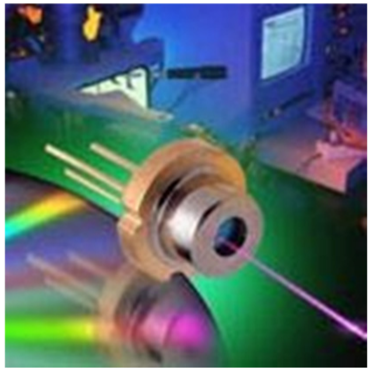
Lecture 11 – 07/05/2025

Light-emitting diodes

- Blue and green LEDs: limiting factors for the IQE

Laser diodes

- Generalities



High efficiency white LEDs

- Commercial white LEDs now available with an efficiency > 175 lm/W (A class efficiency)
- Projected lifetime of 50’000 hours (vs 15’000 hours for conventional white LEDs (E or F class efficiency, ~75 lm/W))

Factors limiting the internal quantum efficiency (IQE) of white LEDs

1. Material quality: *the lack of affordable GaN substrate*
2. Internal electric field: *the green gap*
3. Efficiency droop: *an intrinsic effect?*
4. Efficiency at low injection: *the role of the InGaN underlayer*

Material quality: the lack of affordable GaN substrate

⇒ growth on sapphire, silicon carbide, silicon, …

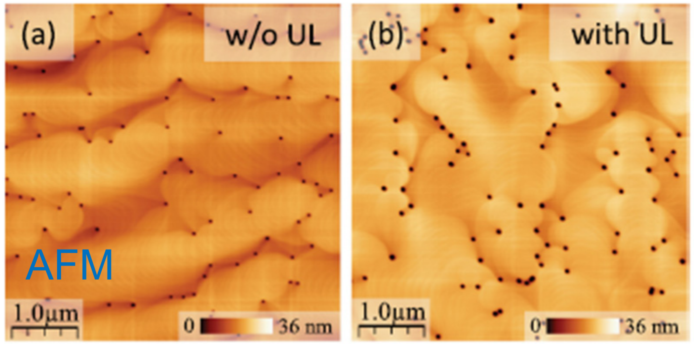
Trade-off between yield (efficiency + fabrication cost) and marketing price (US$18 klm^{-1}, compared with <US$1 klm^{-1} for incandescent light bulbs in 2011, close to US$1 klm^{-1} in 2014, < US$1 klm^{-1} since 2017)

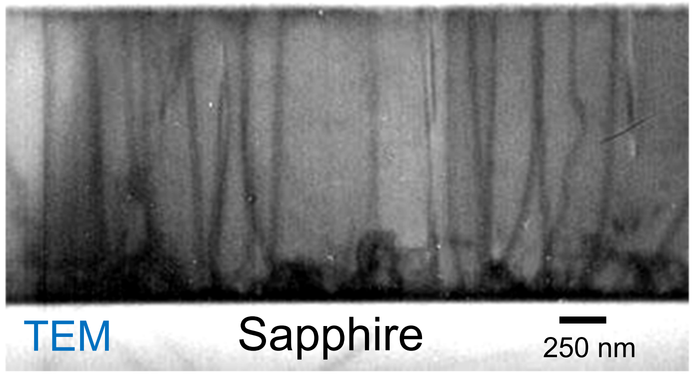
Very large lattice mismatch

Al_2O_3 (0001):	+16%
6H-SiC (0001):	-3.5%
Si (111):	-17%

High density of dislocations

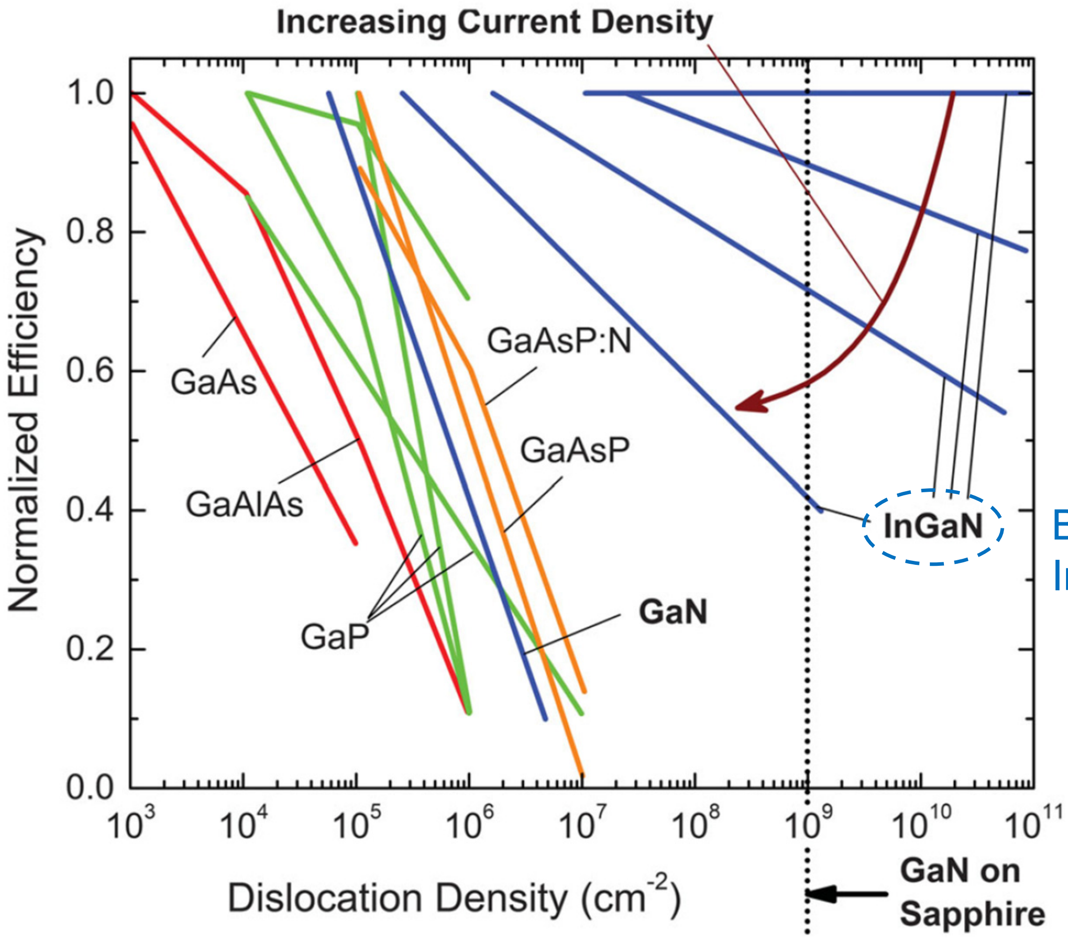
10^8-10^{10} cm^{-2}





Device efficiency and dislocation density

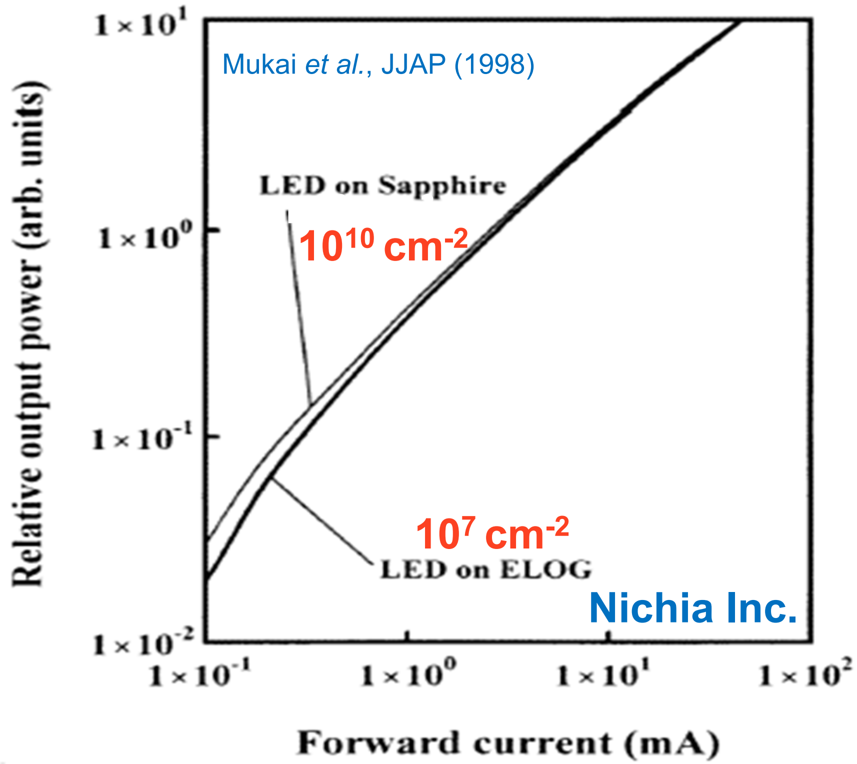
After Nobel Lecture by S. Nakamura, "Background story of the invention of efficient blue InGaN LEDs"



Behavior specific to InGaN

High efficiency despite high dislocation density

Device efficiency and dislocation density



Blue LEDs (⇒ InGaN QW active region) are not sensitive to dislocations (i.e., ≠ from nonradiative centers)

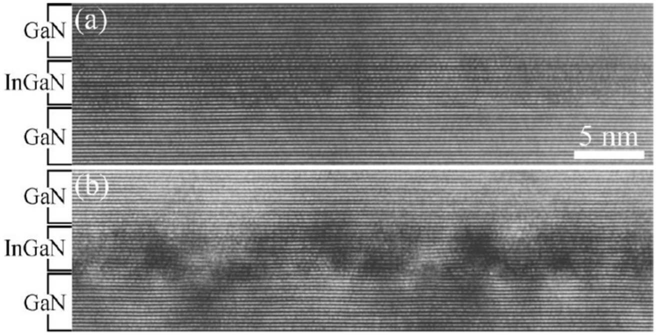
Why?

Carrier localization in InGaN quantum wells

Quantum dots (In-rich clusters), acting as efficient localization centers, have been proposed to explain the high-efficiency of nitride-based light emitters[1] (but disproved by later TEM studies[2])

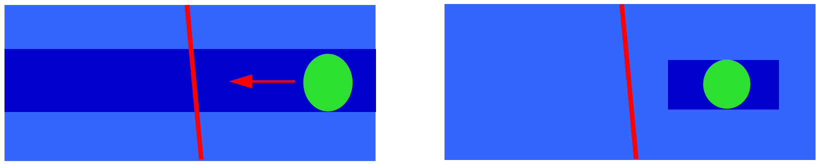
The current dominating picture relies on indium atom assemblies naturally present in the random InGaN alloy (size << clusters, S. F. Chichibu *et al.*, Nat. Mater. **5**, 810 (2006)), whose density exceeds the threading dislocation density, where carriers remain trapped/localized (M. Filoche *et al.*, PRB **95**, 144204 (2017)) but the true role of in-plane carrier localization has been recently challenged (A. David, Phys. Rev. Applied **15**, 054015 (2021) & T. F. K. Weatherley *et al.*, Nano Lett. **15**, 5217 (2021))

[1]*Narukawa et al., APL* ***70****, 981 (1997)*



TEM image of InGaN/GaN QWs grown by MOCVD

[2]*Smeeton et al., APL* ***83****, 5419 (2003)*

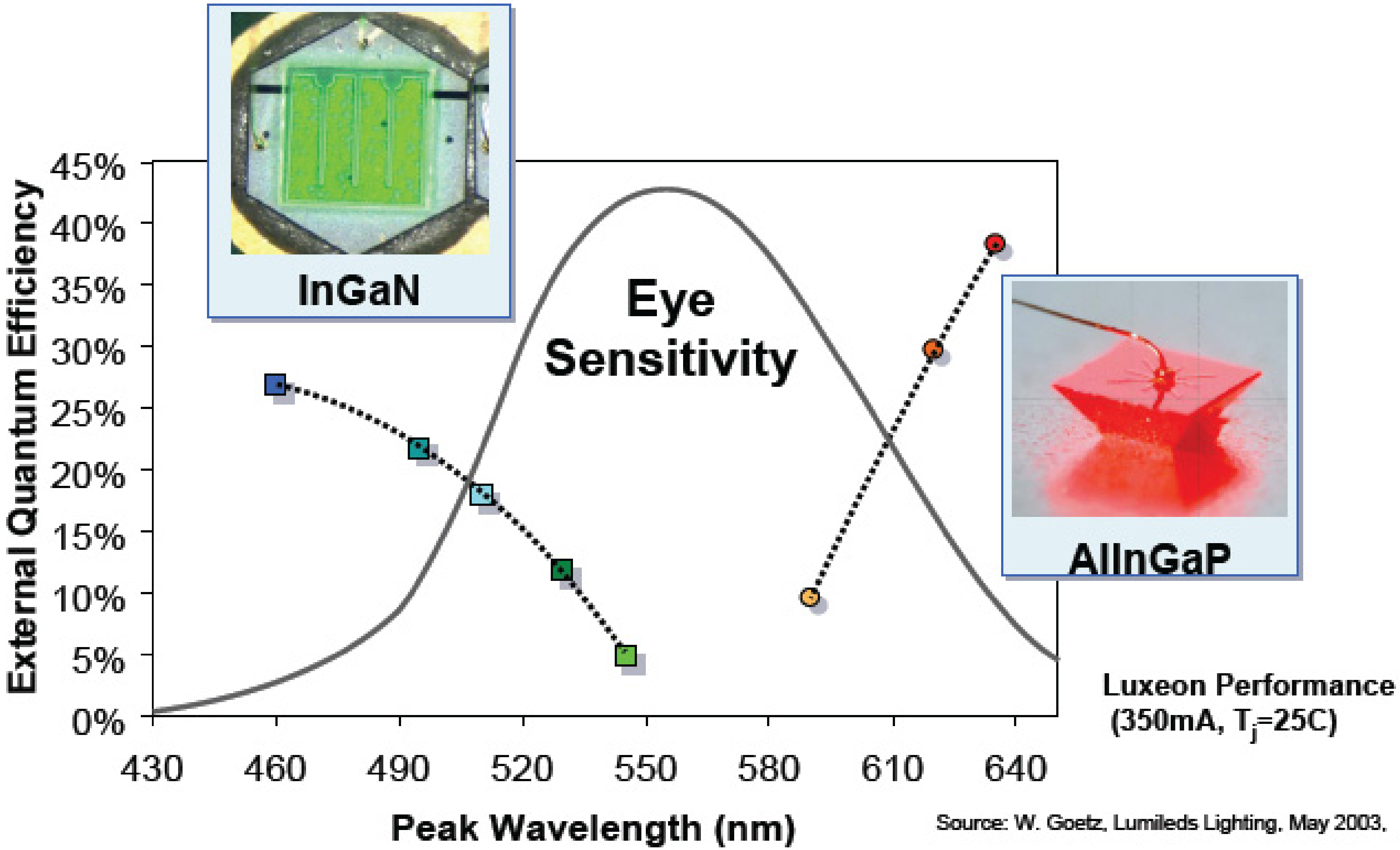


Free carriers (QW) Localized carriers ("QD")

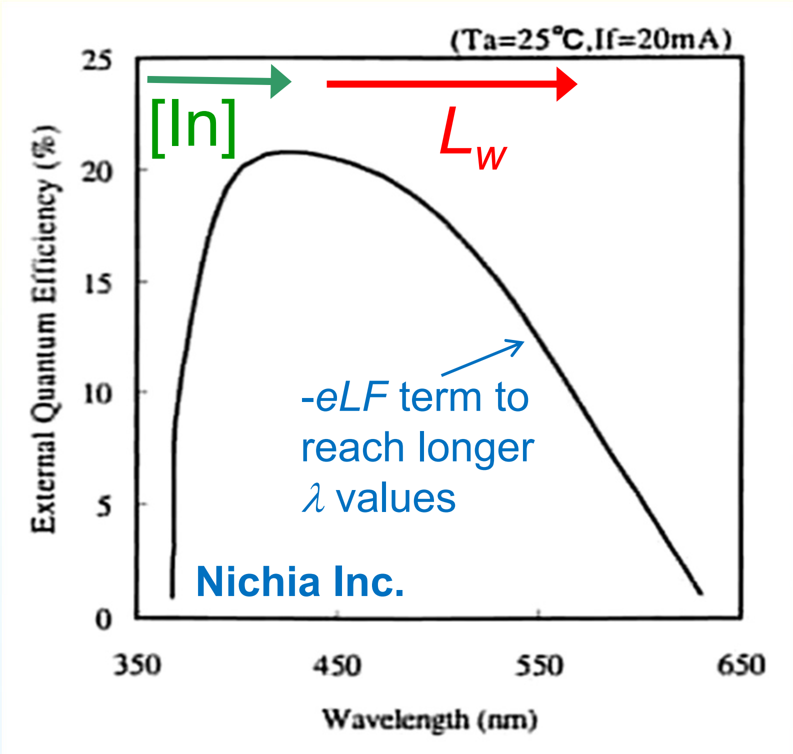
1990: C. Weisbuch and J. Nagle (patent)

1995: J.-M. Gérard *et al., InAs QDs on silicon substrate Appl. Phys. Lett.* ***68****, 3123 (1996)*

InGaN/GaN LED efficiency: the green gap



InGaN/GaN LED efficiency: the green gap



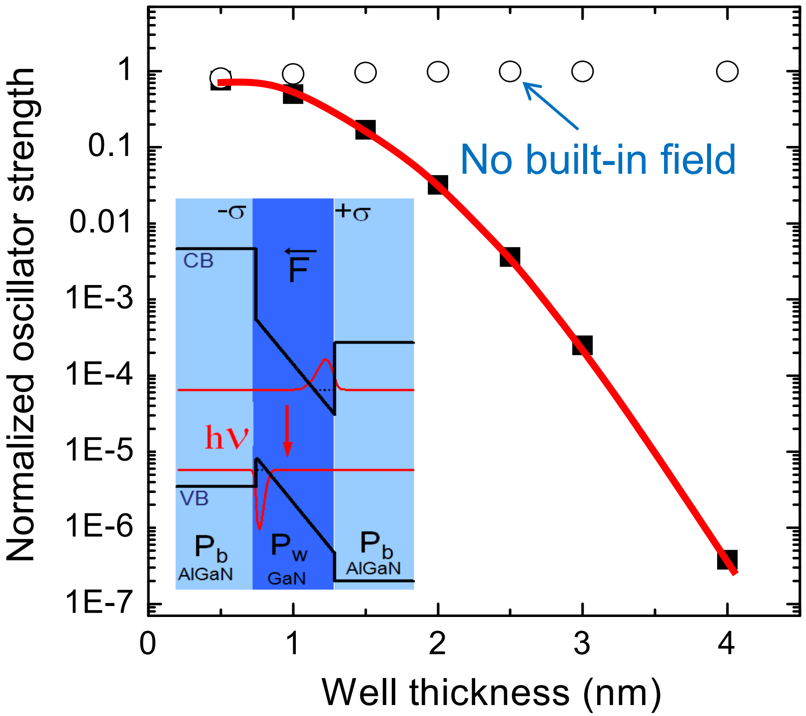
370 - 450 nm: indium content ↑
⇒ efficiency ⬀

BUT: maximum indium content for high quality material ~25%

450 - 600 nm: well thickness ↑
⇒ efficiency ⬂

Motivation for the use of blue LEDs emitting @ 450 nm for the realization of high-brightness white LEDs (automotive industry, solid-state lighting, etc.)

QCSE and oscillator strength in quantum wells



IQE (η_i) dramatically decreases with increasing well width unless appropriate measures are taken (⇒ role of underlayer (slides 14-17) + A. David *et al.*, Phys. Rev. Applied 11, 031001 (2019))

Oscillator strength

$$f_{0_j} = 2\frac{\left|\langle f_j | \eta \cdot \mathrm{p} | i \rangle\right|^2}{m_0 \hbar \omega_{0_j}} = \frac{2 m_0 \omega_{0_j}}{\hbar}\left|\langle f_j | \eta \cdot \mathrm{r} | i \rangle\right|^2$$

$$\Gamma_{sp} = \frac{q^2 r_{12}^2 \omega^3 n_{op}}{3\pi c^3 \hbar \varepsilon_0} = 1/\tau_r$$

Strong decrease in the oscillator strength with increasing well width

$\Rightarrow \tau_r \nearrow$

radiative term

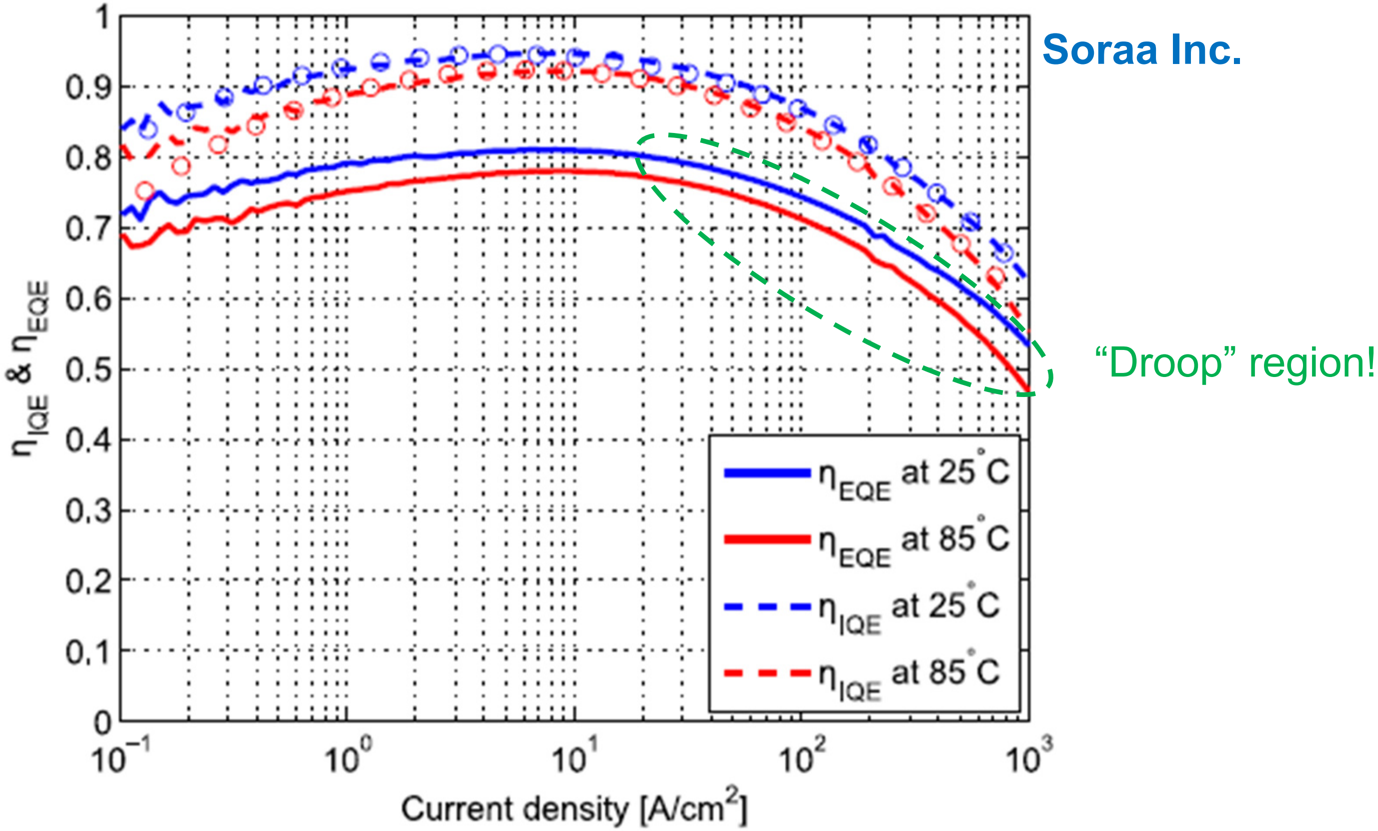
$$\eta_i = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} = \frac{\tau_{tot}}{\tau_r} = \frac{Bn}{A_{nr} + Bn + Cn^2}$$

SRH term

Auger-Meitner term

Efficiency droop: an intrinsic effect?

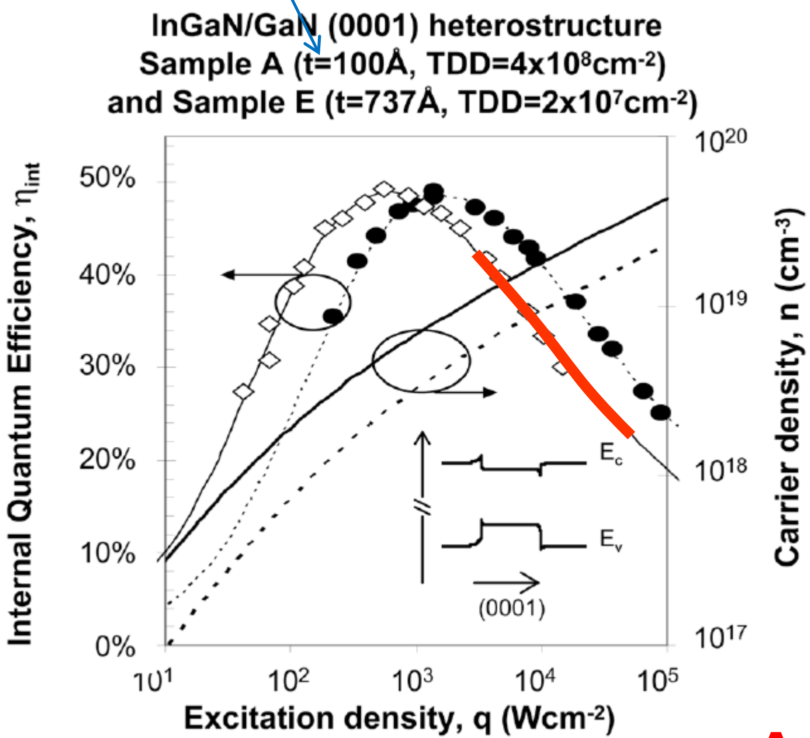
Efficiency curve of high-brightness blue-violet LEDs



Appl. Phys. Lett. **106**, 031101 (2015)

Efficiency droop: Auger-Meitner effect

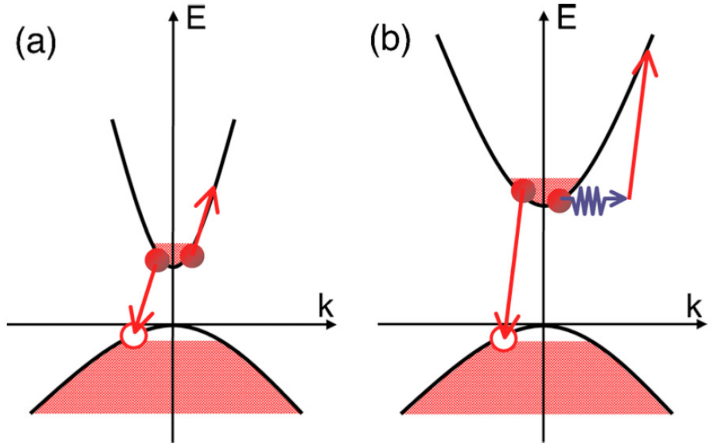
Quasi-bulk active layers



Appl. Phys. Lett. **91**, 141101 (2007)

$$\frac{dn}{dt} = -An - Bn^2 - Cn^3 + G$$

n is the carrier density



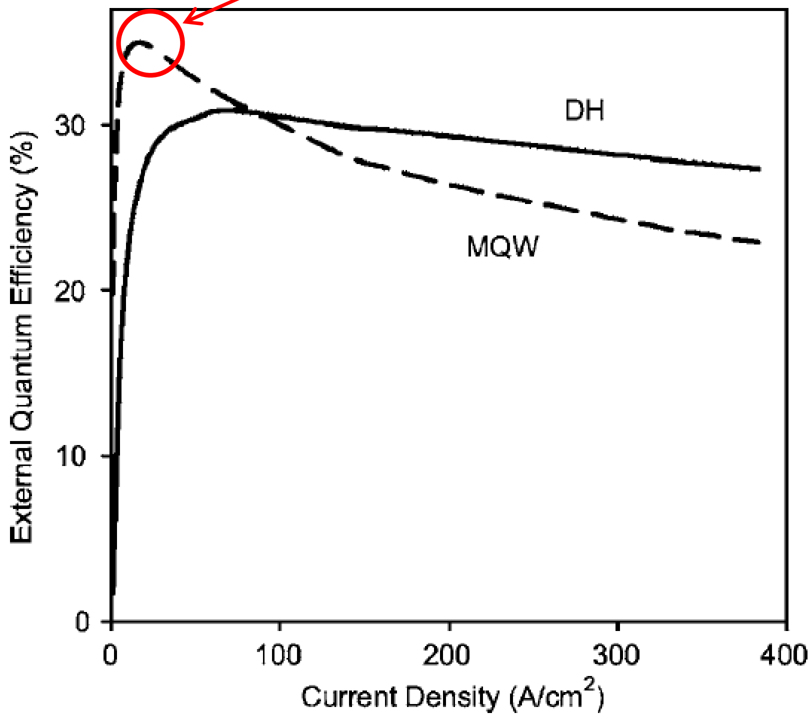
Appl. Phys. Lett. **98**, 161107 (2011)

Auger-Meitner recombinations

Direct and indirect processes

Efficiency droop: Auger-Meitner effect

Peak of EQE (IQE) at $J \in$ 1-10 A/cm^2 in state of the art LED devices relying on thin QWs (see also slide 11)



Appl. Phys. Lett. **91**, 243506 (2007)

Improved LED efficiency at high current by reducing the carrier density

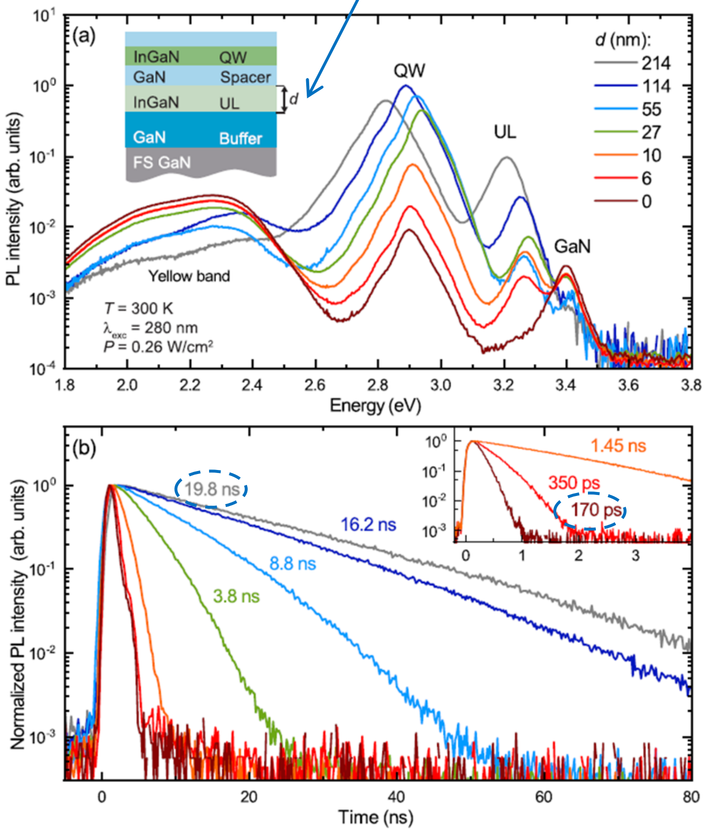
$\Rightarrow$ Use of large quantum wells or double heterostructures (DH)

Move toward larger manufacturing chip size (350 × 350 μm^2 $\rightarrow$ 1 × 1 mm^2 or more) to reach a high luminous efficiency at a lower driving current density ($\Rightarrow$ drive LEDs at J values where the weight of the B term is still significant over the C one)

Made possible thanks to an improved layer uniformity

LED efficiency: role of the underlayer

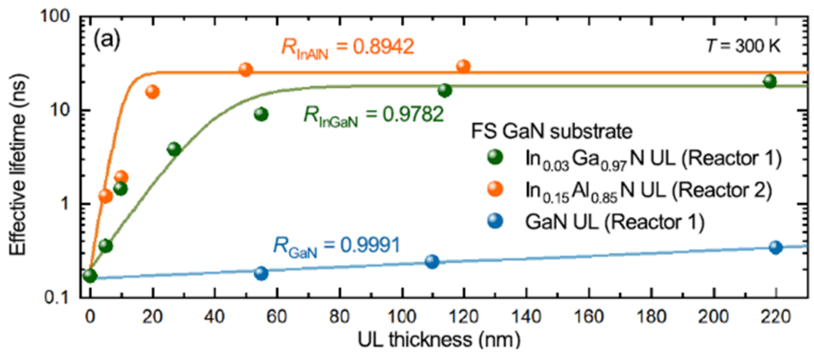
State of the art high-brightness blue LEDs always possess an indium-containing (InGaN or InAlN) underlayer (UL) prior to the QW active region



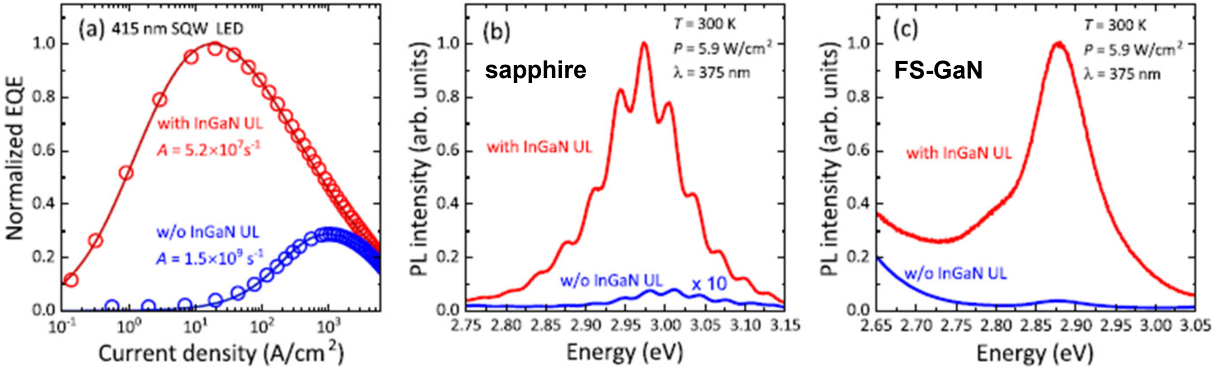
Appl. Phys. Lett. **113**, 111106 (2018)

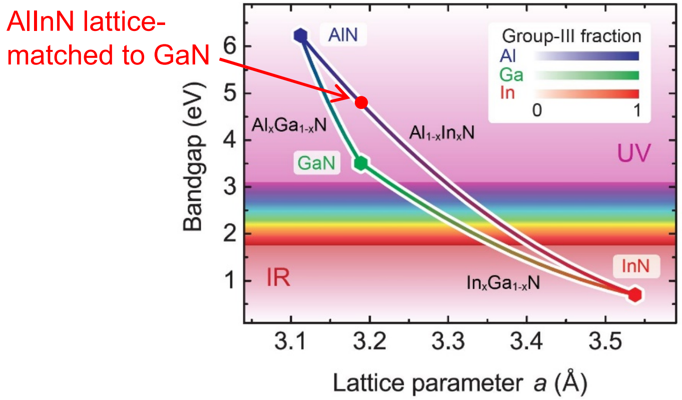
Increase in the effective carrier lifetime (τ_{tot}) of the QW emission with increasing UL thickness for a given indium content or with increasing indium content for a given UL thickness

⇒ Drastic effect (> 2 orders of magnitude) due to the capture of nonradiative centers (SRH term) by the UL prior to the growth of the active region (QWs)



LED efficiency: role of the underlayer





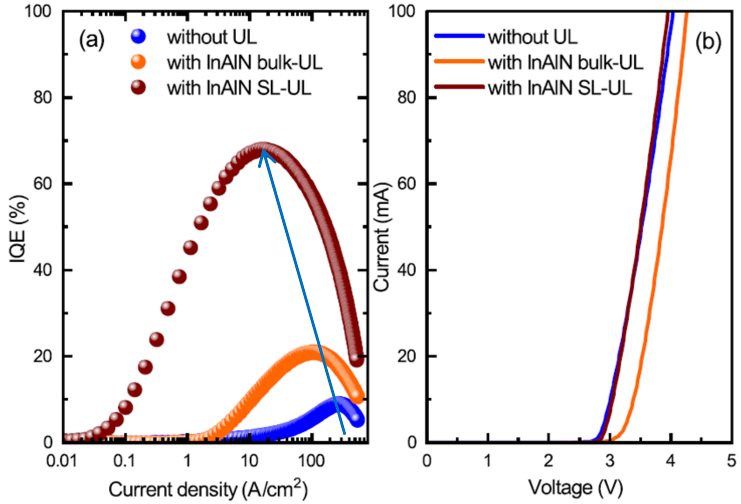
Appl. Phys. Lett. **111**, 262101 (2017)

- Increase in the carrier lifetime (τ_{tot}) due to a decrease in $A_{nr} \Rightarrow$ strong increase in the IQE

- Peak of the IQE at lower current density (and hence lower carrier density, $J(n)$)

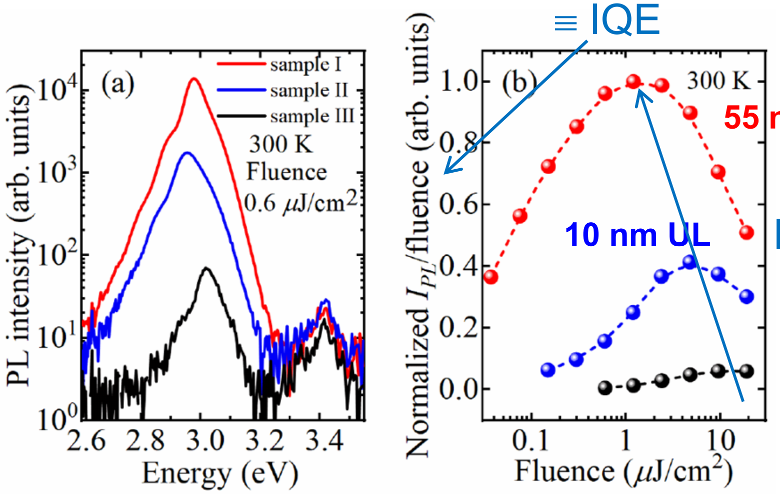
$$\eta_i = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} = \frac{\tau_{tot}}{\tau_r} = \frac{Bn}{A_{nr} + Bn + Cn^2}$$

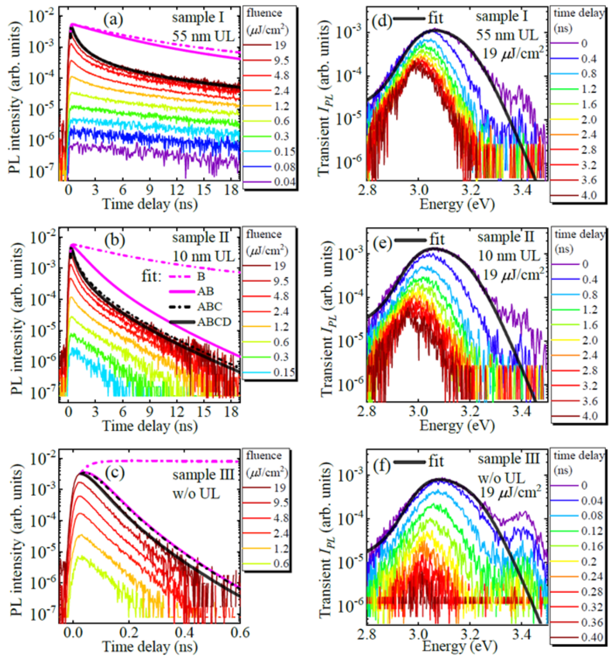
- Effect not related to dislocations, strain, or built-in field but due to the reaction of In atoms with surface defects that create defects acting as deep traps in the InGaN QWs



Appl. Phys. Express **12**, 034002 (2019)

LED efficiency: beyond the ABC model

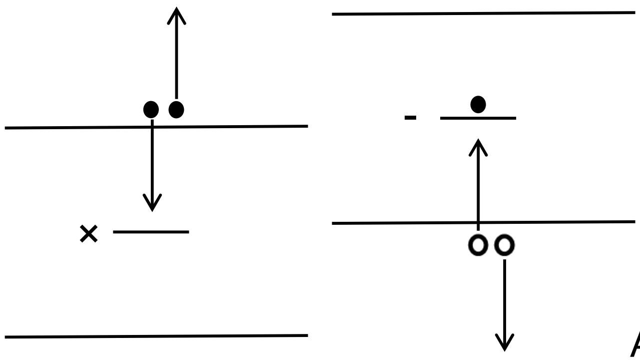




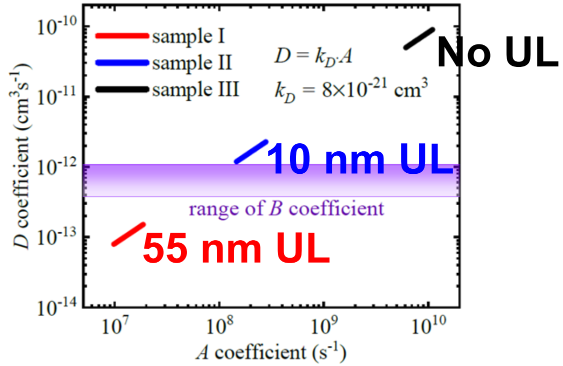
$$\frac{dn}{dt} = -An - Bn^2 - Cn^3 - Dn^2 + G$$

(extrinsic process)

Defect-assisted Auger-Meitner term



$$Dn^2 = k_D A n^2$$

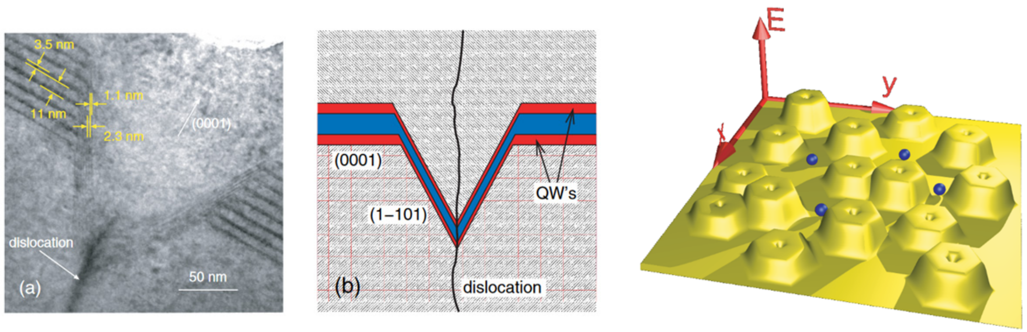


Appl. Phys. Lett. **116**, 222106 (2020)

LED efficiency: latest picture

Nonradiative channels under low injection:

- **Threading dislocations (TDs)**



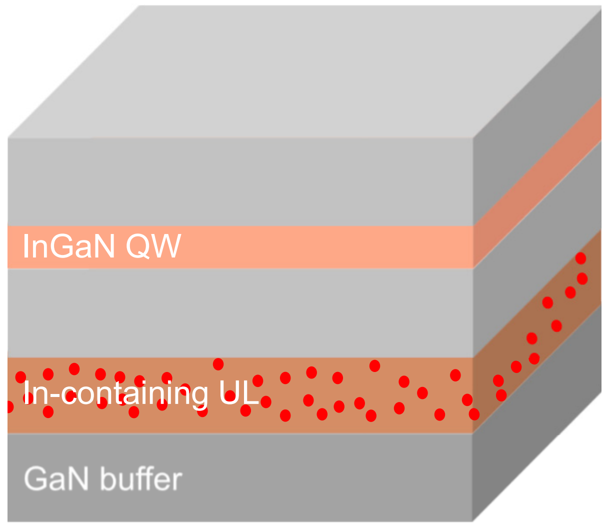
V-pits form around TD termination at the surface and create an energy barrier preventing carriers to reach the dislocations making them mostly inactive

Phys. Rev. Lett. **95**, 127402 (2005)

- **Point defects (PDs)**

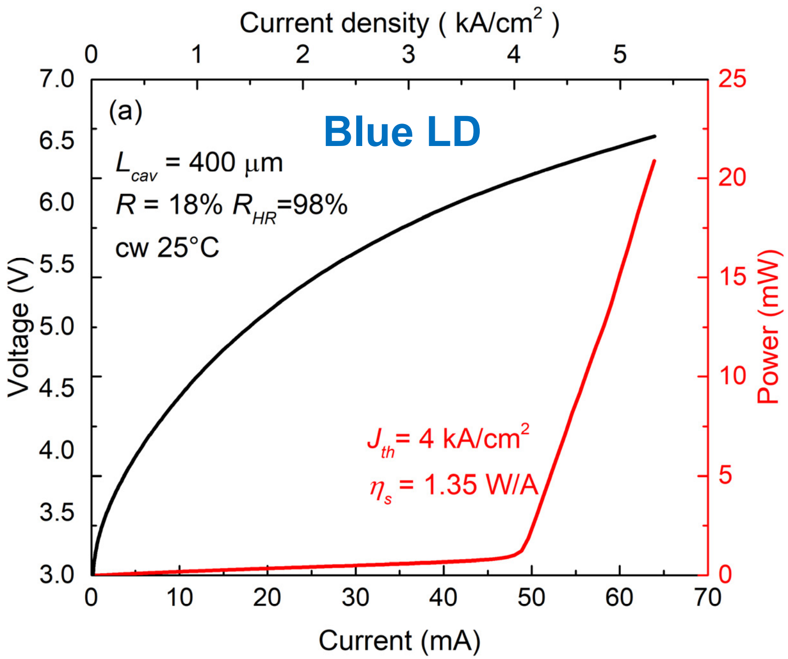
Use of an indium-containing underlayer to mitigate the presence of PDs, i.e., decrease their density in the active region (InGaN QW).

Pending question: in the absence of V-pits, what is the most impactful nonradiative center: TDs or PDs?

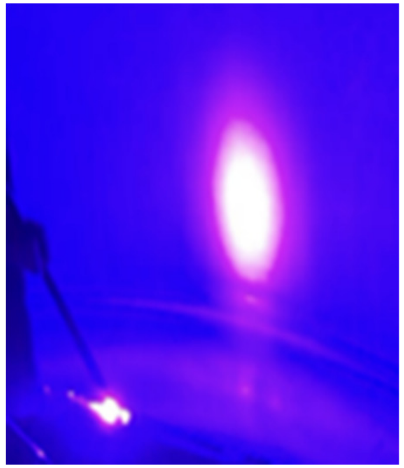


Laser diodes:
Generalities

Laser diodes



Far-field pattern

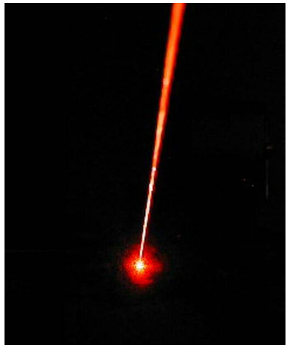


Laser: a clear threshold is observed in the *L-I* curve (+ far-field pattern)

⇒ Light amplification

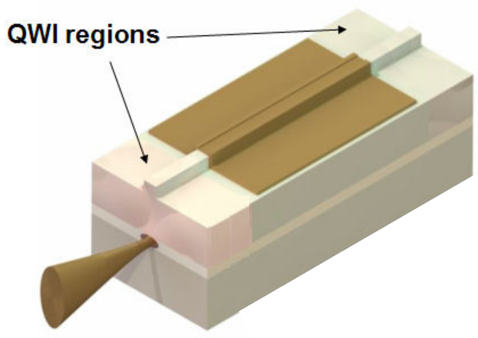
Light Amplification *by* ***Stimulated Emission of Radiation***

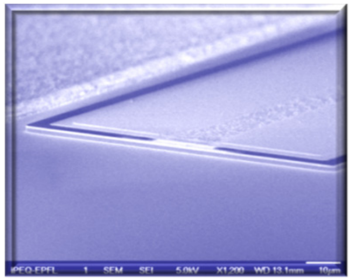
Semiconductors: a brief overview

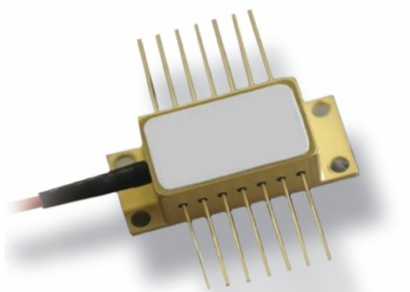


1970
1^{st} laser diode
λ ~780 nm
J_{thr}~ 4.3 kA/cm^2
Ioffe, Russia

1980's → **GaAs based optoelectronics**







2000

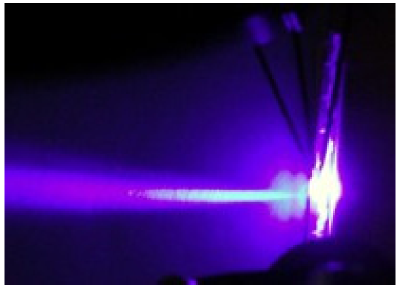
CD, DVD, Telecom

BUT light emission limited to the **Red** and **IR**

Semiconductors: a brief overview

1993

1990's → **GaN short-wavelength optoelectronics**



UV, blue, and green LEDs
High density DVD, color displays

2003

Demonstration of reliable (i.e., long lifetime) green semiconductor laser diodes with a high production yield on the way (available from Nichia. Inc.)!