Design and Performance of P-side down Green Tunnel-Junction LEDs

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Keywords: P-down, GaN/InGaN, Carrier Transport, Green LED, Device Design

Abstract

In this work, we report on the design, optimization, and performance of p-down green LEDs using bottom tunnel junctions. Unlike the conventional p-up configuration, p-side down LEDs provide lower carrier injection barrier with built in barrier in each QW. While low electrostatic barrier can allow low forward voltage, built-in barrier can impede inter-well carrier transport for MQW structure. In this work, using simulations and experiment we develop an understanding of the design and performance of p-down LED active regions. We discuss the impact of the number of multi-quantum well periods and the barrier thickness on forward voltage and optical performance.

Introduction

InGaN/GaN heterostructure-based light emitting diodes are the key technology enabling efficient short-wavelength LEDs with applications ranging from microLED displays, general illumination, automotives, horticulture, etc. InGaN QWs can be designed to provide emission over the whole visible wavelength spectrum making the material system the key choice for color mixing application, true white color LEDs and display applications. While blue/violet emitting InGaN LEDs have near-theoretical efficiency, emitters in the longer wavelength range (> 500 nm) suffer from lower optical and electrical performance. Long wavelength emitters require increased Indium composition in the quantum wells which increases the average polarization sheet charge at the interface of InGaN and GaN. This large polarization sheet charges increases the electrostatic barrier for electron and hole injection for conventional p-up structures which in turn increases the diode turn on voltage and forward voltage drop of operation. While the polarization dipole field direction depends on the crystal orientation (metal or N polar direction for III-nitride material system), the depletion region field in Ga-polar orientation can be reversed using the p-side down configuration where p-GaN layer is below the active region. This reversed structure lowers the electron and hole injection barrier significantly and provides higher carrier confinement through built in barrier compared to conventional p-up LED (as shown in figure 1). However, the reduced carrier injection barriers lead to lower turn-on voltage [1] [2], while the built-in barriers in each quantum well can limit inter-well transport and increase operation voltage as the number of quantum wells increases. This can negatively impact the electrical and optical performance of p-down LEDs. In this work, we investigate the effect of quantum barrier thickness and the number of QWs on the electrical and optical performance for p-down structure through detailed simulation and experimental methods.

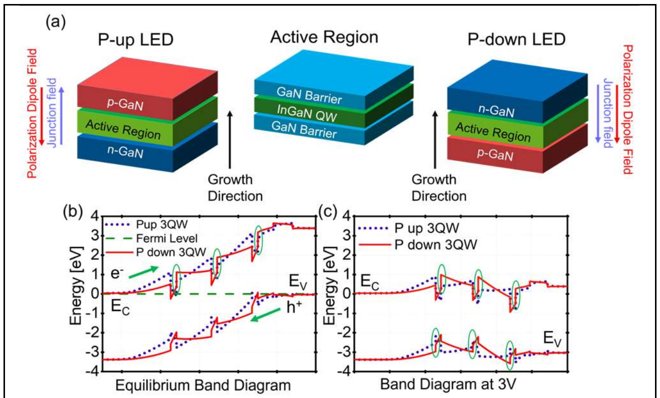

Figure 1: (a) Schematic of p-up vs p-down LED. (b) Equilibrium band diagram of P-up and P-down LED structure (c) Band diagram of P-up and P-down LED under bias (3 V)

Simulation and Experiment

P-down LEDs devices were simulated using a two-composition model developed in Silvaco which is reported in [3]. Devices with varying number of QW/QB periods were simulated to understand the effect of built-in barriers on inter-well carrier transport with increasing number of QWs. The number of QW/QB periods were varied with 1,2,3 periods. The QB thickness was also varied from 18 nm to 5 nm to determine the impact of barrier thickness on the device forward voltage operation and optical performance. The QW thickness was 3 nm in all cases. The GaN quantum barriers were undoped in the simulations, except for the GaN barrier layer near the p-side which was doped at 1×10^{18} cm^{-3} with Mg.

Experimental samples were grown based on the designs of the simulated devices. Devices with identical mesa dimensions were fabricated from all the samples with common metal contacts for both top and bottom n-GaN contacts. The device measurements reported here are from 100 µm × 100 µm square mesa sizes. Optical measurements reported here were performed on-wafer.

RESULT AND DISCUSSION

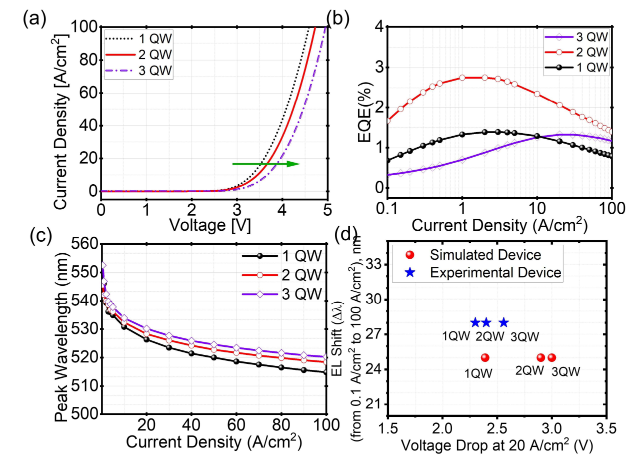

Figure 2: (a) J-V characteristic of p-down LEDs with varying number of QWs (b) EQE and (c) peak wavelength shift of p-down LEDs with 1 QW, 2 QW and 3 QW in the active region.

Figure 2 shows the measured on-wafer electrical and optical characteristics for p-down LED devices with varying number of QW/QB periods. Simulations were done with 1 QW, 2 QW and 3 QW structure and they predict an increase in the forward voltage drop with increasing quantum well number.

Experimental devices with similar active regions showed increased forward voltage drop with increasing QW/QB periods following the trend seen in the simulations. This increase is due to the built-in barrier at each QW, which requires a higher voltage for inter-well carrier transport. On-wafer EQE measurements showed the highest EQE for the 2-QW structure, with emission in the green wavelength range. For a 3-QW structure, a low EQE at low current density was observed with peak EQE shifted to high current densities indicating higher carrier (electron) loss due to SRH recombination. The high built-in barrier in the QWs allows higher electron confinement in the QWs near the n-side which recombines non-radiatively (shown in Figure 3). In case of 2-QW structure the carriers (electrons and holes) are distributed more uniformly, allowing for higher radiative recombination efficiency at low and high current densities (shown in Figure 3). The peak wavelength shift for these devices from 0.1 A/cm^2 to 100 A/cm^2 are shown in figure 2 (c). The difference in wavelength shift is similar for all samples, while the single QW structure shows slightly shorter wavelength due to higher electric field inside the single QW. Voltage drop at 20 A/cm^2 of the LED devices with the tunnel-junction voltage de-embedded and the simulated devices are shown in figure 2(d).

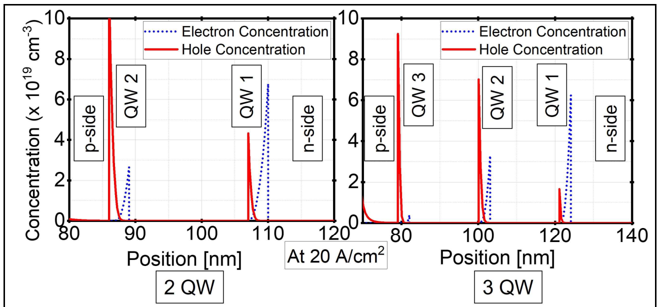

Figure 3: Carrier concentration (electron and hole) in 2 QW and 3 QW structure at 20 A/cm^2.

To further understand the impact of the quantum barrier thickness on the electrical and optical performance, thickness was varied from 18 nm to 5 nm for a 3 QW structure. Figure 3 (a, b, c) shows the performance of devices with 3 nm/3 QW structure with the QB thickness variation. The simulations estimate that as the barrier thickness is reduced, the forward voltage of operation reduces due to lowered injection barrier and improved inter-well carrier transport.

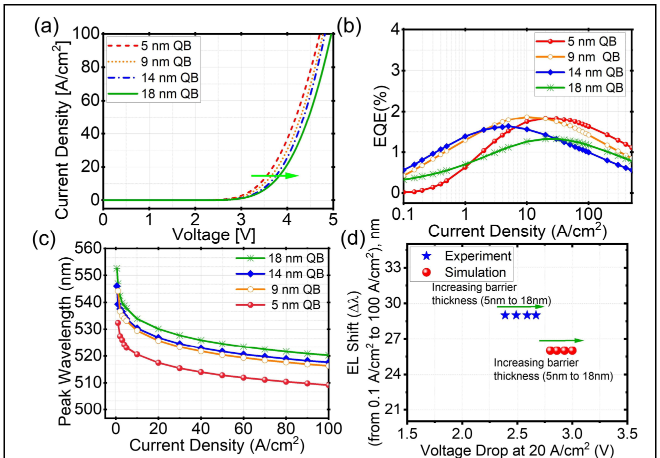

Figure 4. (a), (b), (c) Electrical and optical characteristics of p-down LEDs with 3 QW structure for varying thickness of the QBs.

Experimental devices with similar variations barrier thickness variation shows similar trend of lowered forward voltage drop as the QB thickness decreases. Although the on-wafer EQE/optical measurement show improvement with decreasing barrier thickness, the peak wavelength of operation also blue-shifts as the barrier thickness is lowered, due to change in the field inside the QWs (figure 3(c)). As barrier thickness decreases, the field inside the QW increases and thus the transition energy changes. Low V_f and improved EQE with thinner barrier also indicates improved electron injection efficiency in the 3 QW structure. Overall, for the p-down active region designs shown 2 QW structure with 18nm thick barrier shows the highest EQE performance with good forward voltage. The relatively higher forward voltage seen in these p-down LEDs are due to the extra voltage drop at the tunnel junction. Separate tunnel junction test structures were used to estimate the tunnel junction voltage drop. Voltage drop at 20 A/cm^2 of the LED devices with the tunnel-junction voltage de-embedded and the simulated devices are shown in figure 3(d).

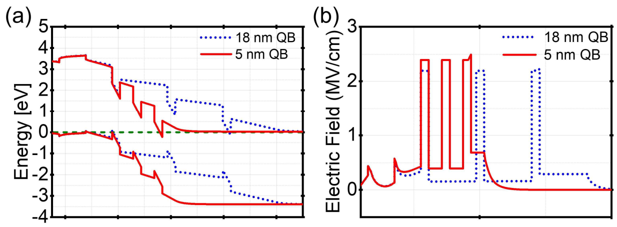

Figure 5. (a) Equilibrium energy band diagram of 3 QW structure with 18 nm and 5 nm barrier thickness. (b) Electric field profile (obtained from simulation) in the active region at 0 V bias for 3 QW structure with 18 nm and 5 nm QB.

CONCLUSIONS

In conclusion, we designed and optimized P-down LED electrical and optical performance though predictive simulation using two composition model. Experimental devices based on the optimization using simulation show qualitative agreement with the simulated devices. The results show that with epitaxial design, p-down LEDs can show favorable voltage and optical performance.

ACKNOWLEDGEMENTS

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office award no. DE-EE0009163.

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ACRONYMS

LED: Light Emitting Diode
QW: Quantum Well
MQW: Multi Quantum Well
QB: Quantum Barrier
EL: Electroluminescence