

Carrier Loss Analysis for Ultraviolet Light-Emitting Diodes

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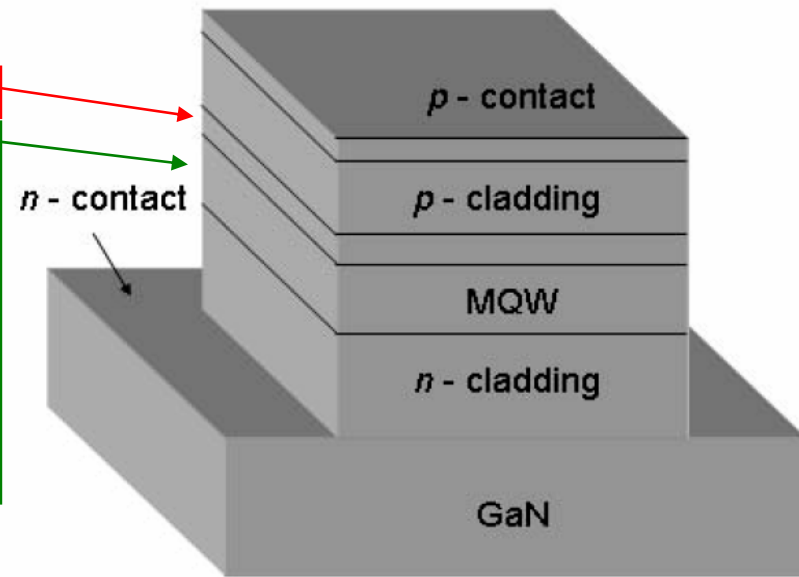
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University of California at Santa Barbara

1. Introduction
2. Experimental Results
3. Model and Parameters
4. Simulation Results

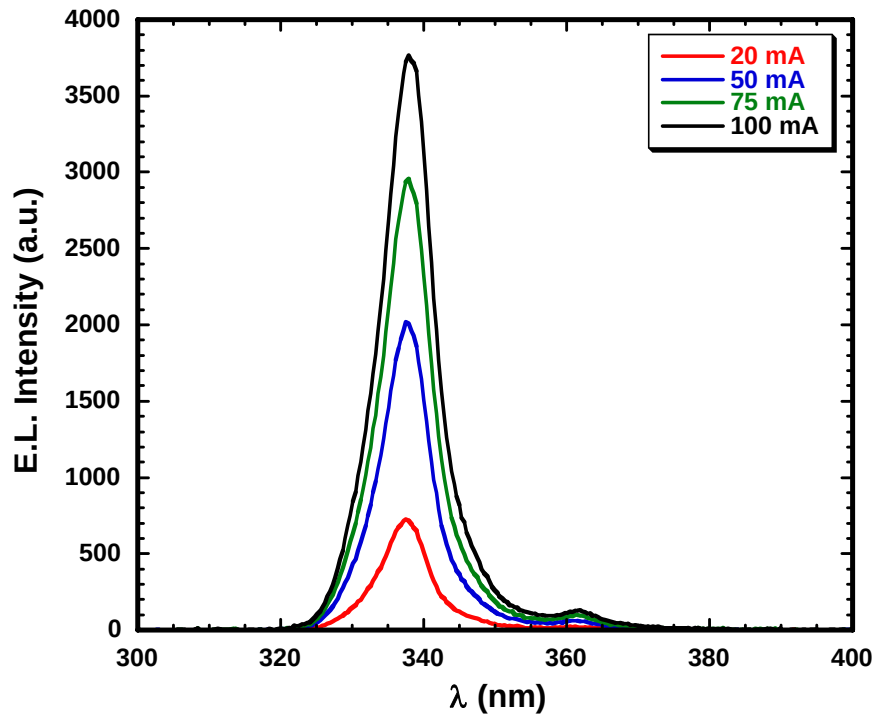


- white light sources
- biochemical detection
- water purification
- short-range communication
- etc.

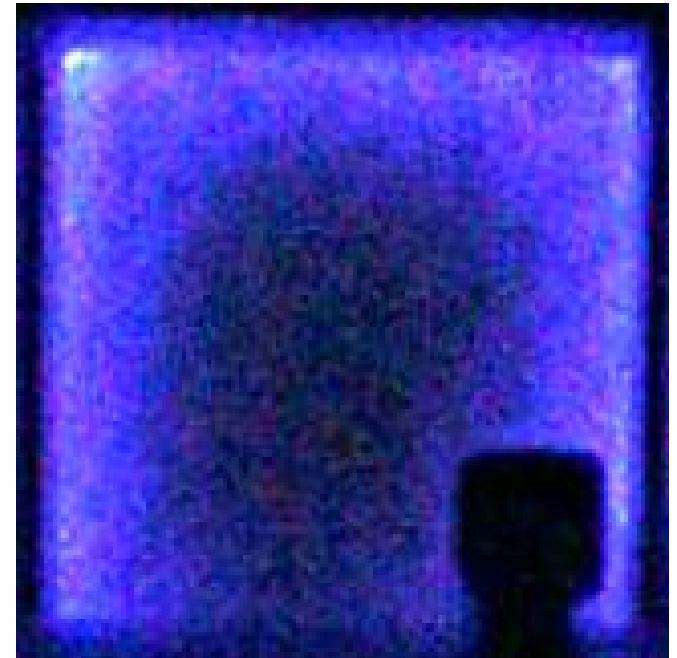
Parameter	d Unit (nm)	N_{dop} ($1/\text{cm}^3$)	μ (cm^2/Vs)	n_r —	κ_L (W/cmK)
p -GaN	5	1×10^{18}	10	2.77	1.3
p -AlGaIn SL cladding	126	4×10^{17}	0.5	2.48	0.2
p -Al _{0.3} Ga _{0.7} N blocker	15	1×10^{17}	5	2.02	0.1
i -Al _{0.10} Ga _{0.90} N well	5	—	300	2.79	0.2
n -Al _{0.16} Ga _{0.84} N barrier	13	2×10^{18}	185	2.48	0.2
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n -GaN contact layer	500	2×10^{18}	200	2.77	1.3



MQW – multi-quantum well active region

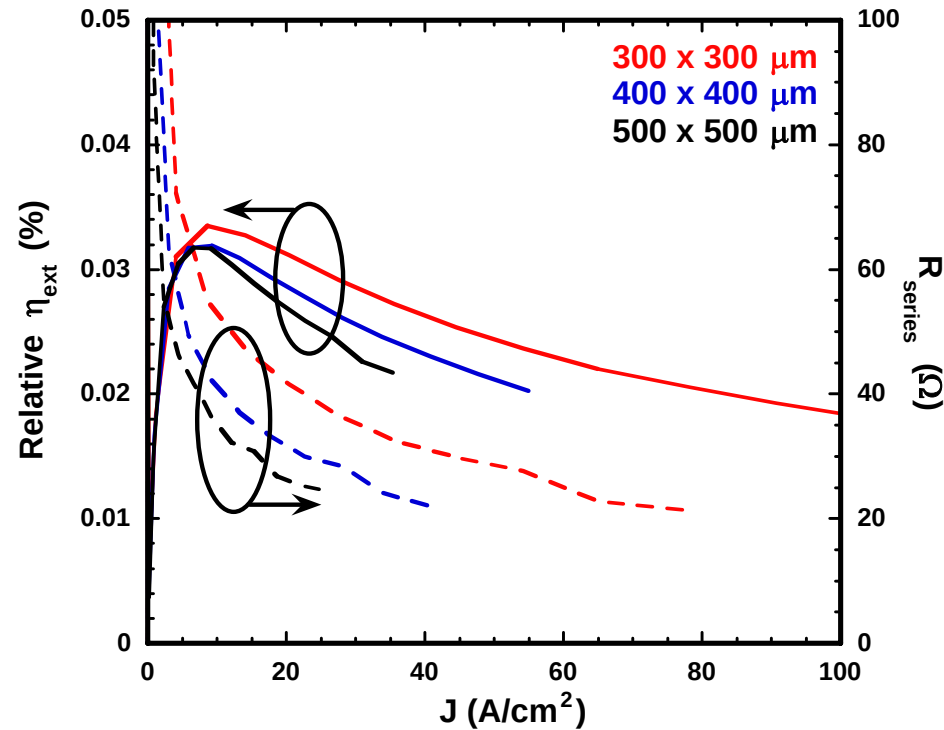
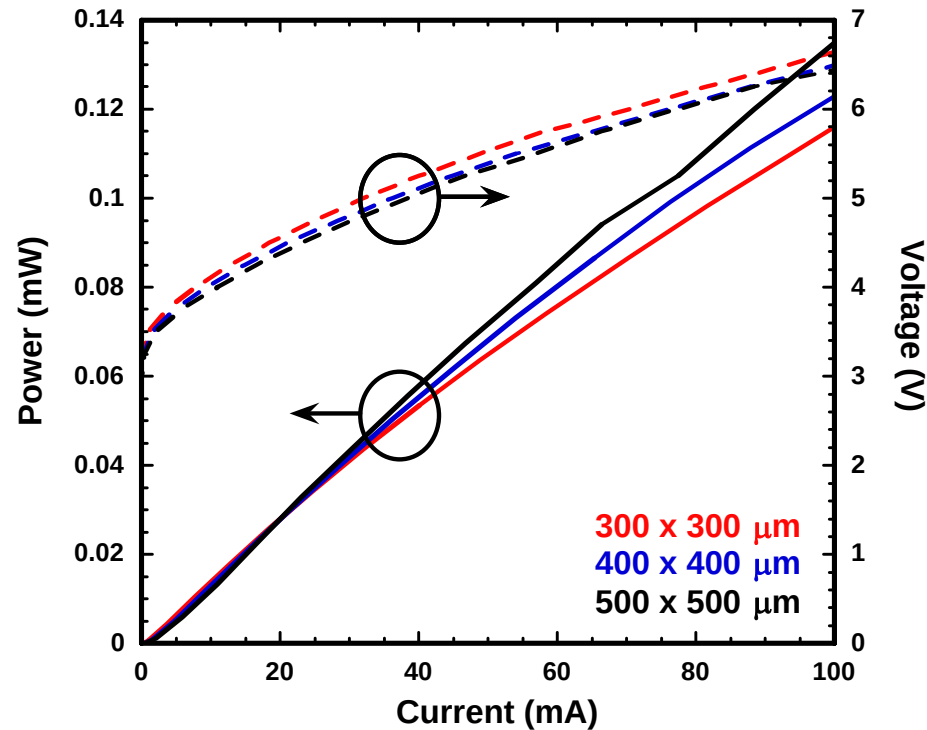


$\lambda_{\text{peak}} = 338 \text{ nm}$ FWHM = 8nm



Max Power = 0.135 mW at 100mA DC

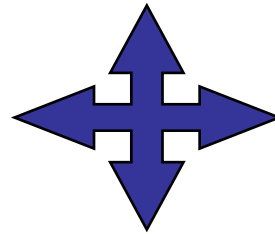
Max Quantum Efficiency = 0.033%



APSYS by Crosslight Software
3D self-consistent and comprehensive treatment of device physics

Drift-Diffusion model (incl. thermionic emission)
for electrons $n(x,y)$ and holes $p(x,y)$

Spontaneous emission spectrum
from wurtzite kp band structure
of strained quantum wells



Internal temperature $T(x,y)$
from heat flux equation

Ray tracing model for light extraction
from every source point

more details: www.crosslight.com

needed: more than 40 material parameters as function of layer composition

mobility (n,p)	$\mu(T,N,F)$	bandgap	$E_g(T)$
SRH lifetime (n,p)	τ	electron affinity	$\chi(T)$
spont. recomb. coeff.	B	electron effective mass	m
Auger coefficient (n,p)	C	hole effective mass par.	$A_1 - A_6$
optical dielectric constant	ϵ_∞	valence split energies	$\Delta_1 - \Delta_3$
dc dielectric constant	ϵ_0	deformation potentials	a, $D_1 - D_4$
refractive index	$n(\lambda)$	elastic constants	C_{13}, C_{33}
absorption coefficient	$\alpha(\lambda)$	lattice constant	a
thermal conductivity	κ	dopant activation energy	E_a
LO phonon energy	E_{LO}	etc.	

most of these parameters are not exactly known for nitride compounds

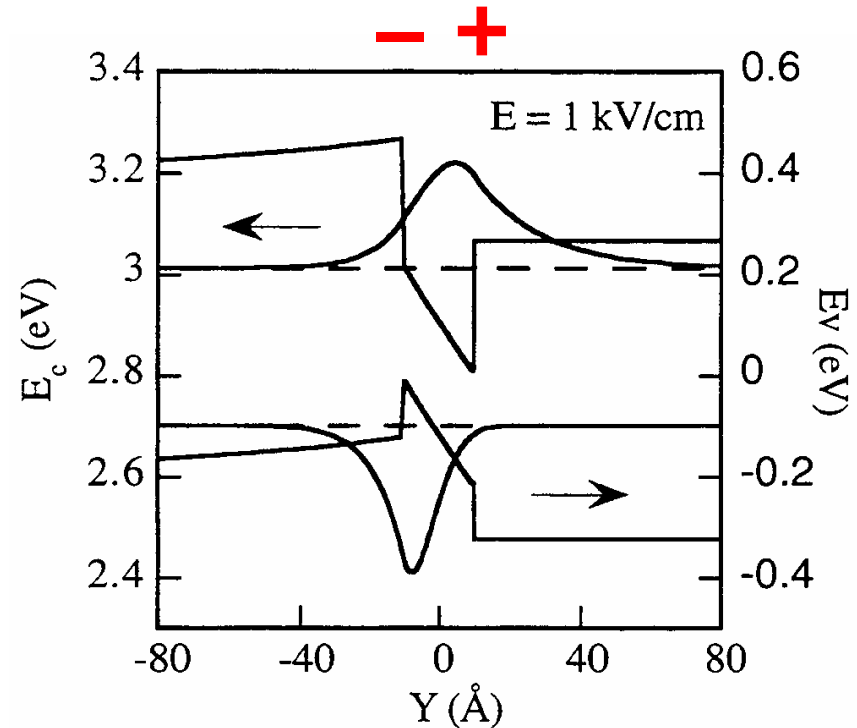
=> main source of uncertainty in nitride laser simulations

interface charges due to

- spontaneous polarization
- strain induced polarization

quantum well effects

- longer emission wavelength
- less transition strength



Fiorentini et al., APL 80, 1204 (2002):

$$P_{\text{sp}} = -0.09x - 0.034(1 - x) + 0.019x(1 - x)$$

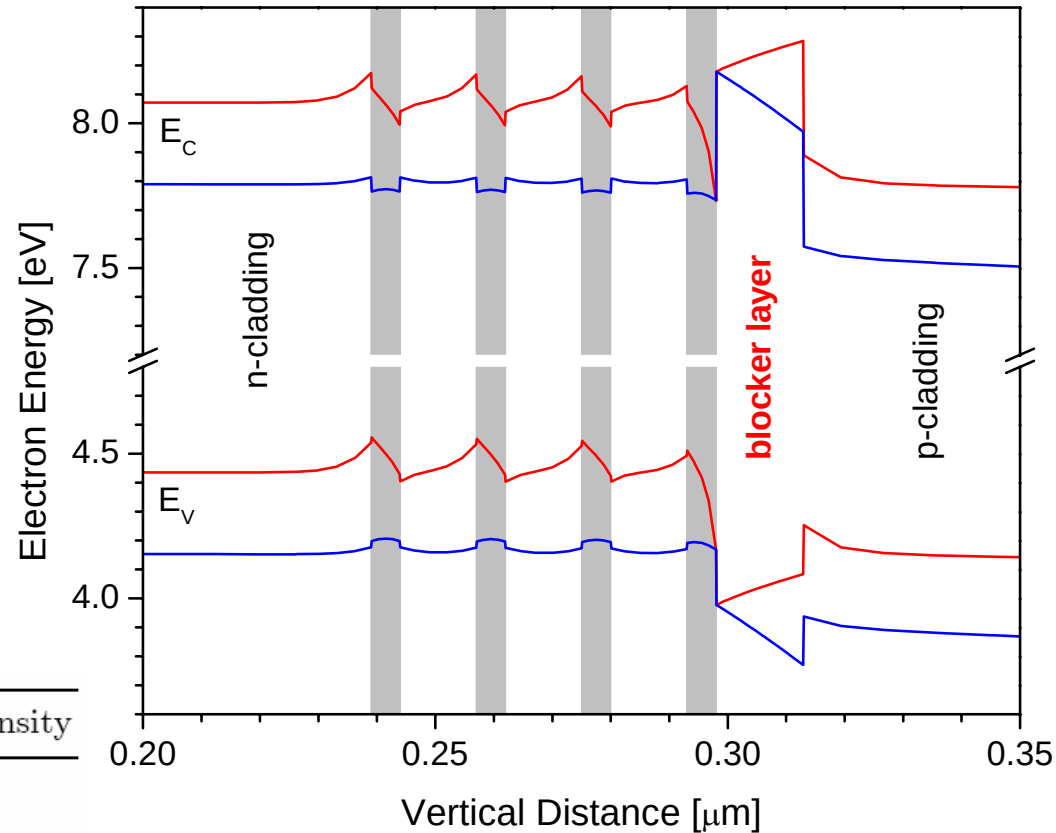
$$P_{\text{pz}} = x(-1.808\epsilon_t(x) - 7.888\epsilon_t^2(x)) + (1 - x)(-0.918\epsilon_t(x) + 9.541\epsilon_t(x)^2)$$

$\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ blocker layer:

bandgap adjusted
from 4.1 eV to 4.5 eV

Polarization charges

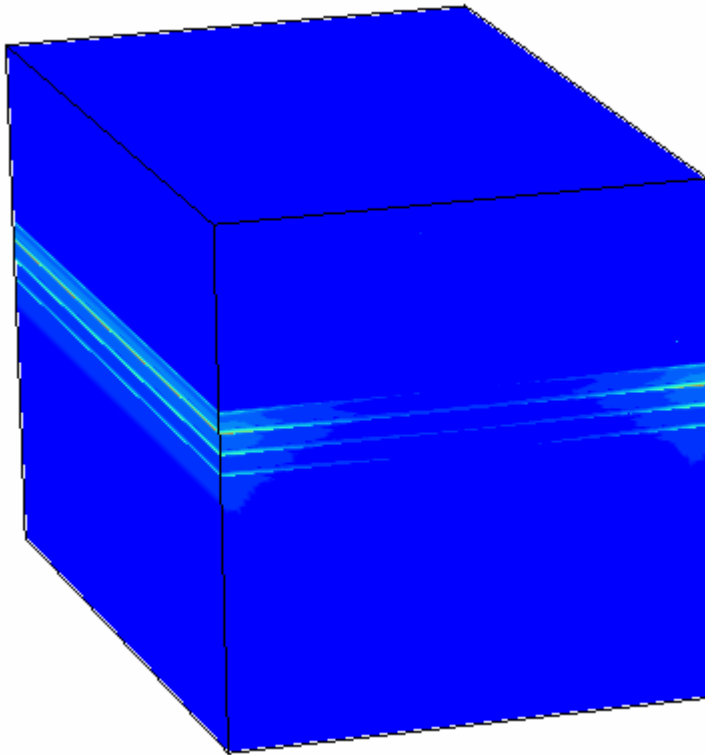
Interface	Built-in Charge Density
GaN/ $\text{Al}_{0.16}\text{Ga}_{0.84}\text{N}$	$+6.88 \times 10^{12} \text{ cm}^{-2}$
$\text{Al}_{0.16}\text{Ga}_{0.84}\text{N}/\text{Al}_{0.10}\text{Ga}_{0.90}\text{N}$	$-2.73 \times 10^{12} \text{ cm}^{-2}$
$\text{Al}_{0.10}\text{Ga}_{0.90}\text{N}/\text{Al}_{0.16}\text{Ga}_{0.84}\text{N}$	$+2.73 \times 10^{12} \text{ cm}^{-2}$
$\text{Al}_{0.10}\text{Ga}_{0.90}\text{N}/\text{Al}_{0.30}\text{Ga}_{0.70}\text{N}$	$+9.89 \times 10^{12} \text{ cm}^{-2}$
$\text{Al}_{0.30}\text{Ga}_{0.70}\text{N}/\text{Al}_{0.16}\text{Ga}_{0.84}\text{N}$	$-7.16 \times 10^{12} \text{ cm}^{-2}$
$\text{Al}_{0.16}\text{Ga}_{0.84}\text{N}/\text{GaN}$	$-6.88 \times 10^{12} \text{ cm}^{-2}$



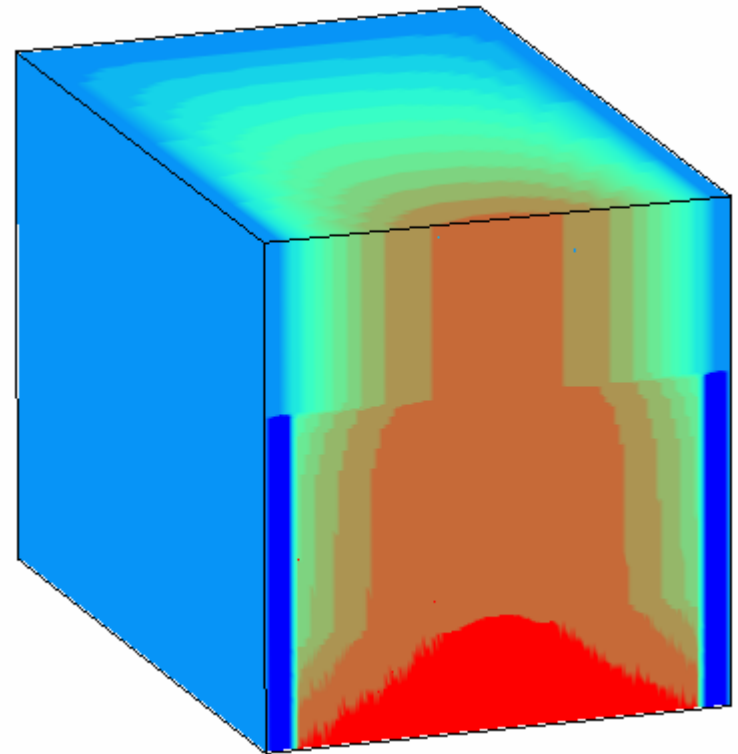
grey
blue

– quantum wells
– no polarization charges

Internal Emission Rate

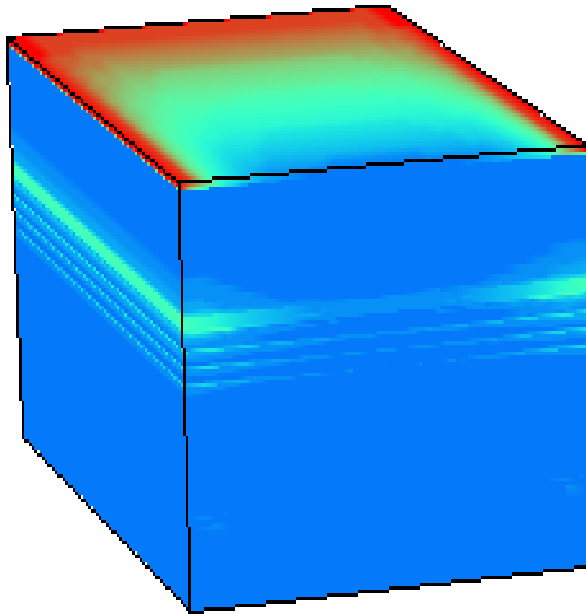


Vertical Current Density



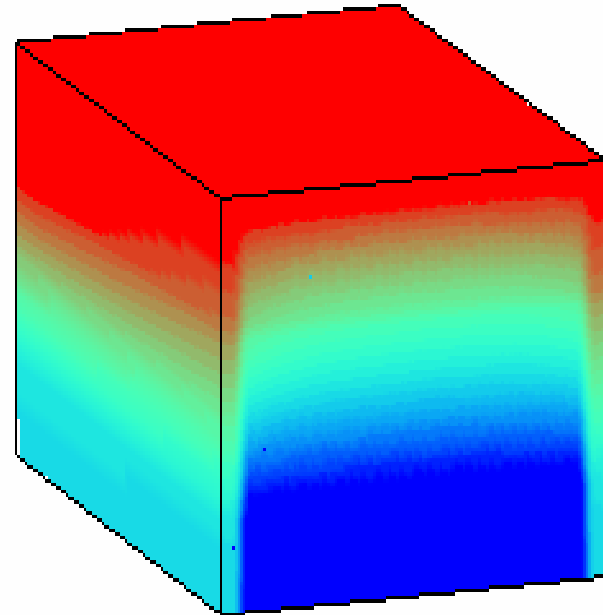
current = 100 mA, bias= 6.5 V

Heat Source

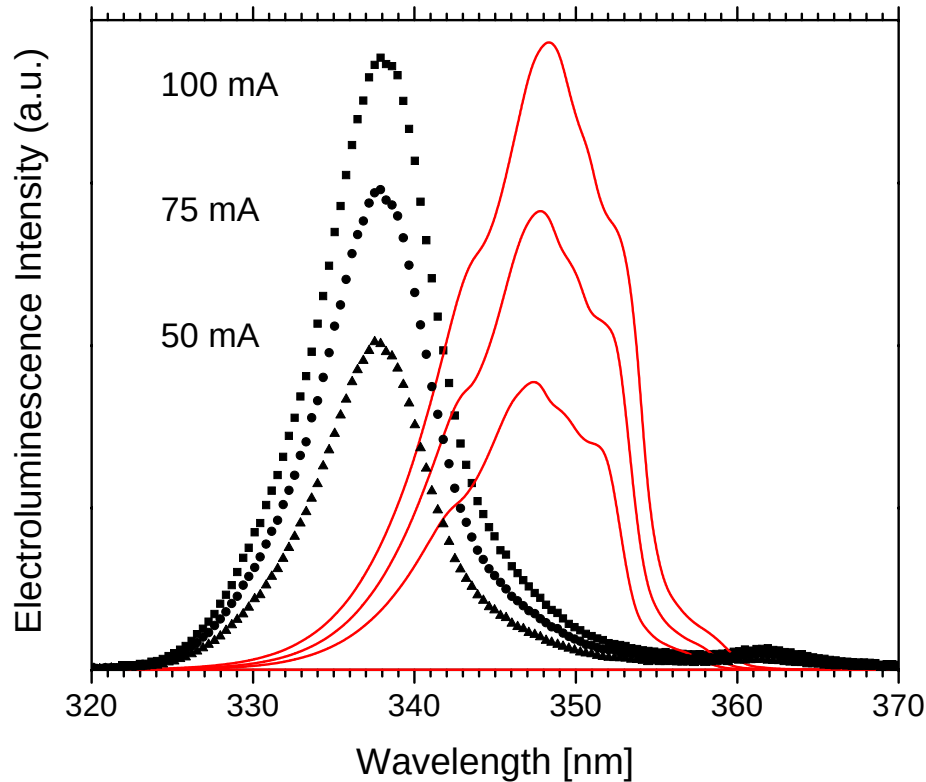


75% Joule heat
24% recombination heat

Temperature



$T_{\max} = 360.6 \text{ K}$
 $T_{\min} = 360.4 \text{ K}$
 $R_{\text{th}} = 100 \text{ K/W}$



dots: measurement

lines: simulation

10 nm disagreement

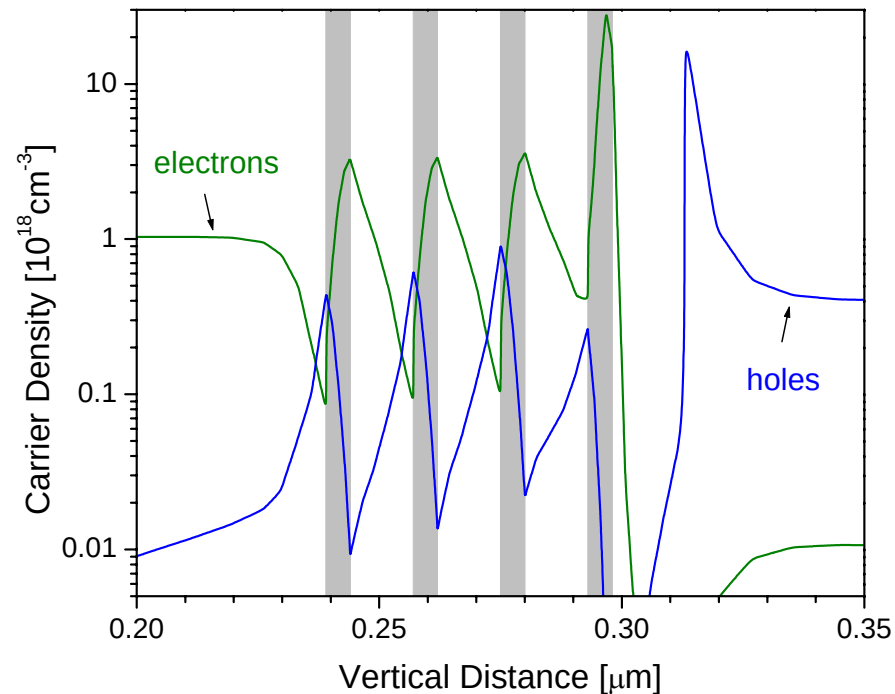
- non-ideal QW growth
- band gap too small
- polarization too strong

thermal red-shift

- no peak shift measured
- 1 nm red-shift simulated

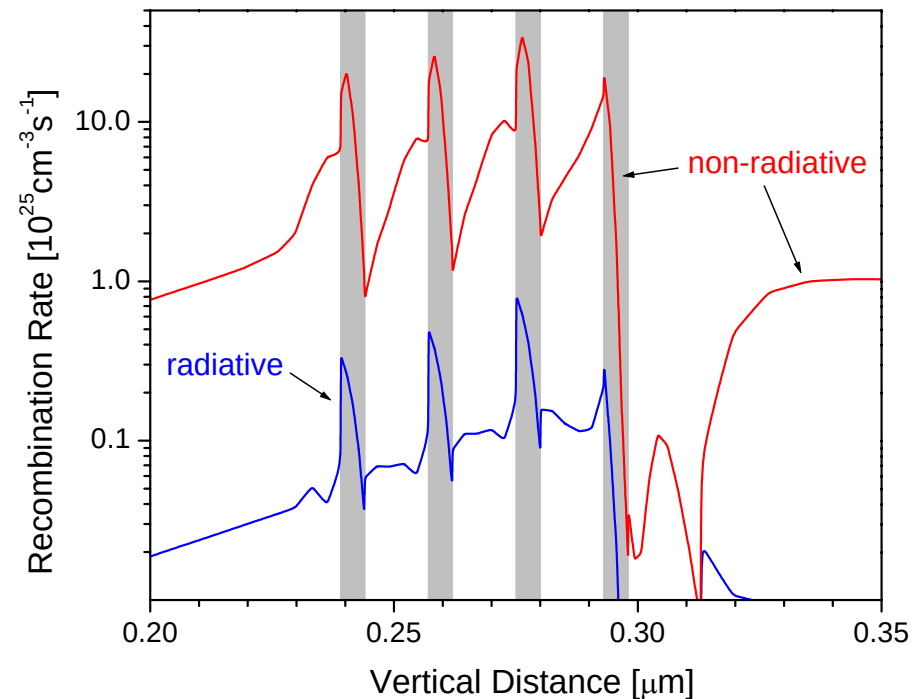
⇒ heating slightly overestimated

Carrier Density

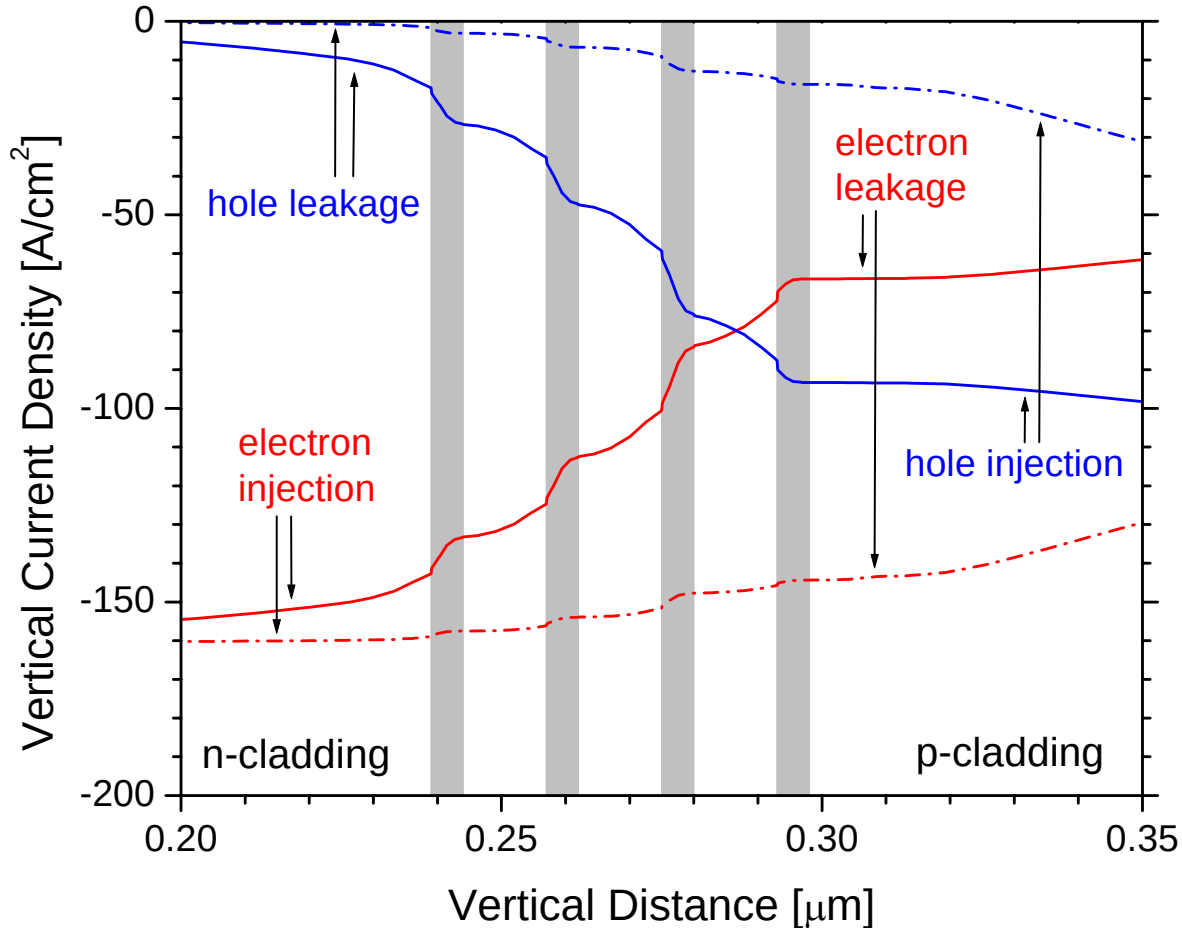


electron – hole separation in QW

Recombination Rate



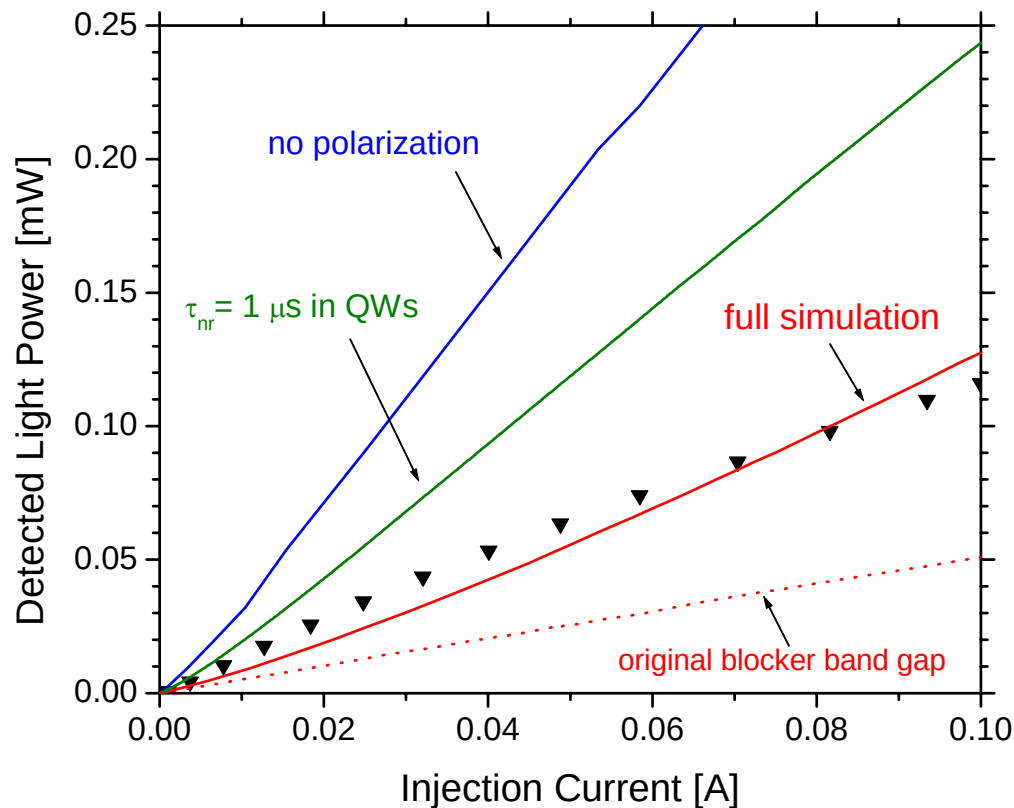
strong non-radiative recombination
non-radiative lifetime = 1 ns



solid lines: $E_{\text{block}} = 4.5$ eV,

dashed lines: $E_{\text{block}} = 4.1$ eV

Light vs. Current



triangles: measurement

Quantum efficiency

$$\eta_{\text{det}} = \eta_{\text{int}} \eta_{\text{opt}} \eta_{\text{cap}}$$

detected eff. $\eta_{\text{det}} = 0.035 \%$

internal eff. $\eta_{\text{int}} = 1.0 \%$

optical eff. $\eta_{\text{opt}} = 4.5 \%$

capture eff. $\eta_{\text{ext}} = 82 \%$

- first comprehensive 3D simulation of GaN LEDs
- good agreement with measurements
- low output power mainly due to
 1. electron leakage
 2. built-in polarization
 3. non-radiative recombination
 4. poor light extraction

Optoelectronic Devices – Advanced Simulation and Analysis (Springer, Nov. '04)

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