Modeling the temperature and excitation dependences of efficiency in InGaN light-emitting diodes

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Abstract: Changes in excitation dependence of efficiency with temperature are modeled for a wurtzite InGaN light-emitting diode. The results show interplay of quantum-well and barrier emissions giving rise to shape changes in efficiency versus current density with changing temperature, as observed in some experiments.

Much interest exists for InGaN light-emitting diodes (LEDs), largely because of application in solid-state lighting. Of particular important is device efficiency, where there is considerable debate on the relative importance of carrier leakage, Auger recombination, junction heating, carrier and defect delocalizations.

This paper investigates LED efficiency as functions of current density and lattice temperature. The analysis uses a model that allows direct input of band-structure properties [1]. Band-structure details are important, because underlying emission properties in a wurtzite quantum-well (QW) structure are the excitation dependences of energy dispersions, confinement energies and optical transition matrix elements. These dependences arise from screening of piezoelectric and spontaneous polarization fields. Band-structure properties are computed by solving Poisson and k·p equations in the envelop approximation. The information is used in a dynamical model for populations in momentum-resolved carrier states.

The model is applied to compute the temperature dependence of internal quantum efficiency (IQE) versus current density. Motivations for adding temperature dependence to the droop investigation are the possibility of further physical insight and to provide more stringent testing of the model. To relate to experiment, simulations are performed for two LED configurations. The experimental devices had single-QW active regions, which circumvented complications arising from nonuniform population in multi-QW structures. One device consisted a 2nm $In_{0.37}Ga_{0.63}N$ QW between GaN barriers [2], while the other device consisted a 3nm $In_{0.20}Ga_{0.80}N$ QW between GaN barriers [3].

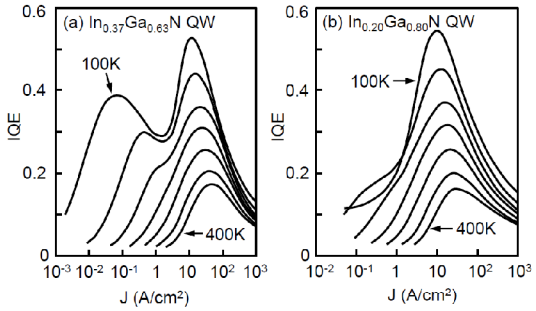

Figure 1. IQE versus current density for LED with (a) $In_{0.37}Ga_{0.63}N$ and (b) $In_{0.20}Ga_{0.80}N$ QWs. The different curves are for lattice temperatures T = 100 to 400K at 50K intervals. The SRH and Auger coefficients, as well as the carrier-phonon scattering rates are assumed same for both QWs.

Figure 1 (a) shows numerical simulation results for the $In_{0.37}Ga_{0.63}N$ LED. Plotted is IQE versus current density at different lattice temperatures. The figure shows double-bump excitation dependence in IQE at low temperatures. The lower excitation bump decreases with increasing temperature. For lattice temperatures $T_L > 250K$ only one bump remains and the IQE versus current density behavior shows the familiar shape, as described relatively well by the ABC model.

Input parameters that are assumed temperature dependent are the SRH and Auger coefficients A and C, respectively, as well as the carrier-phonon scattering rate $\gamma_{c\text{-}p}$. They are adjusted to produce IQE behavior resembling those found in Ref. [2]. Figure 2 plots the

values A, C and $\gamma_{c\text{-}p}$ versus temperature used in computing the curves in Fig. 1. A decrease in A with decreasing temperature is expected for defect related loss. Figures 2 (b) and 2 (c) show increases in Auger coefficient and carrier-phonon scattering rate with increasing temperature, which are also consistent with microscopic calculations. The values of Auger coefficient are within the range predicted for phonon-assisted Auger scattering and smaller than most values obtained from experimental curve fitting with the ABC model. The values used for carrier-phonon scattering are higher than predicted by quantum kinetic calculations for typical III-N structures. However, it should be noted that those calculations are for intraband scattering among nearby states. The present effective rates represent the relaxation of very energetic states populated by Auger scattering to the QW ground state. The energy differences are in the neighborhood of the bandgap energy (2.7eV).

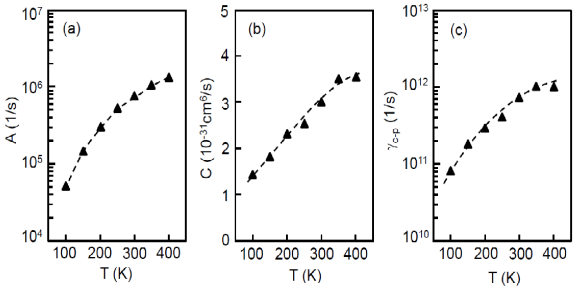

Figure 2. Values of (a) SRH coefficient, (b) Auger coefficient and (c) carrier-phonon scattering rate used in producing the curves in Fig. 1.

The role of band structure is explored by performing simulations for the $In_{0.20}Ga_{0.80}N$ LED, using the same parameter values as plotted in Fig. 2. Figure 1 (b) shows the IQE versus current density for different temperatures. Clearly indicated is a missing or negligible second IQE bump consistent with Ref. [3]. Band-structure calculations traced the reason to a smaller internal electric field with lower In concentration in the QW.

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References

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