Efficiency and Carrier Transport in Polarization-Matched GaInN-based Light-Emitting Diodes

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ABSTRACT

Efficiency is the core figure of merit for light-emitting diodes (LEDs). High efficiency along with other desirable properties of LEDs enables a booming market in LED applications. However, GaInN-based LEDs suffer from a phenomenon called "efficiency droop". The efficiency droop of GaInN-based LEDs refers to the substantial decrease in efficiency as the injection current increases and is a fundamental obstacle for LEDs in general illumination applications. This dissertation focuses on the enhancement of efficiency and the understanding of carrier transport in GaInN-based LEDs. A new approach is used in this pursuit: controlling the material polarization in III-V nitrides. The polarization control is achieved in two ways: (i) changing material composition, and (ii) bending the LED-on-sapphire wafer. We show that (i) controlling the material polarization can greatly enhance the efficiency of GaInN-based LEDs and (ii) electric field has significant effects on carrier transport and recombination in GaInN-based LEDs.

The first chapter gives an overview of LED basics. This chapter briefly reviews the history of LEDs and the evolution of lighting technologies. This chapter also introduces the popular material systems used for visible LEDs and then focuses on the core material system in this dissertation – the III-V nitrides. LED layer structures used in this work and some important definitions are also provided in this chapter.

The second chapter discusses the effects of polarization charges on GaInN-based LEDs, especially effects relating to efficiency. In GaInN-based LEDs, polarization-mismatch at hetero-interfaces induces strong sheet charges and leads to electron leakage out of the active region. This electron-leakage causes the infamous efficiency droop in GaInN-based LEDs. This chapter reports the polarization-matching approach to enhance efficiency and to reduce efficiency droop in GaInN-based LEDs. Compared to the conventional GaN quantum barrier (QB), ternary and quaternary III-V nitride QBs reduce the polarization-mismatch between QWs and QBs in the active region. This approach shows an 18% increase in light-output power and more than a 20% enhancement in power efficiency at high current levels. Moreover, the polarization-matching approach also reduces the forward voltage and the spectral shift.

The third chapter discusses carrier escape in GaInN/GaN multi-quantum-well (MQW) LEDs under resonant optical excitations where electron-hole pairs are generated in the GaInN quantum-well (QW) layers only. Understanding the carrier transport in GaInN-based LEDs is crucial in uncovering the different pathways of carriers. Unfortunately, carrier transport is often assumed to be negligibly small in the case of resonant excitation while investigating the origin of efficiency droop in GaInN-based LEDs. We report that, in contrast to this assumption, carrier escape from QWs does take place, and shows strong dependence upon the duration of excitation and bias conditions.

The forth chapter revisits the GaInN/GaN MQW LEDs under resonant optical excitations and reveals two recombination channels. The first recombination channel is the recombination of photo-excited carriers in the GaInN QWs. The second recombination channel is formed by carriers that leak out of the GaInN MQW active region, self-bias the device in forward direction, induce a forward current, and subsequently recombine in the GaInN active region in a spatially distributed manner. The results indicate dynamic carrier transport involving the active, the confinement, and the contact regions of the device.

The fifth chapter studies the polarization-matching technique as an effective method to reduce the Auger recombination in GaInN QWs. Polarization-matching technique can effectively control the electric field inside the QW structures and consequently manage carrier distribution profiles. With the controllability of carrier distribution profiles, the polarization-matching technique is capable of reducing the Auger recombination irrespective of the debated magnitude of the Auger coefficient. Compared to the reference GaInN/GaN structure, fully- and half- polarization-matched structures reduce the Auger recombination by as much as 79% and 61%, respectively.

In the last chapter, the polarization field is fine-tuned in GaInN-based MQW LEDs by mechanically bending the LED-on-sapphire wafer, therefore, compressively straining the LED epi-layers. Compressive strain on the LED epi-layers increases the polarization sheet charges at the QW/QB hetero-interfaces and decreases the polarization sheet charges at the spacer/electron-blocking-layer (EBL) hetero-interface. Electroluminescence (EL) characteristics of the GaInN MQW LED are measured. All measurements are taken on the same LED with all other conditions fixed, except the wafer curvature, which is either zero or 1.71 m^{-1}. In the low current density region, the LED under a wafer curvature of 1.71 m^{-1} shows a red-shift in the EL spectrum and a decrease in efficiency compared to the same LED under zero wafer curvature. This observation is consistent with the increase of quantum-confined Stark effect (QCSE) in the MQW region. In the high current density region, the LED under a wafer curvature of 1.71 m^{-1} shows an increase in efficiency compared to the same LED under zero wafer curvature. This observation is consistent with the decrease in polarization charges in the EBL region. Simulations and experiments show excellent agreement in the efficiency behavior of the device under testing. The efficiency change in the high current region supports the electron-leakage-over-EBL theory and disproves the Auger recombination as the primary cause of efficiency droop.

Part of this dissertation has been published in the following archival journal articles:

Jiuru Xu, Martin F. Schubert, Ahmed N. Noemaun, Di Zhu, Jong Kyu Kim, E. Fred Schubert, Min Ho Kim, Hun Jae Chung, Sukho Yoon, Cheolsoo Sone, and Yongjo Park, "Reduction of efficiency droop, forward voltage, ideality factor and wavelength shift in polarization-matched GaInN/GaInN multi-quantum-well light-emitting diodes", *Applied Physics Letters* **94**, 011113 (2009).

Martin. F. Schubert, **Jiuru Xu**, Jong Kyu Kim, E. Fred Schubert, Min Ho Kim, Sukho Yoon, Soo Min Lee, Cheolsoo Sone, Tan Sakong, and Yongjo Park, "Polarization-matched GaInN/AlGaInN multi-quantum-well light-emitting diodes with reduced efficiency droop", *Applied Physics Letters* **93**, 041102 (2008).

Martin. F. Schubert, **Jiuru Xu**, Qi Dai, Frank W. Mont, Jong Kyu Kim, and E. Fred Schubert, "On resonant optical excitation and carrier escape in GaInN/GaN quantum wells", *Applied Physics Letters* **94**, 081114 (2009).

Martin. F. Schubert, Qi Dai, **Jiuru Xu**, Jong Kyu Kim, E. Fred. Schubert, "Electroluminescence induced by photoluminescence excitation in GaInN/GaN light-emitting diodes", *Applied Physics Letters* **95**, 191105 (2009).

Some parts of this dissertation are literal citations from the above publications.