Superlattices and Microstructures 104 (2017) 19–23

Contents lists available at ScienceDirect

Superlattices and Microstructures

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

High efficiency improvements in AlGaN-based ultraviolet light-emitting diodes with specially designed AlGaN superlattice hole and electron blocking layers

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A R T I C L E I N F O

Article history:
Received 31 December 2016
Accepted 30 January 2017
Available online 31 January 2017

Keywords:
AlGaN
UVLED
Graded superlattice hole blocking layers
Graded superlattice electron blocking layers
IQE

A B S T R A C T

$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ graded superlattice hole blocking layers (GSL-HBLs) and $Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ graded superlattice electron blocking layers (GSL-EBLs) are applied to the traditional AlGaN-based ultraviolet light-emitting diodes (UVLEDs). This can obtain much higher internal quantum efficiency (IQE) and output power. In order to reveal the underlying physical mechanism of this unique structure, we have studied it numerically by APSYS simulation programs. We find that GSL-EBLs can obviously increase the electron potential height and reduce the hole potential height, produce less electron leakage and more hole injection, leading to higher carrier contration. GSL-HBLs can obviously reduce the hole leakage, reduce the thermal velocity and correspondingly the mean free path of the hot electrons, and increase the electron injection. This enhanced the electron capture efficiency of the multiple quantum wells, which can also help to reduce electron leakage.

1. Introduction

Compared to traditional uv-light sources (e.g. mercury lamp andxenon lamp), the AlGaN-based ultraviolet light-emitting diodes (UV-LEDs) have many advantages such as no mercury pollution, the wavelength controlled, small volume, low power consumption, long service life and so on. Furthermore, in terms of UV curing polymer, surface disinfection, UV medical treatment, high-density optical data storage, and other fields, the ultraviolet light-emitting diodes (UV-LEDs) have a broad application prospect and huge market demand [1–3]. So, the development of UV-LEDs based on AlGaN materials have attracted more and more researchers' considerable attention. However, the internal quantum efficiency (IQE) and emission power of UV-LEDs are relatively low [4]. The direct reasons are poor hole injection efficiency, the electron leakage [5] and the hole leakage due to lattice mismatch [6,7] and high dislocation density [8] in high Al-content AlGaN UVLEDs. The separation of the wave function caused by the spontaneous piezoelectric polarization [9] and large built-in electric field [10] is also the important reason. Furthermore, the heavy P-doping in high Al-content AlGaN material is also a challenge about hole injection [11], which can remedy the inefficient carrier movement in active region. In order to solve these existing problems, the researchers have done a lot of work, such as double electron blocking layers [12,13], AlGaN/GaN superlattice EBL of gradual Al

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http://dx.doi.org/10.1016/j.spmi.2017.01.042
0749-6036/

mole fraction [14,15], graded electron blocking layer (EBL) [16], n-AlGaN hole blocking layer [17], n-type AlGaN electron blocking layer [18] and hole reservoir layer [19,20] and so on. Among them, Zhang et al. inserted an n-$Al_{0.6}Ga_{0.4}N$ layer between the n-$Al_{0.55}Ga_{0.45}N$ layer and the first barrier, since n-AlGaN layer can not only prevent holes from overflowing into the n-side region but also act as another electron source, providing more electrons, the output power and the IQE of the proposed LEDs are improved [12]. Fan proposed and investigated the AlGaN-based deep ultraviolet light-emitting diodes with inverted-V-shaped graded Al composition electron blocking layer, on account of the sufficient electronbarrier height and relatively higher hole injection efficiency which results from the mitigated band-bending [16]. But compared to mature blue light-emitting diodes based on GaN materials, there is still a lot of room for improving UV-LEDs' luminous power and efficiency.

Based on the discussion above, we find that, in blue LEDs, multifarious superlattices electron blocking layer is really helpful for the enhancement of hole injection efficiency and the suppression of electron leakage. So in the process of improving the efficiency of UV-LED, we can get inspiration from mature blue LED technology. In combination with the effect of n-type hole blocking layer, we insert $Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ graded superlattice hole blocking layers (GSL-HBLs) with gradually decreasing Al composition toward the n-type AlGaN layer and $Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ graded superlattice electron blocking layers (GSL-EBLs) with gradually decreasing Al composition toward the p-type AlGaN layer into the traditional AlGaN-based ultraviolet light-emitting diodes (UVLEDs). Compared to above reference [12,16], the improved structure has obvious advantages in carrier concentration, output-power, IQE and radiative recombination rates. The next is the detailed structures and results and discussion.

2. Simulation structure and parameters

The conventional UV-LED employed as the reference (denoted as structure A), as shown in Fig. 1, is designed to be grown on a c-plane sapphire substrate, a 3-μm-thick n-doped $Al_{0.55}Ga_{0.45}N$ layer (n-doping $2 \times 10^{18} cm^{-3}$) is firstly deposited. The active region consists of six 10-nm-thick undoped $Al_{0.55}Ga_{0.45}N$ barriers with five 2-nm thick undoped $Al_{0.45}Ga_{0.55}N$ QWs. Over the active region, the structure A consists of a 10-nm-thick Mg-doped $Al_{0.6}Ga_{0.4}N$ EBL (p-doping $= 1 \times 10^{19}$ cm^{-3}), a 10-nm-thick Mg-doped $Al_{0.55}Ga_{0.45}N$ layer (p-doping $= 1 \times 10^{19}$ cm^{-3}), and a 100-nm-thick Mg-doped GaN cap layer (p-doping $= 3 \times 10^{19}$ cm^{-3}). The device geometry is designed to be a rectangular shape of 300×300 μm^2. As a reference, we also simulated the structure of Zhang's [12] (denoted as structure B). In this study, we propose four new structures with various EBL structures—5-period n-$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ GSL-HBLs (x varies from 0.65 to 0.61) with gradually decreasing Al composition toward the active layer and p-$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ GSL-EBLs (x varies from 0.65 to 0.61) with gradually decreasing Al composition toward the p-type AlGaN layer, 5-period n-$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ GSL-HBLs (x varies from 0.61 to 0.65) with gradually increasing Al composition toward the active layer and p-$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ GSL-EBLs (x varies from 0.61 to 0.65) with gradually increasing Al composition toward the p-type AlGaN layer, 5-period n-$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ GSL-HBLs (x varies from 0.65 to 0.61) with gradually decreasing Al composition toward the active layer and p-$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ GSL-EBLs (x varies from 0.61 to 0.65) with gradually increasing Al composition toward the p-type AlGaN layer, 5-period n-$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ GSL-HBLs (x varies from 0.61 to 0.65) with gradually increasing Al composition toward the active layer and p-$Al_xGa_{1-x}N/Al_{0.6}Ga_{0.4}N$ GSL-EBLs (x varies from 0.65 to 0.61) with gradually decreasing Al composition toward the p-type AlGaN layer, denoted as structure C, D, E, F, respectively, as schematically shown in Fig. 1. They were simulated by using the Advance Physical Model of Semiconductor Devices (APSYS) simulator. In this simulation, in order to close to the experimental results, the operating temperature is set to be 300 K [21]. The Shockley-Read-Hall (SRH) lifetime is set to be 5 ns [22]. The band-offset ratio (ΔEc/Ev) of AlGaN-based LED is assumed to be 0.7/0.3 [23]. The internal loss is $2000 m^{-1}$ [24], and the Auger recombination coefficient is set to be 1×10^{-30} cm^6 s^{-1}. Furthermore, in consideration of the screening by defects, the surface charges densities are set to be 40% [25]. Other detailed material parameters of semiconductors adopted in our simulation can be found in Ref. [26].

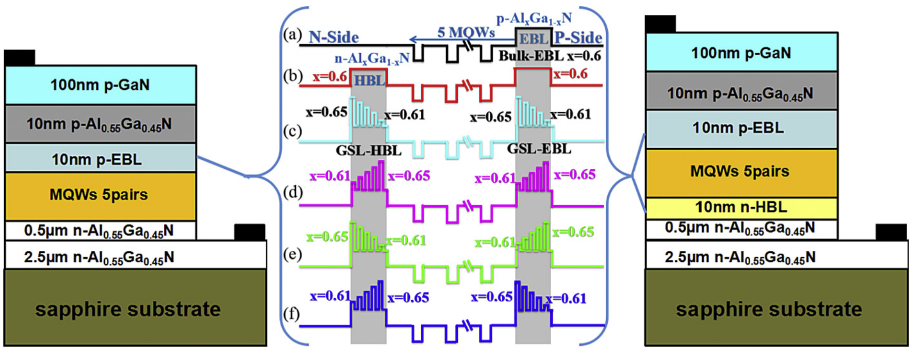

Fig. 1. Schematic diagrams of six structures.