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Improved performance of InGaN/GaN MQW LEDs with trapezoidal wells and gradually thinned barrier layers towards anode

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A B S T R A C T

We design and evaluate the performance of three InGaN/GaN multiple quantum well blue LEDs – A. rectangular quantum wells with a fixed barrier width, B. trapezoidal quantum wells with a fixed barrier width, and C. trapezoidal quantum wells with a decreasing barrier width towards the anode end – in terms of efficiency droop and power output. We obtain band diagram, electric field, emission spectra and carrier concentration using well calibrated APSYS simulation. Use of trapezoidal quantum wells increases better overlapping between electron and hole wavefunctions thereby increasing radiative recombination events. Furthermore decreasing barrier width from n- to p- regions shortens hole transport path which results in better hole transport and distribution in the wells and hence larger radiative recombination rate. Our proposed structure C exhibits efficiency droop reduction of 2.1% and enhancement of optical power of 236.7% compared to conventional rectangular quantum well structure at injection current of 120 mA.

1. Introduction

In recent years InGaN based light emitting diodes (LEDs) have received a great deal of research interest around the globe for their wide range of commercial applications such as full-color displays, television liquid crystal display (LCD) back lighting, mobile platforms, and general lighting [1–5]. Particularly outdoor displays and solid-state lighting demand for high power LEDs together with enhanced efficiency. Growth of good quality InGaN/GaN multiple quantum well (MQW) structures, their subsequent processing combined with physical, electrical and optical characterizations pose a critical role for designing and realizing high performance LEDs. There have been a few remarkable works on the growth and characterization of InGaN/GaN MQW structures [6,7]. Experimental findings reveal that fabrication of InGaN/GaN MQWs with high In contents of more than 30% is a formidable challenge due to formation of threading dislocations at the well/barrier interface and of uncontrolled gradient of In composition leading to quantum dot (QD)–like regions [7]. However, scholarly work of Cheong et al. [7] suggests that the growth of InGaN/GaN MQWs with In content of 30% exhibits a very good quality of well/barrier interface as confirmed by HRXRD spectra, XTEM and HRTEM images and also supported by PL spectra analysis. Despite extensive efforts have been put forward during more than one decade, the blue LEDs suffer from efficiency droop which refers to the reduction of emission efficiency with increasing injection current [8–10]. To date, a number of mechanisms have been proposed to explain this phenomenon including carrier leakage from the active region [11], Auger recombination [12,13], lower hole injection efficiency [14], and inhomogeneous distribution of electrons and holes in the active region. Although the exact origin of efficiency droop remains debatable, the asymmetric transport properties of carriers and their inhomogeneous distribution in the QWs influence greatly this phenomenon. To improve optical performance and reduce efficiency droop numerous schemes are proposed and analyzed in the literature [15–19]. It is also established that the existence of piezoelectric polarization fields in InGaN/GaN quantum well LEDs plays a critical role in degrading their performance. As such, a few research groups have attempted to reduce the polarization field in the multiple quantum wells (MQWs) by adopting various techniques as described below. K.M. Song et al. [20] grew several non polar a-plane InGaN/GaN multiple quantum well LEDs with different well thicknesses and observed that the optimized a-plane InGaN well thickness is much thicker than that in *c*-plane InGaN because of the reduced polarization fields in a-plane QWs. Light output from such LEDs was reported to increase with increasing well thickness up to 4.3 nm, however showing a reverse trend for larger well thicknesses particularly at high injection currents due to the poor crystalline quality

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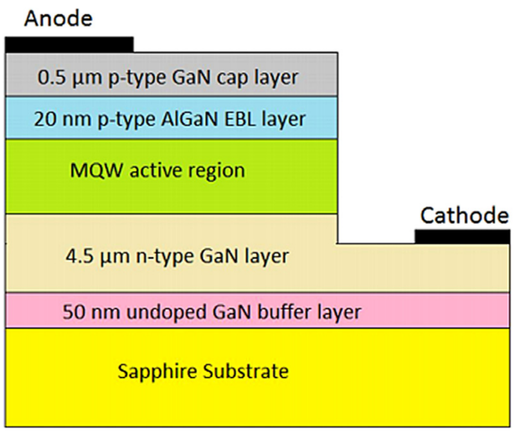

Fig. 1. A schematic cross-section view of the light emitting diode structure.

and associated defects. Schubert et al. [21] demonstrated GaN-based LEDs with InGaN MQWs together with polarization matched AlGaInN barrier in order to reduce the effect of polarization field and electron leakage from the active region resulting in an eventual reduction in efficiency droop at high current densities. In a more recent publication, Lin et al. [22] reported an elegant epitaxial growth technique of the InGaN/GaN structures in which low temperature GaN barriers are utilized to promote strain relaxation in MQWs thereby resulting in reduced polarization field. This in turn weakens the quantum confined Stark effect (QCSE) [23,24] and thus improves the luminous properties of LEDs. Some research groups have adopted different kinds of electron blocking layers such as graded electron blocking layer (EBL) [25], AlInGaN/AlGaN super lattice electron blocking layer (EBL) [26] and In graded last quantum barrier [8]. Although the electron blocking layer reduces electron leakage, it provides additional hole blocking potential that acts as a barrier for hole injection thereby preventing holes from entering the active region. To improve hole injection some elegant techniques are reported including multiple step stage InGaN/GaN quantum wells with Si doped barrier [27], triangular shape last quantum barrier [28] and embedded AlGaN EBL inside active QWs [29]. However, the performance of InGaN blue LEDs is not yet satisfactory particularly at high injection current.

To mitigate the aforesaid problems, we propose a blue LED featuring InGaN/GaN multiple quantum wells (MQWs) with trapezoidal shape clubbed with decreasing barrier width from cathode towards the electron blocking layer (EBL). The trapezoidal QWs exhibit better electron and hole wave functions overlap than rectangular QWs leading to higher radiative recombination rate while reduced the barrier thicknesses from n-side to p-side decreases the hole transport path thereby improving hole injection in the active region. In this study we consider three different LED structures having five quantum wells each – A. InGaN rectangular QWs with GaN barriers of a given width, B. trapezoidal InGaN QWs with fixed width of GaN barriers, and C. trapezoidal InGaN QWs with decreasing width of GaN barriers from cathode to the EBL. The electrical and optical analyses of the three structures are performed using APSYS simulation program [30].

2. Device structure and numerical framework

The *c*-plane sapphire substrate is exploited to form the light-emitting diode (LED) structure which consists of InGaN/GaN multiple quantum wells (MQWs) as the active region sandwiched between n-type GaN cathode and p-type AlGaN electron blocking layer capped by p-type GaN and anode contact. A 4.5 μm thick n-type GaN cathode layer with doping concentration of 5×10^{18} cm^{-3} is grown on a 50 nm thick undoped GaN buffer layer which sits on the top of the substrate as illustrated in Fig. 1. The multiple quantum wells (MQWs) which feature 5 undoped InGaN quantum wells with thickness of 2 nm each and 6 undoped 15 nm thick GaN barrier layers. The electron blocking layer (EBL) is constructed at the top of the MQW region which comprises a 20 nm thick p-type AlGaN with 15% molar content of Al and acceptor doping concentration of 1.2×10^{18} cm^{-3}. The EBL is capped by 0.5 μm thick p-type GaN layer with a doping concentration of 1.2×10^{18} cm^{-3}. The device geometry of the structure is 300×300 μm^2.

In this work we design three different LED structures, labeled A, B and C. They are identical except for the structure of the MQW active region. LED A consists of 2 nm thick 5 undoped InGaN rectangular quantum wells (RQWs) with In mole fraction of 0.21 as shown in Fig. 2(a) clubbed with 6 undoped 15 nm thick GaN barriers. The active region of LED B features 2 nm thick 5 undoped InGaN trapezoidal quantum wells (TQW) in which the In mole fraction increases linearly from 0 to 0.21 over the layer thickness of 0.7 nm, then maintains a constant value of 0.21 for 0.6 nm and finally reduces from 0.21 to 0 across 0.7 nm in a linear fashion as shown in Fig. 2(b) together with 6 undoped 15 nm thick GaN barriers. The design C comprises 5 undoped InGaN TQWs that have identical quantum wells featuring like structure B, except that the barrier thickness decreases from 15 nm in the cathode side down to 5 nm at the EBL end with a step size of 2 nm. The feasibility of the high quality growth of our proposed structure with In composition not exceeding 21% is consistent with the outstanding experimental work demonstrated by Cheong et al. [7]. This work [7] reported the growth of six InGaN/GaN quantum wells with different In contents on *c*-plane sapphire by metal–organic chemical vapor deposition (MOCVD) technique. The precursors of Ga, In, N and Si were trimethylgallium (TMGa), trimethylindium (TMIn), ammonia (NH_3) and silane (SiH_4), respectively. The interface quality of several InGaN/GaN MQW samples with varying In contents in the range 30%–55% and well thicknesses ranging 1.3–2 nm was analyzed using

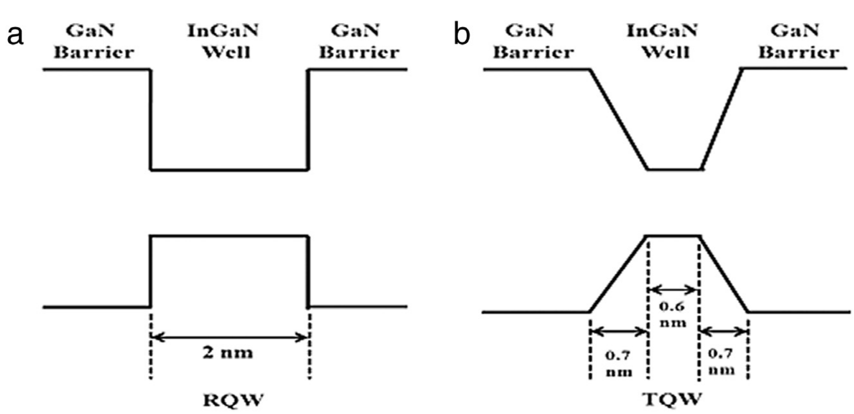

Fig. 2. Schematic band diagrams of (a) rectangular and (b) trapezoidal InGaN/GaN quantum well structures.