Impact of localization on carrier recombination in InGaN and the efficiency of nitride LEDs

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Challenges with nitride LEDs

1. Droop: lower efficiency at high power
2. Green gap: lower efficiency for longer λ
3. Polarization fields separate electrons and holes
4. Composition fluctuations localize carriers


Speck and Chichibu, MRS Bull. 34, 304 (2009)

Carrier recombination in LEDs

Energy

Defects
Conduction band
Valence band

Radiative

Auger

\[ R = A_n \]

\[ R = Bn^2 \]

\[ R = Cn^3 \]

Efficiency:
\[ \eta = \frac{Bn^2}{An + Bn^2 + Cn^3} \]
Origin of efficiency droop

Hypothesis: Droop caused by non-radiative **Auger recombination**: Energy from recombination transferred to a third electron or hole

\[
R = Cn^3
\]

Experimental evidence: optically pumped InGaN shows droop

Calculations for direct Auger coefficient of GaN: $C \sim 10^{-34} \text{ cm}^6\text{s}^{-1}$

Too small to explain experiment:
Experiment: $10^{-31} – 10^{-30} \text{ cm}^6\text{s}^{-1}$

Indirect Auger recombination

But what about higher-order Auger processes?

Carriers get additional momentum from phonons, alloy disorder, or defects:
Indirect Auger dominates in InGaN

Exp: $C = 10^{-31} - 10^{-30} \text{ cm}^6\text{s}^{-1}$

Polar vs. nonpolar GaN LEDs

**Polar** growth: Spatial separation of electrons and holes

**Nonpolar** growth: Stronger electron-hole overlap

Polarization reduces recombination rates, increases carrier density, and Auger recombination loss is amplified ($R_{\text{Auger}} = Cn^3$ vs $R_{\text{radiative}} = Bn^2$)

Speck and Chichibu, MRS Bulletin, May 2009
**Efficiency versus In content**

**Green-gap problem**: efficiency droop increases with increasing polarization fields, lower efficiency for LEDs at longer wavelengths

Random alloy composition fluctuations in InGaN localize electrons and holes. Two consequences for recombination rates:

a) Separation of electron and hole wave functions → reduced overlap.

b) Translational symmetry breaking → no need for momentum conservation.

Effect of localization on radiative and Auger rates?
Localization increases average overlap

Each matrix element is smaller (separation of electrons and holes) but there are many more electron-hole combinations allowed by symmetry breaking.
Fluctuations aggravate droop and green gap

Internal quantum efficiency (IQE) $\eta$:
$An = \text{Shockley-Reed-Hall}$
$Bn^2 = \text{radiative}$
$Cn^3 = \text{Auger}$

$$\eta = \frac{Bn^2}{An + Bn^2 + Cn^3}$$

Fluctuations increase $B$ by $\sim 30\%$ and $C$ by $\sim 400\%$

Alloy composition fluctuations decrease the efficiency at high power and at longer wavelengths

Solution: Lattice-matched BInGaN and BAlGaN

BInGaN and BAlGaN alloys reduce mismatch to substrates without affecting the gap, thick quantum wells improve the LED efficiency.


Kevin Greenman, L. Williams, and E. Kioupakis, *arXiv:1905.00467*
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Thank you for your attention

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