Superlattices and Microstructures 88 (2015) 467–473

Contents lists available at ScienceDirect

Superlattices and Microstructures

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

Efficiency improvements in AlGaN-based deep ultraviolet light-emitting diodes using inverted-V-shaped graded Al composition electron blocking layer

Xuancong Fan, Huiqing Sun*, Xuna Li, Hao Sun, Cheng Zhang, Zhuding Zhang, Zhiyou Guo

Laboratory of Nanophotonic Functional Material and Devices, Institute of Optoelectronic Materials and Technology, South China Normal University, Guangzhou 510631, China

ARTICLE INFO

Article history:
Received 8 July 2015
Received in revised form 29 September 2015
Accepted 1 October 2015
Available online 8 October 2015

Keywords:
Electron blocking layer
Deep ultraviolet light-emitting diodes
AlGaN

ABSTRACT

This paper principally presents the numerical investigation of electron blocking layers (EBL) structures with different Al concentration gradient changing in AlGaN-based deep ultraviolet light emitting diodes (DUV-LEDs). Compared to conventional EBL structure with constant Al composition, the LED with inverted-V-shaped EBL structure has higher output power and carriers recombination rate, but the efficiency droop will decrease obviously while the electron leakage current can reduce much as well. Therefore, the result indicates that appropriate Al component in LED can enhance electron and hole recombination rate in the active region. The improved performance is mainly attribute the sufficient electron-barrier height and relatively higher hole injection efficiency which results from the mitigated band-bending.

1. Introduction

In recent years, InGaN-based brightness visible light-emitting diodes (LEDs) have made considerable headway, and deep ultraviolet light-emitting diodes (DUV-LEDs) based on high Al content AlGaN materials have been taken notice due to their excellent performance in water purification, surface sterilization, medical applications and non-line-of-sight communications [1–3]. However, it is still low in the luminous intensity and external quantum efficiency (EQE) of DUV-LED under high current injection [4]. The EQEs of reported AlGaN-based DUV-LEDs with emission wavelengths below 350 nm are about 10%, which are much less than InGaN-based near UV and visible LEDs whose EQEs have already reached 70% [5,6]. A great number of reasons are reliable for the low efficiency as follows. First of all, the small band offset between quantum wells (QWs) and quantum barriers (QBs) cause limited hole and electron recombination in the active region [7]. Secondly, Auger recombination and carrier delocalization were improved for the low efficiency [8,9]. Furthermore, the strong electrical field caused by spontaneous and piezoelectric polarization makes the band diagrams titled and reduces the overlap of electron and hole wave functions [2,10]. In order to overcome the problems mentioned before, various approaches have been proposed to improve EQE. Zhang inserted a thin p-AlGaN layer between EBL and the last barrier of the MQWs, which made the result in a diminished electron leakage overflow and improved the output power of the device [11]. Un-doped AlGaN electron blocking

* Corresponding author.
E-mail address: sunhq@scnu.edu.cn (H. Sun).

http://dx.doi.org/10.1016/j.spmi.2015.10.003
0749-6036/

layer was introduced by Lin can promote photoluminescence and electroluminescence characteristics of LED [12]. Hirayama put forward multiquantum-barrier (MQB) electron-blocking layers to enhance EQE [13]. Staggered QWs and QBs were proposed and the property was excellent as well [14,15]. Huang verified that n-doped barrier can strengthen light output power of UV-LED because of the shielded polarization field [16]. Frank et al. investigated AlN/$Al_{0.7}Ga_{0.3}N$ electron blocking heterostructures and got high EQE due to its low parasitic luminescence [17]. Piprek et al. demonstrated that the graded Al composition in EBL have a significant impact on electron blocking effect since appropriate aluminum concentration gradient can decrease the polarization filed [18–21].

In this work, we investigated AlGaN-based DUV-LED of conventional EBL structure with constant Al composition and designed EBL structures with decreasing/V-shaped/inverted-V-shaped grading Al component specifically. For the purpose of figuring out the mechanisms of the improvement of optical and electrical properties, The output power, internal quantum efficiency, energy band diagrams, electron and hole concentrations, electron current density, electrostatic field, radiative recombination rate and spontaneous emission are numerically investigated. The results indicate that the band bending in inverted-V-shaped LED is dramatically alleviated, and thus increase electron blocking effect, reduce the electron leakage and intensify luminous efficiency.

2. Structures and numerical parameters

The conventional structure UV LED used as reference grown on a c-plane sapphire substrate consists of a 3-μm-thick n-$Al_{0.55}Ga_{0.45}N$ layer (Si doping = 5×10^{18} cm^{-3}), an active region including five 2-nm-thick $Al_{0.45}Ga_{0.55}N$ wells separated by six 10-nm-thick n-$Al_{0.55}Ga_{0.45}N$ barriers (Si doping = 5×10^{17} cm^{-3}), a 20-nm-thick p-$Al_{0.6}GaN_{0.4}N$ EBL (Mg doping = 3×10^{18} cm^{-3}), and a 100-nm-thick p-GaN layer (Mg doping = 5×10^{18} cm^{-3}). The size of the device is 300 μm × 300 μm. In order to fabricate an LED with small droop efficiency and high power. Various structures by adjusting Al composition in EBL have been proposed to obtain the optimal result. In structure A, the Al content increase linearly from 0.55 to 0.6. In structure B, the Al content in $Al_xGa_{1-x}N$ EBL is V-shaped graded from 0.6 to 0.55 and back to 0.6 along the vertical direction. In structure C, the aluminum content of $Al_xGa_{1-x}N$ EBL is inverted-V-shaped graded from 0.55 to 0.6 and back to 0.55 in the growth direction. The schematic diagram are shown in Fig. 1. We use APSYS simulation program developed by Crosslight Software Inc. to investigate the influence of Al composition in $Al_xGa_{1-x}N$ EBL on the performance of DUV-LEDs. This program can get LED physic properties by means of using Poisson's equation, carrier transport equations, current continuity equations, photon rate equation and quantum mechanical wave equation.

The band gap energy of AlGaN can be expressed as [22].

$$E_g(Al_xGa_{1-x}N) = xE_g(AlN) + (1-x)E_g(GaN) - 0.7x(1-x)$$

where $E_g(AlN)$,$E_g(GaN)$ are the bandgap energies of AlN and GaN, which equal to 6.25 eV and 3.42 eV.

The spontaneous and piezoelectric polarization is a critical effect for nitride-based optoelectronic devices. The built-in polarization causes a separation between electrons and holes, which leads to a reduction in the photo emission rate. The spontaneous polarization of $Al_xGa_{1-x}N$ can be expressed to second order in the composition parameter x as:

$$P_{sp}(Al_xGa_{1-x}N) = -0.090x - 0.034x(1-x) + 0.019x(1-x)$$

Strain-dependent piezoelectric polarization of $Al_xGa_{1-x}N$ can be calculated as:

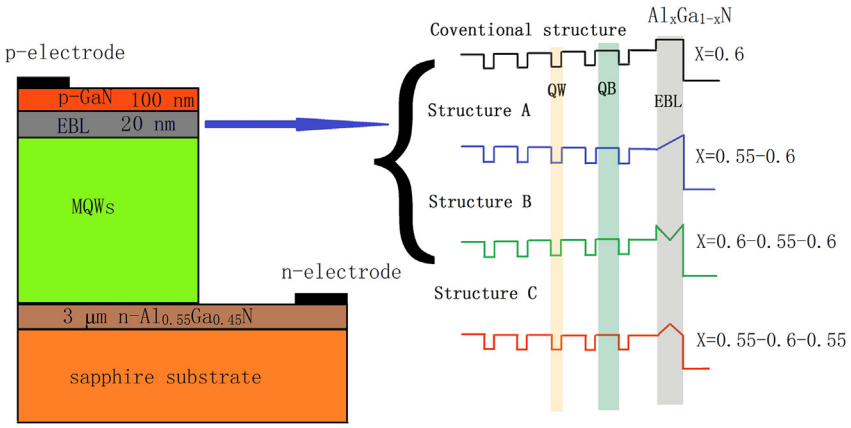

Fig. 1. The schematic diagram of conventional structure and structure A, B and C.