Non-Ideal Properties of Gallium Nitride Based Light-Emitting Diodes

by

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ABSTRACT

The spectacular development of gallium nitride (GaN) based light-emitting diodes (LEDs) in recent years foreshadows a new era for lighting. There are still several non-ideal properties of GaN based LEDs that hinder their widespread applications. This dissertation studies these non-ideal properties including the large reverse leakage current, large subthreshold forward leakage current, an undesired parasitic cyan luminescence and high-concentration deep levels in GaInN blue LEDs. This dissertation also studies the thermal properties of GaInN LEDs.

Chapter 1 gives a brief introduction of non-ideal properties of GaN based LEDs. The leakage current of GaN based LEDs, defects in epitaxially grown GaN devices, and doping problems of p-type GaN materials are discussed. The transient junction temperature measurement technique for GaN based LEDs is introduced.

The leakage current of an LED includes the subthreshold forward leakage current and the reverse leakage current. The leakage current of GaN based LEDs affects the reliability, electrostatic discharge resilience, and sub-threshold power consumption. In *Chapter 2*, the reverse leakage current of a GaInN LED is analyzed by temperature-dependent current-voltage measurements. At low temperature, the reverse leakage current is attributed to the variable-range-hopping conduction. At high temperature, the reverse leakage current is attributed to a thermally-assisted multi-step tunneling. The thermal activation energies (95 meV ~ 162 meV), extracted from the Arrhenius plot for the reverse current in the high-temperature range, indicate a thermally activated tunneling process. Additional room-temperature capacitance-voltage (C-V) measurements are performed to obtain information on the depletion width and doping concentration of the LED. The average internal electric field is estimated by the C-V measurements. The strong internal electric field enhances the thermal emission of electrons in the thermally-assisted multi-step tunneling process.

Another problem of GaInN blue LEDs is the undesired parasitic cyan emission band. The undesired parasitic emission band strongly influence the electrical and optical properties of GaInN blue LEDs including the subthreshold forward leakage current and the color purity of the emission. In *Chapter 3*, GaInN blue LEDs emitting at 445 nm with a parasitic cyan (blue-green) emission band (480 nm), which dominates the

emission spectrum at low injection current, are analyzed. Photoluminescence using resonant optical excitation shows that the cyan emission originates from the active region of the LED. The current- and excitation-density-dependent blue-to-cyan intensity ratio reveals that the cyan emission is due to a transition from the conduction band to a Mg acceptor having diffused into the last-grown quantum well of the active region. The Mg in the active region provides an additional carrier-transport path, and therefore can explain the high subthreshold forward leakage current that is measured in these LEDs.

Deep levels in GaN-based materials strongly affect the electrical and optical properties of GaN-based LEDs. *Chapter 4* describes the basic principle and the setup of a deep-level transient spectroscopy (DLTS) measurement system. This DLTS system is used to determine the concentration and thermal activation energy of deep levels in the depletion region of the GaInN LED. Two types of hole traps in the n-type side of the depletion region are observed in the DLTS measurement. The thermal activation energies of these two types of hole traps are compared with the results reported in literature. The hole trap associated with the major DLTS peak with a thermal activation energy of 0.80 eV is presumably related to the “yellow luminescence band”.

Self-heating of LEDs is an important issue that affects the efficiency and reliability. In *Chapter 5*, the thermal properties, including thermal time constants, of GaN LEDs are analyzed. The transient-junction-temperature behavior of unpackaged LED chips is described by a single time constant, which is the product of a thermal resistance R_{th} and a thermal capacitance C_{th}. Furthermore, a multistage $R_{th}C_{th}$ thermal model for packaged LEDs is developed. The transient response of the junction temperature of LEDs after the power is switched on or switched off can be described by a multi-exponential function. Each time constant of this function is approximately the product of a thermal resistance, R_{th}, and a thermal capacitance, C_{th}. The transient junction temperature after the power is switched off is measured for a high-power flip-chip LED by the forward-voltage method. A two-stage $R_{th}C_{th}$ model is used to analyze the thermal properties of the packaged LED. Two time constants, 2.72 ms and 18.7 ms are extracted from the junction temperature decay measurement and attributed to the thermal time constant of the LED GaN / sapphire chip and LED Si submount, respectively.