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Research Article

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Nanotechnology Approach for Improving Quantum Efficiency in White Light Emitting Diodes

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Abstract

When compared to other light sources that have been made so far, white light emitting diodes (WLED) have been considered to be the most efficient. Of which, multiple quantum well (MQL) LED shows a reasonably better performance than other technology of white light production, except in the efficiency droop, which is found at high current density. Method for improving the efficiency droop at high current density is discussed and analyzed in this paper. The analysis is done through TCAD simulation, and it has been found that the efficiency droop can be minimized as low as 6% by the technology adopted in quantum barrier of quantum well arrangement. It is also found that the light quality has also increased.

Keywords

Multiple quantum well, Quantum barrier, White light emitting diodes.

Introduction

The LED find many applications such as illumination, displays, communication in the fields of home appliances, electronic gadgets, medical and agriculture fields. The supremacy in its performance makes LED the brightest and most acceptable light source among all other artificial light sources. Its major application is in the field of illumination or lighting. The reports show that about 18% of the world's electricity is used for lighting [1]. The LED market is also growing year by year so that almost all the other artificial light sources are replaced by LED. Less electrical energy consumption and non-polluting nature makes it an economical and environment-friendly light source among all other artificial light sources.

There are many techniques for the generation of white light in LED [2]. Here a monolithic dual wavelength WLED [3] is simulated. III-Nitride material is being chosen as it has the advantages of wide and direct bandgap, high-temperature, high-power application, high electron mobility, etc. [4]. Due to its wide band gap, radiation resistance, high thermal conductivity, high intrinsic temperature, strong breakdown electric fields, etc., silicon carbide was chosen as the substrate material [5].

Experimentation

WLED: basic structure

Figure 1 depicts the schematic of a conventional InGaN/GaN white light emitting MQW structure, whereas figure 2 illustrates the energy band diagram of a simulated WLED. A thick c-place sapphire (Al_2O_3) substrate is used to epitaxially develop a conventional MQW HP WLED structure. On the substrate,

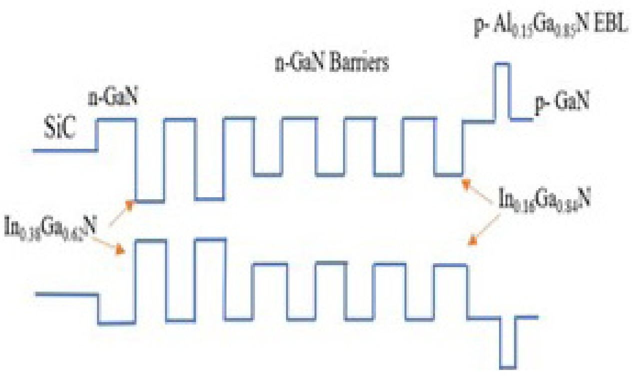

Figure 1: Schematic diagram of a typical InGaN/GaN high power WLED MQW structure.

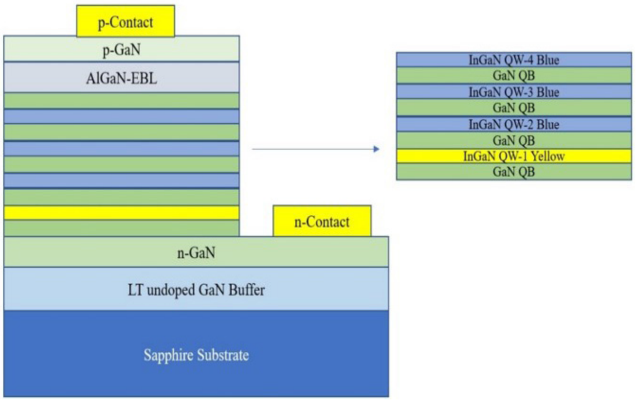

Figure 2: Energy band diagram of a typical InGaN/GaN high power WLED MQW structure.

a low temperature undoped GaN buffer layer is formed to absorb the strain. GaN buffer layer and quantum well structure is less stressed when there is an n-GaN nucleation layer on top of the buffer layer. Quantum well structure consists of 3 nm $In_xGa_{1-x}N$ quantum well layer and GaN quantum barrier layer. Quantum well structure consists of dual wavelength quantum well of blue emitting (x = 0.22) and yellow quantum well (x = 0.36). To lessen the electron overflow at high injection current, a high band energy Al0.15Ga0.85N electron blocking layer is affixed to the top of the quantum well structure. p-GaN layer is placed on the top of EBL [6, 7].

The simulation of the proposed WLED structure is performed using TCAD and table 1 describes the simulation parameters. Figure 3 gives the spontaneous emission spectrum results, and it has been found that the spectrum shows the peaks obtained in blue and yellow region which resembles the dichromatic white light spectrum. The peak emission occurs at a wavelength of 470 nm (Blue) and 575 nm (Yellow).

The internal quantum efficiency obtained from the simulation is replotted and compared with the experimental results reported in [8] and is shown in figure 4. The results show that there exists an efficiency droop effect i.e., as the injection current increases, the efficiency starts decreasing and at 100 A/m², the efficiency decreased by 33% from the peak.

Table 1: Simulation parameters.

Parameter	Value
Device temperature	300 K
Band gap energy	6.138 eV (AlN) 3.435 eV (GaN) 0.711 eV (InN)
Shockley Read Hall recombination lifetime	50 ns
Auger coefficient	2 x 10^{-32} cm^6/s
Radiative recombination rate coefficient	0.4 x 10^{-10} cm^3/s (InN) 1.1 x 10^{-10} cm^3/s (GaN) 2 x 10^{-10} cm^3/s (AlN)
Models used	Drift-diffusion transport model. K.p models and self-consistent Poisson-Schrodinger model

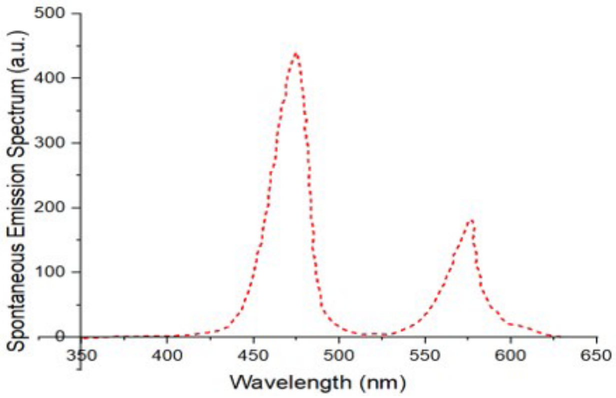

Figure 3: Spontaneous emission spectrum of simulated monolithic dual wavelength MQW HP WLED.

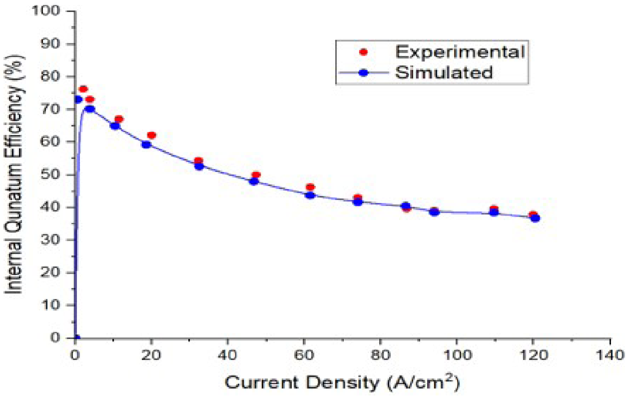

Figure 4: Comparison of experimental and simulated results of IQE vs current density.

Several research are being carried out in this efficiency droop effect which was noticed in high power LED and the reasons for the efficiency droop can be summarized as the insufficient number of charge carriers in the multiple quantum wells [9]. In figure 5, the carrier transport model is shown, with the following abbreviations: IV for current and voltage, pout for light output from the LED, IQE for internal quantum efficiency, RE for recombination efficiency, LEE for light extraction efficiency, IE for injection efficiency, EQE for external quantum efficiency, and ELE for electrical efficiency.

By mathematical modelling, we found that the IQE greatly depends on four different phenomena. Namely, (1) Shockley Read Hall non-radiative recombination, (1) Carrier overflow, (3) Thermionic emission, (4) Auger recombination.

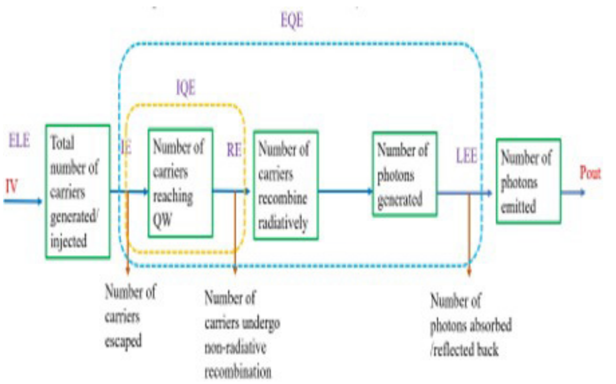

Figure 5: Carrier transport model in MQW WLED.

These four phenomena depend on many factors and height of barrier layer is one such factor [10-12]. This work concentrates on the influence of barrier height on the performance of MQW WLED. The barrier height varies by changing the concentrations of In in InGaN of MQW barrier.

Quantum barrier layers are where LED structures A, B, and C in figure 6 differ most from one another. In LED structure A, quantum barrier layer is made of GaN, whereas in LED structure B, the barrier layer is made of InGaN of x-composition 0.06. In LED structure C, the x-composition of InGaN varies in steps to get graded InGaN barrier layers.

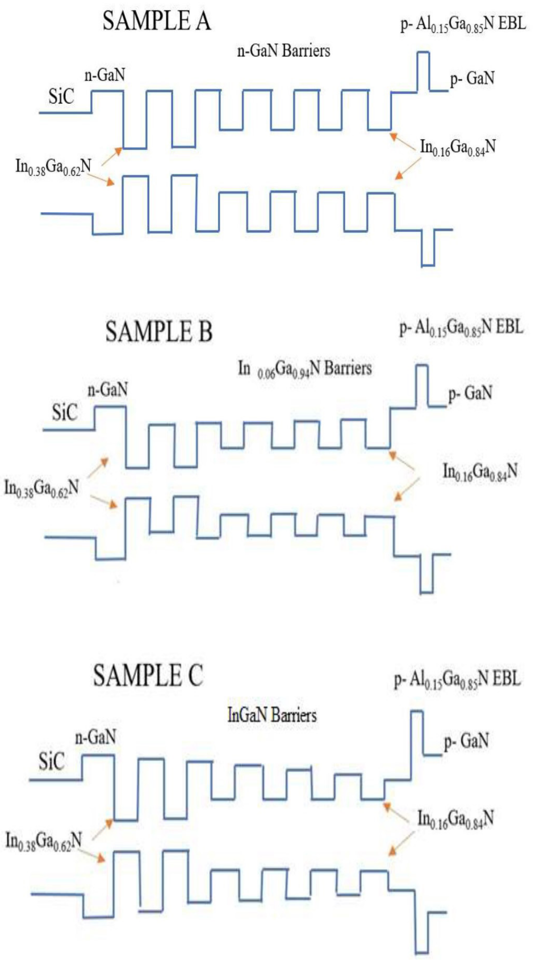

Figure 6: Energy band diagram of MQW WLED samples A, B, and C.

Results and Discussion

The LED light output power of LED samples A, B, and C is shown in figure 7. The application of graded InGaN barrier layer in sample C has been shown to significantly increase output power as a result of decreased lattice strain between the layers of quantum well and quantum barrier, which also results in decreased polarization field and carrier dislocation.

IQE vs injection current for the samples is depicted in figure 8. All of the samples exhibit comparable performance at low injection current levels, and the IQE peaks. The IQE steadily declines, due to the efficiency droop effect, under a high injection current. When compared to the other two samples, the graded InGaN barrier LED exhibits a 6.56% efficiency droop at 200 mA.

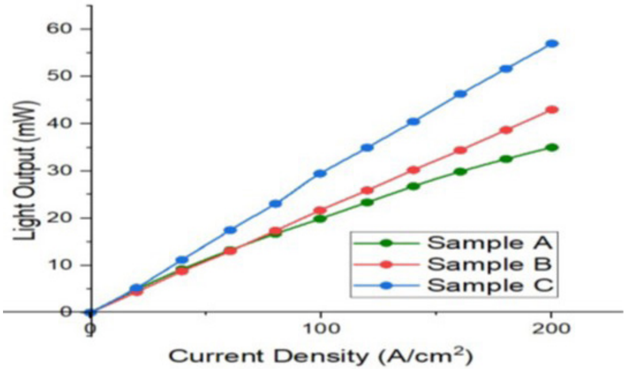

Figure 7: Light output vs injected current density of LED samples A, B, and C.

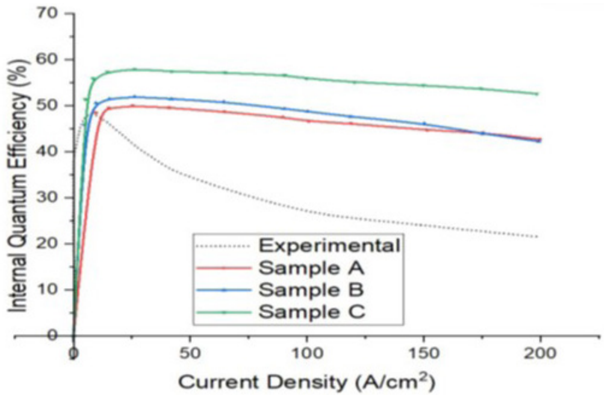

Figure 8: IQE vs injected current density.

The polarization fields are lessened by the lattice matched InGaN/InGaN quantum well-barrier layer, which minimizes the quantum confined stark effect. Thus, the droop effect is reduced here significantly. Compared to the experimental value, here the LED samples A, B and C got a higher IQE at low injection current. It is due to a small structural change in the above structure that the yellow quantum well is placed near to the n-region and blue quantum well near to the p-region. The number of electrons found in the yellow quantum well is a little higher than that of the structure considered experimentally.

Figure 9 shows the electron distribution in the quantum well of GaN barrier, InGaN barrier, graded InGaN barrier

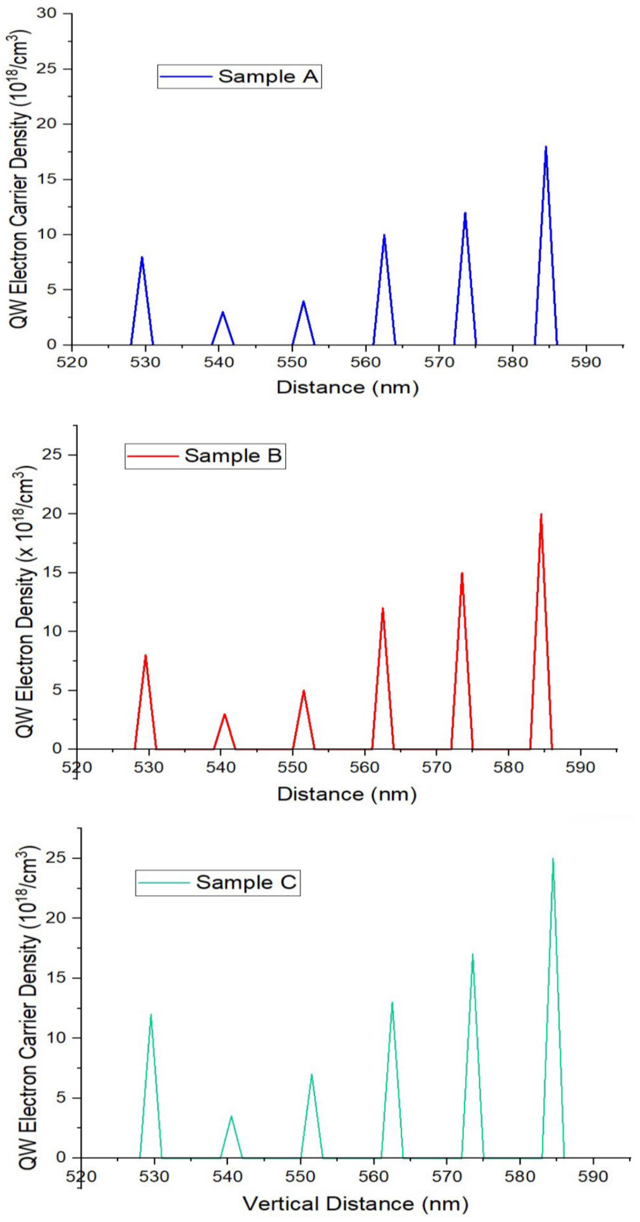

Figure 9: Quantum well electron distribution profile of sample A, B, and C of InGaN barrier MQW HP WLED.

MQW HP WLED, respectively. Because of the lower barrier height in sample C, electrons may more readily pass through quantum barriers and gather in the quantum well close to the p-region. Due to polarization and lattice mismatch in the layers of traditional GaN barrier MQW HP WLED, the carrier capture in sample A is decreased.

GaN, InGaN, and graded InGaN quantum well hole distribution profiles are shown respectively in figure 10. Since holes have a bigger mass and less mobility than electrons, the majority of them will be found in the quantum well close to the p-side. Graded InGaN barrier structure is found to promote carrier uniformity, and it is found that most recombination occurs in the last quantum well close to the p-region, which is situated in the blue region. As a result, the white light that is produced has a blue hue.

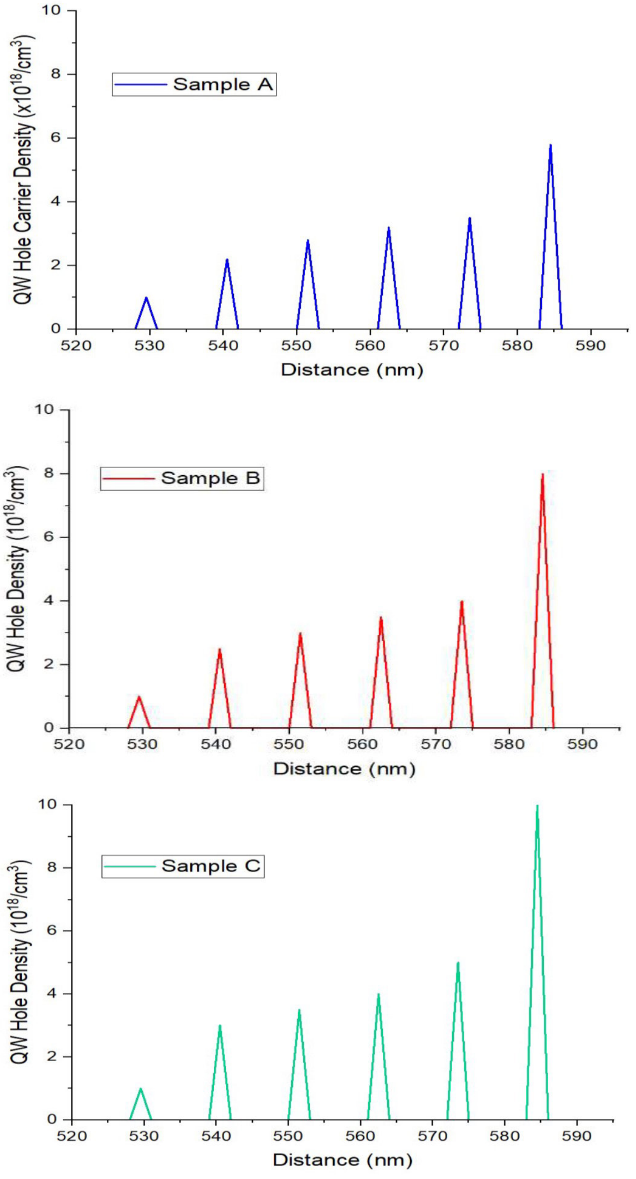

Figure 10: Quantum well hole distribution profile of sample A, B, and C of InGaN barrier MQW HP WLED.

Conclusion

For sample C, a MQW WLED structure utilizing a graded barrier, IQE and the light output power are increased, and the efficiency droop effect is minimized. This is because of the reduced lattice mismatch and improved uniformity in electron carrier density among the quantum wells. The resultant light has a bluish tint.

Acknowledgements

None.

Conflict of Interest

None.

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