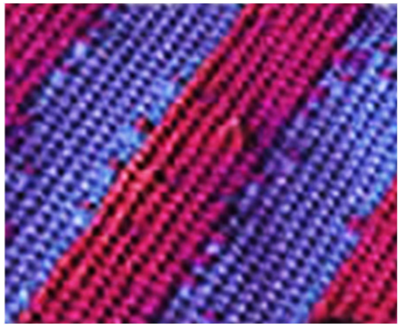


Growth

Nicolas Grandjean

Institute of Physics
EPFL - Switzerland

nicolas.grandjean@epfl.ch

Content

Growth IV: III-V nitrides

- **GaN homoepitaxy:** kinetic roughening
- **GaN heteroepitaxy:** substrates, dislocations, and polarity
- **InGaN alloys**

Content

Growth IV: III-V nitrides

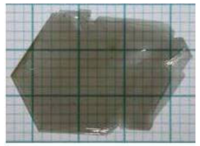
- **GaN homoepitaxy:** kinetic roughening
- **GaN heteroepitaxy:** substrates, dislocations, and polarity
- **InGaN alloys**

GaN homoepitaxy

- GaN substrate

  Lack of GaN bulk native substrates

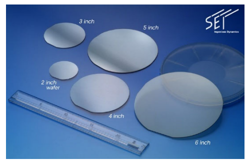
  produced at Unipress (PL) by high pressure growth - 1 cm²

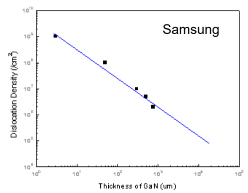


Free-standing (FS) GaN substrates:

HVPE growth on GaAs or sapphire, followed by substrate removal or by amonothermal growth

- Dislocation density: $\leq 10^6$ cm^{-2}
- Size: currently 4 in., 6 in. demonstrated

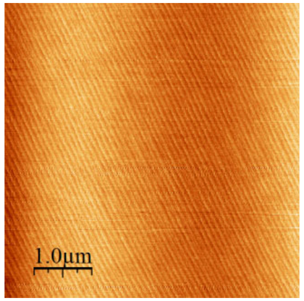


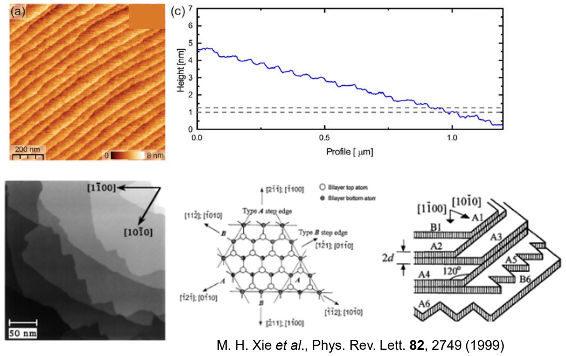


GaN homoepitaxy

EPFL

GaN on (0001) FS GaN substrate





M. H. Xie *et al*., Phys. Rev. Lett. **82**, 2749 (1999)

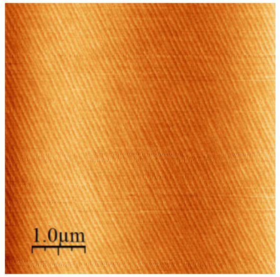
The surface exhibits monolayer or bilayer height step-edges depending on growth conditions

GaN homoepitaxy

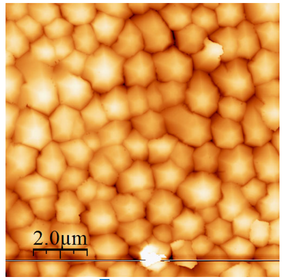
EPFL

Growth of GaN on FS GaN substrate

MOVPE



NH_3-MBE

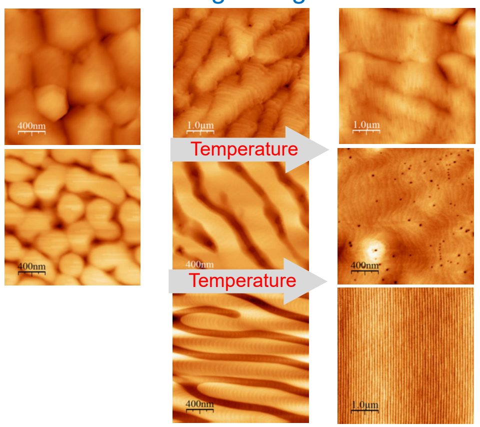


Kinetic roughening

GaN homoepitaxy

EPFL

ESB-induced surface roughening: hillocks and meandering



NH_3-MBE

Plasma-MBE

MOVPE

Content

EPFL

Growth IV: III-V nitrides

- **GaN homoepitaxy:** kinetic roughening
- **GaN heteroepitaxy:** substrates, dislocations, and polarity
- **InGaN alloys**

GaN heteroepitaxy

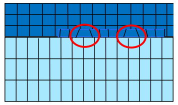
EPFL

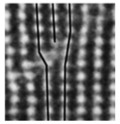
The substrate: sapphire

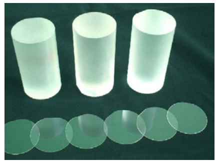
GaN technology has been developed on sapphire from the 80's

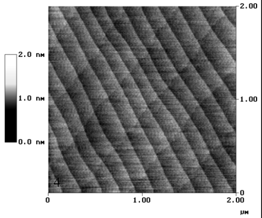
Lattice mismatch to GaN

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









Sapphire (0001) is the most commonly used substrate (up to *8 in.)*

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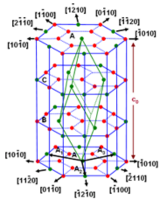
GaN heteroepitaxy

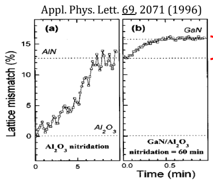
EPFL

The substrate: sapphire

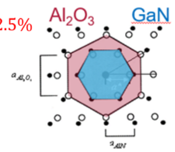
Sapphire nitridation (exposure to NH_3) ⇨ formation of AlN

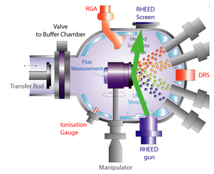


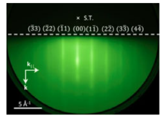
Sapphire crystal structure



$\frac{\Delta a}{a} = 2.5\%$







Aluminum hexagonal sublattice lying in the c-plane of Al_2O_3 crystal

⇨ AlN layer at the surface upon NH_3 exposure at high temperature

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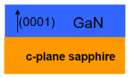
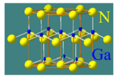
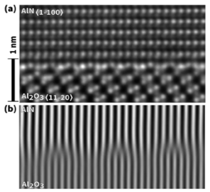
GaN heteroepitaxy

EPFL

GaN polarity

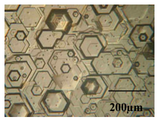




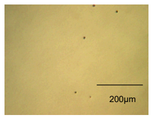


Aluminum oxynitride layer controls the polarity of GaN epilayer

⇒ Ga polarity allows growing high purity GaN layers



16 µm thick GaN, N polar



16 µm thick GaN, Ga polar

surface chemistry controls the polarity

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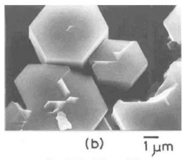
GaN heteroepitaxy

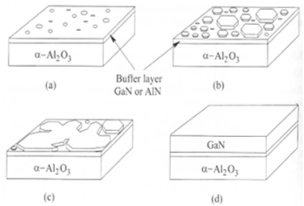
EPFL

GaN on sapphire substrate

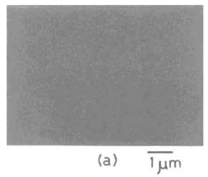
The low-temperature buffer layer



w/o LT buffer



H. Amano *et al.* , Appl. Phys. Lett. 48, 353 (1986)



w LT buffer

Two-step growth procedure:

1) Buffer layer (25 nm) at low-temperature (500°C)
2) Growth at high-temperature (1050-1100°C)

➡ GaN buffer layer to improve the crystal quality

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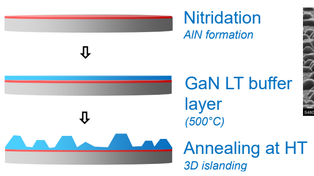
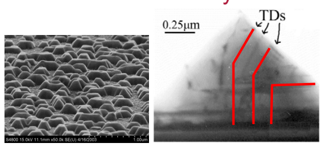
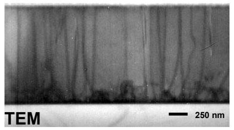
GaN heteroepitaxy

■ GaN on sapphire

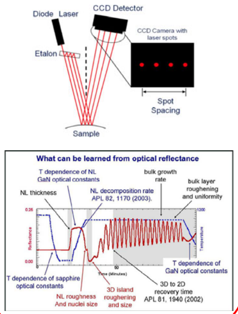
3D islands to reduce the dislocation density







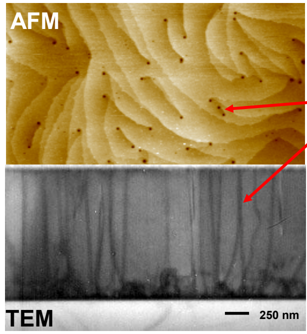
In situ growth monitoring



Dislocation density reduced from 10^{10} to below 10^{8} cm^{-2}

GaN heteroepitaxy

Dislocation density = $5x10^{7}$-10^{8} cm^{-2} in commercial blue LEDs



Surface

Dislocations

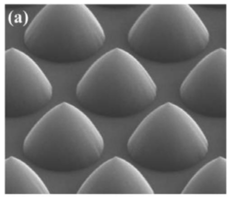
Threading dislocations are supposed to impact the active region of LEDs/LDs

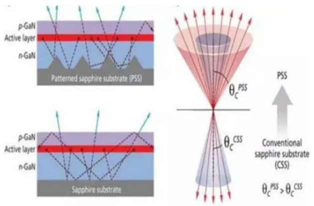
⇒ low impact in blue LEDs

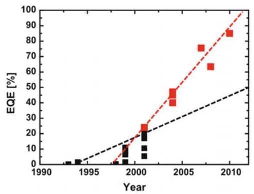
Cross-section

GaN heteroepitaxy

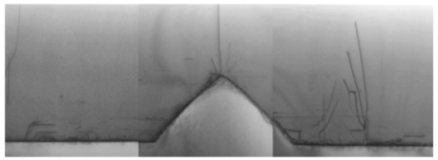
■ GaN on patterned sapphire substrate (PSS)







Progress of the EQE is a combination of better materials quality and improved light extraction efficiency



GaN heteroepitaxy

■ GaN on Silicon substrate

Lattice mismatch

Al_2O_3 (0001): +16 %

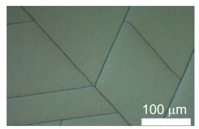
6H-SiC (0001): -3.5 %

Si (111): -17 %

(GaAs/Si: +4 %)

Thermal expansion coefficient mismatch

Si (111): 115 % ⇨ tensile strain



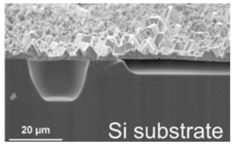
Epilayer cracking when cooling down the wafer from 1000°C to room-temperature

GaN heteroepitaxy

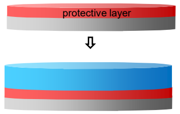
EPFL

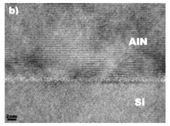
■ GaN on Silicon substrate

Silicon surface is decomposed when exposed to Ga and NH_3 at high temperature



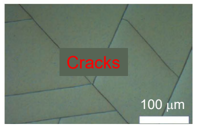
A. Dadgar et al. Journal of Crystal Growth 248, 556 (2003)





phys. stat. sol. (a) 188, No. 2, 501 (2001)

Dislocation density $>10^{10}$ cm^{-2}



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GaN heteroepitaxy

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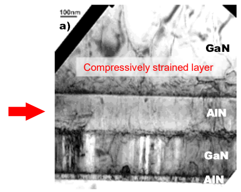
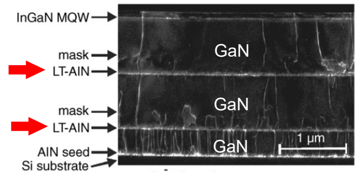
■ GaN on Silicon substrate

Strain engineering to avoid layer cracking

compressive strain is introduced during growth



D. Ducateau et al., IEEE Electron Device Letter 27, 1 (2006)



A. Dadgar et al., Journal of Crystal Growth 248, 556 (2003)

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GaN heteroepitaxy

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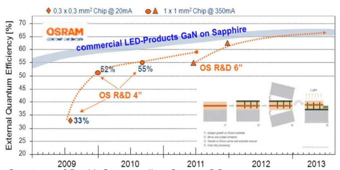
■ GaN on silicon substrate

Blue LEDs on Si



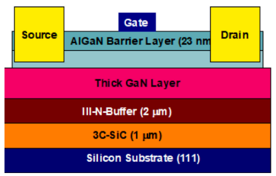
Courtesy of Dr. U. Steegmüller, Osram-OS

2015

GaN on Silicon: typ. ~110 lm/W

GaN on Sapphire: typ. ~118 lm/W

GaN-on-Si for electronics



J. Ajayan *et al.*, Mat. Sc. Semicond. Processing 151, 106982 (2022)

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Content

EPFL

Growth IV: III-V nitrides

- **GaN homoepitaxy:** kinetic roughening
- **GaN heteroepitaxy:** substrates, dislocations, and polarity
- **InGaN alloys**

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InGaN alloys

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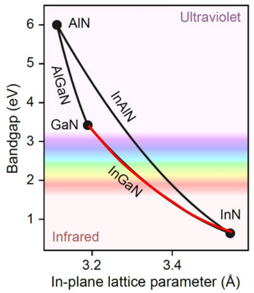
Materials issues



- InN bandgap of 0.65 eV

⇒ InGaN alloy covers the whole visible spectrum

Severe drawbacks:

- Very large lattice mismatch with GaN (11%)
- Poor quality for high In content
- Huge piezoelectric polarization field in InGaN/GaN QWs (16 MV/cm for InN/GaN QWs)
- Poor thermal stability for $x > 0.2$

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InGaN alloys

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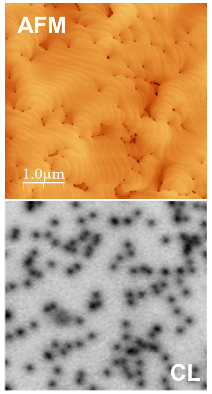
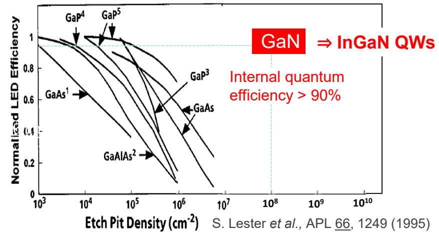
Efficiency of blue LEDs: impact of dislocations





S. Lester *et al.*, APL 66, 1249 (1995)

Is InGaN a magic alloy ?

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InGaN alloys

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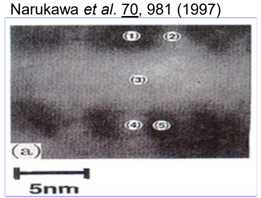
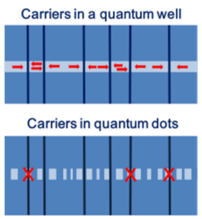
Indium clustering

Narukawa *et al.* 70, 981 (1997)



TEM image of InGaN/GaN QWs



Gérard and Weisbuch (patent 1990)

Indium-rich clusters in InGaN QWs act as quantum dots

Efficiency of LEDs : carrier localization prevents their diffusion towards dislocations

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InGaN alloys

EPFL

Indium clustering

TEM image of InGaN/GaN QWs grown by MOCVD

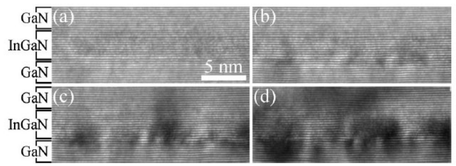

FIG. 3. (0002) lattice fringe images showing strain contrast evolution in an $In_{0.22}Ga_{0.78}N$/GaN MQW during exposure to a 200 kV electron beam flux of ~35 A cm^{-2} after: (a) 20, (b) 220, (c) 420, and (d) 620 s.

T. Smeeton *et al*, APL 83, 5419 (2003)

⇨ Indium clustering induced by e-beam irradiation during TEM observation

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InGaN alloys

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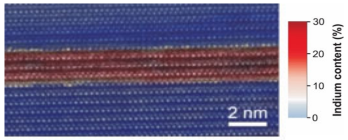
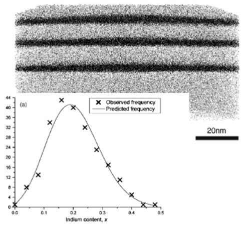
InGaN is a perfectly disordered alloy

TEM - InGaN/GaN QW



No evidence In-rich clusters

Atom probe tomography - InGaN/GaN QWs



M.J. Galtrey *et al.*, JAP 104, 013524 (2008)

The indium distribution correspond to that of a random alloy: no clustering

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InGaN alloys

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Indium clustering

Journal of Crystal Growth 603 (2023) 127033

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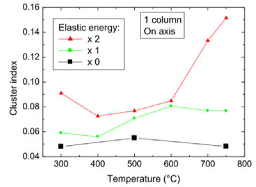
Why and how In composition fluctuations appear in InGaN?

Jean-Yves Duboz *, Wanda Isnard, Jesus Zuniga-Perez, Jean Massies

Université Côte d'Azur, CNRS, CRHEA, 06560 Valbonne, France



Monte Carlo simulations:

In clusters may form for high indium content alloys

⇒ Enhanced by strain

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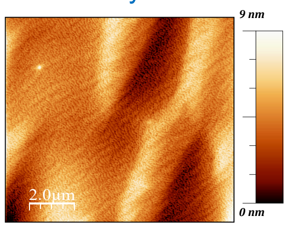
InGaN alloys

EPFL

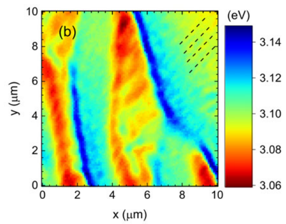
InGaN thick layers on FS GaN

FS GaN substrate

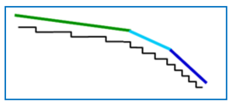


100-nm-thick InGaN epilayer with an indium content of 8.6%

RT near-field optical microscopy



Appl. Phys. Lett. 112, 032106 (2018)



- Indium content depends on surface misorientation
- the higher the misorientation the lower the In content

G. Franssen *et al.*, phys. stat. sol. (c) 5, 1485 (2008)

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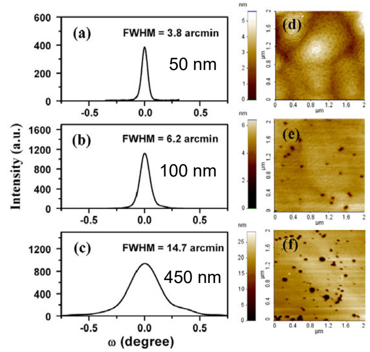
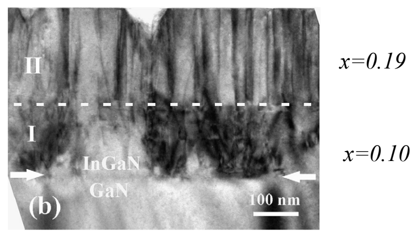
InGaN alloys

EPFL

InGaN thick layers on sapphire





H. Wang *et al.*, Physica B 405 4668 (2010)

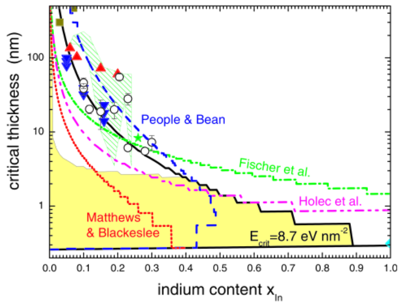
- Formation of V-pits when growing thick InGaN layers on GaN/sapphire template.
- Increase of In content when the layer is relaxed.

28

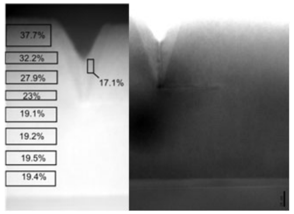
28

InGaN alloys

■ Critical thickness of InGaN layers on GaN



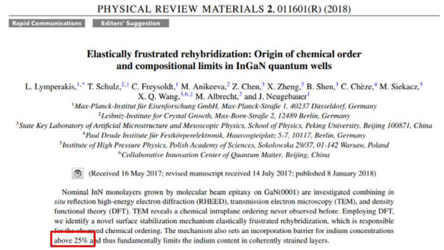
M. Pristovsek, Appl. Phys. Lett. **102**, 242105 (2013)



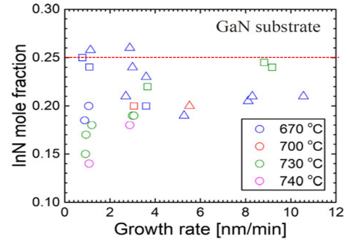
- V-shape defects
- Dislocation and stacking faults
- Pulling effect (due to strain relaxation)

InGaN alloys

■ Maximum indium content for coherent InGaN on GaN


PHYSICAL REVIEW MATERIALS 2, 011601(R) (2018)

Elastically frustrated rehybridization: Origin of chemical order and compositional limits in InGaN quantum wells



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

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

Z. Liu *et al.*, JCG 508, 58 (2019) - Amano's group

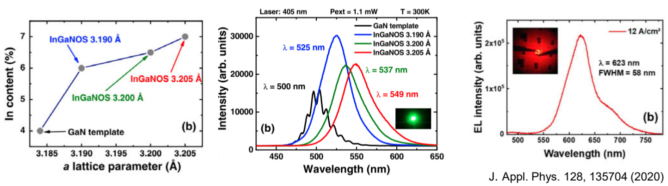
InGaN alloys

■ Indium composition strongly depends on strain

APPLIED PHYSICS LETTERS **110**, 262103 (2017)

Enhanced In incorporation in full InGaN heterostructure grown on relaxed InGaN pseudo-substrate

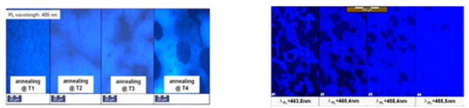
A. Even,[1] G. Laval,[1] O. Ledoux,[2] P. Ferret,[1] D. Sotta,[2] E. Guiot,[2] F. Levy,[1] I. C. Robin,[1] and A. Dussaigne[1,a)]
[1]University Grenoble Alpes, CEA, LETI, MINATEC Campus, F-38054 Grenoble, France
[2]Soitec S.A., F-38190 Bernin, France



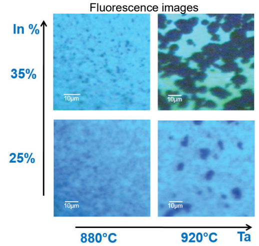
J. Appl. Phys. 128, 135704 (2020)

InGaN alloys

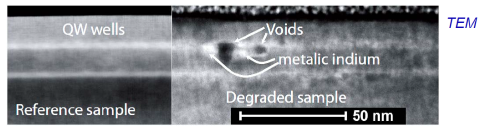
■ Thermal stability of high In content InGaN QWs



D. Queren *et al.*, JCG 311, 2933 (2009)



2 hour annealing to reproduce the thermal budget of the top cladding



Courtesy of F. Ivaldi and S. Kret, IFPAN, Warsaw – FP7 -Rainbow project

Green laser (LED) QWs require In content >25%

⇨ p-type layer must be grown at LT (<900°C)