Simulation Studies of a phosphor-free Monolithic Multi-Wavelength Light-Emitting diode

Sidra Jabeen[1], Shahzad Hussain[2], and Sana Zainab[1]

[1]CEME, National University of Sciences and Technology (NUST), Islamabad, Pakistan
Sidra.jabeen79@ee.ceme.edu.pk, sanaznb67@gmail.com
[2]Semiconductor Educators LTD, 4 Brewery Drive, Brewery Drive Huddersfied, UK, HD2 6EN .
Drshahzadhussain1@gmail.com

Abstract

A monolithic multi-wavelength light emitting diode structure is presented in this paper. The structure is based on two InGaN quantum wells separated by a GaN barrier layer. This structure allows the full activation of each quantum well separately as well as simultaneously with the tuning of applied voltage. Consequently, blue to green color emissions can be generated by tuning the forward bias voltage. The technique of band gap engineering has been deployed to reduce the photon reabsorption hence improving the output power of the device. Dimensions and indium contents of the quantum wells are optimized to enhance the radiative recombination rate and reduce the phonon emission. This paper investigates the carrier distribution profile, IV characteristics, luminous power, radiative recombination rate, conversion efficiency, and spectral power distribution of multi-color light emitting diode.

1. Introduction

Lighting consumes a noticeable amount of energy because of its prevalent applications. III-V based white light emitting diodes (LEDs) are replacing conventional incandescent and fluorescent light sources gradually. These LEDs offer higher efficiency, longer life span, lower power consumption, miniature device size, and captivating spectral characteristics [1].

The three traditional methods to develop white-light LEDs are: use of ultra-violet LED with RGB phosphor, use of blue LED with yellow phosphor and, a multichip array of red, green and blue LEDs. However, these methods have their pros and cons. Use of UV LED with RGB phosphor gives high color rendering index (CRI) but low efficacy. Use of blue LED with yellow phosphor gives high efficacy but low CRI value. Multichip array LEDs give medium efficacy with high CRI value but this method is not cost effective [2]. To avoid these problems, concept of phosphor-free monolithic white-light LEDs was proposed, and is under research and development currently [3-4].

Various monolithic white LED structures have been reported in the literature. Soh et al. proposed phosphor free white LED structure by deploying indium nanostructures in the yellow emission quantum wells [5]. Lu et al. fabricated dual quantum wells LED which produces the white light by combining blue and yellow wavelengths. Dual wavelength LEDs are realized by using quantum wells of different indium content [6]. Fang et al. also reported dual emission LED fabricated using metal organic chemical vapor deposition (MOCVD) [7].

Despite the fact that InGaN based monolithic LEDs have been designed and fabricated successfully, there are numerous phenomenon's which have not been fully comprehended in multi-wavelength LEDs, such as carrier dynamics and various recombination mechanism.

This paper presents the optimization of monolithic multi-wavelength LED structure proposed in an earlier published work [9]. The structure possess two InGaN quantum wells of different indium composition, covering the emission spectrum from blue to green wavelength. The optimization involves detailed study of carrier dynamics, technique of band gap tailoring and the physics behind the photon generation and absorption.

Industrial level SILVACO TCAD simulator has been used for design and simulation of the LED structure. This simulator can simulate LEDs structure for their electrical and optical characteristics as well as the thermal effects [8].

2. Device structure and parameters

The monolithic multi-color LED structure is shown in fig. 1.Fig. Sapphire substrate is used with a 50-nm nucleation layer followed by n-GaN layer of 3.5 um. Active region consists of two InGaN quantum wells (QWs) decoupled by a 15-nm n-GaN layer. Bottom quantum well (BQW) and top quantum well (TQW) have thickness of 3 nm and 5 nm respectively. P-AlGaN layer of 30 nm is used as electron blocking layer and the thickness of p-GaN layer is 0.5 um.

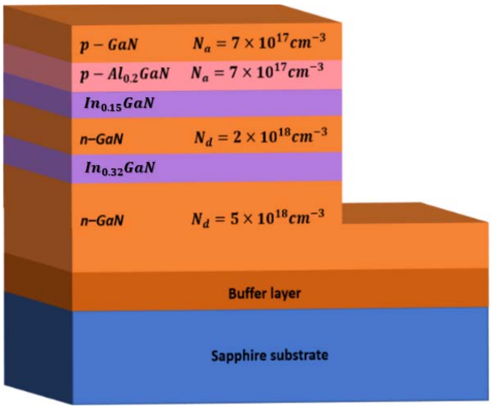

Fig. 1. Structure of a monolithic white LED

Fig. 2 is a close view of the active region with meshing grid. Meshing is kept finer in the critical regions and interfaces while it is coarse at less critical regions. A careful meshing of the device is imperative for better accuracy and computational time.

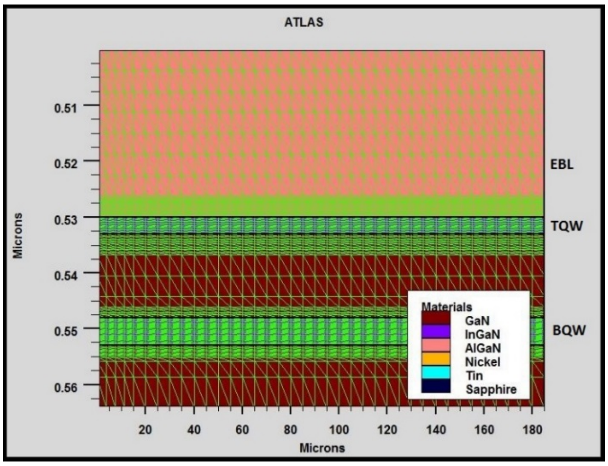

Fig. 2. Close-up view of the active region with the meshing

3. Discussion and results

Energy band diagram of the LED structure at thermal equilibrium is shown in fig. 3. The difference in the conduction band energy level of p-region and n-region is the energy barrier which prevents the movement of carriers toward active region. At equilibrium fermi level is aligned on the both ends of the band diagram. In p-type region, fermi level is closer to valence band , showing the collection of holes in the valence band. In the n-type region fermi level is closer to the conduction band which shows the presence of electrons in the conduction band.

Under the application of forward voltage the barrier is reduced which results in the movement of carriers toward the quantum wells. Fig. 4 shows the energy band diagram at 4V. The carriers get confined in the quantum wells and radiative recombination takes place resulting in the emission of photons. These photons are desired to move out of the device without being reabsorbed into the device. Radiative recombination and extraction of photons out of the device are key parameters for designing of cost effective and robust LED structures.

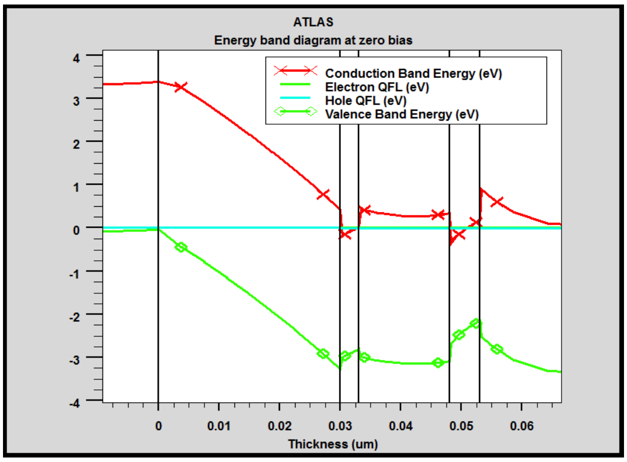

Fig. 3. Energy band diagram under no bias

At equilibrium holes are unable to reach active region due to the presence of the high energy barrier. Fig 5(a) shows carrier concentration at equilibrium. Under the application of forward bias voltage, the barrier is reduced and holes are now able to reach the active region. Carrier concentration under forward bias is shown in fig. 5(b). It shows the hole concentration in the active region has improved effectively.

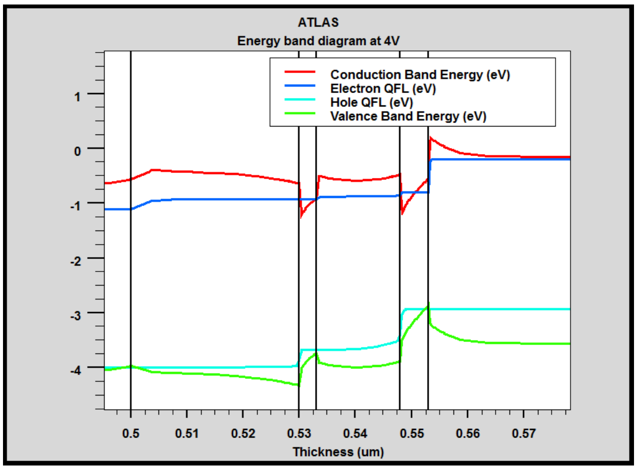

Fig. 4. Energy band diagram under forward bias

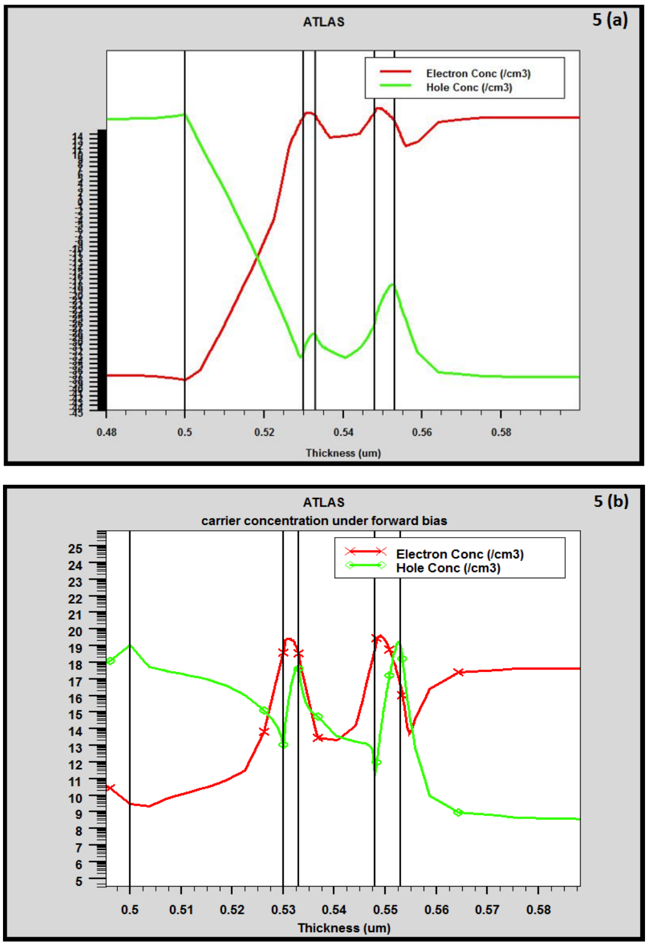

Fig. 5. (a) carrier concentration at equilibrium (b) carrier concentration under forward bias

In InGaN, the effective mass of holes is higher than the electrons hence mobility of holes is lower than the electrons. At voltages lower than 4V, holes can only reach to the TQW due to their lower mobility. At 4V concentration of holes is comparable in both QWs. At voltages above 4V, more holes will diffuse to the BQW. Concentration of electrons in both QWS is equal under forward bias so it is the hole current density which determine the recombination rate. Fig. 6 shows radiative recombination rate at different voltages.

Table 1. Compares the device parameters of old structure and the optimized structure. In case of optimized structure, top quantum well (TQW) has thickness of 3nm and indium composition of 15%. Bottom quantum well (BQW) has thickness of 5nm with indium composition of 32%. Due to difference in the indium composition, both QWs emit light of different wavelength. To mitigate the quantum confined stark effect (QCSE), thickness of the QWs is preferred to be ≤5nm.

Table 1. Device parameters of the structures

Region	**Old structure**		**Optimized structure**	
	Thickness (nm)	***x-composition***	***Thickness (nm)***	***x-composition***
p-GaN	500	-	500	-
p-AlGaN	30	0.2	30	0.2
InGaN (TQW)	5	0.27	3	0.15
n-GaN (spacing region)	15	-	15	-
InGaN (BQW)	3	0.165	5	0.32
n-GaN	3500	-	3500	-

Thickness and indium contents of the quantum wells (QWs) are optimized to reduce the reabsorption of the generated photons. A photon is absorbed in a material if

$$E_{ph} \geq E_g \qquad (1)$$

Where E_{ph} is the energy of photon and E_g is the band gap energy of the material.

- If $E_{ph} = E_g$ photons have energy just sufficient enough to get absorb.
- If $E_{ph} > E_g$ photons absorptions is accompanied by the emission of phonons as well.
- If $E_{ph} < E_g$ photons will not get absorbed and the material will behave as transparent [10].

In case of the old structure, TQW has higher indium composition leading to lower bandgap energy and BQW has lower indium composition hence the higher band gap energy. The photons generated in BQW with higher energy are highly likely to be absorbed by the TQW layer of lower band gap energy. This will result in the emission of phonons and a decrease in the output power. To optimize this structure for higher output power and lesser absorption of photons, technique of band gap engineering is used. The dimensions and indium contents has been modified carefully. TQW has been assigned the material of higher band gap energy and BQW has the material of lower band gap energy. Now, TQW will behave as transparent to the photons coming from the BQW. Consequently, photons will not get absorb by the TQW layer resulting in higher output power.

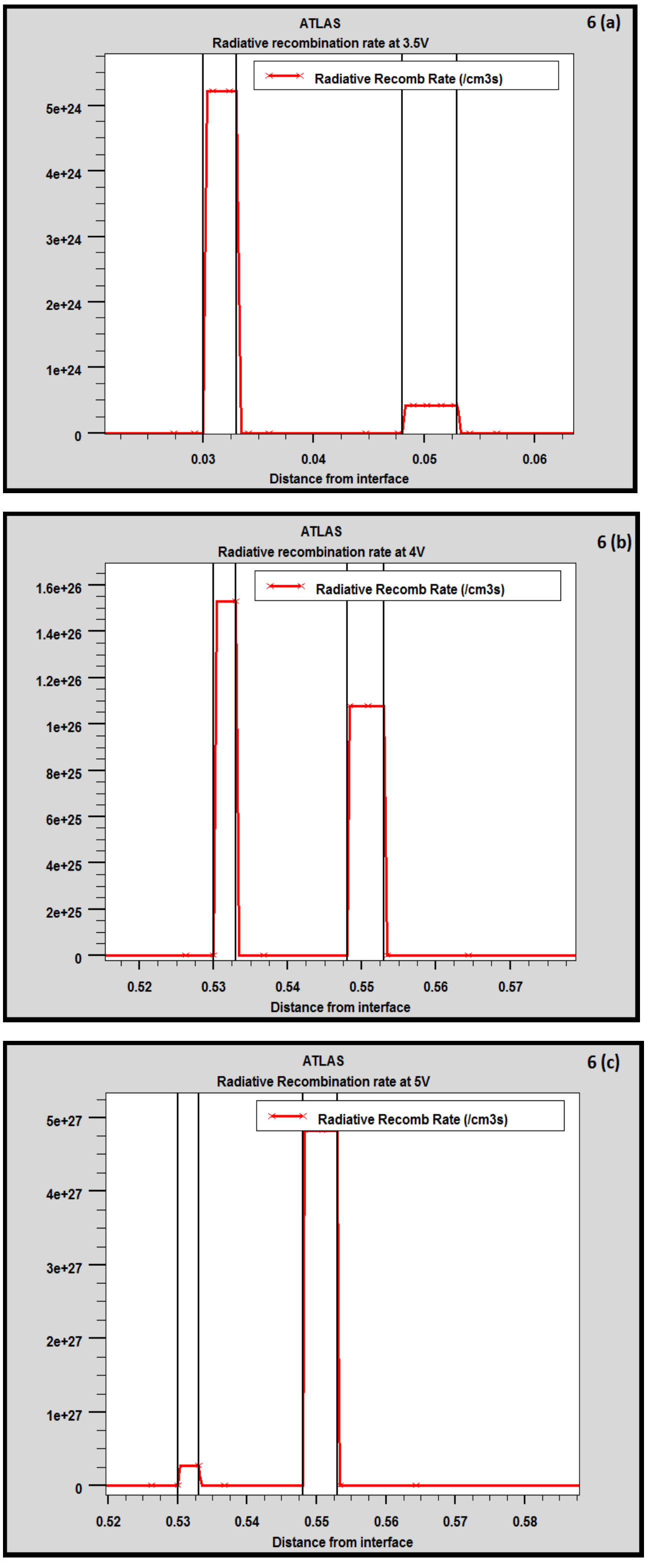

Fig. 6. Radiative recombination (a) at 3.5V (b) at 4V (c) at 5V

Current-voltage (I-V) and output power-current (L-I) characteristics of the LED are shown in Fig. 7(a) and (b) respectively. With of the help of these two graphs, conversion efficiency can be calculated. The optimized structure has the power conversion efficiency of 47.5% at 20mA, whereas the power conversion efficiency of the old structure, fluorescent light and incandescent light is 26%, 21% and 8% respectively.

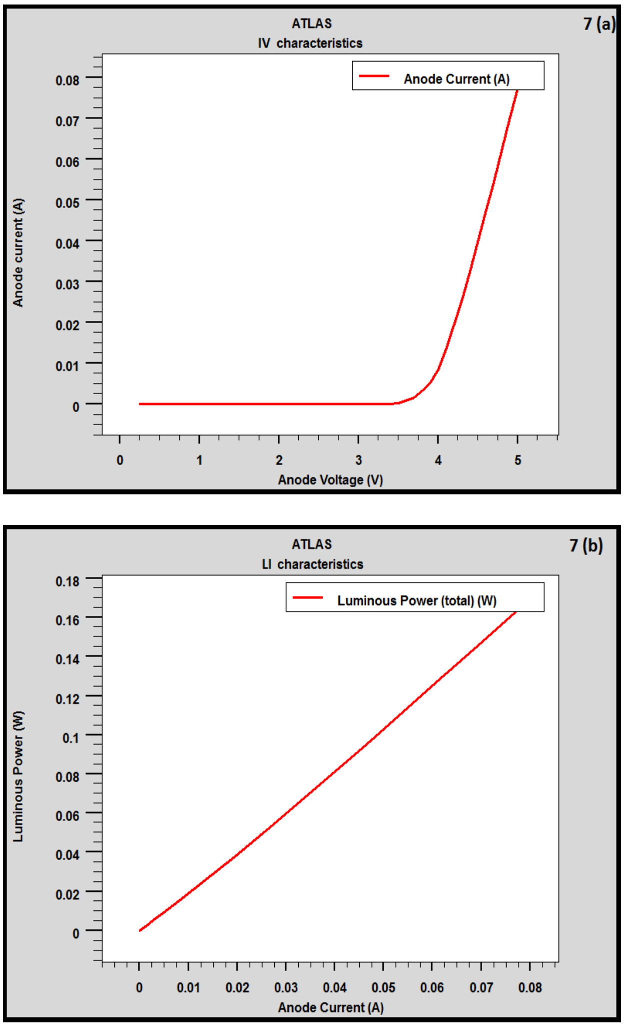

Fig. 7 (a) I-V characteristics of the LED structure (b) L-I characteristics of the LED structure

Spectral power distribution of the LED device is shown in fig. 8. This multicolor LED emits different shades of blue color light at voltages less than 4V. At 4V both quantum wells are activated, TQW emits blue color light and BQW emits green color light, human eye will perceive the mixture of these two colors as cyan color light. Above 4V green color emission start dominating.

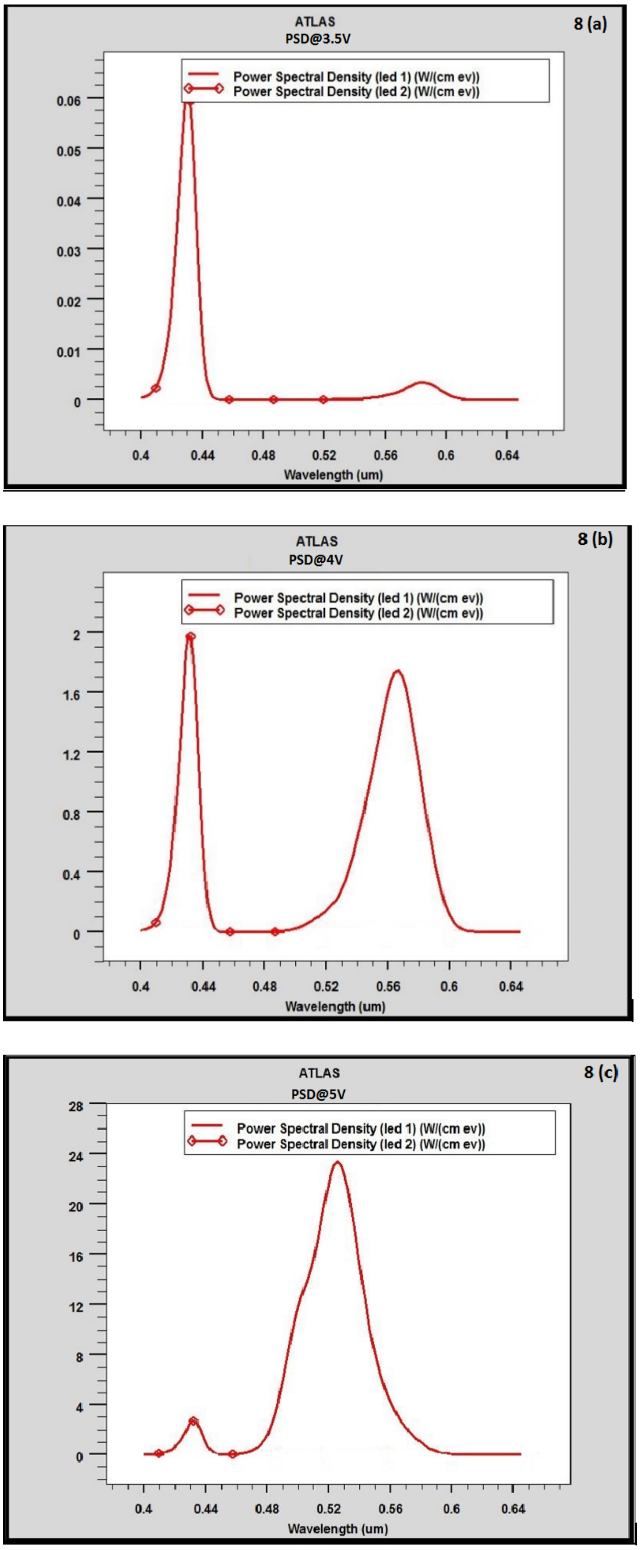

Fig. 8. Power spectral density of the LED at (a) 3.5V (b) 4V (c) 5V

6. Conclusions

An efficient multi-wavelengths LED structure is presented in this work. Dimensions and indium composition of QWs are optimized to reduce the photon absorption. Power conversion efficiency of this LED structure is higher than the earlier proposed structure, incandescent light and fluorescent light. Carriers distribution profile, radiative recombination rate and, power spectral density are in accordance with each other and satisfy the presented theory. This LED emits blue color light at voltages less than 4V, cyan color light at 4V and green color emission at voltages above 4V. A continuous range of emission can be produced with a ramp input voltage.

7. References

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