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On the effect of quantum barrier thickness in the active region of nitride-based light emitting diodes

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ABSTRACT

In this study, the effect of quantum barrier thickness in the multi-quantum wells active region on electrical and optical properties of nitride-based light emitting diodes (LEDs) were investigated and demonstrated. The forward voltage decreased as the thickness of quantum barrier decreased owing to the reduction of series resistance. The external quantum efficiency (EQE) and droop effect can be effectively improved by decreasing the barrier thickness which was attributed to the enhancement of the holes injection and uniform distribution in the active region. However, if barrier was too thin, it would get the opposite effect due to the influence of electron overflow. Regarding the hot/cold factor, the thinner quantum barrier of LEDs achieved a better performance. The reason is that the thicker quantum barrier with poor holes distribution resulted in the holes accumulation of a few MQWs near the p-side layer was more easily influenced by thermal effect and escaped from the QWs.

1. Introduction

Nitride-based materials have already been extensively used in laser diodes (LDs), light emitting diodes (LEDs), photo-detectors (PDs), and even high electron mobility transistors (HEMTs). Especially, high brightness nitride-based LEDs have found widespread application in solid-state lighting, full-color displays, exterior automotive lighting, and backlights of liquid crystal display panels [1–5]. Although these optoelectronic devices have already been commercialized, the light output power of LEDs is still insufficient for the applications in high brightness and power GaN-based LEDs, especially at high injection currents. It is known that this phenomenon with the significantly reduction of the efficiency at high current density has been called the "efficiency droop". Regarding the mechanisms of efficiency droop, different physical explanations have been investigated and proposed, including electron overflow [6–9], poor hole injection [10–12], Auger recombination [13–20], carrier delocalization form In-rich region [21–23], polarization field [24–32], and junction heating [33,34]. However, the origin of the efficiency droop mechanism for nitride-based LEDs is still a controversial and uncertain issue until now. Several researches reported that Auger recombination is believed as a possible origin of the efficiency droop mechanism. Iveland et al. reported that droop phenomenon in GaN light-emitting diodes originates from the excitation of Auger processes by detection of Auger electrons using electron emission spectroscopy [13]. And, Delaney et al. demonstrated that Auger recombination is indeed an important loss mechanism in wurtzite InGaN by means of rigorous first-principles calculations in which the Auger process can explicitly be isolated [16]. Several other researches reported that the droop effect can be improved by suppressing the polarization field and charge separation effect. Zhao et al. reported that several approaches of staggered InGaN QWs have been proposed to suppress the charge separation issue and improve electron–hole wavelength overlap [28]. Feezell et al. reported that the semipolar (2021) orientation emerges with excellent potential for the realization of high efficiency and low droop LEDs [27].

For another competing point of view, the non-uniform distribution of electrons and holes in the active region resulted from electrons overflow effect and poor holes injection efficiency is also a very important key issue for efficiency droop. This result is because that the diffusion coefficient (mobility) of holes is smaller than that of electrons for nitride-based materials. In addition, the

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unintentionally doped GaN of quantum barrier due to the nitrogen vacancy is n-type conductivity with electron density [35,36]. It can be concluded from the above two concepts that it is more difficult for hole to inject into and transport through the MQWs than that of electrons. It has been suggested that the structures of p-doped quantum well barriers or p-type MQWs were used to improve carriers transport and distribution and diminish the efficiency droop effect [10,37]. However, the epitaxy technology by metal–organic chemical vapor deposition (MOCVD) was very difficult to achieve the p-type doping without damaging the InGaN well owing to the magnesium memory effect even if it was only doped in quantum barrier. In this work, the blue InGaN/GaN MQWs LEDs with electron blocking layer (EBL) was investigated and demonstrated by varying the thickness of quantum barrier.

Besides, the hot/cold factor which was the value of degradation for light output powers of LEDs as functions of junction temperature currently is a very important key issue for actual application to LEDs [38]. In other words, this factor can indicate and let us comprehend how a LED can demonstrate in realistic operating conditions. Therefore, the stability performances of LEDs for temperature fluctuations must be enhanced further. Pan et al. achieved the thermal droop of only 9.7% and hot/cold factors greater than 0.9 by using thick single-quantum-well structure in semipolar (2021) substrate [39]. In our study, the temperature stability characteristics of LEDs will also be studied in detail.

2. Experimental

All samples used in this study were grown on *c*-plane (0001) sapphire substrate by MOCVD. During the growth, trimethylgallium (TMGa), trimethylindium (TMIn) and ammonia (NH_3) were used as gallium, indium, and nitrogen sources, respectively, while biscyclopentadienyl magnesium (CP_2Mg) and disilane (Si_2H_6) were used as the p-type and n-type doping sources, respectively. The conventional LED structure, called LED I, consists of a 30-nm thick buffer layer grown at low temperature, a 1.5-μm thick un-doped GaN layer grown at 1040 °C, a 2-μm thick Si-doped n-GaN layer grown at 1040 °C, and an multiple quantum well (MQW) active region grown at 750 °C. The MQW active region consists of 10 periods of 3-nm thick InGaN well layers and 12-nm thick GaN barrier layers. Subsequently, the temperature was elevated to 1000 °C to grow a 30-nm thick Mg-doped p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer (EBL) and a 0.3-μm thick p-GaN. Samples with GaN quantum barrier thickness of 9 and 6 nm were labeled as LED II and LED III, respectively, as shown in the Fig. 1. The as-grown samples were subsequently annealed at 750 °C in N_2 ambient for the activation of acceptors in the Mg-doped layers.

After the growth, the surface of the samples was partially etched until the 2-μm thick Si-doped n-GaN layer was exposed. Subsequently, a 70-nm-thick indium-tin oxide (ITO) layer was deposited by sputter system onto the p-GaN layer to serve as a current spreading layer. A Ni/Au (30 nm/500 nm) metal contact was deposited on the ITO layer to form the p-electrode. A Ti/Al/Ti/Au (15 nm/450 nm/50 nm/500 nm) metal contact was then deposited on the exposed n-GaN layer to form the n-electrode. Then, the 2-inch epi-wafers were lapped down to about 90 nm. Finally, the epi-wafers were diced in order to produce sets of 250 × 580 μm^2 LED chips. After processing, the fabricated LED chips were all mounted on TO-39 metal can packages to collect the emission light through sapphire side without epoxy resin or silicone for LED encapsulation. The current–voltage (I–V) characteristics of these samples were measured by an HP4156C semiconductor parameter analyzer. The light output powers were measured by the integrating sphere detector.

Regarding the hot/cold factor, the standard rules have not been defined very well. In our paper, we define the hot/cold factor for these three fabricated LEDs as the light output ratio at 80 and 30 °C. For the measured parameters, we applied pulse-width-modulated injection currents with a duty cycle of 0.1% in a 1000-ms period on each measured LEDs. In order to minimize the effects of self-heating, we also set the waiting time without injected any current (about 3–5 min) between each measured currents, which was controlled by the software program. The temperature of these three fabricated LEDs was varied using a heat controller, and the starting ambient temperature was 30 °C and was successively increased to 80 °C. The light output intensity was measured by using an electroluminescence (EL) system.

3. Results and discussion

Fig. 2 shows the forward current–voltage (I–V) characteristics of these three fabricated LEDs. Under an injection current of 20 mA, it was found that forward voltages of LED I, II, and III were 3.12, 3.08, and 3.06 V, respectively. The forward voltage decreased as the thickness of quantum barrier decreased. The function of the forward voltage (V_f) can be described as follows:

$$V_f = \frac{E_g}{q} + IR_s + \frac{\Delta E_C - E_0}{q} + \frac{\Delta E_V - E_0}{q} \quad (1)$$

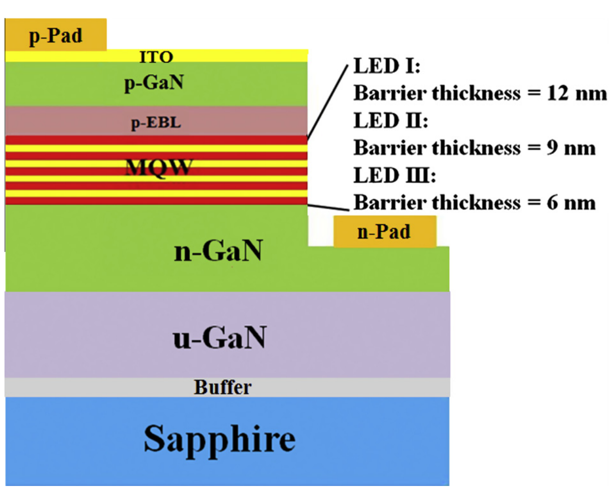

Fig. 1. The schematic structures of these three fabricated LEDs.

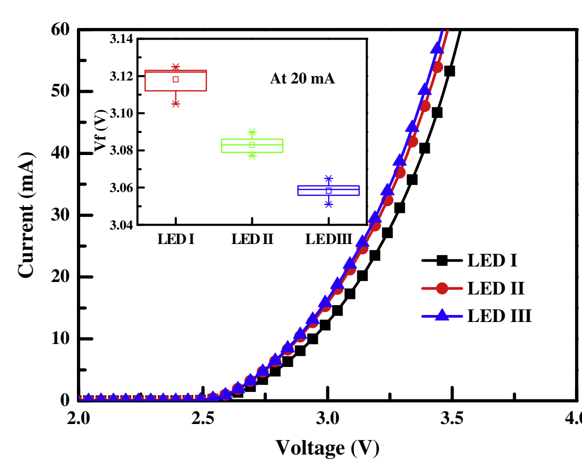

Fig. 2. The I–V characteristics of these three fabricated LEDs. Insert: the box-and-whisker diagram of forward voltage at an injection current of 20 mA.