

Luminescence peculiarities of InGaN/GaN dichromatic LEDs

**D S Arteev, A V Sakharov, A E Nikolaev, S O Usov, W V Lundin and
A F Tsatsulnikov**

Ioffe Institute, Politekhnikeskaya 26, 194021 St-Petersburg Russia

E-mail: dima0724@gmail.com

Abstract. The series of InAlGaN LED structures containing two different quantum wells emitting at wavelengths of ~ 430 nm and ~ 490 nm was grown. The influence of the quantum wells order, thickness of the barrier between the wells and its doping level on the optical properties was studied by photo- and electro-luminescence measurements. It was found that the quantum well with longer-wavelength emission is preferable to be located farther from a p-layer than the shorter-wavelength quantum well to obtain emission from both QWs. Variation of the thickness of the barrier between the QWs and its doping level allows controlling the intensity ratio of two emission peaks.

1. Introduction

The first GaN-based light-emitting diodes were developed in 1971 [1]. Since 1990s, when I. Akasaki, H. Amano, and S. Nakamura fabricated the first high-brightness blue LED, advancement of LED technology has allowed to create high efficiency white solid state light sources. Luminous efficacy of contemporary commercially available white LEDs is above 150 lm/W, when the best ones show efficacy as high as 300 lm/W [2]. A conventional method of white LEDs fabrication is converting blue (~ 440 nm) LED's radiation into yellow-red one, using a phosphor. Mixing blue and yellow lights results in white light with desirable parameters. This method allows achieving high luminous efficiency at low cost. Some disadvantage of these LEDs is a relatively low color rendering index (CRI). The situation can be improved by a proper phosphor mixture, but the usual phosphor-based white LED spectrum has a "gap" in the range of 480 nm to 500 nm, as shown in figure 1. One of the ways to improve CRI over 95 is to use UV LED and several phosphors to get more filled spectrum, but in this case the chip fabrication becomes more complicated and the Stokes' losses increase lowering the total efficiency.

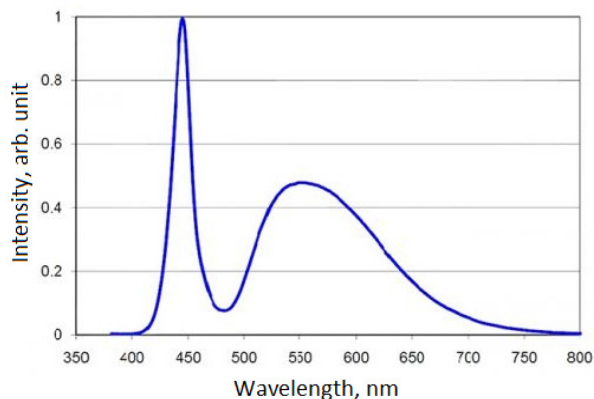


Figure 1. The typical spectrum of a phosphor-converted GaN-based white LED

In this paper, we propose an approach for developing a InAlGaN-based LED with two quantum wells emitting simultaneously at wavelengths of ~ 430 nm and ~ 490 nm to be used as a pumping source for a white phosphor-converted high-CRI LED.

2. Experiments

Samples were grown by metal-organic chemical vapour deposition (MOCVD) on sapphire (0001) substrates. Trimethylgallium, triethylgallium, trimethylaluminum, and trimethylindium were used as the group-III source materials, ammonia was used as the group-V source material. Monosilane and bis(cyclopentadienyl)magnesium were used as doping sources for n- and p-type layers, respectively. Hydrogen and nitrogen were used as carrier gases.

The initial sample was grown as follows. A thick Si-doped n-GaN buffer layer was firstly grown, then a 12 period InGaN/GaN (1 nm/1 nm) short-period superlattice (SPSL) was grown by the InGaN-conversion technique [3]. Afterward, a 20 nm-thick GaN layer was deposited, followed by an active region consisting of two 3 nm-thick InGaN quantum wells (QWs) separated by an 8 nm-thick GaN barrier with an emission wavelength of ~ 430 nm and ~ 490 nm for the first and second QWs (QW1 and QW2), respectively. Thereafter, an unintentionally doped 5 nm-thick GaN layer was grown, a Mg-doped 18 nm-thick $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ electron blocking layer (EBL) was deposited next. At last, the structure was capped with a p-type GaN layer with a thickness of 180 nm. According to the XRD-analysis and simulation using Synopsys Sentaurus TCAD, the indium composition in QW1 and QW2 is about 13% and 19%, respectively. The design of other samples was optimized by changing the relative position of the QWs and varying the thickness of the barrier between the QWs and its doping.

Photoluminescence (PL) studies were performed using excitation by a CW He-Cd laser (325 nm), electroluminescence (EL) studies were performed both on-wafer using In contacts and on processed chips.

3. Results and discussions

In figure 2, PL and EL spectra of the initial sample are shown. As one can see, the PL peak of QW2 has a much higher intensity compared to the QW1 peak. The EL peak of QW1 is almost unnoticeable. Obviously, carriers are mostly injected into QW2 located closer to the p-layers and having more indium in the composition. This situation is fundamentally different from the one observed for blue/green dichromatic LEDs grown in the same geometry [4], where emission from both QWs was observed and the short-wavelength emission was dominant.

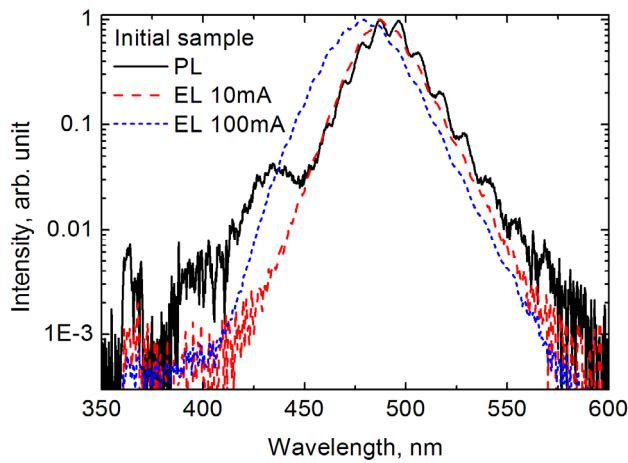


Figure 2. The photoluminescence and electroluminescence (at 10 mA and 100 mA) spectra of the initial sample.

To create the identical conditions for both quantum wells, decreasing the thickness of the barrier layer between wells to improve holes injection was suggested. Two samples with a 1.5 nm-thick barrier were grown. The first sample has the same quantum wells order as the initial sample. In the second sample, the quantum well with a longer emission wavelength (QW2) is farther from the p-layers than QW1. As figures 3 and 4 show, there is practically no emission from QW1 even for PL for both samples. By comparison of the spectra in figures 2, 3 and 4, it can be concluded that there is a redistribution of carriers between quantum wells by direct or thermal-assisted tunneling, when almost all carries are accumulated in the deeper QW.

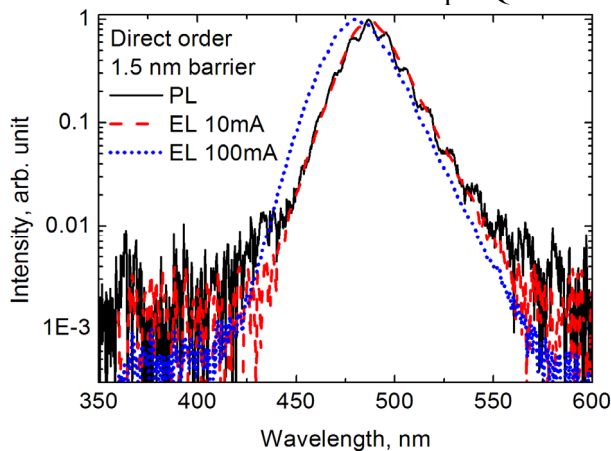


Figure 3. The PL and EL spectra of the sample with a 1.5 nm-thick barrier and a direct wells order.

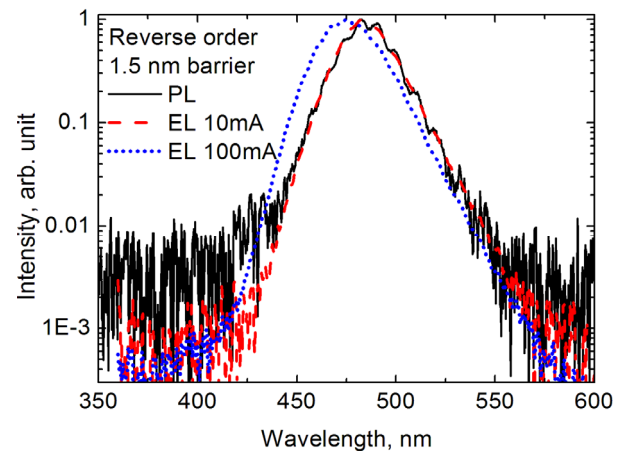


Figure 4. The PL and EL spectra of the sample with a 1.5 nm-thick barrier and a reverse wells order.

The next step was growing two samples with different quantum wells order similar to the previous ones, but with a thicker barrier between the quantum wells. The thickness of the barrier was increased to 44 nm. As one can see in figures 5 and 6, the PL spectra of both samples have two emission peaks, but only the EL spectrum of the sample with a reverse wells order has a short-wavelength peak, while the direct order sample's spectrum does not. The difference between the EL and PL spectrum can be attributed to a strong modification in the band diagram for biased (EL) and unbiased (PL) LED. It is also should be noted that the PL peak intensity ratio slightly differs for these samples, but this effect can be attributed to the nonuniform absorption of UV laser light.

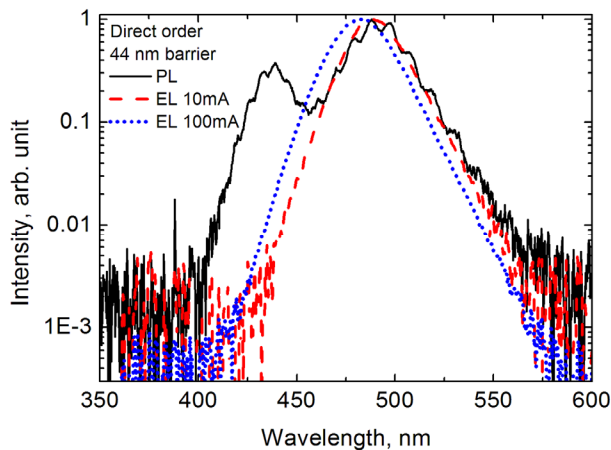


Figure 5. The PL and EL spectra of the sample with a 44 nm-thick barrier and a direct wells order.

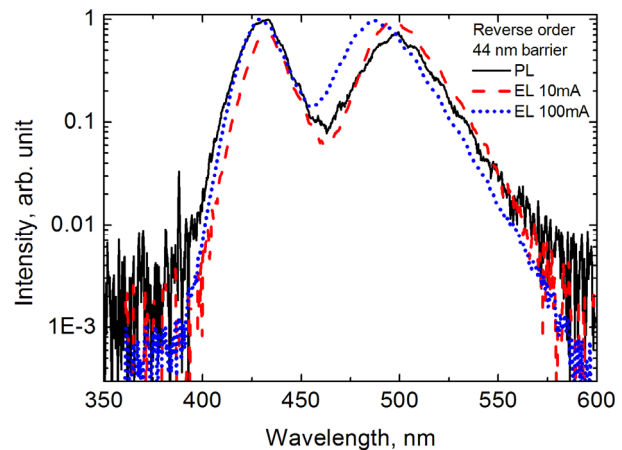


Figure 6. The PL and EL spectra of the sample with a 44 nm-thick barrier and a reverse wells order.

The design of the sample with a reverse QWs order was chosen for further optimization. Two additional samples with barrier thicknesses of 22 nm and 66 nm were grown. A comparison of figures 6, 7 and 8 shows that changing the thickness of the barrier between the quantum wells leads to a change in the ratio of the intensities of the peaks. When the barrier thickness is 22 nm, the ratio of the peaks intensities is 1:3 and it depends on the current. For the 44 nm-thick barrier, the peaks have almost the same intensity and the ratio weakly depends on the current. Increasing the barrier thickness up to 66 nm results in the change of the intensities ratio to 1.5:1. This effect of barrier thickness on the peaks intensity ratio is similar to the one observed for blue/green LEDs [4].

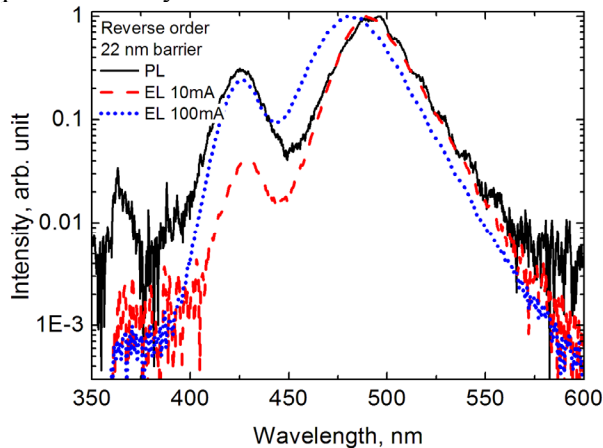


Figure 7. The PL and EL spectra of the sample with a 22 nm-thick barrier and a reverse wells order.

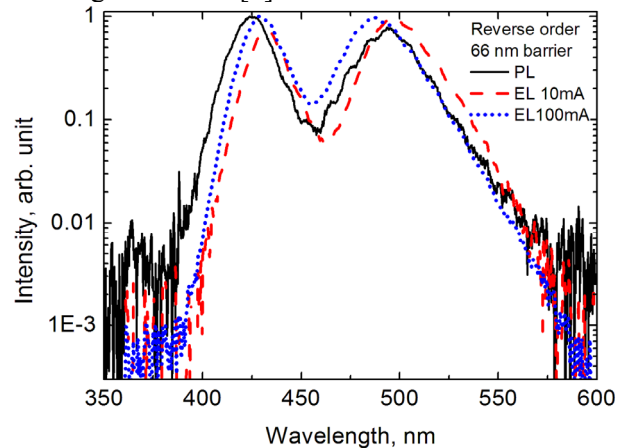


Figure 8. The PL and EL spectra of the sample with a 66 nm-thick barrier and a reverse wells order.

Unfortunately, thickening the barrier between quantum wells causes external quantum efficiency (EQE) decrease, as shown in figure 9. Apparently, it may be due to non-radiative recombination at defects in the barrier, which are generated due to the low temperature required during the growing of this layer. The EQE of the sample with a 22 nm-thick barrier is almost the same as for our standard blue LED; for the sample with a 44-nm barrier, EQE at high currents is nearly unchanged, indicating that the concentration of non-radiative recombination centres in the barrier layer is relatively low, so the most traps are occupied at operating currents of ~ 100 mA.

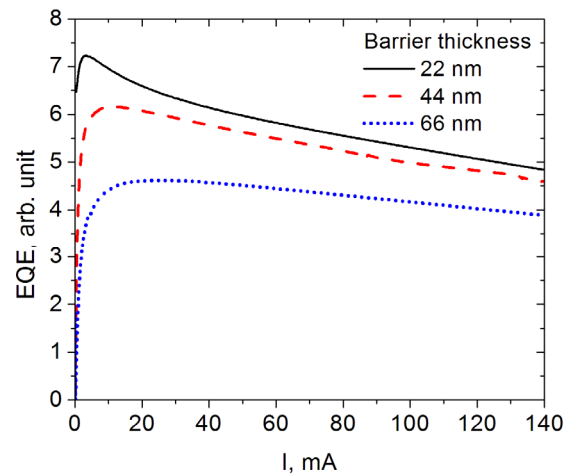


Figure 9. The external quantum efficiencies of samples with a reverse quantum wells order.

To change the peaks intensity ratio of the emission spectrum, doping of the barrier layer can be employed. The sample, similar to the previous one with a 22 nm-thick barrier, but with a barrier that is Si-doped to $\sim 2 \cdot 10^{17} \text{ cm}^{-3}$, was grown. As one can see in figure 10 (blue and red lines), the EL peaks intensity ratio is about 3:1, while the sample with an unintentionally doped barrier has a ratio of 1:3. The EQE of the sample with an n-doped barrier is lower at low currents, but at high operating currents its efficiency is higher than the EQE of the sample with an undoped one. In sum, the EQE doesn't change much with the doping level of the barrier between the QWs.

To prove the proposed approach, several structures were processed into 1 mm^2 chips, and white-light LEDs were made applying a commercially available thin-film phosphor. Figure 11 shows the EL spectra recorded at 100 mA for blue and dichromatic LEDs with and without a phosphor. It can be seen that some improvement of spectral filling was obtained on the short-wavelength side of the visibility curve. CRI calculation for such a dichromatic LED with a phosphor gives a value over 97 varying from chip to chip and it is limited by the red component.

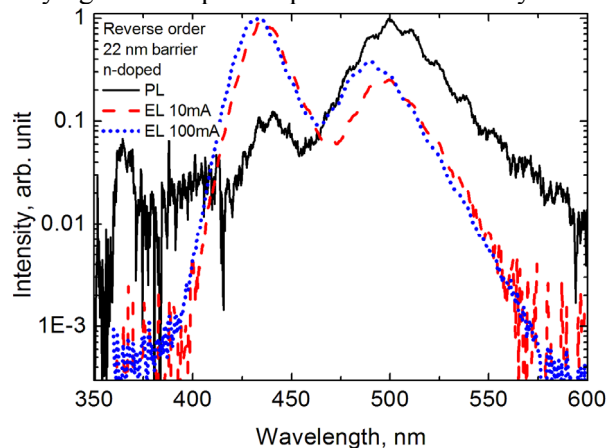


Figure 10. The PL and EL spectra of the sample with a 22 nm-thick n-doped barrier and a reverse wells order.

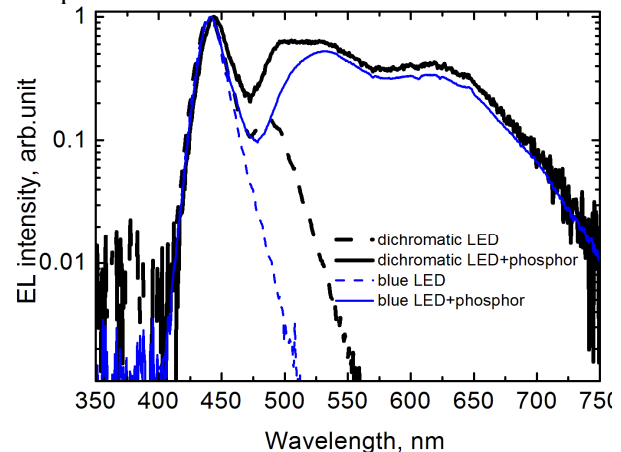


Figure 11. EL spectra recorded at 100 mA for blue and dichromatic LEDs with and without a phosphor

4. Conclusions

The influence of design of the dichromatic LEDs on their properties was investigated. Investigations by photoluminescence, electroluminescence and EQE measurement were employed to study

characteristics of the samples. The analysis of the data indicates that varying different structure parameters, e.g. the quantum wells order, the thickness of the barrier between them and its doping level, allows to control the peaks intensity ratio without a significant reduction of the emission efficiency. The obtained results allowed to optimize the design of the LEDs to be used as a pumping source for phosphor-converted white high-CRI LEDs. Combination of such a dichromatic LED with a phosphor allows to create a white LED with CRI>97.

References

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