Optik 123 (2012) 1287–1292

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Optimization towards reduction of efficiency droop in blue GaN/InGaN based light emitting diodes

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ARTICLE INFO

Article history:
Received 8 March 2011
Accepted 26 July 2011

Keywords:
Light-emitting diodes (LEDs)
Multi-quantum-well (MQW)
Efficiency droop
GaN/InGaN

ABSTRACT

Light emitting diodes (LEDs) based on GaN/InGaN material suffer from efficiency droop at high current injection levels. We propose multiple quantum well (MQW) GaN/InGaN LEDs by optimizing the barrier thickness and high–low–high indium composition to reduce the efficiency droop. The simulation results reflect a significant improvement in the efficiency droop by using barrier width of 10 nm and high–low–high indium composition in MQW LED.

1. Introduction

In recent time, GaN/InGaN based LEDs have been commercialized for indoor and outdoor lighting and displays, however, they suffer from reduction in efficiency at relatively high injection current levels, which has been named as the "efficiency droop" [1]. The quantum efficiency reaches its peak at low current density and thereafter monotonically decreases for further increasing the drive current [2–4]. The radiative recombination rate and output power of the InGaN based LEDs are thus degraded accordingly [5]. Kim et al. [2] reported the effect of polarization field in the active region due to the lattice mismatch among InGaN well layers and GaN barrier layers of the MQWs, which causes inadequate confinement of electrons in the active region, and subsequently causes electron overflow to the p-type region leading to an efficiency droop.

In addition, it has also been reported that at relatively high current density, the carriers escape from indium localized states and recombine non-radiatively in high-density defect sites [6,7]. The dependence of the dislocation density and the well thickness on efficiency droop has also been reported as an explanation for electron overflow as a major cause of efficiency droop [8,9].

Recently, the effect of the Auger recombination at high injection current has been reported, which leads to the efficiency droop [10]. The reason to the essential Auger recombination presented may come from the unusual Auger coefficient of the GaN-based material, which varies from 1×10^{-34} to 5.37×10^{-28} cm^6/s obtained from experimental measurements and theoretical estimations [11]. A double-heterostructure has therefore been proposed as an active layer to solve the problem [2,6]. However, the origin of efficiency droop is still under debate.

One of the approaches to improve the overall efficiency of III-nitride Blue LED is to reduce the electron overflowing problem [12] by optimizing the blue LED structure. The III-nitride compound semiconductors require relatively large injection currents (for their operation due to lower hole concentration), higher series resistance and lower material gain, ultimately making the electron overflowing problem more serious than other compound semiconductors. At present, incorporation of electron blocking layer (EBL) [13] is known to be one of the most effective approaches in reducing this problem. Moreover, it plays an important role in filling the pits, which are initially caused by the lattice mismatch between GaN and the sapphire substrate. The subsequent strained InGaN–GaN MQW that is grown at relatively lower temperature (750 °C) would further intensify density and/or size of the emerging pits [14]. To improve the efficiency of MQW LEDs, EBL plays an important role in confining electrons effectively in the MQW region [12]. The p-type AlGaN EBL is usually used in blue LEDs to reduce the electron leakage current. However, the p-type AlGaN layer also retards the injection of holes, which leads to the degradation of efficiency at higher current level. Yen et al. [15] suggested to use n-type AlGaN layer below the active region and Kuo at al [16] suggested to use InGaN barrier instead of traditional GaN barrier for reduction of efficiency droop in InGaN/InGaN MQW LED.

In this paper, we have optimized an InGaN–GaN MQW blue LED structure for the reduction of efficiency droop at relatively higher current without using n-type AlGaN layer with the same

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doi:10.1016/j.ijleo.2011.07.061

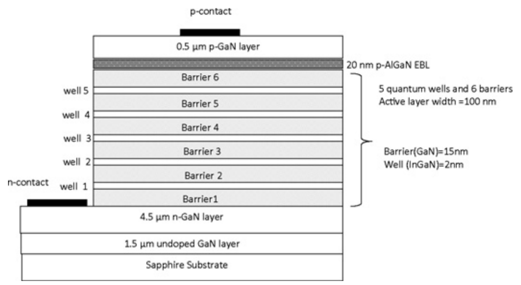

Fig. 1. Structure-A of LED.

structure that has been proposed by Yen et al. [15]. However, in this paper, we have considered a high–low–high indium composition in the quantum wells in order to further reduce the "efficiency droop" of the device, which is the uniqueness of the work. 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. Luminous efficiency of the device has also been estimated. Various recombination models like Auger, Shockley–Read–Hall optical and band-gap narrowing models have been incorporated to take into account effects due to composition variations. The Silvaco ATLAS TCAD simulator tool automatically calculates the polarization charges and includes in the calculations for corresponding region.

2. Structure and parameters

A typical InGaN/GaN based blue LED structure grown on a *c*-plane sapphire substrate, with a 1.5 μm-thick undoped GaN layer, and a 4.5 μm-thick n-GaN layer (n-doping = 5×10^{18} cm^{-3}) has been considered as a reference. The active region is consisting with five 2-nm thick undoped $In_{0.21}Ga_{0.79}N$ QWs sandwiched by six 15-nm thick undoped GaN barrier layers. On top of the active region, a 20-nm-thick p-$Al_{0.15}Ga_{0.85}N$ EBL (p-doping = 1.2×10^{18} cm^{-3}) and subsequently a 0.5-μm-thick p-GaN cap layer (p-doping = 1.2×10^{18} cm^{-3}) have been considered.

The band gap energies of $In_xGa_{1-x}N$ and $Al_xGa_{1-x}N$ ternary alloys can be expressed as [17]

$$\mathrm{Eg}(\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}) = x\mathrm{Eg}(\mathrm{InN}) + (1-x)\mathrm{Eg}(\mathrm{GaN}) - 3.8x(1-x) \quad (1)$$

$$\mathrm{Eg}(\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}) = x\mathrm{Eg}(\mathrm{AlN}) + (1-x)\mathrm{Eg}(\mathrm{GaN}) - 1.3x(1-x) \quad (2)$$

where Eg(InN), Eg(AlN), and Eg(GaN) are the band gap energies of InN, AlN, and GaN values determined as [6]:

$$\mathrm{Eg}(\mathrm{GaN}) = 3.507 - \frac{0.909x10^{-3}T^2}{T + 830.0} \quad (3)$$

$$\mathrm{Eg}(\mathrm{InN}) = 1.994 - \frac{0.245x10^{-3}T^2}{T + 624.0} \quad (4)$$

$$\mathrm{Eg}(\mathrm{AlN}) = 6.23 - \frac{1.799x10^{-3}T^2}{T + 1462.0} \quad (5)$$

Other material parameters of the relevant binary semiconductors used in the simulation can be found in [17]. The operating temperature is assumed to be 300 K. Fig. 1 shows the basic LED structure-A which has been simulated in this work, where the area of the device structure has been considered to be 300 μm × 300 μm.

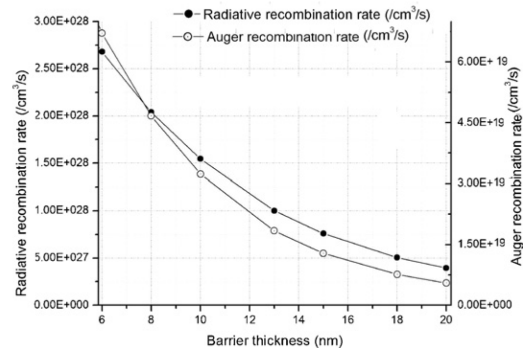

Fig. 2. Effect of barrier thickness on radiative recombination rate and Auger recombination rate.

3. Optimization of LED structure

3.1. Thickness of the active layer

The thickness of the active layer is one of the important parameters that needs to be optimized to achieve an efficient device performance. Thin MQWs within the active layer in LED structure drastically improves the carrier confinement in the active region. This also results in higher radiative recombination rates, thereby increasing the luminous intensity (i.e. luminescent power) of the device. Fig. 2 shows the variation of radiative recombination rate and auger recombination rate with the variation of barrier thickness, for a fixed well width of 2 nm.

There is an increase in radiative recombination rate with decrease in barrier thickness (keeping constant well-width). One reason can be explained that there is an improved electron concentration in quantum well adjacent to p-layer due to higher tunneling probability (inherent to thinner barrier). In addition to this, a major portion of hole-density states is available in this well (due to hole's lower mobility compared to that of electron), which provides an improved radiative recombination rate and luminescent power.

However, very narrow QW would cause reduction in capture rates. For thinner quantum well, quantized states are shifted upwards from bottom of the conduction band and only a few states are available as bound ones, causing a decrease in the carrier capture rate from continuum states into bound states. Whereas, a thicker well may have more bound states having an increased carrier capture rate [18]. At the same time, a significant recombination would occur outside the active region. Auger recombination rate are also increased for thin barrier as shown in Fig. 2. However, to improve the internal quantum efficiency, the non-radiative recombination processes such as SRH and Auger recombination rates should be minimized. Therefore, a trade-off is needed to reduce the non-radiative carrier losses and at the same time, to enhance the injection efficiency. Accordingly, the barrier thickness should be optimized in order to minimize the non-radiative recombination processes and to maximize the luminescent power.

Therefore, as per above discussion, for simulation, we have chosen an optimum active layer thickness of 70 nm having five quantum wells and six barriers with well thickness of 2 nm and barrier thickness of 10 nm.

3.2. Effect of indium composition

The band gap of InGaN varies from ∼0.7 eV (InN) to ∼3.4 eV (GaN) depending upon the Indium composition. Therefore, the wavelength of emission, governed by the equation, $\lambda = 1.24/E_g$, can be extended in region from ultraviolet/blue to the green region of