Investigating and Optimizing Carrier Transport, Carrier Distribution, and Efficiency Droop in GaN-based Light-emitting Diodes

by

Di Zhu

An Abstract of a Thesis Submitted to the Graduate

Faculty of Rensselaer Polytechnic Institute

in Partial Fulfillment of the

Requirements for the Degree of

DOCTOR OF PHILLOSOPHY

Major Subject: PHYSICS

The original of the complete thesis is on file
In the Rensselaer Polytechnic Institute Library

Examining Committee:

Dr. E. Fred Schubert, Thesis Adviser

Dr. Partha S. Dutta, Member

Dr. Kim M. Lewis, Member

Dr. Shengbai Zhang, Member

Rensselaer Polytechnic Institute
Troy, New York

February 2011
(For Graduation May 2011)

ABSTRACT

The recent tremendous boost in the number and diversity of applications for light-emitting diodes (LEDs) indicates the emergence of the next-generation lighting and illumination technology. The rapidly improving LED technology is becoming increasingly viable especially for high-power applications. However, the greatest roadblock before finally breaching the main defensive position of conventional fluorescent and incandescent lamps still remains: GaN-based LEDs encounter a significant decrease in efficiency as the drive current increases, and this phenomenon is known as the efficiency droop. This dissertation focuses on uncovering the physical cause of efficiency droop in GaN-based LEDs and looks for solutions to it.

GaN-based multiple-quantum-well (MQW) LEDs usually have abnormally high diode-ideality factors. Investigating the origin of the high diode-ideality factors could help to better understand the carrier transport in the LED MQW active region. We investigate the ideality factors of GaInN LEDs with different numbers of doped quantum barriers (QBs). Consistent with the theory, a decrease of the ideality factor as well as a reduction in forward voltage is found with increasing number of doped QBs. Experimental and simulation results indicate that the band profiles of QBs in the active region have a significant impact on the carrier transport mechanism, and the unipolar heterojunctions inside the active region play an important role in determining the diode-ideality factor.

This dissertation will discuss several mechanisms leading to electron leakage which could be responsible for the efficiency droop. We show that the inefficient electron capture, the electron-attracting properties of polarized EBL, the inherent asymmetry in electron and hole transport and the inefficient EBL p-doping at high Al contents severely limit the ability to confine electrons to the MQWs. We demonstrate GaInN LEDs employing tailored Si doping in

the QBs with strongly enhanced high-current efficiency and reduced efficiency droop. Compared with 4-QB-doped LEDs, 1-QB-doped LEDs show a 37.5% increase in light-output power at high currents. Consistent with the measurements, simulation shows a shift of radiative recombination among the MQWs and a reduced electron leakage current into the p-type GaN when fewer QBs are doped. The results can be attributed to a more symmetric carrier transport and uniform carrier distribution which help to reduce electron leakage and thus reduce the efficiency droop.

In this dissertation, artificial evolution is introduced to the LED optimization process which combines a genetic algorithm (GA) and device-simulation software. We show that this approach is capable of generating novel concepts in designing and optimizing LED devices. Application of the GA to the QB-doping in the MQWs yields optimized structures which is consistent with the tailored QB doping experiments. Application of the GA to the EBL region suggests a novel structure with an inverted sheet charge at the spacer-EBL interface. The resulting repulsion of electrons can significantly reduce electron leakage and enhance the efficiency.

Finally, dual-wavelength LEDs, which have two types of quantum wells (QWs) emitting at two different wavelengths, are experimentally characterized and compared with numerical simulations. These dual-wavelength LEDs allow us to determine which QW emits most of the light. An experimental observation and a quantitative analysis of the radiative recombination shift within the MQW active region are obtained. In addition, an injection-current dependence of the radiative recombination shift is predicted by numerical simulations and indeed observed in dual-wavelength LEDs. This injection-current dependence of the radiative recombination distribution can be explained very well by incorporating quantum-mechanical tunneling of carriers into and through the QBs into to the classical drift-diffusion model.

In summary, using the LEDs with tailored QB doping and dual-wavelength LEDs, we investigate the origin of the high diode-ideality factor of LEDs and gain insight on the control of carrier transport, carrier distribution, and radiative recombination in the LED MQW active region. Our results provide solid evidence on the effectiveness of the GA in the LED device optimization process. In addition, the innovative EBL structure optimized by the GA sheds light on further paths for the optimization of LED design. Our results are the starting point of applying artificial evolution to practical semiconductor devices, opening new perspectives for complex semiconductor device optimization and enabling breakthroughs in high-performance LED design.