Effect of Electron Blocking Layer on Inter-QW Transport in III-Nitride Multi-QW LEDs

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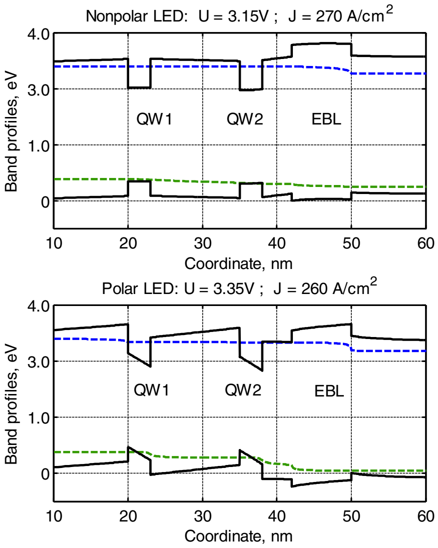
Abstract—**Strong disparity in electron and hole transport characteristics and excessive depth of optically active quantum wells (QWs) in III-nitride materials are the main causes of inhomogeneous carrier distribution and uneven QW injection in multi-QW light emitters of visible range. Both polar and nonpolar LED structures suffer from inhomogeneous injection. Undoped wide-bandgap electron blocking layer (EBL) located on the P-side of the active region can only make the situation worse by further reducing already insufficient hole injection. On the other hand, P-doped EBL facilitates the hole injection, improves the overall active region injection uniformity, and reduces the carrier leakage. We show, however, that EBLs act very differently in polar and nonpolar III-nitride multi-QW structures. While in nonpolar LED the p-doped EBL ultimately promotes the inter-QW carrier exchange, the injection efficiency in polar structure remains limited by strong electron leakage from the marginal p-side QW.**

Keywords—light emitting diodes; quantum wells; carrier injection; semiconductor device modeling; numerical simulations.

I. INTRODUCTION

Multi-QW active regions of visible light emitters suffer from inhomogeneous carrier distribution, unequal QW injection conditions, and imbalanced populations of optically active QWs which critically limit the device performance [1]. Carrier stopper (blocking) layers surrounding the active region were initially proposed to reduce the carrier leakage in mid-infrared devices [2] and electron blocking layers are now widely used to improve the injection efficiency of III-nitride light emitters of visible range.

In this work, we study the effect of p-side electron blocking layer (EBL) on inter-QW carrier transport and injection uniformity in polar and nonpolar multi-QW light-emitting diodes (LEDs). To simplify analysis, all structures are designed with the same 2-QW layout of the active region. For simulations we use MATLAB/COMSOL based Optoelectronic Device Modeling Software (ODMS) developed at Ostendo Technologies Inc. [3].



Nonpolar LED: U = 3.15V ; J = 270 A/cm^2

Polar LED: U = 3.35V ; J = 260 A/cm^2

Fig. 1. Band-edge profiles in 2-QW active regions of nonpolar and polar blue-emitting LEDs with p-doped EBLs at comparable levels of curent injection.

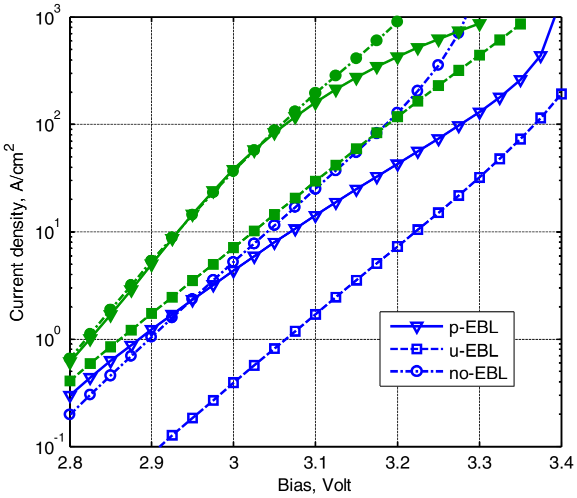


Fig. 2. I-V characteristics of nonpolar (filled markers) and polar (empty markers) LEDs with p-doped EBL, undoped EBL, and no EBL at all.

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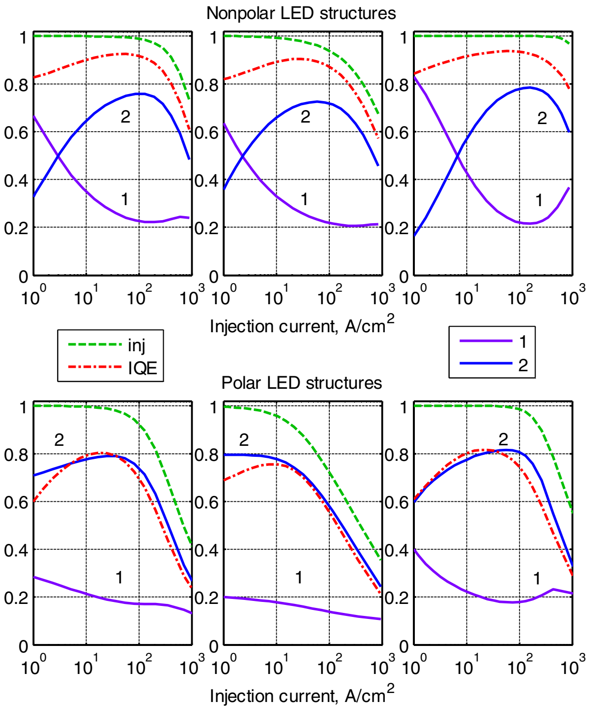

Fig. 3. Active region injection efficiency (dash) and total internal quantum efficiency (dash-dot) in nonpolar and polar LEDs. From left to right: no-EBL, undoped EBL, and p-doped EBL structures. Injection efficiencies of specific QWs are also shown with numbers indicating the QW position.

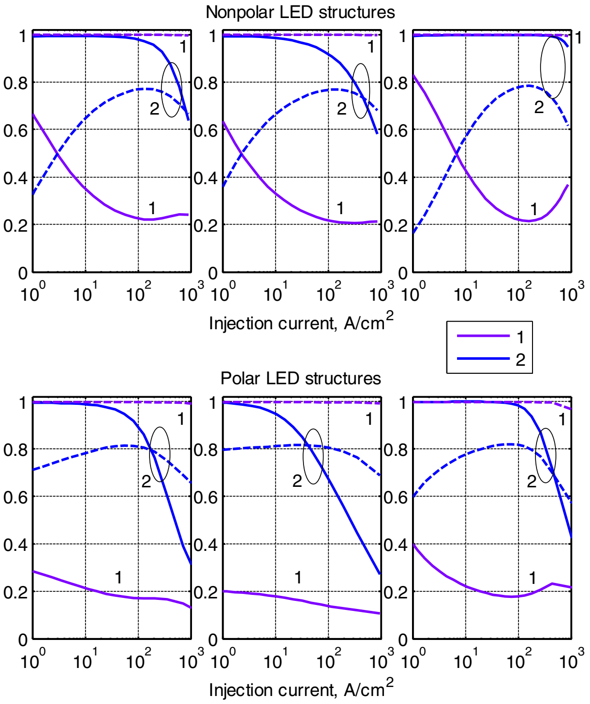

Fig. 4. Partial QW capture efficiencies specifying the QW injection characteristics presented in Fig. 3. Solid lines show electron capture efficiencies; dashed lines indicate hole capture efficiencies. QWs are identified by numbers corresponding to QW position in LED layout.

II. SIMULATION RESULTS

Figure 1 shows active region band profiles in blue-emitting nonpolar and polar 2-QW LED structures at comparable injection currents. For all structures QW compositions used in simulation were nominally the same with 25% indium. EBL layers if present contain 20% aluminum.

Figure 2 shows the I-V characteristics of six modeled LED structures, three polar and three nonpolar. Despite strongly different voltage biases, all structures reveal comparable injection characteristics which are used for analysis of inter-QW carrier exchange; see Figures 3 and 4.

Figure 3 compares the injection and total internal quantum efficiencies of the active regions in structures without EBL (left), undoped EBL (middle), and p-doped EBL (right panels). The subplots are completed with partial injection efficiencies of each active QW defined as ratios of total QW recombination currents over the total LED injection current. It is readily seen that in both polar and nonpolar structures the use of undoped EBLs neither improves the active region injection nor enhances the LED internal efficiency. On the contrary, the p-doped EBL practically eliminates the electron leakage in nonpolar structure though the QW populations remain strongly unequal with notable efficiency swap. In polar structure, internal efficiency remains limited by electron leakage from the p-side QW.

Figure 4 provides more details on the multi-QW injection distribution by showing the partial QW capture efficiencies separately for electrons and holes. Capture efficiency is defined here as a ratio of recombination and injection currents for specific carrier type. Hole capture in p-side QW clearly dominates the carrier redistribution process both in polar and nonpolar structures. Interestingly, the electron leakage remains the leading factor shaping the high-injection LED efficiency in polar structures despite the notable (about 50%) decline in QW hole confinement; see Figure 1. Such behavior can be naturally attributed to the effect of intermediate potential barriers for hole transport induced by interface polarization charges [4].

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