01 Mar 2012

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Recommended Citation

T. Lu and S. Li and C. Liu and K. Zhang and Y. Xu and J. Tong and L. Wu and H. Wang and X. Yang and Y. Yin and G. Xiao and Y. Zhou, "Advantages of GaN Based Light-Emitting Diodes with a P-InGaN Hole Reservoir Layer," *Applied Physics Letters*, vol. 100, American Institute of Physics (AIP), Mar 2012.

The definitive version is available at https://doi.org/10.1063/1.3700722

Advantages of GaN based light-emitting diodes with a p-InGaN hole reservoir layer

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(Received 19 January 2012; accepted 12 March 2012; published online 3 April 2012)

A p-type InGaN hole reservoir layer (HRL) was designed and incorporated in GaN based light-emitting diodes (LEDs) to enhance hole injection efficiency and alleviate efficiency droop. The fabricated LEDs with p-type HRL exhibited higher light output power, smaller emission energy shift and broadening as compared to its counterpart. Based on electrical and optical characteristics analysis and numerical simulation, these improvements are mainly attributed to the alleviated band bending in the last couple of quantum well and electron blocking layer, and thus better hole injection efficiency. Meanwhile, the efficiency droop can be effectively mitigated when the p-InGaN HRL was used. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3700722]

InGaN/GaN based high-brightness light-emitting diodes (LEDs) have attracted much attention because of their applications in signage, back lighting, and general illumination. In spite of the luminous emission efficiency of InGaN/GaN LEDs has been improved dramatically in the last few years, the phenomenon referred to as efficiency droop is still a severe problem for further application of high power GaN based LEDs. Over the past few years, several different mechanisms for efficiency droop have been proposed. Among these factors, the poor hole injection efficiency and insufficient electron blocking are regarded to play a key role for this issue.[1–6] When LEDs are used for high power application, the hole injection and electron current leakage become increasingly important. On one side, holes have a relatively high effective mass and therefore a very low mobility for GaN-based devices, which is difficult for holes to transport from p-type layer to active region. Furthermore, the sloped down electron blocking layer (EBL) is found to act as a potential barrier for hole transportation.[7] In contrast to the holes, electrons have a small effective mass and high mobility. Electrons can overflow across quantum barriers (QBs) and EBL potential easily and give rise to insufficient electron blocking. As a result, the leakage current in the p-type region can recombine with holes, and thus reduce the hole injection efficiency as well as the quantum efficiency.

To improve hole injection, Khan and co-workers reported that accumulation hole layer (AHL) can be created at AlGaN/GaN interface in AlGaN/GaN heterostructure by using polarization effect.[8,9] In this paper, we designed a p-type InGaN hole reservoir layer (HRL) between multiple quantum wells (MQWs) and EBL for InGaN/GaN blue LEDs, which is suggested to enhance the hole injection efficiency without lowering the blocking capability of electrons.

The conventional and HRL LED wafers were grown on c-sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The epitaxial wafer structures consisted of a 25 nm thick low-temperature GaN nucleation layer, a 2.0 μm thick undoped GaN layer, and a 2.0 μm thick Si-doped n-GaN layer. The active region consisted of six 3.0-nm-thick $In_{0.16}Ga_{0.84}N$ quantum wells (QWs), separated by seven 10-nm-thick GaN barriers. On the top of the last QB was a 20 nm thick p-$Al_{0.1}Ga_{0.9}N$ EBL and a 170 nm thick p-GaN cap layer. For the HRL LED, a 10 nm thick p-$In_{0.05}Ga_{0.95}N$ HRL and 2 nm p-GaN cap layer was inserted between the InGaN/GaN MQW and EBL. The device geometry was designed to be a rectangular shape of $300 \times 300\ \mu m^2$. LED chips were fabricated using a conventional mesa structure method. The luminescence properties of the fabricated LEDs were measured with a calibrated integrating sphere at room temperature.

The electroluminescence (EL) spectra from the two samples, at injection currents of 5 mA and 20 mA, are shown in Figs. 1(a) and 1(b). It can be seen that the two structures exhibit similar EL characteristic under the injection currents of 5 mA and 20 mA. That is, the only observed emission comes from the radiative recombination in QWs, which indicates that no radiative emission occurred in p-InGaN HRL. The designed indium composition in p-InGaN HRL is about 0.05, and the corresponding absorption wavelength is about 400 nm, which is much shorter than the emission wavelength of the QWs. Thus, the absorption of the emission light from QWs could be neglected.[10] The EL peak wavelength and full width at half maximum (FWHM) as a function of forward injection current for the two structures are shown in Fig. 1(c). The peak wavelength (460.2 nm at 20 mA) and FWHM (23.6 nm at 20 mA) are similar with conventional LED (460.9 nm and 24.4 nm). However, with the increase of the forward injection current from 1 mA to 200 mA, HRL LED exhibits smaller blueshift of 7 nm and broadening of about 8 nm, compared with 11 nm and 15 nm. Generally, the peak wavelength blueshift of LEDs can be interpreted by the Coulomb screening of piezoelectric filed induced quantum confined Stark effect (QCSE), while broadening of FWHM is commonly due to the band-filling effect of the carriers in QWs and self-heating effect. The smaller blueshift in HRL

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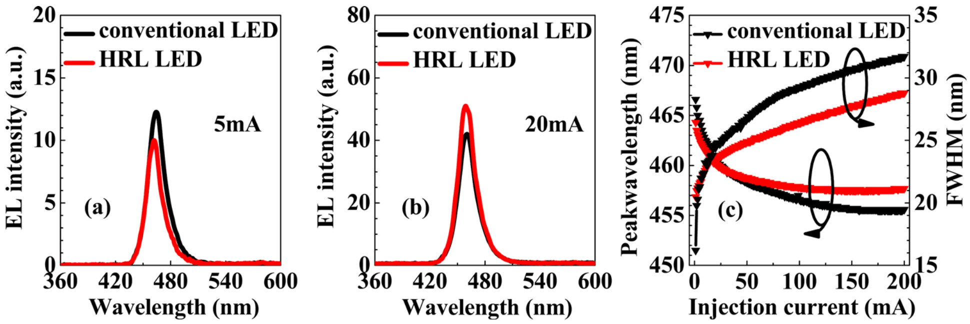

FIG. 1. The EL spectra from the two samples at injection currents of (a) 5 mA and (b) 20 mA. (c) EL peak wavelength and FWHM as a function of injection current for the two structures.

LED may result from low indium composition p-InGaN layer which can alleviate polarization field in MQWs. Smaller polarization field results in less QCSE induced wavelength shift so that the magnitude of blueshift is less.[11] The smaller broadening of FWHM in HRL LED may be attributed to the improvement of crystalline quality in InGaN/GaN active region, due to lower growth temperature in HRL layer than EBL.

The measured light-current (*L-I*) performances of the two structures with increasing current are shown in Fig. 2. It can be seen that the light output power of conventional LED is larger than that of HRL LED at low injection current. With the injection current further increased, the light output power of conventional LED is surpassed by that of HRL LED. The smaller downward bending level of the *L-I* curve is observed in HRL LED, which suggests that the efficiency droop can be alleviated with the adoption of InGaN HRL. Under the injection current of 200 mA, the light output power can be enhanced more than 39.7% by using p-InGaN HRL.

To explain the superior performance in p-InGaN HRL LED, the optical and electrical properties of the two samples were investigated numerically with the APSYS simulation program. The LED structures are consistent with our experimental wafers. Most of the parameters used in this paper are the same as in Ref. 3. Other material parameters of the semiconductors used in the simulation can be found in Ref. 12.

The energy band diagrams of the two structures are plotted in Fig. 3. The polarization field induced band bending, i.e., sloped triangular barriers and wells, and deformed energy band of EBL are observed. As shown in Fig. 3(a), the energy band at the last-barrier/EBL interface is downward sloped, which augments the possibility for electrons spill over the EBL to p-type region and increase the difficulty for holes to transport into the active region, and thus result in a large electron leakage current as well as poor injection efficiency. When a p-type InGaN hole reservoir layer is inserted between the InGaN/GaN MQW and EBL, this phenomenon can be effectively alleviated, as shown in Fig. 3(b). The inserted p-$In_{0.05}Ga_{0.95}N$ HRL can form a shallow well between the last QB and EBL, which may weaken the polarization field induced band bending between the MQWs and EBL, and hence improve hole injection and electron confinement. The effective potential height for electrons in conduction band of the HRL LED is higher than that of conventional one (i.e., 203 meV versus 184 meV), which denotes the enhancement of electron confinement. Hence, more electrons can be blocked in the QWs and recombine with holes. On the other hand, the effective potential height for holes in valence band can be reduced from 249 meV to 219 meV by employing the p-InGaN HRL, which indicates the improvement of hole injection. Furthermore, the p-type $In_{0.05}Ga_{0.95}N$ layer can alleviate the band bending of the last couple of QW and, therefore, reduced QCSE induced emission energy shift.

The simulated carrier concentrations of the two samples in MQW cut from n-side to p-side at 200 mA are plotted in Figs. 4(a) and 4(b). Note that the horizontal position of the LED with p-type HRL has been shifted slightly for better observation. It can be seen that the two structures show the same carrier concentration distribution, that is, a large amount of carrier accumulates in the last QW next to the

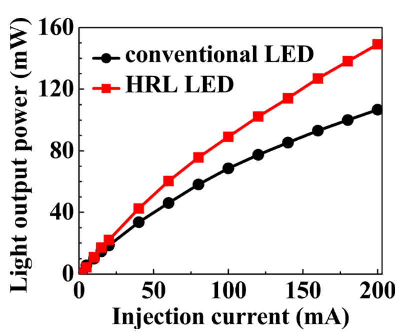

FIG. 2. Light output vs current (L-I) characteristics of the conventional and HRL LEDs.

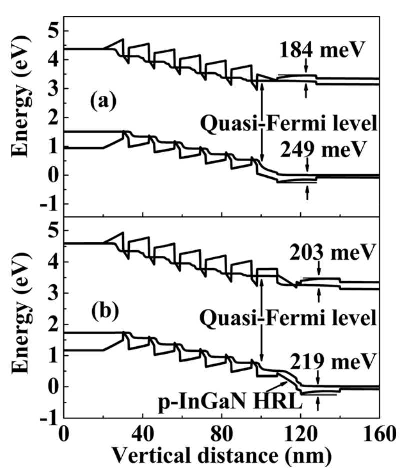

FIG. 3. Calculated energy band diagrams of (a) the conventional and (b) HRL LEDs at 200 mA.

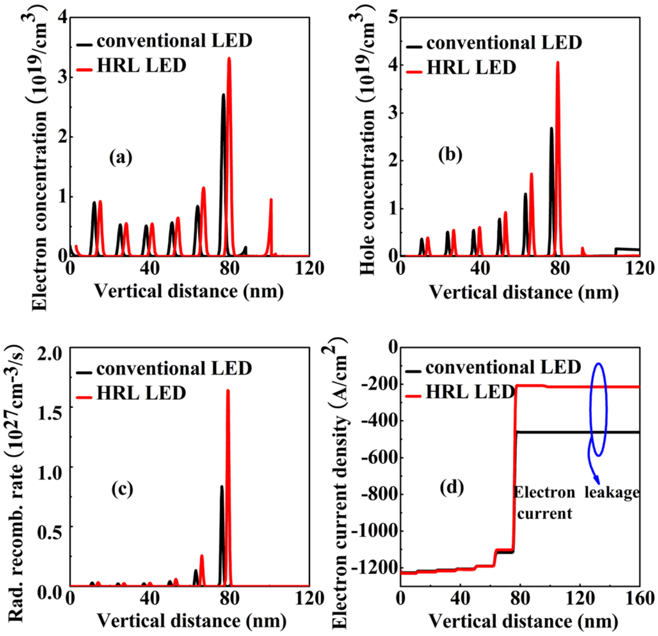

FIG. 4. Distribution of (a) electron and (b) hole concentrations, (c) radiative recombination rate, and (d) electron current density of the conventional and HRL LEDs at 200 mA.

p-type layer.[13] Both the electron and hole concentration in the active region of the HRL LED is larger than that of conventional LED. This improvement can be attributed to the enhancement of hole injection and electron confinement. Due to large amount of polarization charges at InGaN/GaN/AlGaN interface, massive electrons accumulate in the p-InGaN HRL. Because of the non-uniform carrier distribution in QWs, most of the radiative recombination happens in the QWs close to p-side, as shown in Fig. 4(c). The larger radiative recombination rates of the structure with p-InGaN HRL benefits from the larger carrier concentration in the active region. The electron current distribution of the two structures under 200 mA is shown in Fig. 4(d). The electron leakage current is severe in conventional LED. After inserting a p-type HRL, the electron spills over can be significantly suppressed.

The dependence of internal quantum efficiency (IQE) on forward current is presented in Fig. 5. As the forward current increases, both the conventional and HRL LEDs show obvious efficiency droop in IQE. Note that the two structures show almost the same peak efficiency. However, the conventional LED shows sharp peak efficiency at 4 mA, while the HRL LED shows a peak efficiency at 18 mA. The insertion of p-InGaN creates a well between the last QB and EBL, which acts as a reservoir layer. At low injection current, the well may trap the hole transported from p-type region, leading to lower quantum efficiency for the LED with p-InGaN HRL. The simulation result is in consistent with our experiment outcome. On the other hand, the HRL LED shows a reduced efficiency droop with the increasing injection current, indicating enhanced hole injection and electron confinement. The efficiency droop can be effectively alleviated from 36.7% to 11.1% when the p-InGaN HRL is inserted. Improvement in our experiment is not so significant as that in simulation. This may be attributed to non-optimized epitaxial parameters for hole reservoir layer.

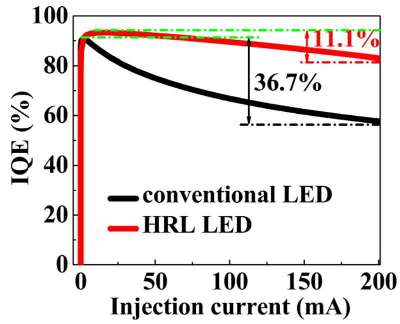

FIG. 5. IQE as a function of current for the conventional and HRL LEDs.

In conclusion, InGaN based LED with p-type InGaN HRL has been designed and investigated both numerically and experimentally. The p-InGaN forms a well between the MQW and EBL, which alleviates the polarization fields induced band bending between the active layer and EBL and, therefore, enhances hole injection and electron confinement. The experimental and simulated results both prove that the LED with p-InGaN HRL has better optical and electrical performance such as improved light output power, smaller emission energy shift and broadening, larger radiative recombination rates, as well as smaller leakage current. Furthermore, the hole injection efficiency and IQE can be effectively improved.

This work was supported by the National Nature Science Foundation of China (Grant No. 51172079), the Science and Technology Program of Guangdong province, China (Grant Nos. 2010B090400456, 2009B011100003, and 2010A081002002), and the Science and Technology Program of Guangzhou City, China (Grant Nos. 2010U1-D00191 and 11A52091257).

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