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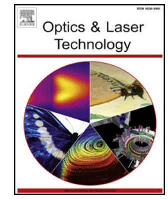

InGaN based tunable green light-emitting diodes using InAlN interlayer and strain compensated AlGaN interlayer for better device performance

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HIGHLIGHTS

- Effect of InAlN and AlGaN interlayer (IL) in the InGaN/GaN QW LEDs has been studied.
- 10 Å thick $Al_{0.8}Ga_{0.2}N$ IL produces the maximum M_{eh}^2 when AlGaN IL is used.
- 10 Å thick $In_{0.2}Al_{0.8}N$ IL also produces the maximum M_{eh}^2 when InAlN IL is used.
- Compared the transition energy and M_{eh}^2, using InAlN and AlGaN ILs with current.
- M_{eh}^2 of 10 Å thick $Al_{0.8}Ga_{0.2}N$ IL, is nearly 2 times higher when IL is absent.

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ABSTRACT

The effect of employing an $In_yAl_{1-y}N$ and $Al_yGa_{1-y}N$ interlayer (IL) in the $In_xGa_{1-x}N$/GaN active region for the green light-emitting diodes (LEDs) has been studied. The high compressive strain in $In_xGa_{1-x}N$/GaN QW is compensated by the tensile strained $Al_yGa_{1-y}N$ IL. The $In_yAl_{1-y}N$ IL reduces the strain between $In_xGa_{1-x}N$ and GaN layers. The $Al_yGa_{1-y}N$ or the $In_yAl_{1-y}N$ layer in between the QW and the GaN barriers increase the barrier height, which potentially suppresses the electron and hole leakage from the QW. These increase the square of the overlap of electron and hole wave functions (M_{eh}^2) of the QW LEDs. By changing the well width and aluminum or indium content in the IL, we obtained better optical properties. It has found that 10 Å thick $In_{0.2}Al_{0.8}N$ and 10 Å thick $Al_{0.8}Ga_{0.2}N$ layers give the maximum M_{eh}^2 for the green LEDs, using $In_yAl_{1-y}N$ and $Al_yGa_{1-y}N$ ILs. Furthermore, we have compared the M_{eh}^2, using $Al_yGa_{1-y}N$ and $In_yAl_{1-y}N$ IL with the current. The best result is obtained for the 10 Å $Al_{0.8}Ga_{0.2}N$ IL, which increases the M_{eh}^2up to 2 times, as compared to the QW LEDs, without any IL.

1. Introduction

III-V nitride-based light-emitting diodes (LEDs) have attracted great importance in solid-state lighting, because of their high-efficiency. Red, green and blue (RGB) based color mixed LEDs provide white light. Recently, blue LEDs with $In_xGa_{1-x}N$ quantum well (QW) have been grown on c-plane sapphire by MOCVD, where the peak external quantum efficiency (EQE), is obtained more than 80% for blue LEDs [1–4]. To produce the green and red light, i.e., longer wavelength emission, using $In_xGa_{1-x}N$ QW LEDs, the EQE abruptly drops. A direct correlation has been observing that for longer wavelength emission, required higher indium (In) content, this turn to low efficiency compared to the blue LEDs. The efficiency reduction in $In_xGa_{1-x}N$ QW based higher wavelength emission LEDs due to defects induced by strong lattice mismatch [5,6]. This increases the carrier localization through quantum confinement [7] and raises the strong built-in polarization fields [8] which increases the quantum-confined Stark effect [9] and significantly increases the spatial separation of electron and hole wave function in the $In_xGa_{1-x}N$ QW LEDs. This reduces the EQE.

Several solutions have been proposed to reduce this detrimental effect and enhance the square of the overlap of electron and hole wave functions (M_{eh}^2), for the emission of higher wavelength, of the $In_xGa_{1-x}N$ QW LEDs[10–20]. Recent improvements have made by applying $Al_yGa_{1-y}N$ or $In_yAl_{1-y}N$ interlayer (IL) in the active region to provide high-efficiency longer wavelength based $In_xGa_{1-x}N$ QW LEDs [1,21–29]. The ILs have provided various benefits for higher efficiency

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green LEDs. These are: (1) the $Al_yGa_{1-y}N$ and $In_yAl_{1-y}N$ IL acts as a cap layer, which reduces the out-diffusion of In from the $In_xGa_{1-x}N$ QW and produces a more abrupt hetero-interfaces. (2) The ILs increase the barrier height, which decreases the electron and hole leakage from the QW [30]. (3) The tensile strain of $Al_yGa_{1-y}N$ can be used to compensate the compressive strain at the $In_xGa_{1-x}N$/GaN interface. The $In_yAl_{1-y}N$ IL with y ≈ 18% of In is lattice-matched to GaN layers, which makes the interface between $In_yAl_{1-y}N$ and GaN nearly strain free [31]. The In content, $y < 18\%$ in $In_yAl_{1-y}N$ IL, has tensile strain, which compensates the compressive strain at the $In_xGa_{1-x}N$/GaN interface. For the In content of $y > 18\%$, in the $In_yAl_{1-y}N$ IL, the tensile strain is converted to compressive strain, as well as higher In content in the $In_yAl_{1-y}N$ IL, reduces the built-in piezoelectric field between $In_xGa_{1-x}N/In_yAl_{1-y}N$ IL heterointerface. These improve the efficiency of the QW LEDs.

Hwang et al. reported that, use of 10 Å thick $Al_{0.9}Ga_{0.1}N$ IL, grown by MOCVD, improved red emission [22]. After a series of experiments, Alhassan et.al. reported that, a 20 Å thick strain compensated $Al_{0.3}Ga_{0.7}N$ interlayer can maximize the green emission [23], whereas Sun et al. shows experimentally that, a 10 Å thick $Al_{0.42}Ga_{0.58}N$ is the better alternative for green LEDs [24]. So there is a contradiction about the $Al_yGa_{1-y}N$ IL thickness and composition for the high efficient green LED structures. Recently, it has shown that the use of 10 Å thick $In_yAl_{1-y}N$ IL in the $In_xGa_{1-x}N$/GaN QW can enhance the green emission [24].

In this paper, we have maximized the efficiencies of green LEDs using ILs, by the variation of the composition and thickness of the $In_yAl_{1-y}N$ and $Al_yGa_{1-y}N$ ILs. Initially, we have compared our theoretically simulated results with standard experimental results to standardize and establish our model. The interesting results reveal that, for a certain width and composition of $In_yAl_{1-y}N$ and $Al_yGa_{1-y}N$ IL, the M_{eh}^2 can be maximized. Finally, we have compared the M_{eh}^2 of $In_xGa_{1-x}N$ LED structures, considering with or without ILs. The maximum overlap is observed in the $In_xGa_{1-x}N$ QW with $Al_yGa_{1-y}N$ ILs.

2. Theoretical details

In our study, we use three different single QW structures, with or without $Al_yGa_{1-y}N$ and $In_yAl_{1-y}N$ IL, as shown in Fig. 1. The structures consist of A: GaN/ $In_xGa_{1-x}N$/GaN QW LED, B: GaN/$In_xGa_{1-x}N$/ $In_yAl_{1-y}N$/GaN QW LED, and C: GaN/$In_xGa_{1-x}N$/ $Al_yGa_{1-y}N$/GaN QW LED. Here GaN and $In_xGa_{1-x}N$ layers are considered as the usual barriers and QW of the LED, respectively. $Al_yGa_{1-y}N$ and $In_yAl_{1-y}N$ act as IL between the QW and barrier. The width of the QW is considered to be 30 Å. The aluminum (Al) and In mole fraction in the ILs are varied. The n-type and p-type doping concentration in the GaN barriers kept as 5×10^{18} cm$^{-3,}$ where both the QW and ILs are considering undoped.

The non-linear variation of the energy bandgaps of $In_xGa_{1-x}N$, $Al_yGa_{1-y}N$, and $In_yAl_{1-y}N$ are obtained by linear interpolation of InN, AlN, and GaN materials. The bandgap of $In_xGa_{1-x}N$, $Al_yGa_{1-y}N$, and $In_yAl_{1-y}N$ are obtained as

$$E_g(In_xGa_{1-x}N) = x\cdot E_{g,InN} + (1-x)E_{g,GaN} - b1\cdot x(1-x) \quad (1)$$

$$E_g(Al_yGa_{1-y}N) = y\cdot E_{g,AlN} + (1-y)E_{g,GaN} - b2\cdot y(1-y) \quad (2)$$

$$E_g(In_yAl_{1-y}N) = y\cdot E_{g,InN} + (1-y)E_{g,AlN} - b3\cdot y(1-y) \quad (3)$$

where $E_{g,InN}$, $E_{g,AlN}$ and $E_{g,GaN}$ are the bandgap of InN, AlN, and GaN. b1, b2 and b3 are the bowing parameters which are 1.4, 0.6 and 5.0, respectively [32].

The detailed calculations of piezoelectric and spontaneous polarization and the direction of fields between GaN, $In_xGa_{1-x}N$, and ILs are taken from [33–35]. The electron-hole wave functions, carrier concentrations in the QW layer with or without IL for applying a forward bias, energy band, and the corresponding energy states in the QW have calculated through the self-consistent solution of Schrödinger and

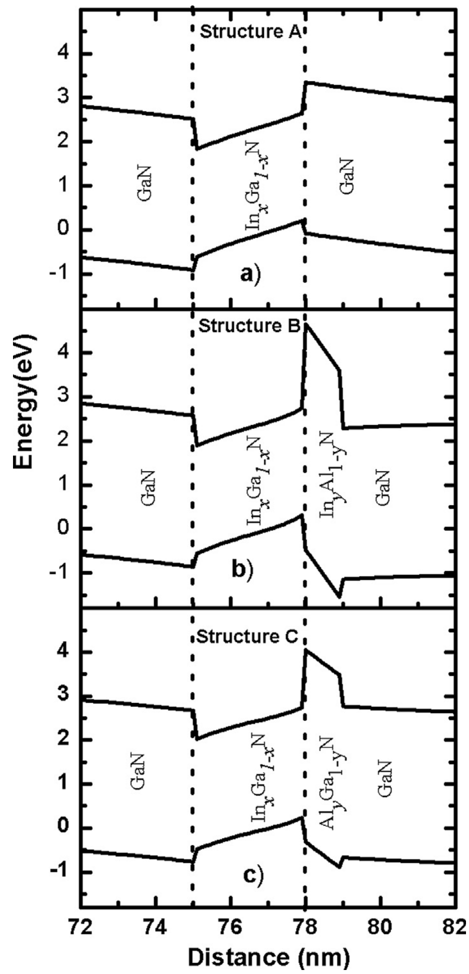

Fig. 1. Schematic band diagram of $In_xGa_{1-x}N$/GaN QW structures (a) A: Without interlayer, (b) B: with $In_yAl_{1-y}N$ IL and (c) C: with $Al_yGa_{1-y}N$ IL.

Poisson's equation. The details of calculations using MATLAB software have been discussed elaborately in our previous reported articles [13,35,36].

The current density through the structure has taken from the relation [37,38].

$$J = qL(U_{SHR} + U_{b-b} + U_A) \quad (4)$$

where U_{SHR} is the Shockley-Hall-Read (SHR) recombination rate, U_{b-b} is the band to band, i.e. radiative recombination rate, U_A is the Auger recombination rate. L is the width of the QW and q is the electronic charge.

For the high injection level, U_{SHR}, U_{b-b} and U_A are approximated as [35]

$$U_{SHR} = A\cdot n \quad (5)$$

$$U_{b-b} = B\cdot n\cdot p \quad (6)$$

$$U_A = \frac{1}{2}C\cdot p\cdot n\cdot(n+p) \quad (7)$$

where n and p electron and hole concentration in QW. A, B and C coefficient are all proportional to the M_{eh}^2 [39], these are

$$A = A_0\ |M_{eh}|^2 \quad (8)$$

$$B = B_0\ |M_{eh}|^2 \quad (9)$$

$$C = C_0\ |M_{eh}|^2 \quad (10)$$

The typical values of A_0, B_0 and C_0 are assumed to be 10^7 s^{-1},