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Advantages of blue InGaN light-emitting diodes with InGaN-AlGaN-InGaN barriers

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Efficiency enhancement of the blue InGaN light-emitting diodes (LEDs) with InGaN-AlGaN-InGaN barriers is studied numerically. The energy band diagrams, carrier concentrations in quantum wells, radiative recombination rate in active region, light-current performance curves, and internal quantum efficiency are investigated. The simulation results suggest that the blue InGaN-InGaN-AlGaN-InGaN LED has better performance over its conventional InGaN/GaN and InGaN/InGaN counterparts due to the appropriately modified energy band diagrams, which are caused mainly by the reduced polarization charges at the interface between the well and barrier. © 2012 American Institute of Physics. [doi:10.1063/1.3678341]

High-performance III-nitride light-emitting diodes (LEDs) have tremendous potential for energy-efficient lighting. However, the optical performance of III-nitride optoelectronic devices could be largely weakened by several mechanisms including the quantum confined Stark effect (QCSE), current injection efficiency, crowding effect, self-heating effect, and polarization effect. Recently, many approaches, such as the usage of InGaN barriers, GaN-InGaN-GaN barriers, staggered quantum wells (QWs), graded electron blocking layer (EBL), and InGaN-delta-InN QWs, are reported toward the improvement of the optical performance. In this letter, InGaN LEDs with InGaN-AlGaN-InGaN barriers are proposed.

Based on our prior studies, when the conventional GaN barriers were replaced by the InGaN barriers, the polarization effect between the well and barrier could be effectively reduced. However, under this circumstance, the potential height for carrier confinement may be reduced due to relatively small energy band gap of InGaN. Thus, the idea of multilayer barriers was proposed with reduced polarization and decreased electron current overflow. For GaN template, the AlGaN layer is with tensile strain and the InGaN layer is with compressive strain. Hence, the use of InGaN-AlGaN heterostructure is beneficial for strain relaxation and is quite feasible for epitaxial growth.

The Caughey-Thomas approximation is employed for the mobility as a function of carrier density

$$\mu(N) = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + \left(\frac{N}{N_{\text{ref}}}\right)^{\alpha}},$$

(1)

where $\mu_{\text{min}}$, $\mu_{\text{max}}$, $N_{\text{ref}}$, and $\alpha$ are fitting parameters according to the experimental mobility measurements. For InGaN, the values of $\mu_{\text{max}}$, $\mu_{\text{min}}$, $N_{\text{ref}}$, and $\alpha$ are 306 cm$^2$/V-s, 386 cm$^2$/V-s, 1.0 $\times$ 10$^{17}$ cm$^{-3}$, and 1.37, respectively. For AlGaN, $\mu_{\text{max}}$, $\mu_{\text{min}}$, $N_{\text{ref}}$, and $\alpha$ are 132 cm$^2$/V-s, 386 cm$^2$/V-s, 1.0 $\times$ 10$^{17}$ cm$^{-3}$, and 0.29, respectively. The values of hole mobility are assumed to be 2 cm$^2$/V-s for InGaN and 10 cm$^2$/V-s for AlGaN in simulation. Thus, the electrons possess higher mobility in InGaN and holes possess higher mobility in AlGaN. In this work, it is proposed that the original GaN barrier be divided into three parts, in which the first part and the third part of the GaN barrier is replaced by InGaN and the middle part is replaced by AlGaN. This proposed barrier is referred as InGaN-AlGaN-InGaN barrier herein this study. With this design, in addition to higher mobility for both electrons and holes, it might be possible that the LEDs could be with reduced polarization charges at the interface between the well and barrier without the price of losing potential height for carrier confinement.

The simulation is executed with APSYS program, which was developed by the Crosslight Software Inc. The LED structure used as a reference and simulation parameters are the same as those used in our previous studies. In addition to the performance of the LED with proposed InGaN-AlGaN-InGaN barriers, the characteristics of the LED with InGaN barriers are also discussed in this study. The original barriers are six 15-nm-thick GaN layers. The InGaN barriers are six 15-nm-thick In$_{0.05}$Ga$_{0.95}$N layers in which the indium composition is optimized according to our prior study. The InGaN-AlGaN-InGaN barriers are also six 15-nm-thick layers. Every layer comprises a 5-nm-thick In$_{0.05}$Ga$_{0.95}$N layer, a 5-nm-thick Al$_{0.05}$Ga$_{0.95}$N layer, and a 5-nm-thick In$_{0.05}$Ga$_{0.95}$N layer. The schematic diagrams of the three LED structures under study are depicted in Fig. 1.

Figure 2 shows the energy band diagrams and quasi-Fermi levels of the three LED structures at 300 mA. Figure 2(a) shows that the serious tilting of energy band largely weakens the optical performance of the LED with conventional GaN barriers due to relatively strong polarization field. As indicated in Fig. 2(b), the use of InGaN barriers is beneficial for enhancing the electron confinement without the price of blocking holes. The effective potential height between the last barrier and EBL increases due to the lower conduction band energy of InGaN. In the conduction band, there is a specific point where the energy is below the quasi-Fermi level at the interface between the last barrier and EBL. Moreover, in the valence band, the quasi-Fermi level is well above the band edge of the first QW. On the other hand, as shown in Fig. 2(c), the energy band of the LED with

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InGaN-AlGaN-InGaN barriers shows superior characteristics of our design. The aforementioned problems have been largely improved due to the elevated potential of AlGaN layer in the conduction band. On the other hand, in the valence band, the distance between the quasi-Fermi level and the band edge of the first QW becomes minimal due to the appropriately modified energy band diagrams.

Figure 3 shows the carrier concentration near the active region of the three LED structures at 300 mA. Figure 3(a) shows that both electrons and holes accumulate in the last QW, which leads to serious electron current overflow and non-uniform distribution of holes in the conventional InGaN/GaN LEDs. Contrarily, in Fig. 3(b), marked improvement of carrier concentration is observed; however, accumulation of carriers in the last well remains unchanged. On the other hand, as indicated in Fig. 3(c), the hole concentration is markedly improved, except for the last QW, and the distribution of electrons and holes in the QWs becomes much more uniform. Calculation shows that the hole concentration

**TABLE:**

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<thead>
<tr>
<th>Barriers: Composition</th>
<th>Thickness</th>
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<tbody>
<tr>
<td>GaN barriers (original)</td>
<td>GaN</td>
</tr>
<tr>
<td>InGaN barriers</td>
<td>In$<em>{0.05}$Ga$</em>{0.95}$N</td>
</tr>
<tr>
<td>InGaN-AlGaN-InGaN barriers</td>
<td>In$<em>{0.25}$Ga$</em>{0.75}$N</td>
</tr>
<tr>
<td></td>
<td>Al$<em>{0.05}$Ga$</em>{0.95}$N</td>
</tr>
<tr>
<td></td>
<td>In$<em>{0.25}$Ga$</em>{0.75}$N</td>
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**FIG. 1.** (Color online) Schematic diagrams of the three LED structures under study.

**FIG. 2.** (Color online) Energy band diagrams of the LEDs with (a) GaN barriers, (b) InGaN barriers, and (c) InGaN-AlGaN-InGaN barriers at 300 mA. Light yellow regions represent the locations of barriers.

**FIG. 3.** (Color online) Carrier concentrations of the LEDs with (a) GaN barriers, (b) InGaN barriers, and (c) InGaN-AlGaN-InGaN barriers at 300 mA.
in the active region increases by 27.9% and 105.6% when the GaN barriers are replaced by the InGaN barriers and InGaN-AlGaN-InGaN barriers, respectively.

Figure 4 shows the radiative recombination rate of the three LED structures at 300 mA. The radiative recombination rate in the active region increases by 41.9% and 135.8% when the GaN barriers are replaced by the InGaN barriers and InGaN-AlGaN-InGaN barriers, respectively. Note that, relatively small efficiency droop is observed when the LED is with InGaN-AlGaN-InGaN barriers.

In conclusion, the performance of the blue InGaN LEDs is markedly improved when the GaN barriers are replaced by InGaN-AlGaN-InGaN barriers due to the appropriately modified energy band diagrams, high carrier injection efficiency, uniform distribution of carriers in the QWs, high radiative recombination rate in the active region, and small efficiency droop.

FIG. 4. (Color online) Radiative recombination rate of the LEDs with (a) GaN barriers, (b) InGaN barriers, and (c) InGaN-AlGaN-InGaN barriers at 300 mA.

FIG. 5. (Color online) (a) Light output power and (b) IQE as a function of current for the LEDs with GaN barriers, InGaN barriers, and InGaN-AlGaN-InGaN barriers.

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15APSYS, Crosslight Software Inc., Burnaby, Canada.