OPTOELECTRONICS LETTERS Vol.11 No.4, 1 July 2015

Experimental study of GaN based blue light emitting diodes with a thin AlInN layer in front of the electron blocking layer*

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(Received 19 April 2015)

The GaN based blue light emitting diodes (LEDs) with a thin AlInN layer inserted in front of the electron blocking layer (EBL) are experimentally studied. It is found that inserting a thin EBL can improve the light output power and reduce the efficiency droop compared with the conventional AlGaN counterparts. Based on numerical simulation and analysis, the improvement on the electrical and optical characteristics is mainly attributed to the reduction of the electron leakage current, which increases the concentration of carriers in the quantum well (QW) when the thin AlInN layer is used.

Document code: A **Article ID:** 1673-1905(2015)04-0248-4

DOI 10.1007/s11801-015-5065-3

Recently, solid-state illumination sources, especially InGaN/GaN based light-emitting diodes (LEDs), have been developed to take place of traditional sources, due to their higher efficiency and longer lifetime[1]. However, the reduction of emission efficiency at high injection current density, which is often called efficiency droop, seriously restricts the InGaN/GaN based LEDs application in the realization of high-power, high-brightness illumination[2]. Various models for the efficiency droop have been proposed, including the ones with Auger recombination[3,4], polarization-assisted electron leakage[5,6], lack of hole injection[7,8], defects[9] and junction heating[10]. Among these factors, electron leakage out of the active region as well as inefficient hole injection has been identified as the major reasons for efficiency droop[11]. To reduce the electron leakage, $Al_xGa_{1-x}N$ electron blocking layer (EBL) is often adopted between last quantum barrier (QB) and p-GaN layer in conventional LED structure. However, due to the lattice mismatch between GaN and $Al_xGa_{1-x}N$, there will be a large polarization field between the last couple of quantum well (QW) and $Al_xGa_{1-x}N$ EBL, which will reduce the effective barrier height for electrons[12]. Thus, the electron leakage can not be suppressed efficiently. On the other hand, the polarization filed included band bending and the valence band offset (ΔE_v) at the interface of GaN and EBL can enhance the effective barrier height for holes, and then retard the hole injection[5]. To avoid these problems, some methods have been proposed. C. H. Wang et al[13] designed a grade-composition $Al_xGa_{1-x}N$ EBL (GEBL) to suppress the electron leakage and also to enhance the hole injection in simulation. Wang Tian-Hu et al[14] used sawtooth-shaped $Al_xGa_{1-x}N$-GaN-$Al_xGa_{1-x}N$ EBLs to enhance the electron confinement and the hole injection efficiency. Suk Choi et al[15] used InAlN with In composition of 0.18, which is lattice-matched to GaN, as the EBL. Yen-Kuang Kuo[16] used AlInGaN to replace the original EBL and barrier layer. Although using InAlN or AlInGaN as the EBL can prevent the electron leakage effectively, the hole injection cannot be improved due to the existence of high ΔE_v between the last couple of GaN barrier and the EBL[12]. It has also been reported that p-AlGaN/GaN or p-InGaN/GaN superlattice (SL) in LED structure can prevent the carrier leakage over the EBL[17,18]. In this paper, we insert a thin AlInN layer before the AlGaN electron blocking layer to prevent the carrier leakage over the EBL as well as to improve the hole injection efficiency. The electrical and optical properties of the LED with and without AlInN layer are experimentally investigated.

The LED samples used in this study were grown by metal organic chemical vapor deposition on c-plane sapphire substrates. The original epitaxial structure (labeled as conventional LED) was composed of a 25 nm-thick low-temperature GaN nucleation layer, a 2.0 μm-thick undoped GaN layer, a 3.0 μm-thick Si doped GaN layer, six-period InGaN/GaN multi quantum wells (MQWs) with 3 nm-thick wells and 10 nm-thick barriers, a 20 nm-thick p-type $Al_{0.1}Ga_{0.9}N$ EBL with Mg doping concentration of 1×10^{19} cm^{-3} and a 170 nm-thick Mg

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* This work has been supported by the Key Scientific Research Project of Higher Education of Henan Province (No.15A510033).

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doped GaN layer. The InGaN QW growth temperature was about 730 °C with In fraction of about 0.16. Another epitaxial structure (labeled as newly designed LED) was composed of the same structure except that a 2 nm-thick p-type $Al_{0.82}In_{0.18}N$ layer was grown at 790 °C and 6.5×10^5 Pa in front of the original AlGaN EBL. The Mg doping concentrations of AlInN and AlGaN are both 5×10^{19} cm^{-3}. The device geometry was designed as a rectangular shape of 300 μm×300 μm. LED chips were fabricated using a conventional mesa structure method and processed into capsulated LEDs. The electrical properties were measured by on-wafer probing, and the luminescence properties were collected by a calibrated integrating sphere with a pulse mode current at room temperature (RT). The band gap energy parameters of the AlGaN, InGaN and AlInGaN alloys can be found from Refs.[19] and [20].

The measured output powers of the two structures with increasing current are shown in Fig.1. It can be seen that the light output power of conventional LED is comparable to that of the newly designed EBL LED at low injection current. With further increasing the injection current, the light output power of conventional LED is surpassed by that of the newly designed EBL LED. The smaller downward bending of the output power-current curve is observed in the newly designed EBL LED, which suggests that the efficiency droop can be alleviated with the insertion of a 2 nm-thick $Al_{0.82}In_{0.18}N$ layer in front of the EBL. At the injection current of 100 mA, the light output power can be enhanced by more than 5 mW by using this newly designed EBL LED.

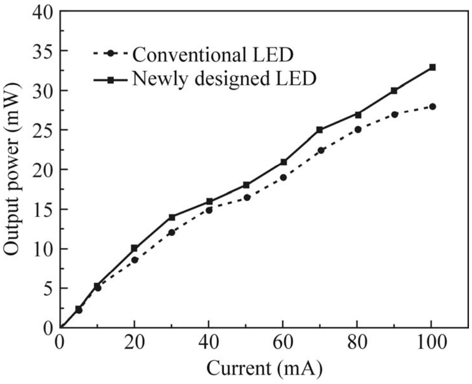


Fig.1 Measured output powers of the two LEDs

The photoluminescence (PL) measurement was carried out using a 325 nm He-Cd laser. Fig.2 shows the normalized RT PL spectra of conventional LED and the newly designed LED. The peak wavelengths of the two samples are both 452 nm, which means the same In composition in the QWs. The full width at half maximum (FWHM) of PL spectrum of conventional LED is 21 nm, and that of the newly designed LED is 16 nm. The FWHMs of the LEDs can be an indication of the crystal quality of the multiple QWs, because the EBL layer is grown behind the InGaN/GaN active region. Normally, the growth temperature of the conventional AlGaN is about 970 °C, which is much higher than that of QW at 730 °C. This high growth temperature is detrimental to the InGaN QWs, while the growth temperature of AlInN is about 790 °C, which is close to that of InGaN QWs. Thus the crystal quality of the InGaN QW can be improved.

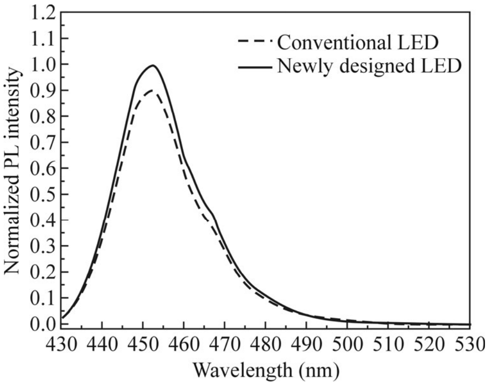
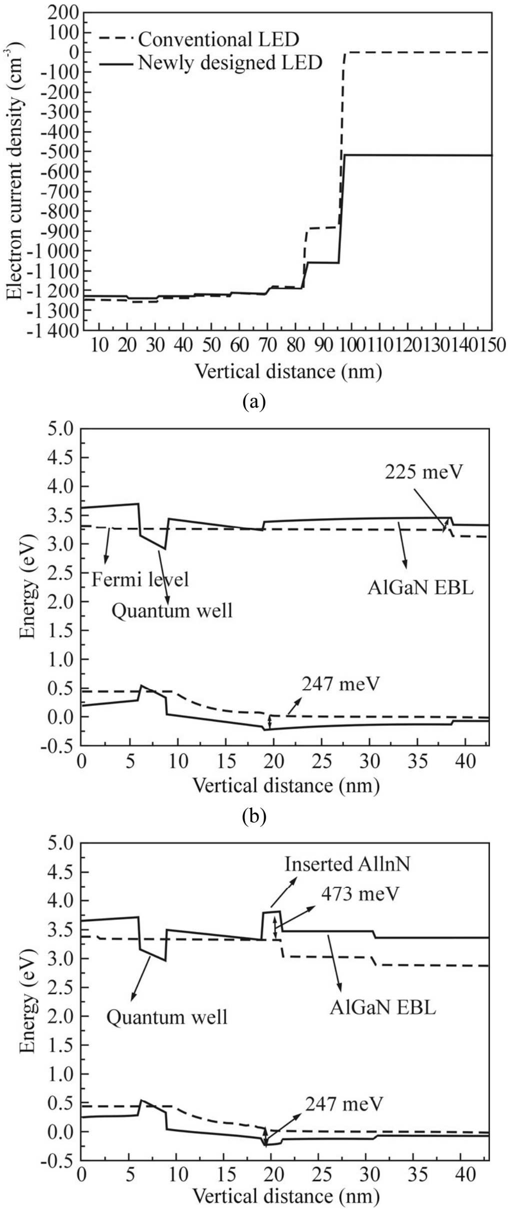


Fig.2 The normalized RT PL spectra of the two LEDs

In order to explain the influence of the insertion of the 2 nm-thick $Al_{0.82}In_{0.18}N$ layer on the LED performance, the optical and electrical properties of the LEDs with the conventional EBL and the newly designed EBL are calculated. The simulation structures remain the same as our experimental samples. Most of the parameters used in this paper are the same as those in Ref.[11]. Other material parameters of the semiconductors used in the simulation can be found in Refs.[12], [13] and [21].

Fig.3(a) shows the electron current distributions of the two structures under 20 mA. As can be seen from Fig.3(a), the electron leakage in the newly designed EBL LED is remarkably reduced compared with that in the conventional LED. This can be explained as follows. The large polarization field induces the band bending in the active region as shown in Fig.3(b) and Fig.3(c). The QB and EBL can hardly block the electron overflow from QWs to p-type layer, and thus leads to the electron current leakage in conventional structure with GaN barriers. However, for the newly designed LED, the inserted $Al_{0.82}In_{0.18}N$ layer can reduce the lattice mismatch between the last QW and EBL, and the bandgap of $Al_{0.82}In_{0.18}N$ is larger than that of $Al_{0.1}Ga_{0.9}N$, thus the electron leakage current can be dramatically reduced.

Fig.4(a) and Fig.4(b) show the simulated carrier concentrations and hole concentrations of two LEDs in MQWs cut from n-side to p-side under the injection current of 50 mA. It can be seen clearly that a large amount of carriers for all the samples accumulate in the last QW next to the p-type layer. Compared with those in the conventional structure, the electron concentration and hole concentration both increase gradually in the newly designed structure, which can be attributed to the enhancement of hole injection efficiency as well as the electron confinement. Fig.4(c) shows the radiative recombination rate of LED samples. It is obvious that most of the radiative recombination happens in the QWs near the p-type layer. This is due to the non-uniform carrier distribution in QWs as discussed above. Besides, it can also be found that the radiative recombination rate of the newly designed LED is higher than that of the conventional structure, which is mainly attributed to the higher electron and hole concentrations compared with those of the conventional one.



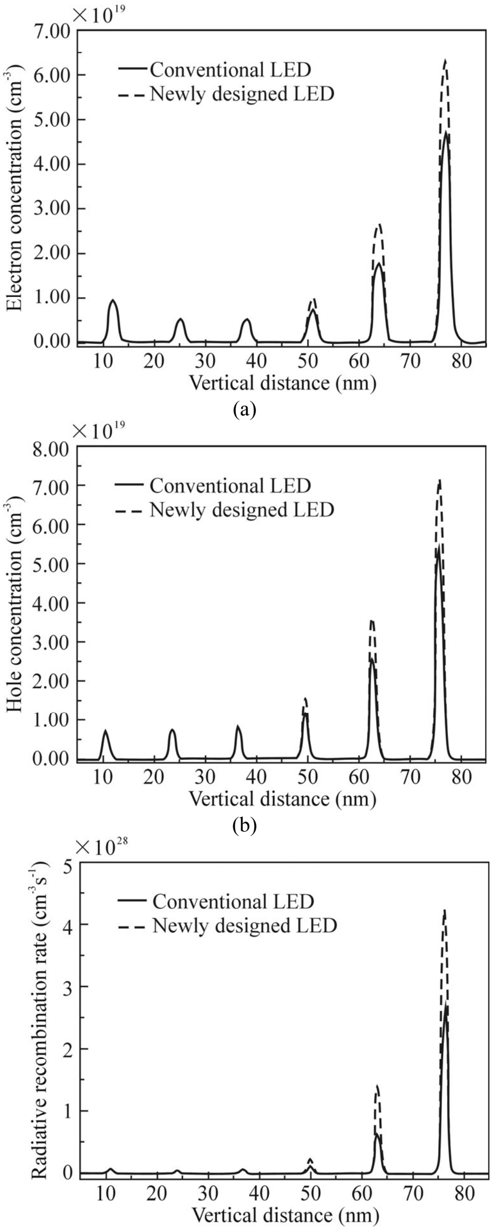
(a)

(b)

(c)

Fig.3 (a) The electron current densities of the two LEDs; The energy bandgaps of (b) conventional LED and (c) newly designed LED

The dependence of internal quantum efficiency (IQE) on forward current is presented in Fig.5. As the forward current increases, both the two samples show obvious efficiency droop in IQE. However, the efficiency droop in the newly designed structure is much smaller than that of the conventional one. Therefore, by inserting a 2 nm-thick $Al_{0.82}In_{0.18}N$ layer in front of the EBL, the efficiency droop can be reduced.



(a)

(b)

(c)

Fig.4 The distributions of (a) electron concentration, (b) hole concentration and (c) radiative recombination rate of the two LEDs under the injection current of 50 mA

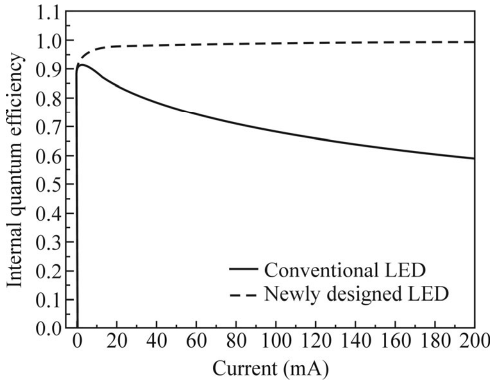


Fig.5 IQE as a function of the injection current for the two LEDs

In conclusion, the LED with a 2 nm-thick AlInN layer inserted in front of the EBL improves the light output power and reduces the efficiency droop. Based on our experimental and theoretical study, the improvement of the electrical and optical characteristics is mainly attributed to the reduction of electron leakage, which improves the crystalline quality of the InGaN QWs.

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