Design and Simulation of Multiple Quantum well based InGaN/GaN Light Emitting Diode for High power applications

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Abstract **– The electrical and optical characteristics of InGaN/GaN based light emitting diodes (LEDs) having V-shaped, trapezoidal and U-shaped quantum well is simulated using TCAD Silvaco software. Comparison of different well shape is studied and simulation results shows that the device with V-shaped quantum well has superior performance in terms of Internal Quantum Efficiency of 80% and optical power of 120 mW for a maximum current of 200 mA when compared with U-shaped and trapezoidal well.**

Index Terms – InGaN/GaN, U-shaped well, Trapezoidal well, V-shaped well, Internal Quantum Efficiency.

I. Introduction

Gallium Nitride-based Light Emitting device (LEDs) were first introduced in early 1990s which replaces conventional incandescent and fluorescent lamps due to compact size, less power consumption and long lifetime [1-4]. Since then was the primary research area for many expertise. Gallium Nitride (GaN) based device was used in many fields like indoor and outdoor lightening's, display devices, printers and storage devices [5-10]. This work concentrates on some technological improvements in the shape of the quantum wells of GaN based LEDs. The efficiency of the device mainly depends on the Internal Quantum Efficiency (IQE) and the reason for reduction of IQE is mainly due to efficiency droop in the device. Many research group works on this efficiency droop analysis to enhance the efficiency of the GaN based device.

Efficiency droop is defined as the reduction in the IQE of the device when large injection current is applied [11]. At low current densities at 10 A cm^{-2}, the efficiency droop was not a major issue. However, the expanded applications of LED at high current density causes efficiency droop problem in the device. The efficiency droop can be suppressed by using many approaches. In recent works, the major contributor of efficiency droop is leakage current [12-16], Auger recombination [17-19], Carrier delocalization [20], [21] and low hole injection efficiency [22]. The leakage current can be reduced by introducing different techniques in band gap engineering. Double heterostructure, increasing the carrier density and Mg-doped very thin barriers are used to reduce the auger recombination, carrier delocalization and low hole injection efficiency respectively.

The possible way to improve the output power and to reduce the efficiency droop is the use of large overlap function of InGaN quantum wells by using U-shaped, trapezoidal V-shaped wells [23-30]. Commonly used quantum well shape in LED is Rectangular or U-shaped well in the $In_xGa_{1-x}N$/GaN active region, in which the molar fraction of indium (x) is maintained constant. Other structures like trapezoidal and V-shaped well is used for different applications.

In this paper, the comparison of U-shapes, trapezoidal and V-shaped well is simulated using TCAD (Technological Computer Aided Design) silvaco. The light emission performance, power, IV characteristics and internal quantum efficiency of the device is investigated.

II. LED device structure

A. Device Structures

The LED device consists of six layers namely, sapphire substrate layer, n-type GaN layer, undoped GaN layer, Multiple Quantum Well (MQW) layer, AlGaN based Electron Blocking layer (EBL) and p-type GaN layer. Firstly the LED structure is grown on c-plane sapphire substrate of 20µm. Secondly, n-type GaN layer is grown above the substrate with thickness of 3µm doped with concentration of Si dopants of $5x10^{18}$ cm^{-3}, followed with undoped GaN layer of thickness 15nm is placed above the n-type GaN layer to reduce lattice mismatch.

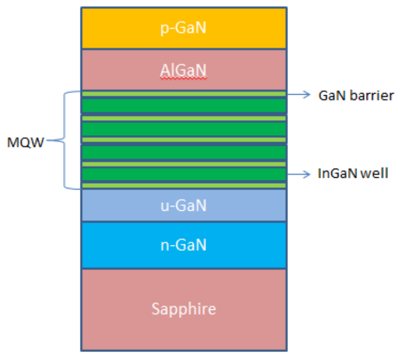

Fig. 1: Structure of MQW based LED device

Thirdly, the active region or MQW is composed of 5 InGaN based wells with thickness of 3nm is grown alternatively with 4 barriers of GaN with thickness of 12nm is grown. Fourthly, the AlGaN based EBL layer is grown with the thickness of 15nm. Finally, the device ends with p-type GaN layer with thickness of 25nm and it is doped with concentration of Mg dopants of $1\text{x}10^{20}$ cm^{-3}. The above figure 1 shows the structure of MQW based LED device.

The above LED is common for all the shapes of well, except the composition of indium content in the MQW well varies accordingly with the shape of the quantum well. The indium composition of U-shape is maintained constant for InGaN based quantum well. In trapezoidal shape well the molar concentration (x) of indium is gradually reduced and after some point it is maintained as constant in the well. In V-shaped well, the indium composition is reduced gradually and linearly to obtain V-shaped well.

B. *Numerical analysis*

Zhao *et al* [14] suggest the efficiency droop for different shapes of the well can be calculated using the below equation (1):

$$Droop = 1 - \frac{Efficiency_{200mA}}{Efficiency_{\max}} \quad (1)$$

Where $Efficiency_{200mA}$ is the efficiency produced at 200 mA injected input current.

$Efficiency_{\max}$ is the efficiency produced at maximum current.

Internal and external quantum efficiency of the device can be calculated by using the equation (2) & (3).

$$IQE = \frac{\text{Number of radiative recombination rate}}{\text{Sum of radiative \& non - radiative recombination rate}} \quad (2)$$

$$EQE = \frac{photons_{out}}{electrons_{in}} \quad (3)$$

III. Simulation Results and Discussion

The simulation is performed for the structure of MQW based device using TCAD Silvaco software. Here, the electrical and optical characteristic of three different shapes of well is studied by varying the indium composition of the active region.

The simulation result of fig 2 shows that the indium composition of V-shaped well shows higher wavelength emission compared to U-shaped and trapezoidal well. Here the wavelength emission is noted from the range of 380 nm to 520 nm. All three shapes of the well increase gradually and reaches the wavelength 520 nm, the indium composition obtained for V-shaped well, trapezoidal well and U-shaped well is 0.46, 0.40 and 0.23 respectively. From the figure it is evident that the V-shaped well produces peak emission wavelength compared with the other two shapes of well. Based on the wavelength, the indium composition of well is selected and used for respective application.

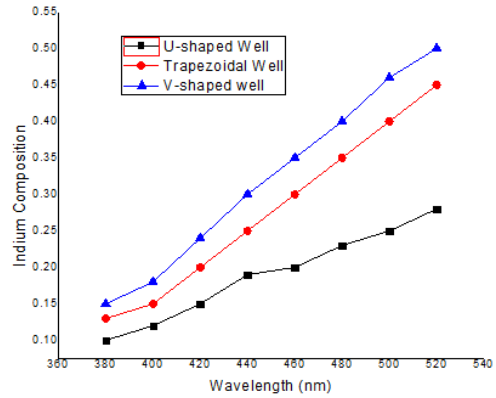

Fig. 2: Wavelength versus Indium composition for U-shape, Trapezoidal and V-shaped well

The injected current of V-shaped well is more power efficient than other two shapes of well. The power obtained for V-shaped well is 120 mW for the input current 200 mA, whereas for trapezoidal well the power obtained is 100 mW and for U-shaped well the power obtained is 35 mW. From the fig 3, it is clear that the device with V-shaped well produce maximum power.

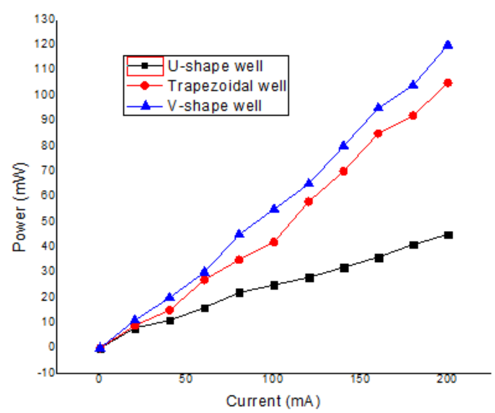

Fig. 3: Current versus Power for U-shape, Trapezoidal and V-shaped well

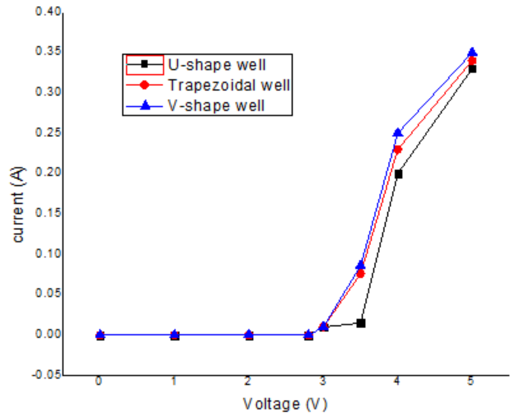

Fig. 4: Voltage versus current for U-shape, Trapezoidal and V-shaped well

Fig 4 shows the comparative analysis of voltage versus current of the InGaN/GaN based device for three different shapes of well. The cutoff voltage of V-shaped well starts early and increases gradually. Here, the simulation result shows till 5V and the V-shaped well gives better result than other two wells.

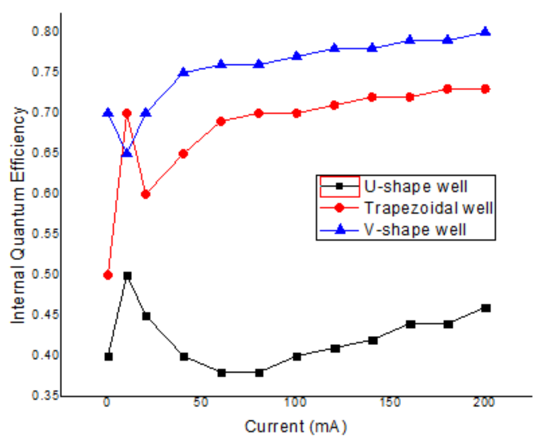

Fig 5: Current versus Internal Quantum efficiency for U-shape, Trapezoidal and V-shaped well

Initially, both the U-shaped and trapezoidal well increases upto 15 mA and then IQE start decreases gradually with respect to input current. The V-shaped well initially decreases and the curve follows the trapezoidal well with higher efficiency. From fig 5, it is evident that the V-shaped quantum well produces improved internal quantum efficiency, which in turn gives improved external quantum efficiency of the InGaN/GaN based device. This is mainly due to higher overlap of electron and hole wave function and also the fact that the V-shaped well has much stronger carrier localization than other two wells.

The comparison study of three different shapes of wells used in InGaN LED device are mentioned namely U-shaped, trapezoidal and V-shaped well is analyzed with the existing data's. The table 1 shows the comparison analysis of three wells of existing and proposed data.

TABLE I. COMPARISON OF EFFICIENCY FOR EXISTING AND PROPOSED DESIGN DATA

S.No.	wells	Existing efficiency	Proposed efficiency
1	V-shaped	0.76	0.79
2	Trapezoidal	0.69	0.69
3	U-shaped	0.45	0.47

IV. CONCLUSION

This paper shows the comparative performance of multiple quantum well based InGaN/GaN LED in the range of 380 to 520 nm having three different well shapes. The simulation results shows that the V-shaped well gives higher performance in terms of internal quantum efficiency and output power when compared with U-shaped and trapezoidal well. This improved internal quantum efficiency gives enhanced external quantum efficiency.

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