Well-in-Well Active Region Based III-Nitride Colour-Tunable LED

Ajeet Singh Rawat*, Ashish Kumar Meena*, Balkrishna Choubey, Kankat Ghosh#
Department of Electrical Engineering, IIT Jammu, Jammu, J&K-181221, India
*Equal contribution, #Corresponding Author: kankat.ghosh@iitjammu.ac.in

Abstract— **A well-in-well structure is proposed in the multiple quantum well (MQW) based active region of the III-Nitride based light emitting diode (LED) in order to achieve tunable emission by varying the applied bias. It has been found that the composite rectangular well structure takes a complex triangular quantum well structure under applied bias and the energy of the n-th electronic level in the QW increases with increasing bias resulting in blue-shift of the emission wavelength with increasing bias. This principle enabled a simulation study that results in a colour tunable model for the III-N based LEDs. It has been found that around 2.7V of applied bias the LED emits in red (~636 nm) with an internal quantum efficiency (IQE) of ~30% whereas at 3.4-3.6V of applied voltage it emits at green (~556 nm) with a promising ~75% of IQE. Hence the proposed structure is promising for realizing colour tunable LED by varying the applied bias. As a result, all the required colours, i.e., RGB will be available on a single material (III-Nitrides) platform for display applications.**

Keywords—Well-in-well, InGaN, LED, Internal quantum efficiency, colour tunability

I. Introduction

For the modern full-colour display applications, though a significant research activity is dedicated to the organic materials based light emitting diodes (LED), the conventional inorganic compound semiconductor based light emitting diodes have many advantages over the organic counterpart. Such as, higher efficiency, longer lifetime, better reliability, more efficient radiative recombination rate and many more [1-5]. The problem lies in the monochromatic emission from the inorganic thin-film heterostructure based LEDs. The III-N based LED can emit at green but as soon as it penetrates towards true green, the efficiency decreases drastically and due to the impossibility to incorporate more % of In, III-N LEDs cannot emit in red. Similarly III-P based LEDs emit in red regime efficiently but the same problem of In incorporation at higher % stops III-P LEDs to emit in green. Thus to have an RGB system for display applications, we need to assemble LEDs of different materials together. Instead, in the present paper, we have proposed a InGaN/GaN based well-in-well structure which under applied bias takes the form of triangular quantum well where the emission wavelength becomes a function of applied bias. Hence simply by tuning the bias we can tune the emission wavelength of the LED and thus the same InGaN based LED can emit both in green and red regime. Since III-N based blue LED is already a market standard, we can achieve an all III-N based RGB display system which will naturally reduce the cost of display fabrication. In this article, we have used 1-Dimensional Poisson, Drift-Diffusion, and Schrodinger Solver (1D-DDCC) software for all our analyses [6].

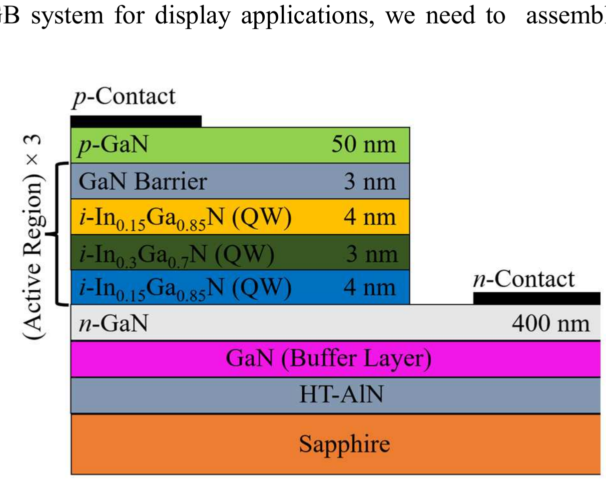

Fig. 1. Device structure of the proposed colour-tunable LED.

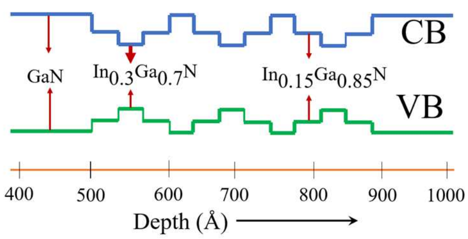

Fig. 2 Well-in-well based MQW active region

II. Device Structure and Parameters

The design of InGaN/GaN-based LED is shown in Fig. 1 which is basically a p-i-n structure comprised of a 400 nm thick n-GaN layer having a doping concentration of 2×10^{18} /cm^3, a specially designed multiple quantum well (MQW) based active region (i-region), and a 50 nm thick p-GaN having a doping concentration of 2×10^{19} /cm^3. This essential

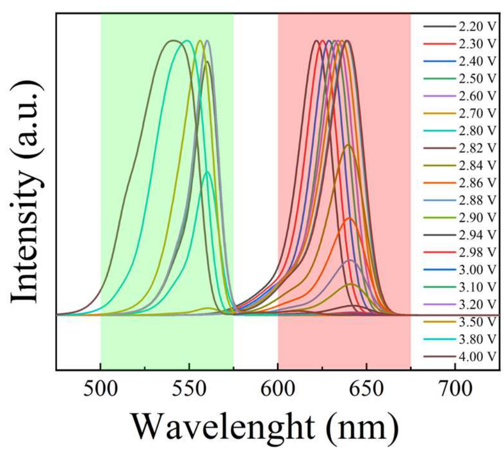

Figure 3. Variation of emission wavelength of the proposed LED with applied bias. Up to 2.7 V, the emission is purely red. From 2.7 V to 3 V, the intensity of the red emission decreases and the green emission increases. Above 3 V of applied bias, the emission wavelength is purely green.

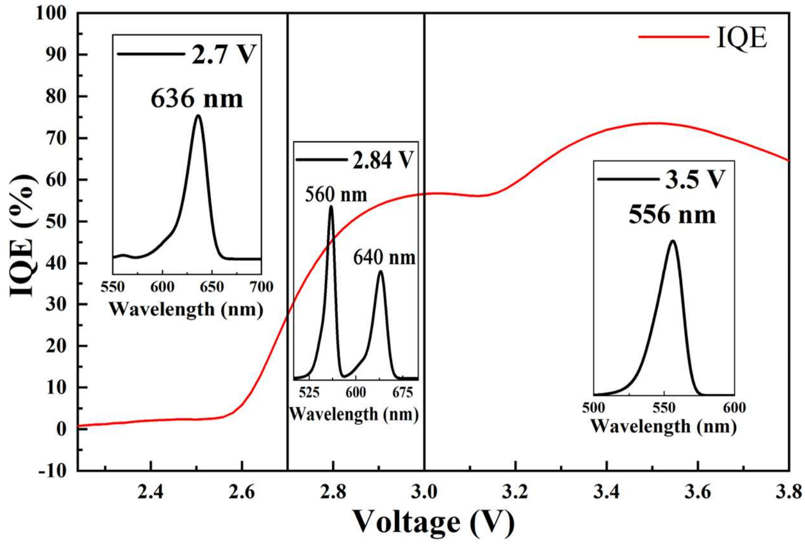

Figure 3. Variation of IQE with applied bias that shows that the red emission still has a lower efficiency than the green emission. Inset EL curves shows the range of emission at different bias regime.

part of the device is grown on a GaN buffer layer grown on HT-AlN/Sapphire substrate. The well-in-well design of the MQW based active region is shown in figure 2. The primary well of $In_{0.15}Ga_{0.85}N$ appears on the both sides of the 3 nm thick embedded well of $In_{0.3}Ga_{0.7}N$ as 4 nm thick each side. The GaN barrier is 3 nm thick. The considered value of the Auger recombination coefficient is 1 x 10^{19} cm^6 /s and the other parameters remain the same as the default values set in the software for InGaN material system.

III. Result and Discussion

The well-in-well structure as shown in figure 2 is visibly rectangular in shape. But as soon as the external bias is applied, the composite quantum well takes the form of two triangular quantum wells embedded in each other (figure not shown). Now, the n-th energy level, E_n, in a triangular quantum well is given by [7]

$$E_n = c_n [(eF\hbar)^2/(2m)]^{1/3} \quad (1)$$

where F is the external field. Hence $E_n \propto F^{2/3}$, i.e., the energy levels in the QW increase with increasing F. Thus, when the applied bias is increased, since the entire voltage drops across the active region of fixed width, the external field (F) in the triangular wells of the active region increase which increases E_n in both the conduction band QW and the valence band QW thereby increasing the emission energy which in turn decreases the emission wavelength. Thus, in figure 3 we observe that when the applied bias is up to 2.7 V, the electroluminescence (EL) emission from the LED is in red regime (620-640 nm). Between 2.7V to 3V of applied bias, both green and red emission is there from the device but the relative intensity of green to red increases with increasing bias. Whereas, for the applied bias more than 3V, the emission is purely green. This is conforming with the triangular model of the proposed quantum well structure in which the emission wavelength decreases with increasing bias.

Figure 4 illuminates the practical aspect of this dual colour emission. We observe that though the proposed structure enables the same device to emit both in green and red regime, the internal quantum efficiency (IQE) while emitting in red regime (at ~ 2.7V of applied bias) is ~30% which is still low compared to standard IQE of the blue counterpart. The IQE in green regime (for applied bias of 3.4-3.6V) is promisingly high (~75%). Thus, the proposed structure is expected to open a dimension of experimental investigations to find the feasibility of planer structure-based III-N LED emitting both in green and red regime.

IV. Conclusion

In summary, we are proposing a well-in-well structure for the active region of III-N based LED so that the same LED can serve the purpose of green as well as red emission. The optimistic result prompts us to predict that experimental investigation can be initiated to find the possibility of realizing such device which could simplify the fabrication procedure of RGB LED for the display application because, then all the colours will be available from the same III-N material system.

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