Design and Fabrication of Multi Quantum well based GaN/InGaN Blue LED

K Meel1, P. Mahala2 and S Singh3

1Physics Department, BKBIET, CEERI road, Pilani-333031, Rajasthan, India
2Birla Institute of Technology and Science (BITS), Pilani-333031, Rajasthan, India
3Flexible and Non-Silicon Electronics Group, CSIR-CEERI, Pilani-333031, Rajasthan, India

krishna.meel@bkbit.ac.in

Abstract. This paper presents the optimization of the multi-quantum well based Light Emitting Diode (LED) structure. We investigate the electrical and optical properties of the device on several factors like well width, barrier width, the number of quantum wells and then optimize the structure. The device is optimized for a well width and barrier width of 3nm and 6nm respectively, consisting of five quantum wells. Simulations were carried out using Silvaco ATLAS TCAD simulation program (Silvaco International, USA). The optimized structure was grown by MOCVD and fabricated. The I-V characteristic was also measured.

1. Introduction

Light Emitting Diodes have acquired a lot of attention towards Solid-State lighting due to their continuous improvement in efficiency and longer life time when compared to other lighting systems including Compact Fluorescent Lamp (CFL) bulbs, filament bulbs etc. [1]. LEDs are capable of producing light in the visible region ranging from violet to red. Technology has been developed for LEDs of red, violet, green, blue etc but for Solid-State lighting it is also important to concentrate on white lights due to their high-energy efficiency and reliable lifetime. The progress in phosphor-converted white LEDs has primarily been enabled by advances in the InGaN-based LEDs as excitation sources reported by several researchers [2, 3]. People have also reported Growth and Fabrication of GaN/InGaN Violet Light Emitting Diode on Patterned Sapphire Substrate [4]. People have also compared performance analysis of InGa/InN multi-quantum-well light-emitting diodes with p- and n-type step-doped barriers [5]. Technological developments have been made and are under process for producing white light using LEDs by several methods like 1) color mixing technology, 2) Phosphor coating on Ultra Violet LEDs and 3) Yellow Phosphor coating on Blue LEDs [6]. In this paper we concentrate on the third method of producing white light using Blue LED. Recently Singh et al. have compared Performances of p-side down vertical InGaN/GaN blue light-emitting diodes with chip size [7].

2. Device Structure

The structure has been considered to have epitaxial layers of Gallium Nitride and Indium Gallium Nitride material to be grown using Metal Organic Chemical Vapour Deposition on C-plane Sapphire substrate of thickness 300nm.
The basic structure consists of a buffer layer of GaN onto which a 2μm n-GaN layer is deposited followed by an active region consisting of unintentionally doped GaN/InGaN layers and a p-GaN layer of thickness 0.2μm. In the

![Figure 1. Device basic structure](image)

figure 1 shows the schematic diagram of the basic structure. The doping concentrations are assumed to be 1x10^{19} cm^{-3} and 5x10^{17} cm^{-3} in n-GaN and p-GaN respectively.

## 3. Structure Optimization

The active region consists of Multi-Quantum Well (MQW) structure in order to avoid and obtain an optimum carrier overflow and efficiency droop caused using a single quantum well structure or a double heterostructure. Hence there is a need for the optimization of multiple quantum well structure. The structure was optimized in a systematic manner starting from a number of quantum wells to well-width and barrier-width optimization. The optical and electrical properties of InGaN/GaN MQW LED are investigated numerically with Silvaco ATLAS TCAD simulation program (Silvaco International, USA) by extracting the integrated radiative recombination rate (radiative efficiency) and total integrated recombination rate [8]. Both optical and electrical characteristics of the device like Internal Quantum Efficiency (IQE) and turn-on voltage are examined carefully to obtain optimum results.

![Figure 2.](image)

(a) Shows the variation of IQE with number of wells and (b) Shows the variation of I-V characteristics with number of wells.

From the above-shown results in figure 2, it is evident that five quantum wells are optimized. If we see the graph of IQE versus current density as we increase or decrease the number of quantum wells from five, we notice
a decrease in efficiency with increasing current density, the reason may be attributed to carrier overflow or less number of carriers being captured resulting in radiative recombination. If the number of quantum wells is reduced the total number of carriers being captured in the well region is reduced and hence the radiative efficiency is reduced. This implies that one should have a high number of quantum wells to capture more and more carriers for recombination. But one can observe that as we increase the number of quantum wells above five efficiencies is again reduced, this may be attributed to the increase in nonradiative recombination rate caused due to the lower mobility of holes as compared to electrons which are not able to reach the well present on the n-GaN side. This results in a lower concentration of holes as compared to electron concentration as we move from p-GaN to n-GaN. Based on the same parameters well-width and barrier-width are also optimized.

Figure 3. (a) Shows the variation of IQE with varying well-width. (b) Shows the variation in I-V curve with varying well-widths.

Figure 4. (a) Shows variation in I-V curve with varying barrier width. (b) Shows variation in IQE with barrier width. (c) Shows the effect on wavelength emission intensity with varying barrier width.
From the above IQE and I-V curves shown in figure 3, it is evident that a well-width of 3nm can be taken as optimized based on its low forward voltage and less droop in IQE as compared with less or higher well-width values. Also for the wider quantum width, the quantum confined stark effect becomes strong, the hole wave functions and electron wave functions are separated more, resulting in less electron and hole recombination. Therefore, the efficiency reduces with larger quantum well width. Also if the well thickness is very thin than carrier overflow increases that again results in low efficiency. Hence the well-width has been optimized to 3nm.

Similarly, as we fix the well width to 3nm and vary the barrier width we notice from figure 4 that with the increase in barrier width the emission intensity decreases and a slight increase in series resistance as obtained from I-V curve. When the thickness of barrier is thin enough, the wave functions of electron and hole would penetrate the adjacent well layer, resulting in inter-well transition. If the inter-well transition of the MQWs occurred, the Photo Luminous (PL) peak might be red-shifted because the band structure of MQW would be inclined due to the large piezoelectric field. If the barrier width is thinner enough, tunnelling current through the LED structure begins to dominate. Reduction of IQE due to tunnelling leakage of carriers from the quantum well to defect states in barriers.

Now if the width of barriers is increased, the overflowing carriers probably tend to diffuse into the barriers rather than going into the quantum wells. This results in a decrease in the intensity. Also as the thickness of the GaN barrier layer is increased, the abruptness of the interface between InGaN and GaN layers deteriorated, probably due to the generation of defects induced by the strain accumulation in the MQWs. Accordingly, the intensity of the line-width of the PL taken from the MQWs is reduced and broadened respectively with an increase of barrier thickness.

Therefore, the final structure has been optimized as five quantum wells with 3nm and 6nm well and barrier width respectively. Figure 5 shows the 1D schematic of the final optimized structure.
4. Fabrication
The above optimized epitaxial layers were grown by using MOCVD system. Then LED of multi finger structure with chip size (500µmx500µm) was fabricated. I-V characteristics of the chip were measured by using Keithley 4200 SCS measurement system. A uniform emission of blue light from the LED chip was observed. In figure 6 shows the measured I-V characteristics and blue light emission from a multi finger LED chip. Current-voltage characteristics of figure 6(a) shows a turn-on voltage of 2.8 V.

![Figure 6](image)

Figure 6. (a) shows the I-V curve measured for the planar LED chip (500 µm x 500 µm) (b) shows uniform blue light emission under biased conditions.

5. Conclusion
In conclusion, MQW GaN/InGaN based LED structure has been simulated by varying various parameters like number of quantum wells, well-width and barrier-width. The result shows that the structure is optimized with five quantum wells, well widths with 3nm and barrier width with 6 nm respectively. The optimized structure was then grown by MOCVD. The chip level fabrication was successfully done and its I-V characteristic was measured.

Acknowledgements
Authors are thankful to the Director, BKBIEIT, Pilani and Director, CSIR-CEERI, Pilani for their encouragement and support. Authors express their gratitude towards all the colleagues of CEERI who helped in experimental work.

References
[1] Held G, 2008 Introduction to light emitting diode technology and applications. New York: CRC press, Auerbach publications.
[2] Li X-H, Zhu P, Liu G, Zhang J, Song R, Ee Y-K, Kumnorkaew P, Gilchrist J F, and Tansu N 2013 Journal of Display Technology 9(5), 324-332.
[3] Zhu P, Liu G, Zhang J, and Tansu N 2013 J. of Disp. Tech. 9(5), 317-323.
[4] Adhikari S, Patra S K, Lunia A, Kumar S, Parjapat P, Kushwaha B, Kumar P, Singh S, Chauhan A, Singh K, Pal S, Dhanavantri C 2014 Journal of Applied Mathematics and Physics 2, 1113-1117
[5] Singh S, Utpalla P, Pal S, and Dhanavantri C 2016 Journal of Computer Electronics 15, 1040–1045.
[6] Schubert E F 2006 Light-Emitting Diode Cambridge University Press, Cambridge, U.K.
[7] Singh S, Kumar S, Pal S, and Dhanavantri C 2017 Optical Laser Technology 95, 165-171.
[8] Silvaco ATLAS TCAD user manual [www.silvaco.com].