Luminous power improvement in InGaN V-Shaped Quantum Well LED using CSG on SiC Substrate

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Abstract. This paper presents the design and simulation of Silicon Carbide (SiC) based technology, Indium Gallium Nitride (InGaN) Multiple Quantum Well (MQW) Light-Emitting Diode (LED) with a Compositionally Step Graded (CSG) InGaN barrier and V-Shaped well in the active region. The simulations are obtained in Silvaco Computer Aided Design simulator and parameters such as Internal Quantum Efficiency (IQE) with respect to input current, spontaneous emission in regard to wavelength and power versus current in the device are theoretically studied. The CSG InGaN barrier LED with V-shaped quantum well shows substantial growth in output power when compared to the CSG GaN barrier structure with conventional MQW. The high carrier confinement in the V-shape well causes, transportation/injection of hole and change in band bending due to polarization effect. Moreover, lattice-matched SiC substrate over GaN material increases the InGaN V-shaped MQW LEDs radiative recombination rate which in turn leads to high output power. The optical luminous power of 160mW and 82% of peak IQE, emitting wavelength at 460 nm and 200mA of injection current is obtained for the proposed LED. The enactment of the V shape MQW CSG-InGaN device technology is a good alternative choice for commercial and industrial lighting applications.

1. Introduction
Among various semiconductor materials, III compound group Nitride materials plays a vital role in Nano scale lighting and display due to their tunable and direct energy bandgap from 0.7eV to 6.2eV [1]. GaN-based LEDs are mainly used in visible light communication, television display and mobile platforms. There are several factors which degrades the performance (in terms of emission efficiency) of the device mainly electron leakage [2]-[7], current crowding [8], auger recombination [9]-[11], poor injection of hole carrier [12], [13], polarization effect [14], [15] and defects [16]. Xuna Li et al. proposed a structure using P-type aluminium gallium nitride Electron Blocking Layer (EBL) to reduce the electron leakage which intern leads to less hole injection efficiency [17]. Yen et al. proposed n-type aluminium gallium nitride EBL structure which increases the output power, hole injection efficiency & photoelectric performance [18]-[20]. Due to strong electric field the position of electron and hole wave function in MQW may get change which leads to more time consumption for carrier recombination. Due to strong electric field the carriers, may spill out from the active region. To overcome this MQW technique is proposed [17]. This paper focuses comparison
of InGaN/GaN based LEDs with V-shape MQW and normal MQW with CSG barrier for the improvement of output power.

2. LED device structure parameters

2.1 Device Structure

The parameters of compositionally step graded InGaN MQW LED device in cross-sectional representation is given in Figure 1. The LED device is designed using undoped GaN buffer layer with 3 μm thickness and n-type GaN with 6 μm thickness. Then silicon concentration of about 5x10^{18} cm^{-3} is also used for the device design. Consecutively six period v-shaped MQW active region with InGaN materials are placed along SiC substrate. The quantum well comprises of 3 nm-thick (6 in number) In_{0.16}Ga_{0.84}N layer and quantum barrier consist of compositionally 18 nm-thick (6 in number) graded InGaN layers. A 3 nm thick p-Al_{0.2}Ga_{0.8}N Electron Blocking Layer (EBL) is present on the top of active region and a p-GaN capping layer with a Magnesium (Mg) concentration of 1x10^{19} cm^{-3}. The entire device is in rectangular shape with the chip size dimension of 300 μm x 300 μm.

![CSG-InGaN based LED Structure with V-shape MQW](image)

**Figure 1.** CSG-InGaN based LED Structure with V-shape MQW

2.2 Model expression

The ternary alloy of InGaN is expressed as

\[ E_g(In_{y}Ga_{1−y}N)=yE_g(InN)+(1−y)E_g(GaN)−1.4y(1−y) \] (1)
The AlGaN energy band gap is expressed by

$$E_g(Al_{y}Ga_{1-y}N) = yE_g(AlN) + (1-y)E_g(GaN) - 0.7y(1-y)$$

Recombinaion of electrons and holes takes place in active region of the device, which emits in the form of photon.

The integral of emitted photon at each point gives the spontaneous emission rate.

$$R_{sp\ active} = \int_0^\infty \rho_{sp}(\hbar\omega) d(\hbar\omega)$$

The total output power of LED device is determined by the following expression

$$P_{total}^p = \int_{active}^\infty \int_0^\infty R_{sp\ active}(\hbar\omega) d(\hbar\omega) dV$$

Where, $\hbar=h/2\Pi$, $h$ is the planck constant and $V$ is the total volume of MQW active region.

3. V-shape multiple quantum well

In recent times, optical and electrical properties are improved by observing the energy, and also the disruptions of interfacial strain facilitates the blue InGaN-based LED performance [21, 22]. Tomita et al. used an elevation angle annula dark field SEM transmission and atom sample tomography to confirm the presence of thin quantum wells in the slope of V-pit region, and Indium (In) concentrations and thickness were much lower than those of the flat region. The dislocations in the V-shaped pits serve as energy barriers for lateral charge transport [23]. In 2014, Kim et al. addressed the power of V-pit and their energy barrier from their facets orientation and revealed that higher V-pit energy barrier heights in InGaN quantum wells effectively overcomes non-radiative recombination at active region, thereby increasing the IQE [24]. Chan et al. used super lattice layers to control the V-pits nanoscale to attain the optimum V-pits size and high-efficiency InGaN/ GaN LEDs of blue wavelength [25].

4. Results and discussion

![Figure 2. Wavelength vs Spontaneous emission](image)
In figure 2, two sample devices with different wavelengths spontaneous emission rate is illustrated. From the obtained results, it is found that a maximum emission is occurring at 460 nm wavelength using V-shape MQW rather than normal MQW, which indicates that the LED emits lights in blue spectrum.

![IQE vs Current](image1.png)

**Figure 3. Current (mA) vs IQE (%)**

In figure 3, IQE versus current characteristics of the two sample are illustrated. At low injection current, all the samples show similar characteristics and the IQE peaks up to 80%. It is observed that IQE gradually decreases in a high injection current due to the efficient droop effect.

![Power vs Current](image2.png)

**Figure 4. Power (mW) vs Current (mA)**

The experimental IQE is valued from the wall plug efficiency ($\eta_p$) and is given by the expression
\[ \eta_P = \frac{P_{\text{out}}}{IV} = \eta_v \eta_{\text{extr}} \quad (5) \]

\[ \eta_{\text{extr}} = \frac{P_{\text{out}}}{IV} = \eta_{\text{int}} \eta_{\text{extr}} \quad (6) \]

Where - 
\( \eta_{\text{extr}} \) - optical extraction efficiency
\( \eta_v \) - voltage efficiency
\( \eta_{\text{int}} \) - internal quantum efficiency
\( V_g \) - bandgap voltage of the active layer

In figure 4, shows the optical luminous power and peak IQE obtained is 160 mW using V-shaped MQW since high electron reconfinement takes place in v-shape MQW rather than normal shape MQW which leads to high output power. Near to the p-contact concentration of the hole in the last quantum well is found to be maximum.

5. Conclusions
The simulated result of V-shape MQW based CSG InGaN barrier LED (sample B) is compared with conventional MQW based CSG InGaN barrier LED (sample A). From the results it can be concluded that sample A requires the light output power of 155 mW and 78% efficiency droop at 200 mA injection current. Where else sample B LED renders higher light output power of 160 mW, 82% of efficiency with at 200 mA injection current. Thus the proposed LED is more advantageous in lowering the overall light fixture cost which in turn reduces the consumption of energy in solid state lighting and visible light communication systems.

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