Study of dual-blue light-emitting diodes with asymmetric AlGaN graded barriers

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A dual-blue light-emitting diode (LED) with asymmetric AlGaN composition-graded barriers but without an AlGaN electron blocking layer (EBL) is analyzed numerically. Its spectral stability and efficiency droop are improved compared with those of the conventional InGaN/GaN quantum well (QW) dual-blue LEDs based on stacking structure of two $In_{0.18}Ga_{0.82}N$/GaN QWs and two $In_{0.12}Ga_{0.88}N$/GaN QWs on the same sapphire substrate. The improvement can be attributed to the markedly enhanced injection of holes into the dual-blue active regions and effective reduction of leakage current.

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III-V nitride based light-emitting diodes (LEDs) have attracted much attention for applications, such as solid-state lighting and backlight in liquid-crystal displays[1,2]. For the case of lighting, the $Y_3Al_5O_{12}$:Ce^{3+} (YAG:Ce) phosphor-converted white LED is a strong competitive candidate due to relatively easy fabrication, low cost and high brightness[3]. However, this kind of white LED suffers from low color-rendering index (CRI) and efficiency droop at the high injection current. The efficiency droop is influenced by the carrier localization[4], threading dislocation and strong built-in electrostatic field caused by the large lattice mismatch between InGaN and GaN in the multiple-quantum well (MQW) active region[5,6]. Many techniques to eliminate the efficiency droop have been proposed, such as using newly staggered InGaN quantum well (QW) structure[7], the δ-AlGaN layer in InGaN QW[8,9], type-II InGaN-GaNAs QW[10], InGaN-delta-InN QW[11] and the strain compensated InGaN-AlGaN QW[12]. Recently, it has also been shown that the use of asymmetric AlGaN composition-graded barriers (CGBs) can reduce the leakage current and enhance the injection of holes into the active region markedly[13], which is important for achieving high performance LEDs.

The current technological target in the white LED is to achieve high color rendering properties without degrading emission efficiency. Our recent study shows that CRI of the white LED based on YAG:Ce phosphor conversion can be significantly improved by using dual-blue active layers[14,15]. However, this conventional dual-blue emission peaks are strongly dependent on the injection current due to the nonuniform distribution of electrons and holes in the dual-blue active regions. In this paper, we fabricate two kinds of dual-blue LEDs based on stacking structure of two $In_{0.18}Ga_{0.82}N$/GaN QWs and two $In_{0.12}Ga_{0.88}N$/GaN QWs on the same sapphire substrate. In order to realize blue and blue-violet light emission with better spectral stability and efficiency, the QW structure with grading AlGaN barriers is utilized in our dual-blue active regions, and the AlGaN electron blocking layer (EBL) is removed.

The optical and electrical properties of two kinds of dual-blue LEDs are analyzed and discussed by using the advance physical model of semiconductor devices (APSYS) simulation program[16] which is capable of dealing with the physical properties of LEDs. Most of the parameters used in this paper are the same as those in Ref.[17]. Other material parameters of the devices used in the simulation can be found in Ref.[18].

The original structure used in this paper is grown on (0001)-oriented sapphire substrate by metal-organic chemical vapor deposition (MOCVD) with a Thomas Swan close-spaced showerhead reactor. As shown in Fig.1(a), the conventional InGaN/GaN QW dual-blue LED consists of a GaN buffer layer, a 2 μm-thick undoped GaN layer, a 2 μm-thick Si-doped GaN, a two-period $In_{0.18}Ga_{0.82}N$(3 nm)/GaN(10 nm) QW active region, a two-period $In_{0.12}Ga_{0.88}N$ (3 nm)/GaN(10 nm) QW active region, a 15 nm-thick p-type $Al_{0.15}Ga_{0.85}N$ layer as EBL and a 200 nm-thick Mg-doped p-GaN layer.

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The typical carrier concentrations of n-GaN and p-GaN at room temperature are 4×10^{18} cm^{-3} and 5×10^{17} cm^{-3}, respectively. For the AlGaN CGBs dual-blue LED without an AlGaN EBL, the p-AlGaN EBL is removed and the Al composition of AlGaN barriers is varied gradually from 10% to 8% for the first AlGaN barrier, which is close to the n-side, and 8% to 6% for the second AlGaN barrier, and so on. The device geometry is designed with a rectangular shape of 300 μm×300 μm.

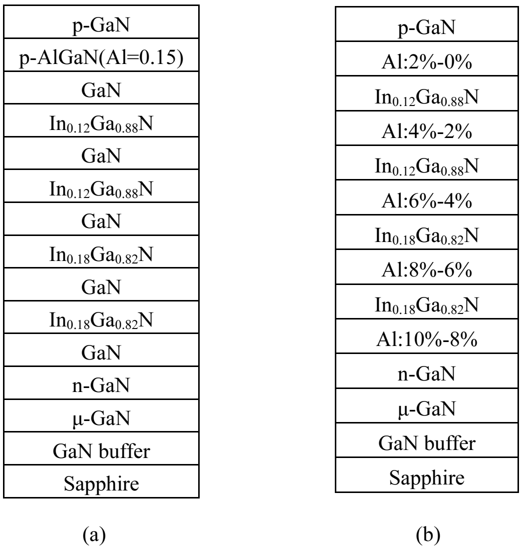
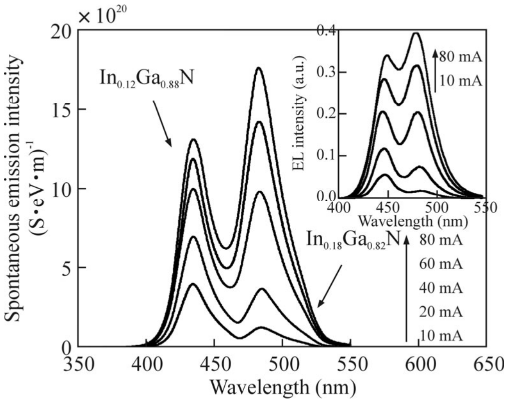
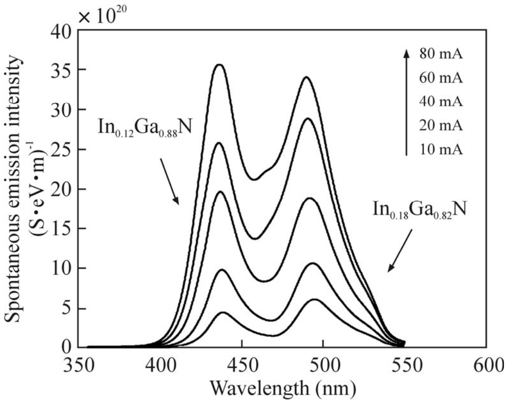


Fig.1 Schematic diagrams of (a) conventional InGaN/GaN QW dual-blue LED and (b) AlGaN CGBs dual-blue LED without an AlGaN EBL

The insert of Fig.2(a) demonstrates the experimental electroluminescence (EL) spectra of a traditional InGaN/GaN dual-blue LED at different forward currents. Two clear EL peaks are observed in the insert of Fig.2(a), which originate from the $In_{0.12}Ga_{0.88}N$/GaN QWs and $In_{0.18}Ga_{0.82}N$/GaN QWs, respectively. The blue-violet and blue emission peaks are located at about 440 nm and 470 nm, respectively. At the low injection current, the intensity of blue-violet emission is far stronger than that of blue emission, and then the intensity of blue emission increases gradually with the increase of injection current. When the injection current reaches 40 mA, the EL intensities of these two emission peaks are almost the same. As the injection current is further increased, the intensity of blue emission becomes larger than that of blue-violet emission. The corresponding intensity ratio of blue-violet light to blue light for InGaN/GaN QW dual-blue LED in a range from 10 mA to 80 mA changes from 4.1 to 0.90, which indicates that carrier distribution of dual-blue active layers with GaN barriers is more nonuniform. Fig.2(a) and (b) show the simulated EL spectra of InGaN/GaN LED and AlGaN CGBs LED without EBL at different forward currents, respectively. In this calculation, some simulation parameters are adjusted in order to make the simulated emission spectra of InGaN/GaN LED consistent with the experimental results. For the AlGaN CGBs without EBL structure, when the Al composition is varied gradually in different barriers, the EL intensity ratio of blue-violet light to blue light in a range from 10 mA to 80 mA is almost equal to 1.0, which indicates that the carrier distribution of dual-blue active layers employing AlGaN CGBs and removing EBL is more uniform than that of the original structure, as shown in Fig.2(b).



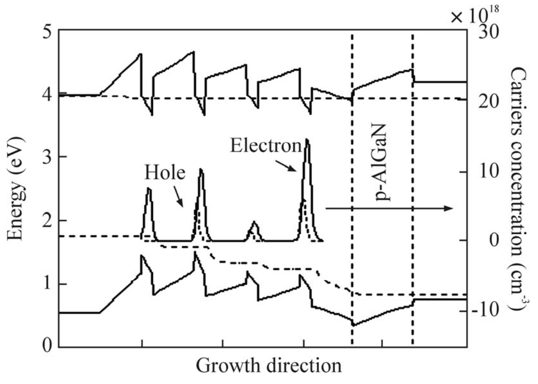
(a) InGaN/GaN LED



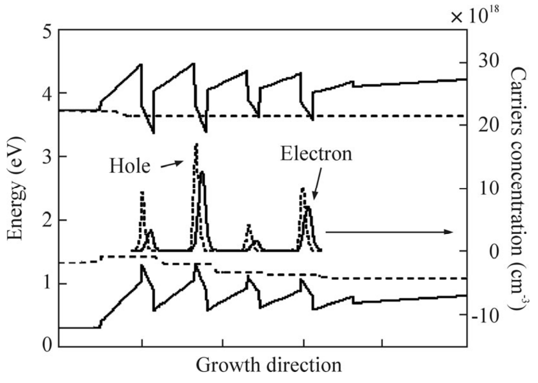
(b) AlGaN CGBs LED without EBL

Fig.2 Simulated EL spectra of InGaN/GaN LED and AlGaN CGBs LED without EBL (The inset shows the experimental EL spectra of InGaN/GaN QW structure.)

Fig.3 shows the calculated band diagrams, quasi-Fermi levels and carrier concentrations of InGaN/GaN LED and AlGaN CGBs LED at 20 mA, respectively. It can be observed from Fig.3(a) that when the LED has GaN barriers, the strong electric field caused by the spontaneous and piezoelectric polarization charges at the interface between well and barrier layers leads to serious electron current leakage and significant reduction of electron-hole wave functions overlapping due to the lattice mismatch. Thus, low performance can be expected to appear in this structure. On the other hand, for the GaN-based materials, relatively large effective mass and low mobility of holes lead to nonuniform distribution of holes in the dual-blue emitting active layers, resulting in a large number of electrons and holes accumulating in the QW close to the p-side layer. This is consistent with the experimental result that the EL emission intensity from the $In_{0.12}Ga_{0.88}N$/GaN QW close to p-GaN side is stronger than that from $In_{0.18}Ga_{0.82}N$/GaN QW near n-GaN side. However, as seen in Fig.3(b), when the dual-blue LED is with the asymmetric AlGaN CGBs but without an AlGaN EBL, the quasi-Fermi level in the valence band becomes closer to the band edge of the mixture QWs, while the quasi-Fermi level in the conduction band gets farther away from the band edge of the mixture QWs. As a result, electrons are confined in the active region more effectively, and holes are injected into the active region more easily as shown in Fig.3(a) and (b). Therefore, the electron and hole distributions become more matching in the whole dual-blue active layers with AlGaN CGBs but without EBL. The spectrum stability of dual-blue emission becomes better, and it is consistent with the simulated EL spectra.



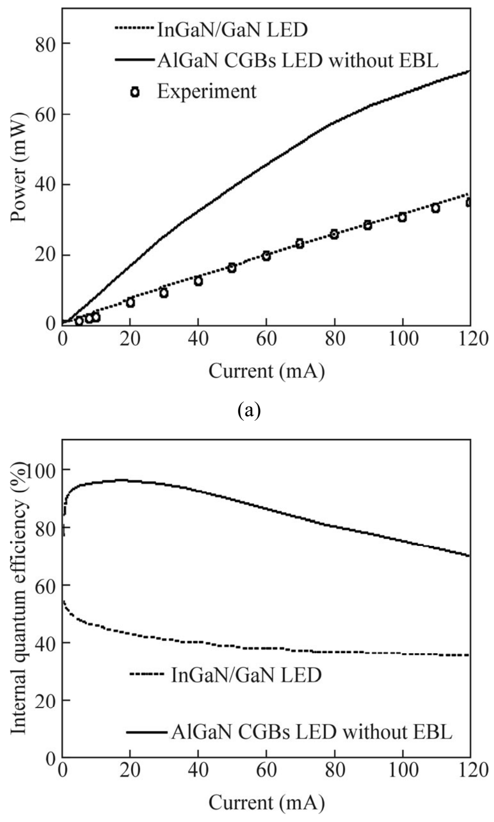
(a) InGaN/GaN LED



(b) AlGaN CGBs LED without EBL

Fig.3 Band diagrams, quasi-Fermi levels and carrier concentrations of InGaN/GaN LED, and AlGaN CGBs LED without EBL at 20 mA

Fig.4(a) shows that the simulated light output power-current (*P-I*) performance curve of the original LED is in good agreement with the total extracted light obtained experimentally. When grading AlGaN barriers are utilized in dual-blue active regions and the AlGaN EBL is removed, the AlGaN CGBs LED has better lighting efficiency. The light output power of AlGaN CGBs LED at 120 mA is improved by a factor of 1.90 as compared with that of InGaN/GaN LED. The internal quantum efficiencies (IQEs) of the two LEDs as a function of injection current are shown in Fig.4(b). It is noteworthy that there is almost no obvious efficiency droop for AlGaN CGBs LED, and the serious efficiency droop of the original LED can be mitigated consequently. Because of the advantages in hole injection and electron blocking, the performance of the AlGaN CGBs LED is expected to be superior to that of InGaN/GaN LED.



(a)

(b)

Fig.4 (a) Light output power versus current and (b) IQE versus current of InGaN/GaN LED and AlGaN CGBs LED without EBL

In summary, a dual-blue wavelength LED with stable spectrum and high efficiency is realized by using the AlGaN CGBs and removing the AlGaN EBL, which is mainly attributed to the markedly enhanced injection of holes into the dual-blue active regions and effective reduction of leakage current.

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