Combining photoluminescence and photocurrent measurements to distinguish photovoltaic losses

T. H. Gfroerer, Ben Stroup, and Collin J.C. Epstein, Davidson College, Davidson, NC
Yong Zhang, University of North Carolina at Charlotte, Charlotte, NC
Zhiqiang Liu, Institute of Semiconductors, Chinese Academy of Science, Beijing, CHINA

Motivation: Blue PV and LED Droop

We measure the photoluminescence and photocurrent of a blue LED under open- and short-circuit conditions to distinguish between drift and non-drift related carrier loss mechanisms. We also vary the excitation intensity and temperature to monitor changes in recombination parameters. Using a simple rate equation model, we find that diffusion-related non-radiative recombination is thermally activated with an activation energy equal to approximately 44 meV, while drift-related losses account for an excitation- and temperature-independent 10% short-circuit current deficit when the carrier density exceeds a threshold of $5 \times 10^{14}$ cm$^{-3}$.

Abstract

We measure the photoluminescence and photocurrent of a blue LED under open- and short-circuit conditions to distinguish between drift and non-drift related carrier loss mechanisms. We also vary the excitation intensity and temperature to monitor changes in recombination parameters. Using a simple rate equation model, we find that diffusion-related non-radiative recombination is thermally activated with an activation energy equal to approximately 44 meV, while drift-related losses account for an excitation- and temperature-independent 10% short-circuit current deficit when the carrier density exceeds a threshold of $5 \times 10^{14}$ cm$^{-3}$.

Photoluminescence Images and Spectra

The high energy portion of the solar spectrum can be converted into electricity most efficiently by a wide-bandgap semiconductor. Nitride-based blue LEDs operate effectively in the is regime, only in reverse: they convert current into light. But the LED conversion efficiency falls off at high currents, a phenomenon commonly referred to as droop.

Model

Rate Equations (in steady state):

Open Circuit:

$$\frac{dn}{dt} = G - Bn - A_n(T)n = 0$$

(1)

Short Circuit:

$$\frac{dn}{dt} = G - Bo - \frac{I_{SC}}{qV} \left( n - N_t \right) - \frac{N_t}{qV}$$

(2)

$n =$ density of free carriers

$G =$ carrier generation rate

$B =$ T-dependent radiative recombination coefficient

$I_{SC} =$ short-circuit current

$qV =$ charge x volume

$N_t =$ density threshold

At each temperature, open-circuit experimental results for are modeled according to Eq. 1, with $A_n$ as the only adjustable parameter. We obtain lower error when this term is omitted from the short-circuit model. Why? Perhaps drift along the direction of the internal field precludes capture at the diffusion-related recombination centers that dominate in the open-circuit configuration.

Diffusive Non-radiative Recombination Coefficient

The diffusive non-radiative recombination coefficient depends strongly on temperature, with a thermal activation energy of 44 meV.

Excitation-Dependent Quantum Efficiency

The photovoltaic quantum efficiency (i.e. the photocurrent divided by the excitation power) decreases with increasing excitation, particularly at low temperature. The photoluminescence efficiency (i.e. the integrated PL signal divided by the excitation power) increases with increasing excitation, particularly under high-temperature open-circuit and low-temperature short-circuit conditions. The solid lines on the PL efficiency graph are model results.

Conclusions

• The decrease in radiative efficiency with increasing temperature for the low excitation, open-circuit configuration is due to an increase in diffusive non-radiative recombination.

• The decrease in radiative efficiency with increasing temperature for the high-excitation, short-circuit configuration is due to the decrease in the radiative recombination rate.

• Above a relatively low excitation threshold, a systematic 10% loss of the short-circuit current (could limit the conversion efficiency above a thermal activation energy of 44 meV).

Acknowledgement

We would like to thank the Davidson College Faculty Study and Research Committee for supporting this research.