

Crystal Growth: Physics, Technology and Modeling

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Lecture 3. Epitaxy of semiconductor structures

<http://www.unipress.waw.pl/~stach/cg-2022-23>

Epitaxy of semiconductor structures

Michał Leszczyński

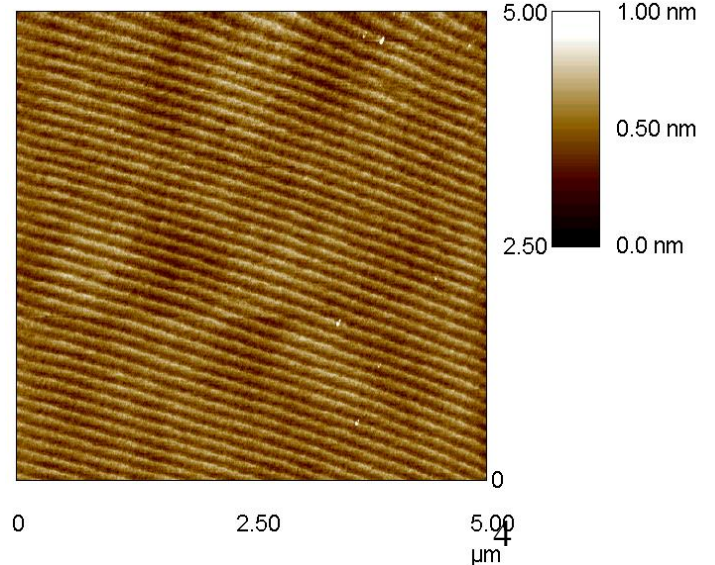
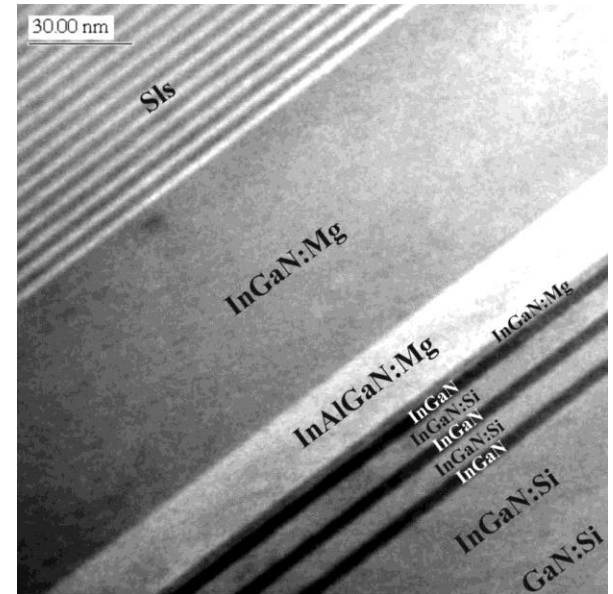
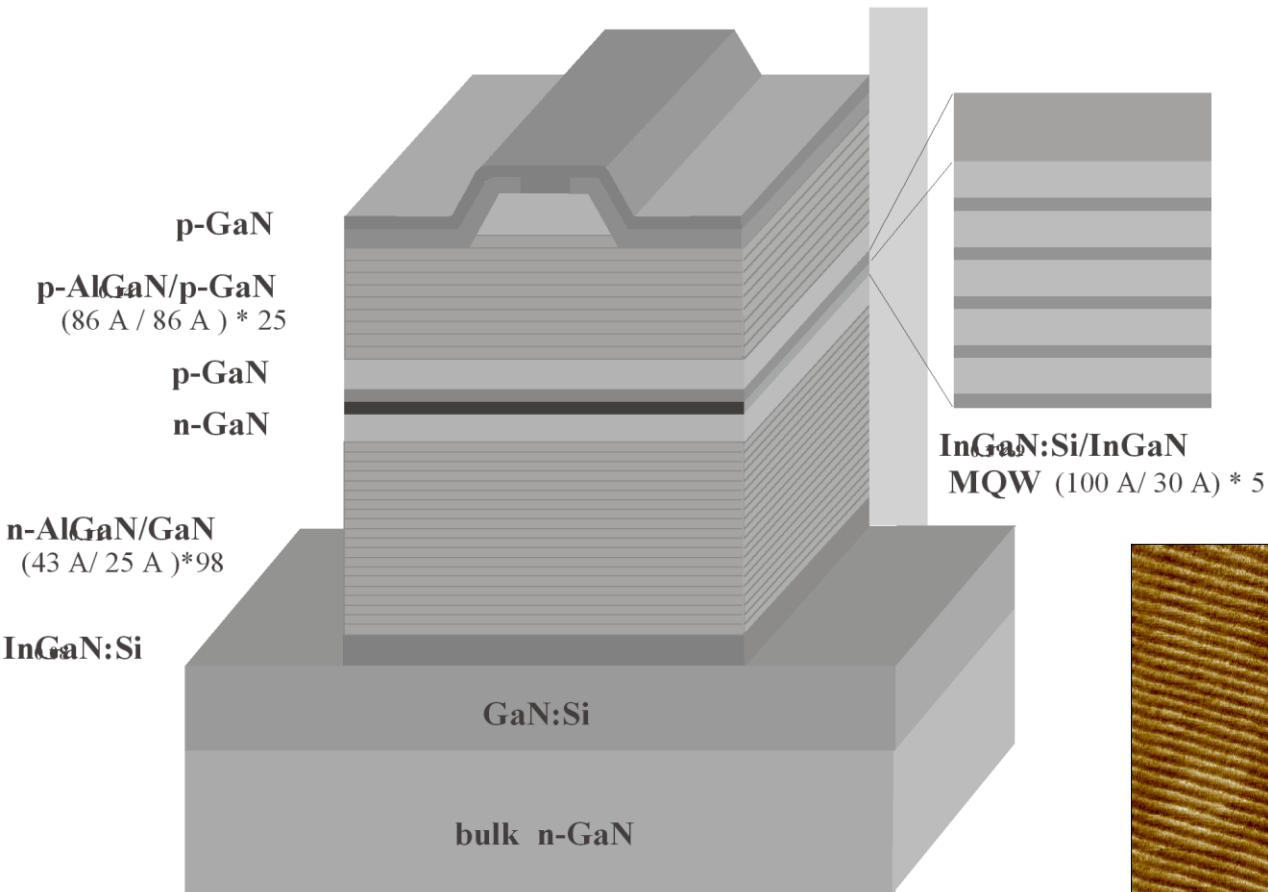
Instytut Wysokich Ciśnień PAN

And TopGaN

Outline

1. Epitaxial reactors
2. Substrate off-cut
3. Problem of lattice mismatch
4. Non-lateral growth
5. Atom incorporation efficiency
6. Examples of MOVPE growth: InGaN Quantum Wells

What is to be grown? For example, blue LD.

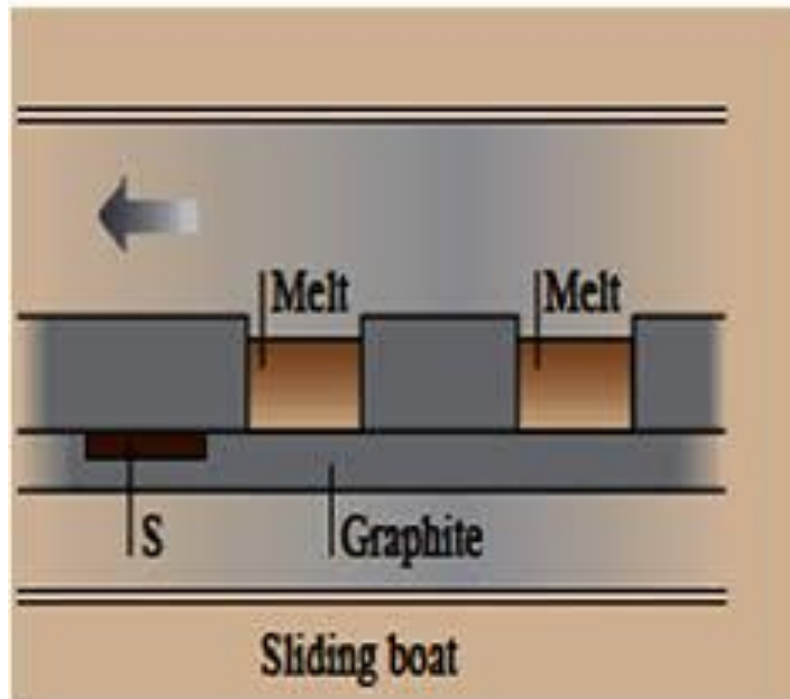


What we need from epitaxy:

1. Proper chemical composition (including doping)
2. No defects (dislocations, vacancies, etc)
3. Perfect interfaces
4. Perfect uniformity across the wafers

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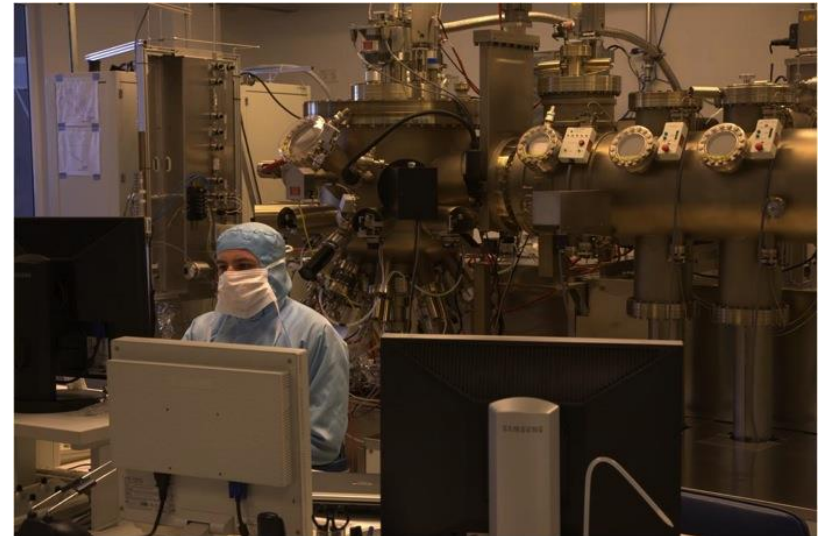
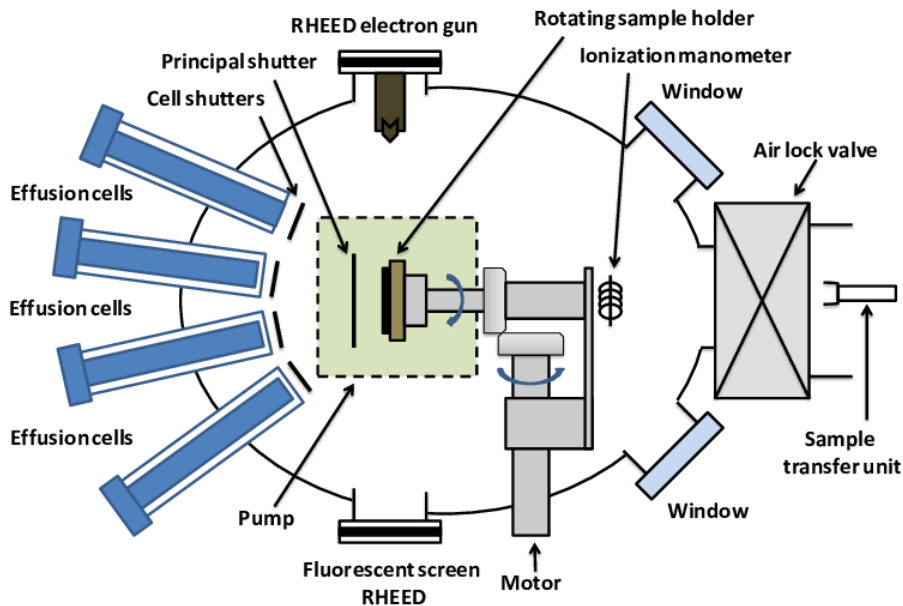
Liquid Phase Epitaxy (LPE)



**Technology abandoned
by industry**

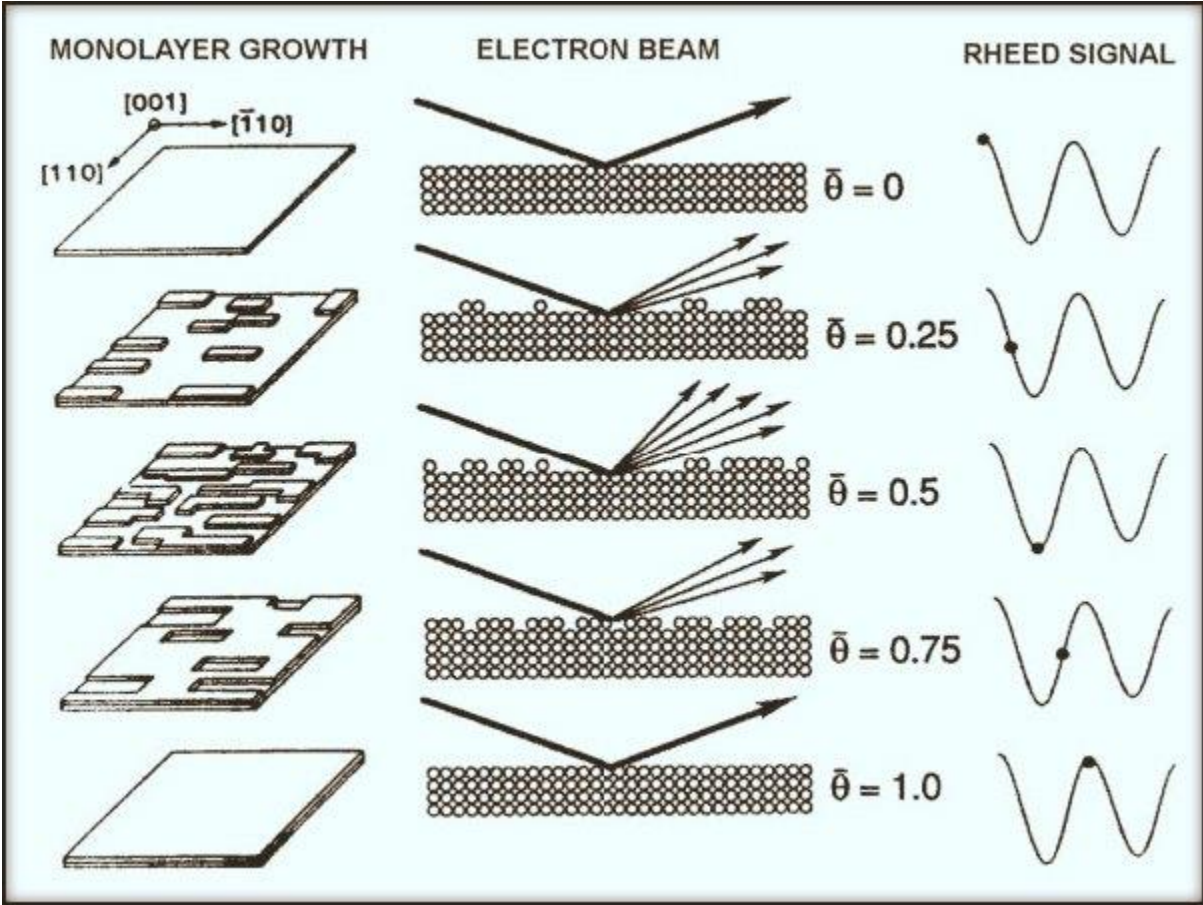
- **Only small wafers**
- **Not perfect interfaces**
- **Not highest purity**

Molecular Beam Epitaxy (MBE)

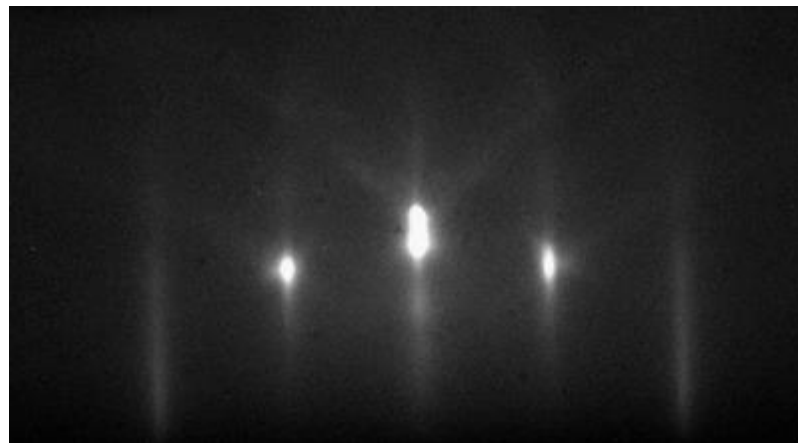
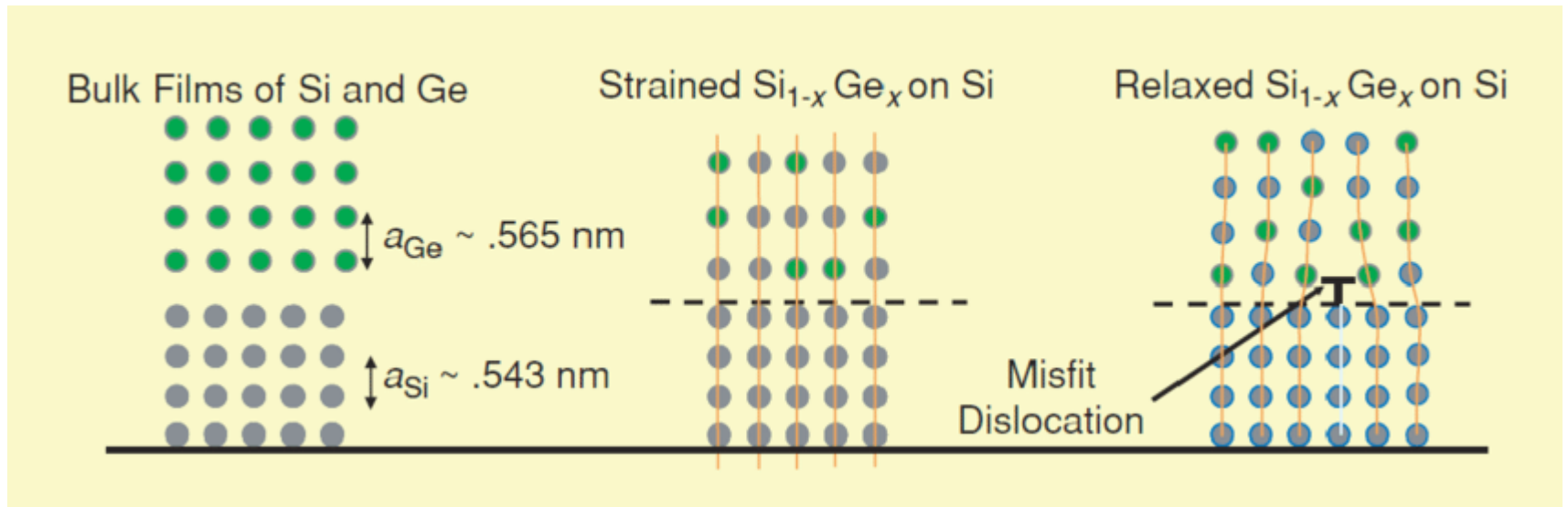


- + High purity, perfect interfaces, no hydrogen in the system
- Costs, no multiwafer machines (one six-inch wafer)

RHEED growth rate and roughness control



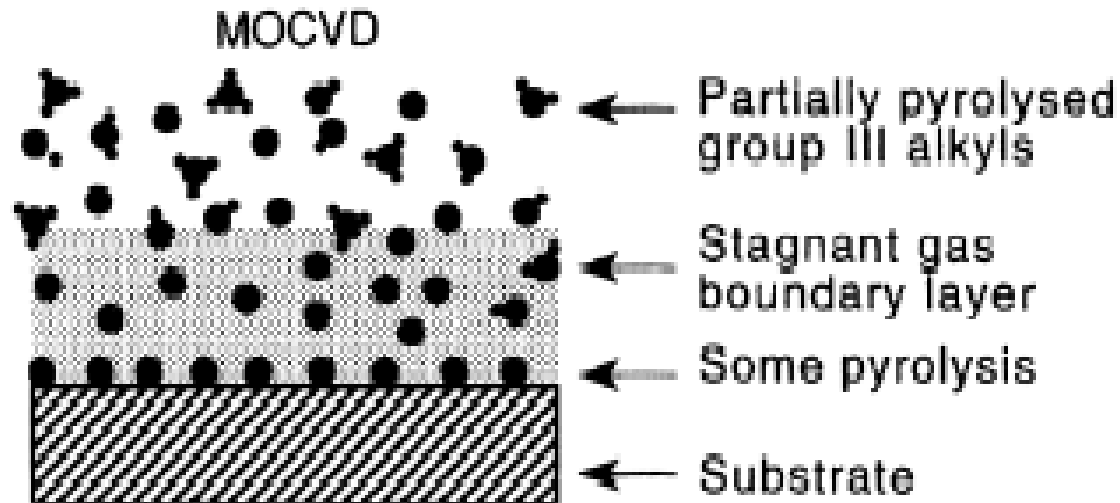
RHEED: lattice relaxation control



Metalorganic Chemical Vapour Phase Epitaxy MOVPE



$A = Ga, In, Al, B = N, As, P$



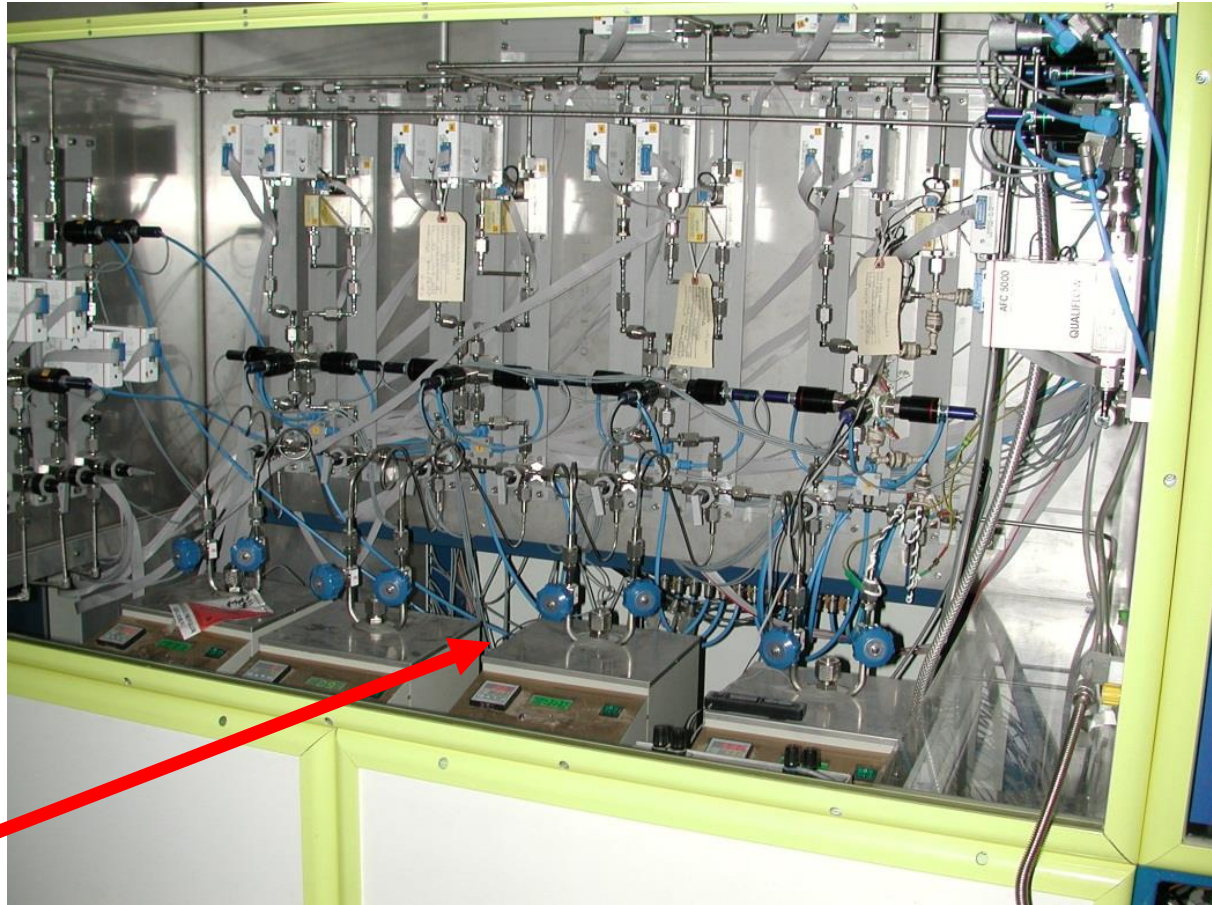
Gas panel, MOVPE, AlGaInN:Mg, Si

Purifiers

Carrier gas
N₂, H₂

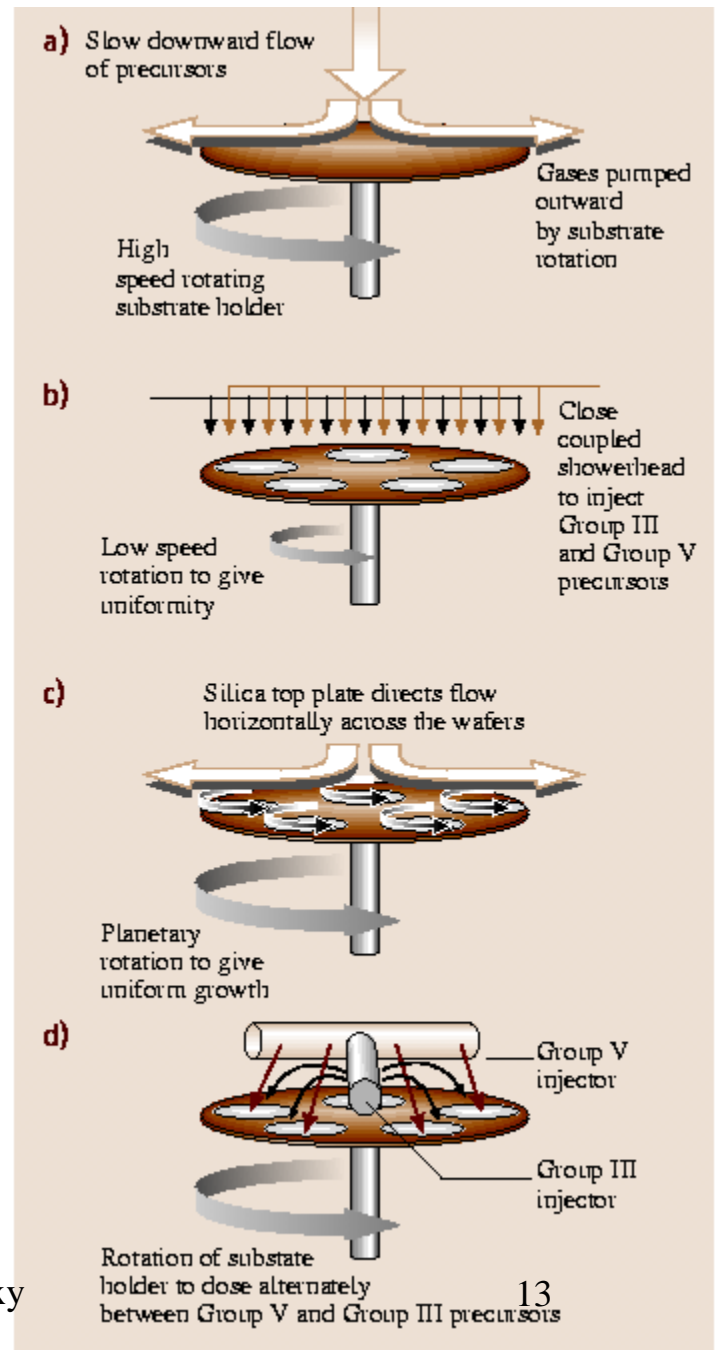
NH₃
SiH₄

Bubblers
TMGa
TEGa
TMAI
TMIn
Cp₂Mg

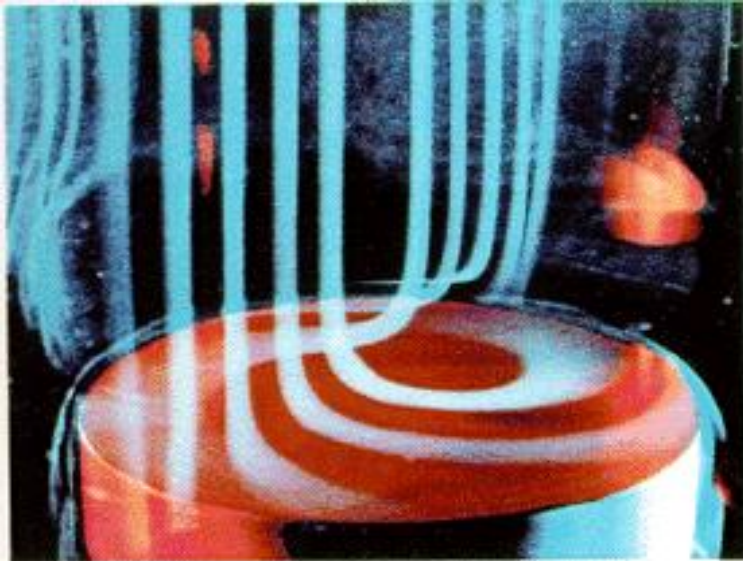


To reactor

MOVPE reactors



Turbodisc VEECO

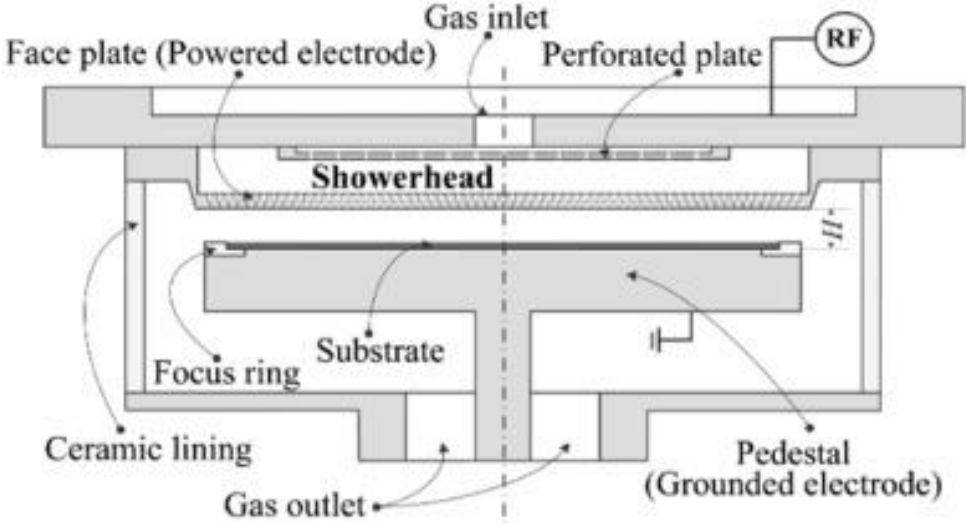


Smoke Flow Patterns in Rotating Disk System (EXPERIMENTAL).
(Data courtesy of Sandia National Laboratories)



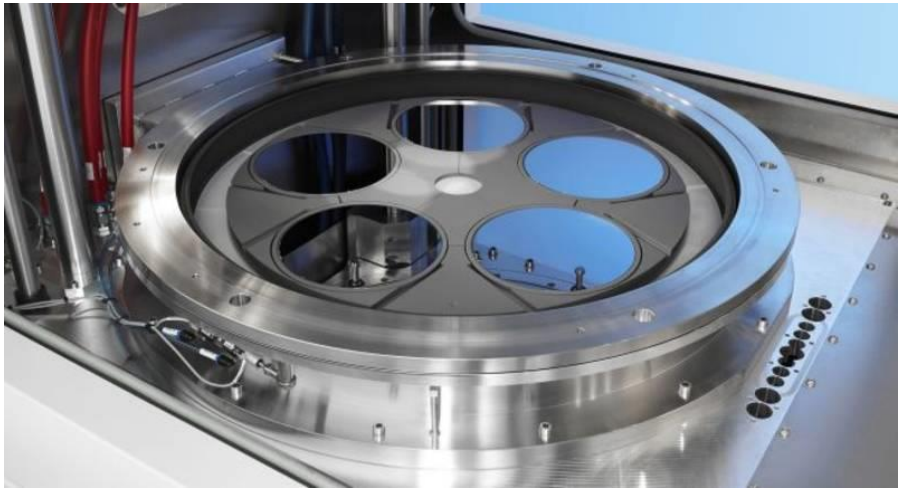
The largest system: 31 × 4", 12 × 6" and 6 × 8"

Showerhead (AIXTRON)

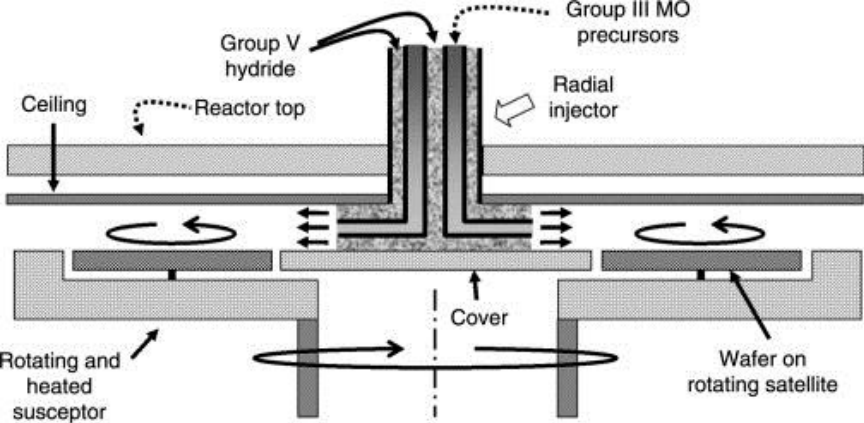


Planetary reactors

(AIXTRON)



5x8-inch

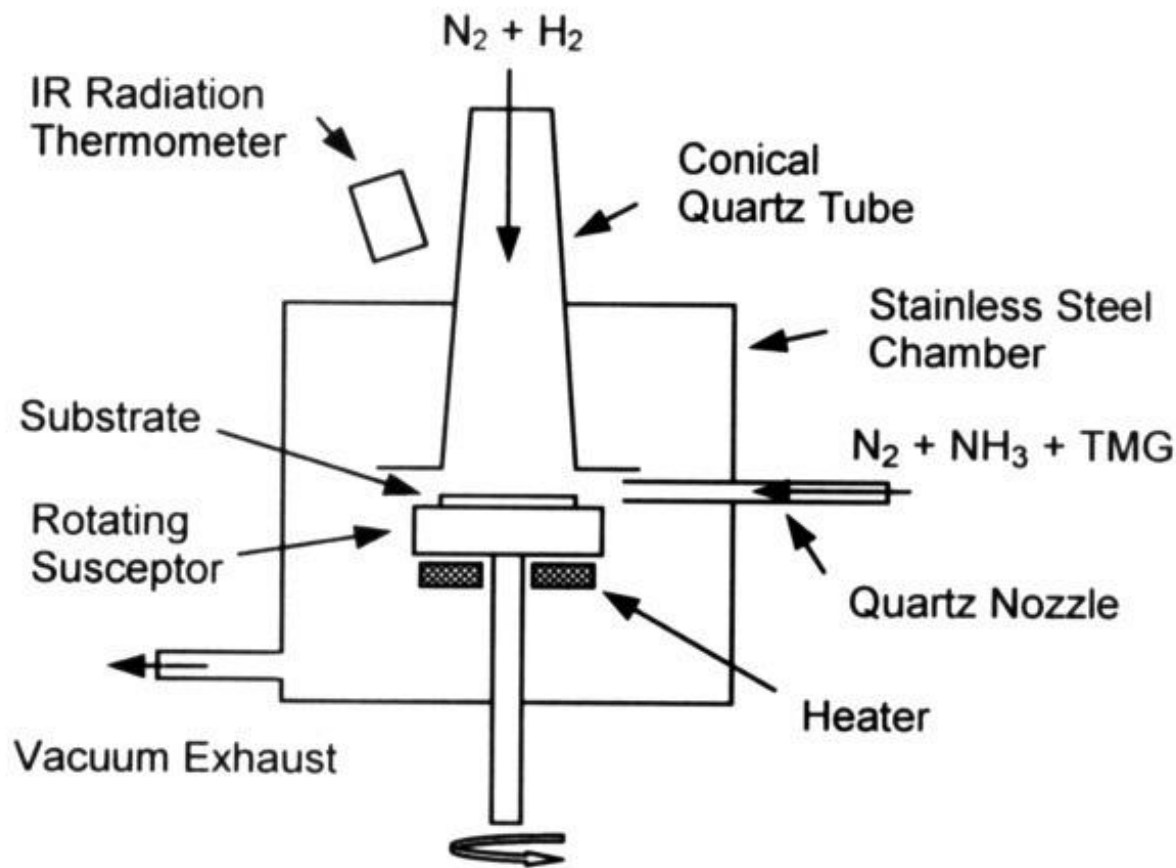


56x2-inch
19.10.2022 – Epitaxy

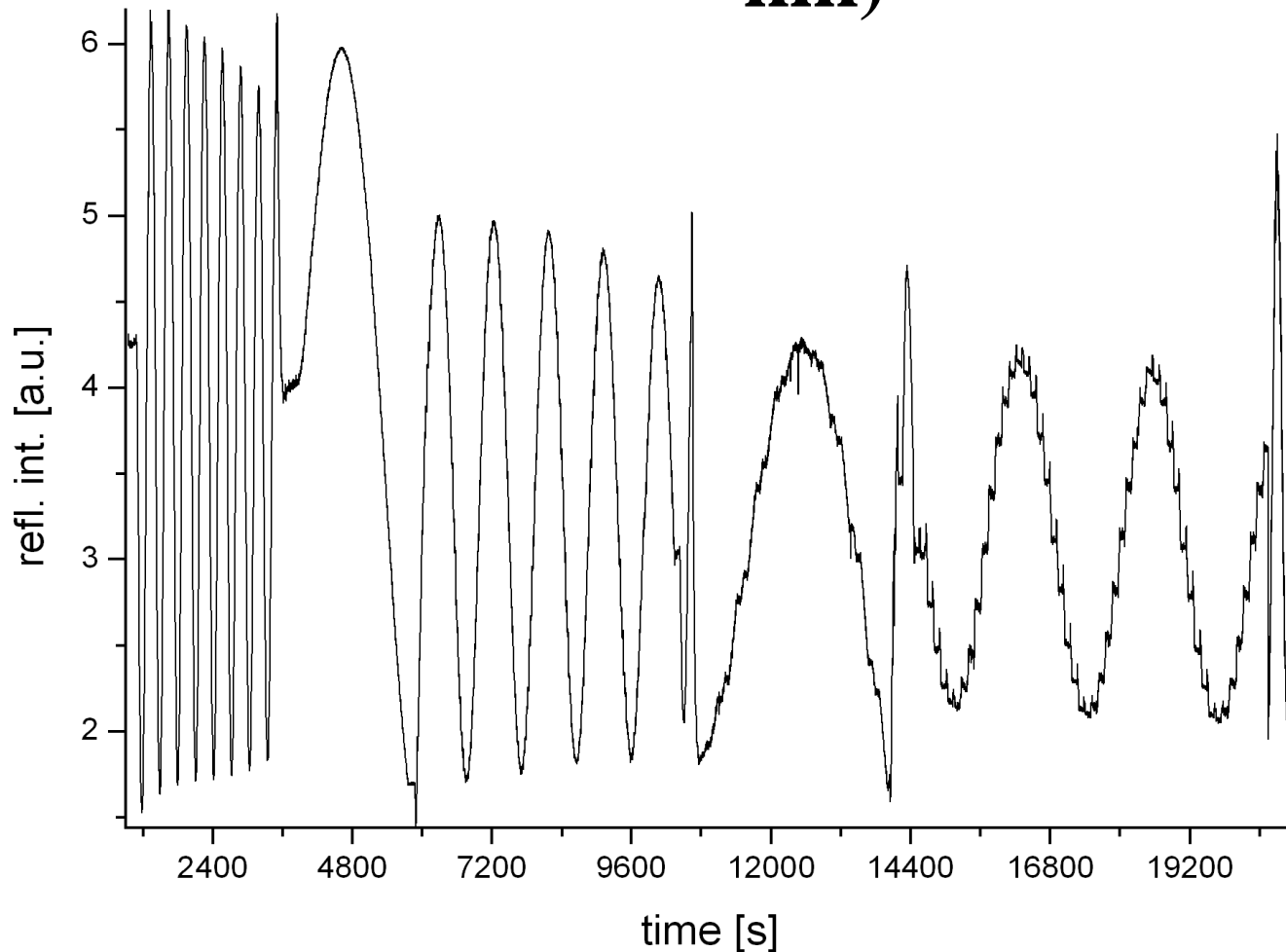


Nakamura's reactor (Nichia)

A little bit similar reactors are offered by Nippon Sanso



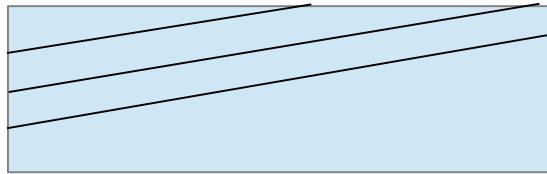
Laser reflectometry used in every MOVPE (every oscillation corresponds to 100-400 nm)



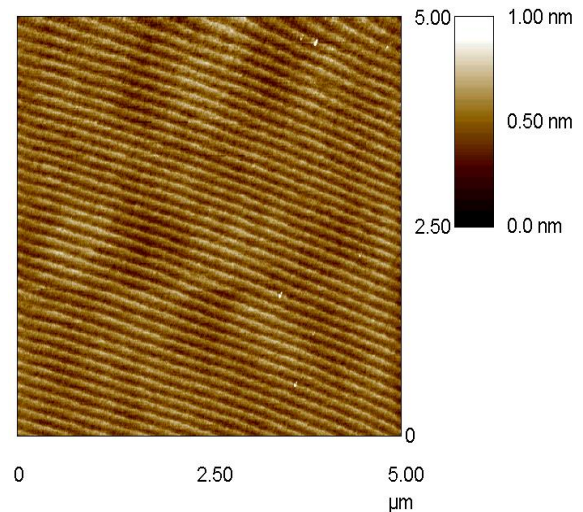
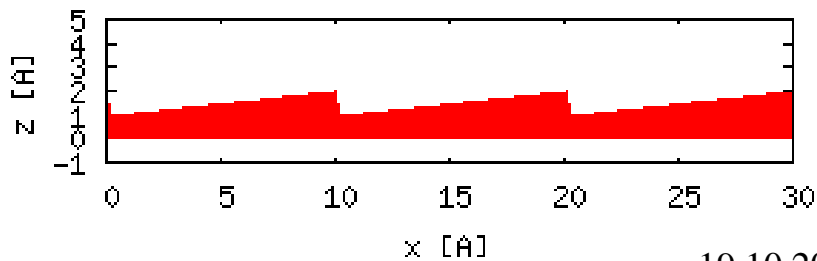
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Quantum Wells

Step-flow growth mode and substrate off-orientation

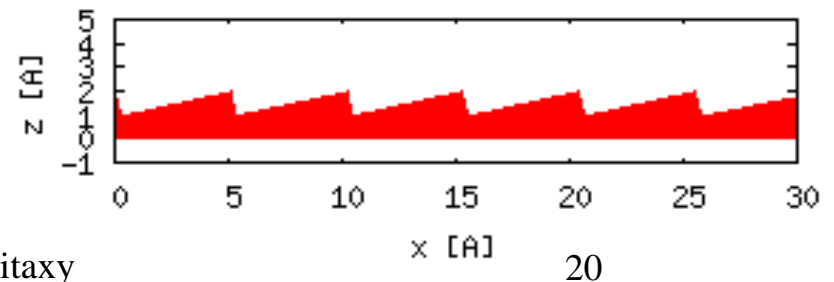
- The steps flow slower for higher off-orientation



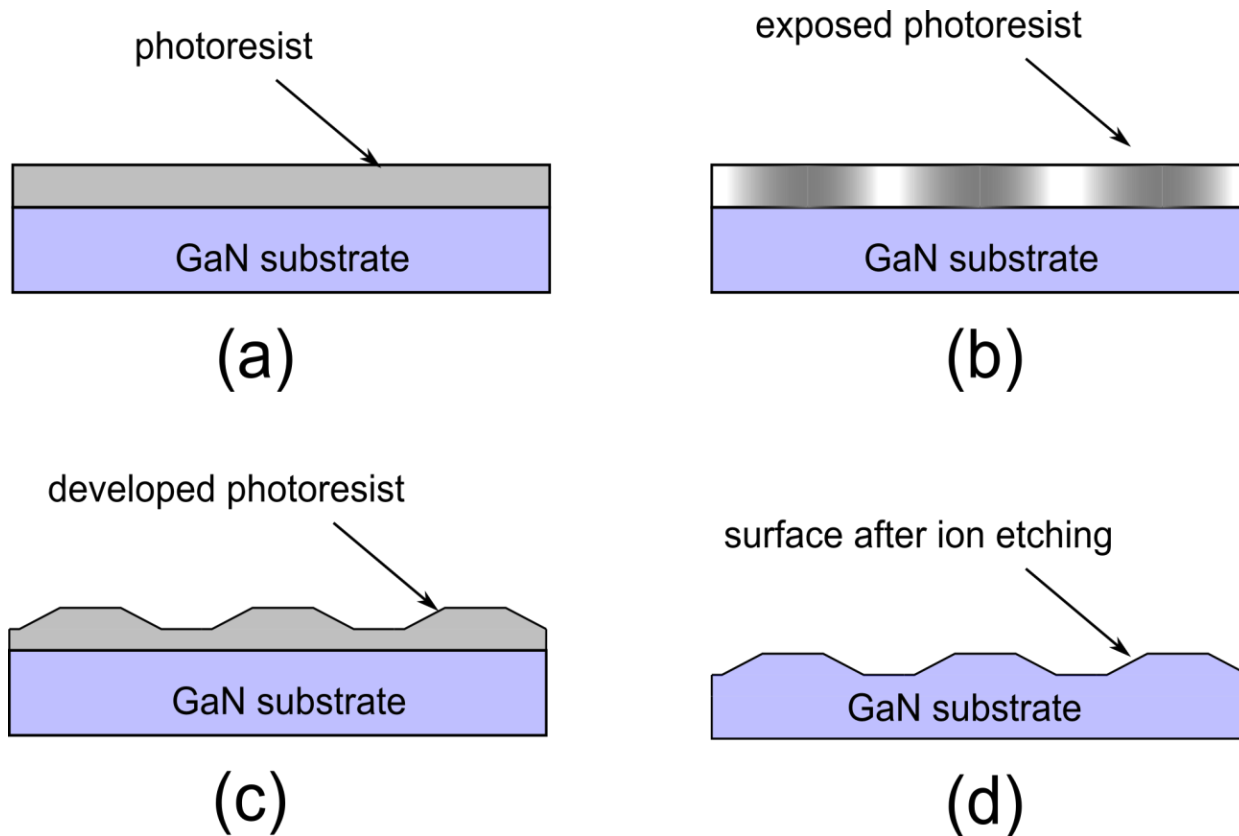
Low misorientation - fast atomic steps



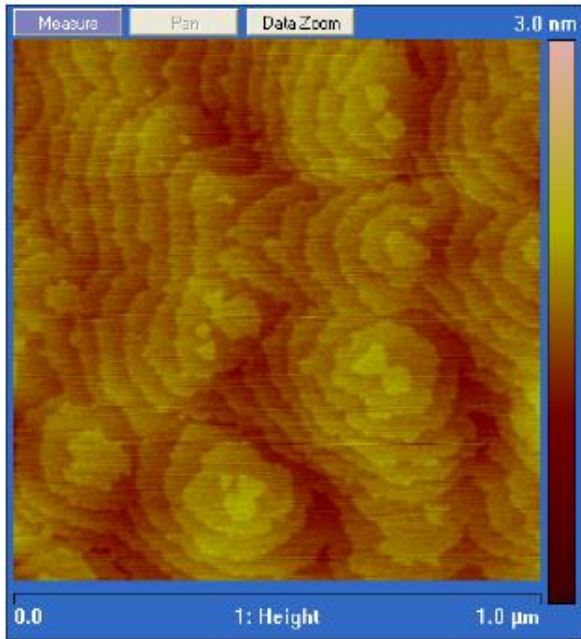
Higher misorientation - slower atomic steps



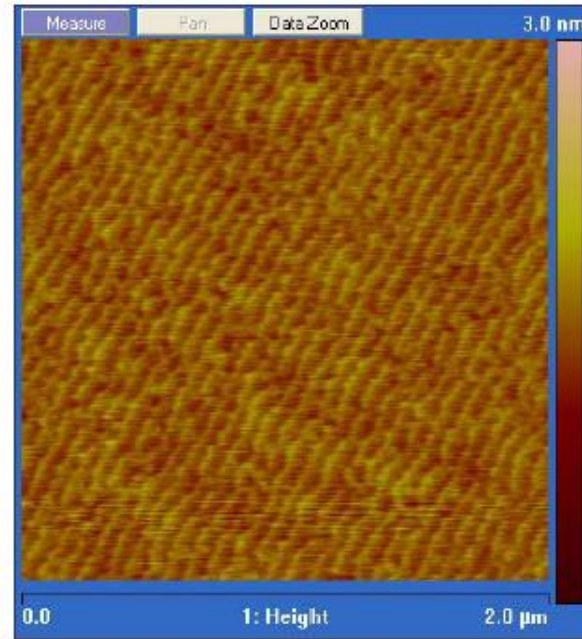
Lateral patterning



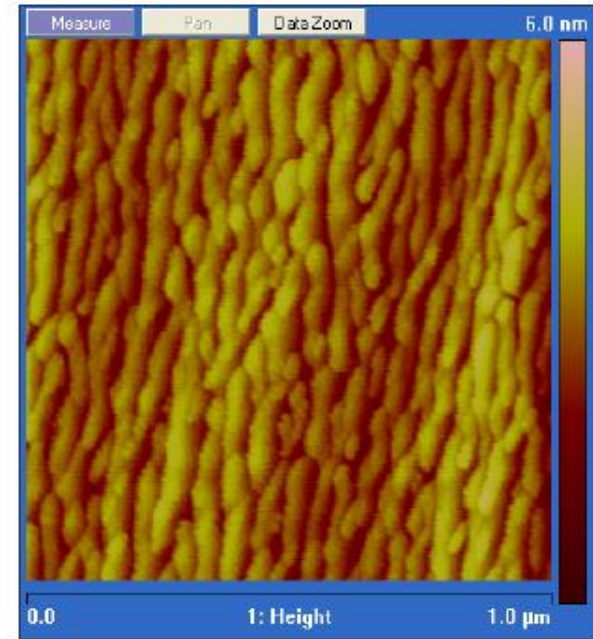
Morphology of **InGaN** layers grown on GaN substrates of different misorientation, $T_{\text{growth}} = 820^{\circ}\text{C}$



0.2 degree



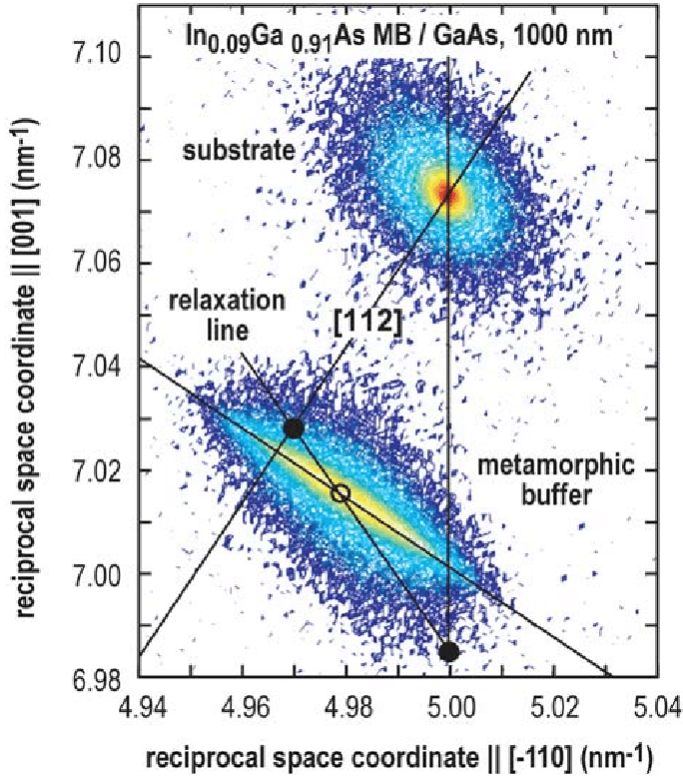
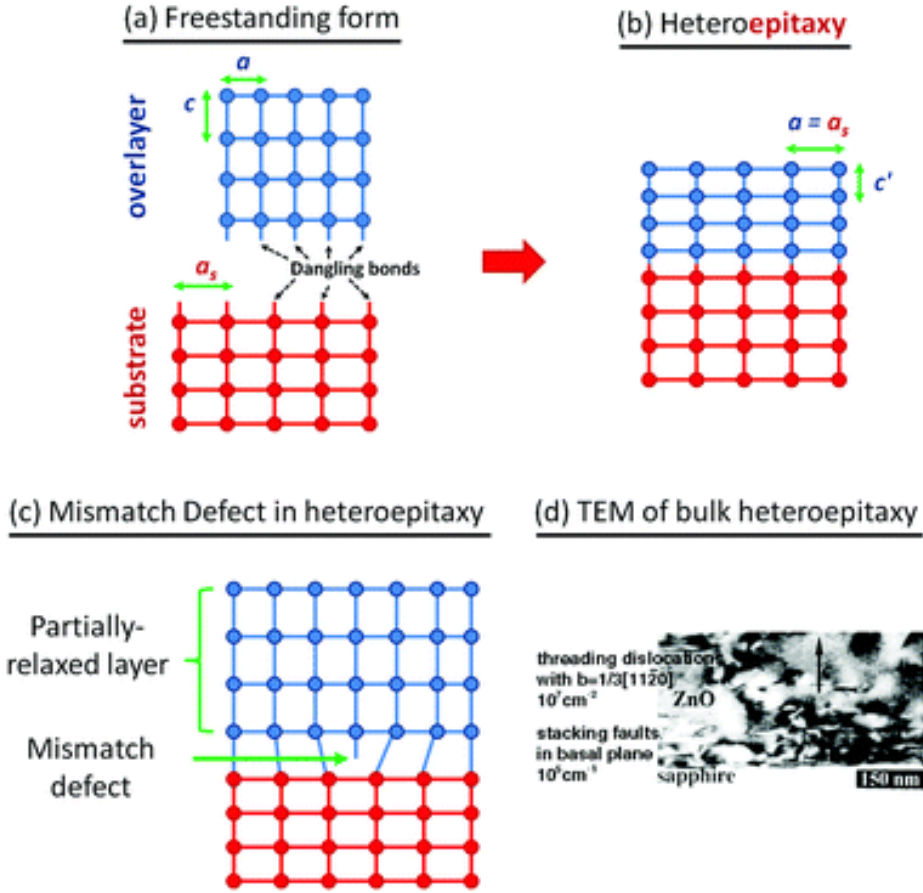
0.8 degree



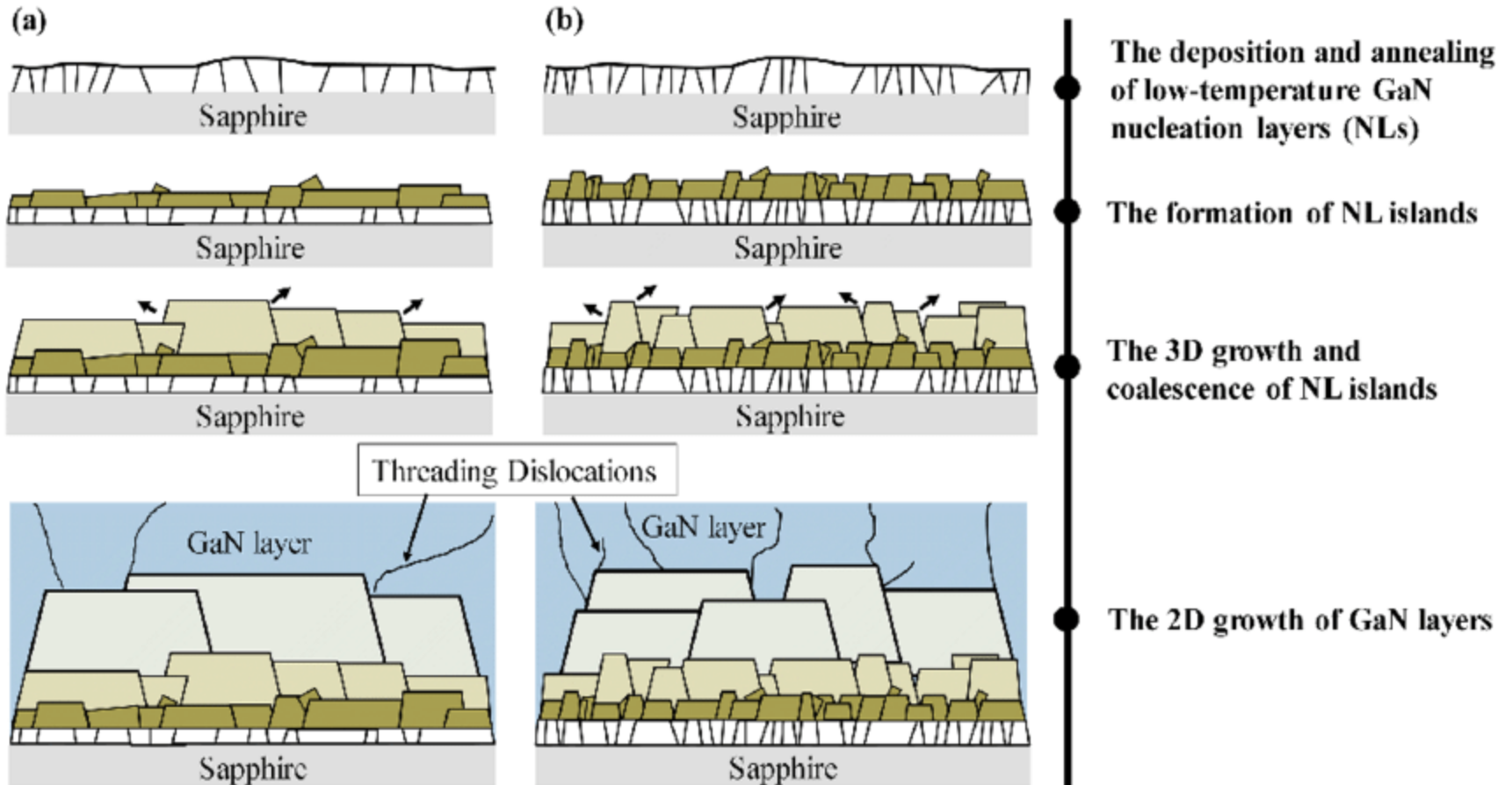
1.8 degree

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Lattice relaxation



Growth on highly mismatched substrates

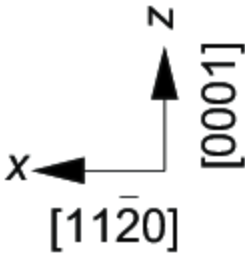
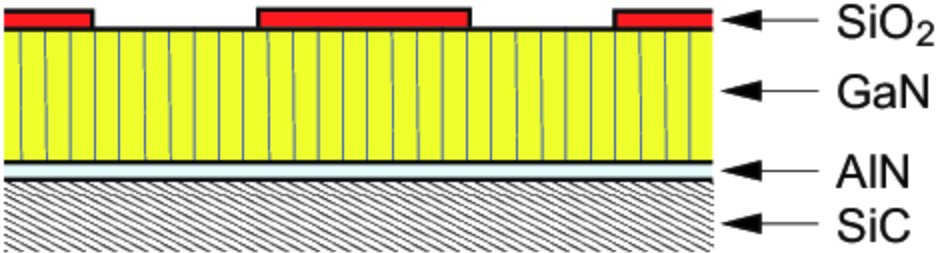


Schematic of the growth process of GaN layers for (a) samples S1 and (b) S2 with H₂ and N₂ as nucleation layer carrier gases.

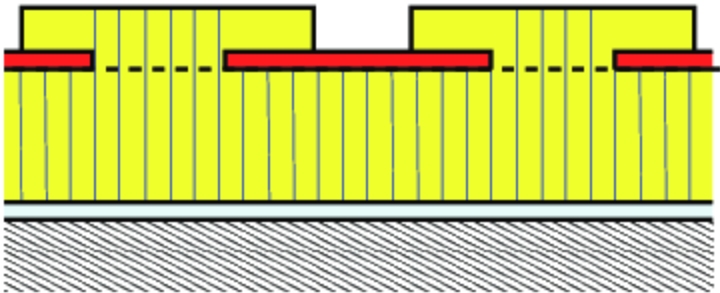
Epitaxial Lateral Overgrowth

Lateral epitaxial overgrowth (LEO)

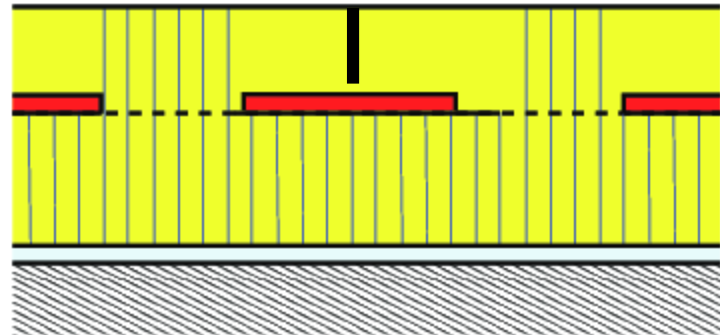
prior to overgrowth



uncoalesced structure

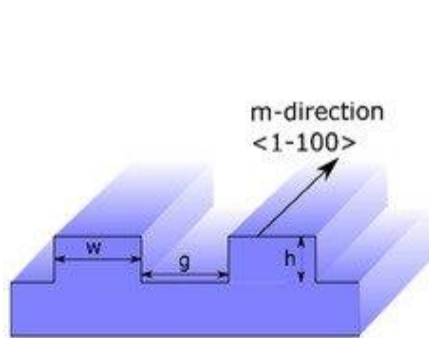


coalesced structure

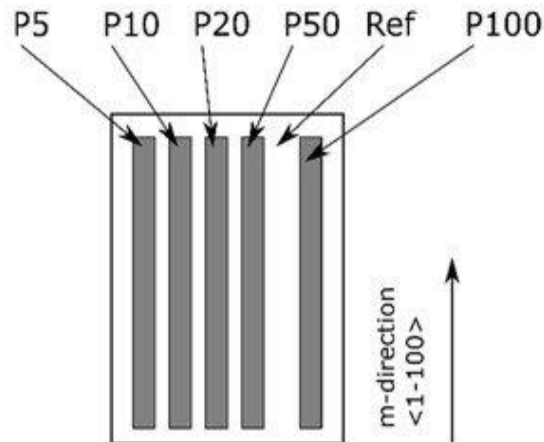


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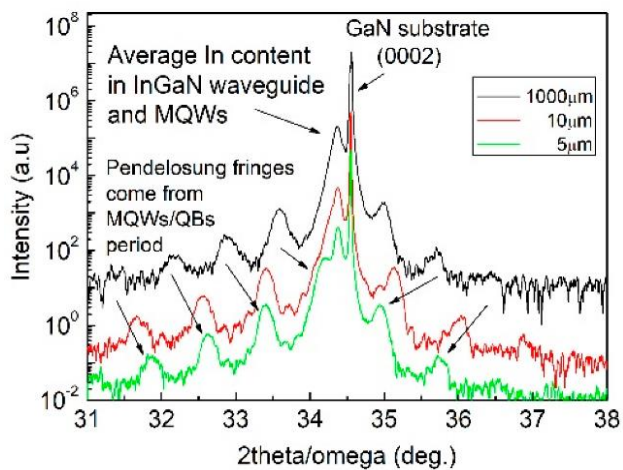


(a)



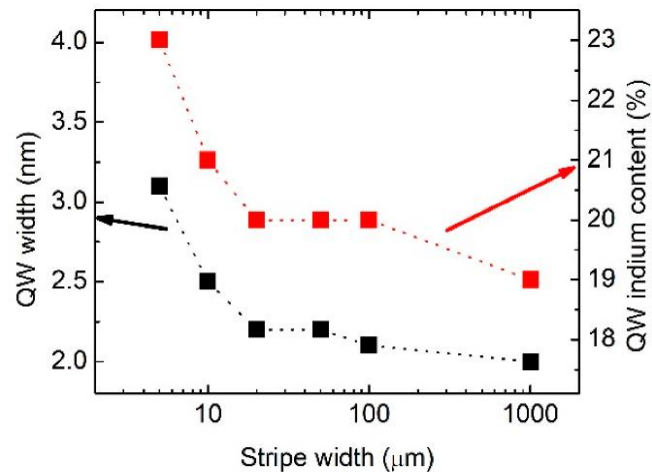
(b)

GaN:u (8 nm)
In _{0.25} Ga _{0.75} N (2 nm)
In _{0.03} Ga _{0.97} N (170 nm)
GaN:Si (0.5 μm)
GaN substrate

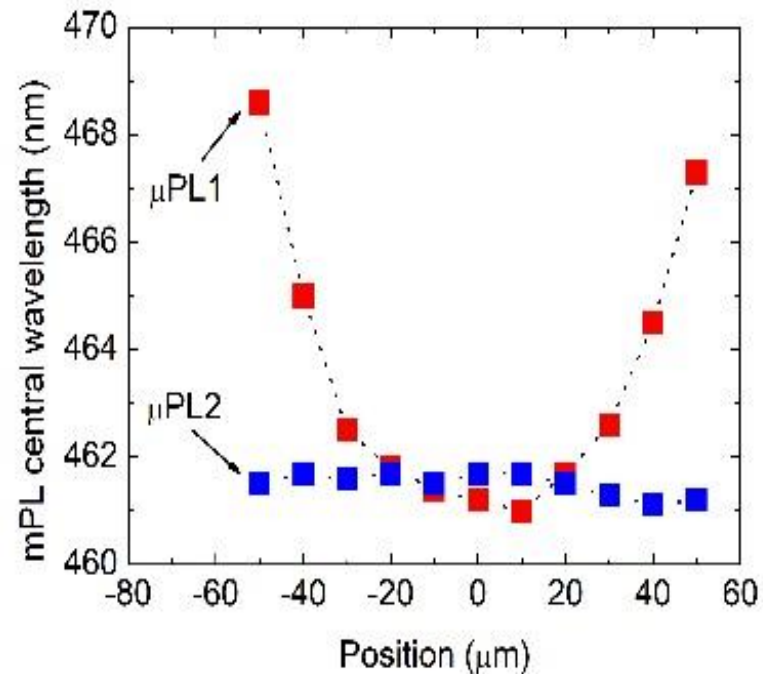
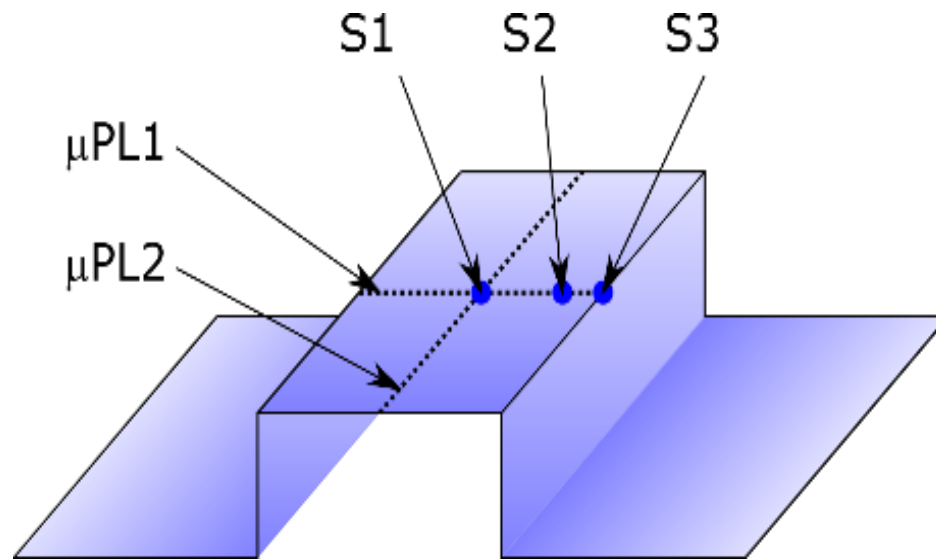


(a)

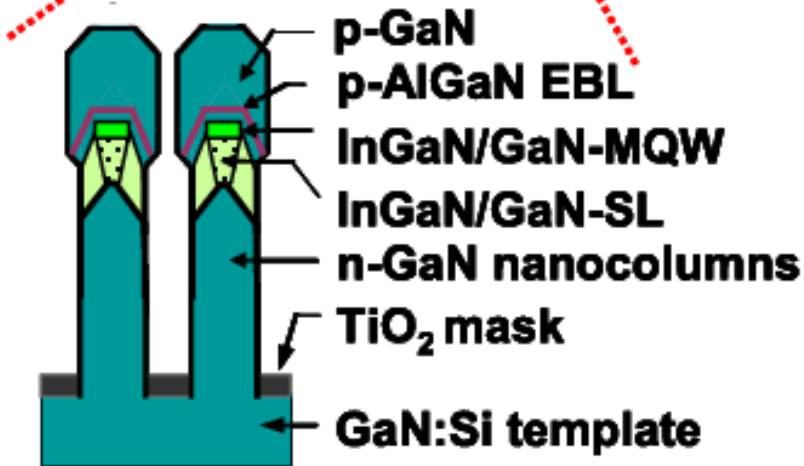
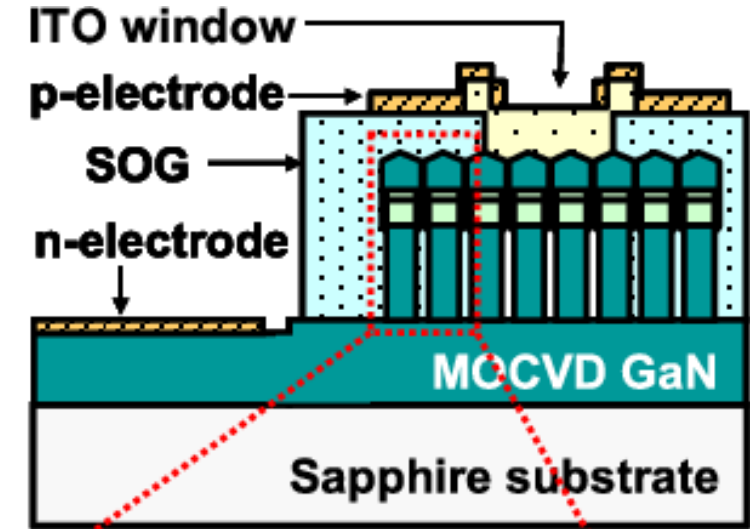
19.10.2022 – Epitaxy



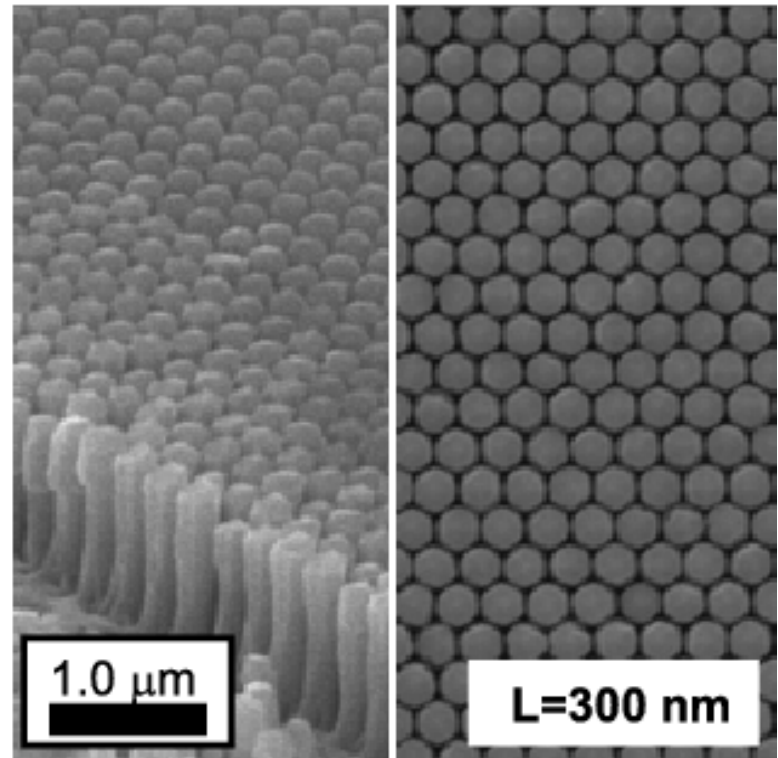
(b)



Nanocolumns



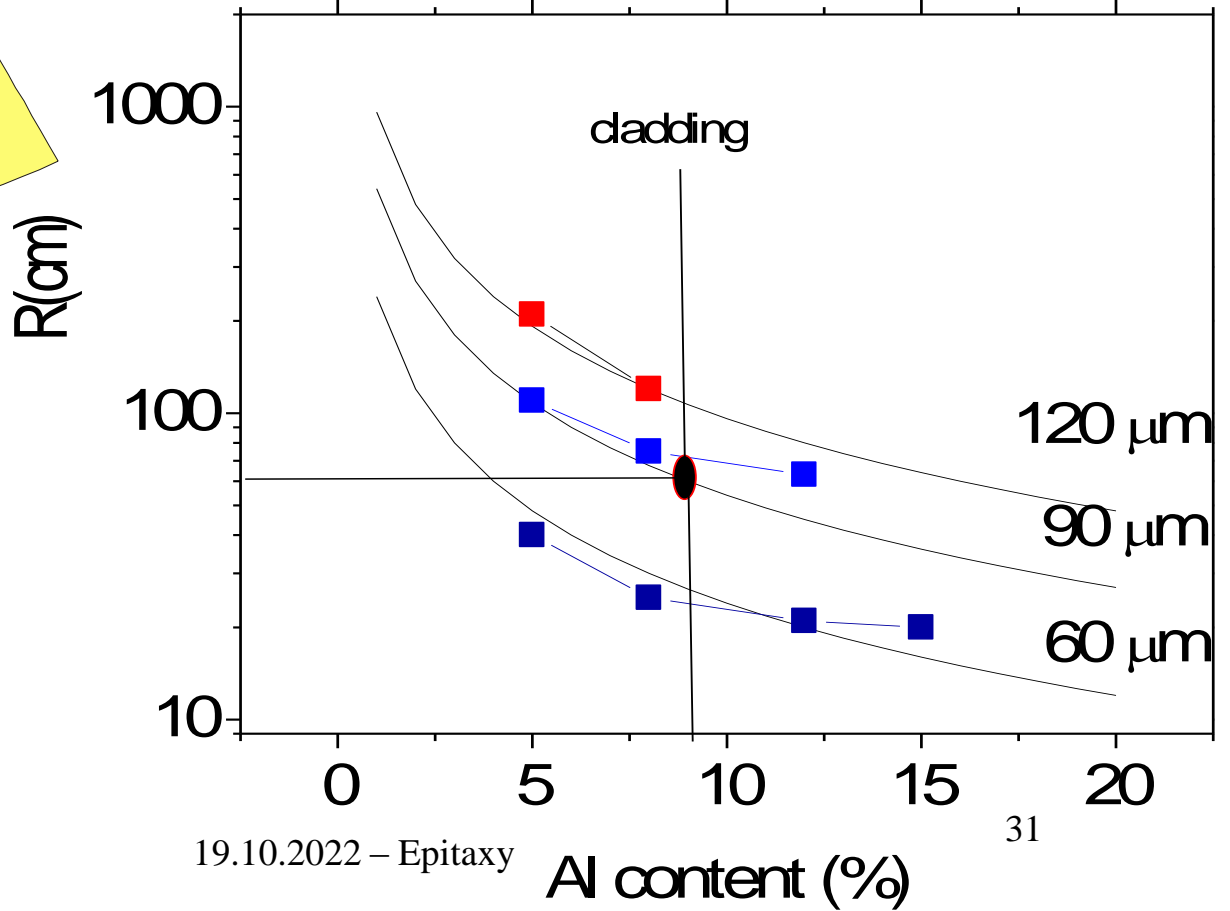
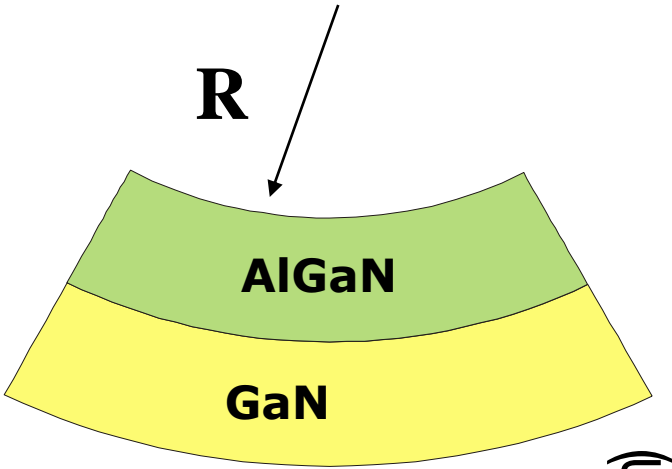
(a)



(b)

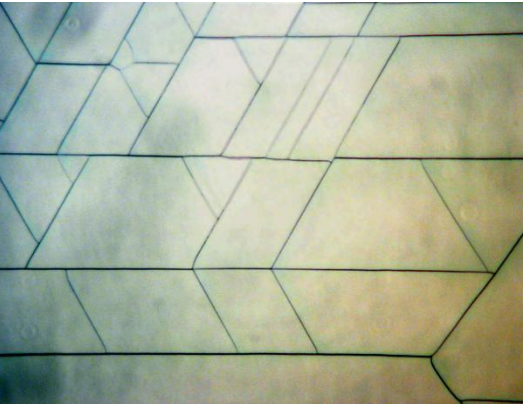
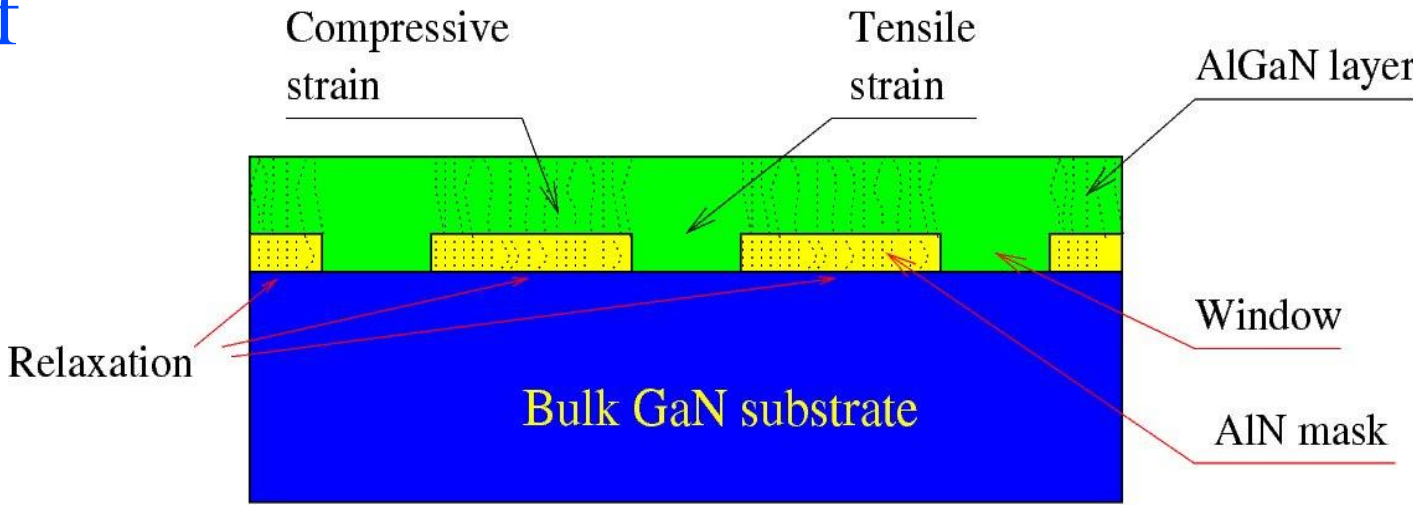
In LDs, we need to have thick AlGaN cladding layers

Tensile strain: cracking and bowing

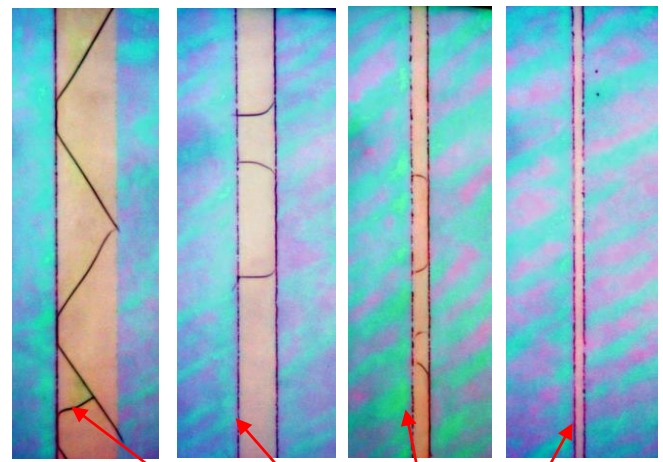


Elimination of cracking and bowing

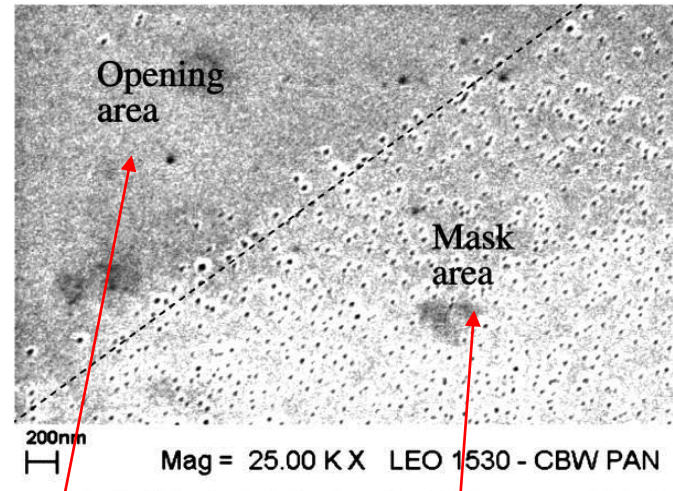
AlGaN 27%
220 nm



No mask AlN



With mask 15 10 5 3 μm

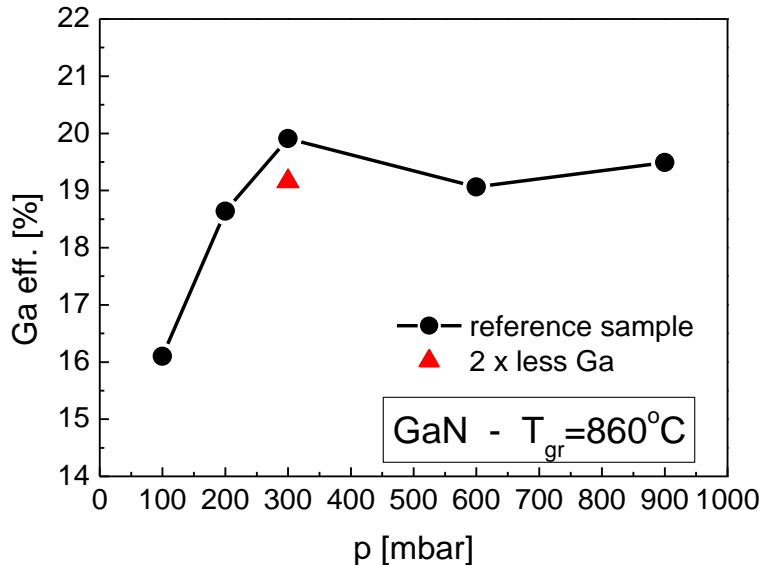


Density of defects: 19.10.2022 – Epitaxy
window $< 10^6/\text{cm}^2$ on mask $10^{10}/\text{cm}^2$

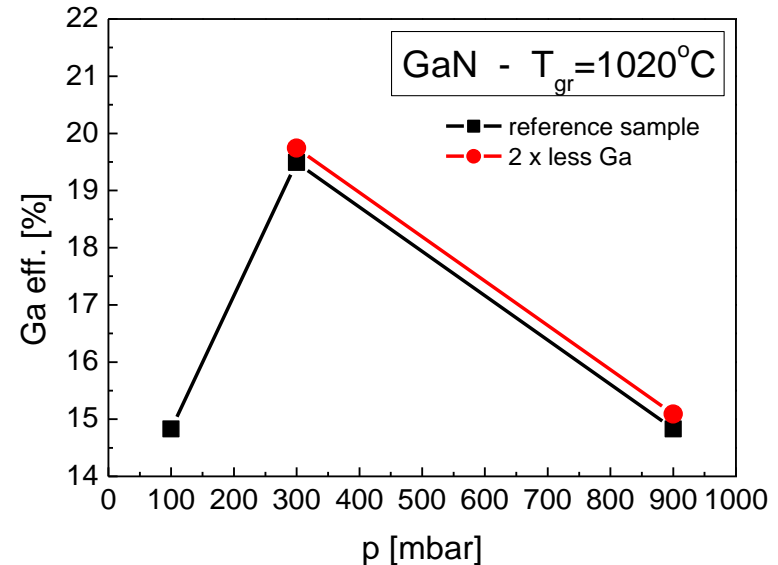
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Efficiency of Ga incorporation into GaN in HM

Efficiency= number of atoms in gas phase/ number of atoms incorporated into the epi layer



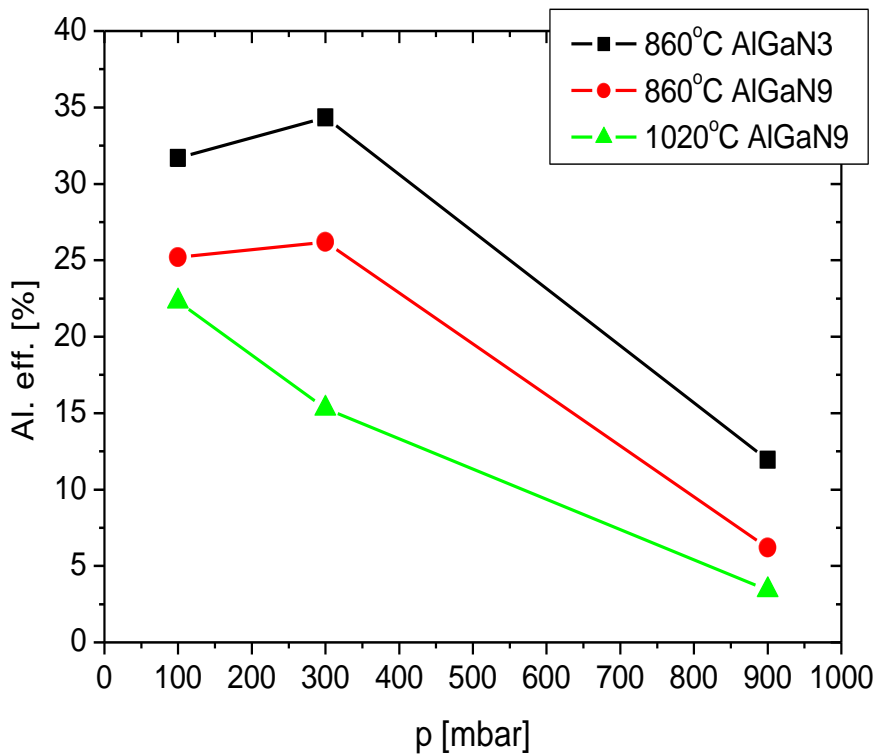
At low pressure, the Ga atoms are blown away from the surface.



At high pressure and temperature, the rate of prereactions increase which prevents Ga incorporation

Efficiency of Ga incorporation independent on amount of TEGa

Efficiency of Al incorporation into AlGaN



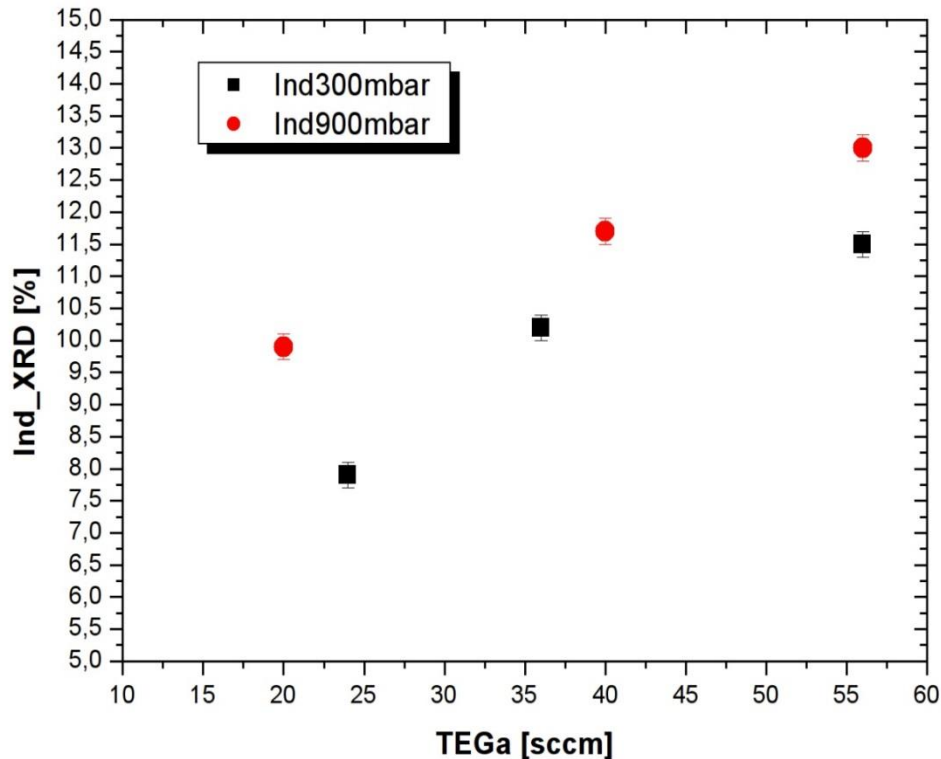
Efficiency of Al incorporation falls down with TMAI flow increase

Prereactions rate higher than in the case of GaN

More prereactions at high temperature and pressure

3 sccm of TMAI
9 sccm of TMAI

Efficiency of In incorporation into InGaN versus TEGa flow

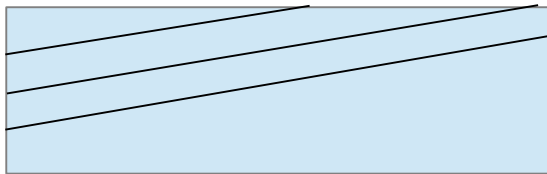
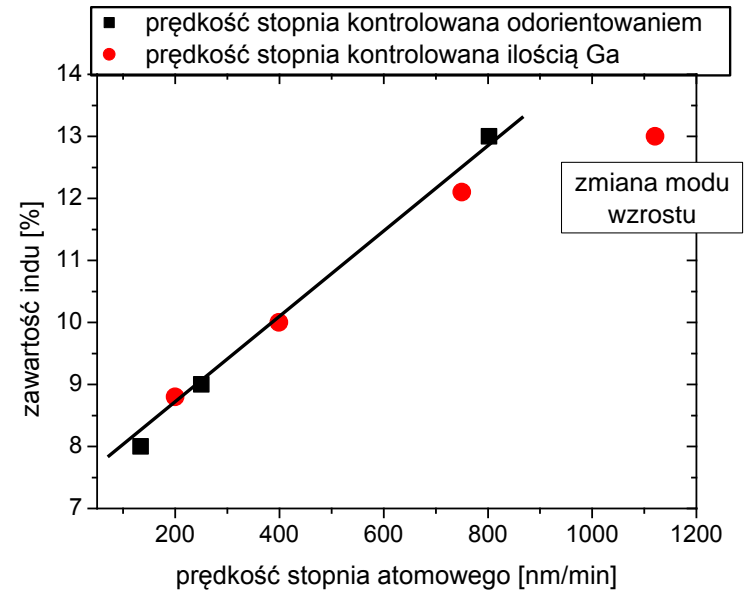
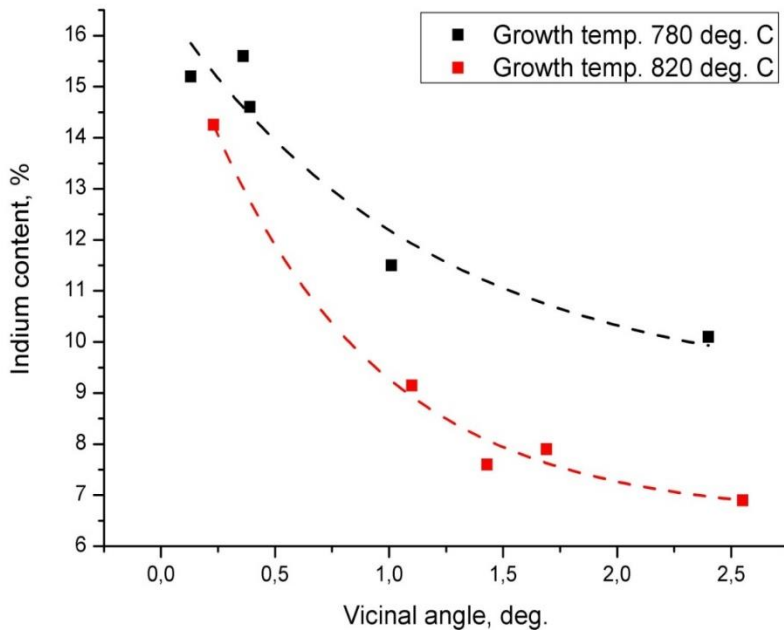


More Ga source in the gas phase, but more In in InGaN solid phase.

More indium at elevated pressure (not for every reactor!)

In atoms to be incorporated must be surrounded by Ga atoms

In incorporation into InGaN layers versus GaN substrate off-orientation

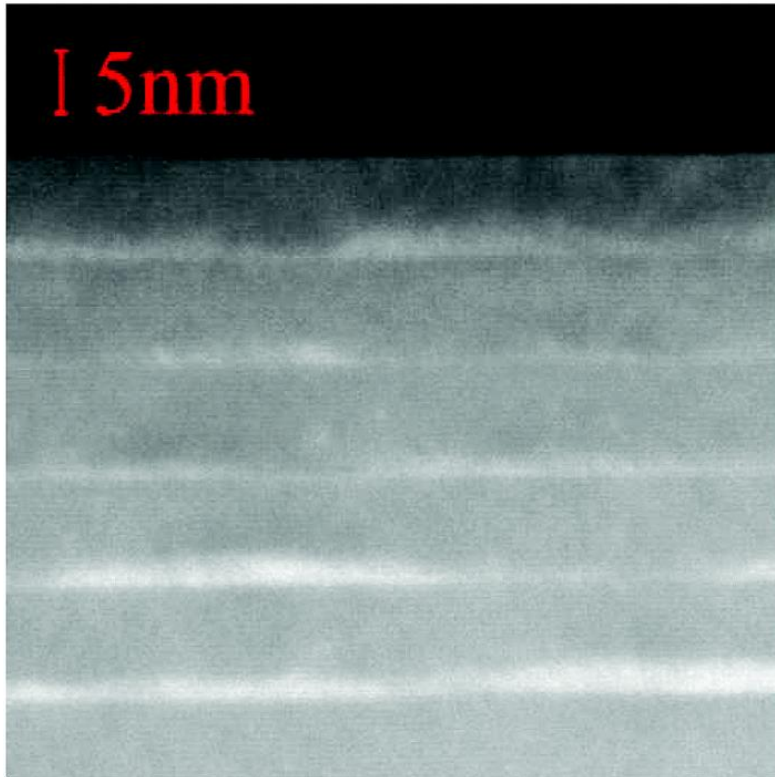


If we have bad morphology (steps are not identical), we deal with In inhomogeneous incorporation

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As grown InGaN QWs



Indium fluctuations

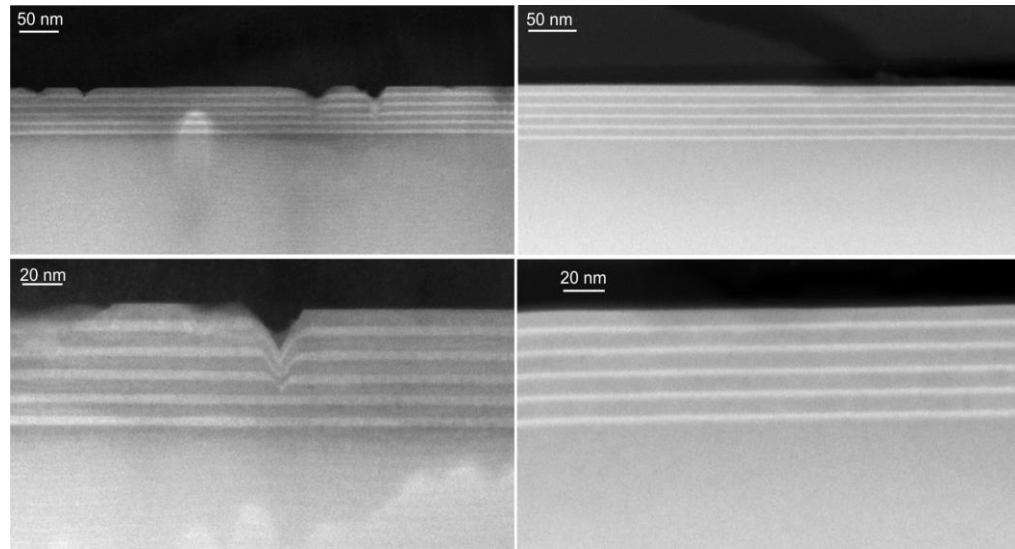
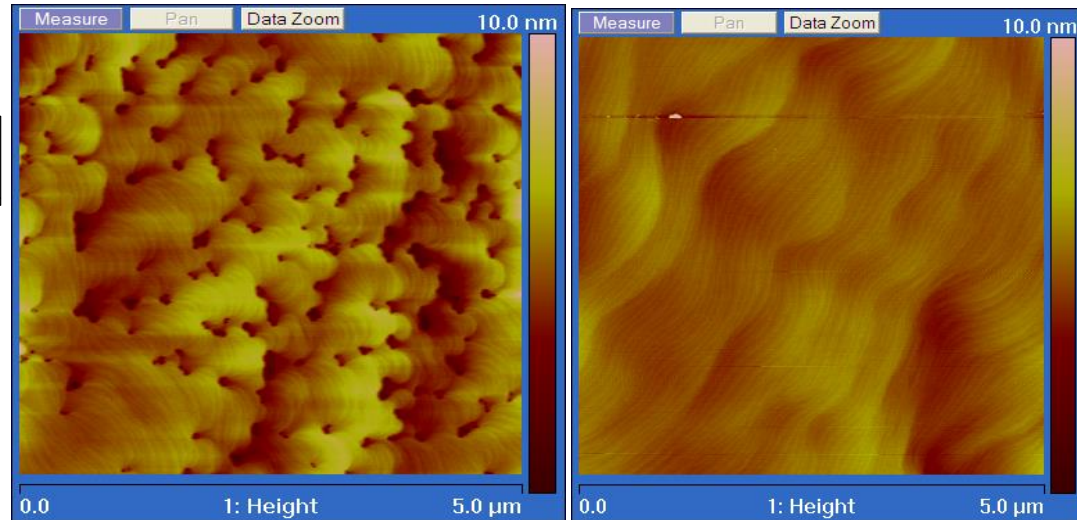
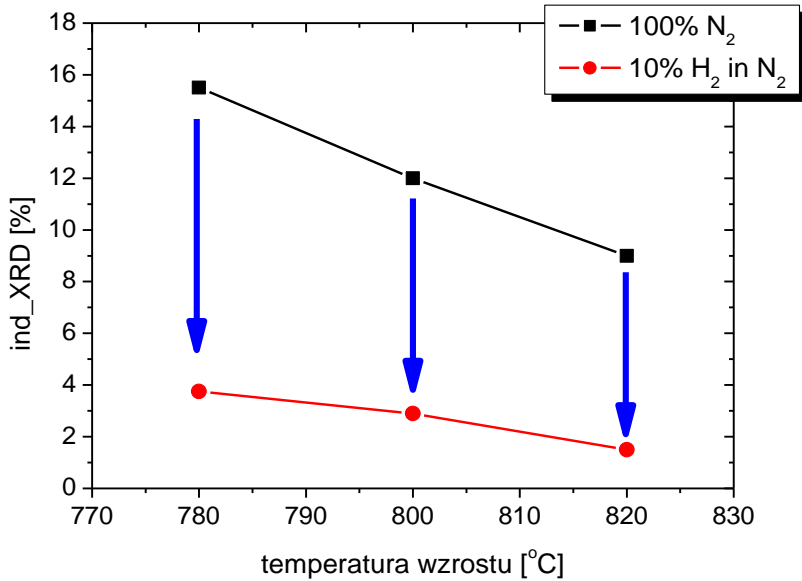
QW thickness fluctuations

**Acceptable for LEDs
Not for LDs**

Examples of MOVPE growth: InGaN Quantum Wells

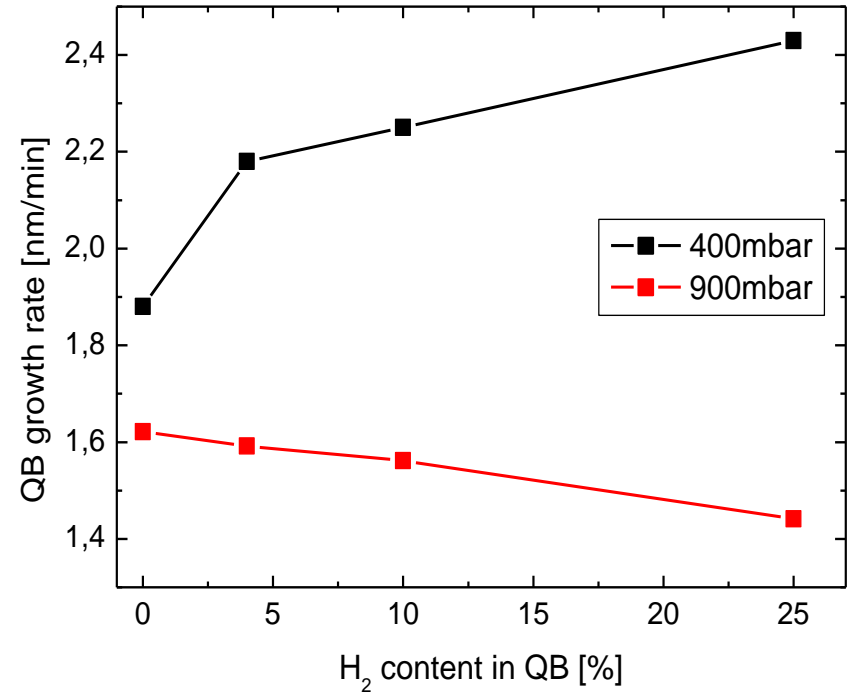
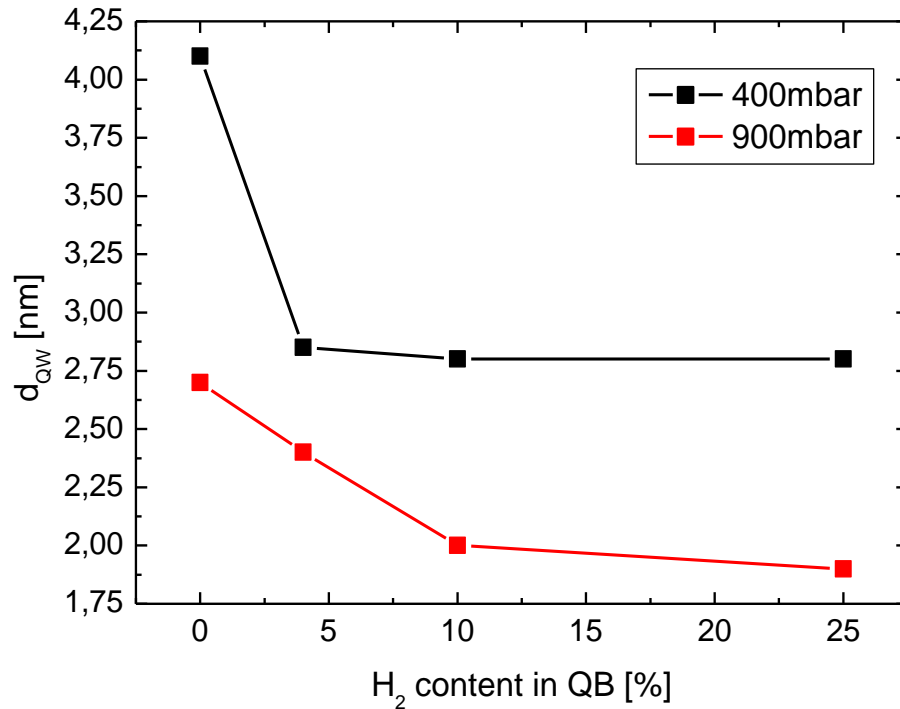
1. Influence of temperature
2. Influence of hydrogen as a carrier gas
3. Homogenization and decomposition

Influence of hydrogen used in the carrier gas



We use hydrogen for growing the QBs- but with special care

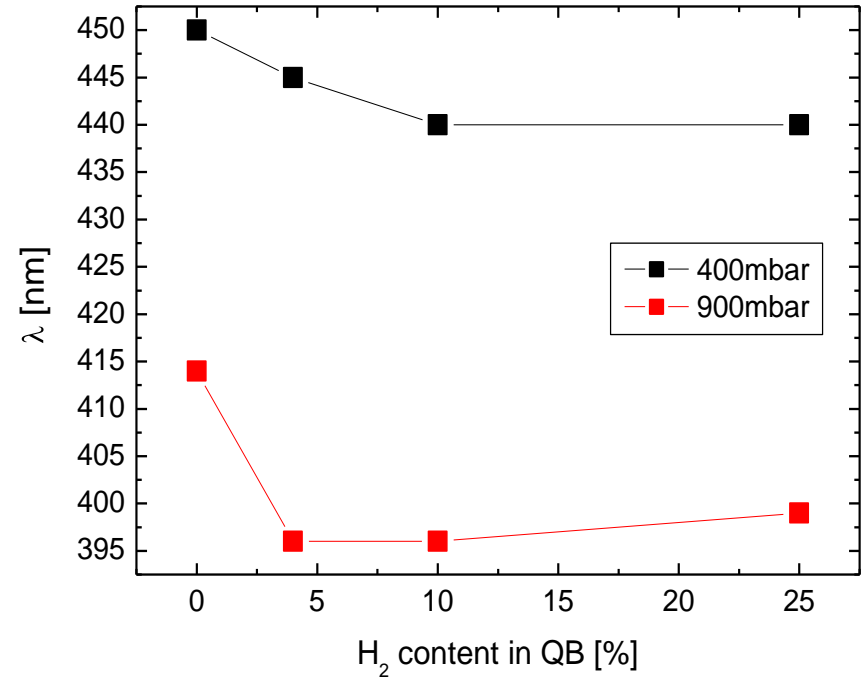
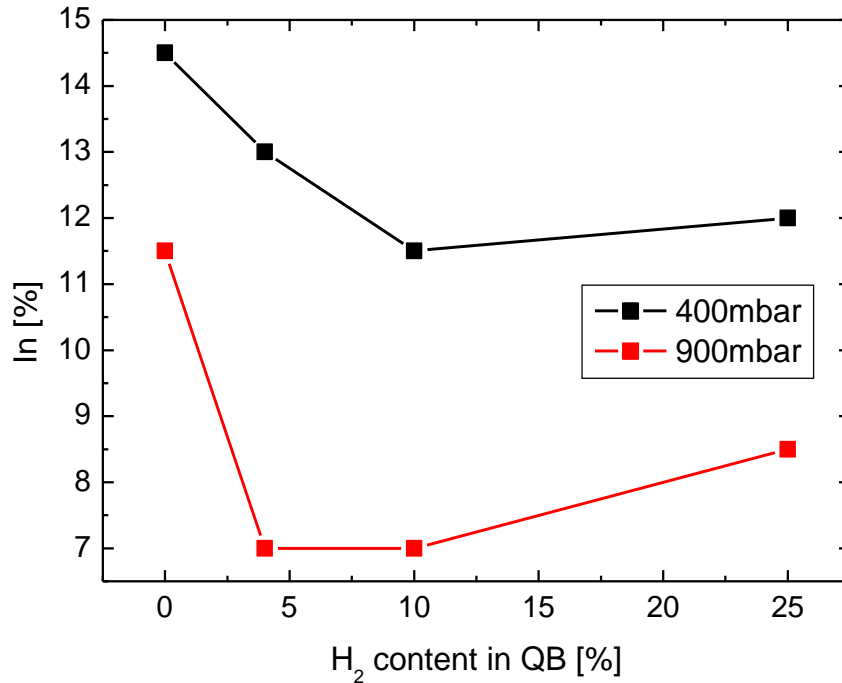
Influence of hydrogen used in the carrier gas during GaN barrier growth in CCS



Hydrogen used in QB growth etches off InGaN QW more efficiently at high pressure

Hydrogen increases the growth rate of GaN (QB) at low pressure, decreases at higher pressure.

Influence of hydrogen used in the carrier gas during GaN barrier growth in CCS



Hydrogen used in QB growth etches In off InGaN QW more efficiently at high pressure

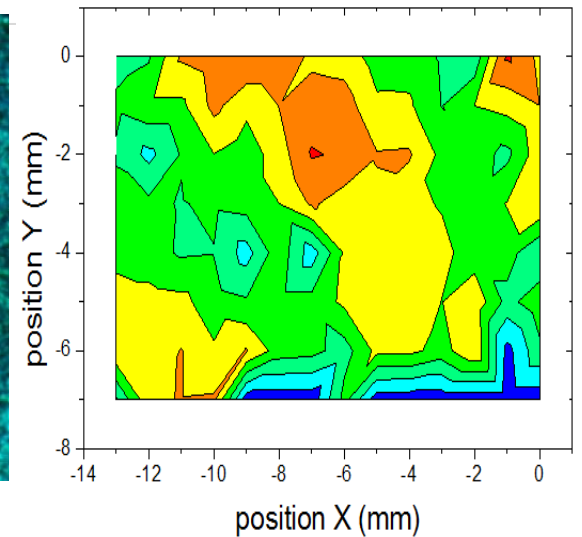
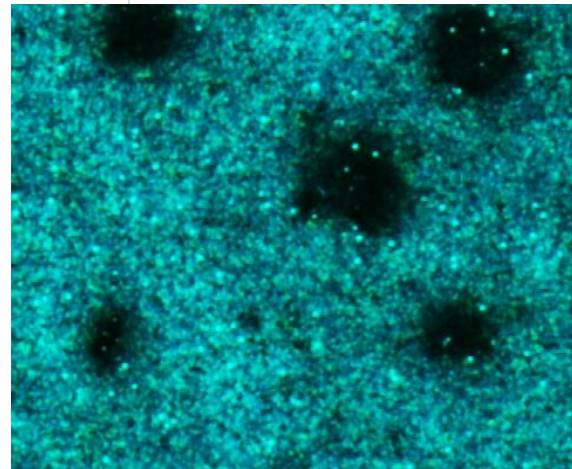
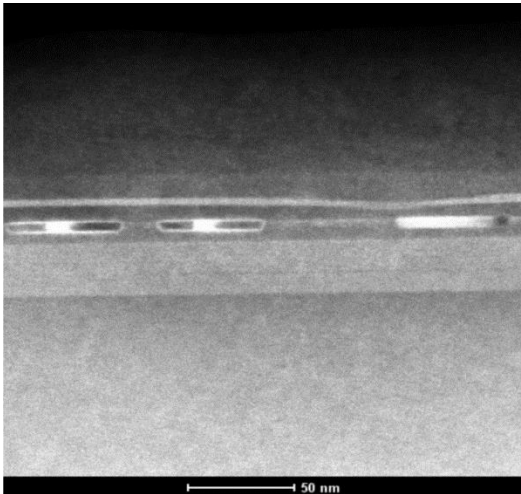
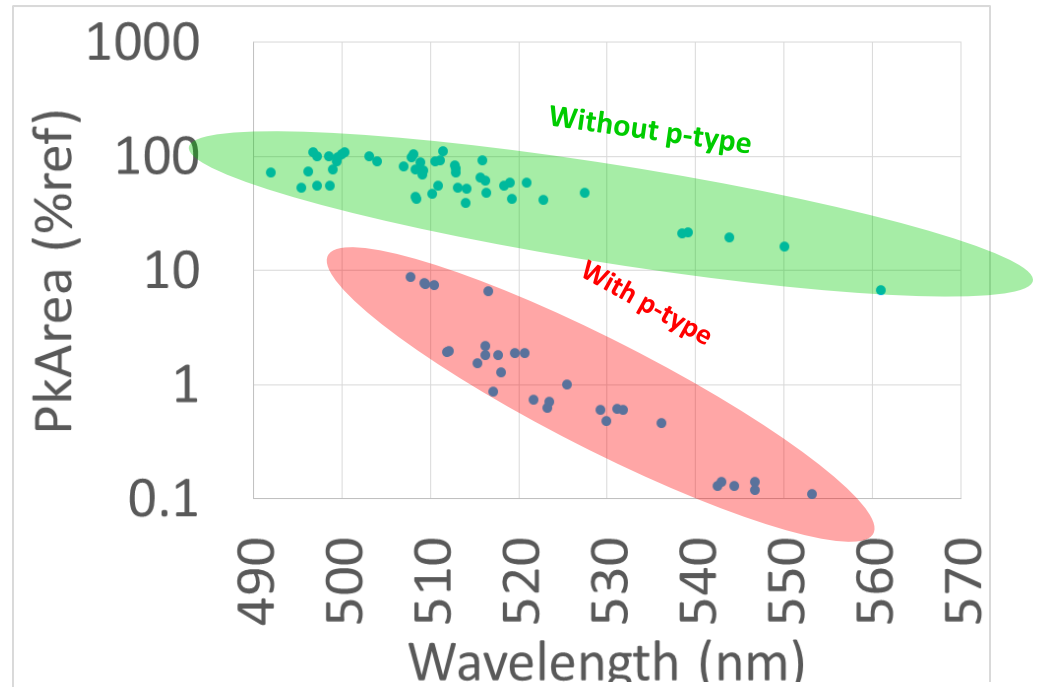
Growth temperatures of the laser diode structure

GaN:Mg	$T_{Gr} = XXXX^{\circ}C$
AlGaN:Mg	
GaN:Mg	
EBL - AlGaN:Mg	
Cap – GaN	
Cap – GaN	$T_{Gr} QW < 740^{\circ}C$
QW - InGaN	
QB – GaN	
InGaN	
GaN	$T_{Gr} QB > 740^{\circ}C$
AlGaN:Si	
GaN:Si	
Substrate	

To obtain good p-type XXXX should be as high as possible (above 900°C).

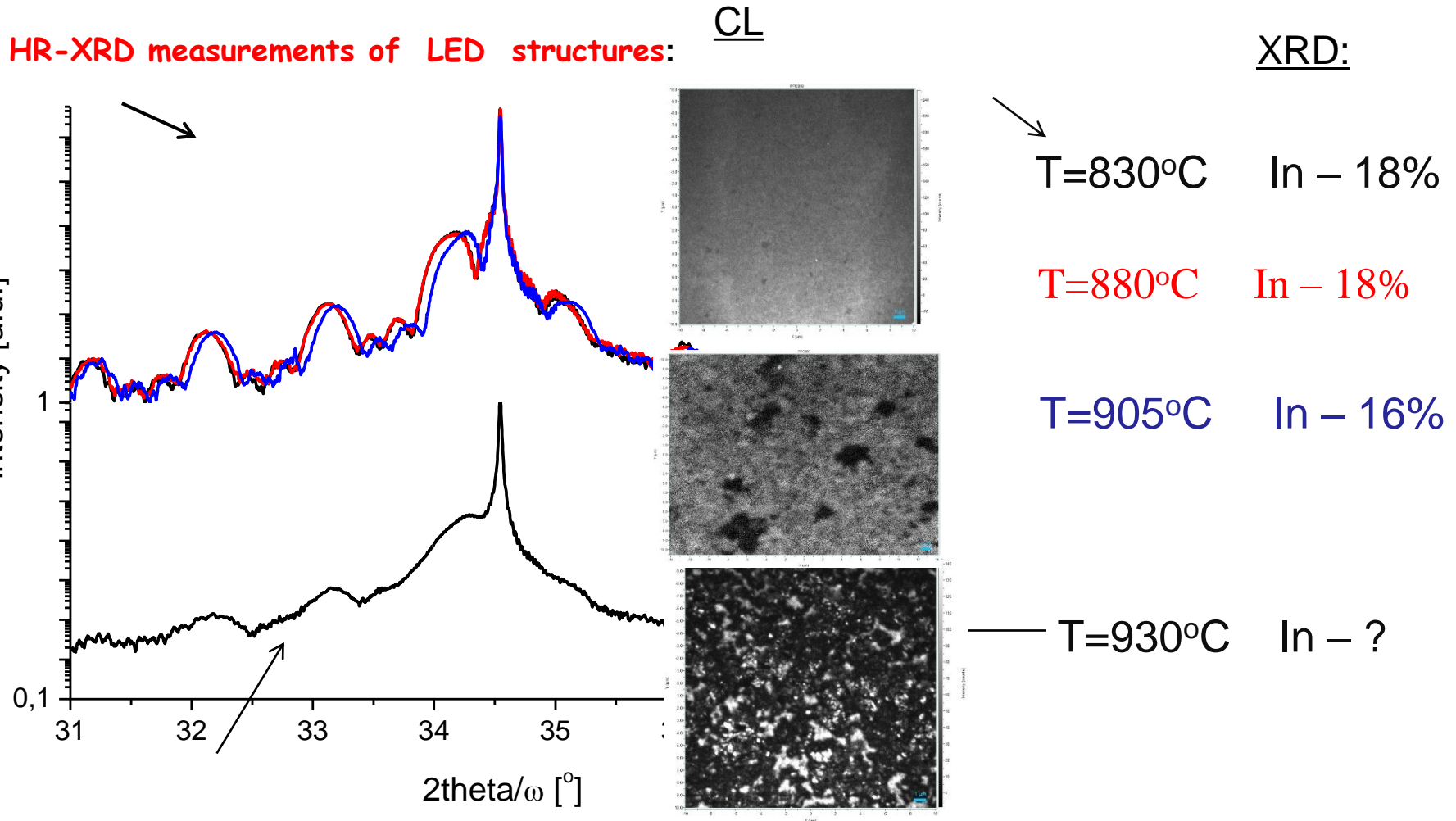
At high temperatures, InGaN QWs change

InGaN MQW decomposition

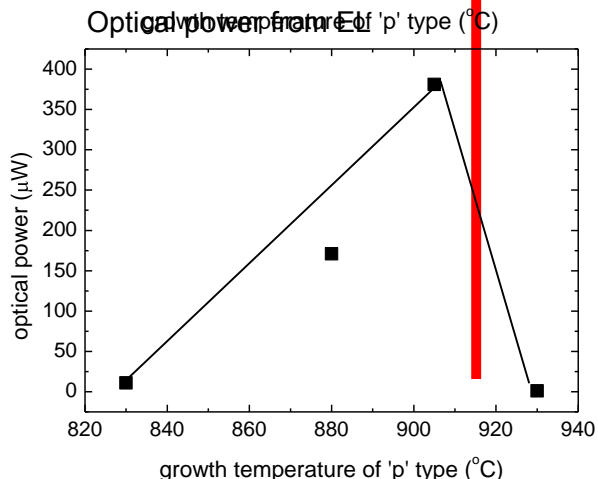
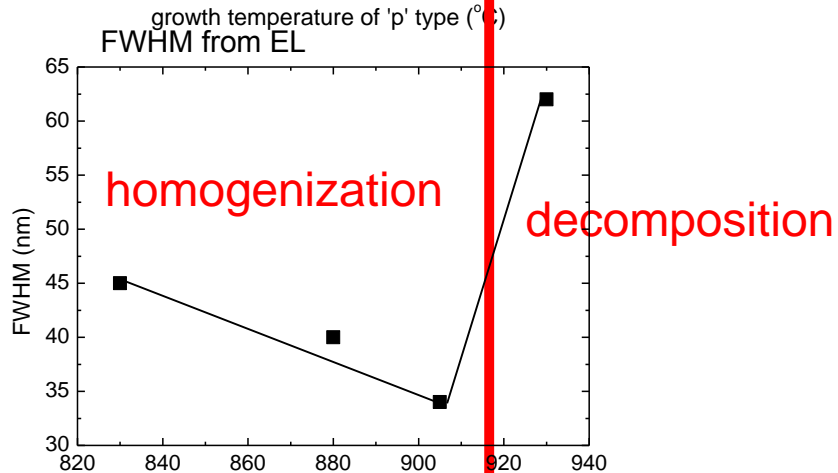
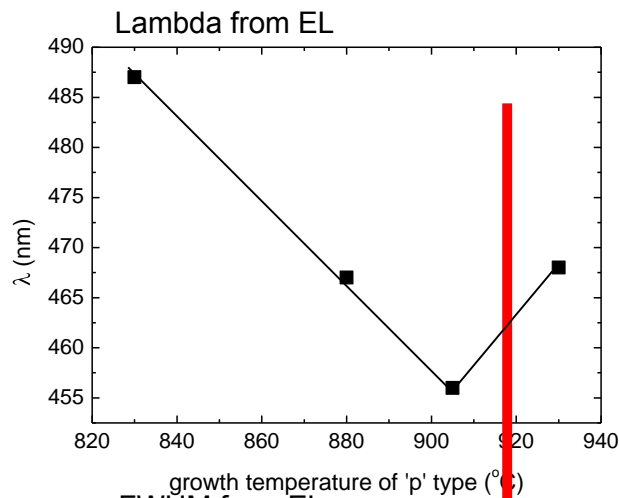


TEM: nanometer scale, Fluorescence microscopy: micrometers, MicroPL: millimeters

Changes of the MQWs during p-type growth at high temperature: samples on sapphire



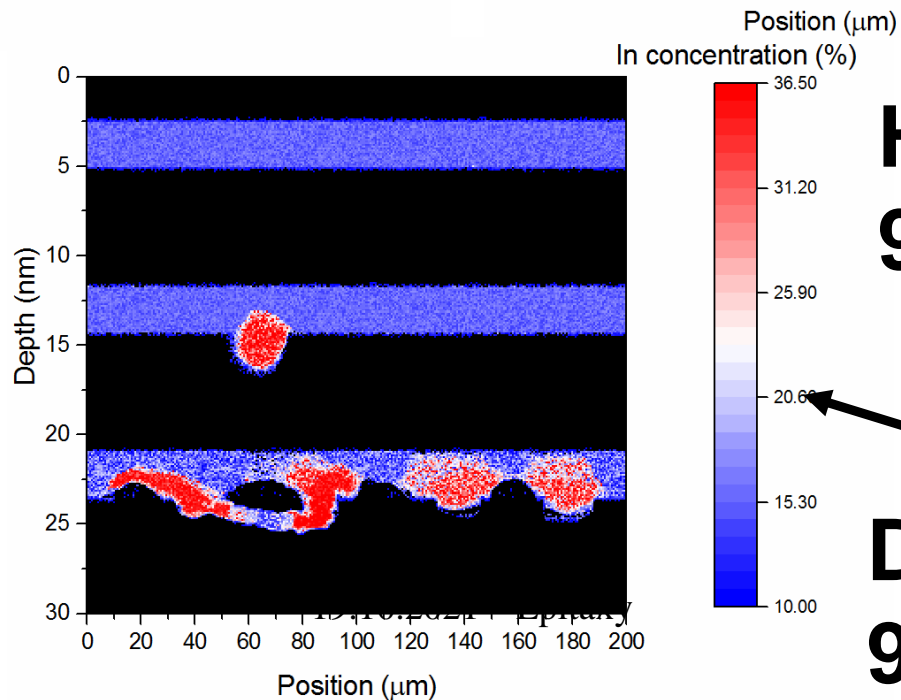
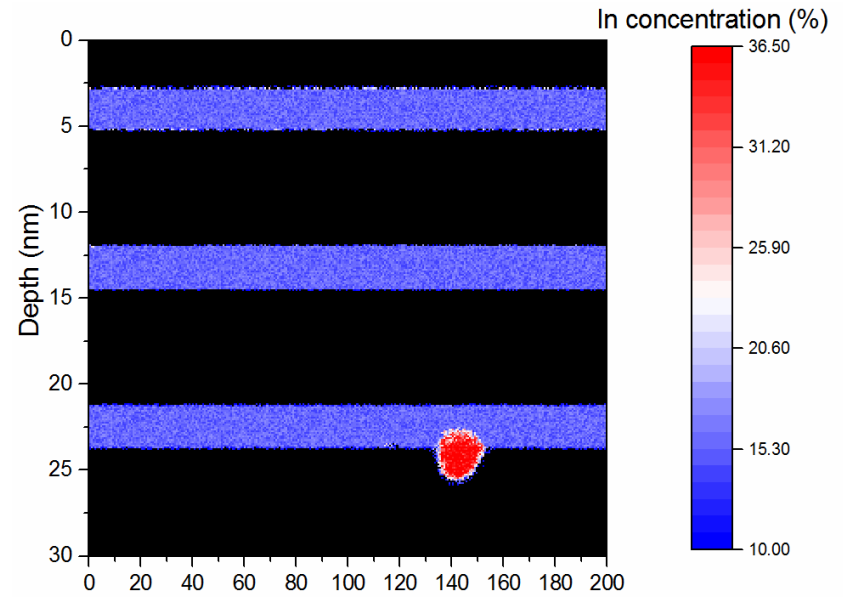
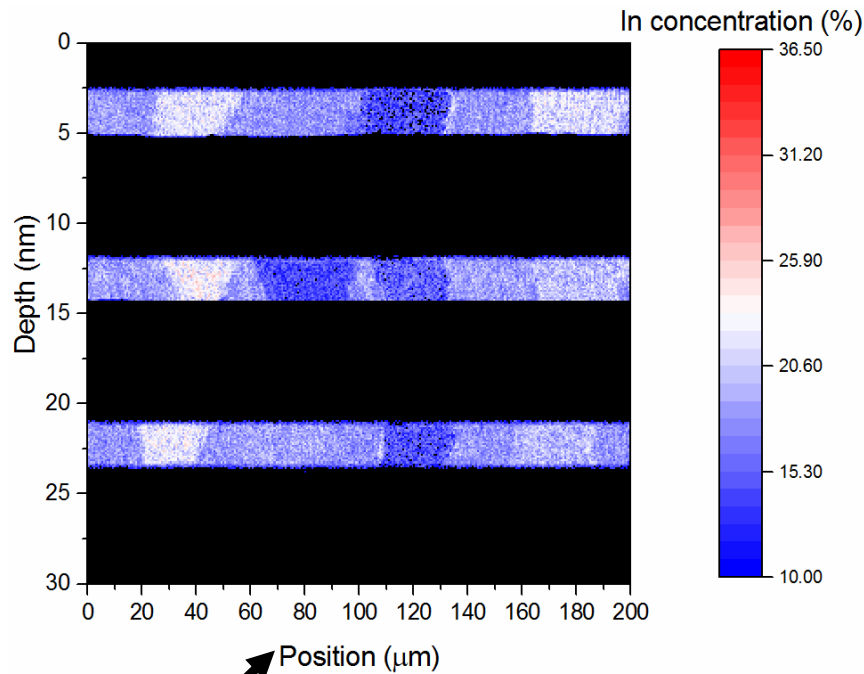
At high temperature satellite peaks becomes much more broader and disappear : QWs degradation occurs



For samples on sapphire (high dislocation density) we are able to homogenize InGaN QWs by growing p-type at high temperature.

If this temperature is too high, we deal with a catastrophic damage

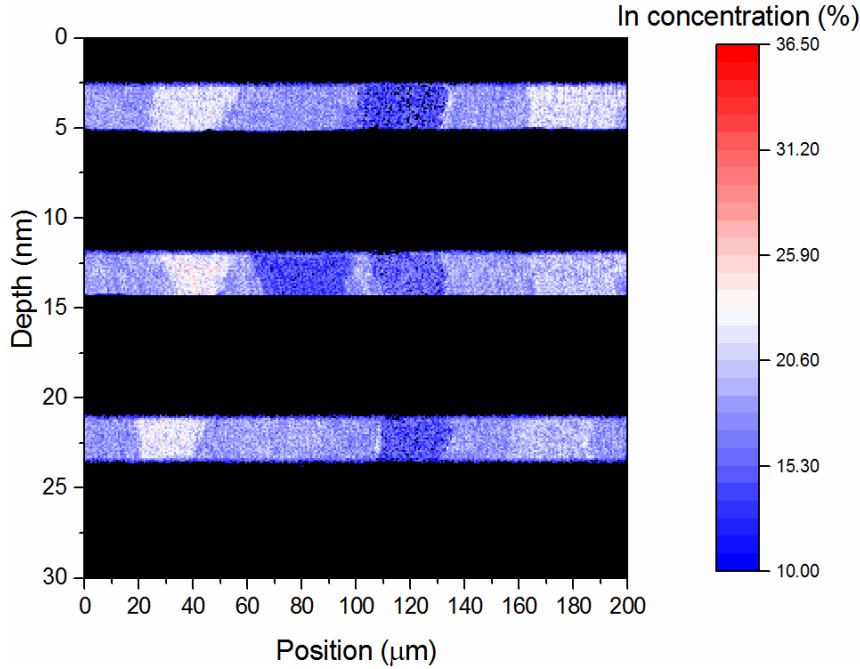
SIMS data of In-content



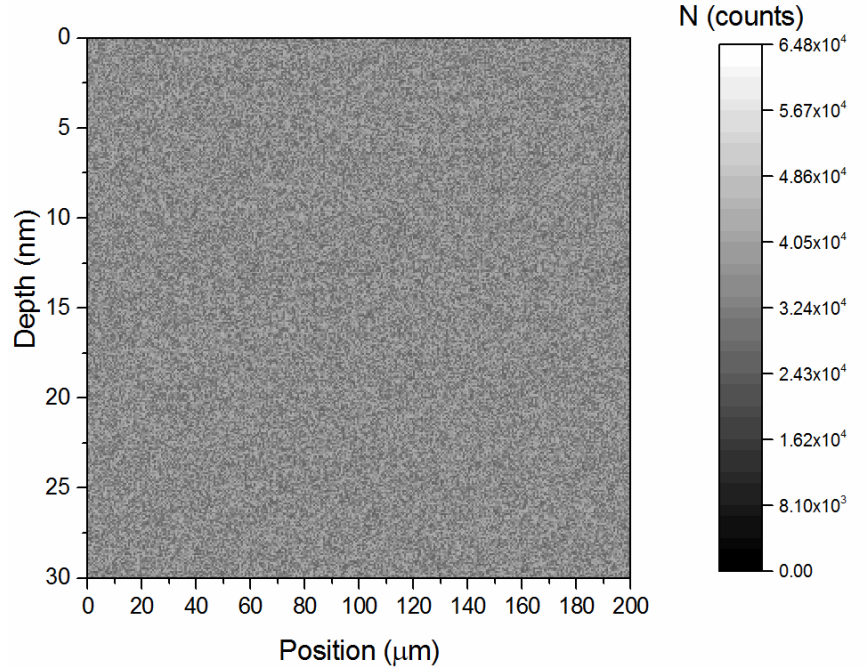
Homogenized
905°C

Decomposed
930°C

as grown

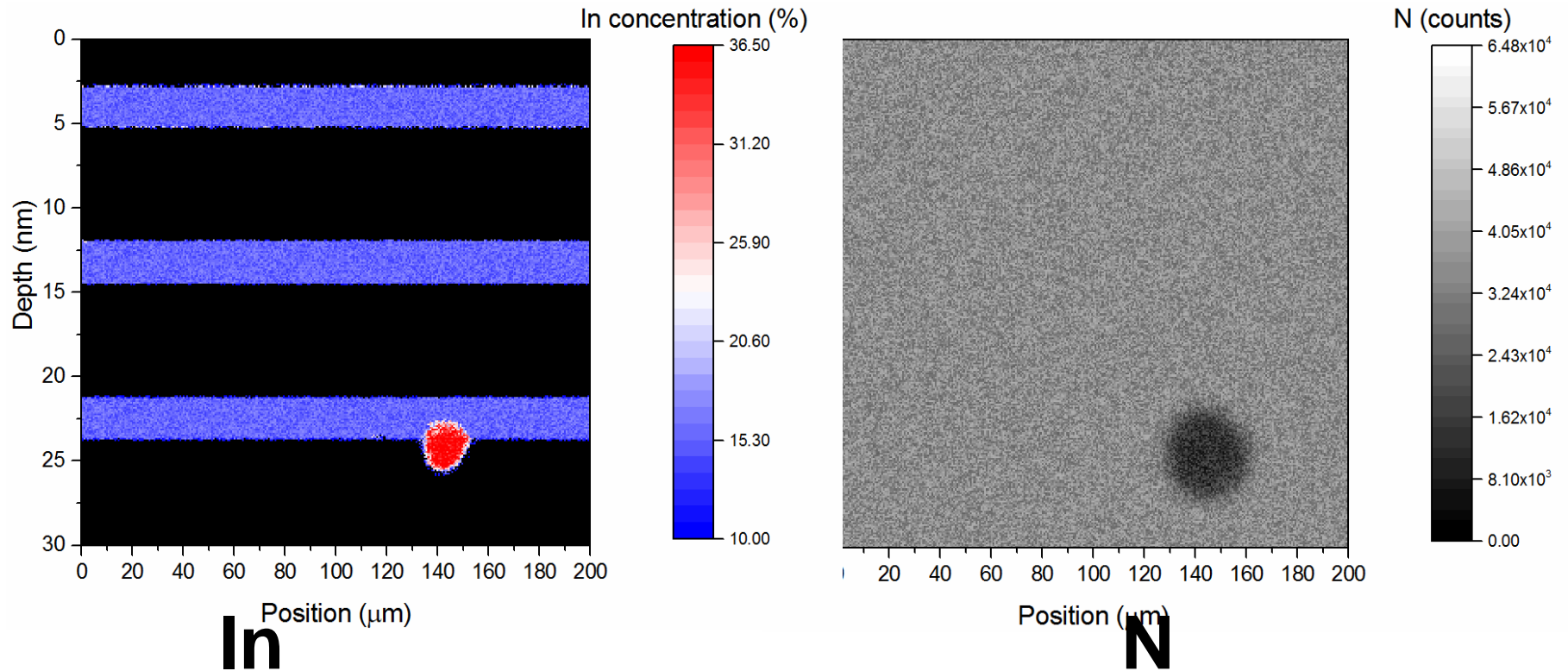


In

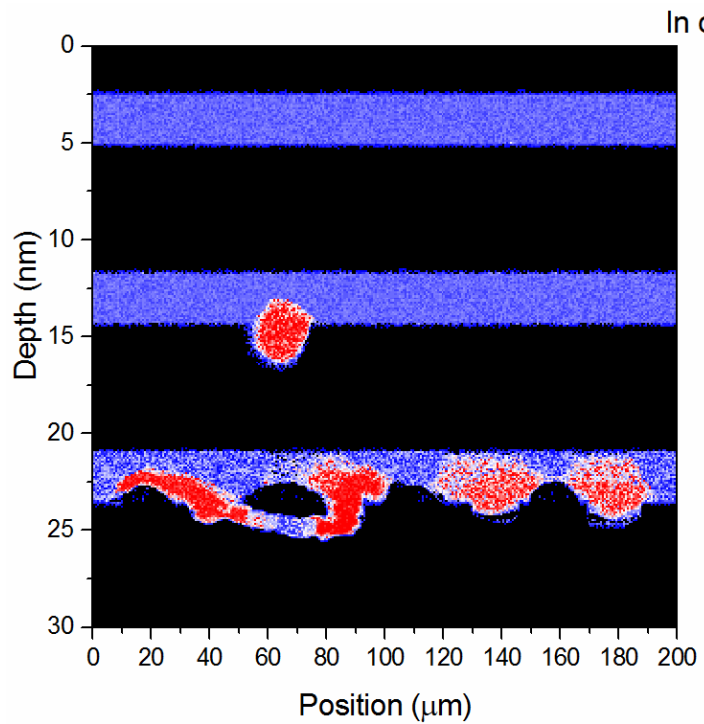


N

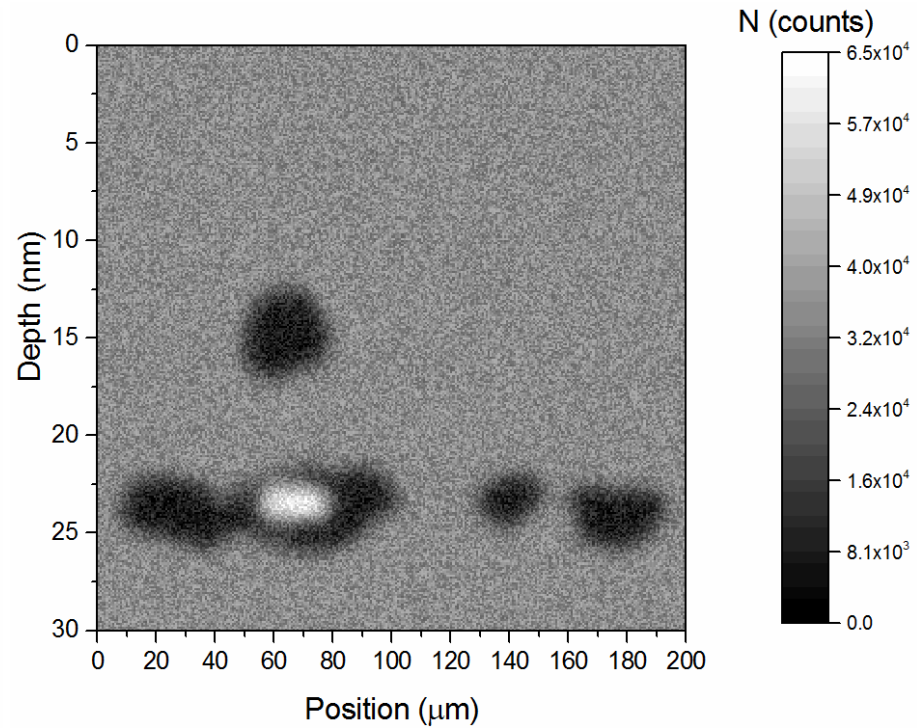
homogenized



decomposed

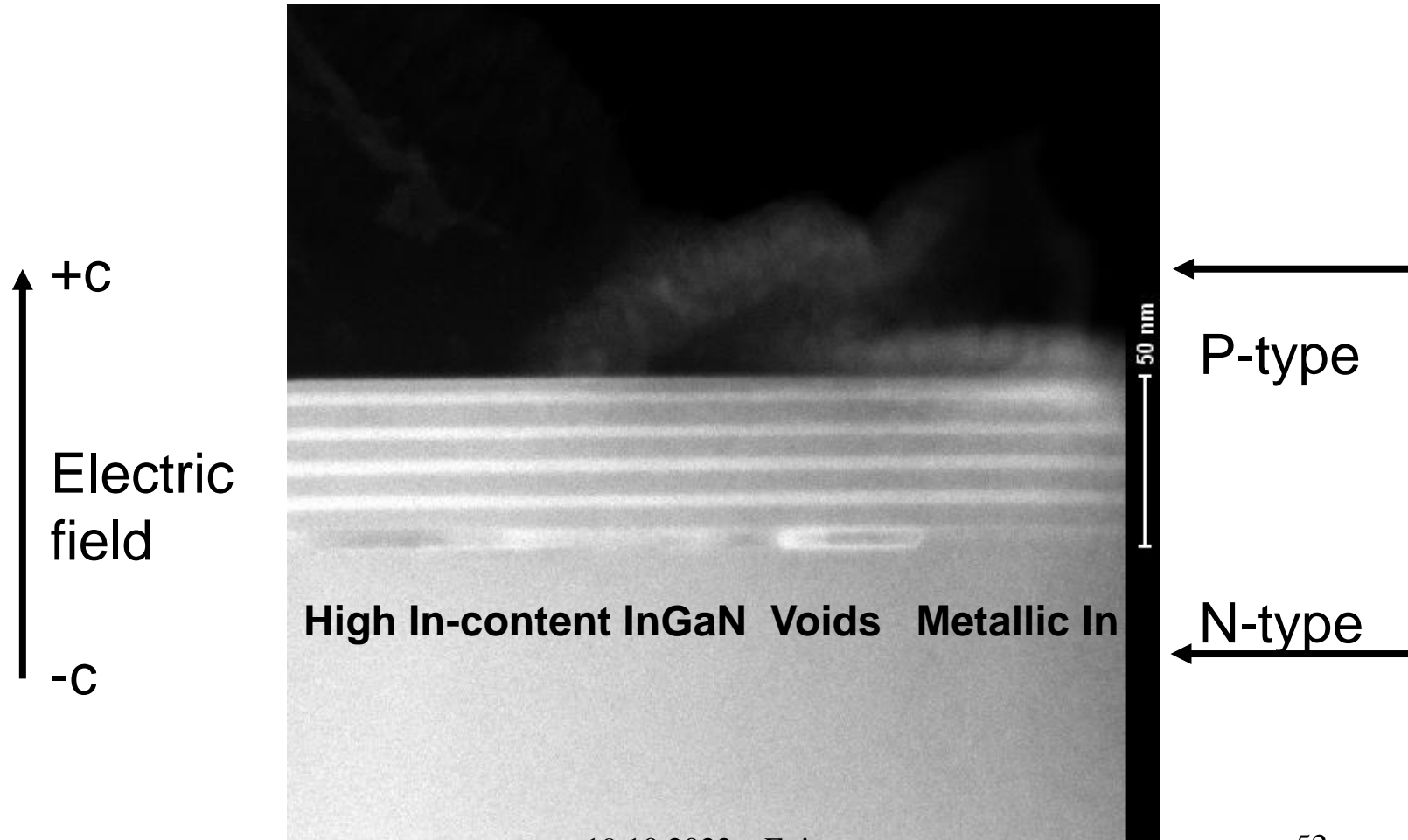


In



N

Why does the decomposition start from the first QW?



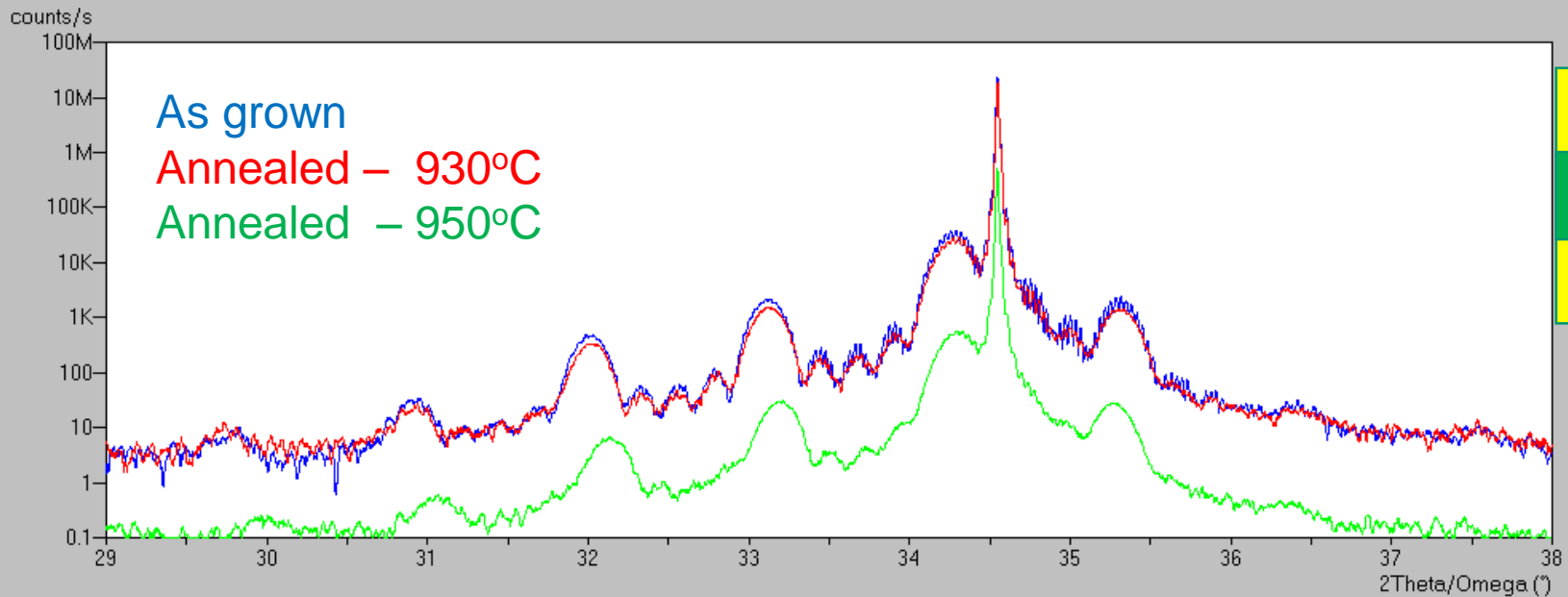
Diffusion of vacancies?

In GaN:Si we have more Ga-vacancies

In GaN:Mg we have more N-vacancies

Diiferent doping below and above the InGaN/GaN MQWs

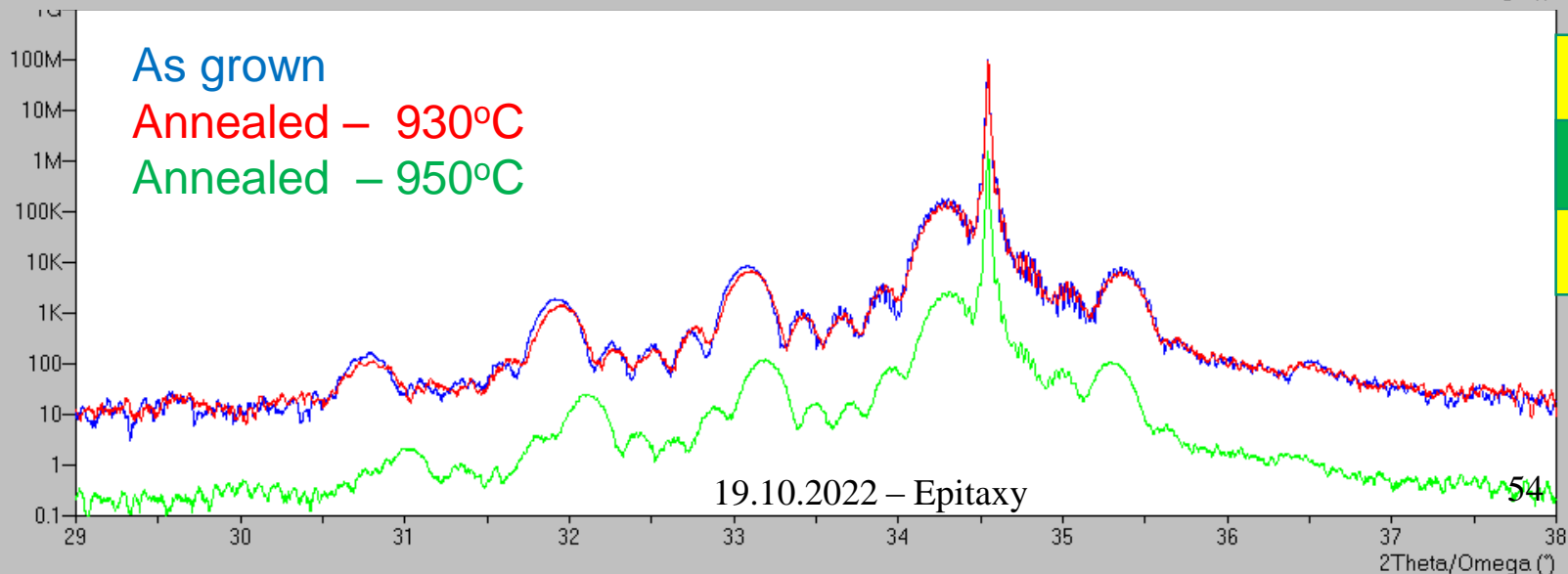
5QWs - (460 nm) - 17%In



GaN:Si

5QWs

GaN:Si



GaN:Mg

5QWs

GaN:Mg

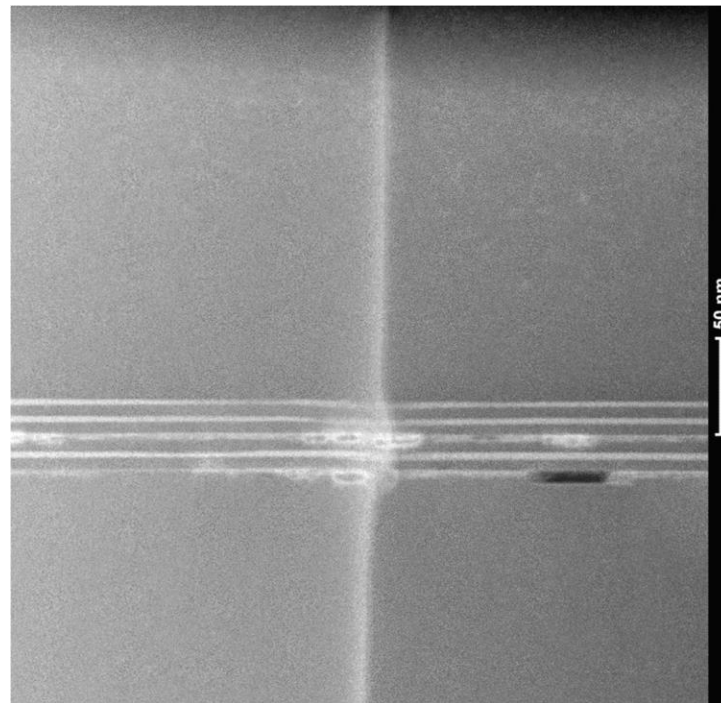
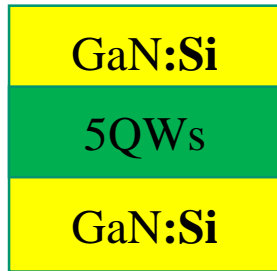
19.10.2022 – Epitaxy

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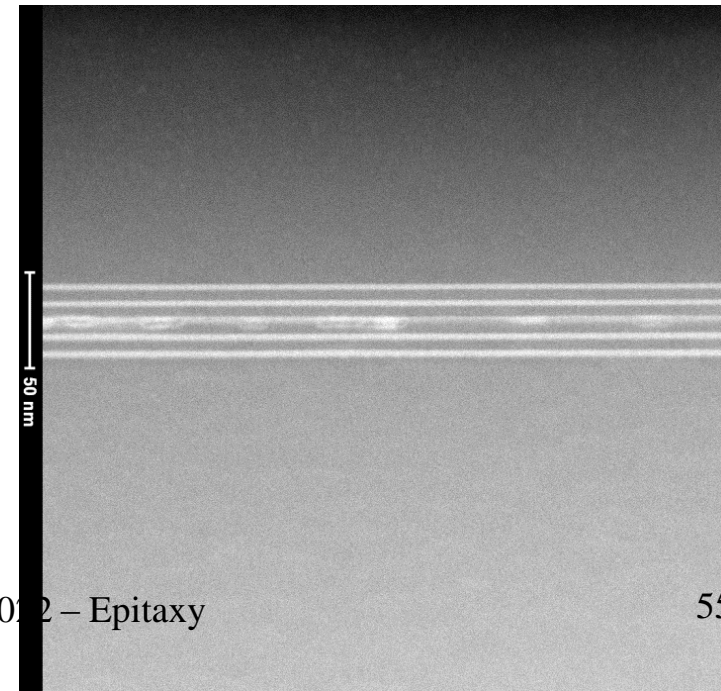
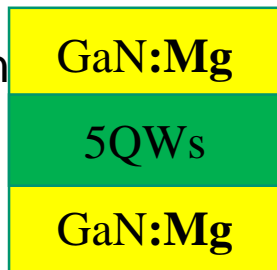
After annealing at 950°C

No decomposition from the top

Electric field
driven diffusion?
Yes!



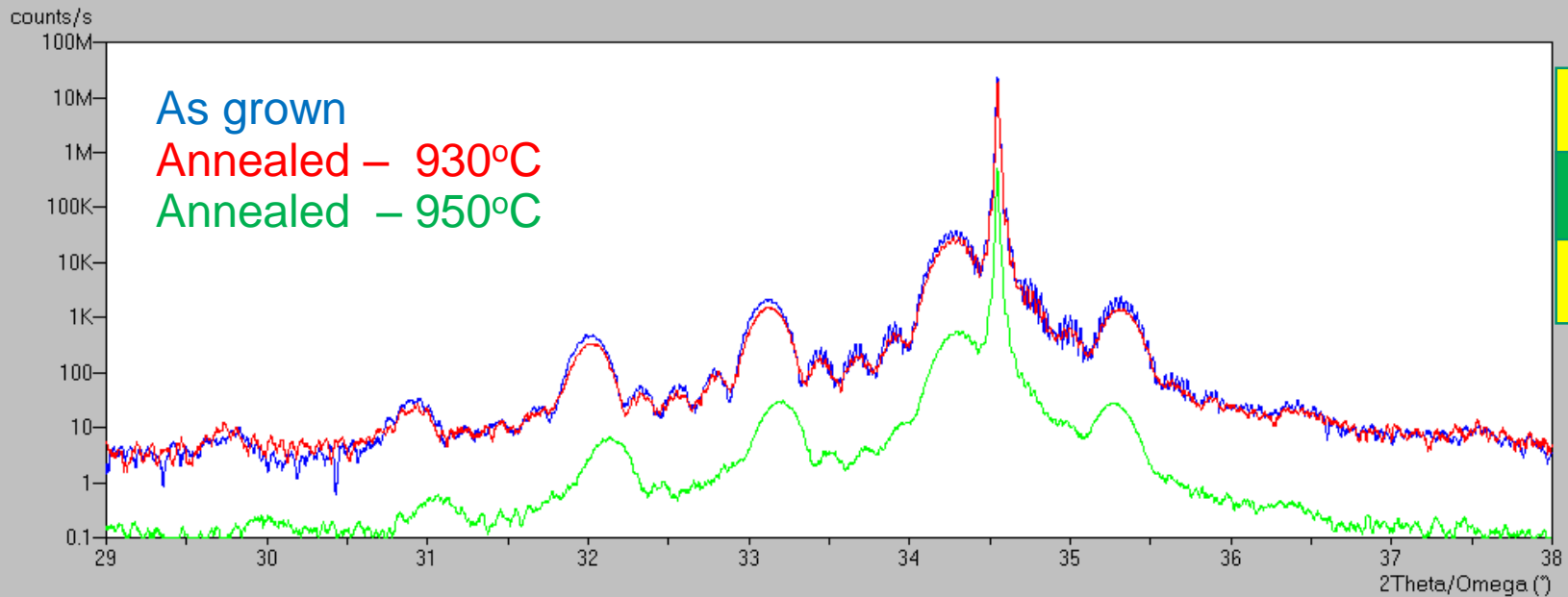
No decomposition
above and below
GaN:Mg



Ga-vacancies?
Yes!

Diiferent doping below and above the InGaN/GaN MQWs

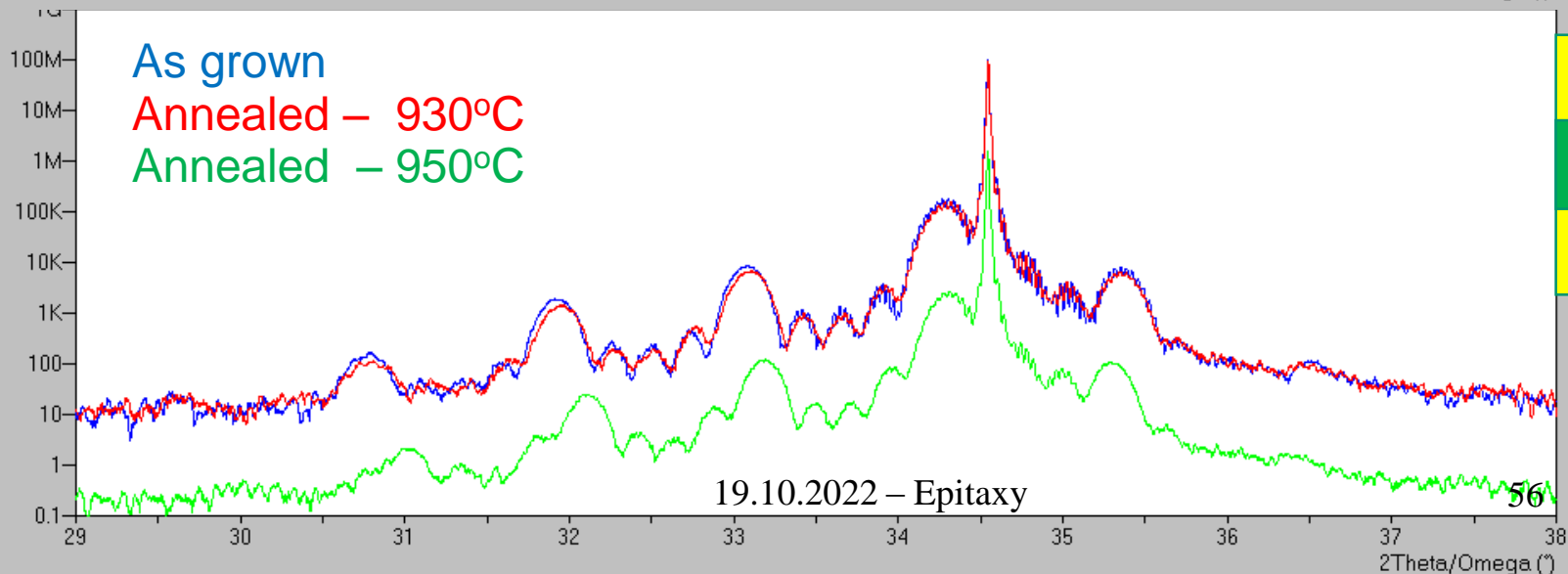
5QWs - (460 nm) - 17%In



GaN:Si

5QWs

GaN:Si



GaN:Mg

5QWs

GaN:Mg

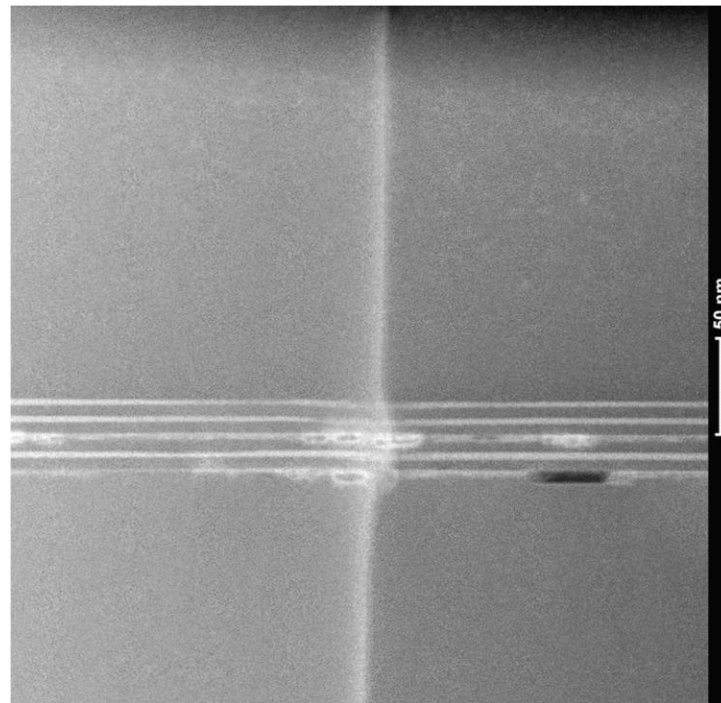
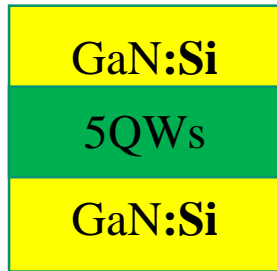
19.10.2022 – Epitaxy

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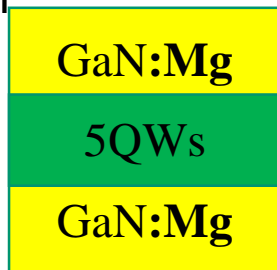
After annealing at 950°C

No decomposition from the top

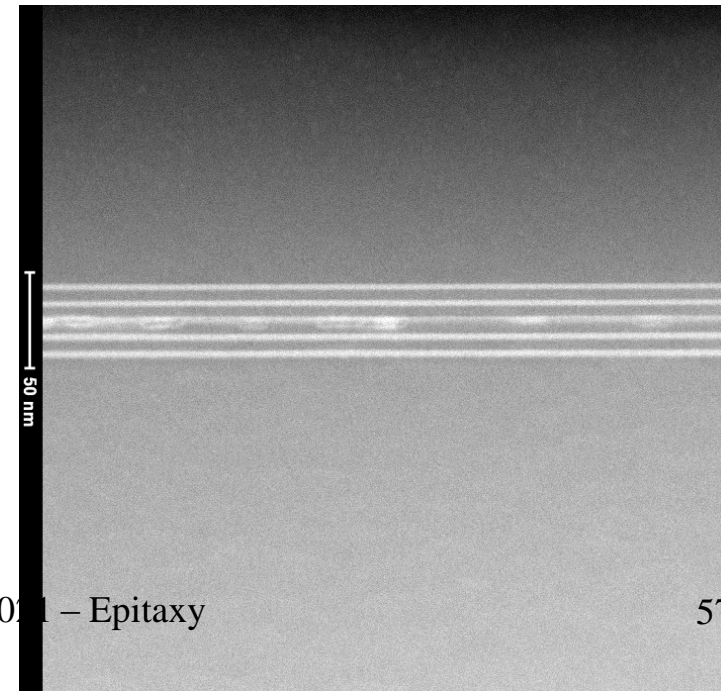
Electric field
driven diffusion?
Yes!



No decomposition
above and below
GaN:Mg



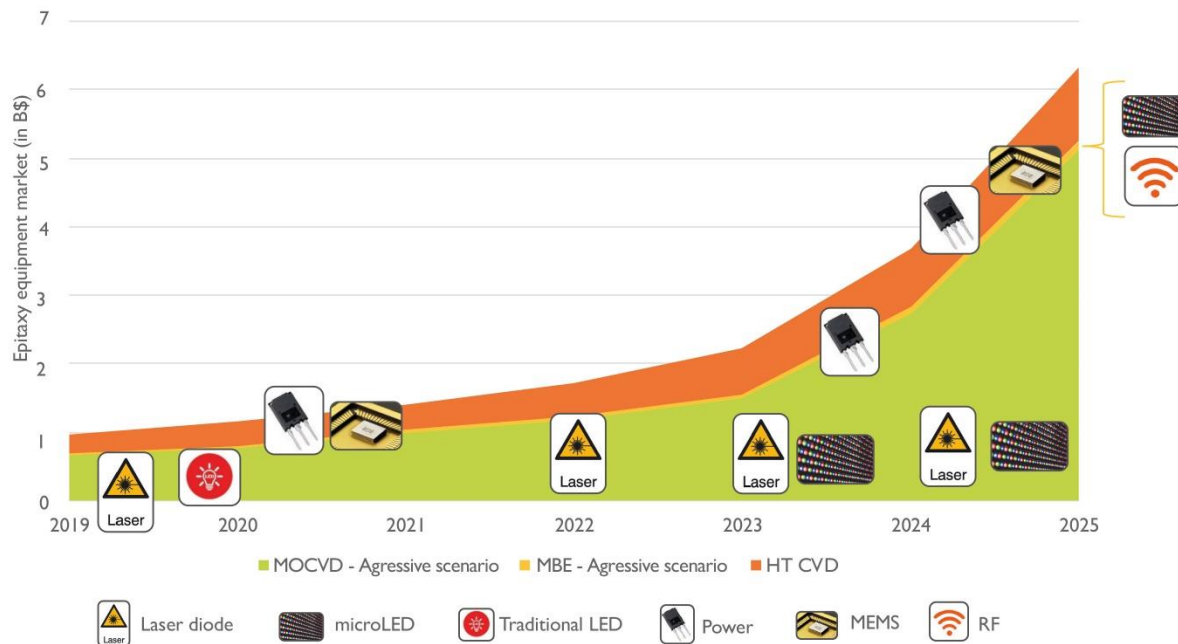
Ga-vacancies?
Yes!



Thank you for your attention!

Epitaxy equipment market for More than Moore devices: 2019-2025 breakdown by technology

(Source: Epitaxy Growth Equipment for More Than Moore Devices Technology and Market Trends 2020 report, Yole Développement, 2020)



About 500 epitaxial systems installed every year, 2000 in 2025.