Efficiency of InGaN LEDs: Beyond a total carrier density model

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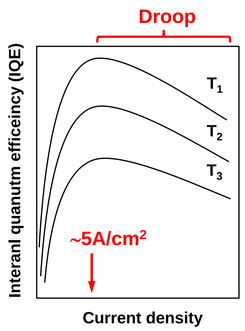
Question: What is C?

Typical measurement of LED efficiency versus excitation



Good fit to experiment with :

$$\mathrm{IQE} = \frac{BN^2}{AN + BN^2 + CN^3}$$

Cause of droop (C>0)

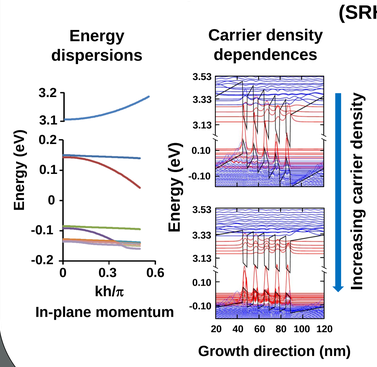
? ?

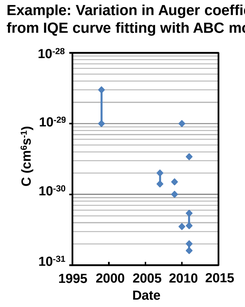
Extrinsic	Intrinsic
Localization	Auger
Current leakage	Piezoelectric field
Defect loss	

Goals for microscopic* model

(a) Direct input of bandstructure & excitation dependences

(b) Precise quantitative estimation of physical mechanisms (SRH, capture and leakage, Auger)





* Description in terms of momentum-resolved carrier populations

Model

Hamiltonian: $\mathrm{H}=\sum_i \varepsilon_i^e a_i^\dagger a_i + \sum_j \varepsilon_j^h b_j^\dagger b_j + \sum_q \hbar\Omega_q c_q^\dagger c_q - \sum_{i,j,q} \wp_{ij}\sqrt{\frac{\hbar\Omega_q}{V\epsilon_b}}\left(a_i b_j c_q^\dagger + c_q b_j^\dagger a_i^\dagger\right)$ + Coulomb interaction

(Single-particle energies; Light-matter interaction)

Dynamical equations:

Quantum-well $\frac{\mathrm{d}n_{\sigma,\alpha_\sigma,k_\perp}}{\mathrm{d}t} = -n_{\sigma,n_\sigma,k_\perp}\sum_{\alpha_{\sigma'}} b_{\alpha_\sigma,\alpha_{\sigma'},k_\perp} n_{\sigma',\alpha_{\sigma'},k_\perp} - A n_{\sigma,n_\sigma,k_\perp} - \gamma_{c-c}\left[n_{\sigma,n_\sigma,k_\perp} - f\left(\varepsilon_{\sigma,k_\perp},\mu_\sigma,T\right)\right] - \gamma_{c-p}\left[n_{\sigma,n_\sigma,k_\perp} - f\left(\varepsilon_{\sigma,k_\perp},\mu_\sigma^L,T_L\right)\right]$

(e or h; Bandstructure determined from iterative solution of dynamical, k·p and Poisson's equations; Spontaneous emission; Carrier injection; Carrier-phonon; Carrier-carrier; Similar for holes)

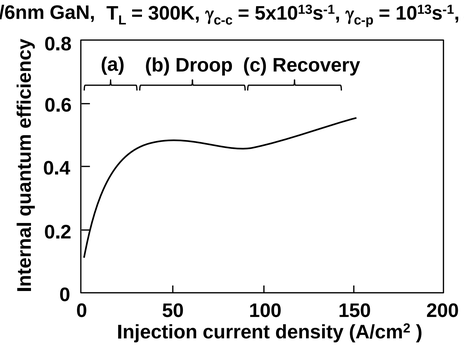
Barrier $\frac{\mathrm{d}n_{\sigma,k}^b}{\mathrm{d}t} = -b_k n_{e,k}^b n_{h,k}^b + \frac{J}{eN_\sigma^p} f\left(\varepsilon_{\sigma,k}^b,\mu_\sigma^p,T_p\right)\left(1-n_{\sigma,k}^b\right) + A_b n_{\sigma,k} - \gamma_{c-c}\left[n_{\sigma,k}^b - f\left(\varepsilon_{\sigma,k}^b,\mu_\sigma,T\right)\right] - \gamma_{c-p}\left[n_{\sigma,k}^b - f\left(\varepsilon_{\sigma,k}^b,\mu_\sigma^L,T_L\right)\right]$

Details: IEEE JQE **38** 402, 2002 (for QW); IEEE JQE **41** 495, 2005 (for QD); APL 97, 121105, 2010 (for InGaN LEDs); Optics Express **19**, 21818, 2011 (for QCSE screening).

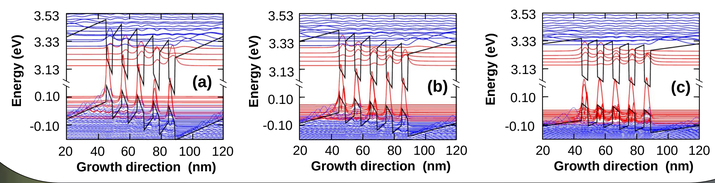
Results to date: Contributions to efficiency droop

Excitation-induced bandstructure changes

4nm $In_{0.2}Ga_{0.8}N$/6nm GaN, T_L = 300K, $\gamma_{c\text{-}c} = 5\text{x}10^{13}s^{-1}$, $\gamma_{c\text{-}p} = 10^{13}s^{-1}$, A = $10^{-7}s^{-1}$, C = 0

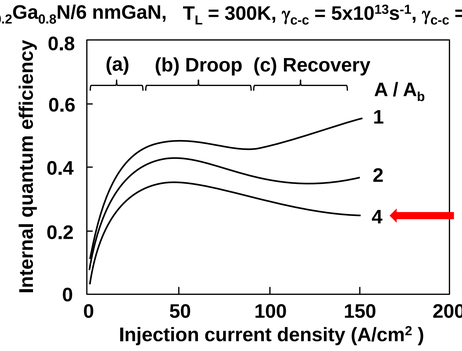


No Auger!

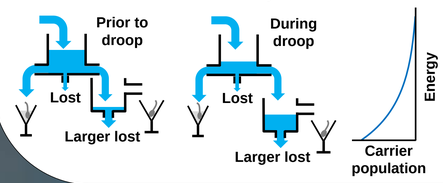


Localized defect loss

4nm $In_{0.2}Ga_{0.8}N$/6 nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5\text{x}10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, C = 0



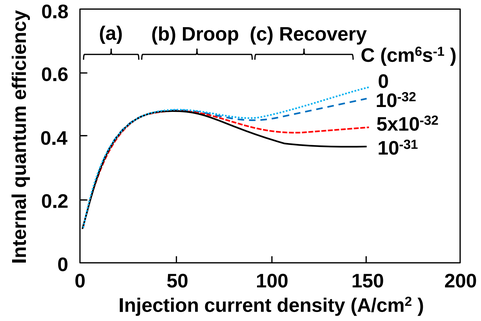
Consistent defect density measurements

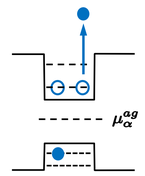


SRH (linear) +Bandstructure ⟹ N^3 loss!

Auger carrier loss

4nm $In_{0.2}Ga_{0.8}N$/6nm GaN, T_L = 300K, $\gamma_{c\text{-}c} = 5\text{x}10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, A = A_b = $10^{-7}s^{-1}$





$$\left.\frac{\partial n_{\sigma,\alpha_\sigma,k_\perp}}{\partial t}\right|_{Auger} = -CN_\sigma^2\left[n_{\sigma,\alpha_\sigma,k_\perp} - f_{\sigma,\alpha_\sigma,k_\perp}\left(\mu_\sigma^{ag},T_{ag}\right)\right]$$

- Auger loss prevents IQE recovery
- Required Auger coefficient (C)
  - --- smaller than ABC model estimation
  - --- consistent with microscopic calculations

Plans: Comparison with experiment and extension of model

Model verification (FY12)

Challenge: fitting experimental IQE versus current for range of temperatures.

Application of model (FY12 – FY14)

Investigate defect, carrier transport and Auger contributions to IQE. SRH and Auger coefficients extracted from experiments will be more precise than ABC model, because spontaneous emission, carrier capture and leakage are not treated using free parameters.

Extend model to compute optical emission spectra (FY12 - FY13)

Theory/experiment comparison, correlating IQE data and spontaneous emission spectra, will allow determination of carrier distributions (carrier density and plasma temperature) in experiments. Should significantly improve identification of physical mechanisms affecting IQE. **Challenge:** incorporate many-body Coulomb effects.

Compare polar versus non-polar LEDs (FY13-FY14)

Challenge: Extend model to account for increased bandstructure asymmetries with arbitrary QW/crystal orientations.

Investigate cavity-enhanced optical emission (FY14)

Incorporate stimulated emission and resonator effects. Extended model will enable consistent description of device operation from LED to cavity-enhanced LED and from cavity-enhanced LED to laser operation.

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