctuation and disposed outside the depleted region. Thus, the both phenomena leads to the huge $\eta$ droop. The common feature for all investigated LEDs is the predominant contribution of delocalized carriers at $j > 50$ A/cm$^2$ and the current dependences of efficiency approximated by as $\eta(j) \propto j^{-b}$ where $0.2 < b < 0.3$. The $\eta$ droop values are about 20 %.

4. Conclusions

The shape of external quantum efficiency dependences on current density in green and blue LEDs is determined by radiative recombination of localized and delocalized carriers. The contribution of localized carriers predominates at $j < 50$ A/cm$^2$. In this range the most prominent variety of dependences’ shapes is observed. The impact of 3D nanoscale indium fluctuations and conductive paths on external quantum efficiency values and their droop at $j > 10$ A/cm$^2$ as well as the shape of $\eta(j)$ dependences in green and blue LEDs is of high variety and is sometimes contradictory. The conductive paths localized at extended defects reduce the radiative recombination of localized carriers.
and the values of the relative efficiency droop. 3D nanoscale indium fluctuations resulting in the formation of irregular InGaN composition containing In enriched local regions also reduce the radiative recombination of localized carriers and the values of relative efficiency droop. The continuous 3D nanoscale indium fluctuations resulting in distorted MQWs and the thin depleted layer leads to the huge external quantum efficiency droop (~ 50 %). The common feature for all investigated LEDs is the predominant contribution of delocalized carriers at $j > 50$ A/cm$^2$ and the current dependences of efficiency, approximated by as $\eta (j) \propto j^{-b}$ where $0.2 < b < 0.3$.

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