InGaN LED efficiency droop without Auger

SAND2012-1224P

Weng Chow, Sandia National Labs.

Semiconductor lights, III-N material system

Efficiency challenge: intrinsic or extrinsic?

Thanks to:

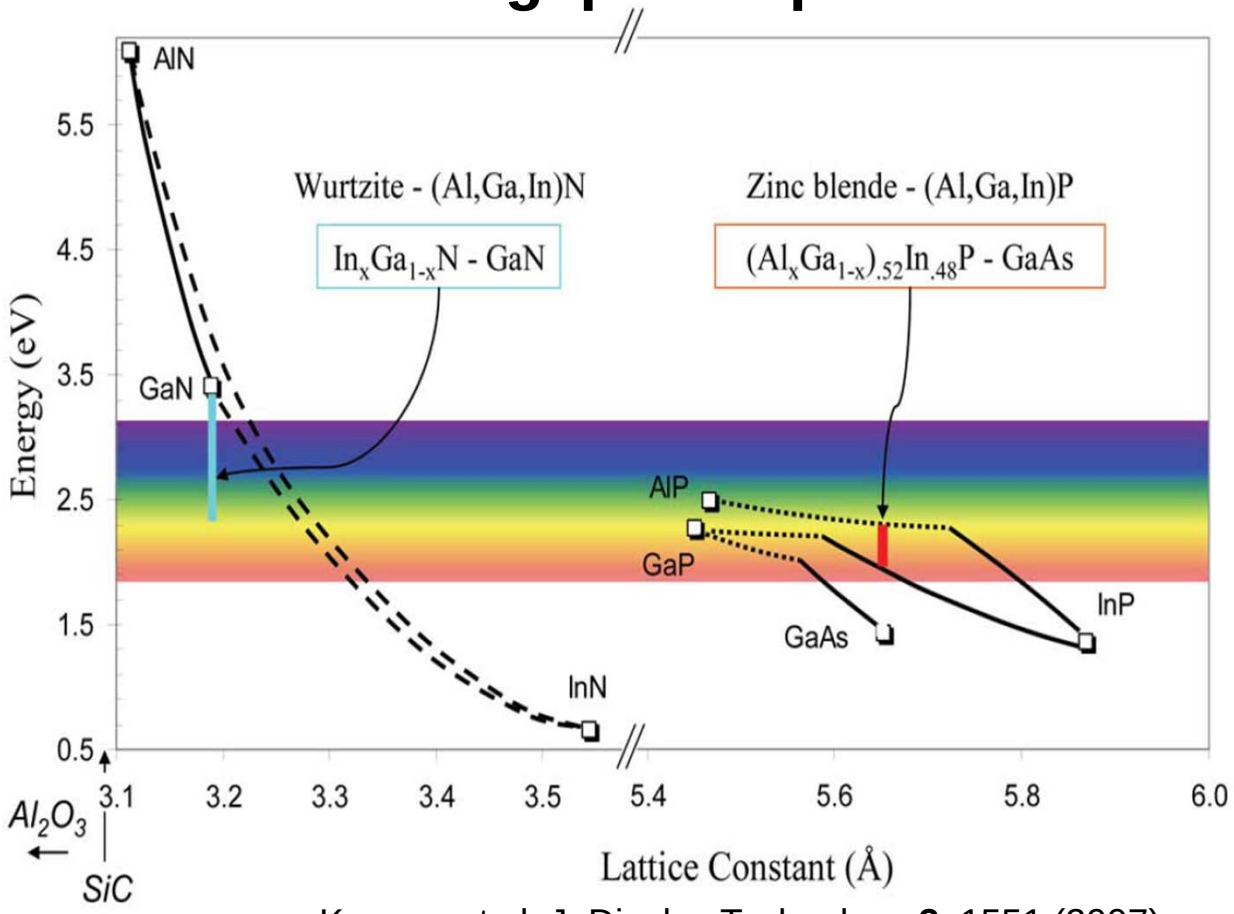
Sandia's Energy Frontier Research Center (EFRC)

DOE, Basic Energy Sciences

Sonderforschungsbereich (SFB) 787

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000

Wide bandgap Group-III Nitrides



Krames et al, J. Display Technology **3,** 1551 (2007)

Important applications: visible and ultraviolet lasers and LEDs

Interesting physics: Strong quantum-confined Stark effect

Strong many-body interaction

Significant excitation dependences in transition energies and matrix elements

Problem

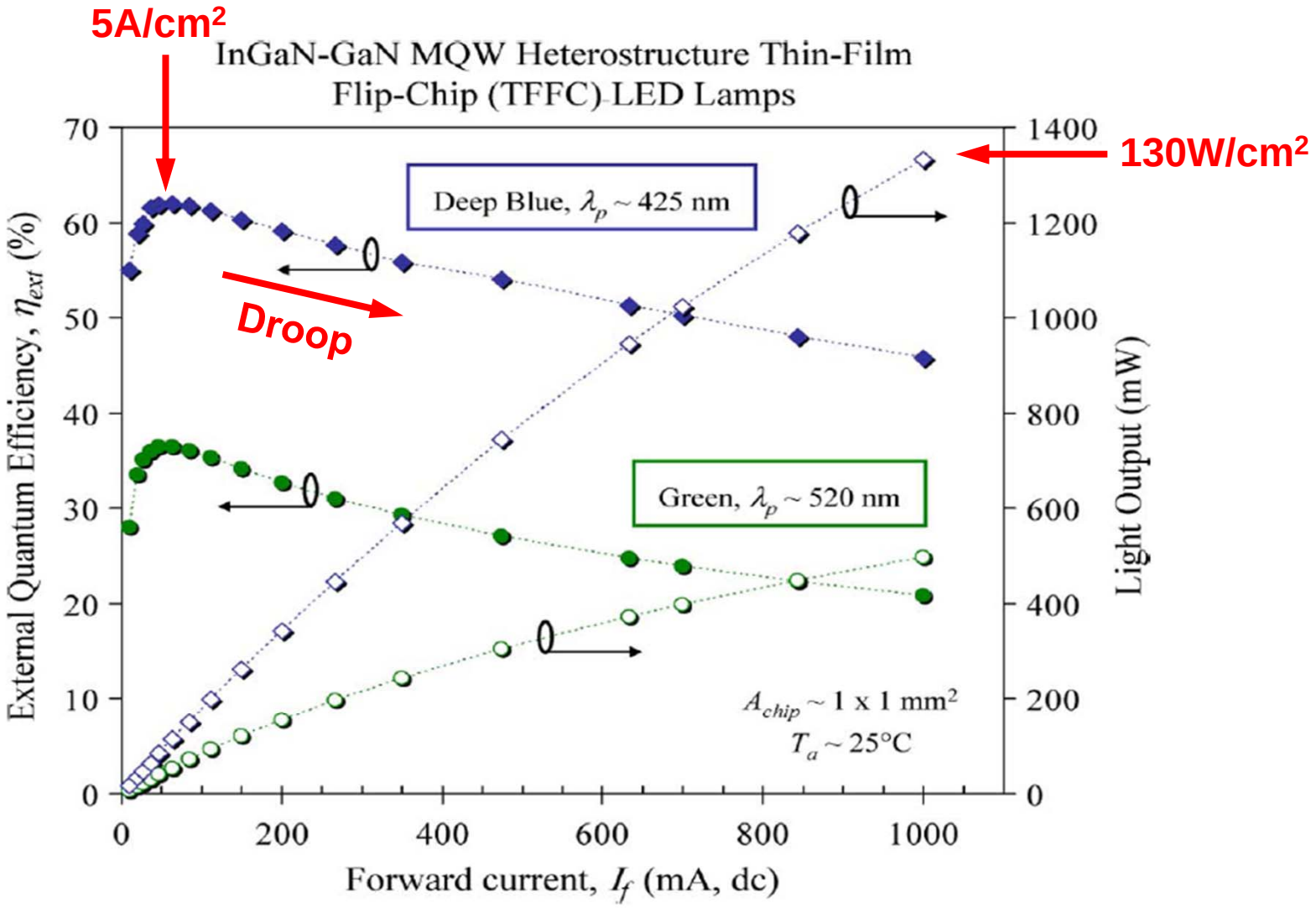
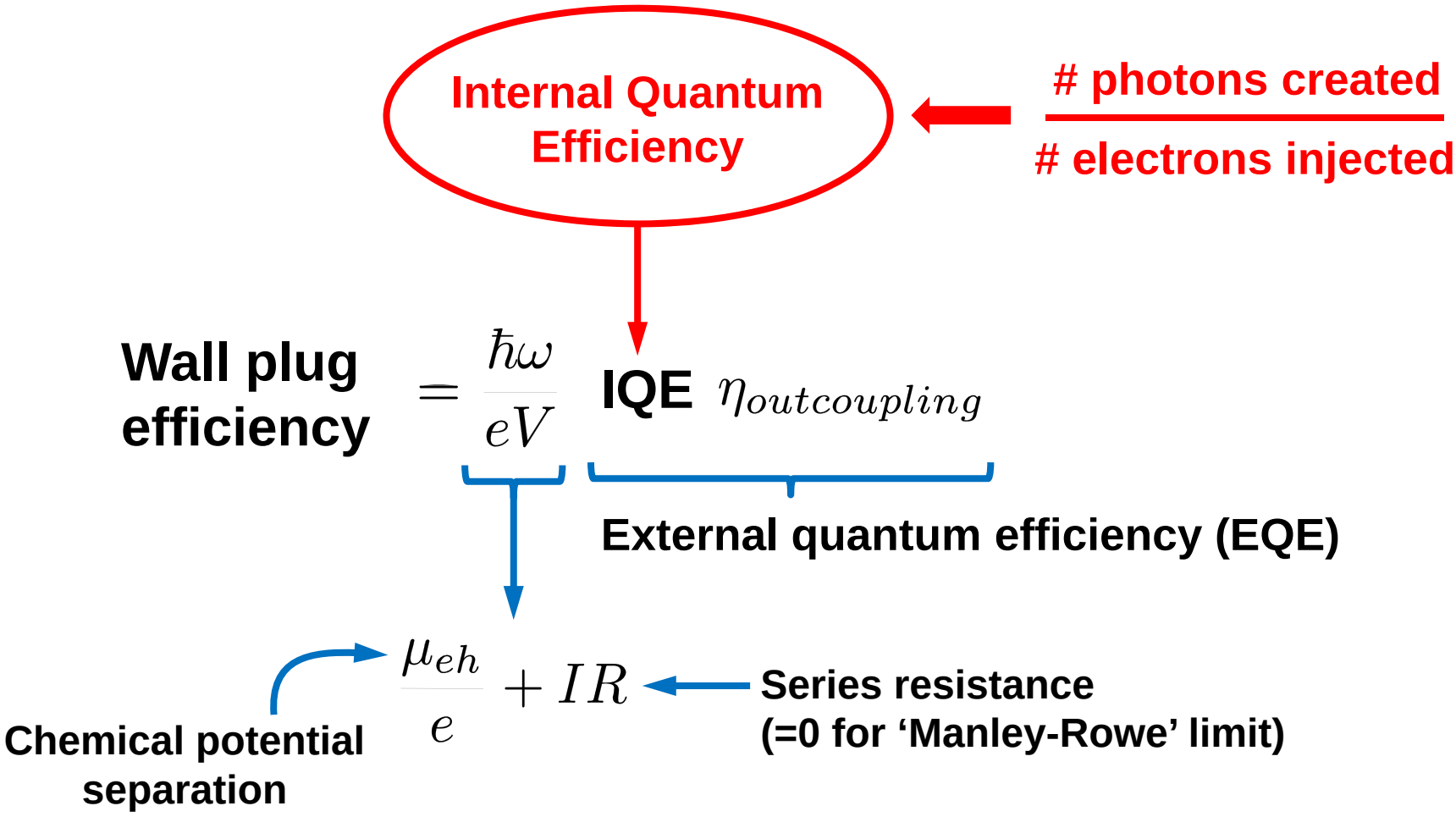


Fig. 8. External quantum efficiency and light output versus dc forward current for both blue and green InGaN-GaN QW-based TFFC LED lamps. Chip sizes are 1×1 mm².

Krames et al, J. Display Technology 3, 1551 (2007)

LED efficiency



ABC model for LED efficiency

Carrier density rate equation

Injection efficiency (carrier overshoot and escape)

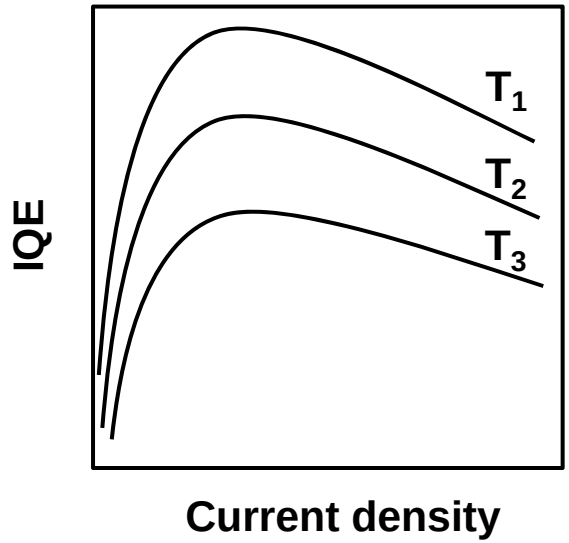
$$\frac{dN}{dt} = \frac{\eta_{inj} J}{ed} - AN - BN^2 - CN^3$$

Steady-state

$$\frac{dN}{dt} = 0 \Rightarrow \frac{\eta_{inj} J}{ed} = AN + BN^2 + CN^3$$

Internal quantum efficiency

$$\text{IQE} = \frac{BN^2}{\frac{J}{ed}} = \frac{\eta_{inj} BN^2}{AN + BN^2 + CN^3}$$



ABC model for LED efficiency

Carrier density rate equation

Injection efficiency (carrier overshoot and escape)

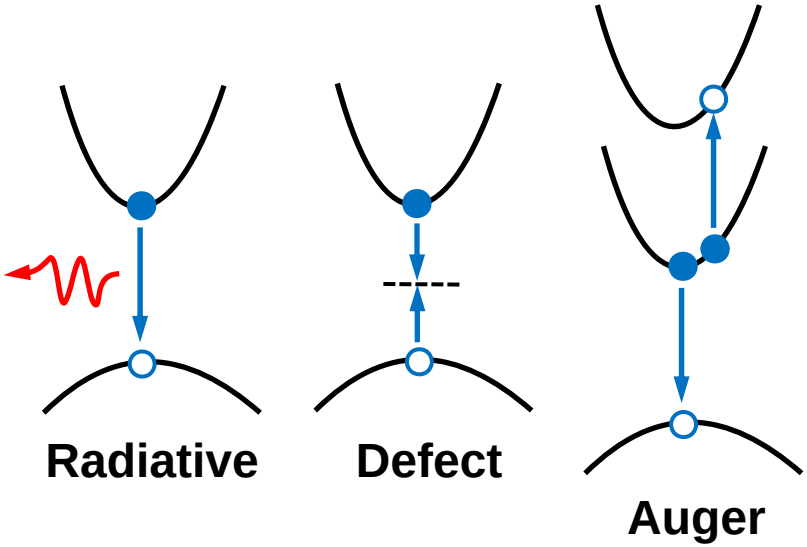
$$\frac{dN}{dt} = \frac{\eta_{inj} J}{ed} - AN - BN^2 - CN^3$$

Defects — AN

Spontaneous emission — BN^2

Auger — CN^3

Carrier losses

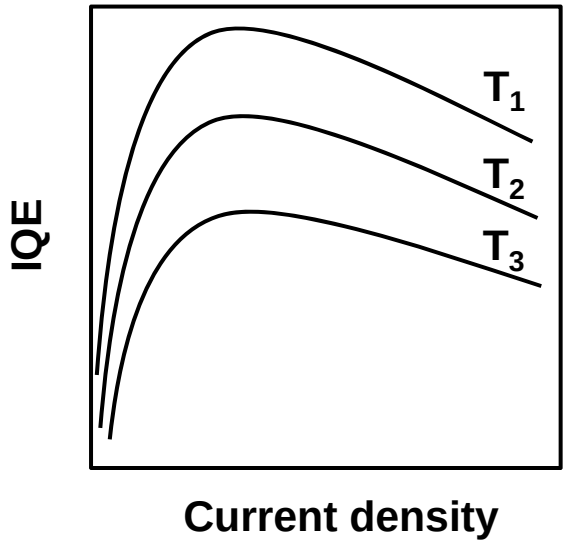


Steady-state

$$\frac{dN}{dt} = 0 \Rightarrow \frac{\eta_{inj} J}{ed} = AN + BN^2 + CN^3$$

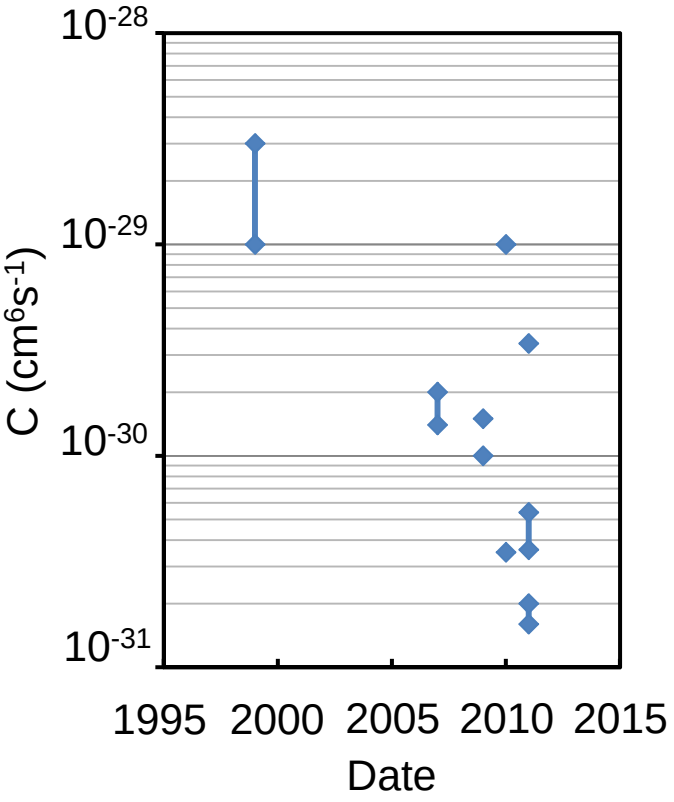
Internal quantum efficiency

$$\text{IQE} = \frac{BN^2}{\frac{J}{ed}} = \frac{\eta_{inj} BN^2}{AN + BN^2 + CN^3}$$



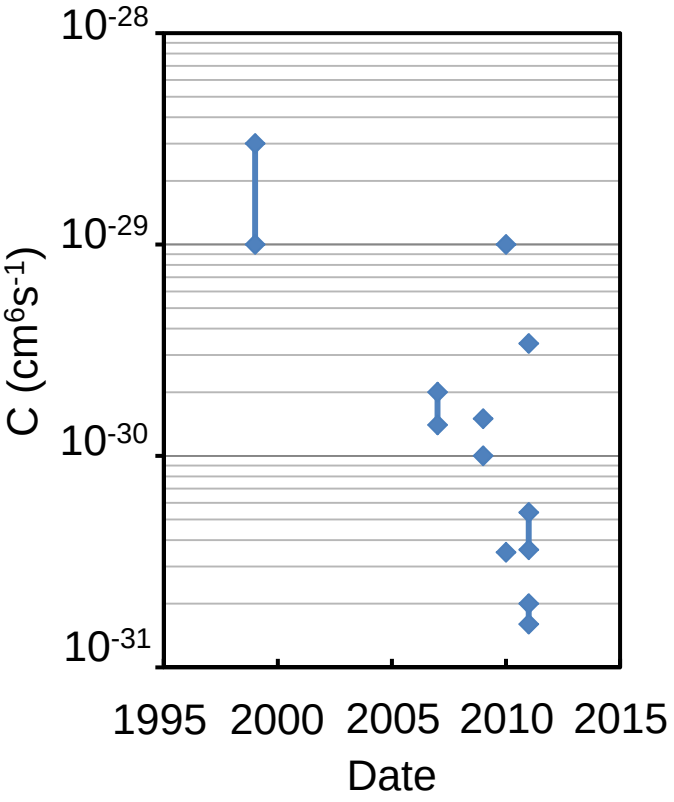
Motivations for a more detailed model

Variation in Auger coefficient from IQE curve fitting with ABC model

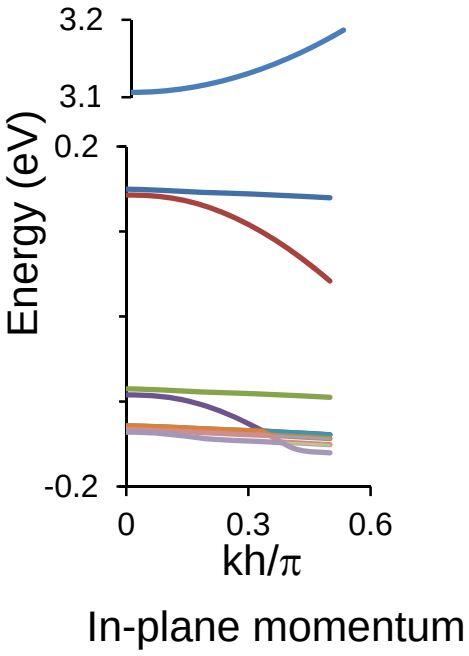


Motivations for a more detailed model

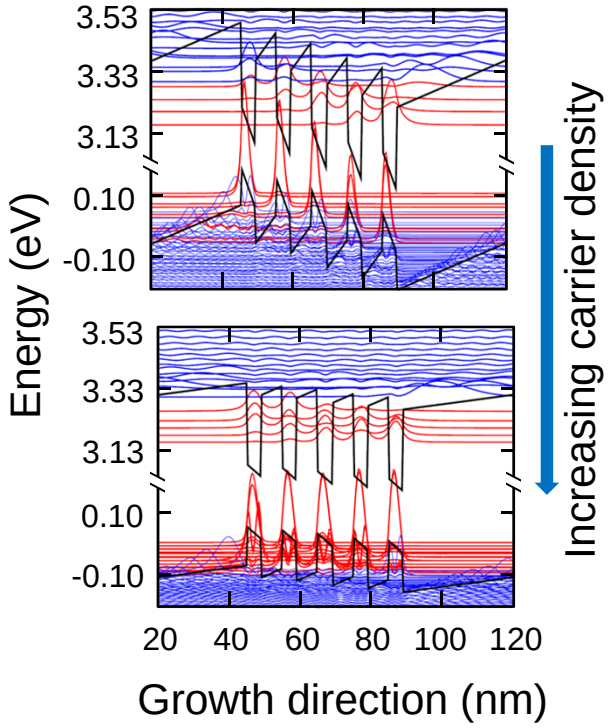
Variation in Auger coefficient from IQE curve fitting with ABC model



Energy dispersions



Carrier density dependent band structure changes



Approach

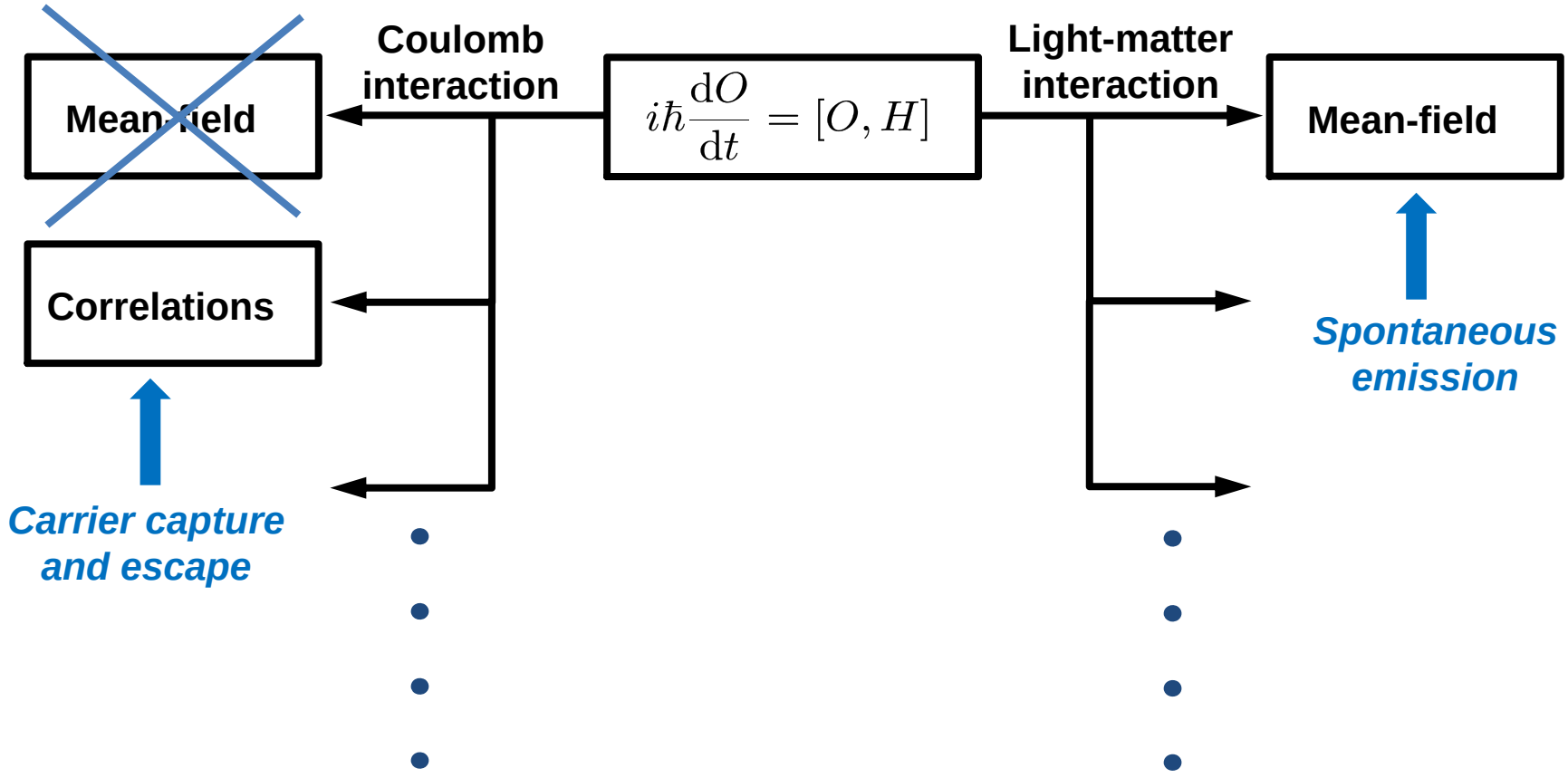
Hamiltonian

Single-particle energies | Light-matter interaction

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

+ Coulomb interaction

Hiesenberg Picture



Model

e or *h*

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

$$\frac{\mathrm{d}n^b_{\sigma,k}}{\mathrm{d}t} = -b_k n^b_{e,k} n^b_{h,k} + \frac{J}{eN^p_\sigma} f\left(\varepsilon^b_{\sigma,k},\mu^p_\sigma,T_p\right)\left(1-n^b_{\sigma,k}\right) + A_b n_{\sigma,k}$$
$$-\gamma_{c-c}\left[n^b_{\sigma,k} - f\left(\varepsilon^b_{\sigma,k},\mu_\sigma,T\right)\right]$$
$$-\gamma_{c-p}\left[n^b_{\sigma,k} - f\left(\varepsilon^b_{\sigma,k},\mu^L_\sigma,T_L\right)\right]$$

Similar for holes

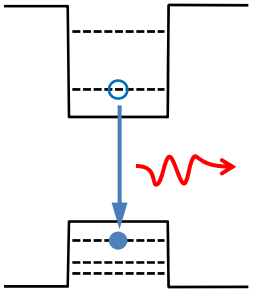
IEEE JQE **38** 402, 2002 (for QW); IEEE JQE **41** 495, 2005 (for QD); APL 97, 121105, 2010 (for InGaN LEDs)

Model

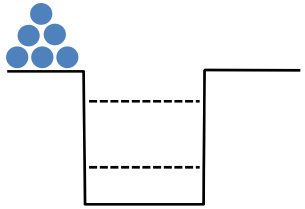
e or *h*

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

Spontaneous emission (>ns)



Carrier injection



$$\frac{\mathrm{d}n^b_{\sigma,k}}{\mathrm{d}t} = -b_k n^b_{e,k} n^b_{h,k} + \frac{J}{eN^p_\sigma} f\left(\varepsilon^b_{\sigma,k},\mu^p_\sigma,T_p\right)\left(1-n^b_{\sigma,k}\right) + A_b n_{\sigma,k}$$
$$-\gamma_{c-c}\left[n^b_{\sigma,k} - f\left(\varepsilon^b_{\sigma,k},\mu_\sigma,T\right)\right]$$
$$-\gamma_{c-p}\left[n^b_{\sigma,k} - f\left(\varepsilon^b_{\sigma,k},\mu^L_\sigma,T_L\right)\right]$$

Similar for holes

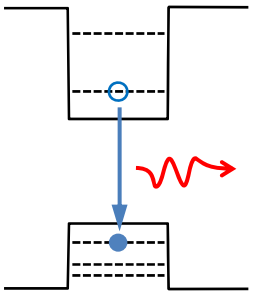
IEEE JQE **38** 402, 2002 (for QW); IEEE JQE **41** 495, 2005 (for QD); APL 97, 121105, 2010 (for InGaN LEDs)

Model

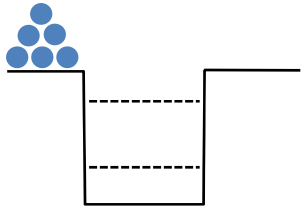
e or *h*

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

Spontaneous emission (>ns)

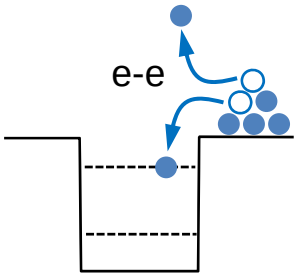


Carrier injection

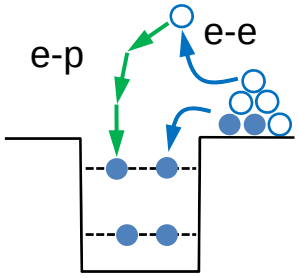


$$\frac{\mathrm{d}n^b_{\sigma,k}}{\mathrm{d}t} = -b_k n^b_{e,k} n^b_{h,k} + \frac{J}{eN^p_\sigma} f\left(\varepsilon^b_{\sigma,k},\mu^p_\sigma,T_p\right)\left(1-n^b_{\sigma,k}\right) + A_b n_{\sigma,k}$$
$$-\gamma_{c-c}\left[n^b_{\sigma,k} - f\left(\varepsilon^b_{\sigma,k},\mu_\sigma,T\right)\right]$$
$$-\gamma_{c-p}\left[n^b_{\sigma,k} - f\left(\varepsilon^b_{\sigma,k},\mu^L_\sigma,T_L\right)\right]$$

Carrier-carrier (100fs)



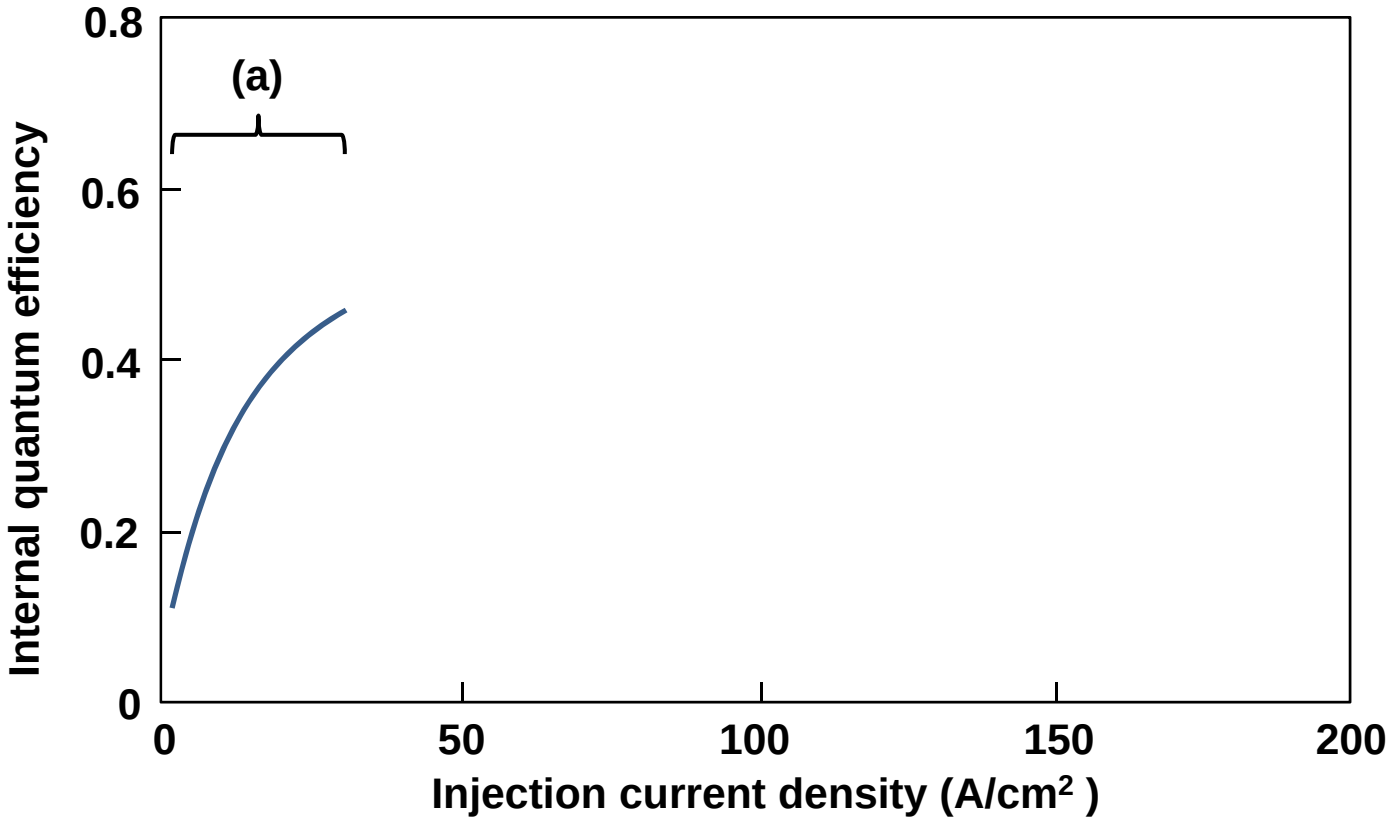
Carrier-phonon (<1ps)

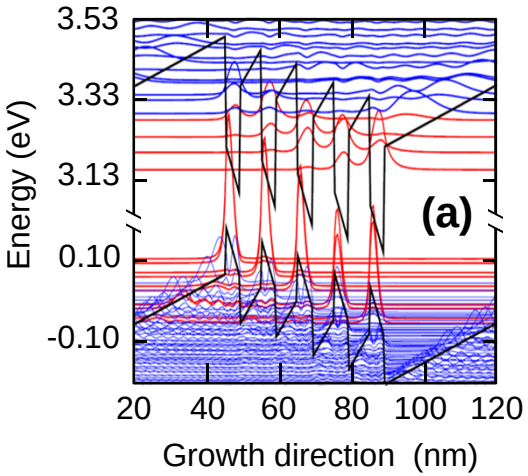


Similar for holes

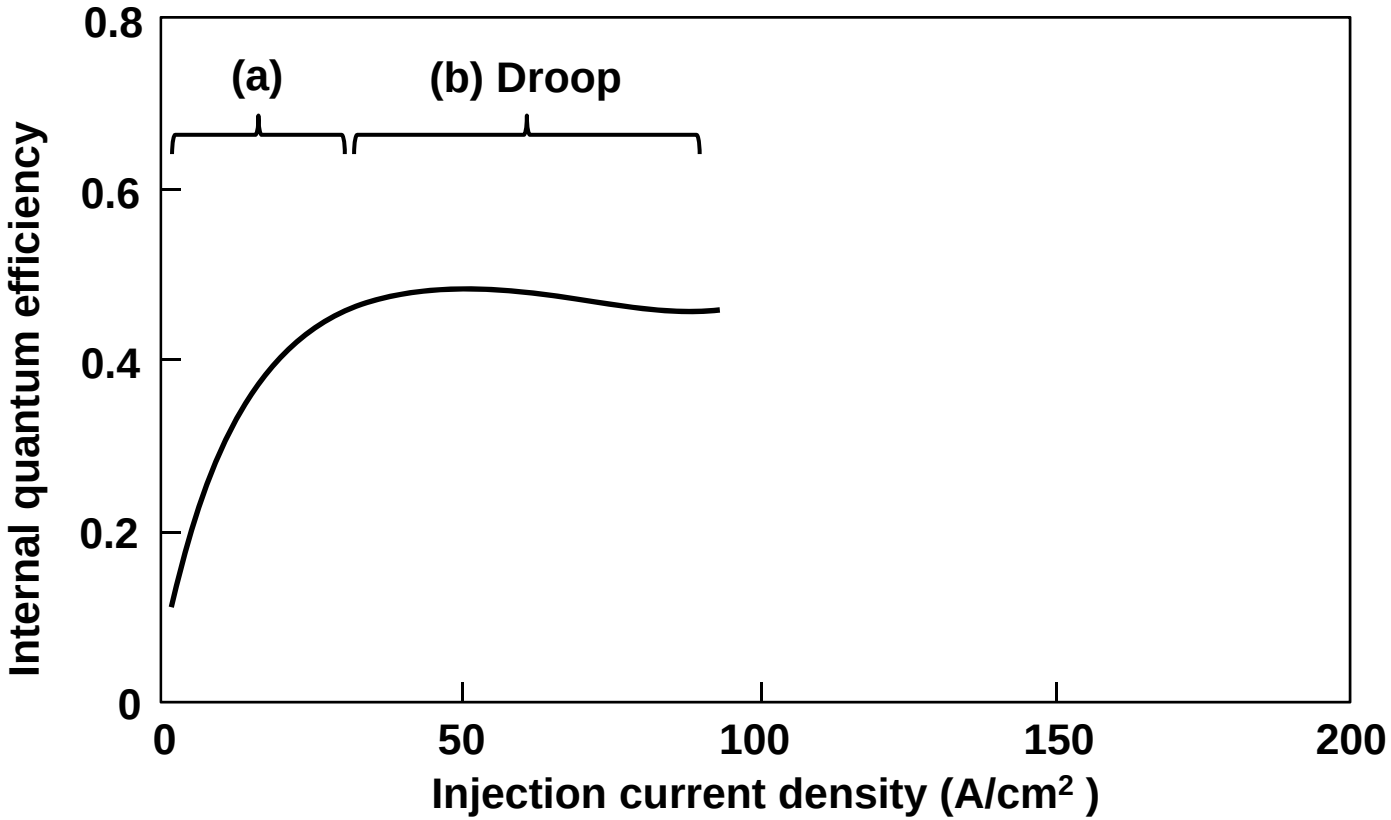
IEEE JQE **38** 402, 2002 (for QW); IEEE JQE **41** 495, 2005 (for QD); APL 97, 121105, 2010 (for InGaN LEDs)

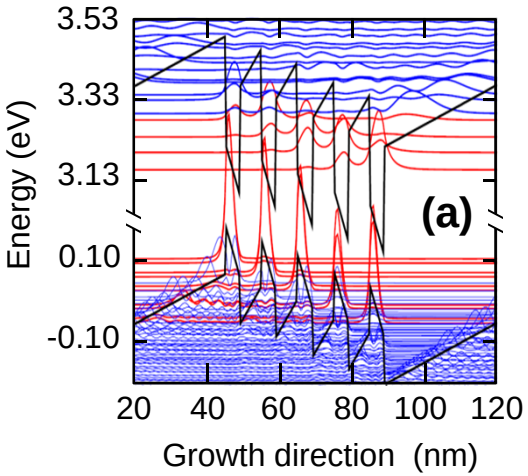
4nm $In_{0.2}Ga_{0.8}N$/6nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5x10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, $A = 10^{-7}s^{-1}$, C = 0

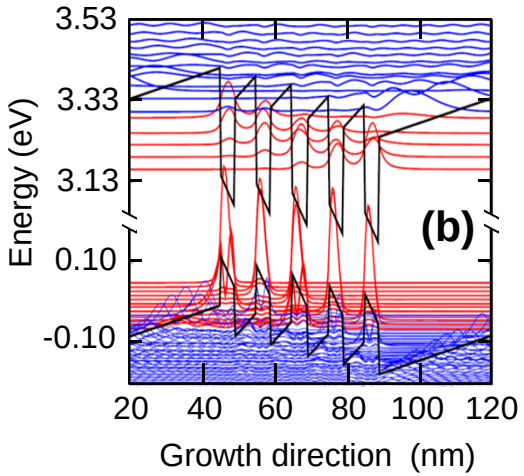




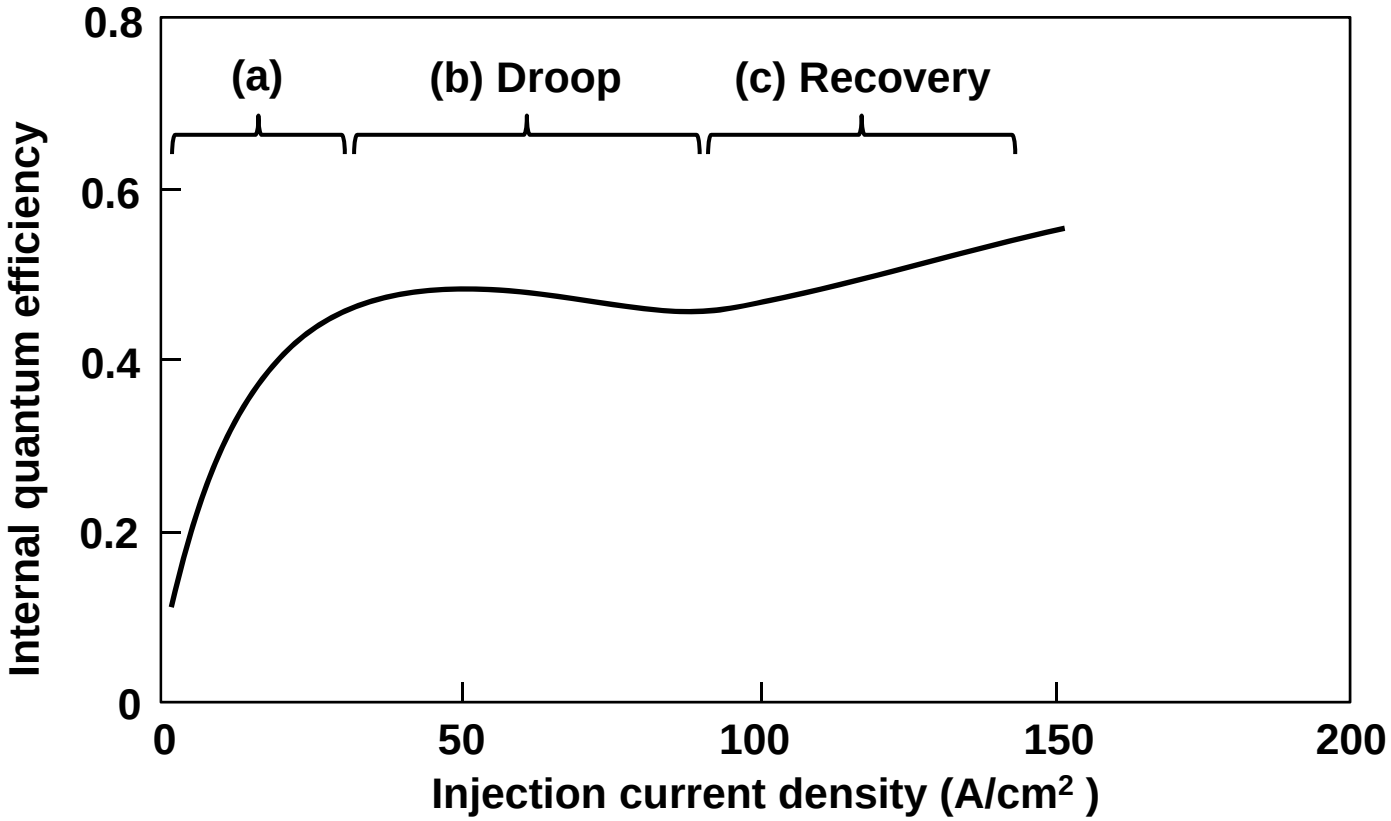
4nm $In_{0.2}Ga_{0.8}N$/6nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5\times10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, $A = 10^{-7}s^{-1}$, C = 0

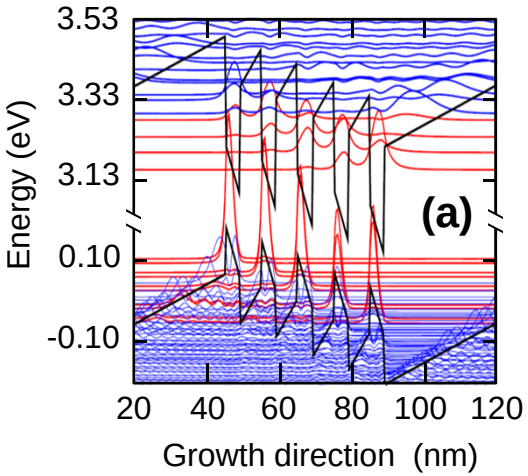


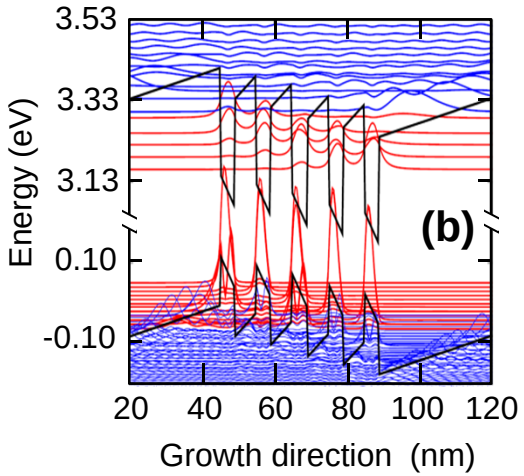


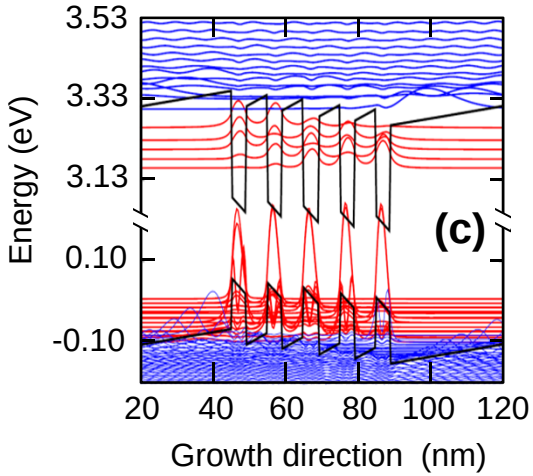


4nm $In_{0.2}Ga_{0.8}N$/6nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5x10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, $A = 10^{-7}s^{-1}$, C = 0

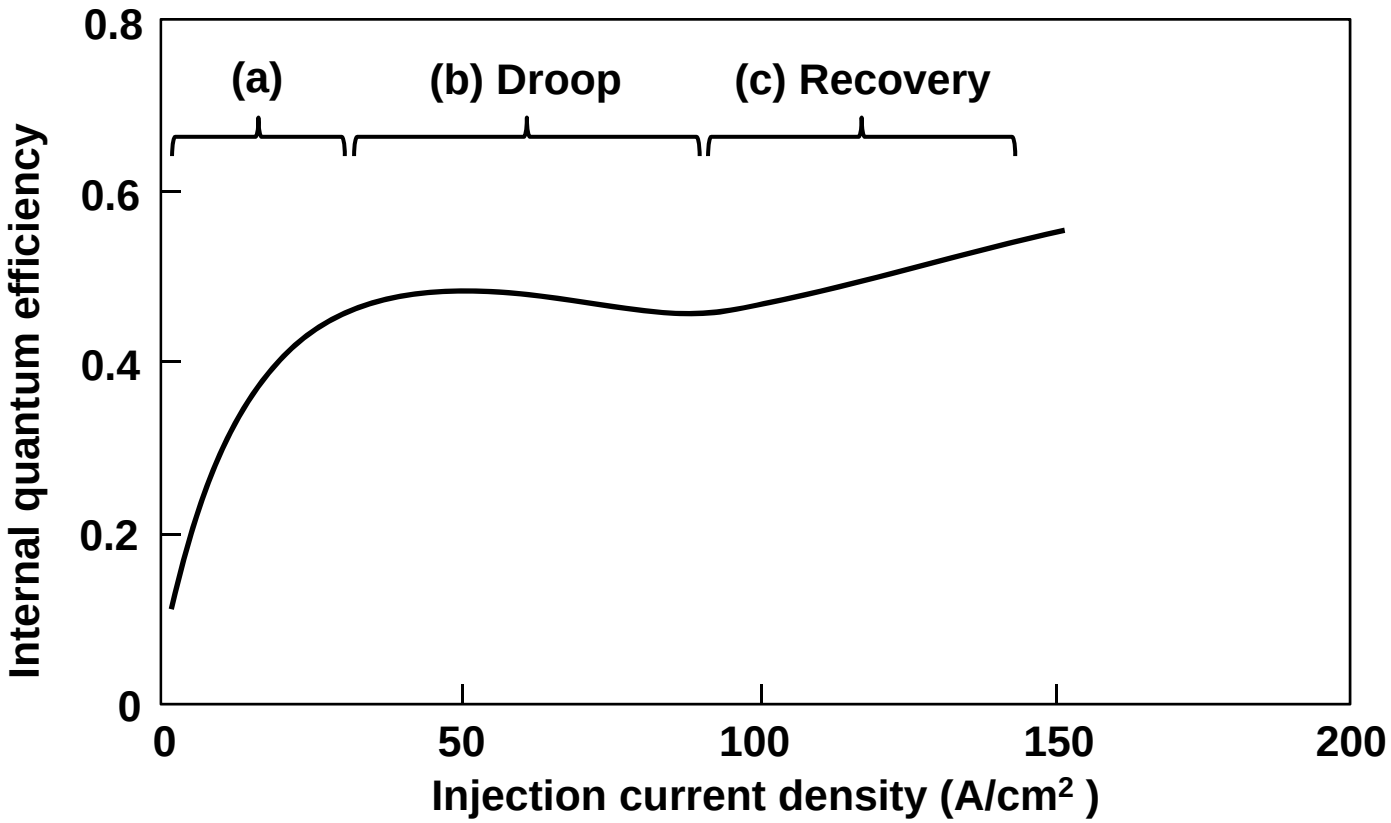




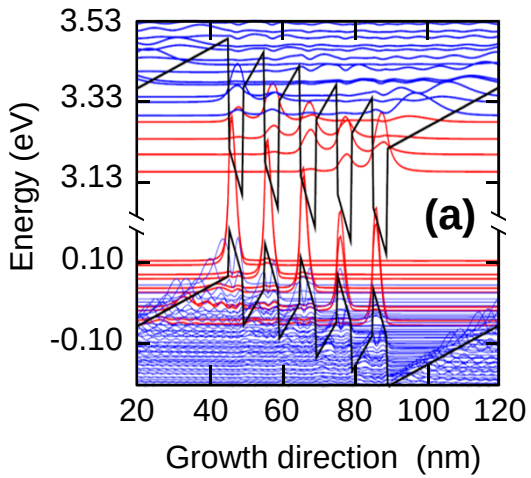


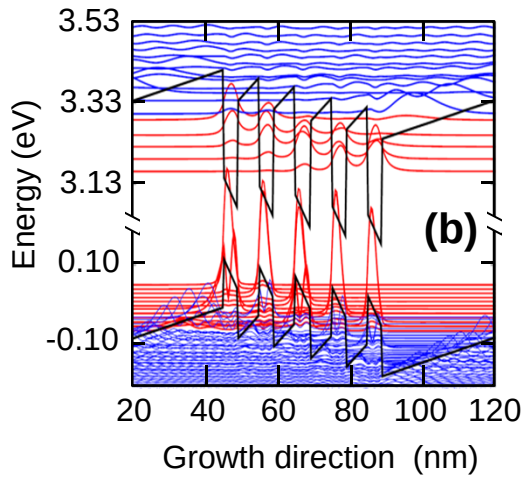


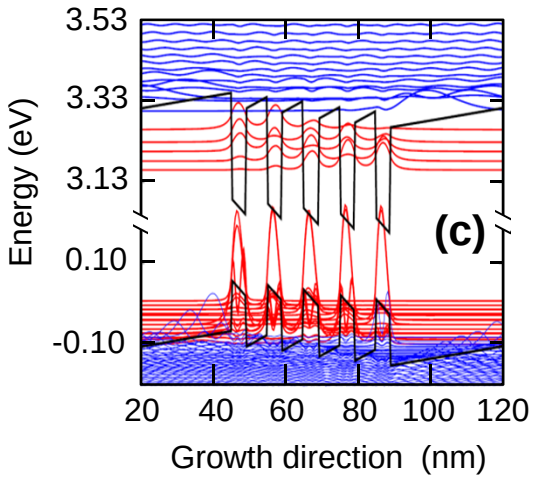
4nm $In_{0.2}Ga_{0.8}N$/6nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5x10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, $A = 10^{-7}s^{-1}$, C = 0



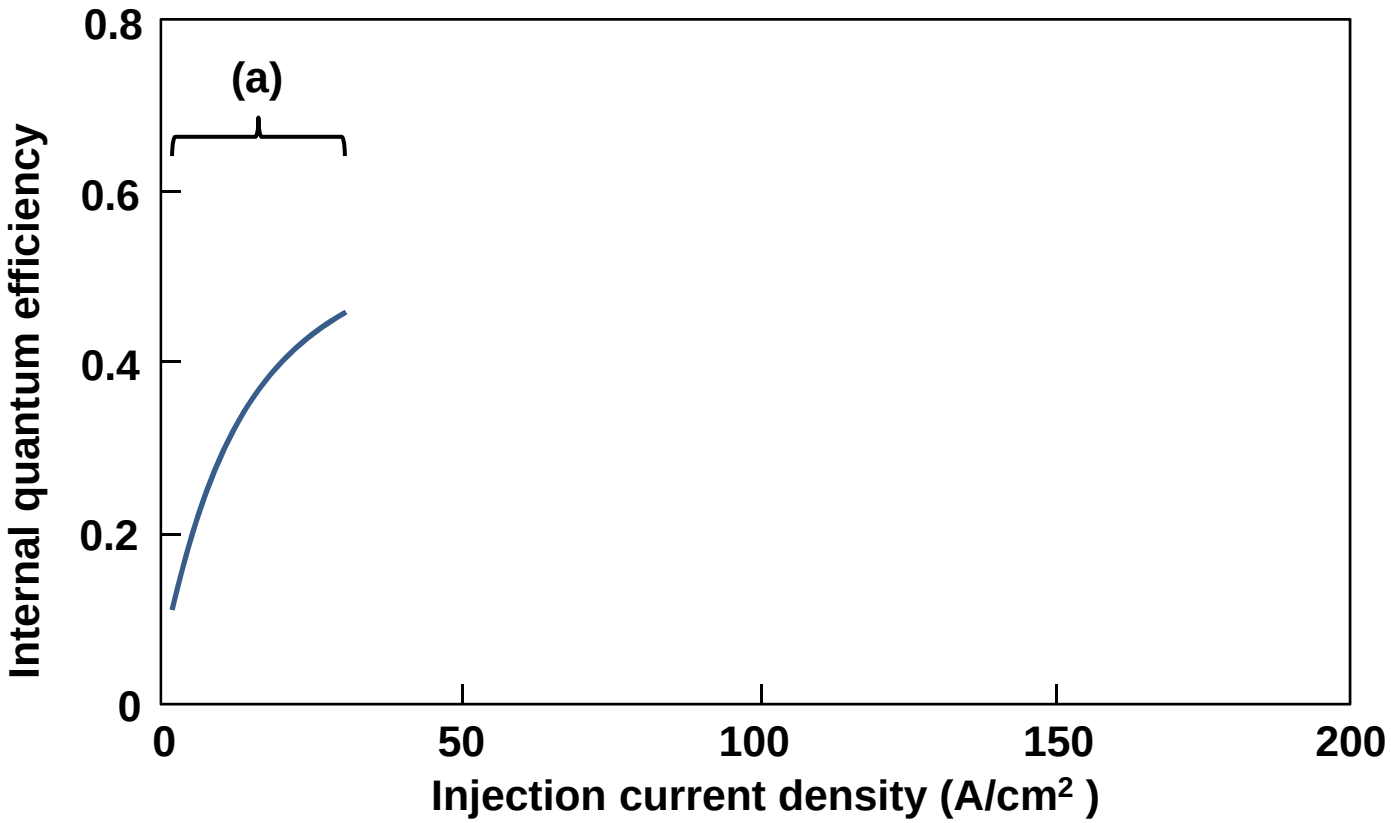
No Auger!



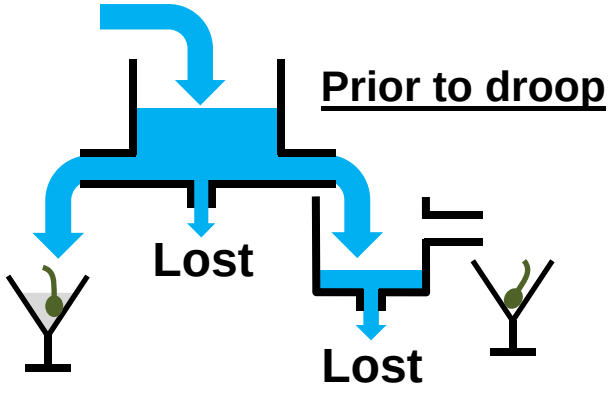




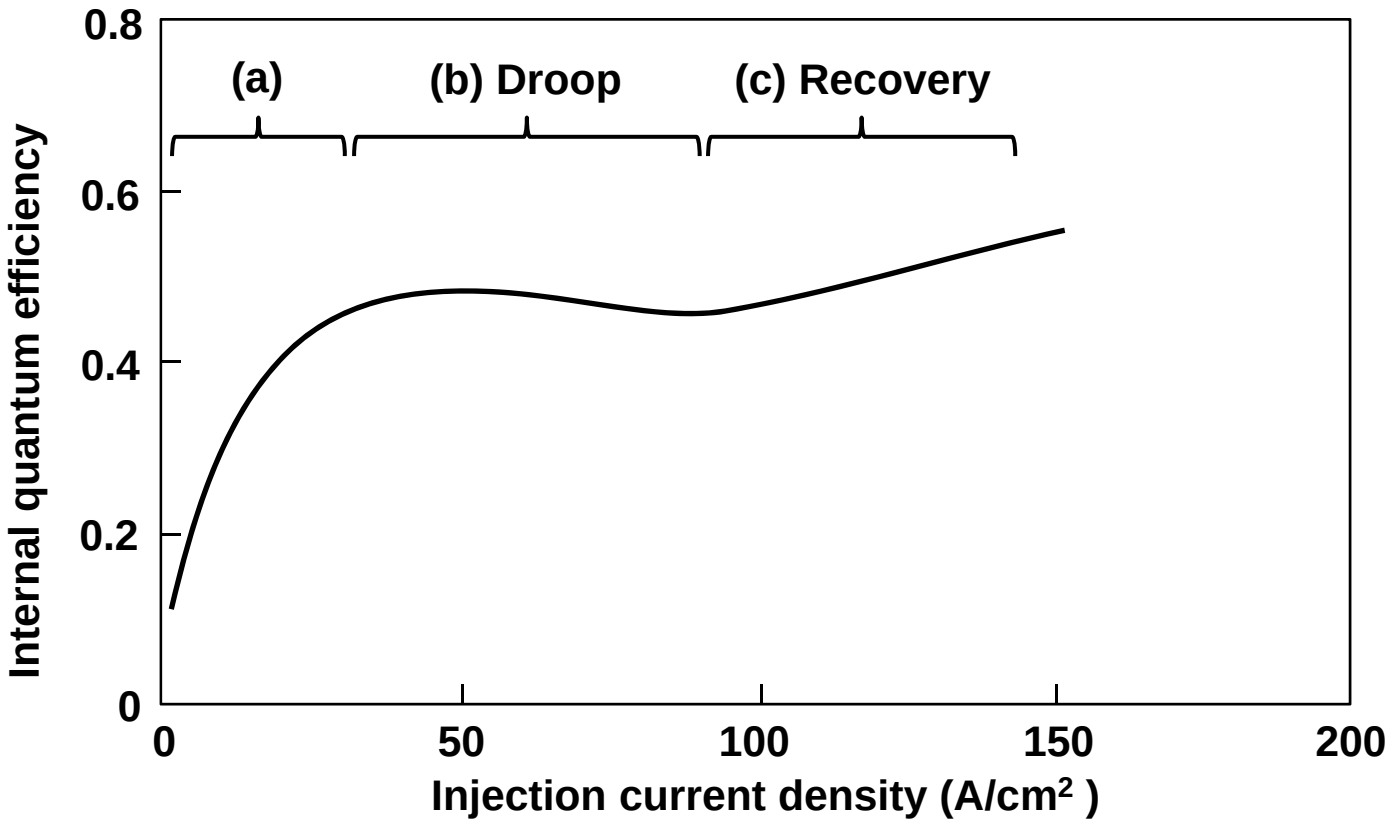
4nm $In_{0.2}Ga_{0.8}N$/6nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5x10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, A = $10^{-7}s^{-1}$, C = 0



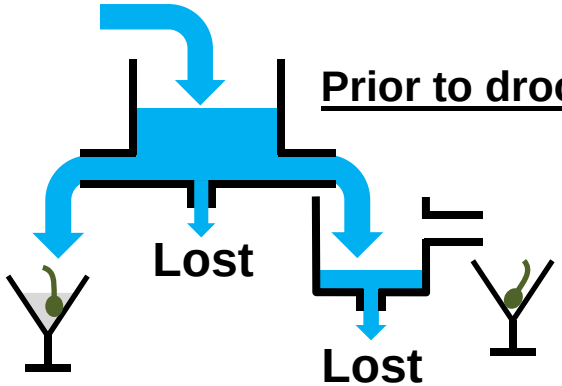
No Auger!

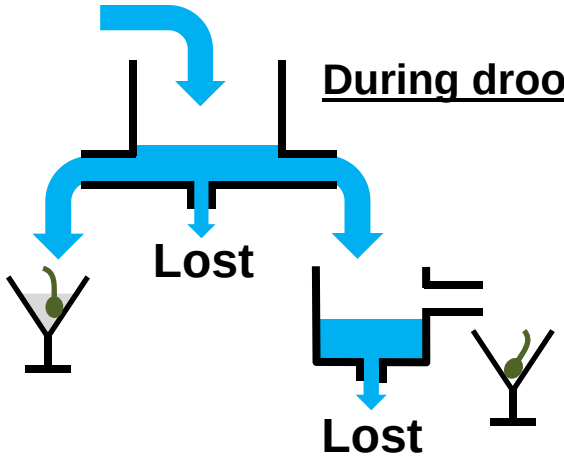


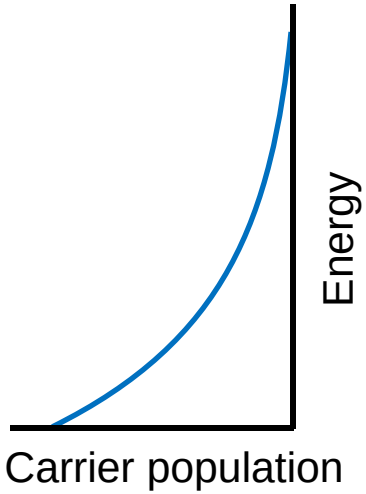
4nm $In_{0.2}Ga_{0.8}N$/6nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5x10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, A = $10^{-7}s^{-1}$, C = 0



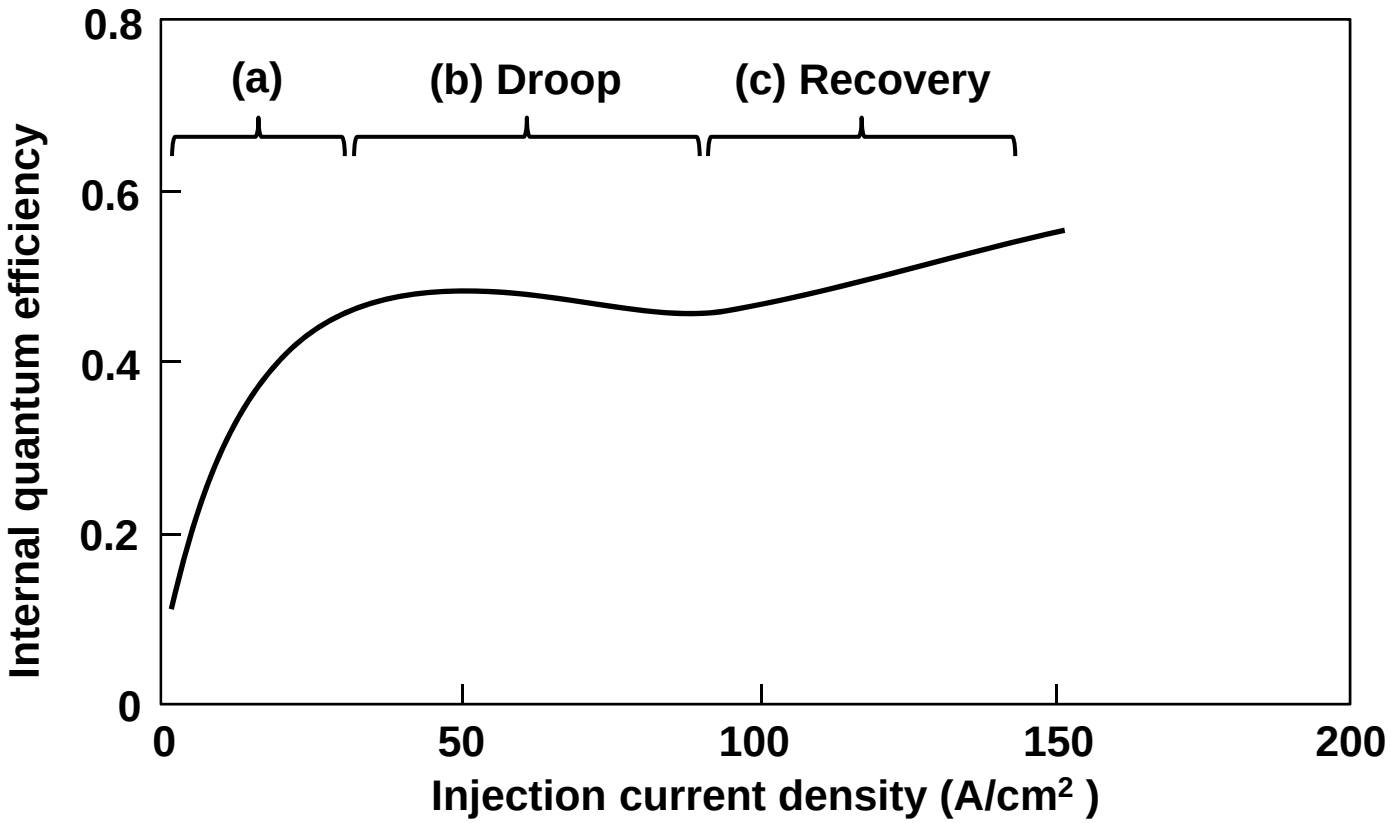
No Auger!



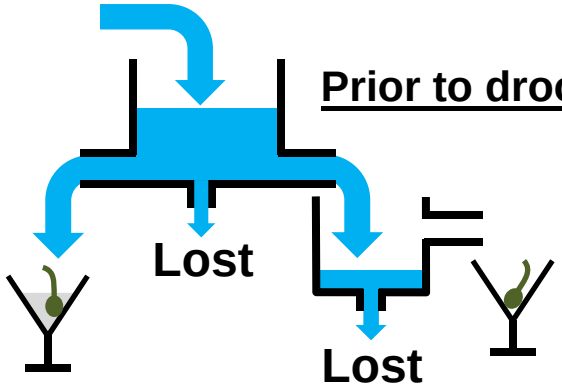


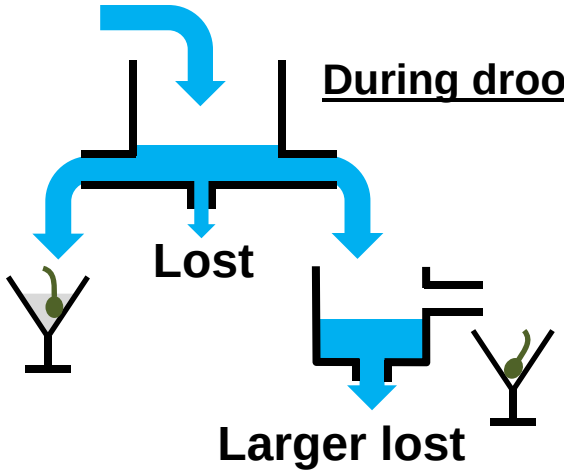


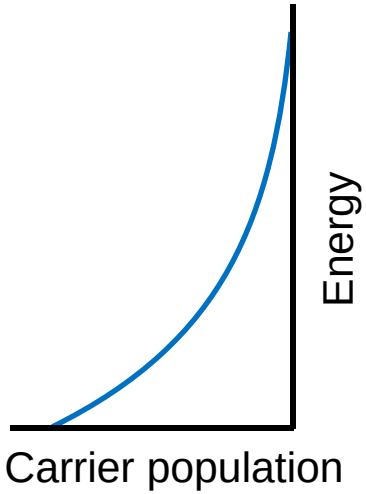
4nm $In_{0.2}Ga_{0.8}N$/6nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5x10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, A = $10^{-7}s^{-1}$, C = 0



No Auger!

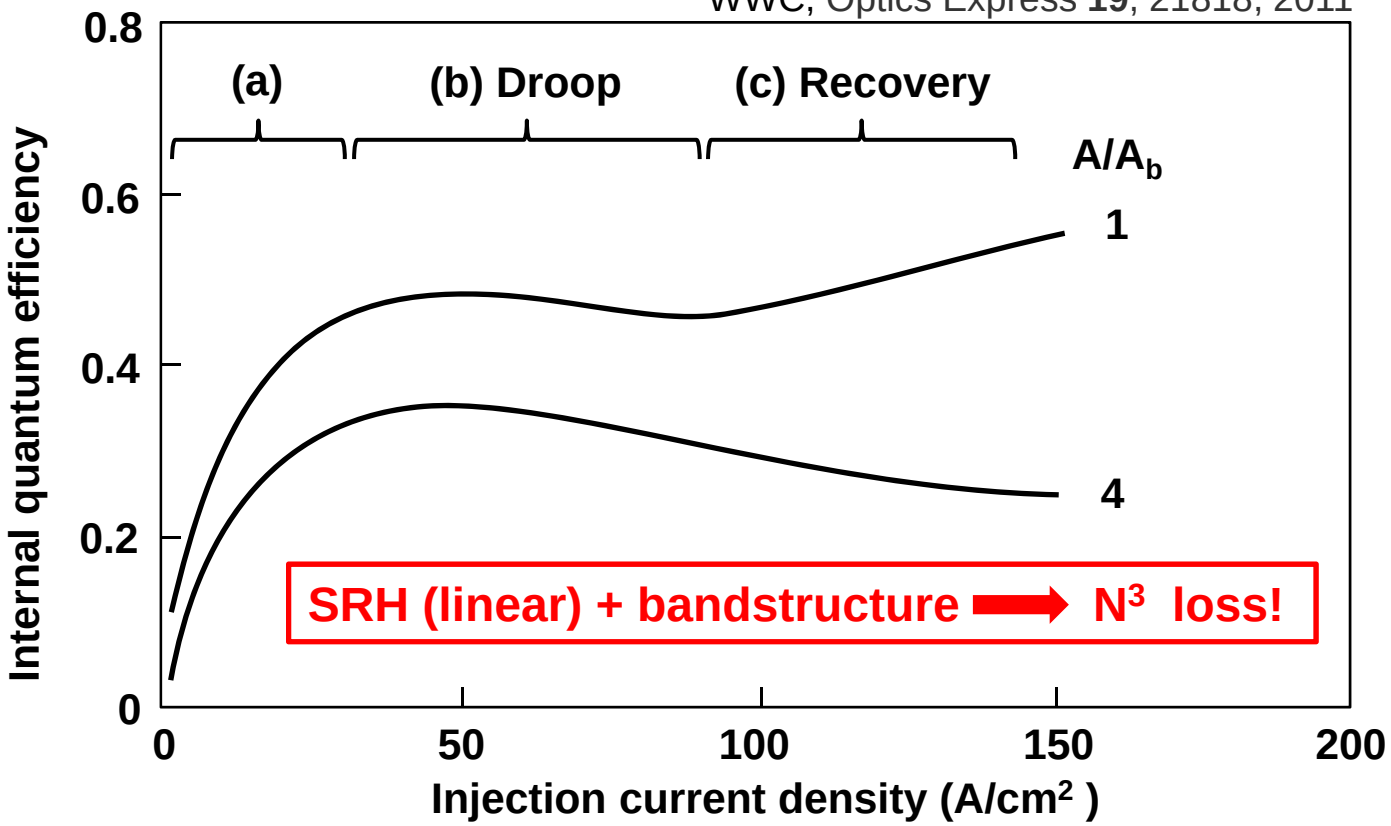




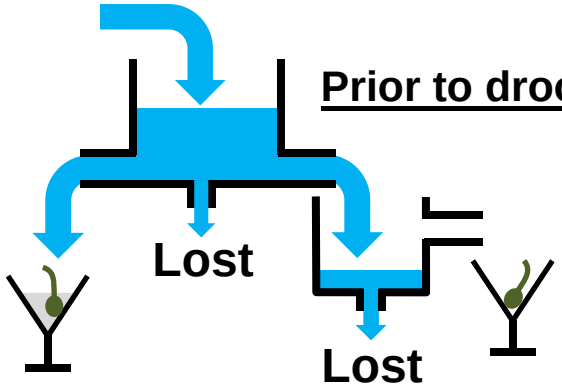


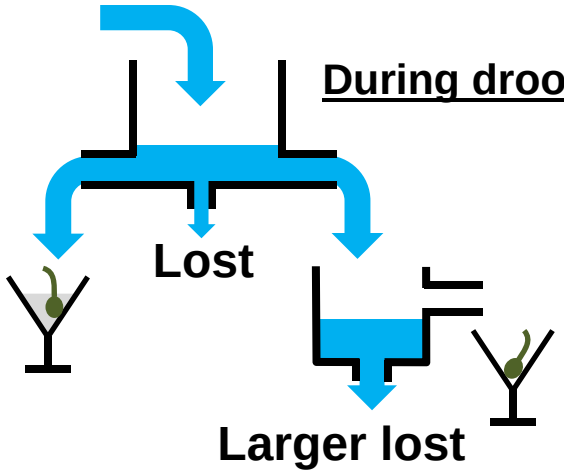
4nm $In_{0.2}Ga_{0.8}N$/6nmGaN, T_L = 300K, $\gamma_{c\text{-}c} = 5x10^{13}s^{-1}$, $\gamma_{c\text{-}c} = 10^{13}s^{-1}$, A = $10^{-7}s^{-1}$, C = 0

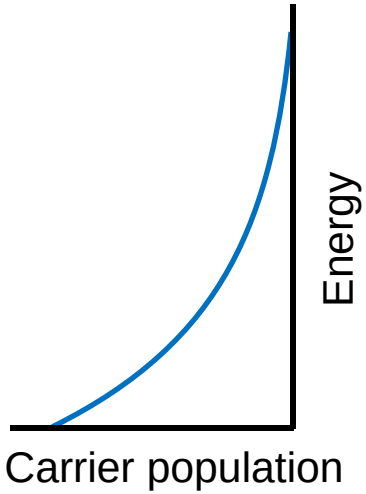
WWC, Optics Express **19**, 21818, 2011



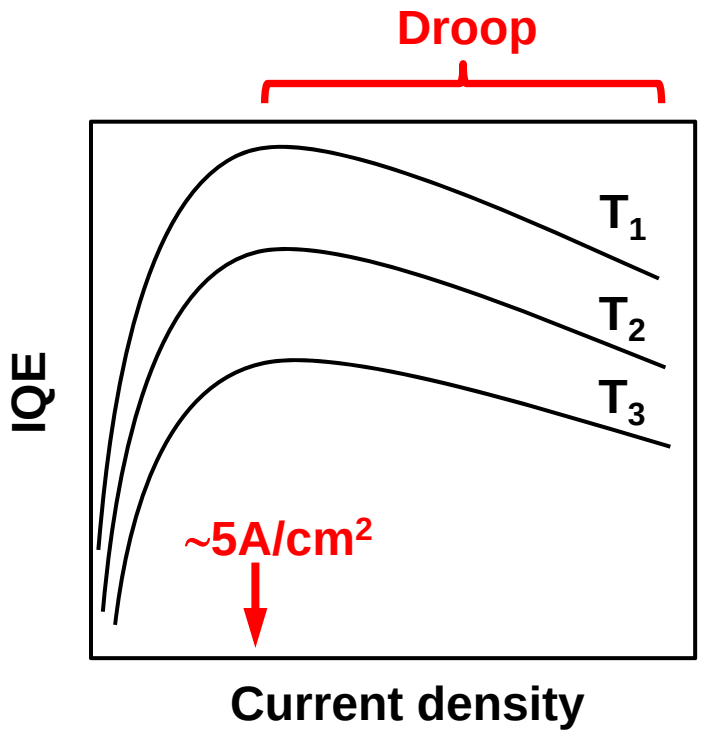
No Auger!







Summary



Can fit experiment with : $\mathbf{IQE} = \dfrac{BN^2}{AN + BN^2 + CN^3}$

? ?

Extrinsic	Intrinsic
Localization	Auger
Current leakage	Screening of piezoelectric field
Defect loss	