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Enhanced carrier injection in InGaN/GaN multiple quantum wells LED with polarization-induced electron blocking barrier

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HIGHLIGHTS

- A novel LED structure with polarization-induced barrier (PIB) was designed.
- Numerical study shows enhanced carrier injections in the PIB LED.
- Significant improvement in quantum efficiency of the PIB LED compared with the conventional LED with an AlGaN electron blocking layer.

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ABSTRACT

In this report, we designed a light emitting diode (LED) structure in which an N-polar p-GaN layer is grown on top of Ga-polar $In_{0.1}Ga_{0.9}N$/GaN quantum wells (QWs) on an n-GaN layer. Numerical simulation reveals that the large polarization field at the polarity inversion interface induces a potential barrier in the conduction band, which can block electron overflow out of the QWs. Compared with a conventional LED structure with an $Al_{0.2}Ga_{0.8}N$ electron blocking layer (EBL), the proposed LED structure shows much lower electron current leakage, higher hole injection, and a significant improvement in the internal quantum efficiency (IQE). These results suggest that the polarization induced barrier (PIB) is more effective than the AlGaN EBL in suppressing electron overflow and improving hole transport in GaN-based LEDs.

1. Introduction

GaN-based light emitting diodes (LEDs) usually suffer from a gradual efficiency reduction as the injection current increases. This phenomenon, well known as efficiency droop, is especially significant at high current injection [1]. The electron overflow out of the active region has been suggested as one of the main causes of the efficiency droop [2]. To suppress the electron overflow, an $Al_x Ga_{1-x}N$ electron blocking layer (EBL) is usually employed in conventional *c*-plane GaN-based LED structures [3]. However it has been reported that the effective barrier height for electrons of the EBL can be reduced due to the downward band bending induced by the large polarization field in the AlGaN layer. As a result, the electron overflow cannot be suppressed effectively [4]. An increase in the Al content of the AlGaN EBL may increase the barrier height for electrons, but it also increases the barrier height for holes due to the increased valence band offset at the interface of AlGaN/GaN, which in turn retards the hole injection [4]. To reduce the polarization field in EBL, AlInN or AlGaInN EBLs with polarization matching that of GaN were proposed and demonstrated to be more effective in suppressing electron overflow [5,6]. Unfortunately, such EBLs are not easy to realize in epitaxial growth due to the conflicting optimal growth conditions of AlN and InN. While these proposals attempt to mitigate the polarization field at the heterostructure interface in order to increase the barrier height, an opposite but promising approach is to exploit the interface polarization field to create a barrier for electrons. Such a concept has been introduced earlier in Jia's work, in which a polarization-induced barrier (PIB) height was estimated to be over 1.0 eV in a GaN/$Al_{0.13}Ga_{0.87}N$ (10 nm)/GaN heterostructure, several times higher than the band offset [7,8]. In addition, X-ray photospectroscopy results showed that the polarization-induced band bending at the Ga-polar GaN surface can be as high as 0.9 eV [9]. These results imply that the polarization charge in III-nitrides is an alternative method to create effective electrostatic barriers.

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Following this concept, we designed an LED structure which employs the PIB to suppress the electron overflow. The energy band diagram, carrier distribution and quantum efficiency are investigated numerically using the Sentaurus device simulator [10] and compared with those of a conventional LED structure with AlGaN EBL.

2. Simulation

The original LED structure under study consists of 1 μm thick n-GaN layer (5×10^{18} cm^{-3}), three pairs of In$_{0.1}$Ga$_{0.9}$N/GaN quantum wells (QWs) with 3-nm-thick wells and 12-nm-thick barriers, a 50-nm-thick p^{+}-GaN (1×10^{19} cm^{-3}) and a 200-nm-thick p-GaN (1×10^{18} cm^{-3}). The QWs and the n-GaN layers are Ga-polar, but the polarity of the p-GaN layer is inverted to N-polar. Experimentally, the polarity inversion can be achieved by heavy Mg-doping (e.g., $\sim 10^{20}$ cm^{-3}) during the GaN growth via inducing planar defects at the interface;[11–15] P-type N-polar GaN films have also been realized as reported by Fichtenbaum et al. [16] This LED structure is schematically illustrated in Fig. 1(a) and, hereafter, referred to as LED-A. As a comparison, a conventional Ga-polar LED structure (shown in Fig. 1(b)), denoted as LED-B, has also been investigated. All other parameters of LED-B are the same as those of LED-A except for the 20-nm-thick Al$_{0.2}$Ga$_{0.8}$N EBL inserted between the p-GaN and the top GaN quantum barrier. Commonly accepted parameters, including a screening ratio of 0.7 (i.e., 70% of the theoretical polarization charges), a band offset ratio of 0.7 (i.e., $\Delta E_c/\Delta E_g = 0.7$), a Shockley–Read–Hall (SRH) coefficient of 1×10^{9} s^{-1}, and a Auger coefficient of 1×10^{-31} cm^6/s, were used in the simulations [2,17,18].

3. Results and discussion

The insets of Fig.2 show the polarization charge distributions in the AlGaN, p-GaN, and the top GaN barriers of both LED structures. For LED-B, both AlGaN and GaN have the same polarity but since the AlGaN has a larger spontaneous polarization charge density than that of GaN [19] positive net polarization charges will present at the Al$_{0.2}$GaN$_{0.8}$/GaN interface (i.e. 0.0177 C/m^2). However, for LED-A, the p-GaN and the GaN barrier have opposite polarities, therefore there exists a large density of negative polarization charges (i.e. -0.058 C/cm^2) at the polarity inversion interface. Because of such differences in the polarization charge distributions, energy band profiles of the two LEDs are different as well. Shown in Fig. 2 are the band diagrams of both LEDs under a forward current injection of 100 mA. For LED-B, at the AlGaN/GaN interface, both the conduction- and the valence-band bend downwards to lower energies (see the left inset in Fig. 2). The downward bending of the conduction band in the top GaN barrier lowers the barrier height for electrons while the downward bending of the valence band in the AlGaN EBL increases the barrier height for holes. In other words, electrons cannot be effectively confined and holes cannot be efficiently injected. In contrast, for LED-A, both the conduction- and the valence-band bend upward at the polarity inversion interface (see the right inset in Fig. 2). In this light, a potential barrier for electrons and a potential well for holes are created at this interface. Compared with the EBL barrier height for electrons (ΔE_B^e) of LED-B, the polarization-induced barrier (PIB) height (ΔE_A^e) for electrons of LED-A is 95 meV higher. On the other hand, the hole injection barrier height (ΔE_A^h) in LED-A is 96 meV lower than that (ΔE_B^h) in LED-B. These comparisons in the barrier heights imply that LED-A (i.e., with PIB) should be more effective than LED-B (i.e., with EBL) in electron confinements and hole injections.

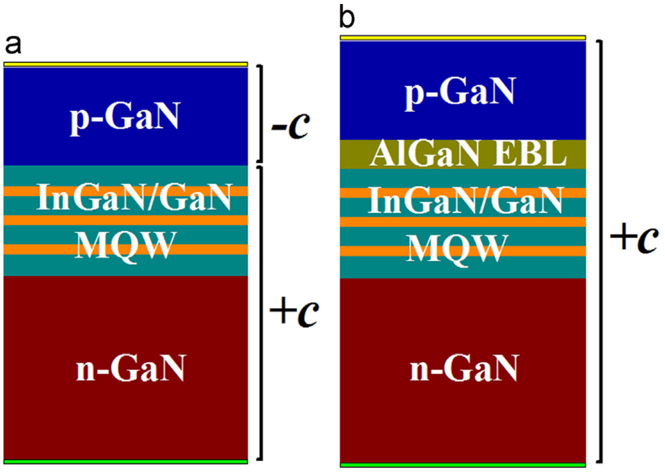

Fig. 1. Schematics of the structures of (a) LED-A and (b) LED-B. The polarity inversion in LED-A and the insertion of AlGaN EBL in LED-B should be noted.

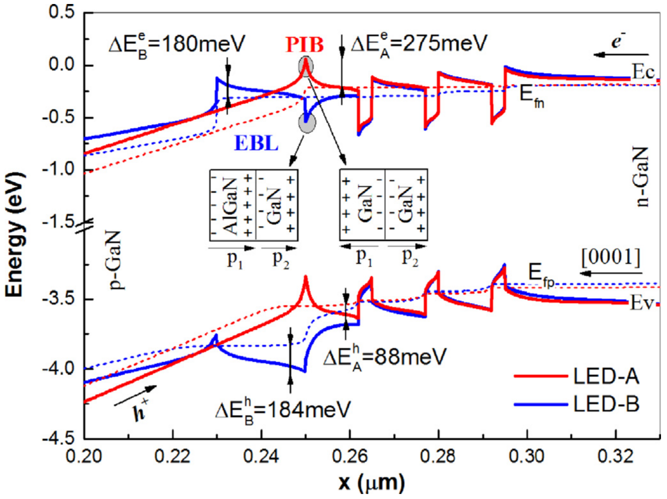

Fig. 2. Energy diagrams of LED-A (red) and LED-B (blue) under a forward bias current of 100 mA. E_{fn} and E_{fp} are the quasi Fermi levels of LED-A (red dashed) and LED-B (blue dashed). $\Delta E_A^e(\Delta E_B^e)$ and $\Delta E_A^h(\Delta E_B^h)$ are the effective potential barriers for electrons and holes of LED-A (LED-B), respectively. The insets show the polarization induced charge distribution at the interfaces next to the top GaN barriers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To examine the effectiveness of electron confinement by the PIB and EBL, electron current distribution profiles across the LED structures under forward current injections of 20 mA and 100 mA are shown in Fig. 3(a). It is seen that for LED-A, at 20 mA the electron current is almost 100% injected into the QWs region; at 100 mA, about 17% current is leaked out of the QWs. However, for LED-B, almost half of the current is leaked out of the QWs region at both low and high current injections. The current injection efficiencies of LED-A and LED-B, defined as $\eta_{inj} = 100\% \times (I_{\text{total}} - I_{\text{leakage}})/I_{\text{total}}$, are shown in Fig. 3(b). It can be seen that the η_{inj} of LED-B sharply drops to ~50% at very low current (< 10 mA), whereas the reduction in η_{inj} of LED-A is much slower at low current injections and a drop of 17% occurs at a high current injection of 100 mA (see Fig. 3(b)). The sharp dropping and smaller η_{inj} of LED-B while a slower dropping and larger η_{inj} of LED-A in the range of small driving current can be attributed to the much faster decreasing of ΔE_B^e than ΔE_A^e in the small current range (e.g. ΔE_B^e drops to ~0.45 eV and ΔE_A^e drops to ~1.0 eV at ~6 μA) as seen also in Fig. 3(b). These results provide direct evidence for the