Improvement in internal quantum efficiency of InGaN/GaN light emitting diodes by linear grading of quantum wells

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Linear grading is introduced in InGaN quantum wells, to improve the internal quantum efficiency of InGaN/GaN LEDs. A constant Indium composition LED structure shows efficiency degradation at low injection current level in comparison to graded composition LED structures, with linear and inverse grading profile. This increase in efficiency can be correlated to decrease in the internal field in the active region of LED. In constant composition LED efficiency droop occurs at 75 mA/cm^2, whereas in graded composition LED efficiency droop occurs at 4686 mA/cm^2. The band diagram, internal quantum efficiency, radiative and non-radiative recombination rates and power spectral density are studied by using ATLAS simulation software from Ms Silvaco.

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1. Introduction

AlGaInP based semiconductor alloys were manufactured in 1990s. At that time yellow, red and orange Light Emitting Diodes (LEDs) were manufactured, containing external quantum efficiency 50%. But now days, InGaN based blue LEDs are used which contains 56% external quantum efficiency. Gallium nitride, indium gallium nitride and aluminum gallium nitride are the principal materials for manufacturing of multiple quantum well light emitting diode. Recently, InGaN/GaN (which is active material) based blue LEDs gained a considerable interest as an alternative of fluorescent and incandescent bulb. InGaN/GaN LEDs are emerging technology which gained lots of interest due to its low energy consumption, compact size, long lifetime and reliability [1-3]. LEDs has different strategies for extraction of light and controlling of emitted light than traditional light sources. Direct band gap of $In_xGa_{1-x}N$ varies from 0.7eV(InN) to 3.4eV(GaN). Therefore InGaN based LEDs are used for a wide range of wavelength from ultraviolet to blue/green region [4]. InGaN LEDs being used to such a great extent in mobile phone and general illumination purposes. LEDs are used in various applications, like general lighting (solid state lighting), optical storage, traffic signals, full-color display, DVD players, liquid crystal display backlighting, mobile platforms, purification of environmental, medical diagnostics etc. [5-6]. In spite of the wide variety of applications, use of LED is still limited. General illumination requires high brightness and it motivates higher power operation of LEDs. The internal quantum efficiency of LEDs suffers a significant decrease as injection current increases (efficiency droop) [7-11]. Auger recombination, carrier delocalization, defects [Shockley-Read-Hall], threading dislocations in crystal structure, piezoelectric polarization, non-radiative recombination etc. are also considered as some major cause of efficiency droop [12-16]. Many possible solutions had been suggested for reducing this efficiency degradation in InGaN/GaN based LEDs [17-18]. Yen-Kuang Kuo et. al. introduced an electron blocking layer (EBL) in between p-GaN and active region to reduce the carrier overflow [19-20]. Carrier overflow is also reduced by using multiple quantum well structure in active region [21]. Nonpolar or semi-polar structures were suggested by many authors to reduce this efficiency droop in InGaN/GaN LEDs [22-23].

In this paper, we introduce, a linear graded InGaN quantum well structures and investigate the effect of grading on efficiency at the high injection current level.

2. Structure

The basic LED structure used in this study consists of an 150 nm thick n-GaN (n = 2×10^{19} cm^3), 5 pairs of quantum wells and barriers of InGaN/GaN (3 nm $In_{0.25}Ga_{0.75}N$ QW / 7 nm GaN barrier), p-$Al_{20}Ga_{80}N$ electron blocking layer of thickness 15 nm (2×10^{17} cm^3) and p-GaN layer of thickness 1 μ (p = 2×10^{18} cm^3). The schematic of the basic LED structure is shown in Fig. 1 (a). Graded composition quantum wells LEDs as shown in Fig. 1 (b), L1, L2, R1 and R2 consists of same basic structure, with indium compositions in QWs linearly graded from 35% to 0%, 25% to 0%, 0% to 35% and 0% to 25%, respectively in direction from n-GaN to p-AlGaN. The electron and hole mobilities are taken as 1.4×10^{-6} and 2×10^{-8} cm^2 V^{-1} s^{-1} respectively [24].

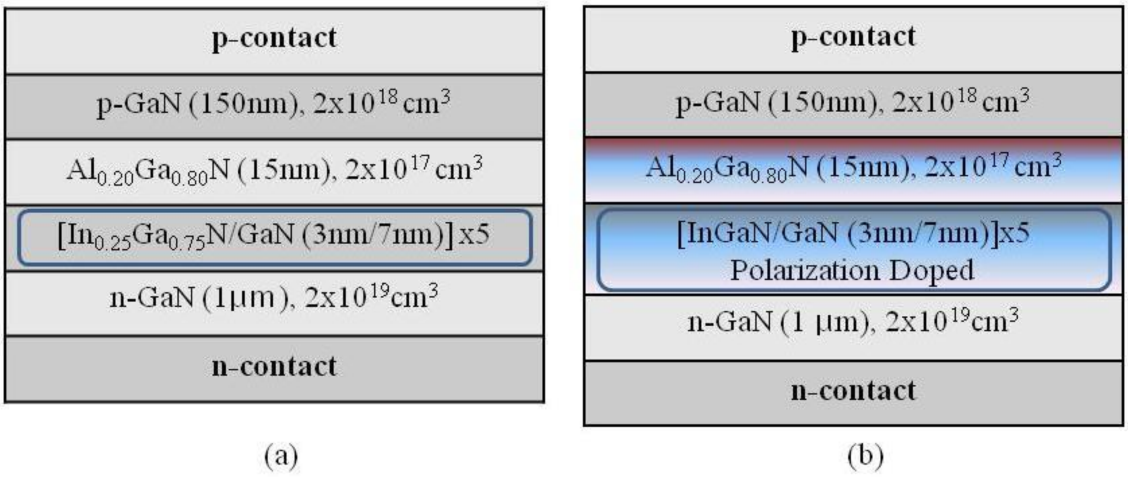

Fig. 1. Schematic of InGaN/GaN multi quantum wells LED structure (a) Basic (b) Graded composition.

3. Results and discussions

ATLAS (version 5.18.3.R) from M/s Silvaco is used for calculating electrical and optical characteristics of the device [25]. Material properties, designing of LEDs structure, problem of efficiency droop and improvement of efficiency are studied from literature [26-28].

The band diagram of basic, L2 and R2 LED structures at 0 mA/cm^2 and 30 mA/cm^2 are shown in Fig. 2 (a) and (b).

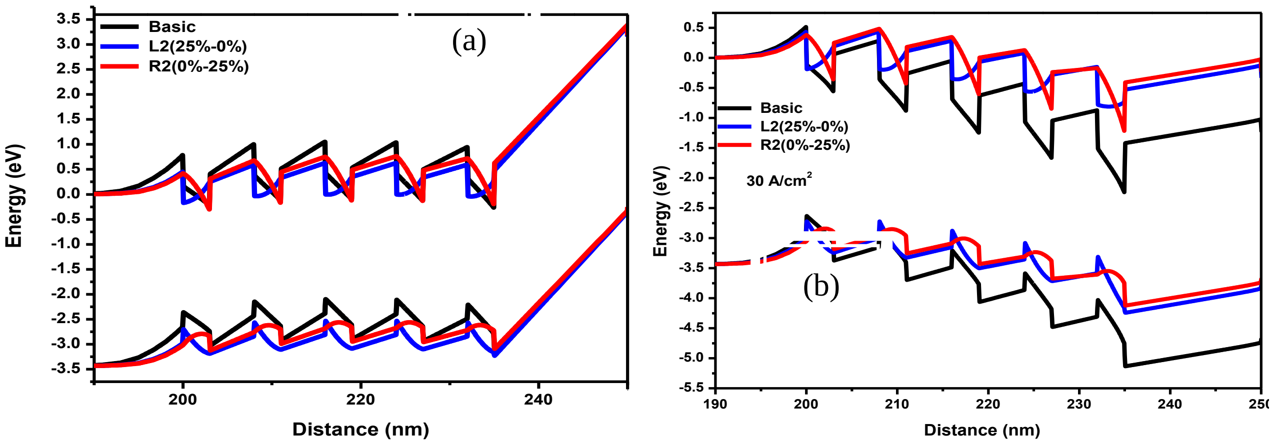

Fig. 2. Band diagram of Basic, L2 and R2 LED structures at (a) 0 mA/cm^2, and (b) 30 mA/cm^2

As shown in Fig. 2 (b), as the forward bias increases, carrier starts overflowing. This phenomenon occurs due to band bending. In case of a basic LED band diagram obtained triangular shape whose slope occurs from n-side to p-side. This band bending occurs from n-side to p-side due to the effect of polarization between barrier and quantum well. Whereas in proposed graded quantum well LED L2 shows smaller slope from p-side to n-side. This type of slope shows that the effect of internal polarization is reduced from n-side to p-side [29]. In case of LED R2 direction of slope is similar to basic LED but, the magnitude of the slope is reduced. This occurs due to reduction in effect of internal polarization by grading from p-side to n-side. In basic LED structure, at high injection current density potential spikes are obtained in the valance band due to GaN barrier. For injection of holes from p-GaN side to multiple quantum well these spikes creates an obstacle, as a result, there is improvement in non-radiative recombination and reduction in internal quantum efficiency occurs. This problem is reduced in LED structure L2 and R2 by using grading.

The emission peak of basic LED is obtained at 587 nm. The emission peak of LEDs L1, L2, R1 and R2 are obtained at 478,434.5, 460 and 422 nm respectively. All peaks are blue shifted than basic LED and emission intensity is improved, which is the main requirement of blue LEDs. This blue shift is obtained as a result of grading of indium in well.

Internal quantum efficiency of basic, L1 and L2 LEDs are shown in Fig. 3. Mitigation of the internal quantum efficiency in basic LED structure occurs at 75 mA/cm^2. However, in LEDs structure L1 and L2 efficiency droop occurs at 2136 mA/cm^2 and 4686 mA/cm^2, respectively.

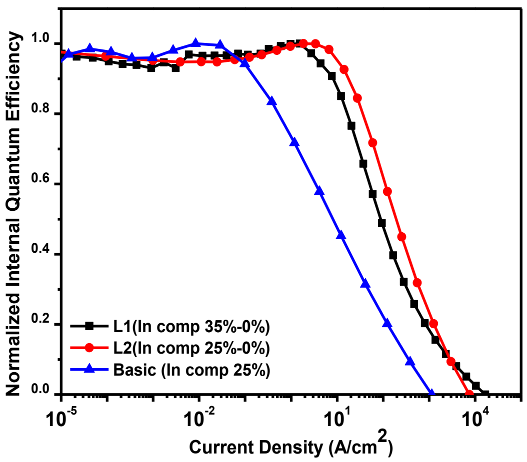

Fig. 3. Internal Quantum Efficiency of basic, L1 and L2 LED structures

The improvement in droop in L1 and L2 structures can be explained on the basis of internal field. In L1 and L2 internal electric field is relaxed due to grading and band-bending, and less dominant at high bias. This improvement in efficiency for graded composition LEDs can also be correlated to reduction of lattice mismatch between InGaN and GaN. In basic LED structure, 25% In doped GaN layer was incorporated just above GaN layer. As a result lattice mismatch occurs between InGaN and GaN. Whereas, in case of graded composition LED structure, In composition increases linearly not abruptly. So lattice mismatch decreases and efficiency of graded composition LED increases.

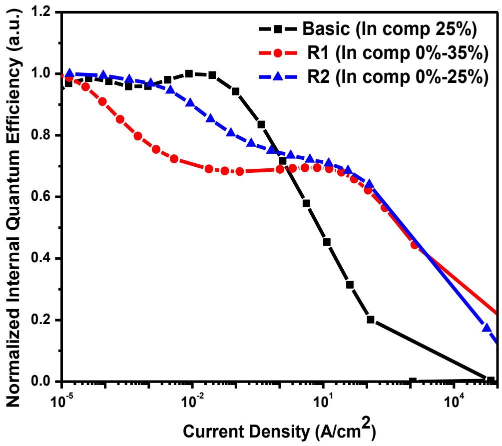

Fig. 4. Internal Quantum Efficiency of basic, R1 and R2 LED structures

Similarly, in Fig. 4, internal quantum efficiency of basic, R1 and R2 LED structures are shown. Reduction in internal quantum efficiency for LED structure R1 and R2 occurs at 1105 mA/cm^2 and 1881 mA/cm^2 respectively. The cause of this improvement is the blue shift of emission peak, reduction of carrier overflow and lattice mismatch between GaN and InGaN.

4. Conclusions

Depending on grading profile, the efficiency droop in InGaN/GaN LED can be tailored to a large extent. Use of profile, like L1 and L2 the efficiency droop improve and the LEDs can operate without any reduction in efficiency at higher current. Similarly for grading profile R1 and R2, the efficiency droop improves and efficiency starts decaying at higher current. This tailoring of droop is directly related to reduction of lattice mismatch between InGaN and GaN.

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