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Monolithic high performance InGaN/GaN white LEDs with a tunnel junction cascaded yellow and blue light-emitting structures

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ABSTRACT

We propose a phosphor-free dual wavelength monolithic white LED comprising a tunnel junction that separates a yellow light-emitting InGaN/GaN multiple quantum well (MQW) structure without an electron blocking layer (EBL) from a blue light-emitting MQW structure. Using a well-calibrated APSYS simulation software we investigate its performance in terms of output power, wall plug efficiency, and CIE plot of the emitted light and analyze its operation on the basis of band diagram, carrier distribution, EL spectra and radiative recombination rate taking into account the carrier confinement and carrier reuse effects due to removal of an EBL and incorporation of a tunnel junction, respectively. At the injection current density of 250 A/cm^2, our proposed white LED exhibits 232% improvement in output power as compared to a conventional blue LED and only 40% droop reduction of wall plug efficiency as opposed to 56% in a reported white LED. The Commission Internationale de l'Eclairage (CIE) coordinates of the emitted light from the proposed white LED structure are found to be (0.310, 0.309) at 100 A/cm^2 which signify a good quality white light emission.

1. Introduction

The group III nitride-based light-emitting diodes (LEDs) have emerged as attractive optoelectronic light sources due to their small size, high efficiency and prolonged lifetime. High efficiency LEDs are now commercially available and are finding their use in a wide variety of applications such as full-color displays, liquid crystal display (LCD) back lighting, mobile platforms, and general lighting [1–6]. White LEDs are of special importance because of their myriad of applications and they are manufactured primarily in two different techniques. The first one employs a yellow phosphor coating over a blue InGaN LED to convert a part of the blue light to a longer wavelength and realize the white light spectrum [5,6]. This method, however, suffers from the problem of stability due to ageing of the phosphor coating, high packaging cost and the efficiency being dependent on properties of the LED [6]. In the other scheme a multichip approach [4] is adopted where emissions from red, green and blue (RGB) monochromatic LEDs are mixed together to produce white light. This processing technique, however, increases the production cost owing to additional processing steps and also demands for a driver circuitry. Extensive research efforts were put forward to realize a monolithic, highly efficient and good quality white light LED source by using different schemes [7–12] such as inserting shallow quantum wells between deep wells and barrier [7], stacking different wavelength multiple quantum well regions [8], adopting nanostructure engineering techniques like the use of quantum dots [9], nanowires [10], pyramids [11], and patterned substrates [12]. All these methods are, however, complex and difficult to implement for a large scale production. Recently, Ooi et al. [13] suggested the growth of a phosphor-free white LED consisting of blue and yellow quantum wells grown on a ternary InGaN substrate to reduce the strain which develops due to lattice mismatch between the layers forming the active region of LEDs. Apart from the quality of white light, the output power is also an important parameter for a white LED in solid-state lighting applications. Hence realizing a good quality white LED with a high output power poses a formidable challenge.

Using a nitride-based tunnel junction (TJ) is a dexterous technique for significant improvement of optical power in GaN LEDs [1,14,15]. Several structures with monolithic stacking of III-nitride LEDs separated by a TJ were investigated [16–18]. The TJ allows the reuse of injected electrons and holes for generation of photons

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thereby resulting in the external quantum efficiency (EQE) of LEDs exceeding 100%. But the wall plug efficiency (WPE), defined as the ratio of output power to the input power [19], remains less than 100% and is considered as a performance parameter for different LED structures. While there have been many reports on white LEDs in the literature [4,5,20,21], the work towards the tunnel junction cascaded monolithic white light sources with high quality and efficiency is not addressed yet.

In this paper, we propose a monolithic InGaN/GaN white light LED in which a tunnel junction is sandwiched between yellow and blue light-emitting regions for mixing two colors to produce white light. We design the yellow LED without any electron blocking layer which helps achieve appropriate contribution from the yellow and blue LEDs in realizing good quality white light spectrum. Various performance metrics such as output power, wall plug efficiency, and CIE coordinates of our proposed white LED are compared with the corresponding parameter for a conventional blue LED and/or a recently reported white LED [13]. Furthermore, the performance of the LED is analyzed in the light of physical effects and utilizing numerical results obtained using APSYS [22].

2. Device structure and simulation framework

In this study we propose a monolithic white light TJ LED structure grown on a *c*-plane sapphire having yellow and blue light-emitting multiple quantum well regions separated by a tunnel junction as shown in Fig. 1. The proposed structure may be fabricated using metal organic chemical vapor deposition (MOCVD) technique as experimentally demonstrated by Chang et al. [17] and Kuo et al. [23]. At low temperature (~550 °C) GaN buffer layer having thickness of 50 nm may be grown on top of a 2 inch sapphire substrate followed by a deposition of 4.5 μm thick Si doped GaN (n-GaN) layer at 1000 °C. On top of this 5-period of $In_{0.38}Ga_{0.62}N$(3 nm) multiple quantum wells (MQWs) separated by $In_{0.15}Ga_{0.85}N$ (6 nm) barriers may be grown to realize the yellow-emitting active region [13] following the growth technique adopted by Fu et al. [24] which employed a low pressure horizontal MOCVD reactor equipped with two heating elements. The active region is followed by 0.5 μm thick Mg doped p-GaN layer grown at 1000 °C. The tunnel junction consisting of p^+-GaN (5 nm)/i-$In_{0.2}Ga_{0.8}N$ (3 nm)/n^+-GaN (5 nm) [25] may be deposited on top of this yellow-emitting LED. The GaN (p^+ and n^+) and the i-$In_{0.2}Ga_{0.8}N$ layers of the tunnel junction may be grown at 1000 °C and 750 °C, respectively [23]. The p^+ and n^+ doping concentrations of the tunnel junction are chosen to be 3×10^{19} cm^{-3} and 5×10^{19} cm^{-3}, respectively. Subsequently, the layers of the blue light-emitting LED may be fabricated sequentially. The active region of the blue LED consists of 5-period $In_{0.21}Ga_{0.79}N$(2 nm)/GaN (15 nm) [26] which may be grown at 750 °C. Following the active region a 20-nm-thick p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer (EBL) may be deposited at 980 °C as suggested in Ref. [27]. Rest of the layers for the blue LED may be grown following the similar method adopted for the yellow LED. After epitaxial growth of the structure, standard photolithography and dry etching techniques may be employed to form a ridge from the top p-GaN layer of the blue LED to the n-GaN layer of the yellow LED and to define a mesa area of 300 × 300 μm^2. Next the indium tin oxide (ITO) may be sputtered on the LED that acts as a transparent current spreading layer. Finally, Ti/Au (30 nm/150 nm) may be deposited on the ITO and the exposed n-GaN using e-beam evaporation technique to form p-contact and n-contact, respectively [28].

We use APSYS simulation program to simulate the proposed white light TJ LED as illustrated in Fig. 1. Various model parameters used in the simulation are chosen from reported results in the literature [29–37]. The band gap energies of InGaN and AlGaN ternary alloys are calculated as

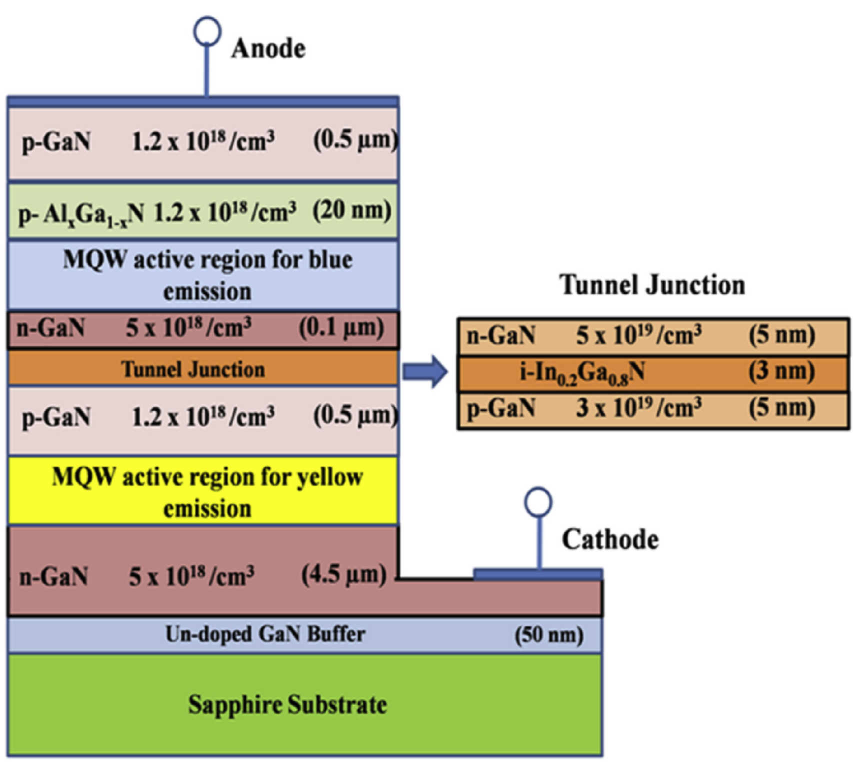

Fig. 1. Schematic cross-sectional view of the proposed white light-emitting diode structure.