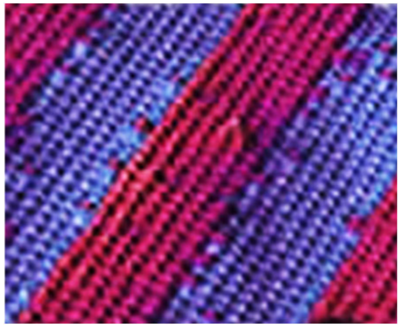
EPFL



Growth

Nicolas Grandjean

Institute of Physics
EPFL - Switzerland

nicolas.grandjean@epfl.ch

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Growth VI: recent views on blue LED efficiency

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Content

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Growth VI: recent views on blue LED efficiency

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InGaN underlayer

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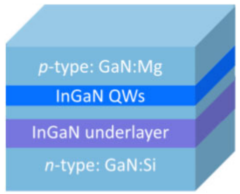
- A look at the blue LED structure



InGaN underlayer (UL):

- Present in all blue LEDs
- Low indium content to limit internal losses
- Either a superlattice or a bulk layer

What is the actual role of the InGaN underlayer?

4

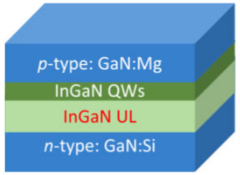
InGaN underlayer

EPFL

■ Proposed mechanisms

Promote V-pit formation

Zhao *et al.*, Solid State Elec. 54, 1119 (2010)



Less non-radiative centers

Akasaka *et al.*, Appl. Phys. Lett. 85, 3089 (2004)
Armstrong *et al.*, Appl. Phys. Lett. 117, 134501 (2015)

Strain mitigation

Nanhui *et al.*, Solid State Elec. 51, 860 (2007)
Li *et al.*, App. Phys. Lett. 102, 04115 (2013)
Okada *et al.*, J. Appl. Phys. 117, 025708 (2015)

Higher injection efficiency

Takahashi *et al.*, Physica E 21, 876 (2004)
Otsuji *et al.*, J. Appl. Phys. 100, 113105 (2006)
Ju *et al.*, J. Appl. Phys. 102, 053519 (2007)
Xia *et al.*, IEEE 57, 2639 (2010)

Electric field reduction

Davies *et al.*, pss (b) 252, 866 (2015)
J.-Y. Park *et al.*, pss (a) 213, 1610 (2016)

InGaN underlayer

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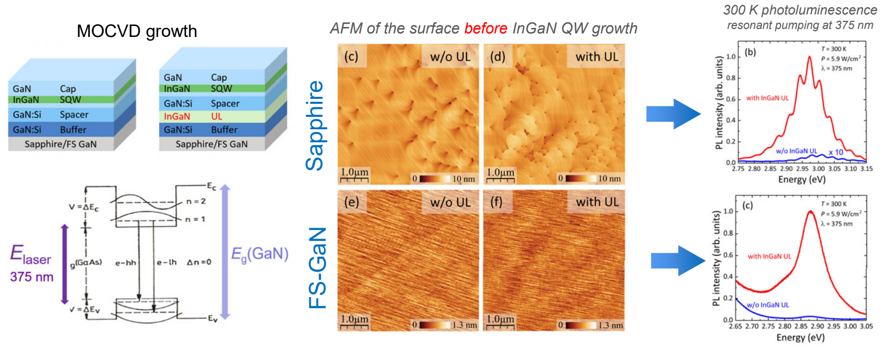
■ IQE improvement is independent of the dislocation density



InGaN UL strongly increases the QW IQE even on GaN substrate

APL 111, 262101 (2017)

InGaN underlayer

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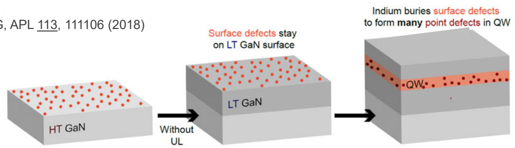
■ Burying GaN surface defects in the InGaN UL

⇒ defect at surface are trapped in the UL and subsequently form NRCs InGaN

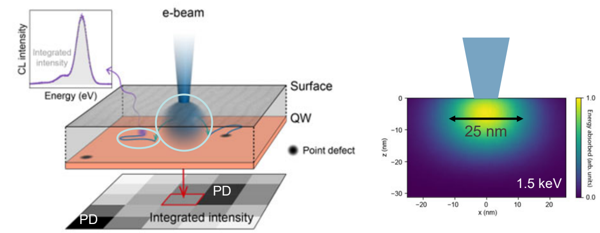
C. Haller, ... NG, APL 113, 111106 (2018)

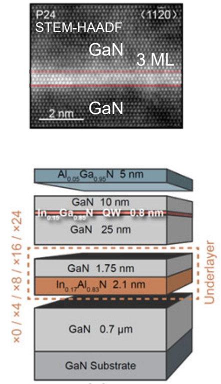


InGaN underlayer

EPFL

■ Cathodoluminescence imaging of point defects





→ Beam energy 1.5 keV

Limit diffusion length → Cryogenic temperature

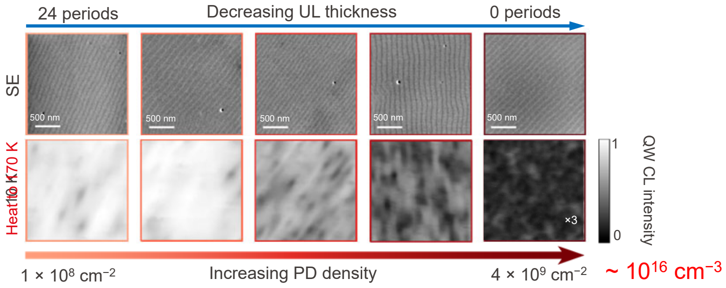
→ 3 ML QW (short radiative lifetime)

Nano Lett. 21, 5217 (2021)

InGaN underlayer

EPFL

Cathodoluminescence imaging of point defects



~ 10^{16} cm^{-3}

F. Piva *et al.* J. Phys. D: Appl. Phys. 54, 025108 (2021)

- Surface defects induce efficient non-radiative recombination centers
- There are active even at 10K (this questions the commonly used I_{PL}(300 K)/I_{PL}(10K))
- The thicker the UL, the lower the point defect density

Nano Lett. 21, 5217 (2021)

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Side remark about IQE measured by PL

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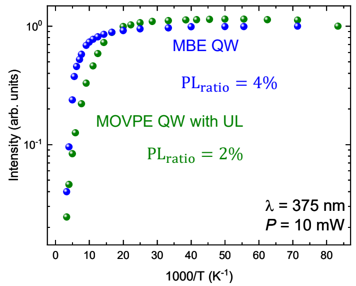
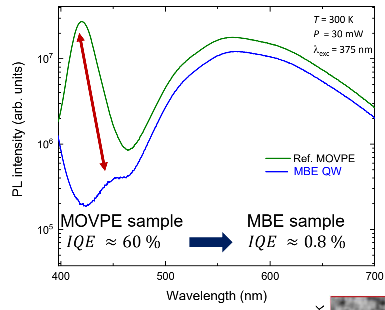
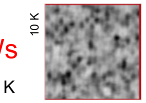




PL intensity ratio misleading for poor efficiency QWs



NRCs are still active at 10 K

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Content

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Growth VI: recent views on blue LED efficiency

- InGaN underlayer
- **Surface defects and indium interaction**
- Origin of surface defects

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Surface defects and indium interaction

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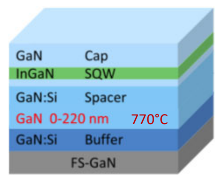
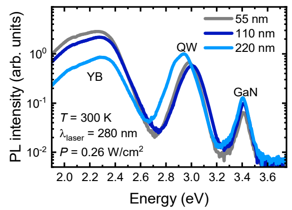
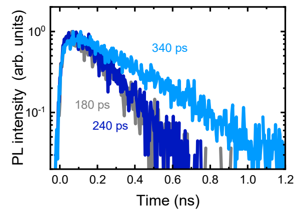
Burying impurities/defects with low-temperature GaN underlayer

2.7 nm thick $In_{0.12}Ga_{0.88}N$ Single QW







➲ Slight increase of the efficiency with low-temperature GaN underlayer


APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 15 11 OCTOBER 2004

High luminescent efficiency of InGaN multiple quantum wells grown on InGaN underlying layers

Tetsuya Akasaka,[a] Hideki Gotoh, Tadashi Saito, and Toshiki Makimoto

NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi-shi, Kanagawa, 243-0198 Japan

Indium is the "key" ingredient

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Surface defects and indium interaction

Modeling of the effective lifetime

Hypothesis: the incorporation of a SD in InGaN alloy generates a NRC

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_0} + \frac{1}{\tau_{NR,SD}}$$

- τ_0: lifetime of the QW free of NRCs induced by the SDs
- $\tau_{NR,SD}$: non−radiative lifetime depending on SD incorporation

$\tau_{NR,SD} \propto \frac{1}{[SD]_{QW}}$ with $[SD]_{QW}$ the concentration of SDs incorporated in the QW

- θ_0 : initial density of SDs after the GaN buffer grown at high-temperature
- SDs segregate at the growth front: $[SD]_{QW} \propto \theta_0 R^N$ K. Muraki *et al.*, APL 61, 557 (1992)
  with N the number of deposited monolayers
  R the segregation coefficient (probability to pass from the n^{th} layer to the $n+1^{th}$ layer)
- SDs are buried when they interact with indium atoms: $R = R_{GaN} - xp$
  with R_{GaN} the segregation coefficient of SDs in GaN
  x the indium composition of the InGaN underlayer
  p the interaction efficiency between indium atoms and SDs

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Surface defects and indium interaction

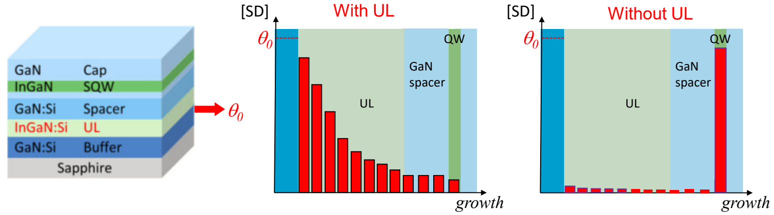
Modeling of the effective lifetime

$$\tau_{eff} = \tau_0 \cdot \frac{1}{1 + (\tau_0 \cdot C_{n,p} \cdot C_{QW} \cdot \theta_0 (R_{GaN} - x \cdot p)^N)}$$

SDs after the growth of N monolayers of $In_xGa_{1-x}N$ UL

Capture coefficient of SRH centers induced by SD incorporation

Number of SD trapped in the QW: $C_{QW} = \left(1 - (R_{GaN} - x_{QW}p)^{N_{QW}}\right)/L_{QW}$



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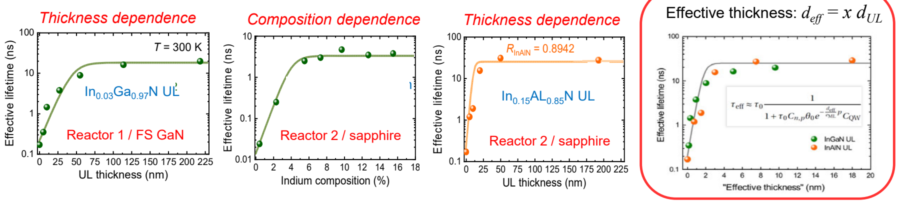
Surface defects and indium interaction

Modeling of the effective lifetime



- ➲ SD interaction with indium is independent of the material
- ➲ Same behavior whatever the MOCVD reactor/substrate
- ➲ Strong interaction between indium atoms and SDs

APL 113, 111106 (2018)

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Surface defects and indium interaction

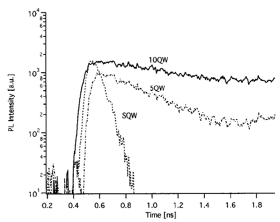
Consequence for InGaN/GaN MQW properties

APPLIED PHYSICS LETTERS VOLUME 72, NUMBER 9 2 MARCH 1998

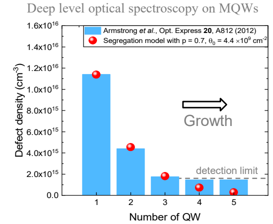
Characterization of high-quality InGaN/GaN multiquantum wells with time-resolved photoluminescence

M. S. Minsky, S. B. Fleischer, A. C. Abare, J. E. Bowers, and E. L. Hu
Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106

S. Keller and S. P. Denbaars
Department of Materials, University of California, Santa Barbara, California 93106

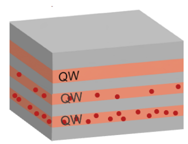


Deep level optical spectroscopy on MQWs



A. Armstrong *et al.*, Opt. Express 20, A812 (2012)

MQWs



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Surface defects and indium interaction

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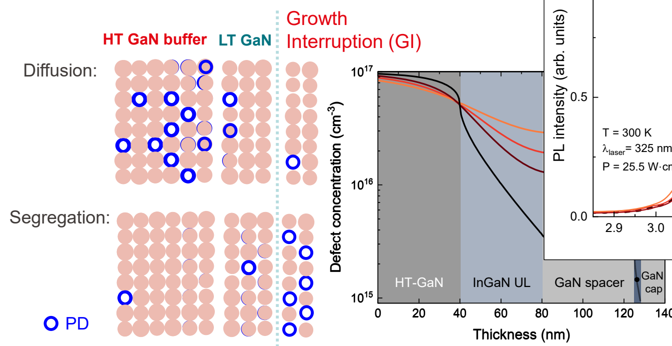
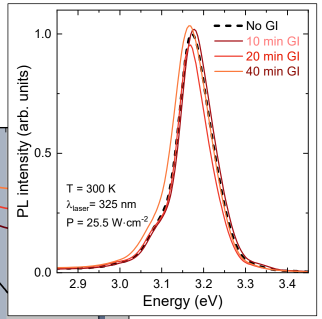
Segregation or diffusion

- Diffusion happens if a **gradient** exists in the structure
- Surface segregation is a *migration* process toward the surface





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Surface defects and indium interaction

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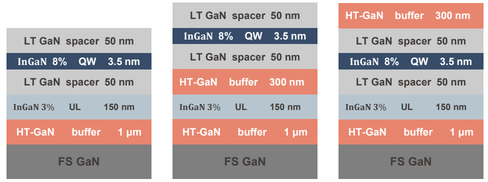
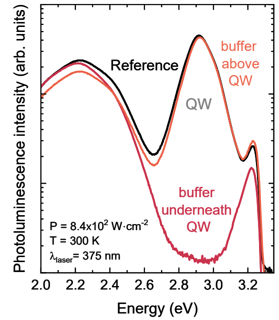
Segregation or diffusion





- HT growth above the QW does not degrade efficiency
  → inline with commercial blue LEDs: p-GaN are commonly grown around 1000 °C
- Strong indication that bulk diffusion of defects is not at play

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Content

EPFL

Growth VI: recent views on blue LED efficiency

- InGaN underlayer
- Surface defects and indium interaction
- **Origin of surface defects**

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Origin of the surface defects

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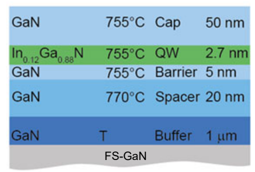
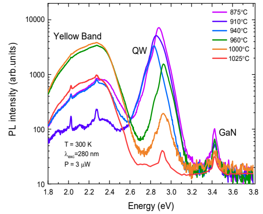
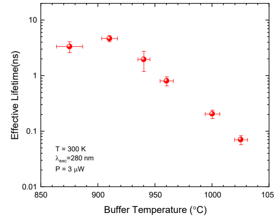
Impact of the growth temperature

InGaN SQW grown on 1 µm thick GaN buffer on FS-GaN substrate



$T_{buffer}(°C)$ = 875, 910, 935, 995, 1050





➲ The HT growth of GaN buffer generates surface defects

Appl. Phys. Lett. 118, 111102 (2021)

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Origin of the surface defects

EPFL

What could be these SDs?

Impurities

Li, C, O, Na, Mg, P, K, Ca, Fe, Ti, Cr, Ni, Cu, Zn, Mo (SIMS at EAG Laboratories)

Measured concentration:	[C] = 2×10^{16} cm^{-3}	[O] = 7×10^{16} cm^{-3}	[Fe] = 4×10^{14} cm^{-3}	[Ca] < 2×10^{14} cm^{-3}
Critical concentration:	[C] > 4×10^{17} cm^{-3}	[O] > 2×10^{17} cm^{-3}	[Fe] > 1×10^{15} cm^{-3}	[Ca] > 1×10^{14} cm^{-3}

➲ no correlation between impurities and QW efficiency (detection limit?)

What we learned:

- SDs are created at high temperature (> 870°C)
- SDs strongly segregate in GaN even at low temperature (770°C)
- SDs are independent of the reactor/substrate

➲ SDs could have an intrinsic origin

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Origin of the surface defects

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Intrinsic point defects

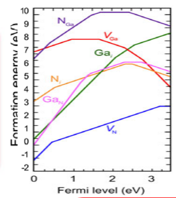

npj Computational Materials www.nature.com/npjcompumats

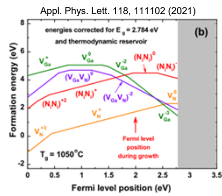
REVIEW ARTICLE OPEN

Computationally predicted energies and properties of defects in GaN

John L. Lyons and Chris G. Van de Walle

24 March 2017





Surface defect : V_N

- large formation energy and thus unlikely to incorporate in bulk GaN
- form complexes with V_{Ga}
  - ➲ $V_N - V_{Ga}$: major NRCs in *n*-GaN

  S. F. Chichibu *et al.*, JAP 123, 161413 (2018)
- formation energy of V_N lower in InGaN

  Obata *et al.*, JCG 311, 2772 (2009)

NRC in InGaN QWs: V_{III}

- large formation energy but V_{Ga} can form complexes with oxygen and/or hydrogen, which are NRCs

  C.E. Dreyer *et al.*, APL 108, 141101 (2016)

- V_N are incorporated in InGaN in the form of a V_N-V_{In} complex?

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Origin of the surface defects

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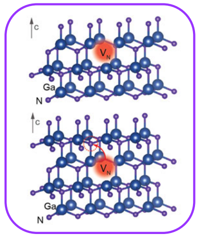
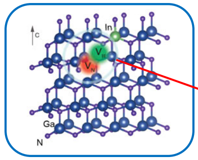
- GaN surface defects and NRCs in InGaN alloy

GaN



InGaN



- V_N created during **HT GaN growth** segregate at the surface
- V_N incorporate into the **InGaN QW** in the form of $V_{In} - V_N$, due to reduced formation energy

> "…the ***major defect species*** (in $\mathrm{In_xGa_{1-x}N}$) was identified as ***complexes*** between a *cation vacancy* and a ***nitrogen vacancy***"
>
> Uedono *et al.*, J. Appl. Phys. **113**, 123502 (2013)

> Major intrinsic NRCs in n-GaN is divacancy composed of $V_N - V_{Ga}$
>
> Chichibu *et al.*, J. Appl. Phys. **123**, 161413 (2018)

V_{In}-V_N complex as the main NRC in InGaN QW

APL Mater. 13, 031111 (2025)

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Summary

EPFL

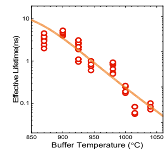
- Surface defects (VN) are generated at HT

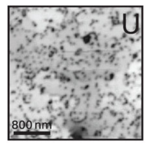
  They segregate at GaN surface even at LT
- They incorporate in InGaN where they form NRCs

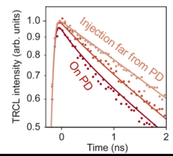
  Hypothesis: V_{In}-V_N complex as the main NRC in InGaN QW
- PDs are non-radiative at 10K

  Questions the assumption of 100% IQE at LT
- Dislocations are "screened by V-pits

  V-pit sized engineering







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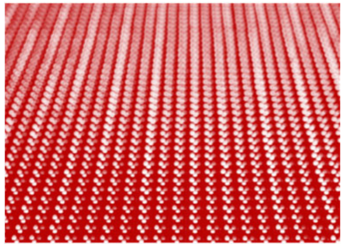
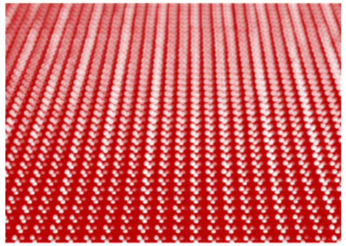
Are III-nitrides suitable for red LEDs?

- How to push the wavelength to the red?
- Less strain for more indium



Are III-nitrides suitable for red LEDs?

- How to push the wavelength to the red?
- Less strain for more indium



How to push the wavelength to the Red ?

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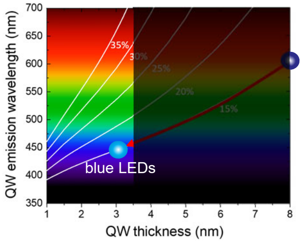
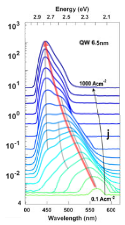
- InGaN/GaN QW emission wavelength

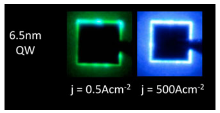


$E_{QW} = E_g^{InGaN} + E_{conf}^{e,h} - qL_wF$ Stark shift

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

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





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

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

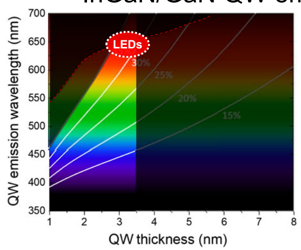
The indium content must be larger than 30%

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

How to push the wavelength to the Red ?

EPFL

- InGaN/GaN QW emission wavelength



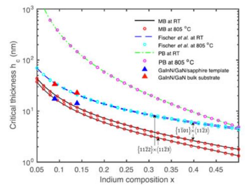
$E_{QW} = E_g^{InGaN} + E_{conf}^{e,h} - qL_wF$ Indium content

« ... 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%

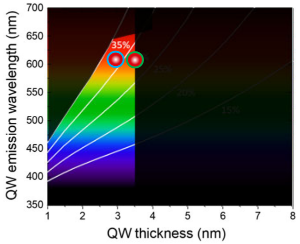
L_w = 3-3.5 nm

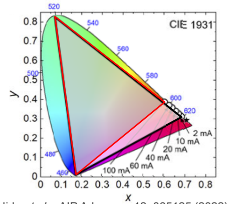
How to push the wavelength to the Red ?

EPFL

- Red-LEDs on GaN/sapphire template

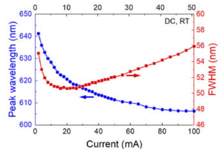
At high current density, due to the field screening and band filling, the emission is barely red (610 nm)





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

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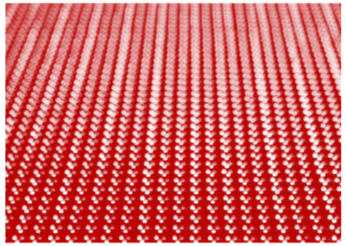
Outline

EPFL

Part II: Can we make red LEDs from III-nitrides?

- How to push the wavelength to the red?

- Less strain for more indium



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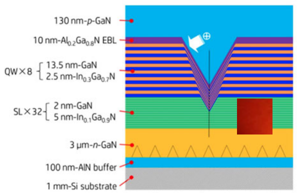
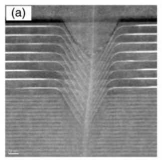
Less strain for more indium

EPFL

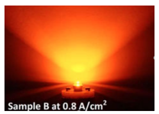
- Strain relaxation from surface morphology and growth on Si(111)

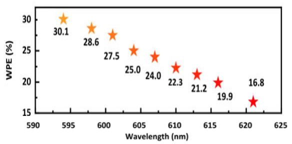


- Growth on silicon
  - ⇒ tensile strain
- Large V-pits
  - ⇒ strain relaxation
  - ⇒ Lateral hole injection



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.

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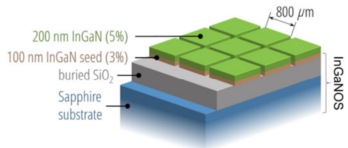
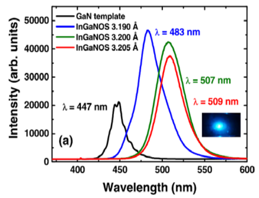
Less strain for more indium

EPFL

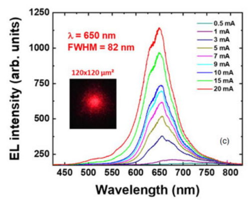
- Pseudo-InGaN substrate (InGaNOS)



- 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

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

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

InGaNOS discontinued

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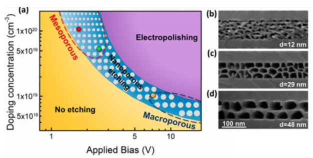
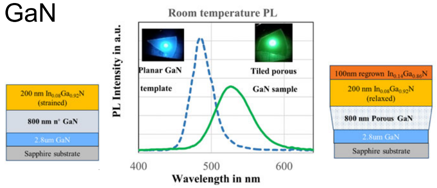
Less strain for more indium

EPFL

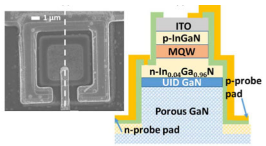
- Strain relaxation from porous GaN

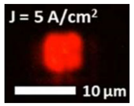


C. Zhang *et al.*, ACS Photonics 2, 980 (2015) – Yale



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. and Porotech

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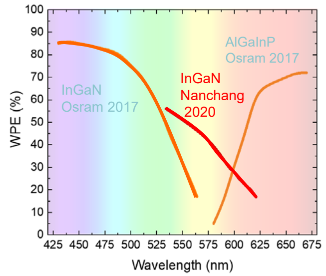
Conclusion

EPFL

WPE of InGaN based LEDs – state of the art



InGaN red LEDs

- WPE ≈ 17% at 621 nm

Large devices 1x1 mm^2

Nanchang U.

- WPE ≈ 2 % at 630 nm

Small devices 25x25 µm^2

KAUST + National Taiwan U.

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

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