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Special AlGaN graded superlattice hole and electron blocking layers improved performance of AlGaN-based ultraviolet light-emitting diodes

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ABSTRACT

In order to improve the electrical and optical performance of ultraviolet light emitting diodes (UV-LEDs), $Al_{0.65}Ga_{0.35}N/Al_xGa_{1-x}N$ graded superlattice hole blocking layers (GS-HBLs) and $Al_{0.65}Ga_{0.35}N/Al_xGa_{1-x}N$ graded superlattice electron blocking layers (GS-EBLs) are applied to the traditional AlGaN-based UV-LEDs. Compared to conventional structure, our new structure can obtain much higher internal quantum efficiency (IQE), output power and lower efficiency droop. In order to reveal the underlying physical mechanism of this unique structure, we have studied it numerically by the Advance Physical Model of Semiconductor Devices (APSYS) simulator. We find that GS-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 carriers concentration. GS-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 and improve recombination rate and IQE.

1. Introduction

AlGaN semiconductor materials have wide direct band gap, and the forbidden band width is adjustable continuously from 3.4 to 6.2 eV, this makes the light response cover from near ultraviolet (UVA) wavelengths to deep ultraviolet (UVA) wavelengths. In addition, AlGaN semiconductor materials have high heat conductivity, high electron saturation rate, high breakdown voltage, low dielectric constant, resistance to radiation, stable physical and chemical properties, and many other excellent performance. So it becomes the irreplaceable semiconductor materials of ultraviolet and deep ultraviolet light-emitting diodes (LEDs), laser diodes (LDs) and Photo detectors (PD) and other optoelectronic devices [1,2]. Compared to traditional uv-light sources (e.g. mercury lamp and xenon lamp), UV-LEDs have many advantages such as no mercury pollution, the wavelength controlled, small volume, low power consumption, long service life and so on. In terms of high color rendering index of white light illumination, anti-counterfeiting recognition, UV curing polymer, surface disinfection, water and air purification, UV medical treatment, high-density optical data storage, and other fields have a broad application prospect and huge market demand [3–5]. 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 [6]. The direct reasons are poor hole injection efficiency, the electron leakage [7] and the hole leakage due to lattice mismatch [8,9] and high dislocation density [10] in high Al-content AlGaN UV-LEDs. The separation of the wave function caused by the spontaneous piezoelectric polarization [11] and large built-in electric field [12] is also the important reason. Furthermore, the heavy P-doping in high Al-content AlGaN material is also a challenge about hole injection [13], 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 [14,15], luminescence properties of Eu^{3+} and Sm^{3+} coactivated Gd (III) tungstate phosphor for light-emitting diodes [16], green light emission by Ce^{3+} and Tb^{3+} co-doped $Sr_3MgSi_2O_8$ phosphors for potential application in ultraviolet white light emitting diodes [17], Photoluminescence properties of novel red-emitting $NaSrBO_3:Eu^{3+}$ phosphor for near-UV light-emitting diodes [18], AlGaN/GaN superlattice EBL of gradual Al mole fraction [19,20], graded electron blocking layer (EBL) [21], n-AlGaN hole blocking layer [22], InGaN/AlInN/InGaN composition-graded barriers [23],

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AlGaN superlattice hole and electron blocking layers [24], n-type AlGaN electron blocking layer [25] and hole reservoir layer [26,27] 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 [14]. 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 electron barrier height and relatively higher hole injection efficiency which results from the mitigated band-bending [21]. 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 $Al_{0.65}Ga_{0.35}N/Al_xGa_{1-x}N$ graded superlattice hole blocking layers (GS-HBLs) with gradually decreasing Al composition toward the n-type AlGaN layer and $Al_{0.65}Ga_{0.35}N/Al_xGa_{1-x}N$ graded superlattice electron blocking layers (GS-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 Refs. [14,21], 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 2×10^{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 $Al_{0.65}Ga_{0.35}N$ EBL (p-doping = 1×10^{19} cm^{-3}), a 10-nm-thick Mg-doped $Al_{0.55}Ga_{0.45}N$ layer (p-doping = 1×10^{19} cm^{-3}), and a 100-nm-thick Mg-doped GaN cap layer (p-doping = 3×10^{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 [14] (denoted as structure B). In this study, we propose a new structure (denoted as structure C) with special AlGaN superlattice hole and electron blocking layers–5-period n-$Al_{0.65}Ga_{0.35}N/Al_xGa_{1-x}N$ GS-HBLs (x varies from 0.60 to 0.64) with gradually increasing Al composition toward the active layer and p-$Al_{0.65}Ga_{0.35}N/Al_xGa_{1-x}N$ GS-EBLs (x varies from 0.64 to 0.60) with gradually decreasing Al composition toward the p-type AlGaN layer, as schematically shown in Fig. 1. They were simulated by using the APSYS simulator. In this simulation, in order to close to the experimental results, the operating temperature is set to be 300 K [28]. The Shockley-Read-Hall (SRH) lifetime is set to be 5 ns [29]. The band-offset ratio (ΔEc/Ev) of AlGaN-based LED is assumed to be 0.7/0.3. [30] The internal loss is 2000 m^{-1} [31], and the Auger recombination coefficient is set to be 1×10^{-30} $cm^6 \cdot s^{-1}$. Furthermore, in consideration of the screening by defects, the surface charges densities are set to be 40% [32]. Other detailed material parameters of semiconductors adopted in our simulation can be found in Ref. [33].

3. Simulation results and discussion

The basic properties were plotted in the Fig. 2. The diagrams have plotted the simulation results of three different structures including total output power and IQE. Fig. 2(a) has showed the total output power. Three structures grew linearly along the current with different speeds, and reached 19.56 mW, 22.39 mW, 60.03 mW respectively for structure A, B and C at 180 mA. Compared with the reference structure A and B, it is obvious that the light output power of our new structure enhanced markedly, which could be attributed to the improved IQE as depicted in Fig. 2(b). We can see that the IQE of our new structure shows a remarkable enhancement, which means more carriers are consumed in the active region. The IQE of structure C reached the maximum value of 77.82% at current of 162 mA, which is increased by 137% and 105% as compared with the maximum value of the sample A and B. As the efficiency droop is formulated as [IQE(max) − IQE(180 mA)]/IQE(max). We also calculated the three samples' efficiency droop, they were 23.06% for sample A, 23.76% for sample B and 0.44% for sample C. Obviously, sample C had the lowest droop just as the presentation in Fig. 2(b). The mechanism of these improvements will be discussed later.

For a GaN based LED structure, the electron leakage and poor hole injection efficiency are believed to be the major causes of low IQE, low emission power and high efficiency droop. In order to study the advancement of the special AlGaN superlattice hole and electron blocking layers in LED, the energy band diagrams of three samples have been investigated. As shown in Fig. 3, the effective potential height of the electron in the conduction band (D/e) of conventional structure A, structure B and C are 287.8 meV, 284.7 meV and 533.9 meV, respectively. Ulteriorly, the effective potential height of the hole in the valence band (D/h) are 264.2 meV, 264.3 meV and 220.1 meV, respectively for conventional structure A, structure B and C. Compared with the conventional structure A and reference B, we can find that our new structure has significant enhancements. So the electrons would flow to the p-side more

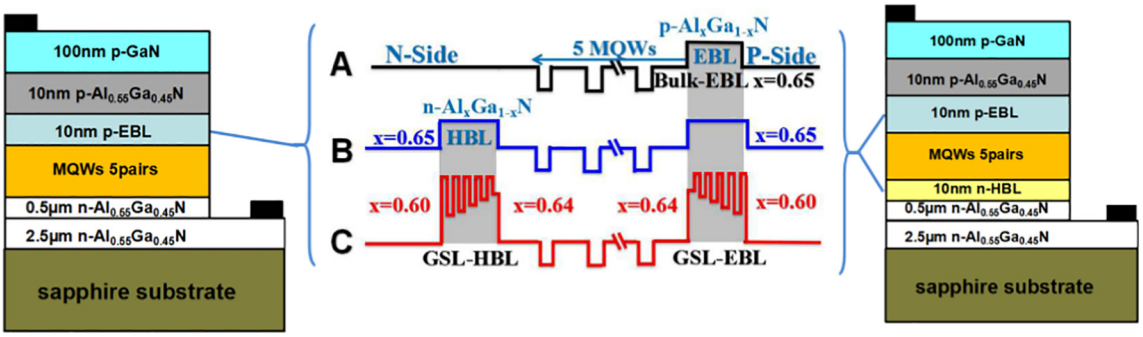

Fig. 1. Schematic diagrams of three structures.