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SSLS EFRC

SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

Application of a microscopic model to efficiency droop of InGaN LEDs

Mary H. Crawford, Normand A. Modine, Andrew M. Armstrong,
Jeffrey Y. Tsao, Weng W. Chow

Sandia National Laboratories

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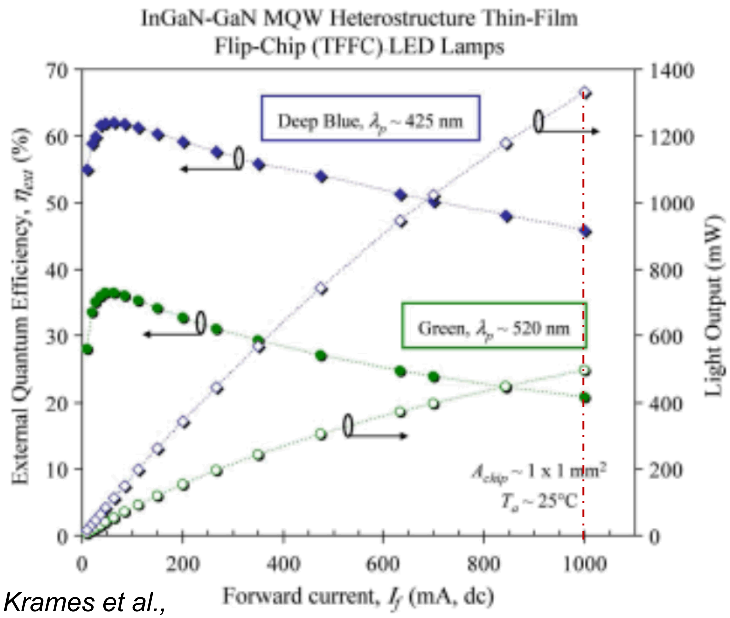
Motivation: High Efficiency InGaN LEDs for Solid State Lighting



Krames et al., J. Displ. Technol. (2007)

Primary Efficiency Limitations

- High operating currents ("efficiency droop")
- High operating temperatures
- Longer wavelengths (e.g., green and longer)

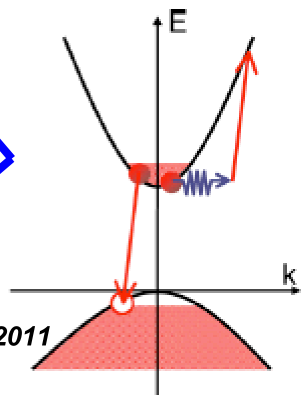
Recombination model:

$$\varepsilon_{IQE} = \frac{Bn^2}{An + Bn^2 + Cn^3 + Dn^m + \ldots}$$

Shockley-Read-Hall (nonrad at defects) — Radiative — Auger and higher order processes

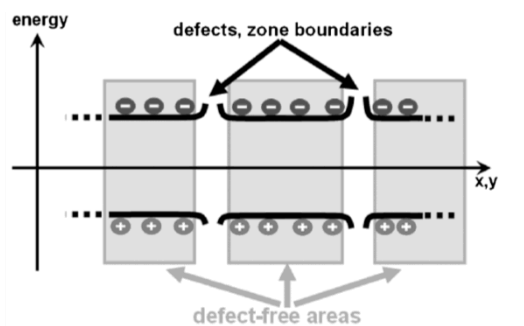
potential non-radiative mechanisms

Indirect Auger recombination



Kioupakis et al, APL, 2011

Carrier delocalization/ defect recombination



Hader et al, APL 2010

Carrier capture / leakage

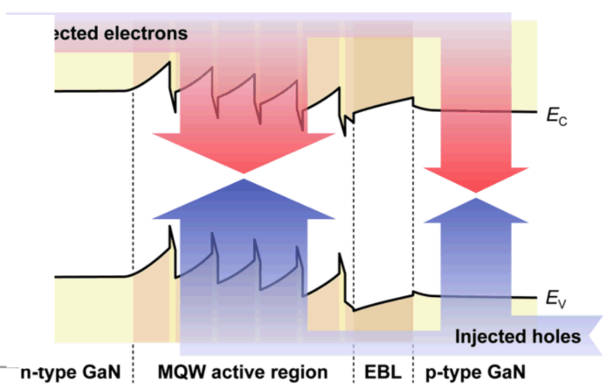


Figure: E. F. Schubert

I. Application of a Microscopic Model to Study Efficiency Limitations in InGaN LEDs

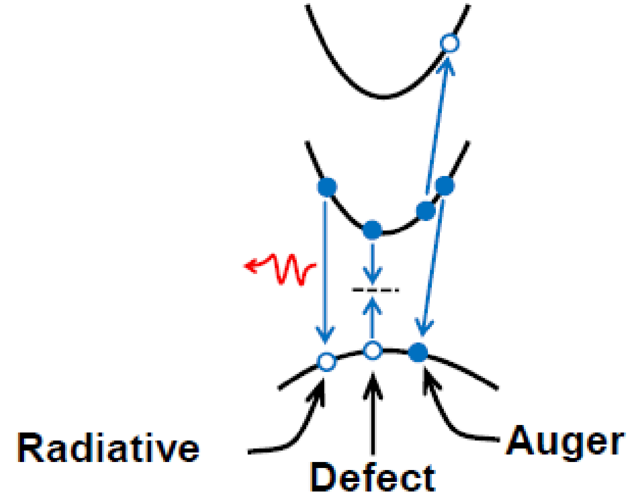
LED rate-equation model ("ABC")

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

- AN: Defects
- BN^2: Spontaneous emission
- CN^3: Auger?

$$\text{Internal quantum efficiency} = \frac{BN^2}{AN + BN^2 + CN^3}$$

Radiative and Non-radiative Processes



Model Shortcomings:

a) True density dependence not simple N^m

b) Carrier capture/leakage ignored

c) Plasma heating and other non-equilibrium effects ignored

Approach:

- **Advance rate equation model:**
  - *-microscopic radiative component*
  - *-non-equilibrium effects*
- **Explore non-linear contributions of defect-related recombination**

Model Approach

“ABC” Quasi equilibrium model (phenomenological rate equations)	k-resolved, relaxation rate approx.	k-resolved, quantum kinetic theory

Key Advances from “ABC” model

$$N = \sum_k n_{e(h),k}$$

→Replace total “N” with k–resolved distributions

→ *bandstructure implemented directly into model*

→Track carrier distributions in both QWs and barriers

→ *treatment of carrier injection and leakage*

→Carrier-carrier and carrier–phonon interactions

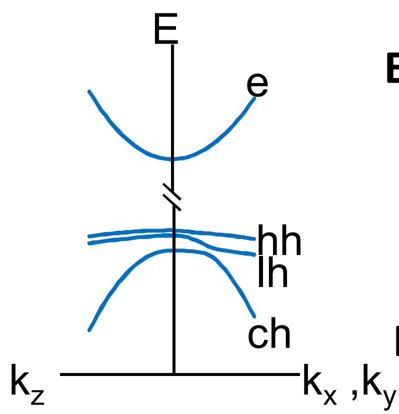
→ *Relaxation rate approximation*

$$\left.\frac{\partial n_{\sigma,\alpha_\sigma,k_\perp}}{\partial t}\right|_{col} = -\gamma_{c-c}\left[n_{\sigma,\alpha_\sigma,k_\perp} - f_{\sigma,\alpha_\sigma,k_\perp}(\mu^p_\sigma, T_p)\right] - \gamma_{c-p}\left[n_{\sigma,\alpha_\sigma,k} - f_{\sigma,\alpha_\sigma,k_\perp}(\mu^l_\sigma, T_l)\right]$$

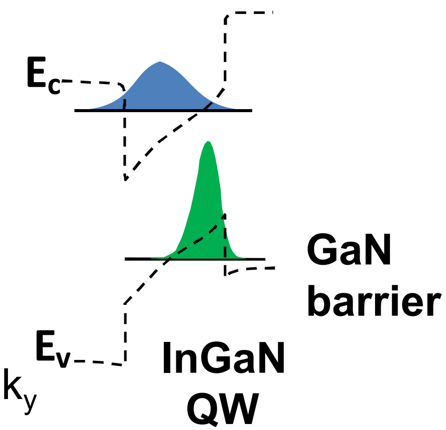
→Calculate radiative contribution directly

→ *avoids constant B parameter*

Band-structure



Quantum – confinement & polarization fields



"ABC model"

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

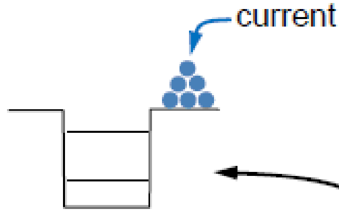
Defects (AN); Spontaneous emission (BN^2); Auger? (CN^3)

Summary of model and equations

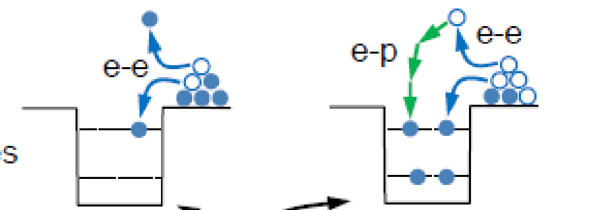
New Model

IEEE JQE **38** 402, 2002 (for QW)
IEEE JQE **41** 495, 2005 (for QD)

Carrier injection



Carrier-carrier (100fs) Carrier-phonon (1ps)



Similar for holes

e or h

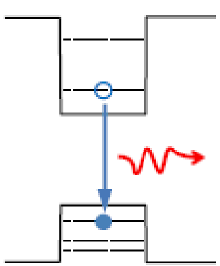
Barrier:

$$\frac{dn^b_{\sigma,k}}{dt} = \frac{J(t)}{eN^p_\alpha} f\left(\varepsilon^b_{\sigma k}, \mu^p_\alpha, T_p\right)\left(1 - n^b_{\alpha,k}\right) - A_b n^b_{\sigma,k} + \left.\frac{\partial n^b_{\sigma,k}(t)}{\partial t}\right|_{col}$$

QW:

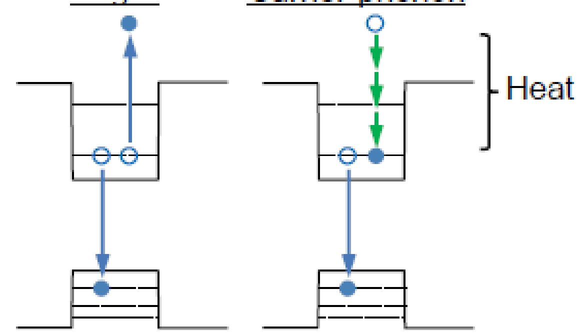
$$\frac{dn_{\sigma,\alpha_\sigma,k_\perp}}{dt} = -n_{\sigma,\alpha_\sigma,k_\perp} \sum_{\alpha_{\sigma'}} \frac{\wp^2_{\alpha\beta k}\Omega^3_k}{\pi\varepsilon\hbar c^3} n_{\sigma',\alpha_{\sigma'},k_\perp} - A n_{\sigma,\alpha_\sigma,k_\perp} + \left.\frac{\partial n_{\sigma,\alpha_\sigma,k_\perp}}{\partial t}\right|_{col}$$

Spontaneous emission (>ns)



$\tau = CN^2$

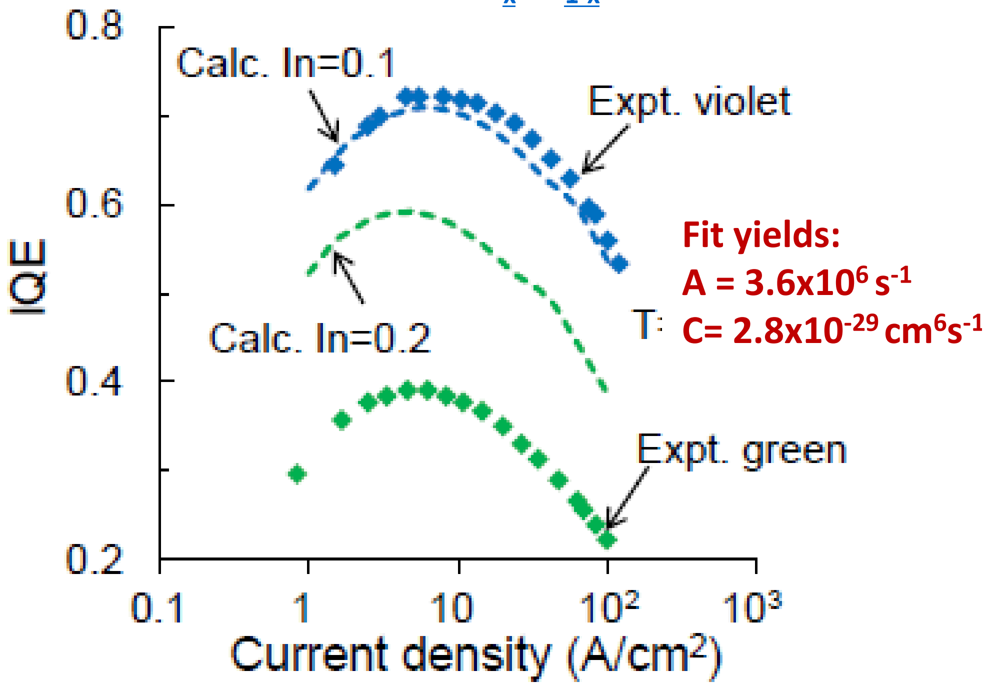
Auger Carrier-phonon



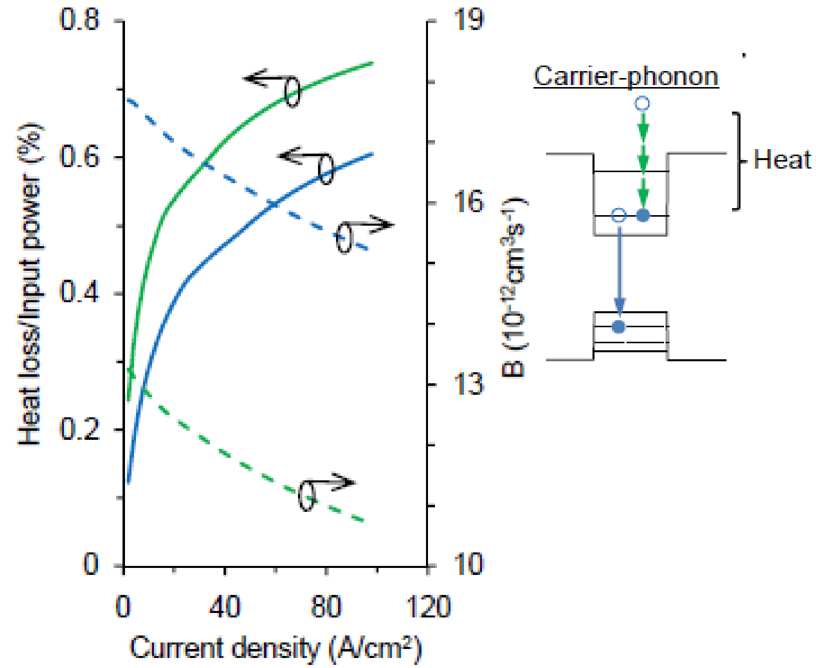
Contributions to LED Efficiency Dependence on Wavelength

Outstanding issue: why are longer wavelength (green) InGaN LEDs less efficient ?
→ **hypotheses: increased strain/polarization fields, increased non-radiative defects**

IQE of Commercial $In_xGa_{1-x}N$ QW LEDs



Contributions to lower green efficiency

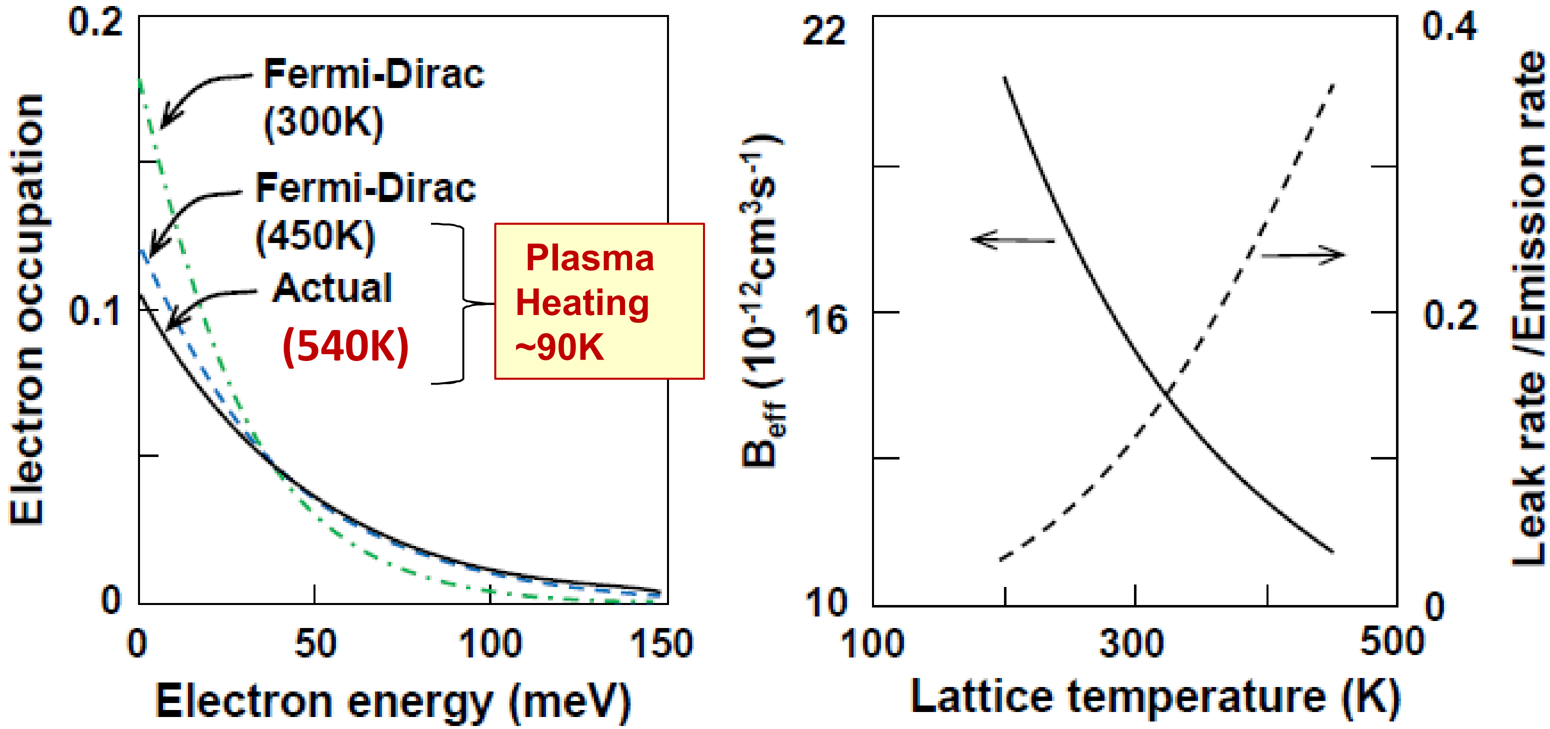


Model insights: ~1/3 of difference between violet and green LED efficiency is due to intrinsic contributions
→ **enhanced heat loss (phonons), reduced effective B coefficient**

$$B_{eff} = N - 2\sum_{k_\perp} |\wp_{k_\perp}|^2 \Omega^3_{k_\perp} (\pi\varepsilon\hbar c^3)^{-1} n_{e,k_\perp} n_{h,k_\perp}$$

Contributions to LED Efficiency Dependence on Temperature

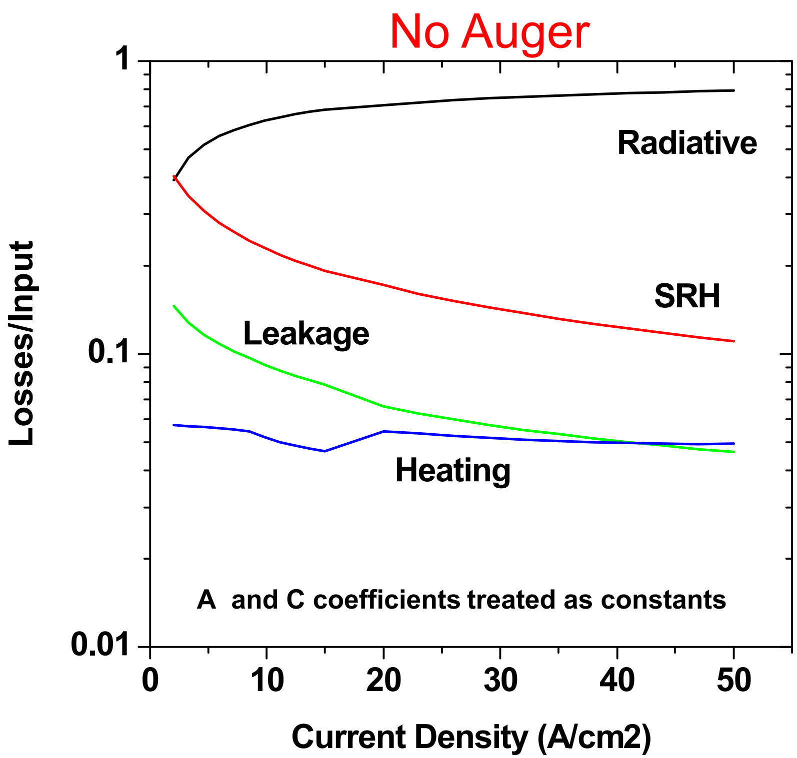
Assumptions: In $_{0.1}$Ga$_{0.9}$N QW LED (violet) J = 100 A/cm^2 T= 450K

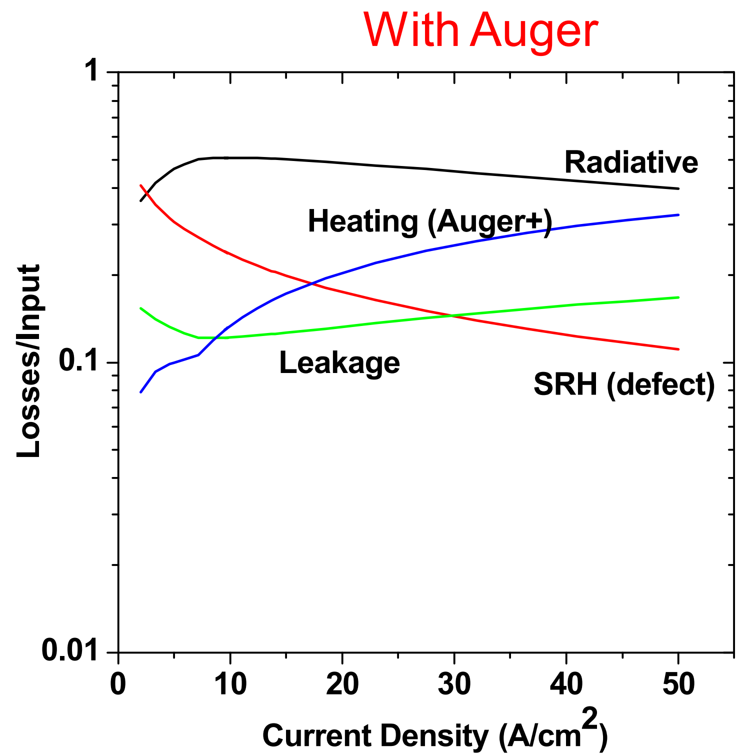


- Model quantifies plasma heating at high current densities (100 A/cm^2)
- Quantifies contributions to lower efficiency at elevated temperatures:
  → carrier leakage out of QWs, reduced B_{eff}

Interdependences of Loss Contributions

$In_{0.1}Ga_{0.9}N$ QW





- For violet QWs, losses due to phonon emission (heating) is minimal up to 50 A/cm^2 in the absence of Auger recombination
- Auger-related heating drives enhanced carrier leakage

II. Potential Role of Defects in Efficiency Droop

LED rate-equation model

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

AN: Defects; BN^2: Spontaneous emission; CN^3: Auger?

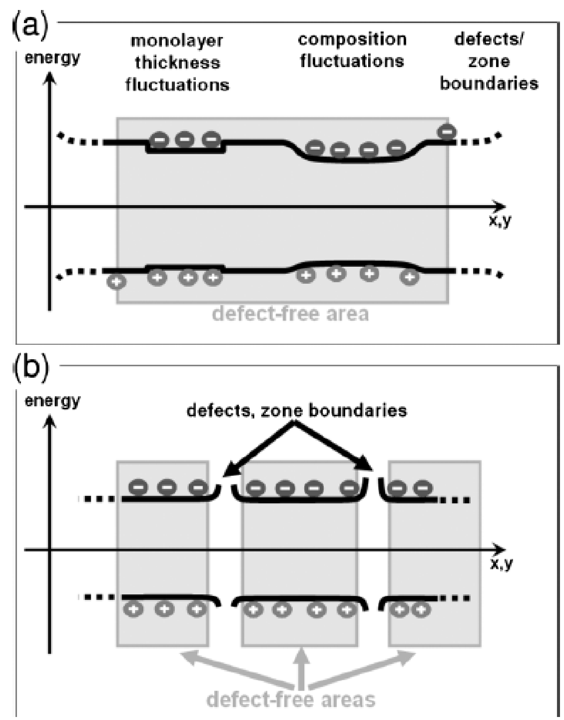
$$\text{Internal quantum efficiency} = \frac{BN^2}{AN + BN^2 + CN^3}$$

Questions:

- *Can defects contribute nonlinear terms in the absence of localization?*
- *What defect properties are required to impact efficiency in the droop regime?*

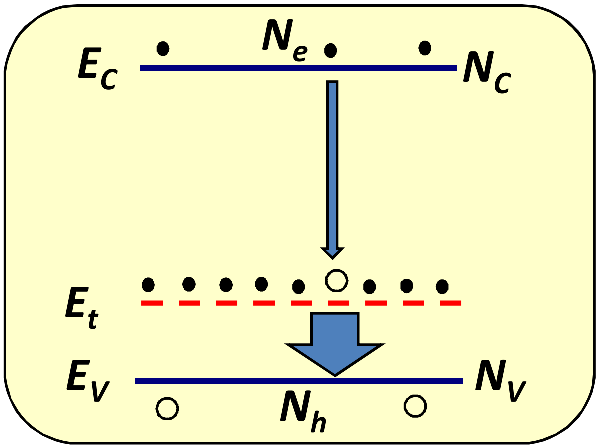
Density-Activated Defect Recombination

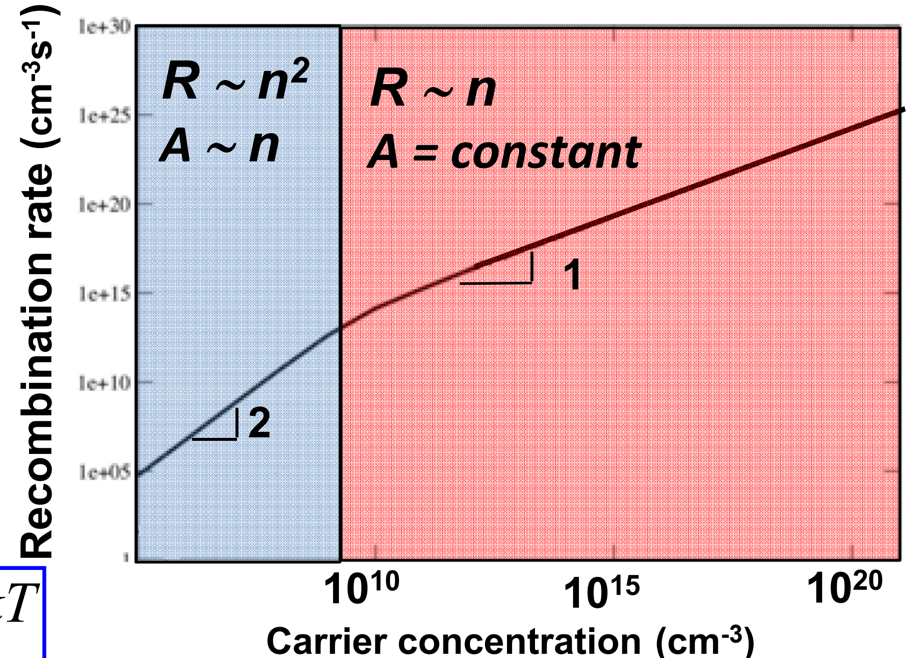
$$J_{\mathrm{DADR}} = \begin{cases} 0, & \text{for} \quad N < N_0 \\ \dfrac{e n_w}{\tau_{\mathrm{DADR}}} \dfrac{(N - N_0)^2}{2N_0}, & \text{for} \quad N > N_0 \end{cases}$$



Hader et al., APL 2011

Basic SRH Theory Predicts A(n)



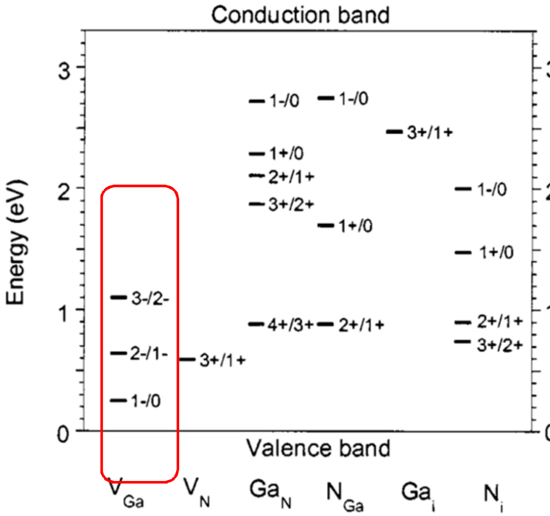


For $N_e = N_h = n \ll N_V \exp(E_v - E_t)/kT$

$$R_{SRH} \approx \frac{n^2}{\tau_{n0} N_V \exp(E_v - E_t)/kT}$$

- ***$R \sim n^2$* when hole emission outpaces hole capture**
- ***A is not constant even for simple defects***
- ***BUT, simple defects cannot explain droop***

What About Multilevel Defects?



Limpijumnong and Van de Walle, PRB 2004.

V_{Ga}–like test case:

$N_{TOTAL} = 3 \times 10^{17}$

$E^{-3/-2} = 1.00$ eV

$E^{-2/-1} = 0.55$ eV

$E^{-1/0} = 0.15$ eV

$C_n^{-3/-2} = 6.2\text{e-}13\ cm^3s^{-1}$

$C_n^{-2/-1} = 1.3\text{e-}11\ cm^3s^{-1}$

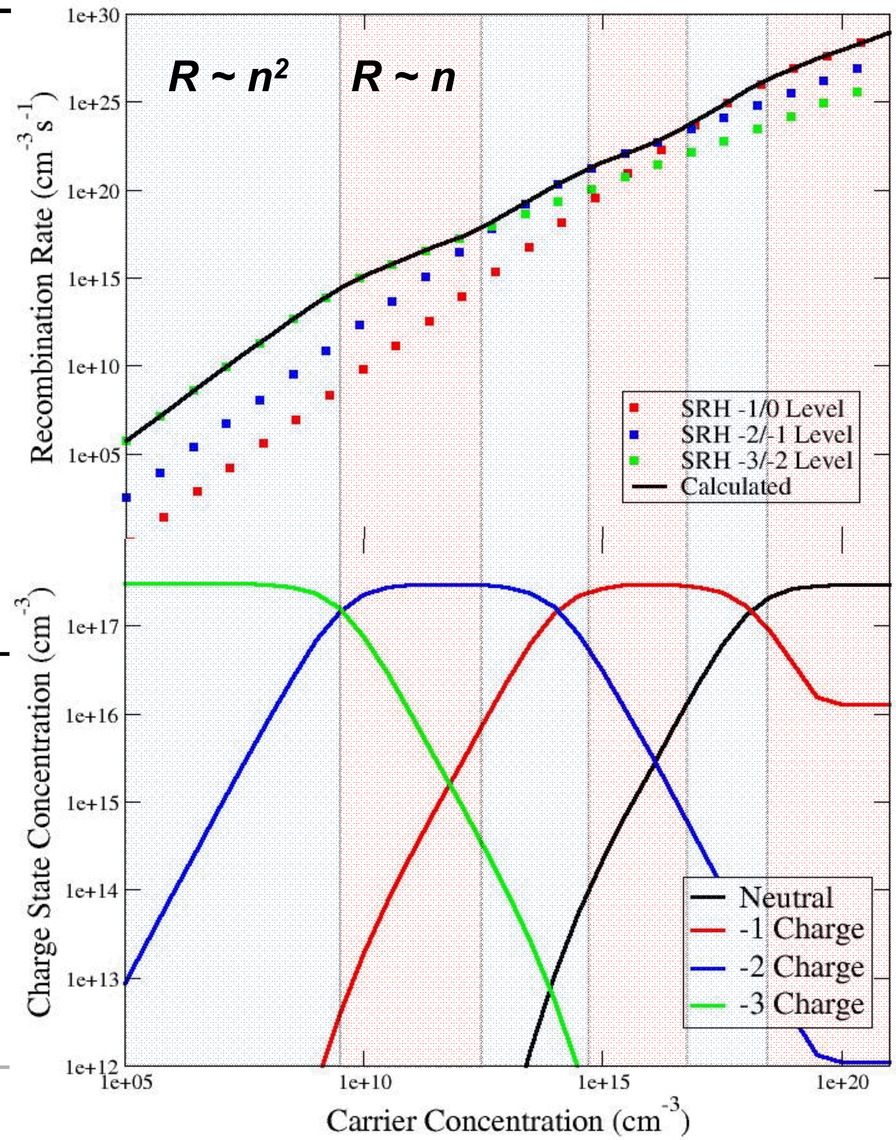
$C_n^{-1/0} = 3.0\text{e-}10\ cm^3s^{-1}$

$C_p^{-1/0} = 6.7\text{e-}9\ cm^3s^{-1}$

$C_p^{-2/-1} = 1.5\text{e-}7\ cm^3s^{-1}$

$C_p^{-3/-2} = 3.3\text{e-}6\ cm^3s^{-1}$

Calculated *R*(*n*)



- **Multiple *R* ~ n^2 regimes**
- **Summing SRH rates gives decent approximation**
- **Shallower levels have n^2 to n cross-over at larger *n***
- → ***Still not $R \sim n^{>2}$***

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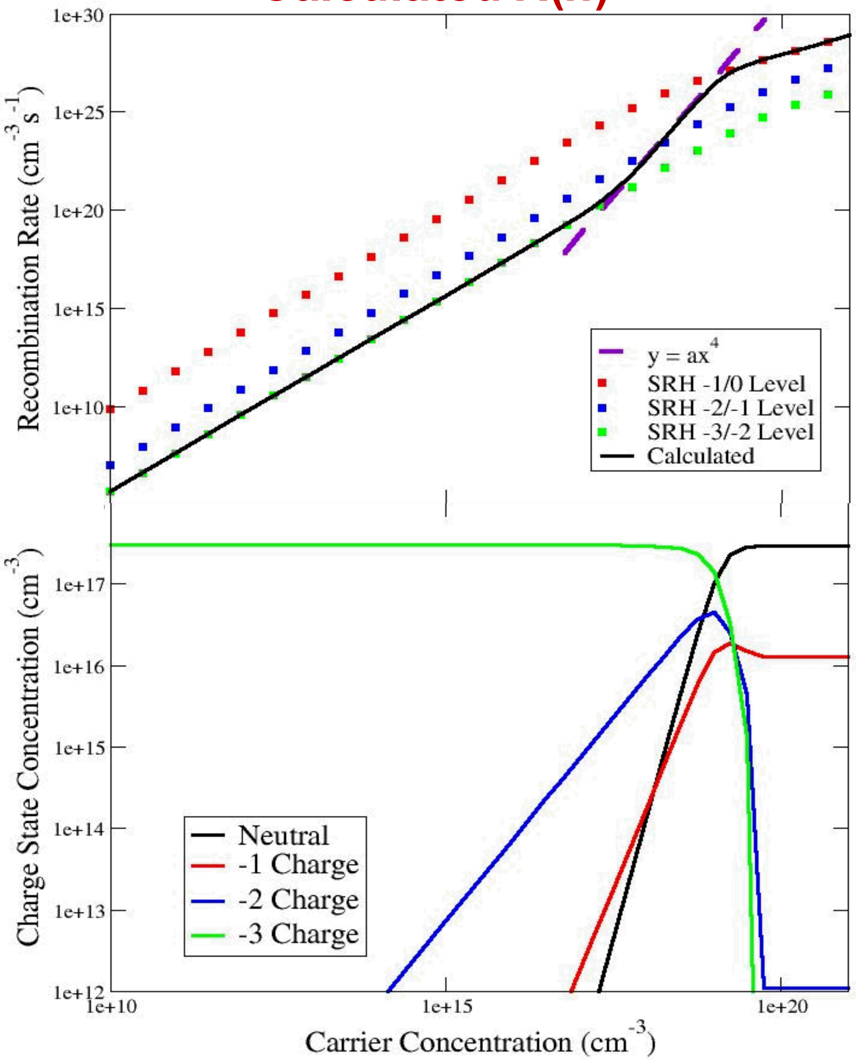
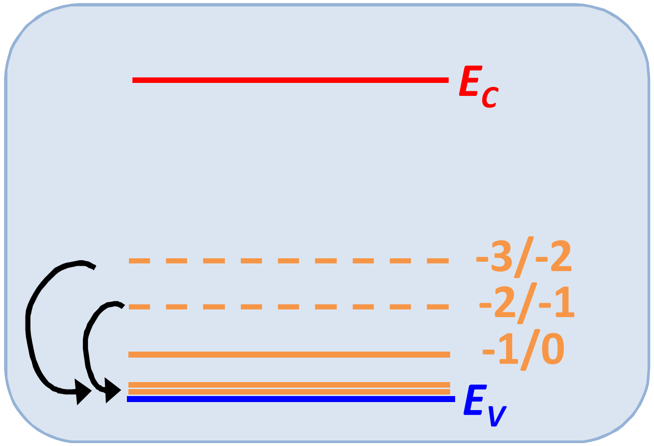
What About Negative-U Defects?

Calculated *R*(*n*)



Defect Energy Levels

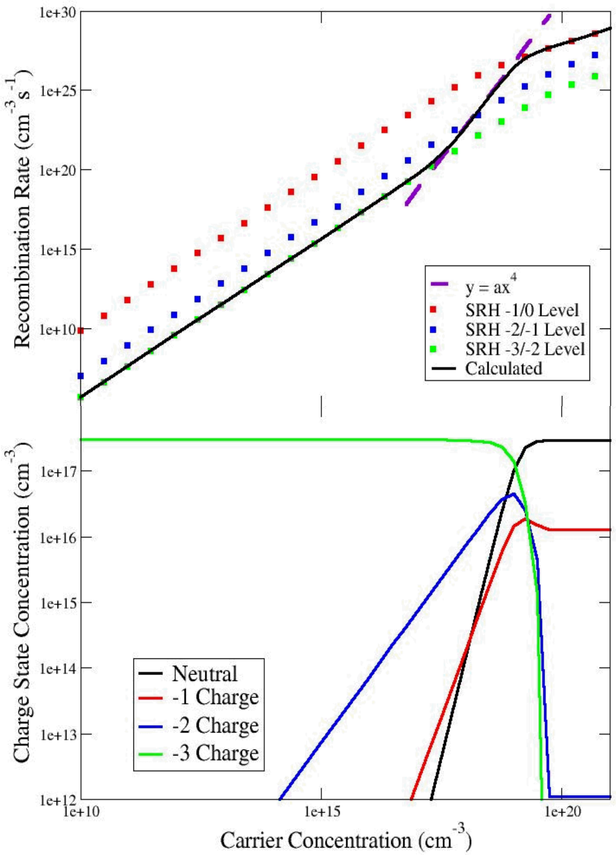


- ***-U* behavior** makes the -2 and -1 charge states unstable
- **Shallow levels** keep defect in -3 state until 10^{18} – 10^{19} cm^{-3} carriers
- Defect recombination requires $3h^+ + e^-$ giving $R \sim n^4$

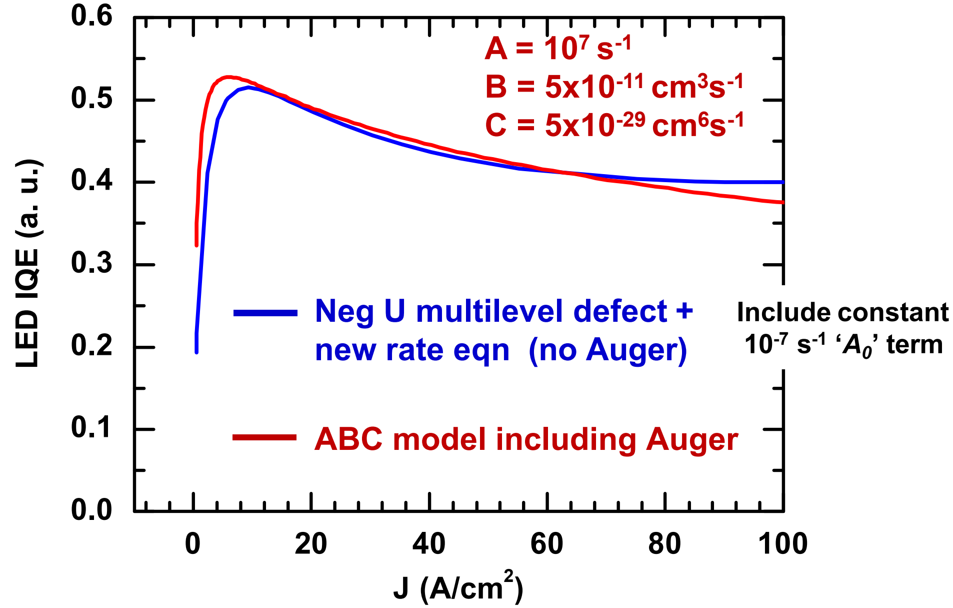
→ ***Combined conditions sufficient to contribute in the droop regime***

Influence of $A(n)$ on LED IQE

Calculated $R(n)$--Negative U defect



Comparing two models for LED IQE



- Multilevel defect can contribute to droop, given:
  - *Negative-U defect*
  - *Sufficiently shallow defect level*
- ***Auger or other $n^{>2}$ mechanism still required*** at highest currents to match experiments

Summary

- **Modified rate equation model enables insights into contributions to reduced LED efficiency up to high carrier densities; impact of bandstructure and plasma heating on:**

  → LED efficiency versus wavelength

  → LED efficiency at elevated temperatures

  → Impact of Auger on other loss terms , including radiative recombination and leakage

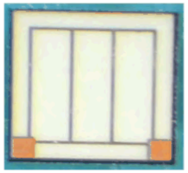
- **Explored conditions for non-linear loss via recombination at defects without invoking carrier localization**

  → multi-level defect with negative U behavior, V_{Ga} –like defect, R~n4

  → Shallow defect to delay nonlinear contribution to high carrier densities (1e18-1e19 cm^{-3})

  → may contribute to higher order coefficients

LED Chip



Packaged LED

Luminaires

Figures from DOE EERE SSL MYPP March 2010