Upping the internal quantum efficiency of green light-emitting diodes by employing a graded AlGaN barrier and an electron blocking layer

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Abstract
Two different device structures are numerically studied, and their optoelectronic characteristics with standard structure are compared. The authors minimized the uneven carrier distribution across the active region. By replacing the first quantum barrier with graded AlGaN and using a graded AlGaN electron blocking layer in the structure proposed by the authors, the injection of holes into the active region is improved. By using the graded AlGaN barrier, the concentration of injected electrons is also controlled because of the additional barrier height. As a result, the contribution of radiative recombination is boosted. The droop ratio of the proposed structure is reduced to ~34% at 100 A cm⁻² in comparison to other devices.

1 | INTRODUCTION

In the early 1990s, the invention of gallium nitride (GaN)-based blue light-emitting diodes (LEDs) revolutionised the technology of solid-state lighting [1,2]. In conventional white light sources, a significant amount of electrical energy is wasted in interconversion phases for the production of white light [3]. These energy losses can be minimised by the replacement of conventional light sources with LEDs. The production of white light by colour mixing of primary additive colours that is red, green and blue is energy efficient and eco-friendly as compared to fluorescence-based technology [4]. But the dominant problem in the successful replacement of conventional white light sources with GaN-based LEDs is the renowned green gap challenge [5]. The internal quantum efficiency (IQE) of green GaN-based LEDs is distinctly low as compared to red and blue LEDs [6–8]. In GaN-based LEDs, the InGaN/GaN layer is commonly used as an active layer [9]. For the emission of green light, a high composition of indium is required in the InGaN layer [10,11]. The high composition of indium in the active layer has a major degradation role in the efficiency of green GaN-based LEDs [12–14]. Myriad reasons are reported behind the degradation of IQE. Some of the key issues are high piezoelectric field [14–16], Auger non-radiative recombination [17,18], uneven distribution of carriers (electrons and holes) [11], asymmetric injection and transport of carriers in the active region [19], overflow/leakage of electrons from the active region [20] and the presence of defects in materials leading to non-radiative recombination [21]. Various approaches have been proposed for the minimization of the aforementioned degrading factors [22]. Some of the approaches for the better injection and distribution of holes across the active region include employing an engineered electron blocking layer (EBL) instead of a conventional EBL [23,24], graded AlGaN quantum barriers (QBs) in a multiquantum well (MQW) structure without using EBL [25], InGaN QB instead of conventional GaN QB [26], graded InGaN last QB [27], graded superlattice EBL [28] and InGaN/AlGaN (MQW) [29]. To improve the green LED efficiency, recently, our group employed an all-quaternary-based device [30]. By introducing quaternary quantum well (QW) along with the QB as well as quaternary EBL in a single structure, a significant efficiency droop reduction has been achieved in comparison to the conventional LED.

Nevertheless, further effective and feasible approaches, especially in green wavelength, are needed for better optoelectronic characteristics of LEDs at high current density.
For the improvement of device efficiency, researchers have reported different device engineering strategies in the EBL [31,32] and last barrier [27,33] to mention a few. Both the EBL and last barrier lie on the p-side of the active region which makes the transport of the holes towards n-side difficult. There are hardly any reported layer configurations on the n-side to enhance the carrier transport in the active region. In this work, we propose an MQW structure in which n-side GaN QB is replaced with ungraded p-AlGaN QB. Next, we employ the graded AlGaN QB and graded AlGaN EBL simultaneously. Both QB and EBL are graded with increasing composition of aluminium from 0% to 5% and 0% to 15%, respectively. The proposed structures exhibit better characteristics as compared to their standard structure.

2 | DEVICE STRUCTURES AND PARAMETERS

Three different green InGaN-based structures have been numerically investigated using Advanced Physical Models of Semiconductor Devices (APSYS) simulator. The active region of all the LEDs consists of three pairs of InGaN QWs each having 30% composition of indium and thickness of 2.6 nm. Similarly, the thickness of each QB is 8.5 nm. The active region is placed between n- and p-GaN layer. The thickness and doping concentration of n-GaN is 3 μm and 5 × 10^{18} cm^{-3}, respectively. Similarly, thickness and doping concentration of p-GaN is 0.15 μm and 1 × 10^{19} cm^{-3}, respectively. The EBL is also employed between the active region and p-GaN for the blockage of electrons which are leaked out of the active region. Thickness and p-doping concentration of EBL is 0.020 μm and 3 × 10^{17} cm^{-3}, respectively. The Auger and Shockley-Read-Hall (SRH) coefficients are 5 × 10^{-31} cm^{6} s^{-1} and 2 × 10^{-7} s^{-1}, respectively. Remaining details of the parameters employed and model used are given in Ref. [34]. The conventional structure is denoted by LEDA having In_{0.3}Ga_{0.7}N QWs and GaN QBs with Al_{0.15}Ga_{0.85}N EBL. In LEDB, the first GaN QB of LEDA is replaced with p-Al_{0.05}Ga_{0.95}N. In proposed structure, which is denoted as LEDC, the first p-AlGaN QB and p-AlGaN EBL are graded simultaneously with uniformly increasing composition of aluminium from 0% to 5% and 0% to 15% (Figure 1).

3 | RESULTS AND DISCUSSION

It can be seen in Figure 2a that LEDA consists of three pairs of In_{0.3}Ga_{0.7}N QWs and GaN QBs with Al_{0.15}Ga_{0.85}N EBL with uniform composition of aluminium. Figure 2b shows LEDB, in which only first GaN QB is replaced with p-Al_{0.05}Ga_{0.95}N QB. This not only provides an extra barrier in the path of injected electrons but also is useful for the proper confinement of holes into the active region. In LEDC, the first p-Al_{0.05}Ga_{0.95}N QB and p-Al_{0.15}Ga_{0.85}N EBL of LEDB are replaced with graded p-Al_{1−x}Ga_{x}N QB and p-Al_{1−x}Ga_{x}N EBL both simultaneously, with increasing composition of aluminium from 0% to 5% and 0% to 15%, respectively, which is shown in Figure 2c. The graded EBL is helpful for the better injection of holes into the active region which is according to literature [23]. The effective barrier height in the path of injection of holes at EBL/QB(last) interface, due to EBL grading, is reduced in LEDC to ~709 meV in comparison to LEDA and LEDB.

The distribution of electrons and holes across the active region is shown in Figure 3a,b, respectively. Usually in conventional MQW structure, the concentrations of electrons and holes are high in the last QW which is near to p-side [35]. In LEDA, the electron concentration is high in QW1 as shown in Figure 3a. In QW1, the probability of non-radiative recombinations of carriers is also high due to comparatively lesser population of holes in the well as shown in Figure 3b. To avoid this situation, we proposed LEDC in which the highlighted issue of poor hole injection as well as their poor transport across the active region is minimized. The overall average hole concentration of LEDC is enhanced by ~55% and ~38% as compared to LEDA and LEDB, respectively, which is clear from Figure 3b. In QW3, the average hole concentration of LEDC is enhanced by ~52% and ~43% as compared to LEDA and LEDB, respectively. In a similar fashion, in QW2, the concentration is also enhanced by ~57% and 37% as compared to LEDA and LEDB, respectively. The comparatively higher concentration of holes in QW1 of LEDB (inset of Figure 3b) in comparison to other LEDs can be attributed to ungraded p-AlGaN QB on the n-side. The overall enhancement in the concentration of holes is attributed to the graded p-AlGaN QB and AlGaN EBL.

The radiative recombination of conventional structure is more affected due to the separation of electron-hole wavefunctions. Therefore, the probability of radiative recombinations is reduced. Figure 4a shows the radiative recombination rate of QW1, QW2 and QW3 in all the LEDs. The radiative recombination rate, in all the QWs, of LEDC is improved. In LEDC, the recombination rate is enhanced by ~52% and ~35% as compared to LEDB & C respectively. It is clear from Figure 4a–e, that all the QWs of LEDC contribute significantly as compared to LEDA and LEDB. The contribution of QW1, QW2 and QW3 of LEDC is improved by ~70%, ~58% and ~48%, respectively, as compared to LEDA. Similarly, the QW1, QW2 and QW3 of LEDC is improved by ~22%, ~44% and ~35%, respectively, as compared to LEDB. In short, the radiative recombination of LEDC is observed to be the best as compared to rest of the LED structures. The better confinement of carriers in QWs and reduction of barrier in the path of
Figure 2: Energy band diagram of (a) LEDA, (b) LEDB and (c) LEDC. The shaded circles show the influence on band offsets by employing p-AlGaN QB/EBL before current injection.
injected holes, into the active region, have the fundamental role in the improvement of radiative out turn of LEDC.

Figure 5 shows the emission spectra of LEDA, LEDB and LEDC with respect to wavelength. The peak emission spectra of LEDA, LEDB and LEDC lies in the spectrum of green wavelength that is ∼515 to ∼520 nm. The peak as well as full width at half maxima of LEDC is enhanced as compared to LEDA (conventional) and LEDB. The peak of the spectrum is improved nearly twice as compared to LEDA. Insertion of p-AlGaN on the n-side of the active region is reported to result in redshift of the peak wavelength [36] which is the case for LEDB and LEDC. In case of LEDC, we believe that the grading may have redshifted the peak further.

Figure 3 Carriers distribution across the active region (a) electron and (b) holes in LEDA, LEDB and LEDC. The inset of (b) shows enlarged QW1

Figure 4 (a) Radiative recombination of LEDA, LEDB and LEDC. Enlarged view of (b) QW1 and (c) QW2
In comparison to LEDA, LEDB and LEDC, LEDC shows extremely good performance in IQE as well as in light output power (LOP) which is clear from Figure 6. The decrease of efficiency with the increase of current density is known as ‘efficiency droop’. The goal is to not only increase the efficiency peak but also minimise the efficiency droop with the increase in current density. In LEDC, the efficiency peak is improved as well as droop ratio is reduced. The efficiency droop ratio of LEDC at 100 A cm⁻² is ~34%. In comparison, LEDA and LEDB droop ratios are ~58% and ~52%, respectively. Similarly, the LOP of LEDC is also nearly doubled as compared to LEDA at 100 A cm⁻².

4 | CONCLUSION

In summary, we have numerically investigated three different structures. LEDC shows extremely good performance as compared to other structures. In LEDC, the concentration of holes in the active region is also enhanced due to graded AlGaN QB as well as EBL. Therefore, all the QWs of proposed LEDC contributed well in radiative recombination. It is clear from the discussion that sandwiching the active region between graded p-AlGaN QB and graded p-AlGaN EBL can lead to efficient green InGaN-based LEDs.

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