Superlattices and Microstructures 113 (2018) 585–591

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Efficiency improvement of green light-emitting diodes by employing all-quaternary active region and electron-blocking layer

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ARTICLE INFO

Article history:
Received 29 August 2017
Received in revised form 21 November 2017
Accepted 23 November 2017
Available online 24 November 2017

ABSTRACT

High efficiency of green GaAlInN-based light-emitting diode (LED) has been proposed with peak emission wavelength of ~510 nm. By introducing quaternary quantum well (QW) along with the quaternary barrier (QB) and quaternary electron blocking layer (EBL) in a single structure, an efficiency droop reduction of up to 29% has been achieved in comparison to the conventional GaN-based LED. The proposed structure has significantly reduced electrostatic field in the active region. As a result, carrier leakage has been minimized and spontaneous emission rate has been doubled.

1. Introduction

Gallium Nitride (GaN)-based materials have revolutionized solid state lighting due to their exceptional optoelectronic properties in the visible range of electromagnetic spectrum [1]. Despite great advancement in the development of GaN-based light-emitting diodes (LEDs), efficient LEDs in green wavelength range are still a challenge and this challenge is commonly known as 'green-gap'. In the longer wavelength emission regime *i.e*. green and beyond, internal quantum efficiency (IQE) is seriously affected essentially due to high In-content in the active region. Such high In-content results in increased strain in the active region due to increased lattice mismatch between the epilayers causing large piezoelectric fields of the order of ~MV/cm within the active region [2]. Such a high built-in field causes quantum confined Stark effect (QCSE) which reduces the overlap of electron and hole wave fuctions because of the tilted conduction and valance bands [3]. As a result, the optoelectronic performance of Indium Gallium Nitride (InGaN)-based green LEDs is significantly affected by the strong built-in field in the active region [4]. Many solutions have been proposed to mitigate the strong effect of built-in field including the insertion of Aluminum Gallium Indium Nitride (AlGaInN) as a polarization-matched layer between the active region and the electron blocking layer (EBL) [5]. Mostly AlGaN is used as EBL in InGaN-based LEDs because of the increased effective barrier height of the EBL to reduce the overflow of electrons from the active region. This EBL results in poor hole transport because of higher effective mass of holes and increased polarization-induced downward band-bending between last quantum barrier (QB) and EBL [5–7]. To mitigate this problem, many possible designs of EBL have been suggested *e.g*. AlGaN/GaN/AlGaN composed EBL [8], graded composition EBL [9] and polarization-matched quaternary AlGaInN EBL [10] etc.

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https://doi.org/10.1016/j.spmi.2017.11.046
0749-6036/

In this work, we have proposed a numerical solution for the improvement in the IQE of InGaN-based conventional green LEDs by replacing the conventional InGaN QW, GaN barrier and AlGaN EBL with GaAlInN QW, GaAlInN barrier and GaAlInN EBL respectively. IQE of the proposed structure has been found to be significantly improved because of the improved lattice match and polarization-match between the epilayers. The proposed design improves the effective barrier height for electrons in the conduction band and reduces the effective barrier height for holes in the valence band between the last quantum barrier and the EBL resulting in improved carrier recombination in the last QW of the proposed structure. However, the overall hole distribution in case of the proposed all-quaternary LED is not uniform as compared to the conventional LED. Nonetheless, the IQE of the proposed LED is significantly better than the conventional LED.

2. Device structure

Two different LED structures have been used in this work. One is the conventional InGaN-based LED structure having 30% Indium-content *i.e.* $In_{0.30}GaN$ in the QW layers for the emission in green wavelength *i.e.* ~515 nm. Thickness of each QW layer is 0.0025 μm. Each QW is separated by two GaN barriers having thickness of 0.01 μm each. On top of the active region, $Al_{0.1}GaN$ EBL having thickness of 0.02 μm with p-doping of 5×10^{17} cm^{-3} is followed by p-GaN layer having thickness of 0.15 μm and p-doping of 1×10^{18} cm^{-3}. Below the active region, n-type GaN layer of thickness 2 μm and having n-doping of 5×10^{18} cm^{-3} has been employed. This is shown in Fig. 1(a). Fig. 1(b) shows the second LED structure which is the proposed all-quaternary structure comprising of quaternary well, quaternary barrier and quaternary EBL in contrast to the conventional InGaN well, GaN barrier and AlGaN EBL respectively. Quaternary QW layer has thickness of 0.0025 μm. The QW layer composition is $Ga_{0.66}Al_{0.07}In_{0.27}N$, which is separated by two $Ga_{0.75}Al_{0.15}In_{0.10}N$ barriers having thickness of 0.01 μm each. On top of the active region, p-doped $Ga_{0.65}Al_{0.20}In_{0.15}N$ electron blocking layer (EBL) having thickness of 0.02 μm and doping concentration of 5×10^{17} cm^{-3} is followed by p-GaN layer having thickness of 0.15 μm and p-doping of 1×10^{18} cm^{-3}. Below the active region, n-type GaN layer of thickness 2 μm and having n-doping of 5×10^{18} cm^{-3} has been employed. Shockley-Read-Hall (SRH) recombination coefficient is 2×10^{7} s^{-1} whereas Auger recombination coefficient is 5×10^{-31} cm^6/s. The

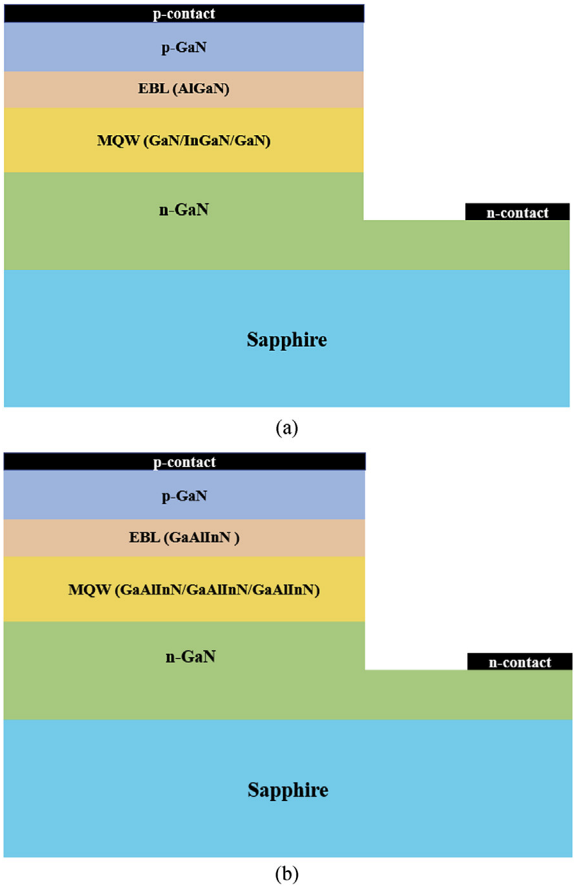

Fig. 1. Schematic of green (a) conventional InGaN-based LED (b) proposed all-quaternary LED. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)