Carrier recombination mechanisms and efficiency of gallium nitride based light-emitting diodes

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ABSTRACT

In this dissertation, carrier recombination mechanisms in GaN-based light-emitting diodes (LEDs) are analyzed. The analysis is used to investigate the "efficiency droop" and the internal quantum efficiency (IQE) of GaN-based LEDs. The efficiency droop is the gradual decrease of LED efficiency as the injection current increases. It is the preeminent barrier for white LEDs in their penetration into the general illumination market.

We compare the efficiency droop found in electroluminescence (EL) and photoluminescence (PL) measurements. The result indicates that carrier leakage from the multi-quantum well (MQW) active region plays a role in the efficiency droop. A polarization-matching technique is proposed to reduce the carrier leakage out of MQWs and thus reduce the efficiency droop.

In the technical literature, the efficiency droop has been frequently described by the *ABC* recombination model: $IQE = Bn^2 / (An + Bn^2 + Cn^3)$. Based on the *ABC* model's even symmetry of IQE-versus-n curves, demonstrated here, and based on the even symmetry of the *ABC* model not being consistent with experimental results, we find that the *ABC* model is insufficient in modeling the efficiency droop. Therefore we introduce a carrier leakage term $f(n)$ and add this term to the *ABC* recombination model. Our analysis shows that the leakage term, $f(n)$, can have significant 2nd, 3rd, and 4th power contributions of n to the recombination rate.

We perform PL measurements on GaInN/GaN MQW LEDs with different threading dislocation densities. The IQE as a function of carrier concentration and its dependence on the threading dislocation density are obtained based on a rate-equation analysis. We show that this measurement technique can be used to measure the IQE of semiconductor active regions.

It has been assumed that carrier transport effects (escape of electrons and holes from MQWs) can be neglected under resonant optical excitation (where the excitation energy is approximately equal to bandgap energy of the QW). However, our study shows that carriers do escape from the active region and the amount of leakage can be significant. The carrier leakage has a strong dependence upon bias conditions and the duration of optical excitation. Furthermore, we find a new phenomenon "photoluminescence-induced electroluminescence": carriers that escape from the active region accumulate at the p- and n-sides of the device, self-bias the device in forward direction, and induce a forward current. This current causes electroluminescence in a spatially distributed manner.