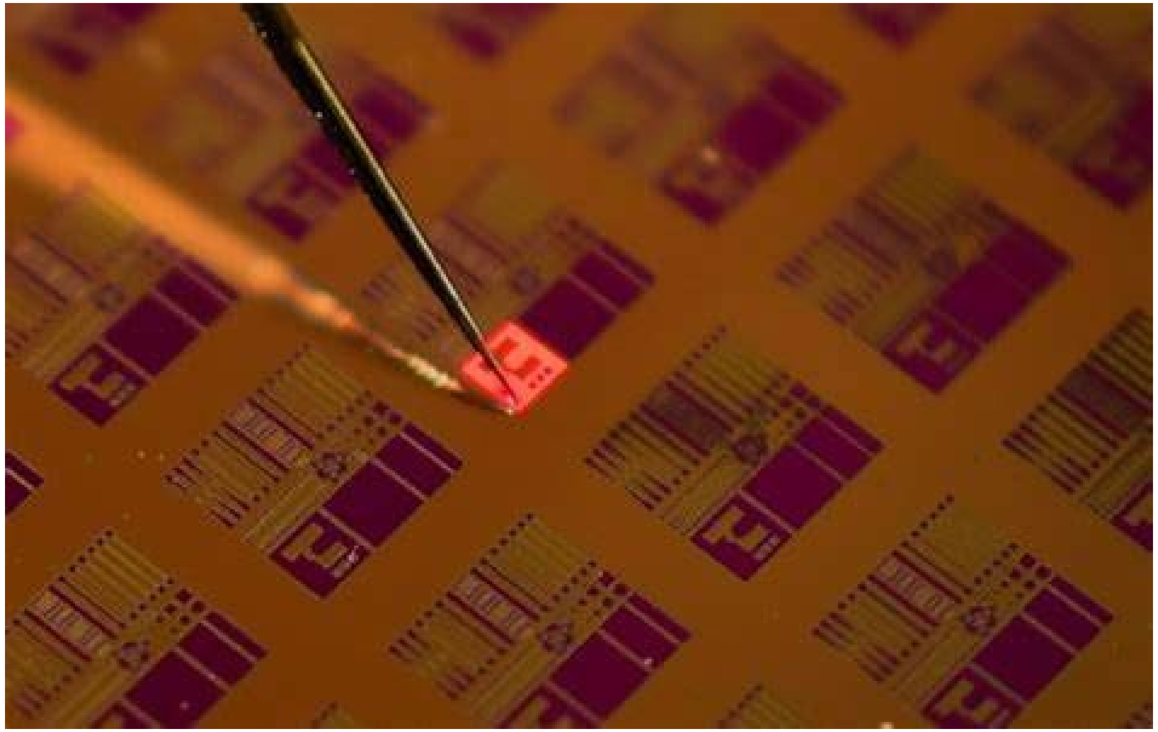
Advanced III-nitride semiconductor devices



https://www.microled-info.com/micledi-demonstrates-alingap-ferrari-red-microled-devices

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LEDs

- Polarization field and LED efficiency

- Red microLEDs

LED efficiency

letters to nature

Acknowledgements
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Nitride semiconductors free of electrostatic fields for efficient white light-emitting diodes

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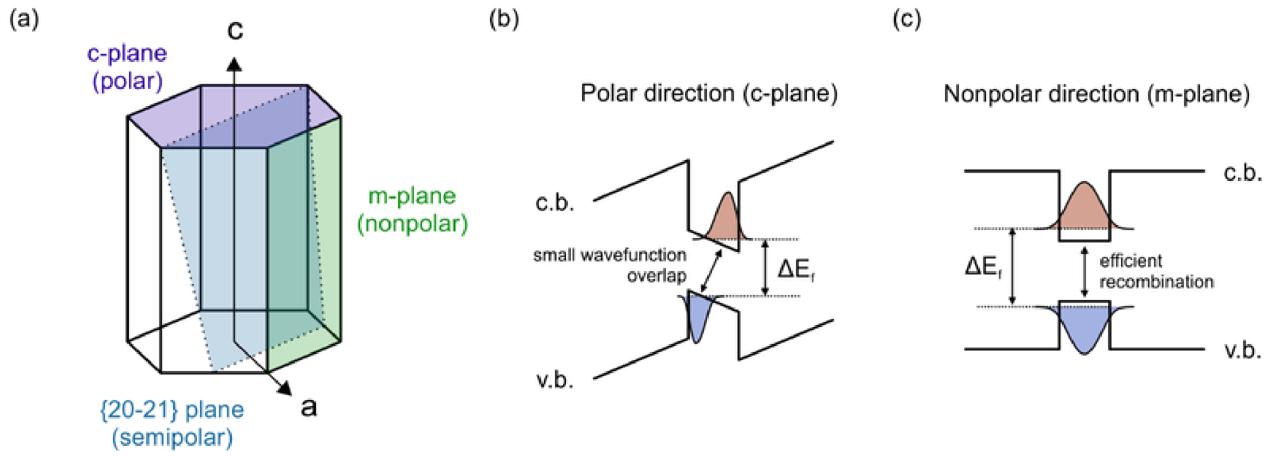
The polarization field is commonly believed to be detrimental for the LED efficiency



Chapter

Nonpolar and semipolar LEDs

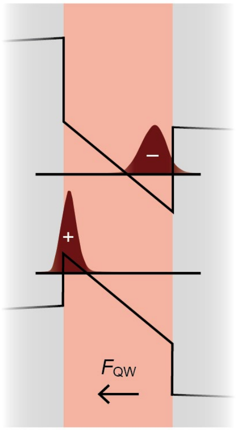
8.1.5 Advantages of nonpolar and semipolar LEDs

The QCSE imposes a limit on device performance for c-plane LEDs. To circumvent the detrimental effects of the internal polarization, growing devices along orientations that have zero or minimal polarization has been proposed as the solution for many unsolved issues. When there are no polarization-induced electric fields in the QW, the IQE is enhanced and there is an improved overlap between carrier wave functions. The QWs can be grown thicker without much reduction of the IQE as long as the defect density is not significantly increased. Therefore, the unbalanced carrier transport in MQW devices resulting from the over-thin QWs can be mitigated. Additionally, lower polarization

LED efficiency

Impact of the large internal electric field

F_{QW} = 2-3 MV/cm

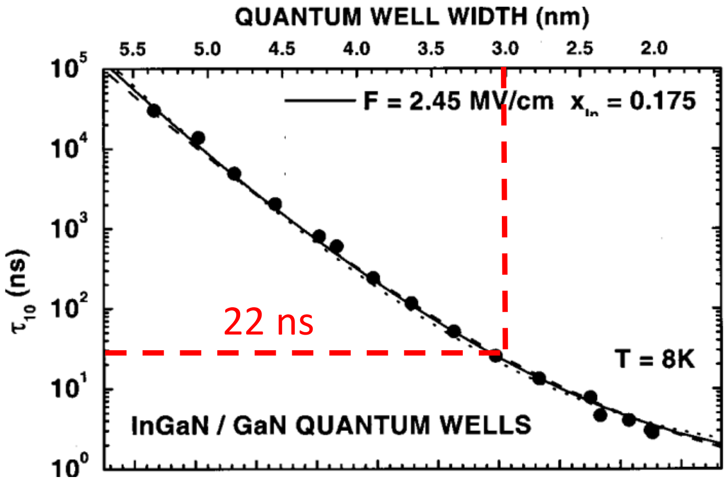


Quantum Confined Stark Effect (QCSE)

Radiative lifetime: $\tau_R \propto \frac{1}{|\langle \varphi_e | \varphi_h \rangle|^2}$

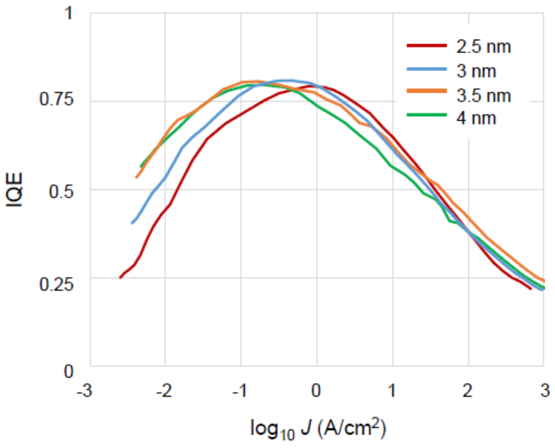
Few 10s of nanoseconds for blue LEDs

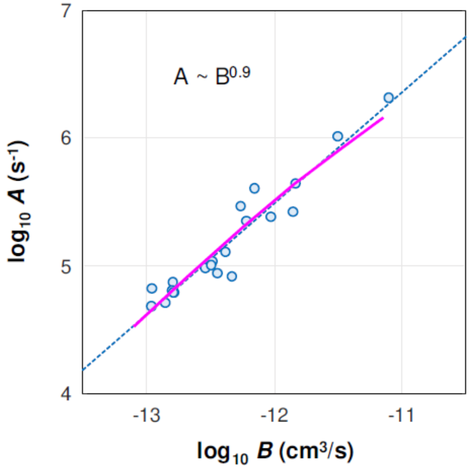
$$IQE = \frac{\tau_{NR}}{\tau_{NR} + \tau_R}$$



P. Lefebvre,..., NG, J.Massies *et al.*, APL 78, 1252 (2001)

Important: τ_{NR} is inversely proportional to the e-h wavefunction overlap A. David *et al.*, Phys. Rev. Appl. 11, 031001 (2019)

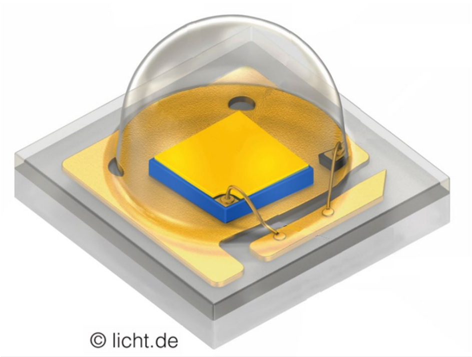




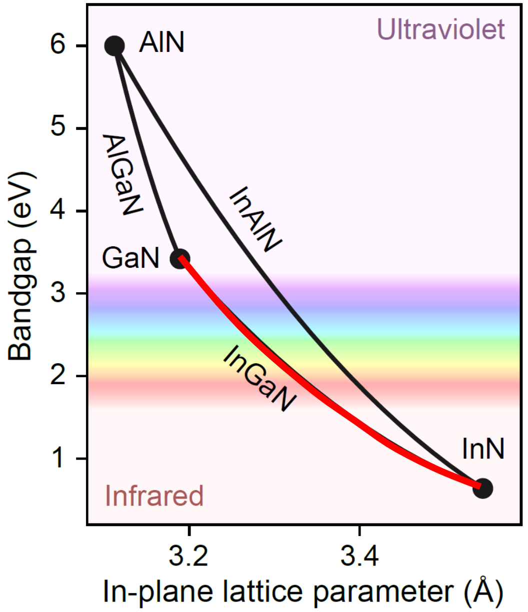
The B coefficient decreases when the polarization field increases, but the A coefficient decreases too.

The polarization field does not impact the efficiency.

III-V nitride semiconductors



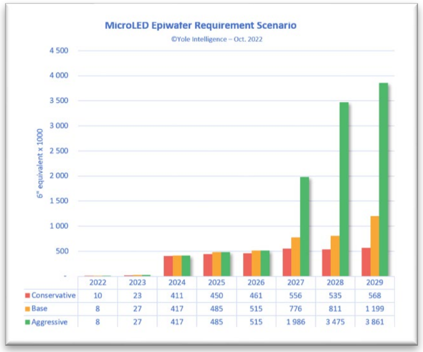
- Blue LEDs are extremely efficient
- WPE > 80% (IQE > 90%)
- White LEDs with record luminous efficacy of 300 lm/W



- InN bandgap of 0.65 eV

⇒ InGaN alloy covers the whole visible spectrum

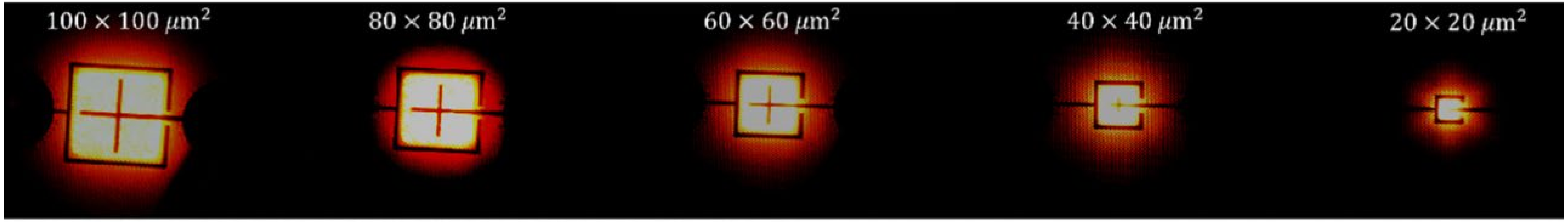
III-V nitride semiconductors

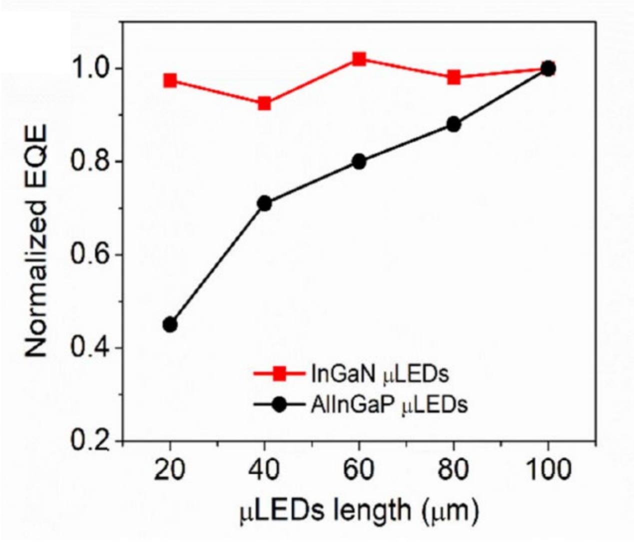


	2022	2023	2024	2025	2026	2027	2028	2029
Conservative	10	23	411	450	461	556	535	568
Base	8	27	417	485	515	776	811	1 199
Aggressive	8	27	417	485	515	1 986	3 475	3 861

- InGaN MicroLEDs for RGB displays

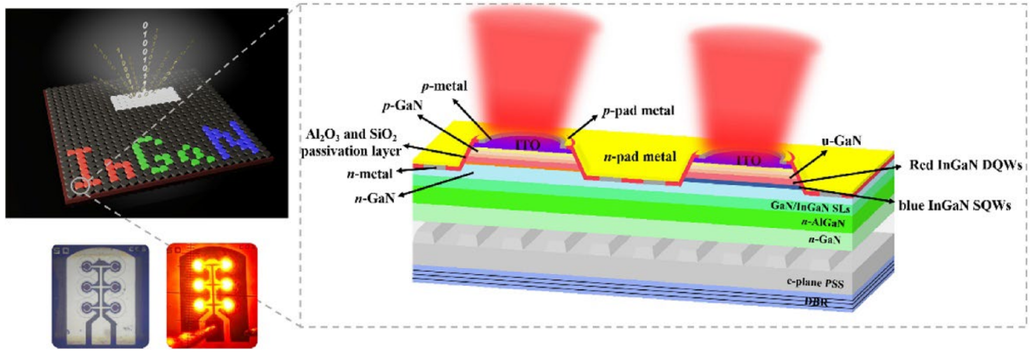
1. Less sensitive to sidewall non-radiative recombination



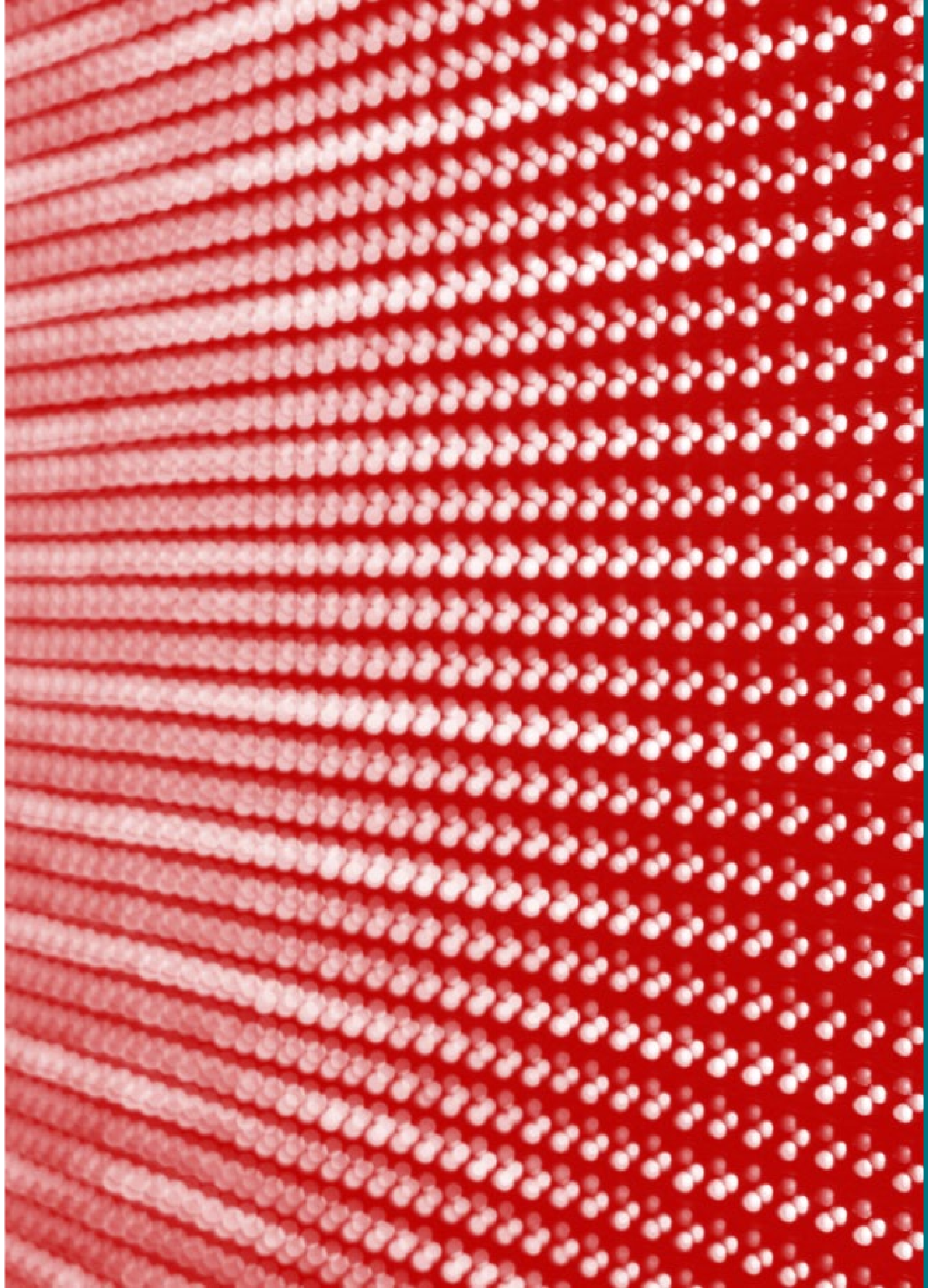


P. Li *et al.*, Crystals 12, 541 (2022)

2. A single material platform



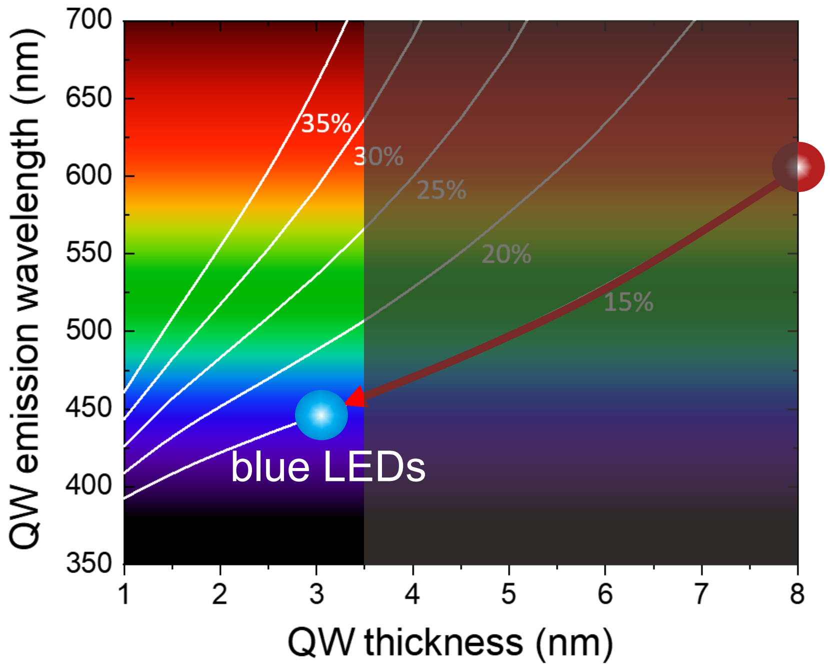
Y.-M. Huang *et al.*, Photonics Research 10, 1978 (2022)



How to push the wavelength to the Red ?

How to push the wavelength to the Red ?

- InGaN/GaN QW emission wavelength

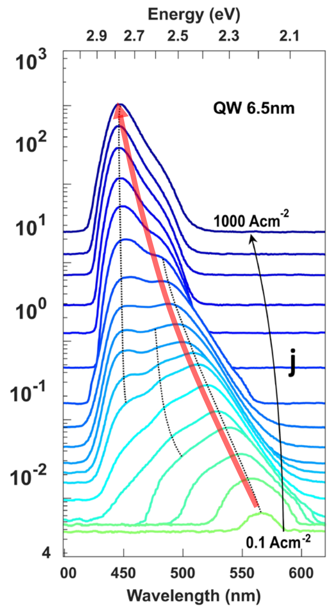


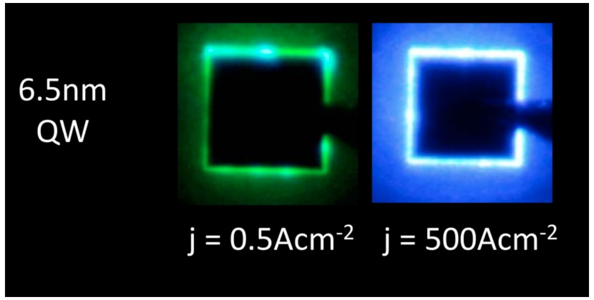
$$E_{QW} = E_g^{InGaN} + E_{conf}^{e,h} - qL_wF$$ Stark shift

$$x = 15\% \Rightarrow F \approx 1.5\ MV/cm$$

Red emission (~610 nm) with 15% In and $L_w = 8$ nm

The indium content must be larger than 30%





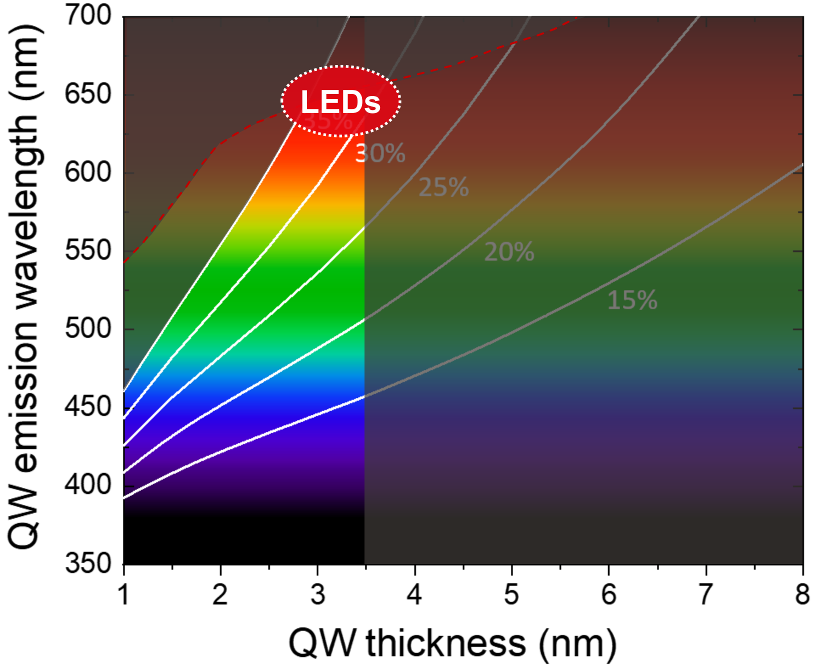
- Screening of the electric field induces a strong blue-shift

$\Rightarrow L_w$ **lower than 4 nm**

M. Hajdel *et al.*, Materials 15, 237 (2022)

How to push the wavelength to the Red ?

- InGaN/GaN QW emission wavelength



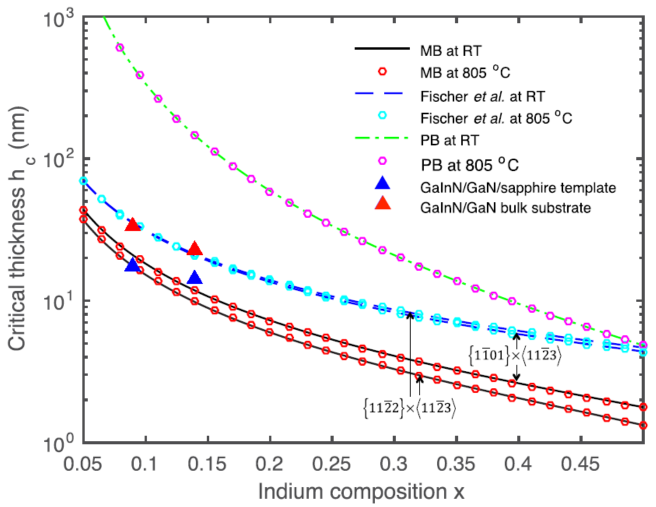
$$E_{QW} = E_g^{InGaN} + E_{conf}^{e,h} - qL_wF$$ Indium content

« ... less than 35% In composition is normally reported.”

N. Hu *et al.*, APL 121, 082106 (2022) - Amano’s group

InGaN on GaN critical thickness

G. Ju *et al.*, APL 110, 262105 (2017) Amano’s group



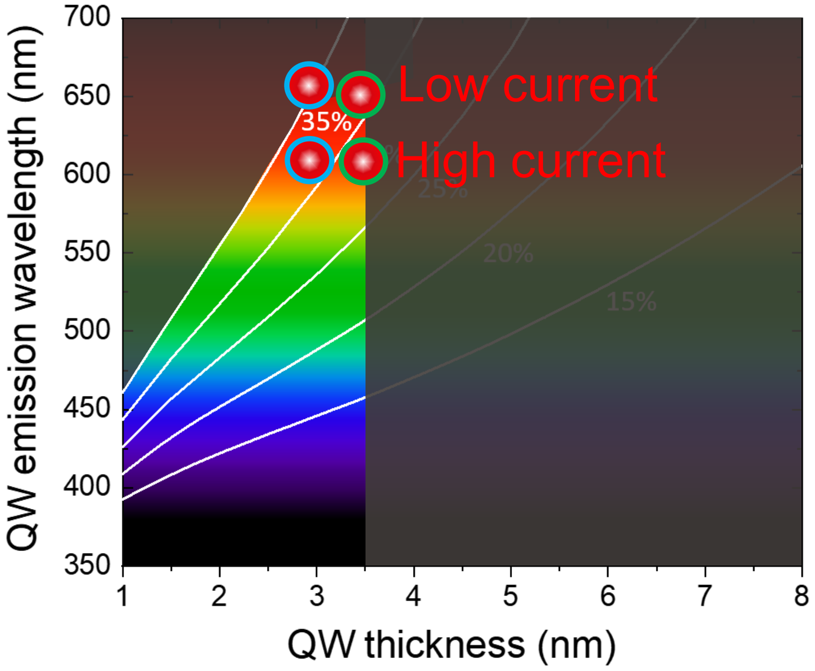
- The parameter space for red LEDs is quite limited

In content = 30-35%

L_w = 3-3.5 nm

How to push the wavelength to the Red ?

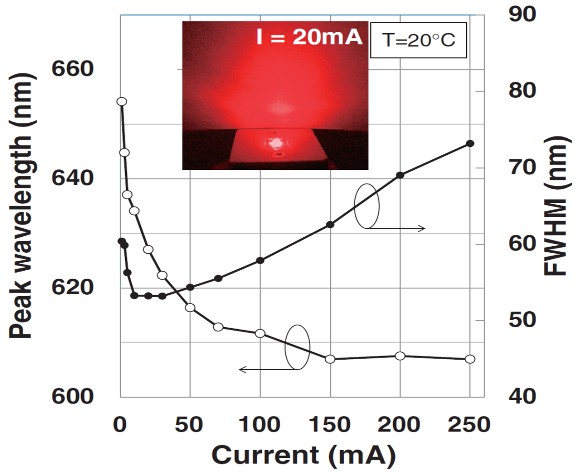
- Red-LEDs on GaN/sapphire template



2014 : Toshiba J.-I. Hwang *et al.*, APEX 7, 071003 (2014)

x = 0.35, L_w= 3 nm, λ_{max}= 655 nm

At 20 mA and 629 nm:
- Power = 1.1 mW
- EQE = 2.9%
- WPE = 1.3%

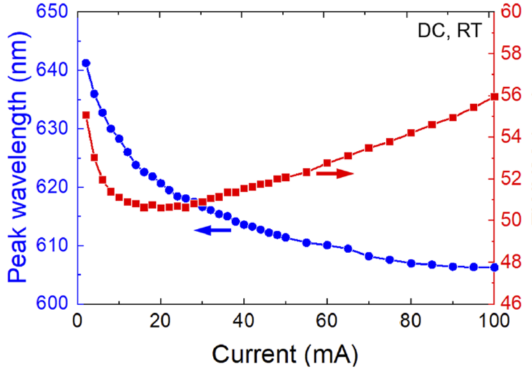


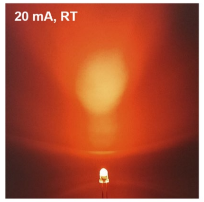
2022 : KAUST D. Iida *et al.*, AIP Advances 12, 065125 (2022)

x = 0.32, L_w= 3.5 nm, λ_{max}= 641 nm

At 20 mA and 621 nm:
- Power = 1.7 mW
- EQE = 4.3%
- WPE = 2.9%

Paper 12421-61



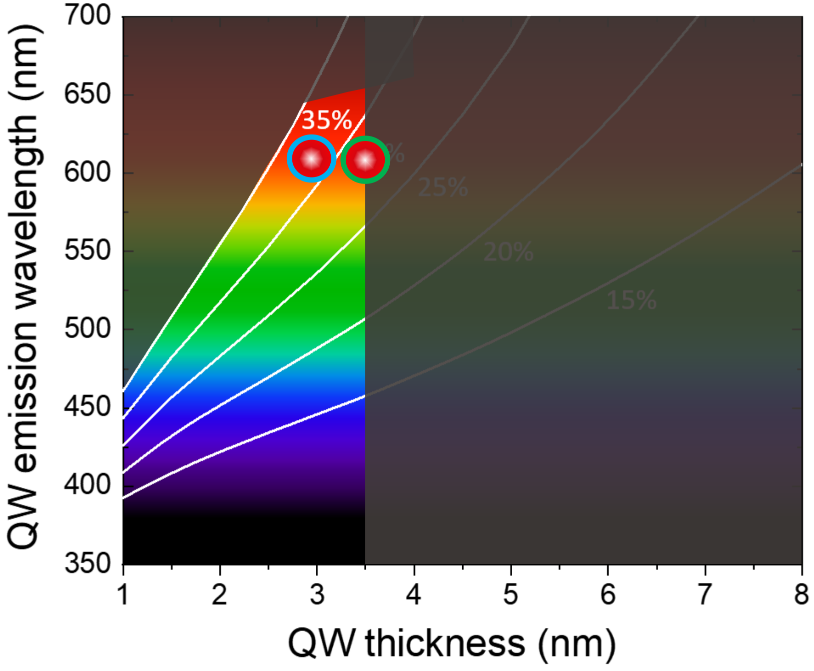


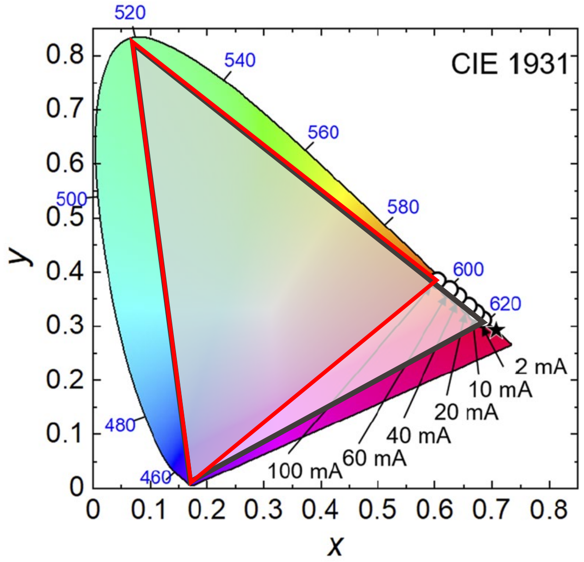
How to push the wavelength to the Red ?

Nicolas Grandjean

- Red-LEDs on GaN/sapphire template

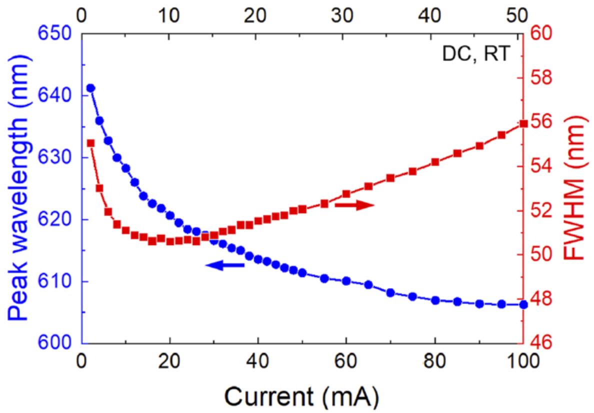
At high current density, due to the field screening and band filling, the emission is barely red (610 nm)





D. Iida *et al.*, AIP Advances 12, 065125 (2022)

The color gamut strongly depends on the "red" wavelength and the FWHM



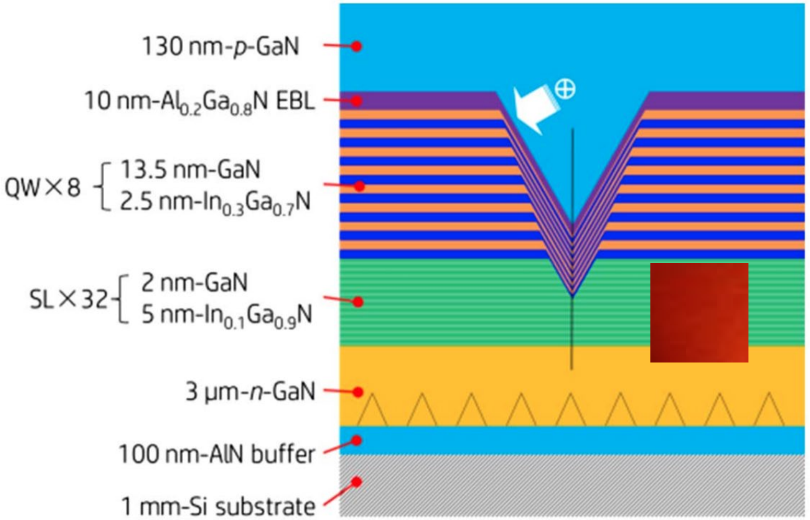
EL peak ≠ dominant wavelength

- Extend further the emission wavelength
- Reduce the emission linewidth
- Improve the efficiency

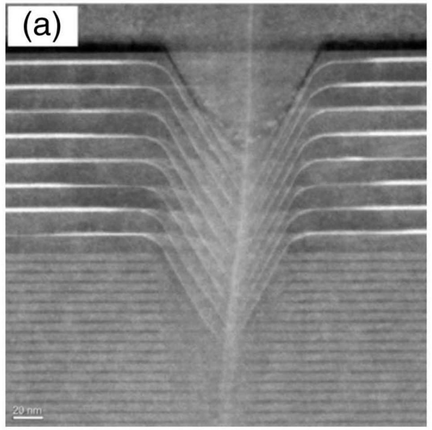
Higher In content ⇒ Decrease the strain

Less strain for more indium

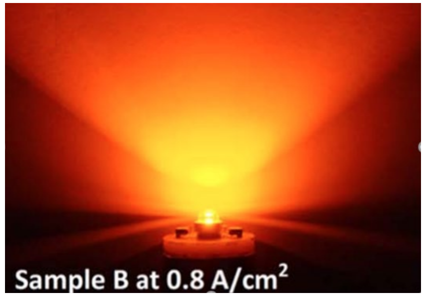
- Strain relaxation from surface morphology and growth on Si(111)

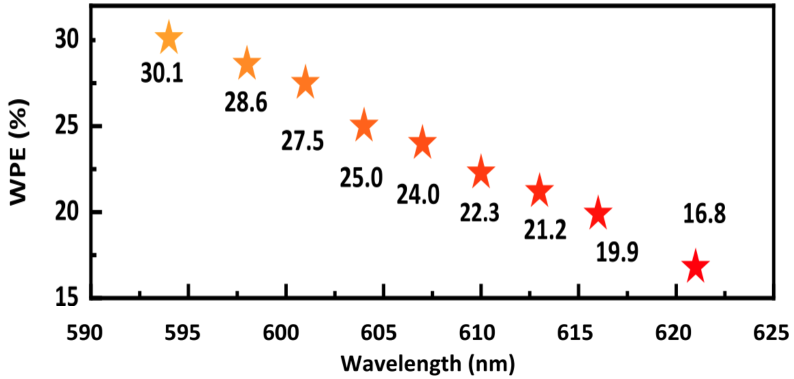


- Growth on silicon
  - ⇒ tensile strain
- Large V-pits
  - ⇒ strain relaxation
  - ⇒ Lateral hole injection



F. Jiang *et al.*, Photonics Research 7, 144 (2019) – Nanchang U.





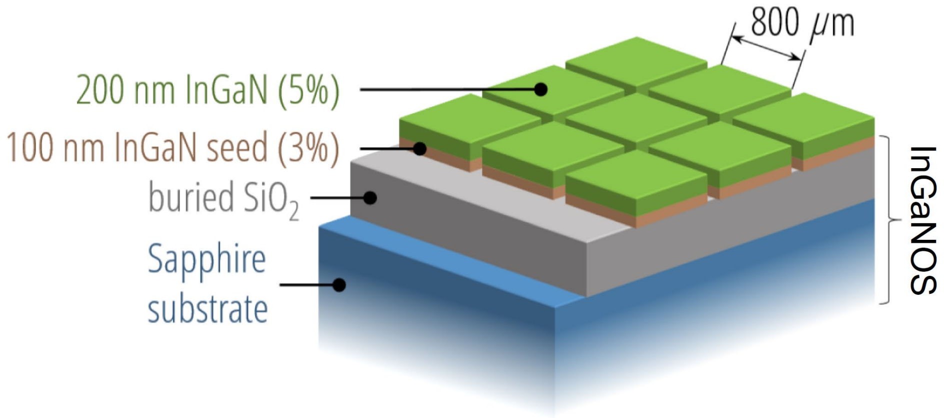
- WPE = 16.8% at 621 nm

  Large devices 1x1 mm^2

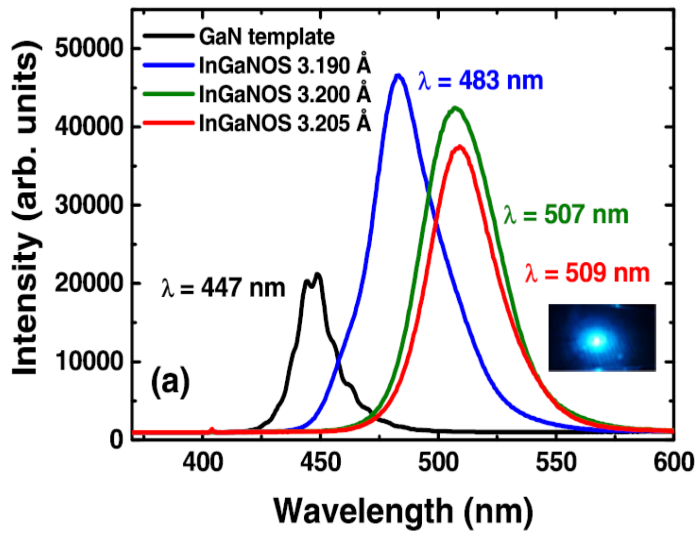
S. Zhang *et al.*, Photonics Research 8, 1671 (2020) Nanchang U.

Less strain for more indium

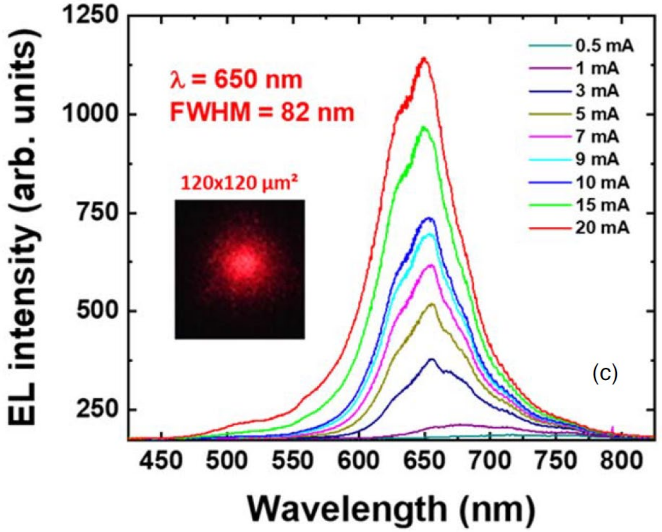
- Pseudo-InGaN substrate (InGaNOS)



- 200nm-thick $In_xGa_{1-x}N$ (x=0.015-0.08) layer on GaN/sapphire
- Transferred using Soitec's Smart Cut™ technology onto a compliant layer
- The InGaN layer is patterned to enable strain relaxation



A. Even *et al.*, APL 110, 262103 (2017)
CEA/LETI and Soitec



A. Dussaigne *et al.*, APEX 14, 092011 (2021)
CEA/LETI and Soitec

Paper 12441-20

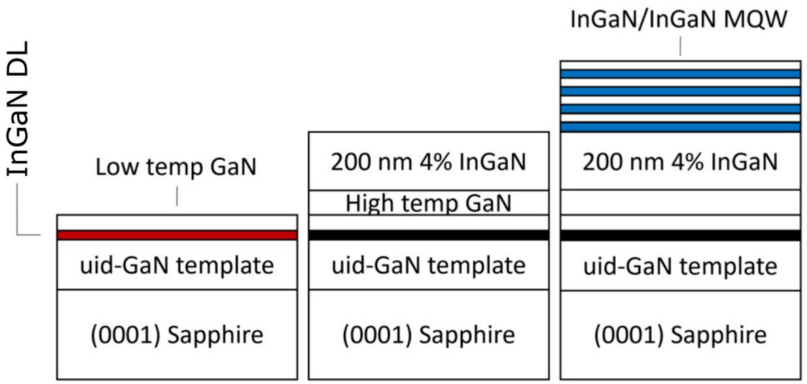
- In content ~40%
- 650 nm with small blueshift

IQE = 10%
EQE = 0.14% (with a LEE<4%)

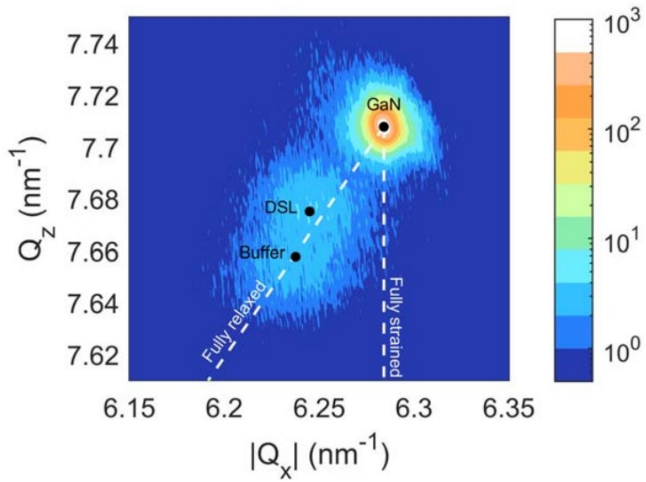
InGaNOS discontinued

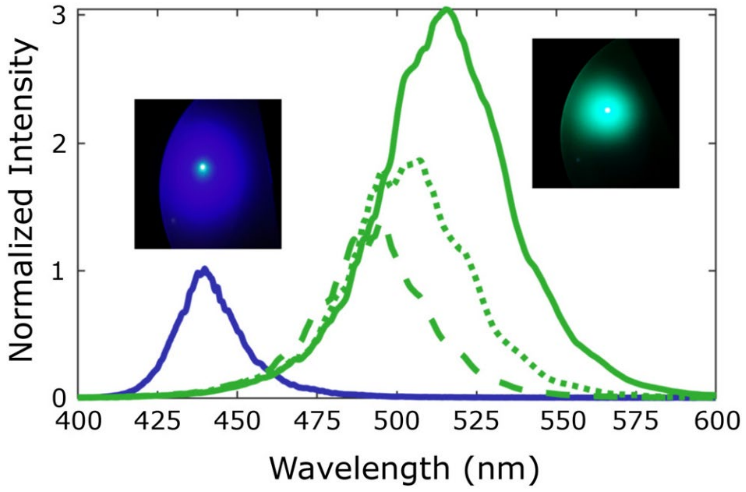
Less strain for more indium

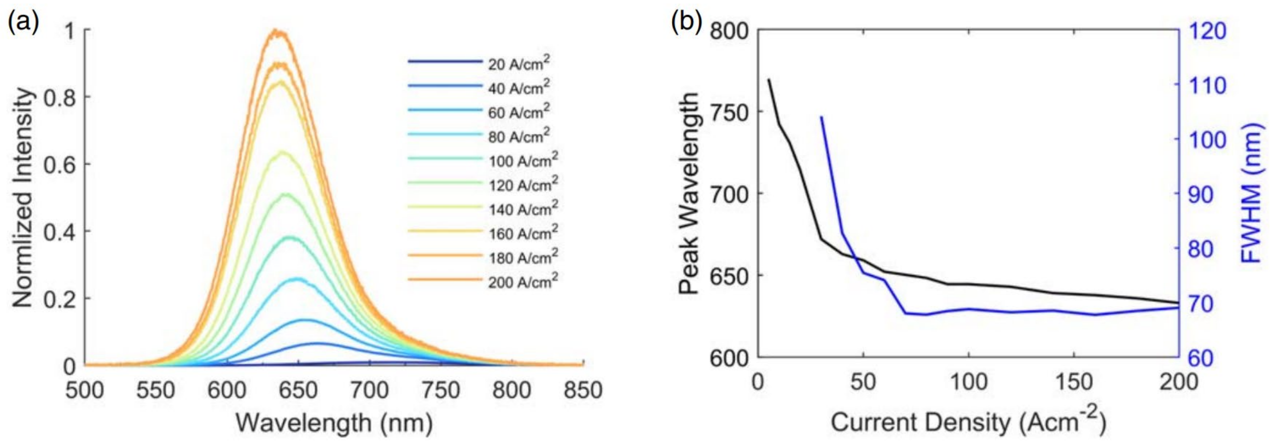
- Pseudo-InGaN substrate *via* decomposition layer



P. Chan *et al.*, APL 119, 131106 (2021) - UCSB







P. Chan *et al.*, APEX 14, 101002 (2021) - UCSB

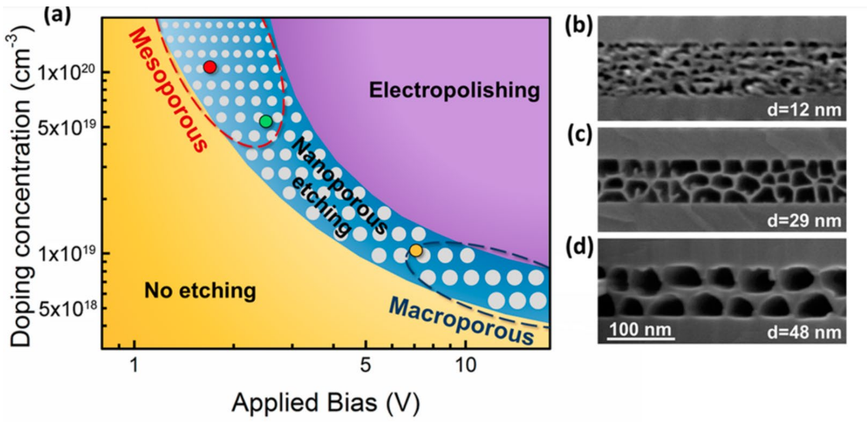
Paper 12441-57

- 770 nm at low current
- 633 nm at 200 A.cm^{-2}

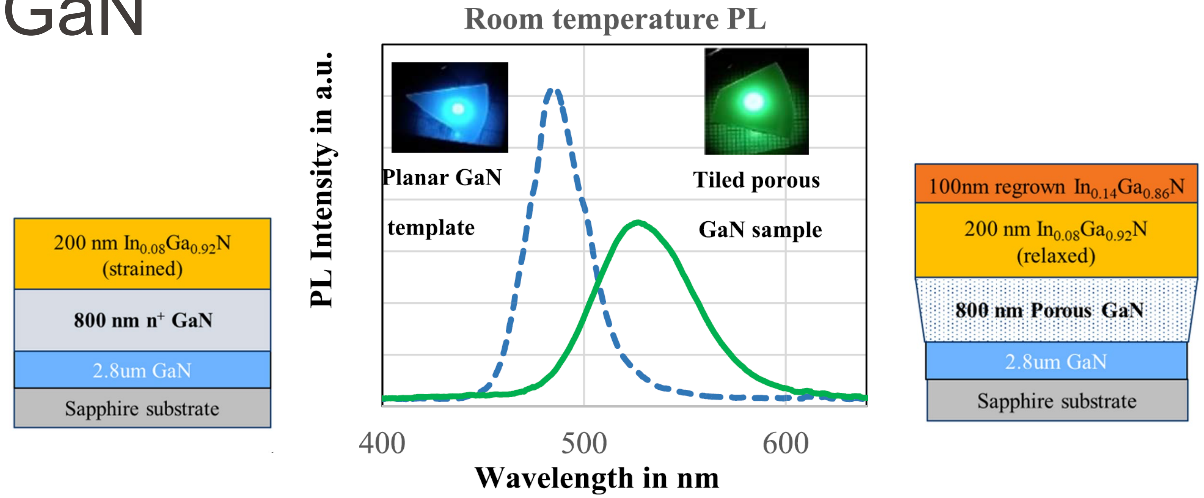
EQE = 0.05% (due to poor surface morphology)

Less strain for more indium

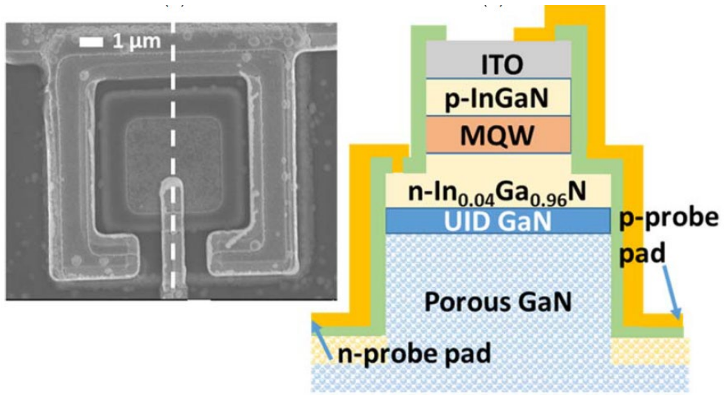
- Strain relaxation from porous GaN

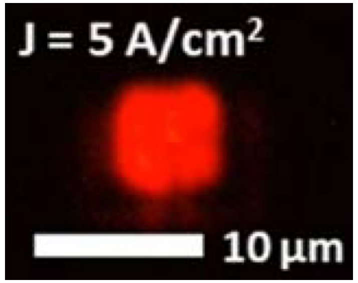


C. Zhang *et al.*, ACS Photonics 2, 980 (2015) – Yale



S.S. Pasayat *et al.*, Semicond. Sci. Technol. 34, 115020 (2019)- UCSB





- 632 nm at 10 A.cm^{-2}
- 6 µm × 6 µm µLEDs

EQE = 0.2%

S.S. Pasayat *et al.*, APEX 14, 011004 (2021) - UCSB

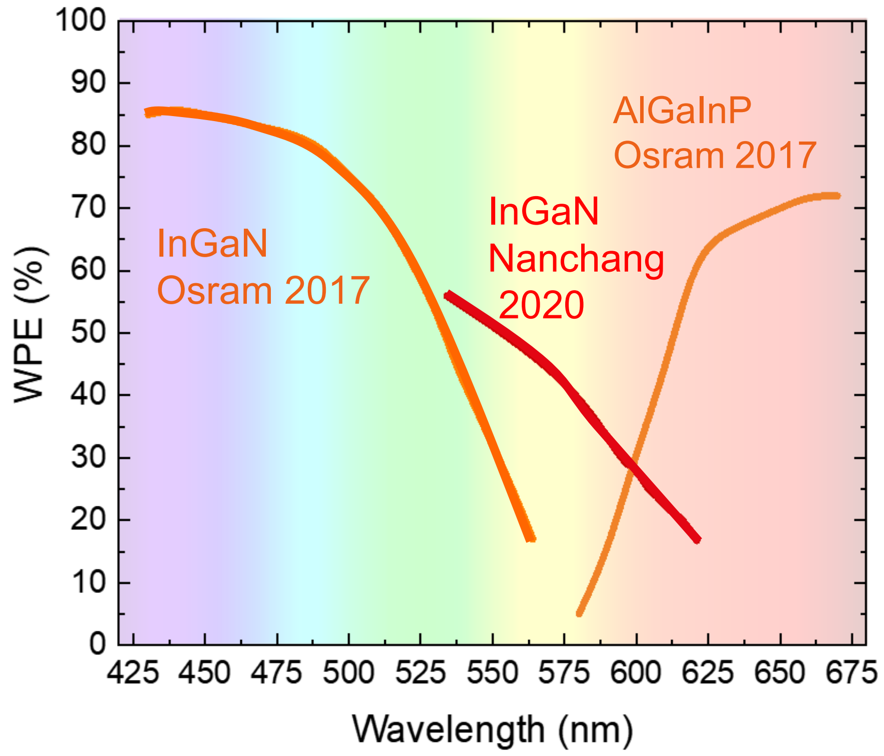
R. Oliver, Cambridge U. Paper 12441-65

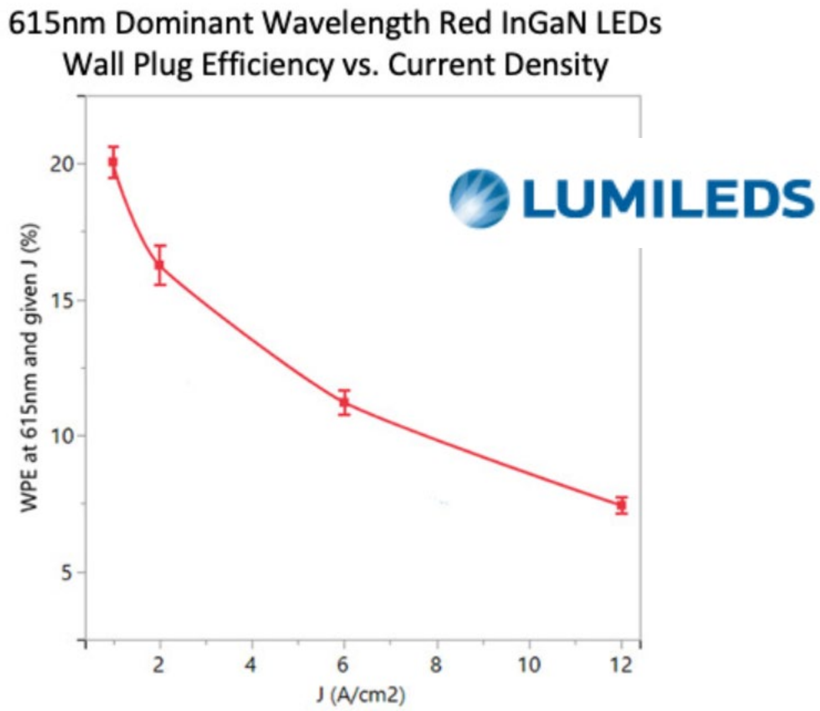
Nicolas Grandjean

Nicolas Grandjean

Conclusion

- WPE of InGaN based LEDs – state of the art





https://lumileds.com/lumileds-continues-to-lead-advances-for-red-ingan-leds/

- ➲ The green gap is closing
- ➲ The III-nitrides may compete for red microLEDs
- ➲ InGaN pseudo-substrates are needed.

Laser diodes

Electrical injection

$$n = J\tau / qd$$

A few remarks:

- The effective recombination time τ depends on the carrier density
- The Auger recombination term is significant only at high injection
- The carrier density depends on the active region thickness

Geometry of the active region:

- homojunction: $d = L_{Dn} + L_{Dp}$ (1-10 µm) (No RT operation)
- heterojunction: d = 100 nm
- quantum well: d = 1-10 nm

Laser diodes

Population inversion

n increases with the current

$$n = \int_{E_c}^{\infty} \rho_c(E) \frac{1}{1+e^{\left[\frac{E-E_{Fc}}{kT}\right]}} dE$$

E_{Fc} (E_{Fv}) ↑

and the absorption is given by

$$\alpha(\omega) = -\gamma(\omega) = \alpha_0(\omega)\left[f_v(\hbar\omega) - f_c(\hbar\omega)\right]$$

where γ is the gain

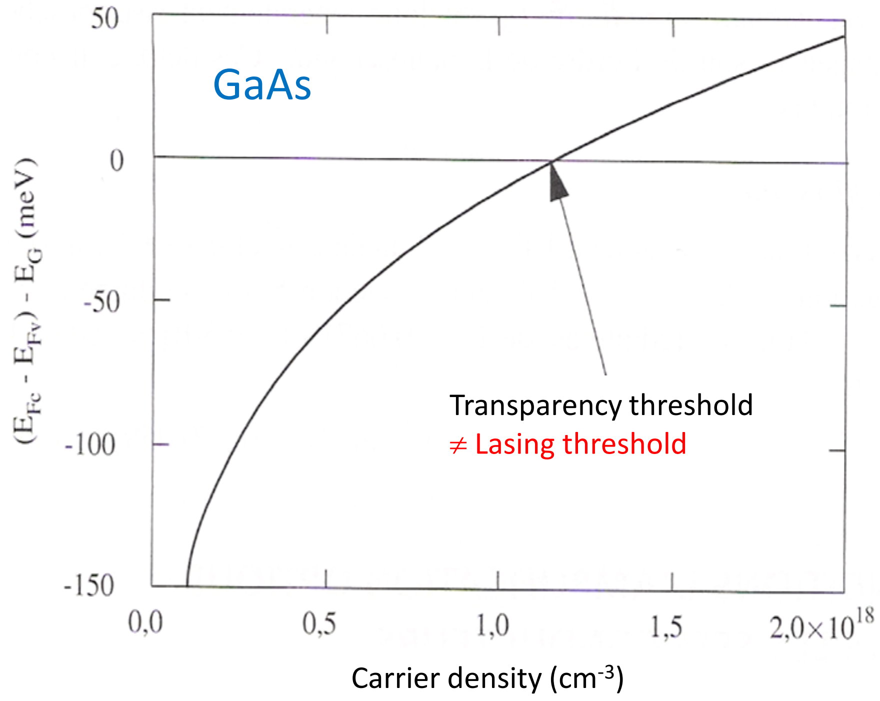
When α is negative $\Rightarrow$ stimulated emission

$$f_c(\hbar\omega) \geq f_v(\hbar\omega) \quad \Rightarrow \quad \boxed{E_{Fc} - E_{Fv} \geq \hbar\omega \geq E_g}$$

Bernard-Duraffourg condition

Laser diodes

Transparency threshold



The material becomes transparent when

$$E_{F_c} - E_{F_v} = E_g$$

Minimum requirement to fulfill the Bernard-Duraffourg condition

$t = 1\ \mu m$	$\Rightarrow$	$J_{tr} \sim 16\ kA/cm^2$	bulk (1960)
$t = 100\ nm$	$\Rightarrow$	$J_{tr} \sim 1.6\ kA/cm^2$	heterostructure (1970)
$t = 10\ nm$	$\Rightarrow$	$J_{tr} \sim 160\ A/cm^2$	quantum well (1980)

Laser threshold

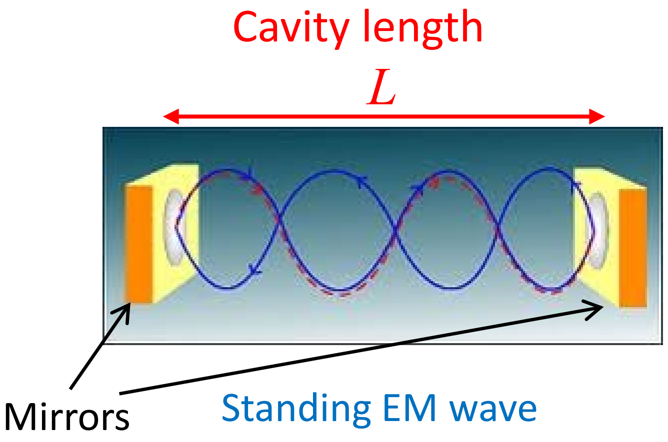
gain = losses $\Rightarrow \Gamma\gamma_{thr}(h\nu) = \alpha_p + 1/(2L) \times \ln(1/R_1R_2)$

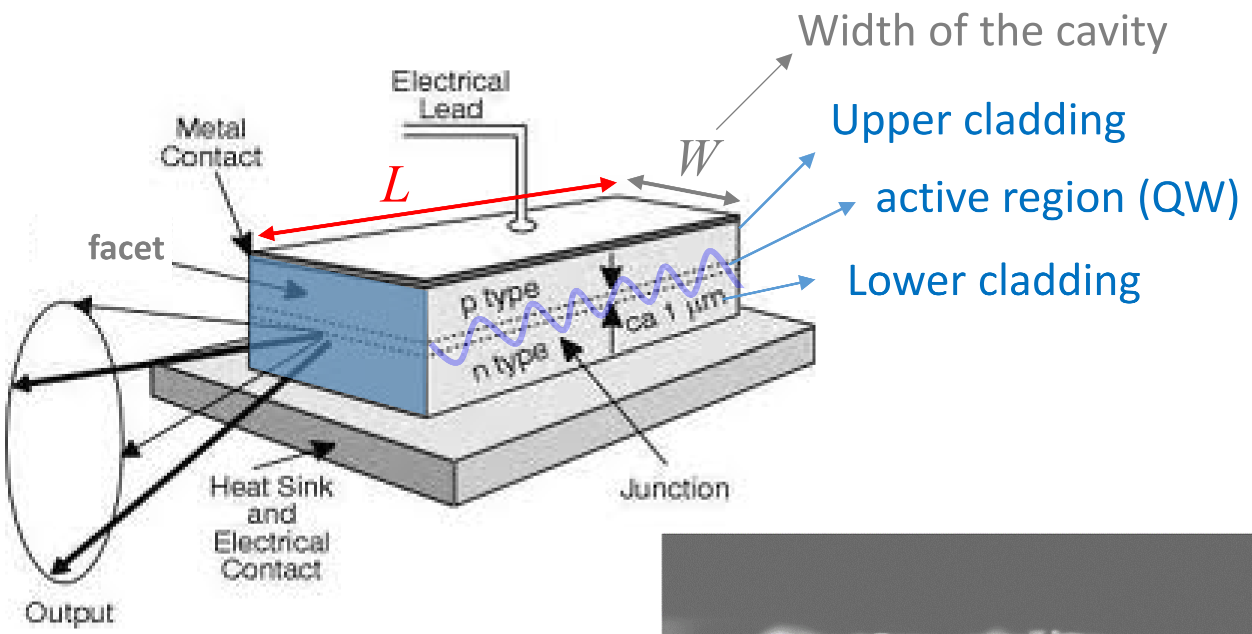
Modal gain
Γ is the confinement factor

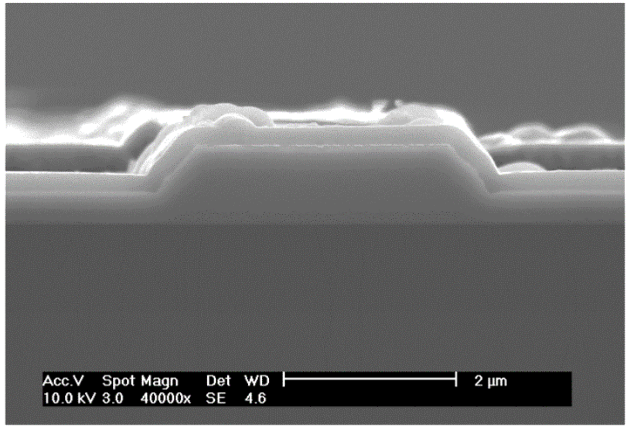
Edge-emitting laser diode

Laser cavity

Resonant cavity $\Rightarrow$ optical feedback







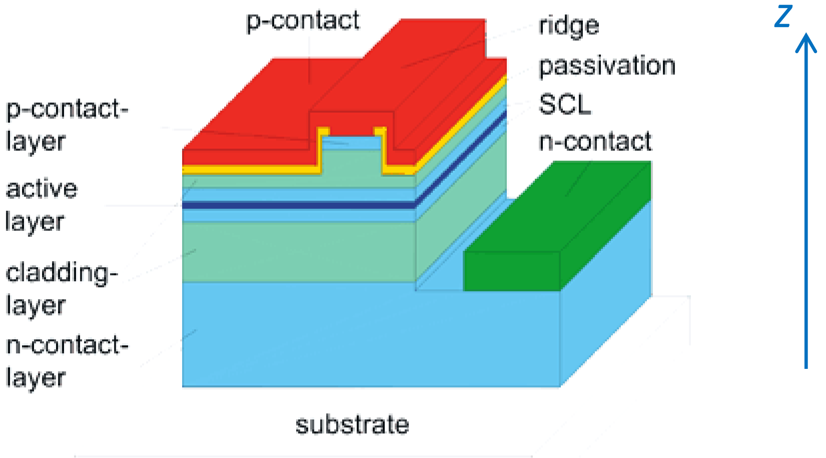
The mirrors are achieved by crystal cleavage. This defines atomically flat planes.

The reflectivity is given by $R_m = (n_{sc}-1)^2/(n_{sc}+1)^2$ e.g., for GaAs, R_m= 0.32

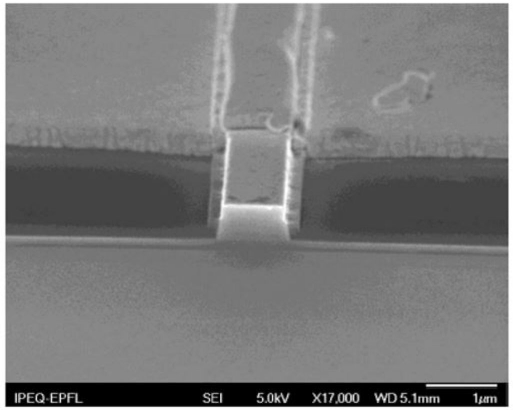
The facet reflectivity is further increased by dielectric surface coating (DBRs).

Edge-emitting laser diode

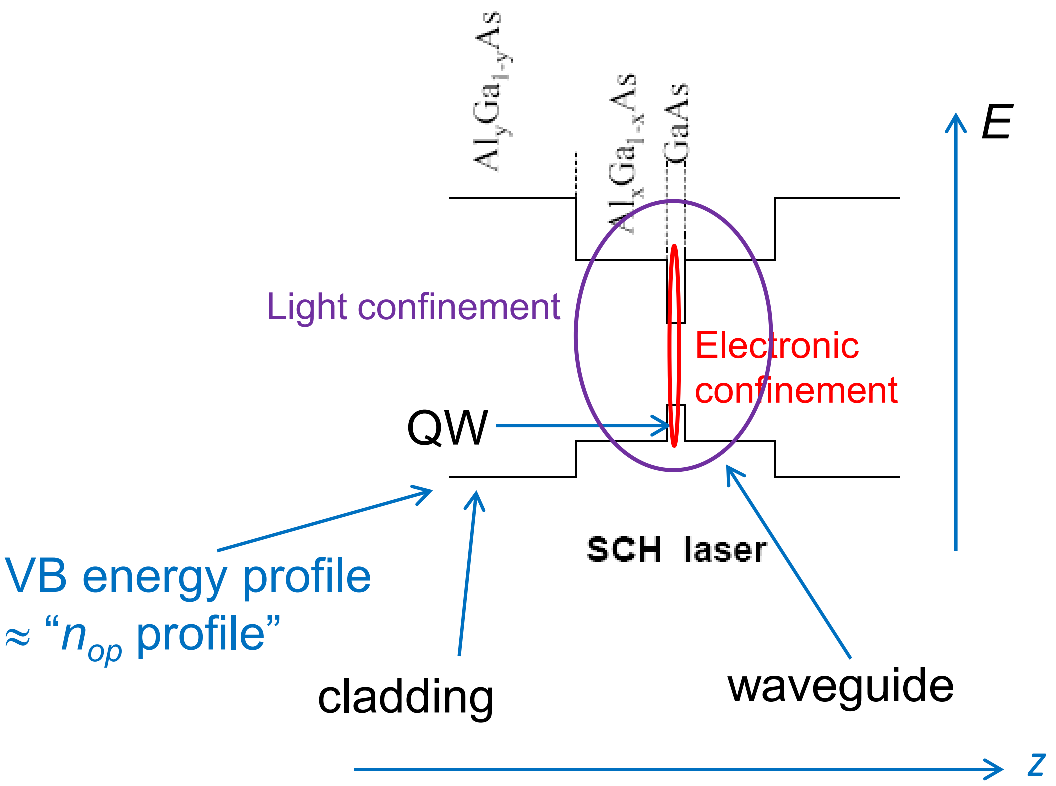
Laser diode structure



0.2-1 µm x 2-5 µm x 200-1000 µm



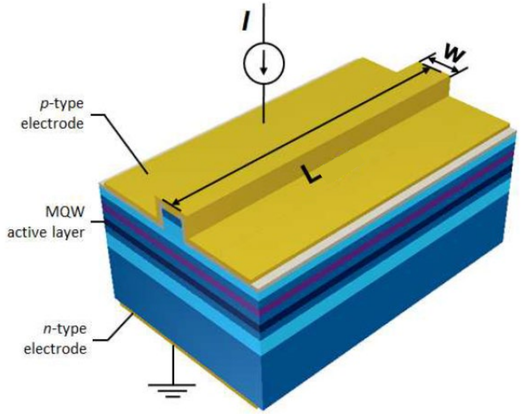
"LED" + cavity (mirrors)



SCH: separate confinement heterostructure

Edge-emitting laser diode

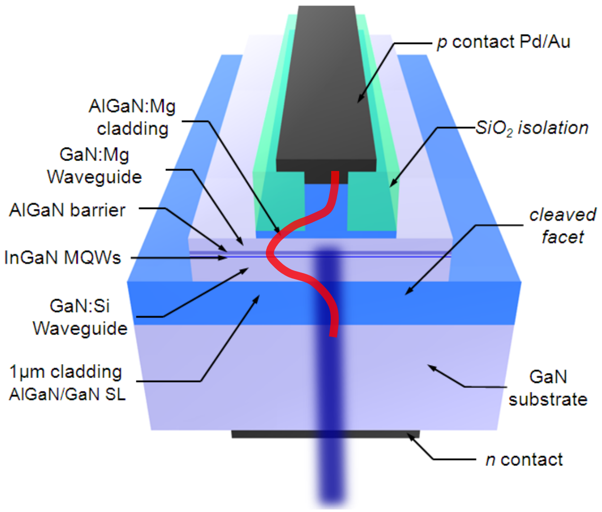
Confinement factor and modal gain

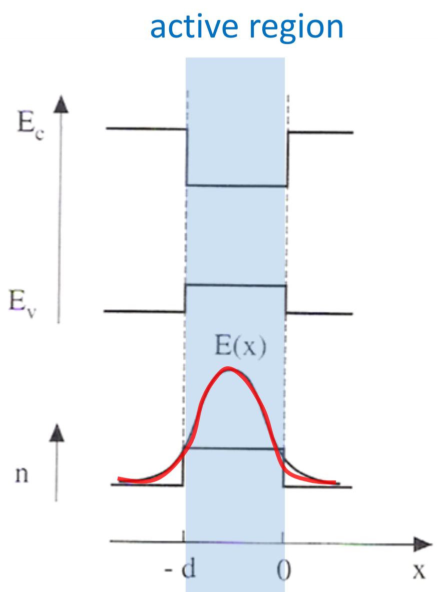


The confinement factor (Γ) is given by the overlap between the optical mode and the active region (e.g. QWs):

$$\Gamma = \frac{\int_{-d}^{0} |E(x)|^2 \, dx}{\int_{-\infty}^{+\infty} |E(x)|^2 \, dx}$$

Optical waveguide:





For a QW-based LD (SCH), Γ = 0.5-5%

For a double heterostructure (DHS), Γ ~ 1 ($d \approx$ 100 nm)

Then, the modal gain is

$$\gamma_m = \Gamma \gamma$$

Edge-emitting laser diode

Laser threshold

In an ideal case, *i.e.* without any losses, the laser threshold would be the transparency threshold ($n_{tr} = n_{thr}$)

However, in real devices, parasitic absorption is always present ($n_{tr} < n_{thr}$)

The laser threshold is then defined as Gain = Losses

$$\gamma_m = \Gamma\gamma$$

γ *increases with injected current*

- Internal losses (parasitic light absorption, eg. not the active region)
- Mirror losses

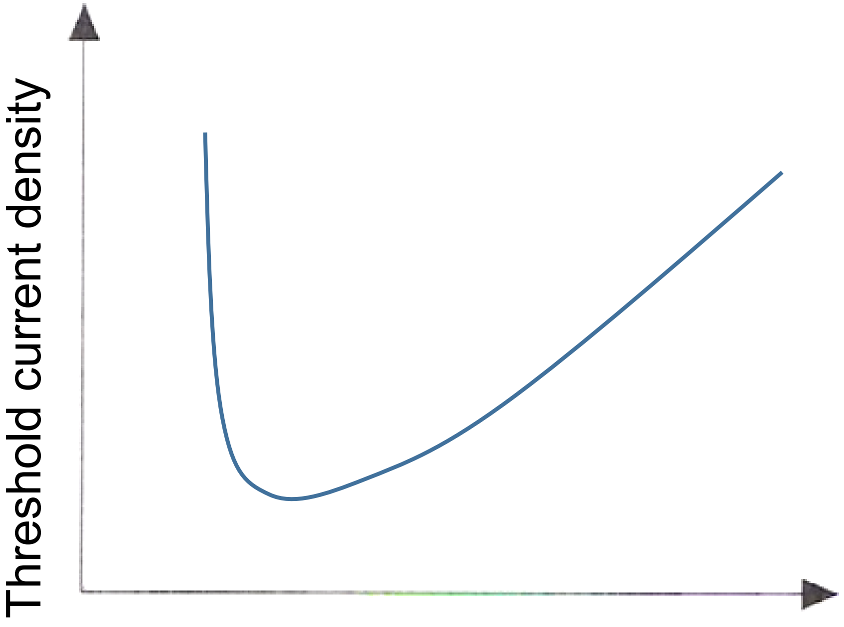
Condition for lasing: Modal gain = losses $\Rightarrow \Gamma\gamma_{thr} = \alpha_p + 1/(2L) \times \ln(1/R_1R_2)$

Modal gain — Parasitic losses — Mirror losses

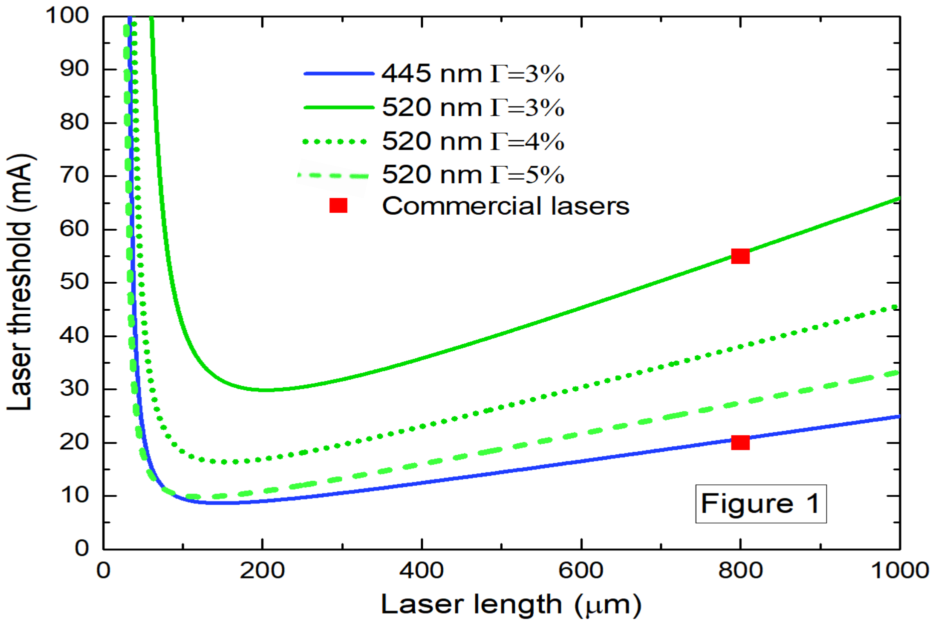
R_1, R_2 are the mirror reflectivity

Edge-emitting laser diode

Laser threshold



For a given laser diode size, there is a minimum threshold current density which is determined by the tradeoff between carrier density in the active region and the confinement factor.



Evolution of the laser threshold as a function of cavity length, confinement factors, and different emission wavelengths

Edge-emitting laser diode

Light output characteristics

1. Below the transparency threshold: linear dependence with the current

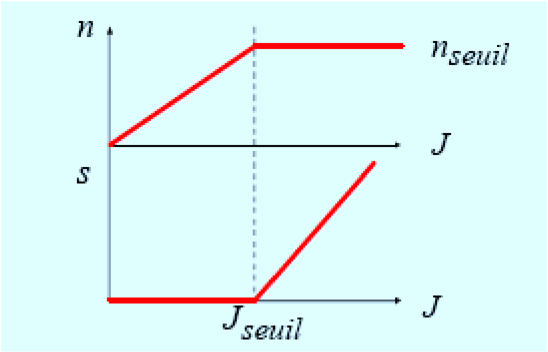
2. Above the transparency threshold: amplified spontaneous emission (ASE),

$\Rightarrow$ *superluminescence* $n_{tr} < n < n_{thr}$

3. When $\Gamma\gamma$ (modal gain) equals the losses: laser oscillations start (strong linewidth reduction)

Important: once the lasing threshold is reached, the carrier density is clamped (n is constant)

each newly added electron gives rise to 1 stimulated photon (x IQE)

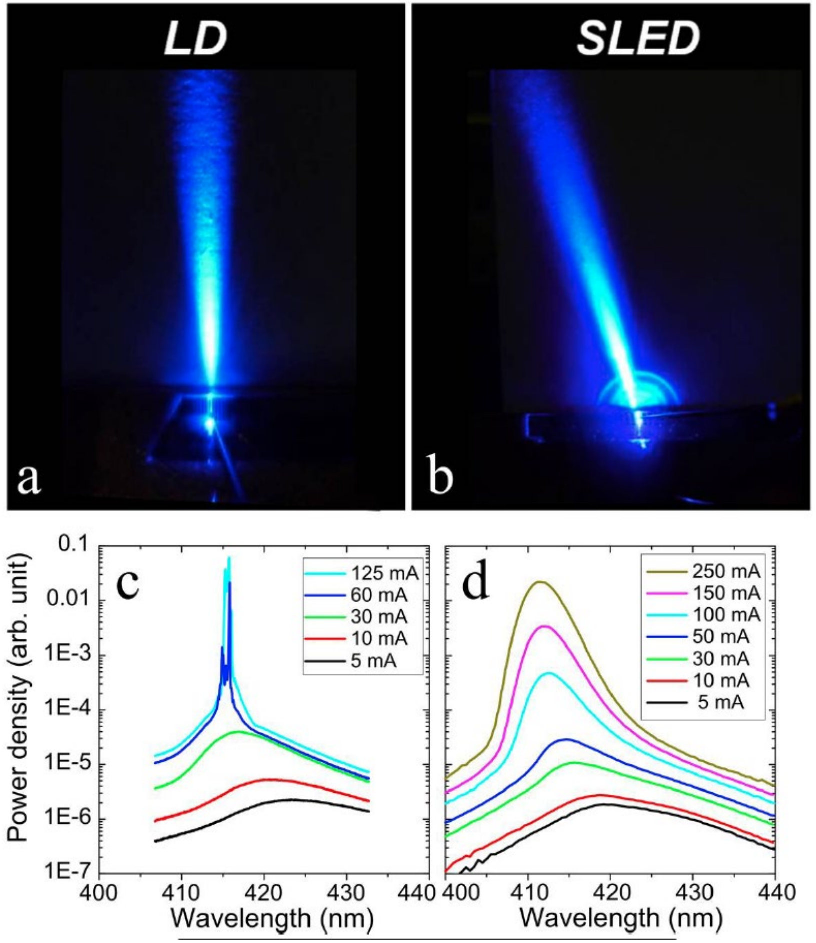


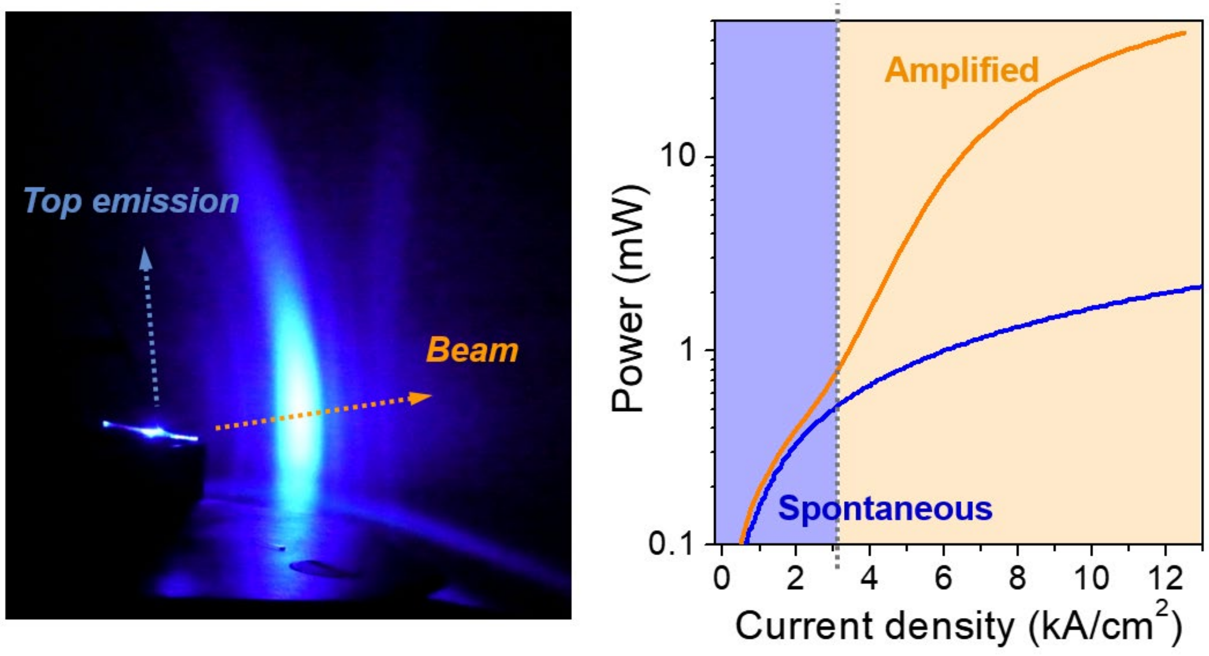
s is the number of stimulated photons in the cavity

Edge-emitting laser diode

Lasing and amplified spontaneous emission

Laser diode versus superluminescent LED

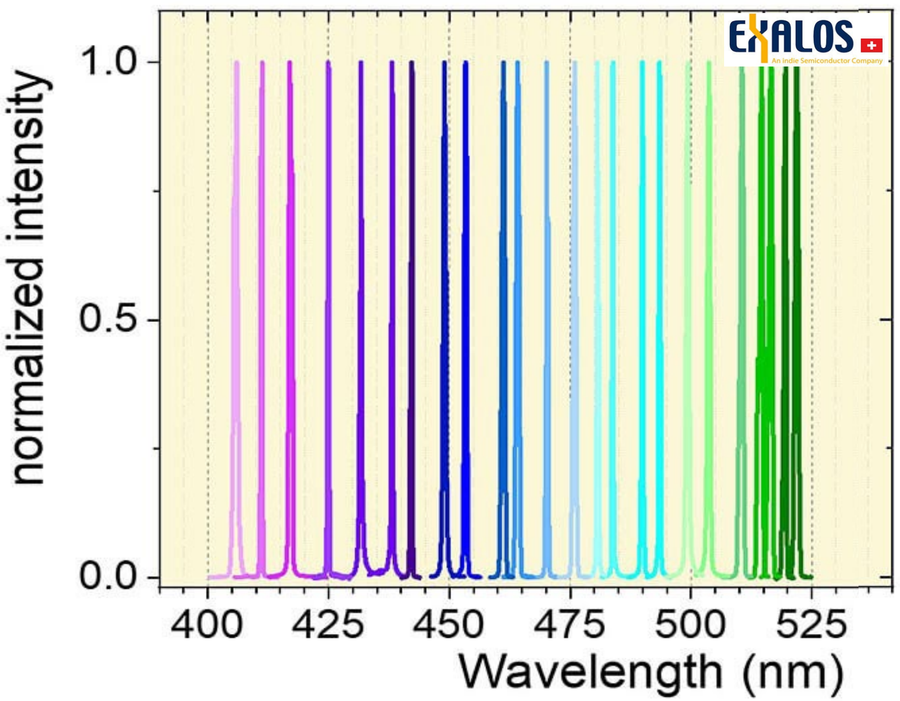


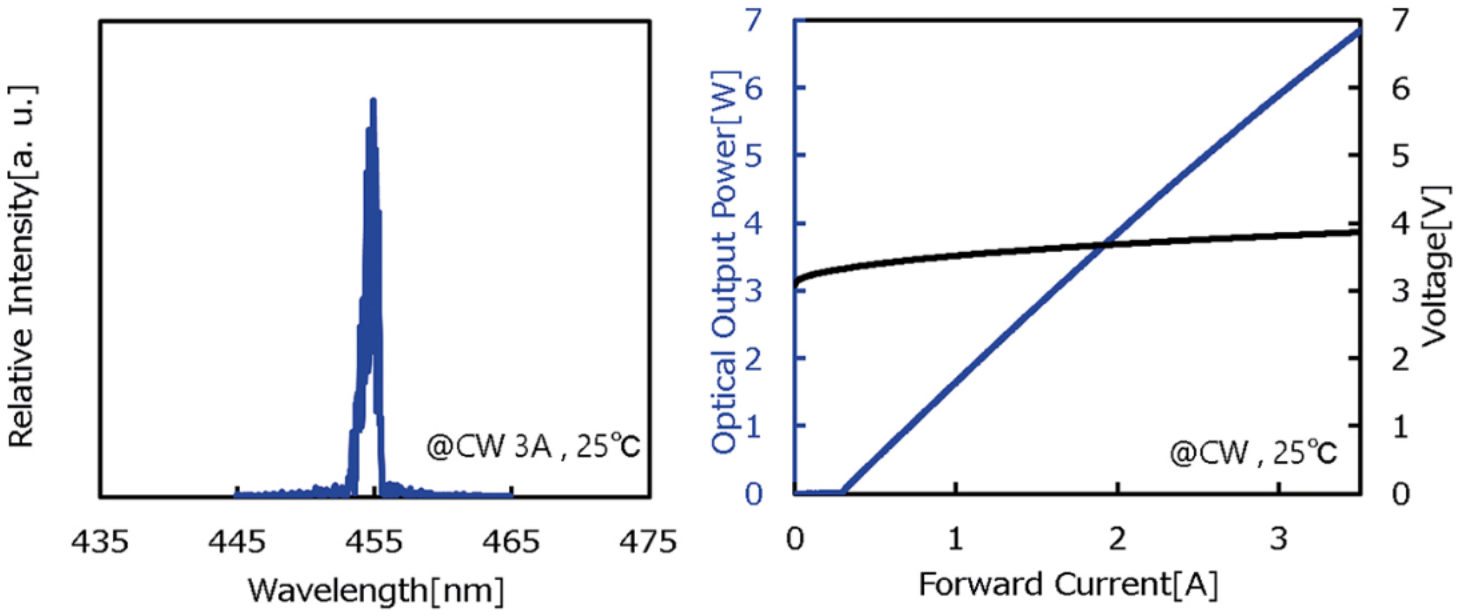


Note: a superluminescent LED (SLED) is a laser diode structure without any internal light reflection (no cavity effect=no feedback)

https://www.exalos.com/ https://www.exalos.com/bridge-the-gap-superluminescent-leds/

Edge-emitting laser diode



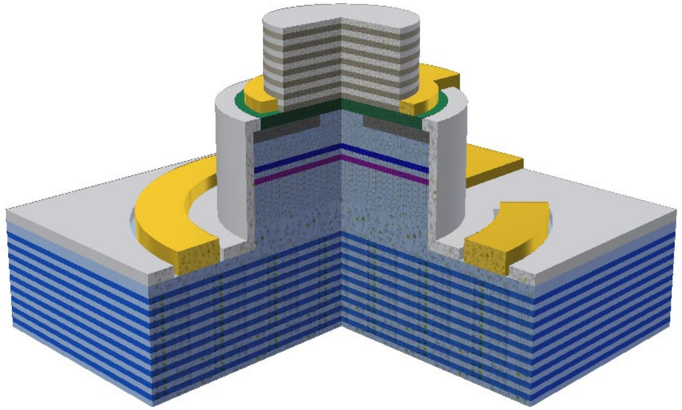


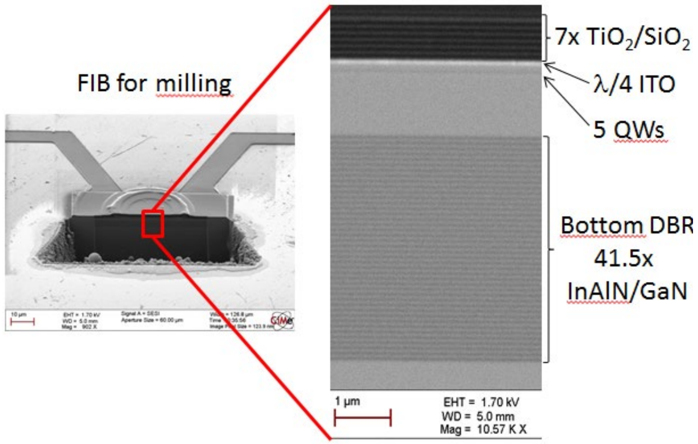
https://compoundsemiconductor.net/article/117364/Building_better_blue_and_green_lasers

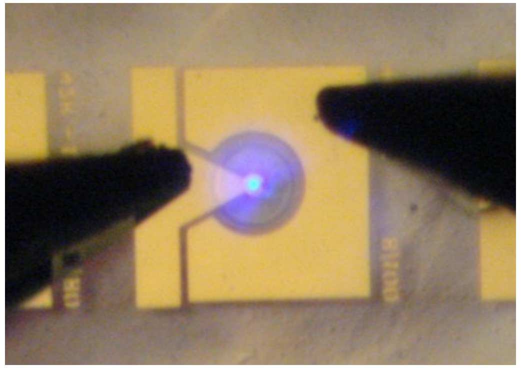
WPE > 50% at 450 nm
WPE > 25% at 525 nm

VCSELs

Vertical cavity surface emitting laser (VCSEL)







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5 March 2021

Blue and green GaN-based vertical-cavity surface-emitting lasers with AlInN/GaN DBR

Kenichi Terao, Hitoshi Nagai, Daisuke Morita, Shingo Masui, Tomoya Yanamoto, Shin-ichi Nagahama

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■ WPE vs I_{th} of blue VCSELs