Crystal Growth: Physics, Technology and Modeling

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Lecture 2. Epitaxy of semiconductor structures

http://www.unipress.waw.pl/~stach/cg-2021-22

Epitaxy of semiconductor structures

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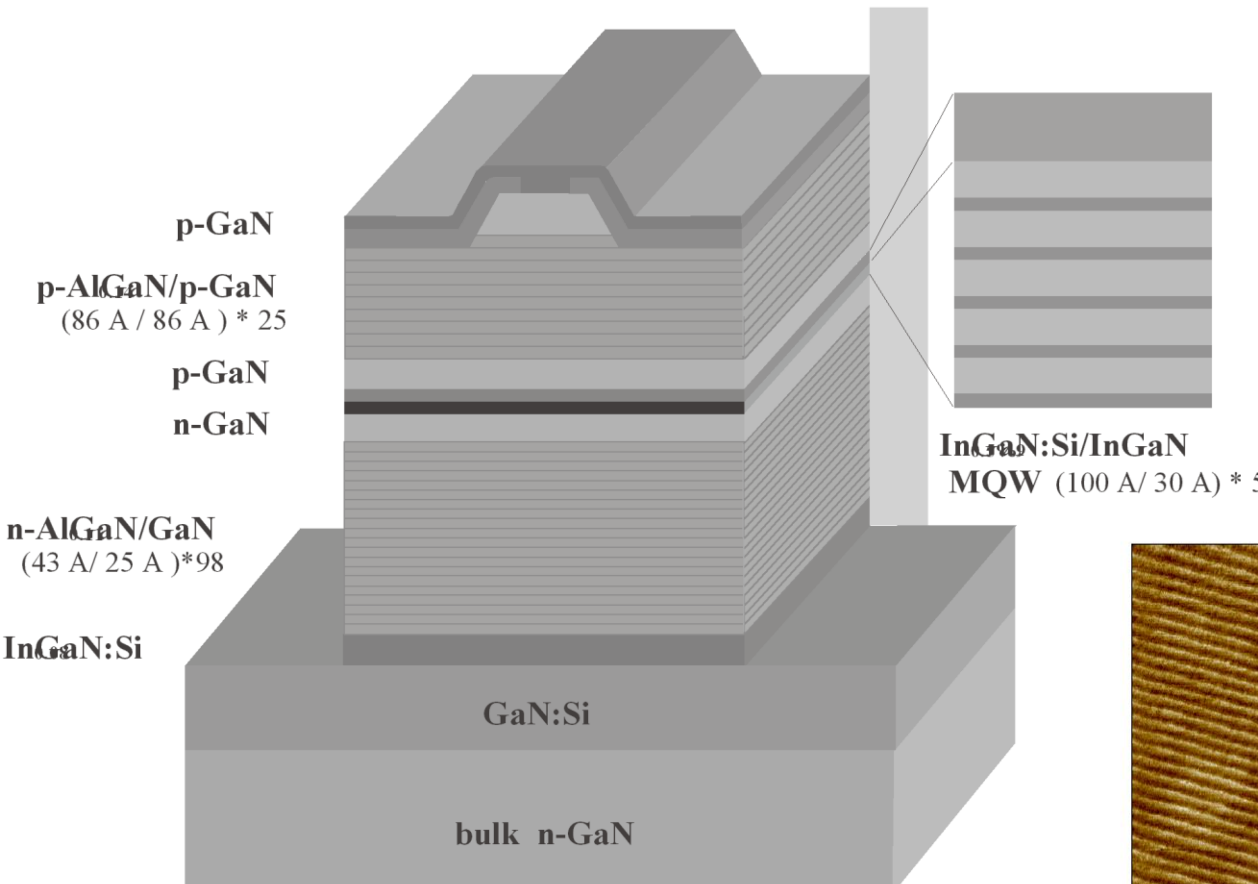
Instytut Wysokich Ciśnień PAN

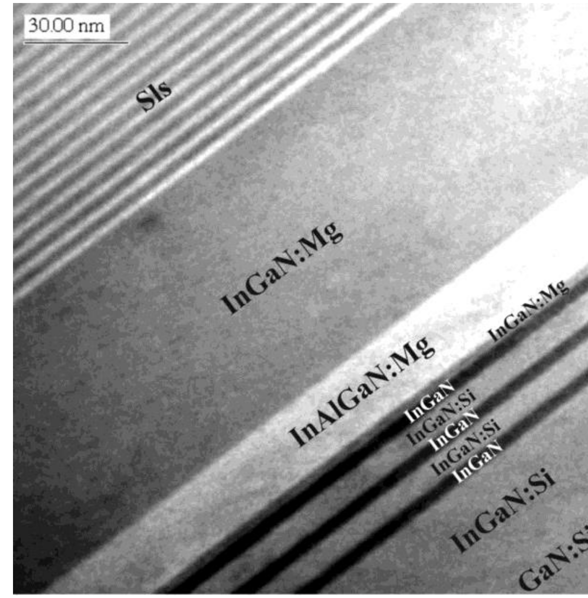
And TopGaN

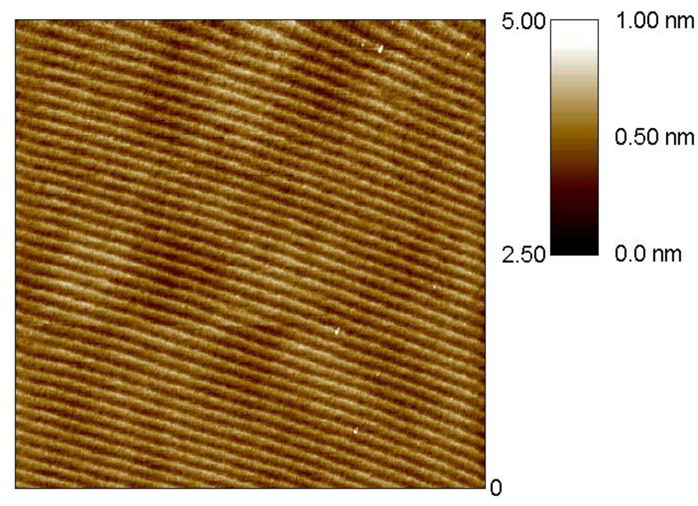
Outline

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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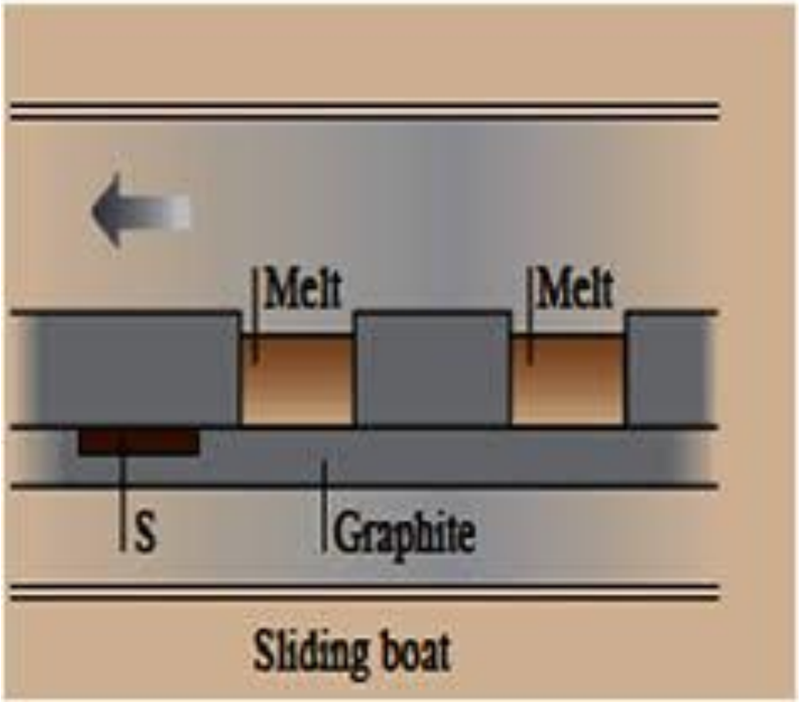
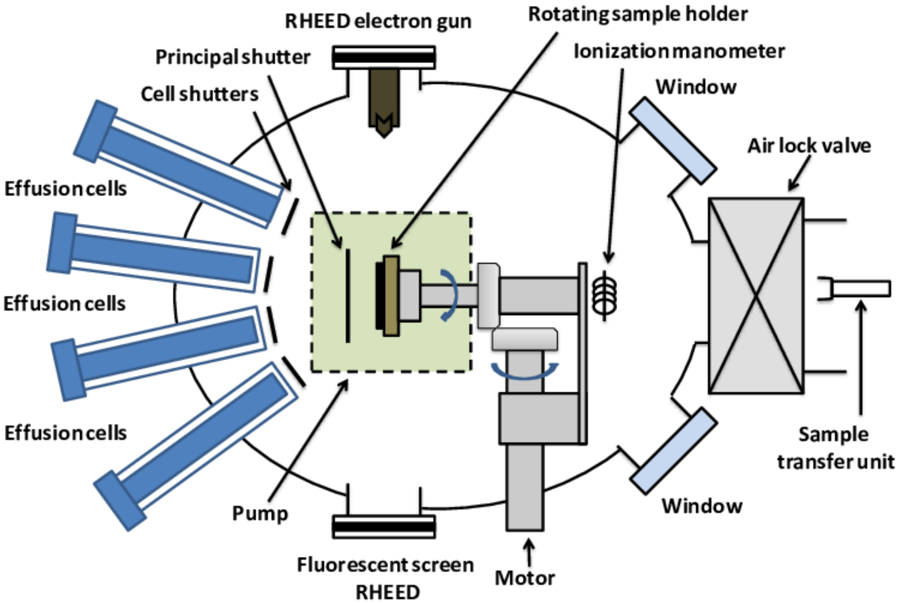
Liquid Phase Epitaxy (LPE)

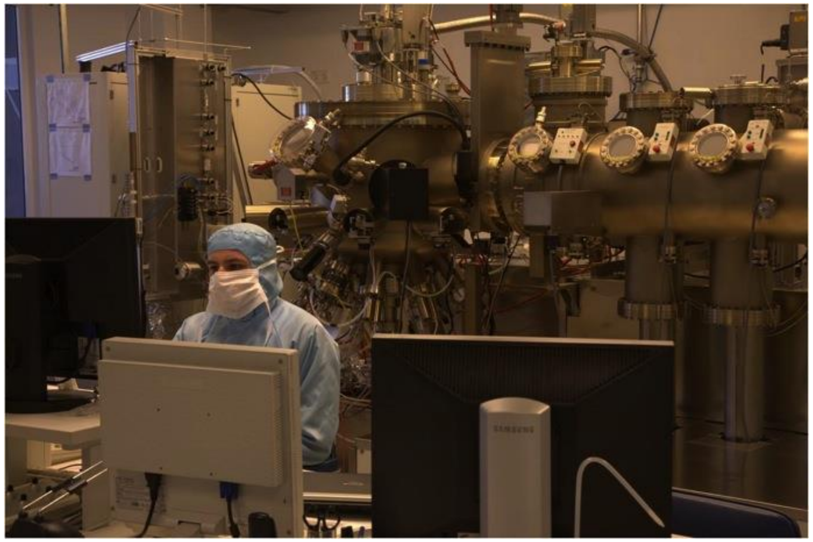


Technology abandoned by industry

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

Molecular Beam Epitaxy (MBE)

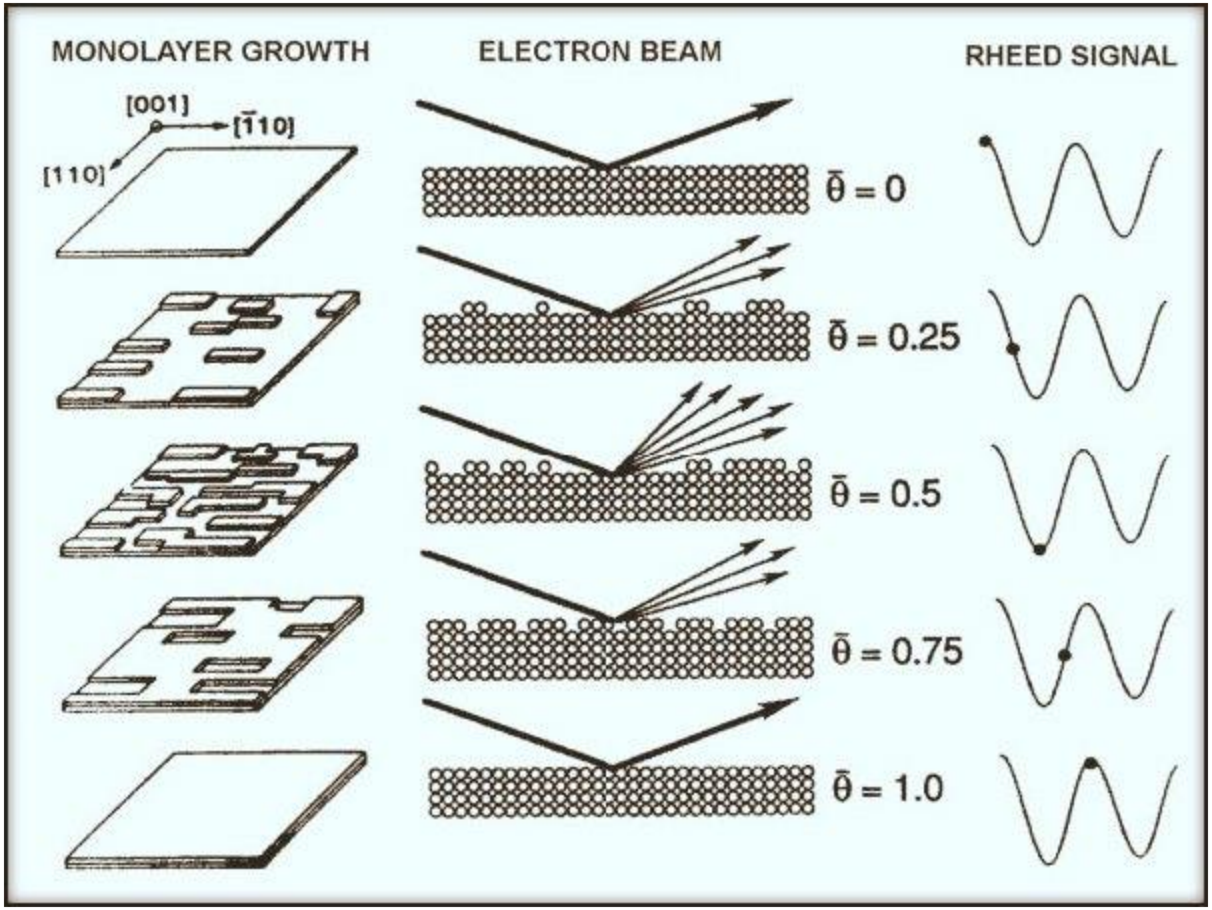




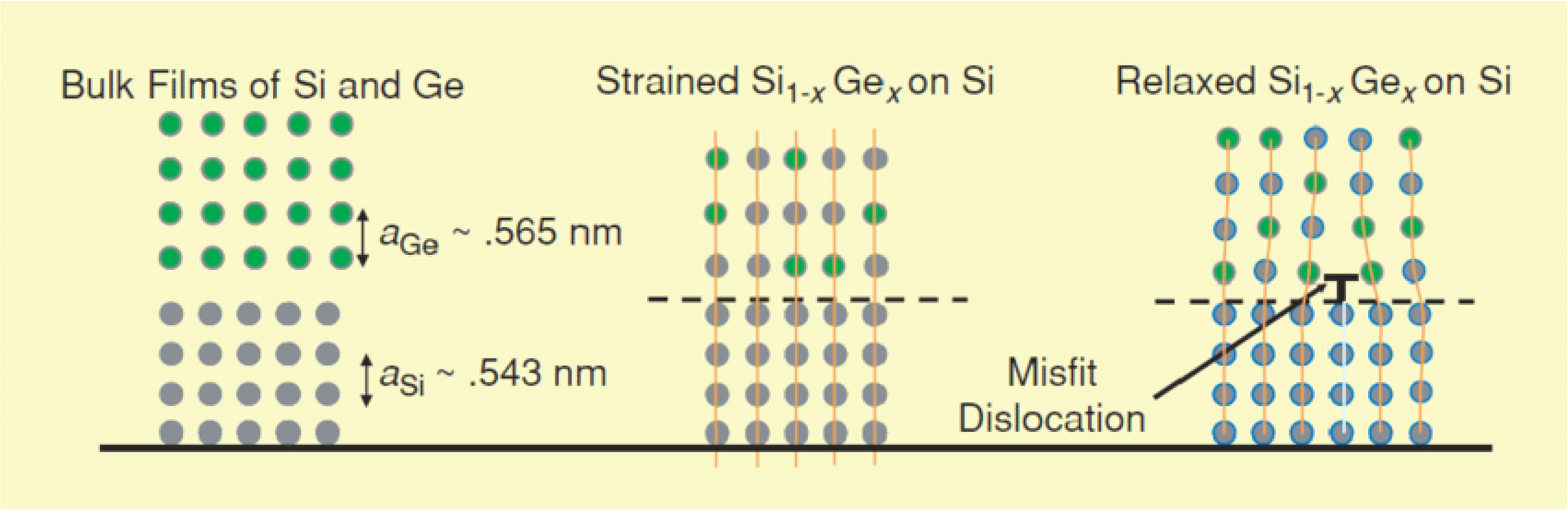
+ High purity, perfect interfaces, no hydrogen in the system

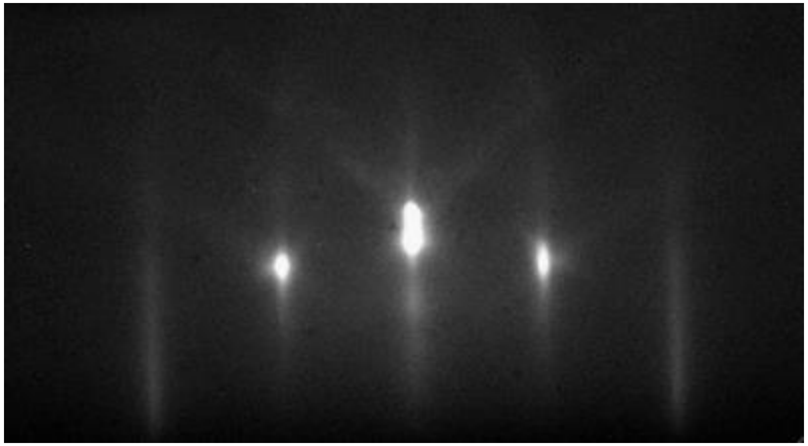
- Costs, no multiwafer machines (one six-inch wafer)

RHEED growth rate and roughness control



RHEED: lattice relaxation control

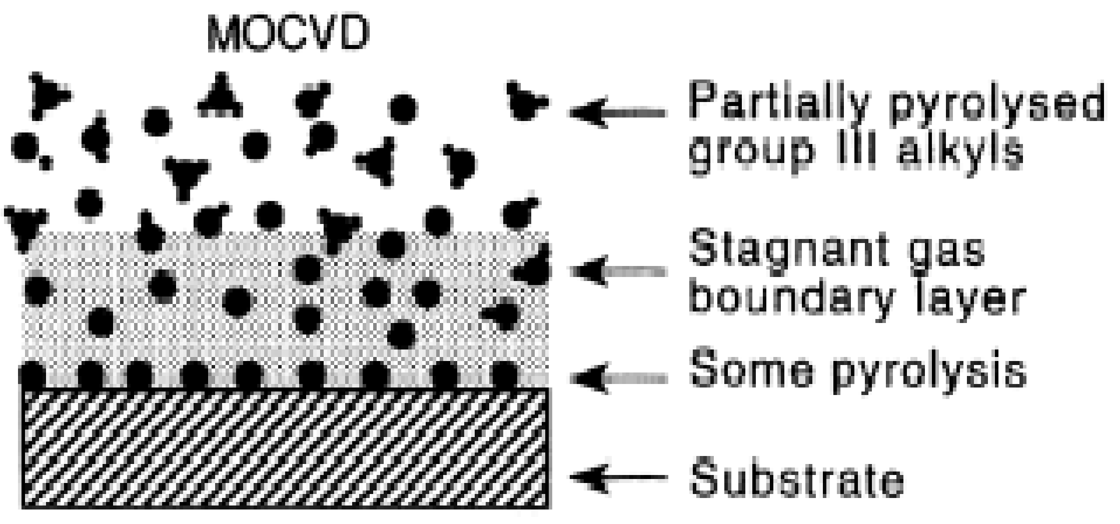




Metalorganic Chemical Vapour Phase Epitaxy MOVPE

A(CH3)3+BH3->AB+3CH4

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

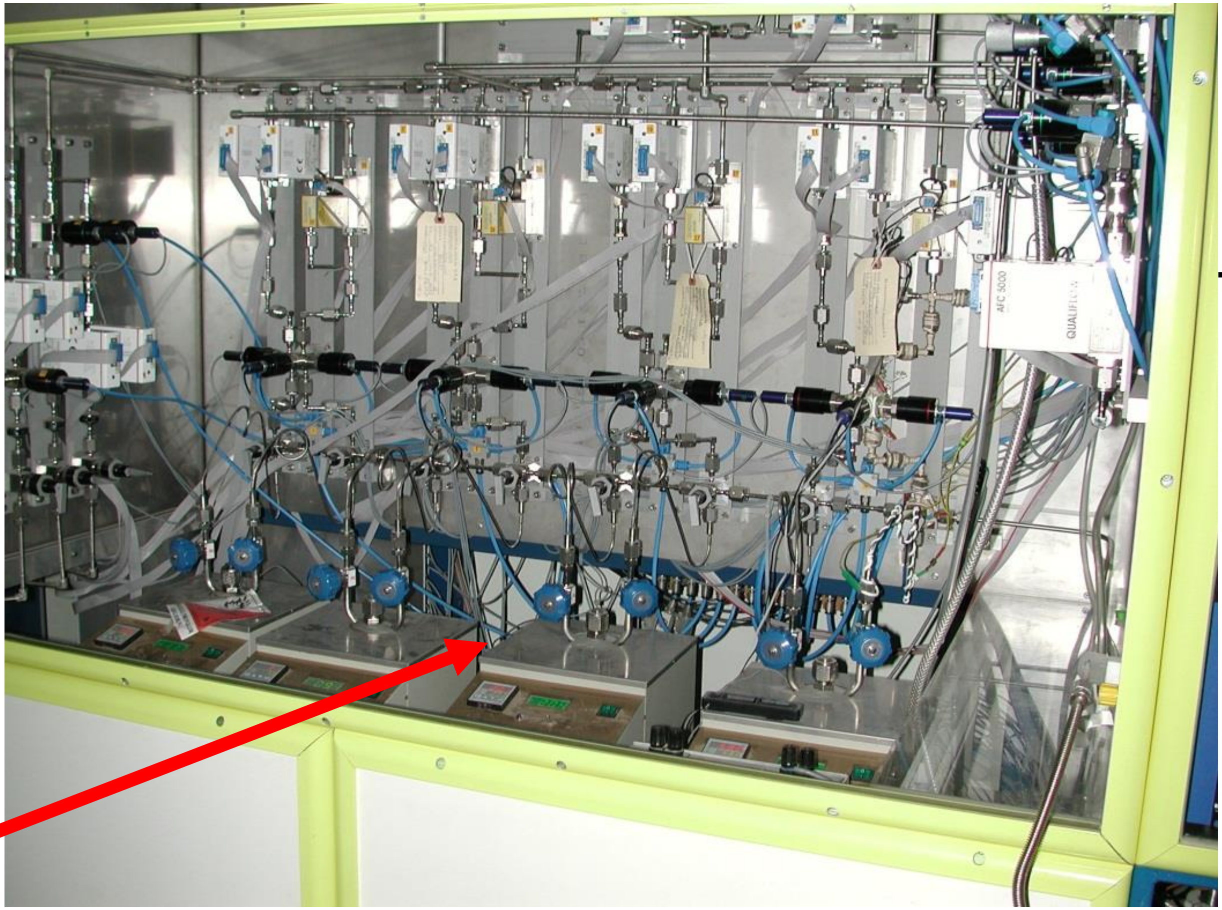


Gas panel, MOVPE, AlGaInN:Mg, Si

Purifiers

Carrier gas
N2, H2

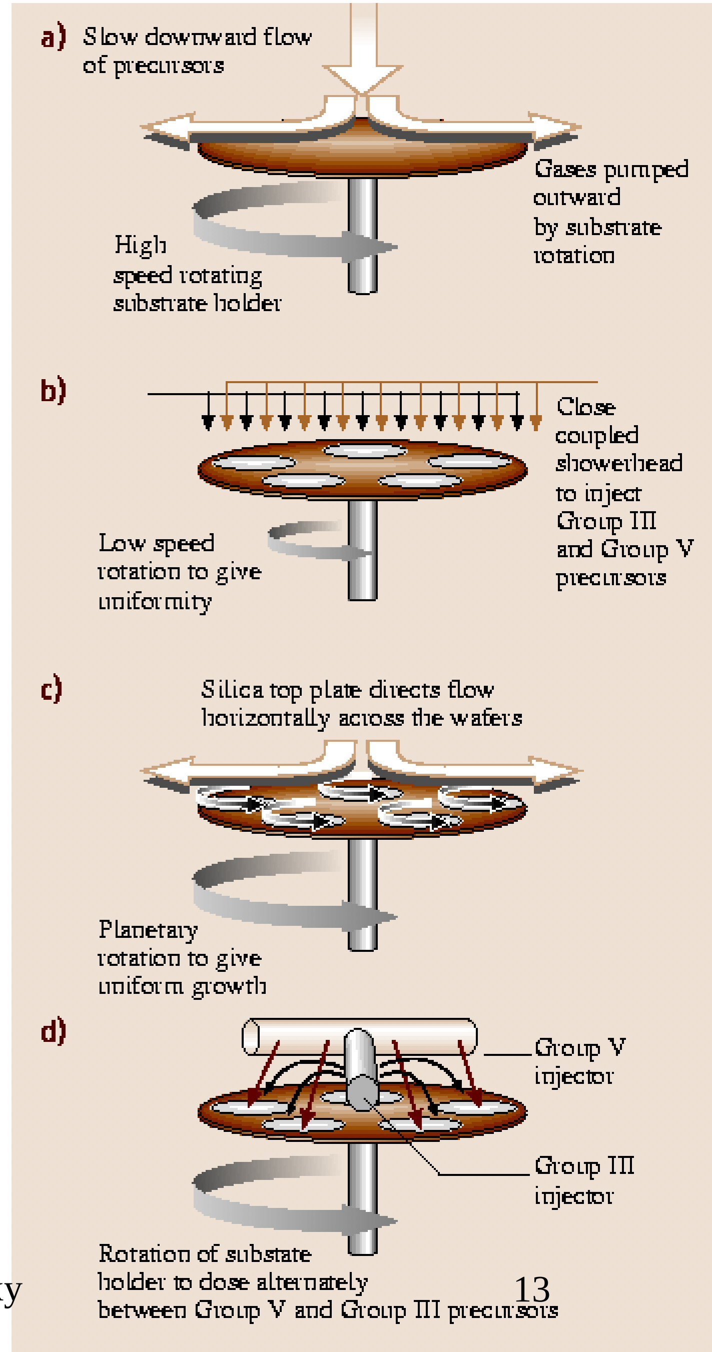
NH3
SiH4



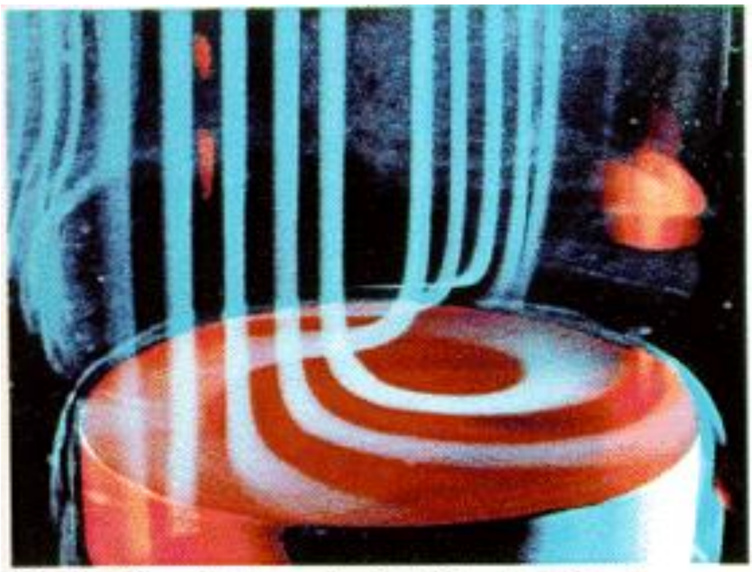
To reactor

Bubblers
TMGa
TEGa
TMAl
TMIn
Cp2Mg

MOVPE reactors



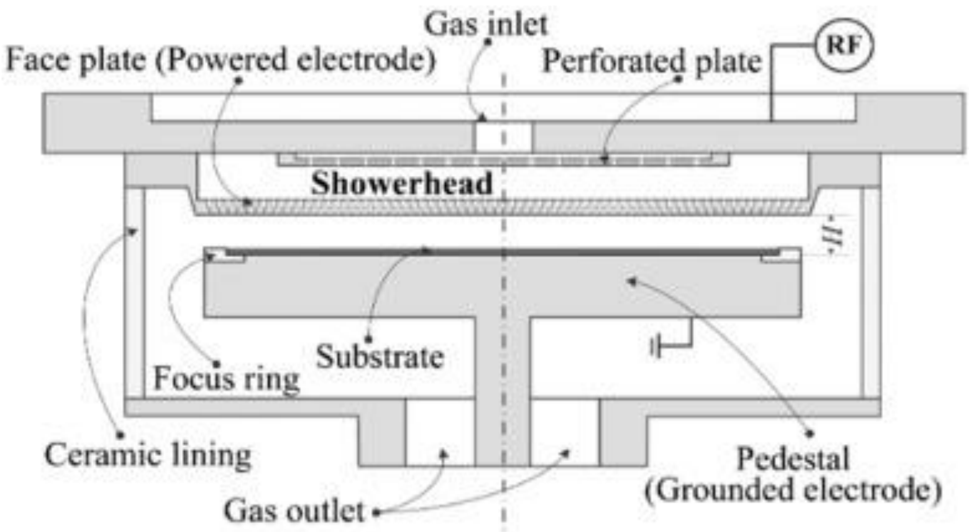
Turbodisc VEECO



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

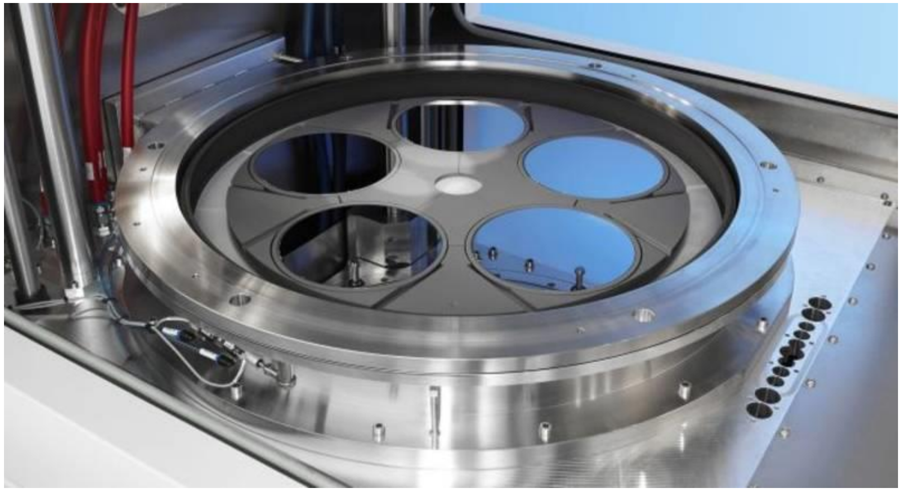
The largest system:31×4”, 12×6” and 6×8”

Showerhead (AIXTRON)

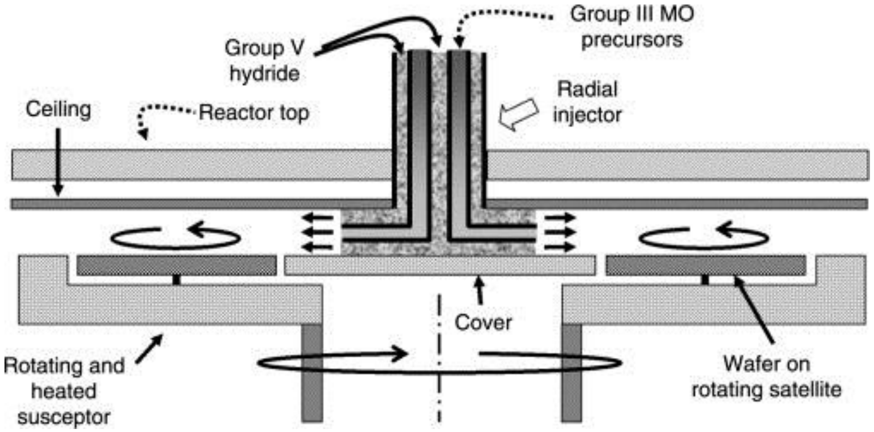


Planetary reactors

(AIXTRON)



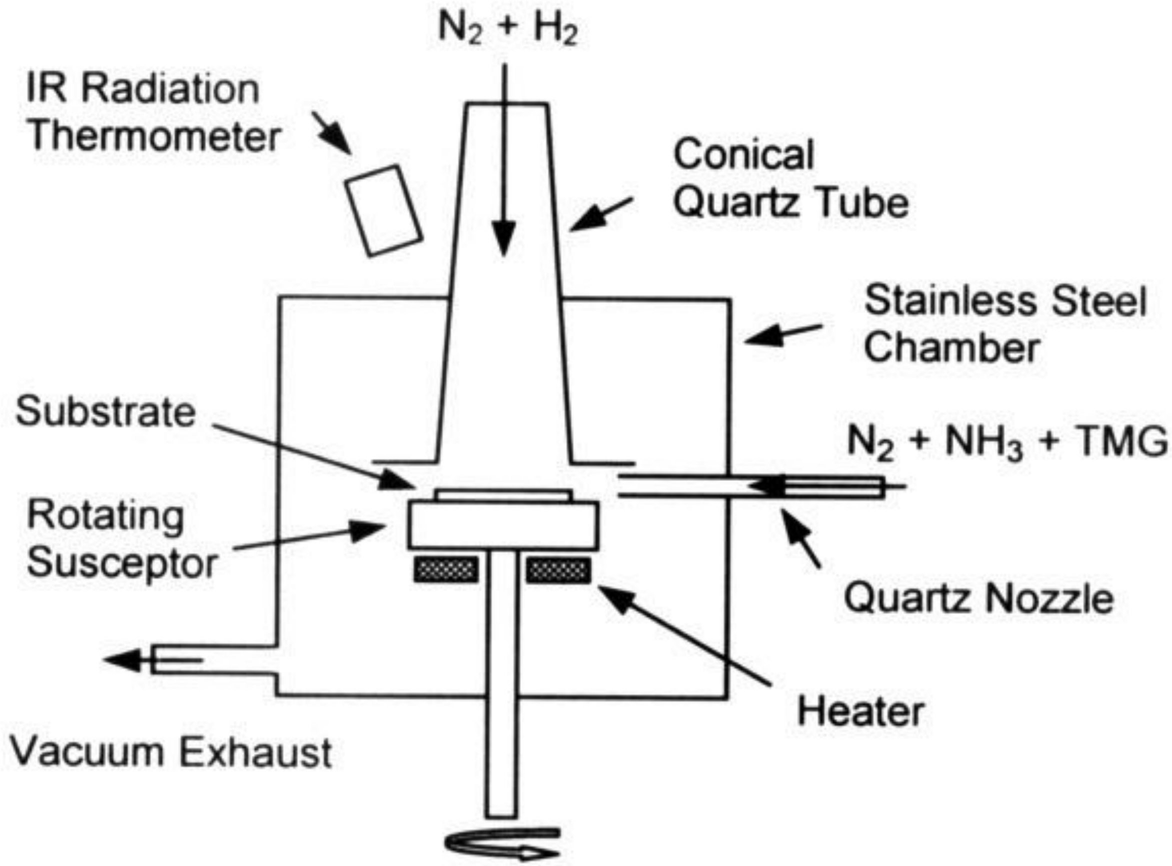
5x8-inch



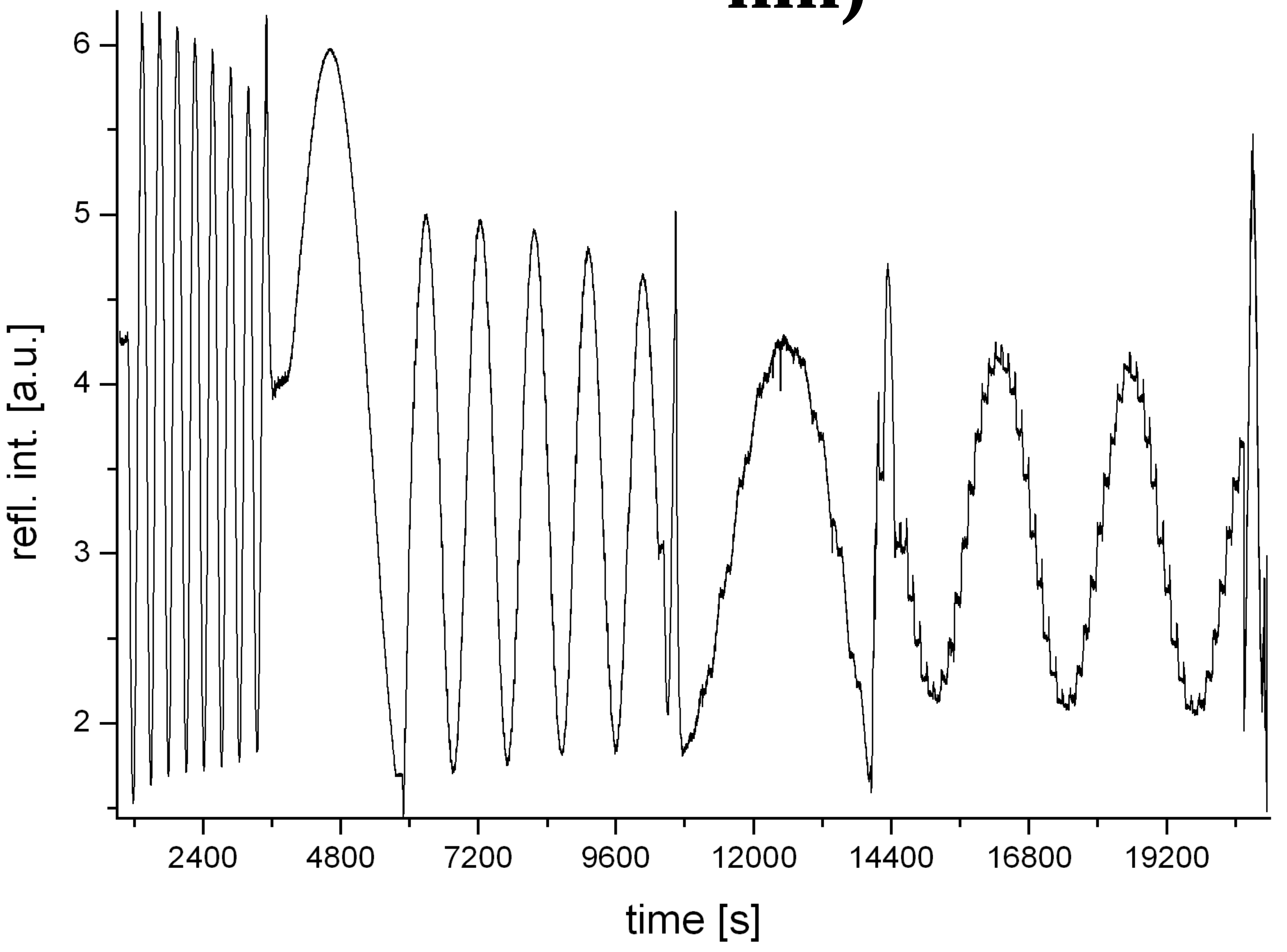
56x2-inch

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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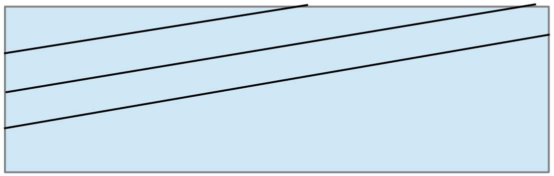
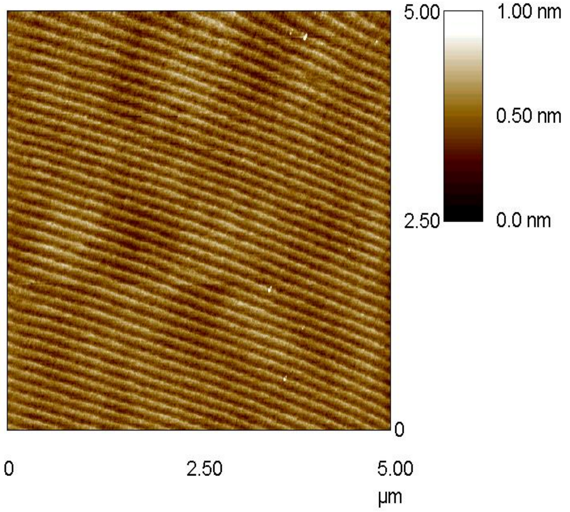
Step-flow growth mode and substrate off-orientation

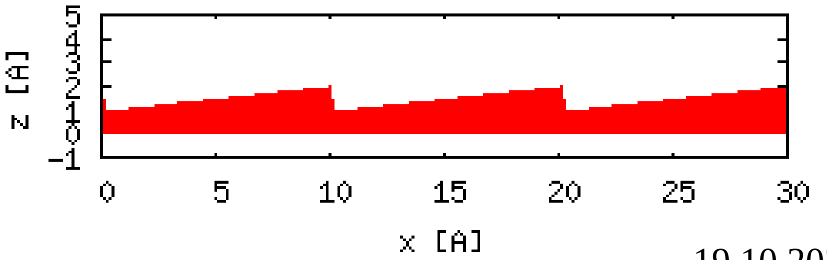
- The steps flow slower for higher off-orientation

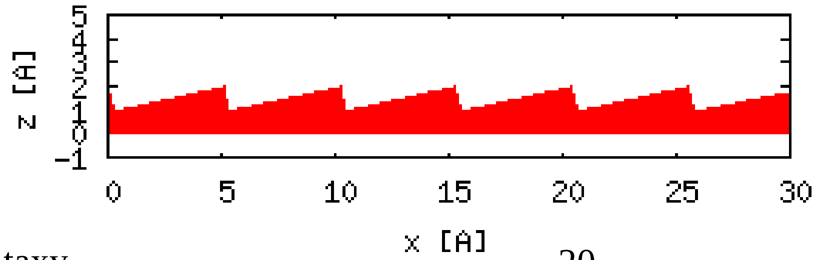




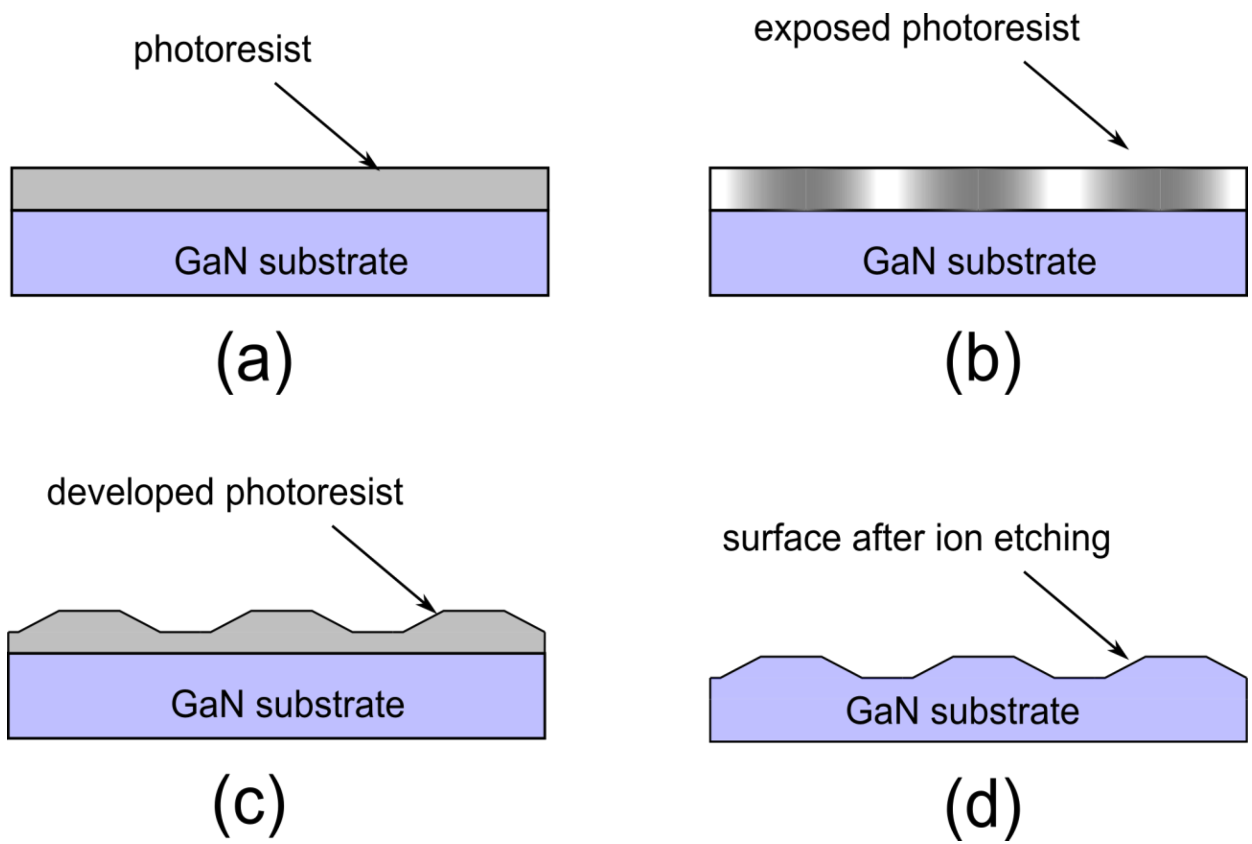
Low misorientation - fast atomic steps

Higher misorientation - slower atomic steps



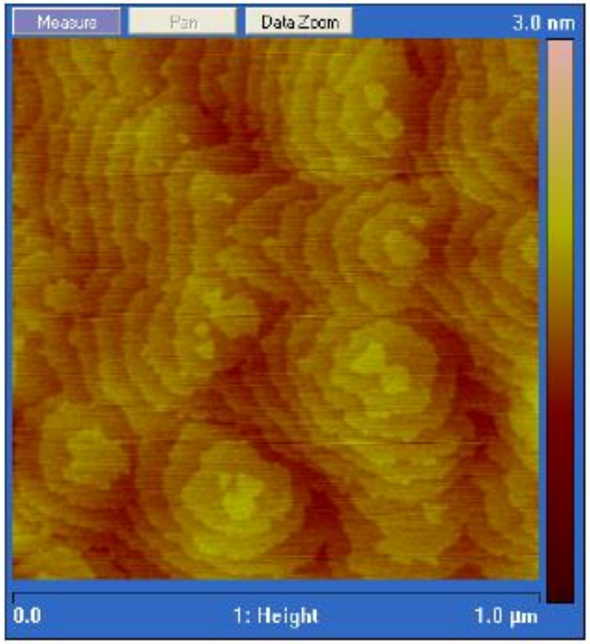


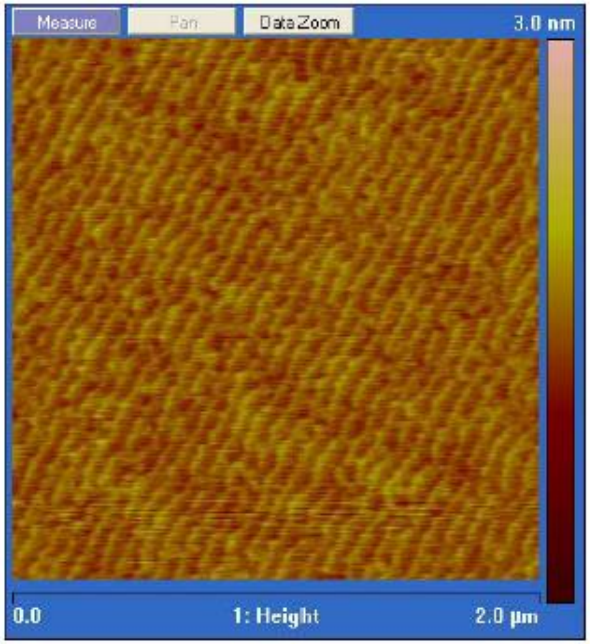
Lateral patterning

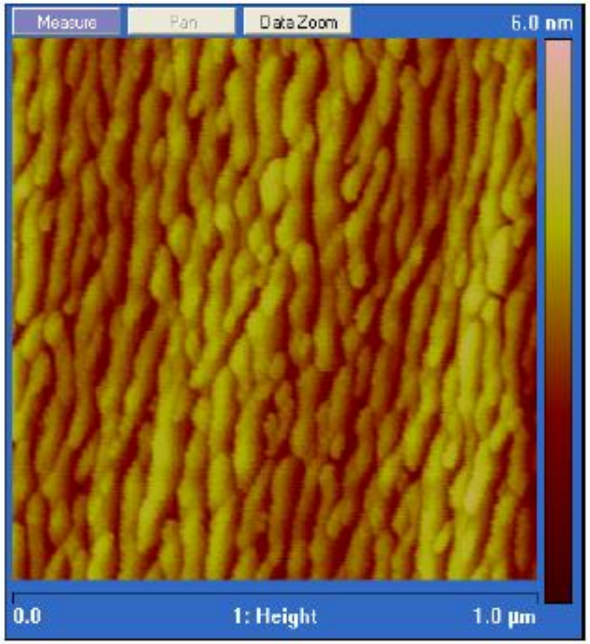


M. Sarzynski idea
Patented by TopGaN/Unipress

Morphology of InGaN layers grown on GaN substrates of different misorientation, Tgrowth = 820oC







0.2 degree

0.8 degree

1.8 degree

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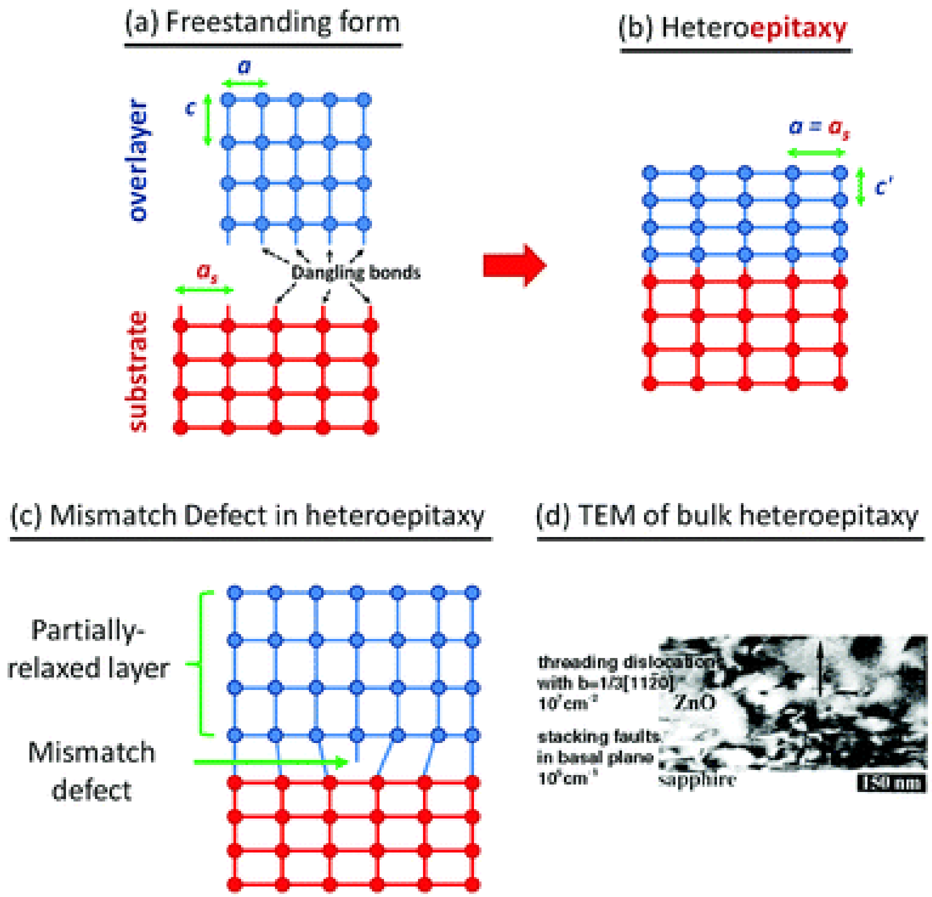
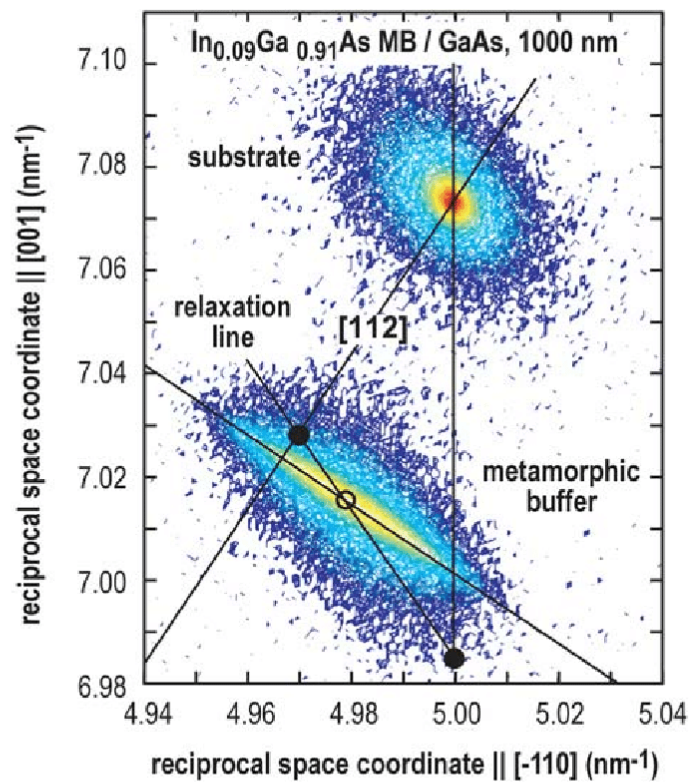
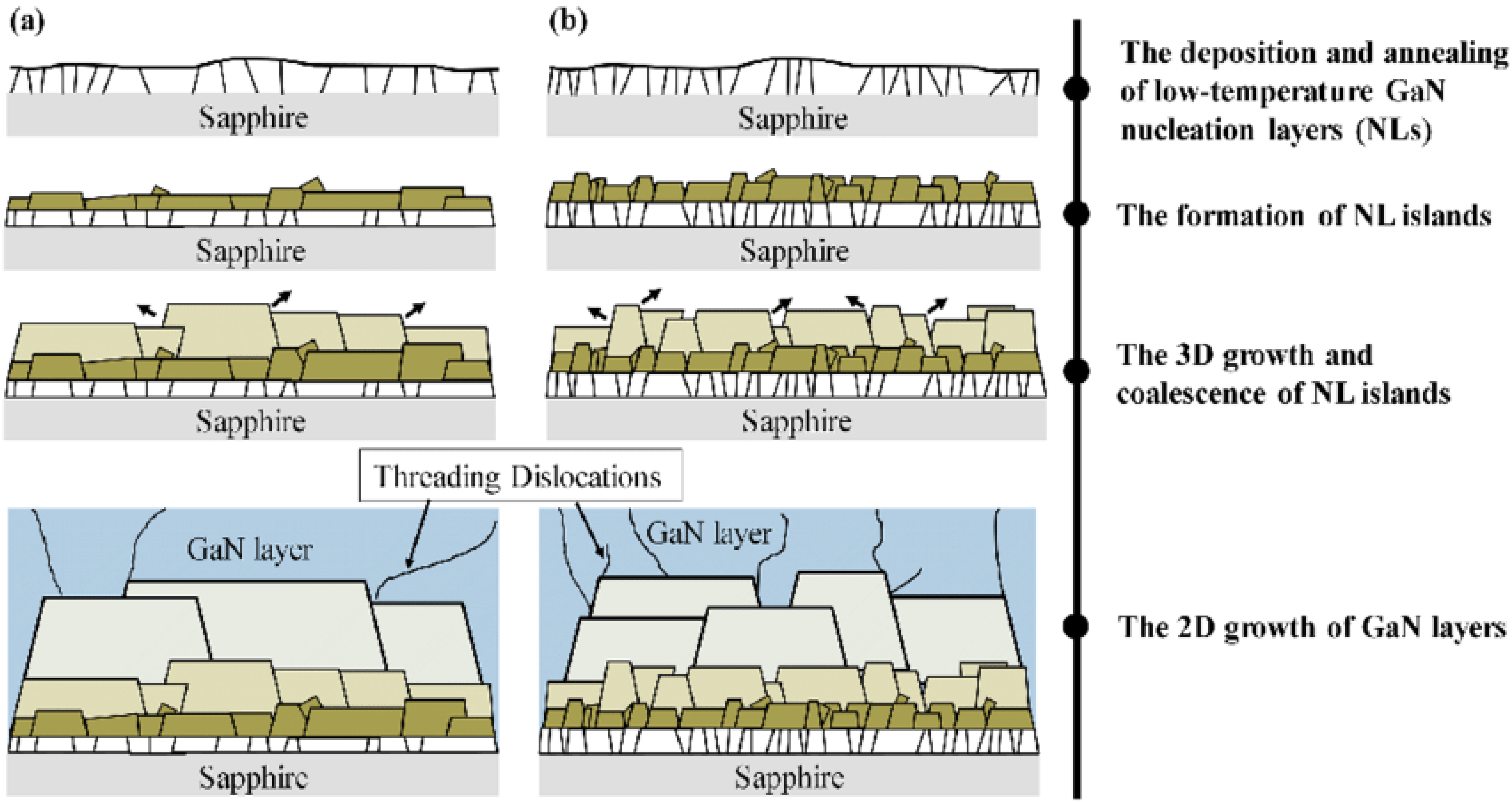
Lattice relaxation



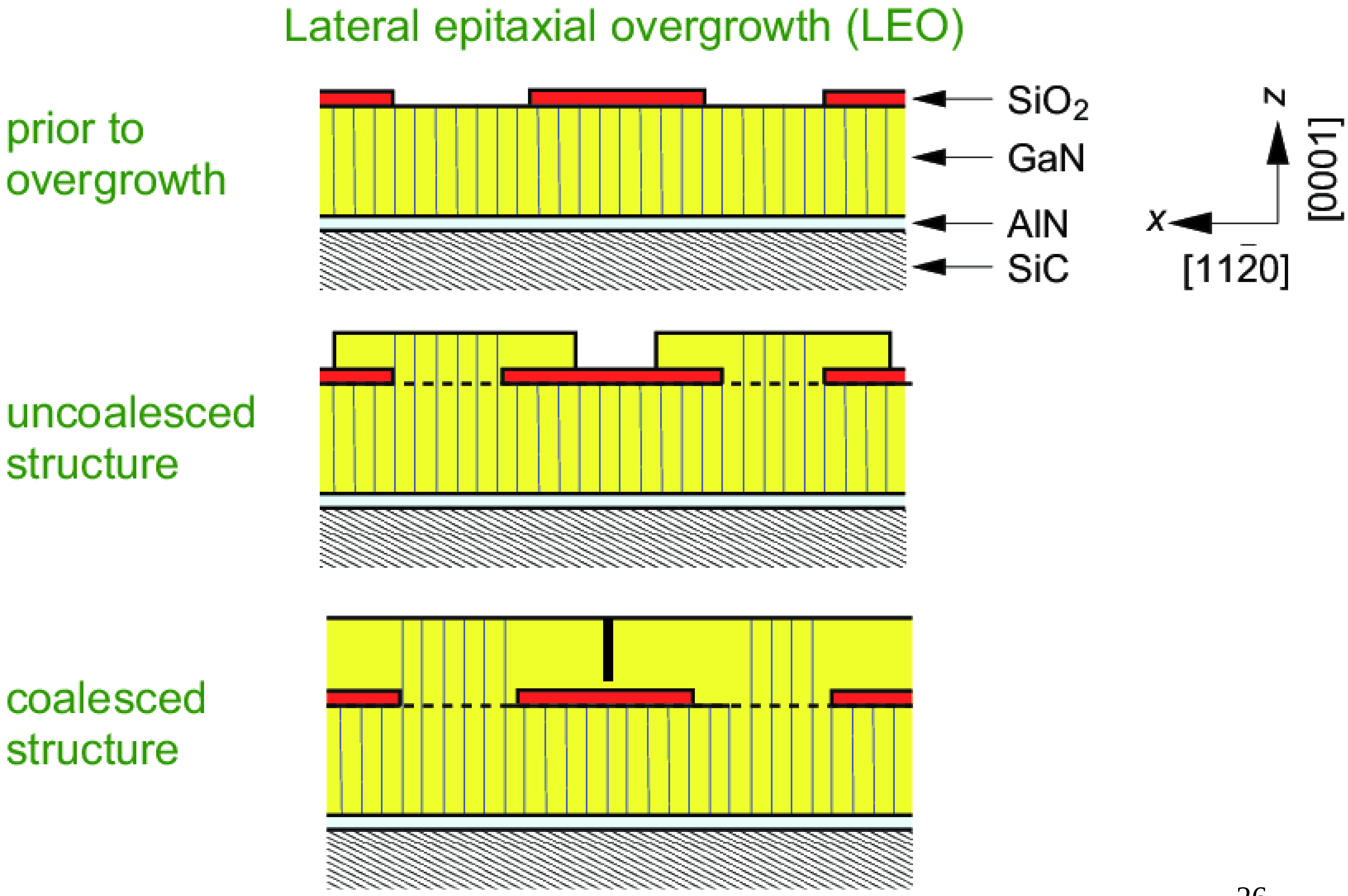


Growth on highly mismatched substrates



Schematic of the growth process of GaN layers for (a) samples S1 and (b) S2 with H 2 and N 2 as nucleation layer carrier gases.

Epitaxial Lateral Overgrowth



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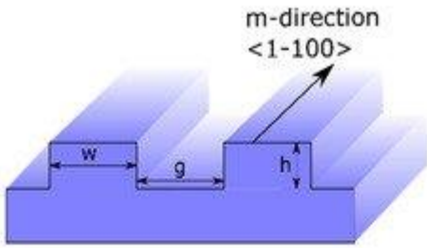
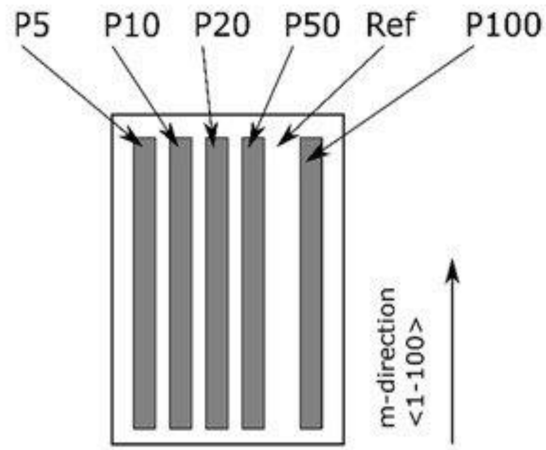
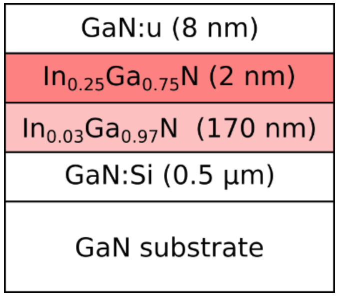
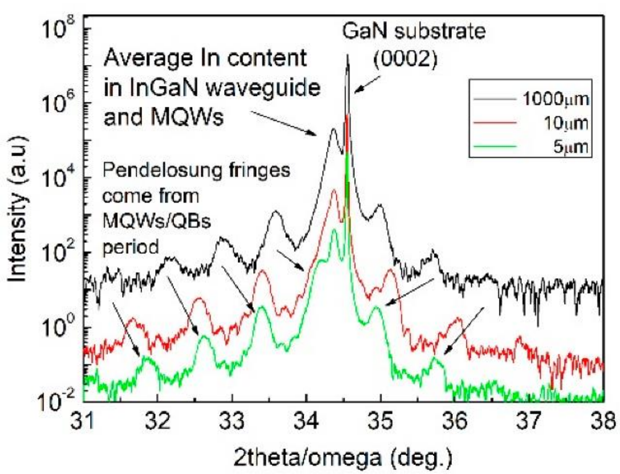

m-direction
<1-100>
w
g
h

(a)

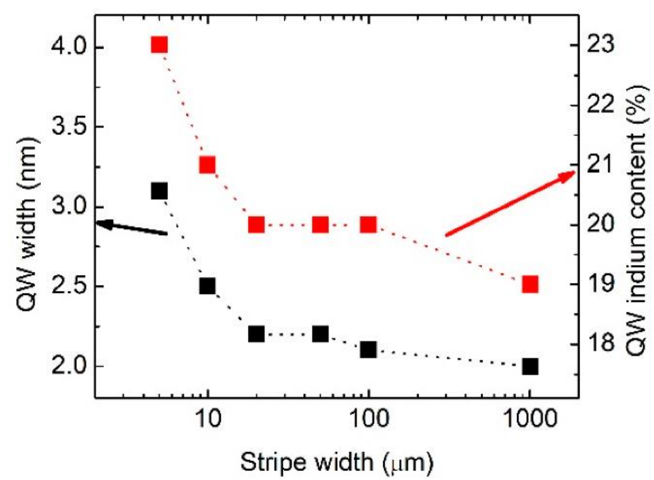

P5
P10
P20
P50
Ref
P100
m-direction
<1-100>

(b)

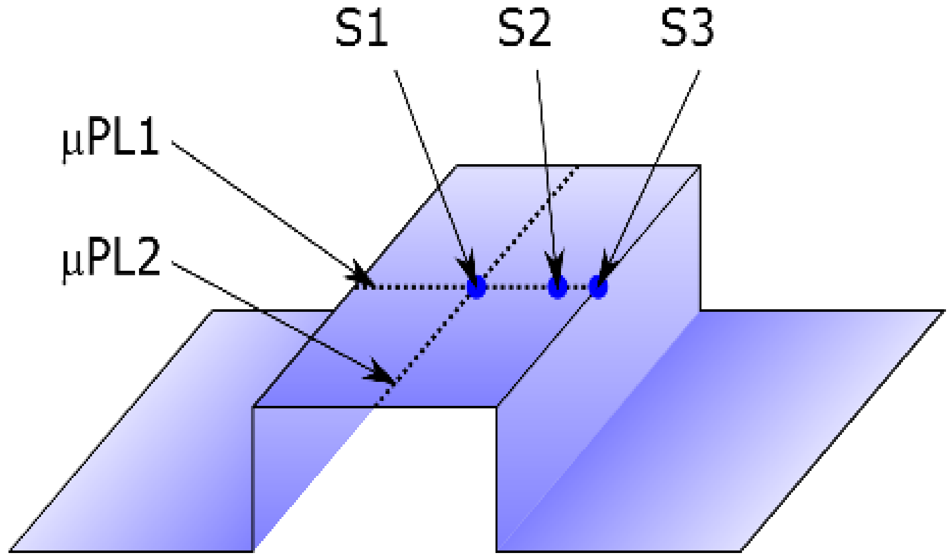

GaN:u (8 nm)
$In_{0.25}Ga_{0.75}N$ (2 nm)
$In_{0.03}Ga_{0.97}N$ (170 nm)
GaN:Si (0.5 µm)
GaN substrate

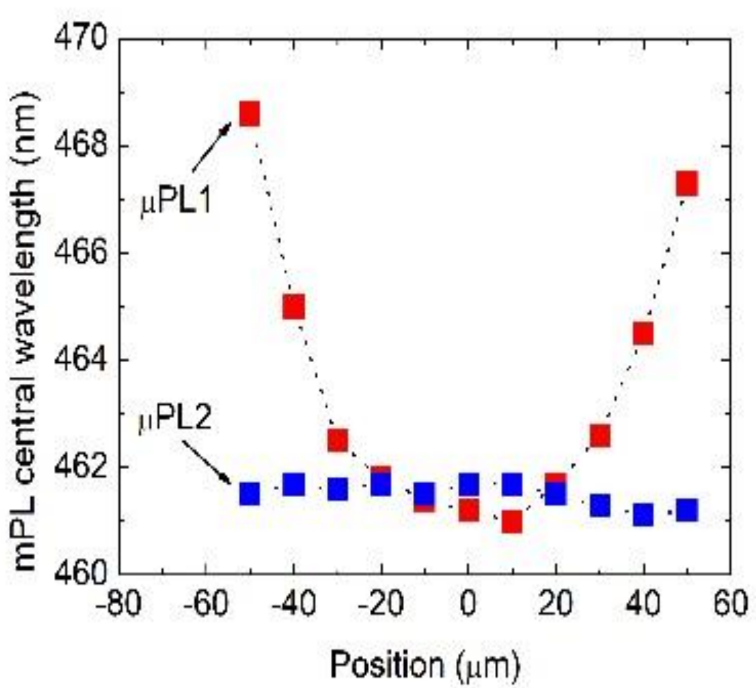

GaN substrate
(0002)
Average In content
in InGaN waveguide
and MQWs
Pendelosung fringes
come from
MQWs/QBs
period
1000µm
10µm
5µm
Intensity (a.u)
2theta/omega (deg.)

(a)

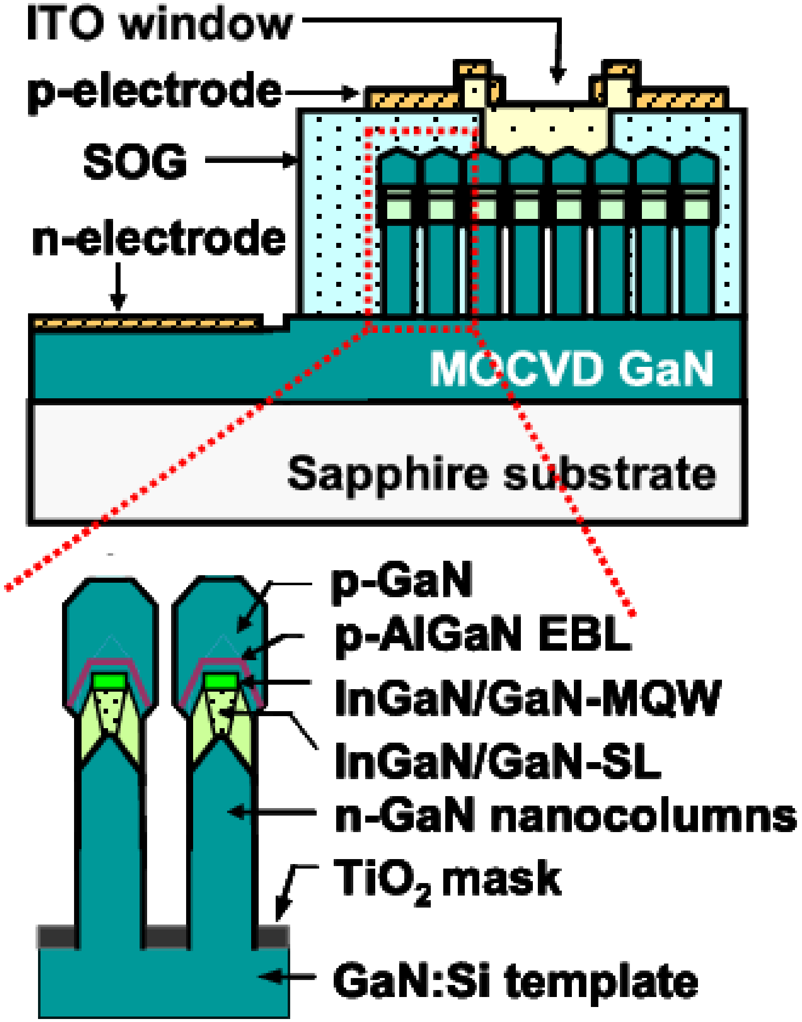

QW width (nm)
QW indium content (%)
Stripe width (µm)

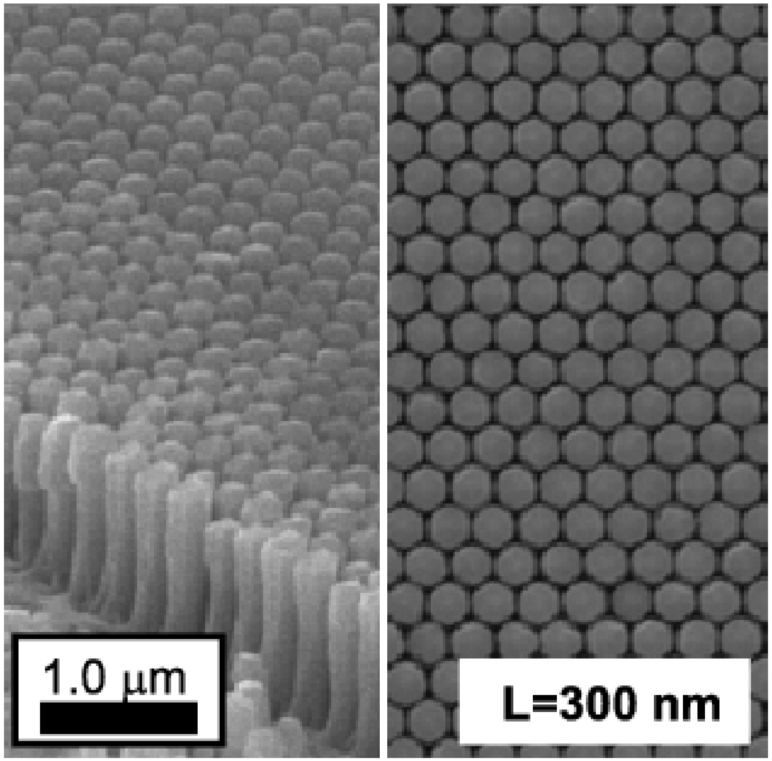
(b)


S1
S2
S3
μPL1
μPL2


470
468
466
464
462
460
mPL central wavelength (nm)
μPL1
μPL2
-80
-60
-40
-20
0
20
40
60
Position (μm)

Nanocolumns



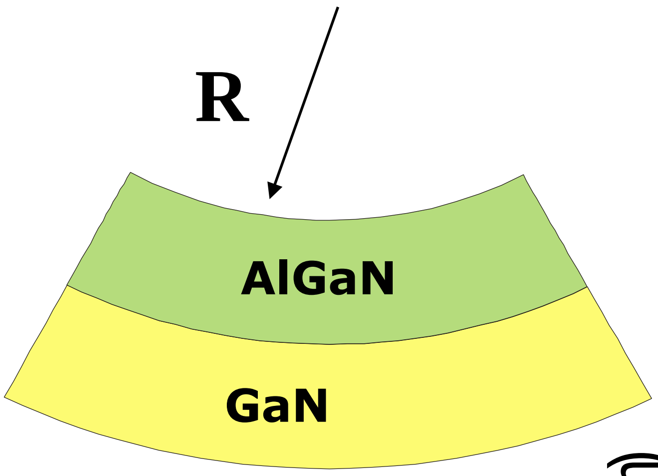


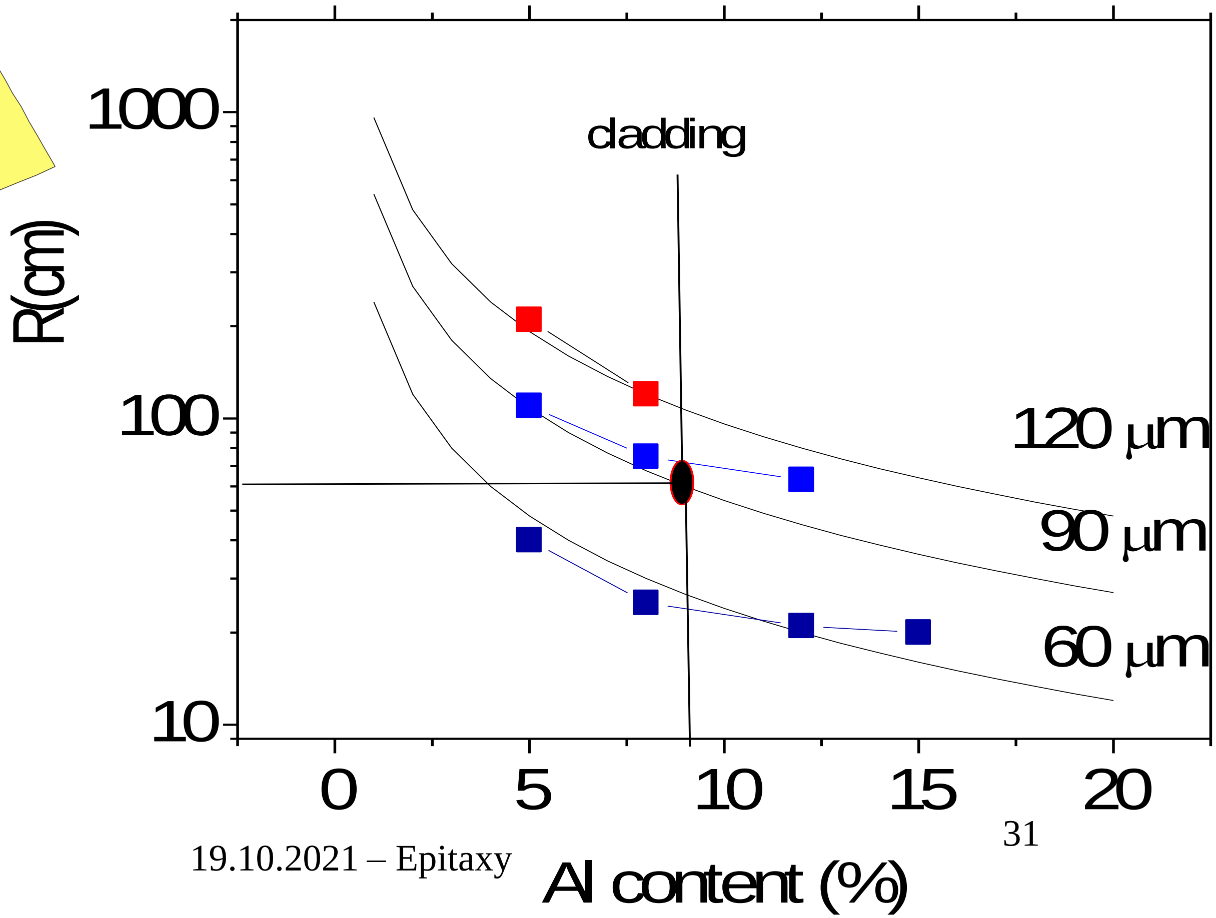
(a)

(b)

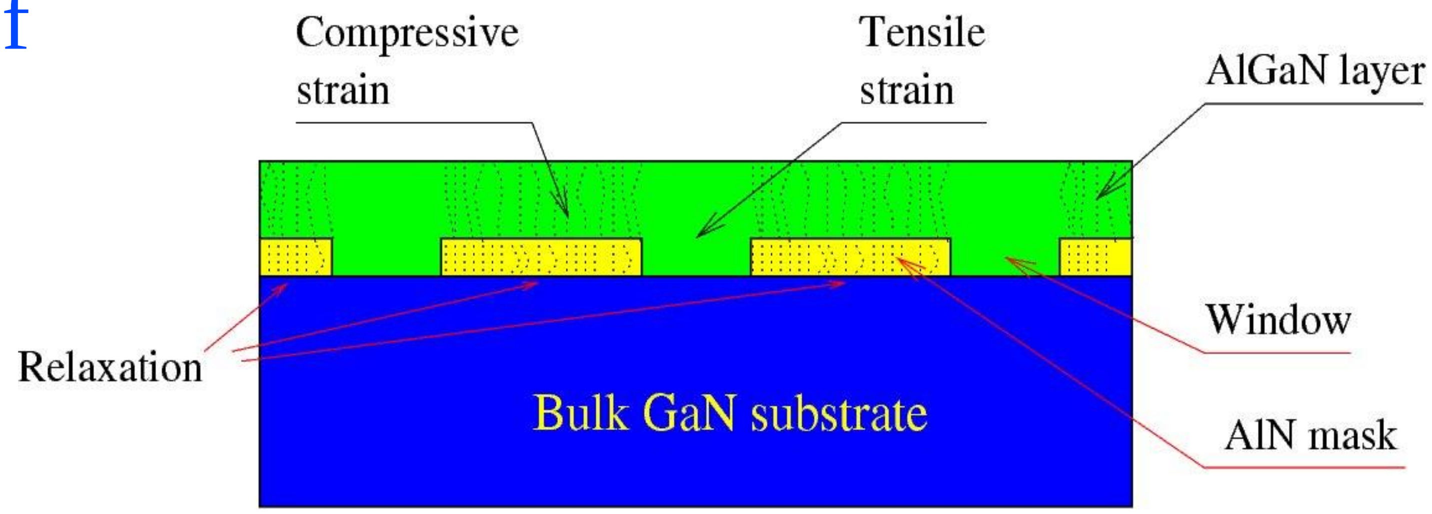
In LDs, we need to have thick AlGaN cladding layers

Tensile strain: cracking and bowing

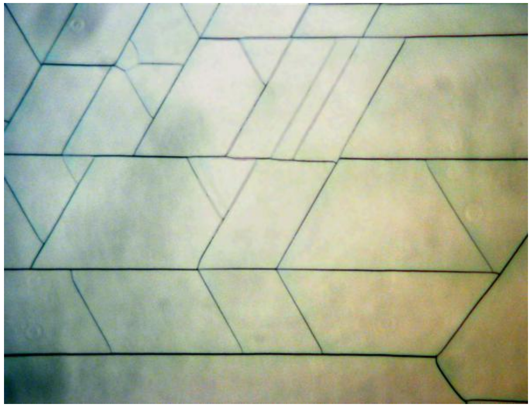




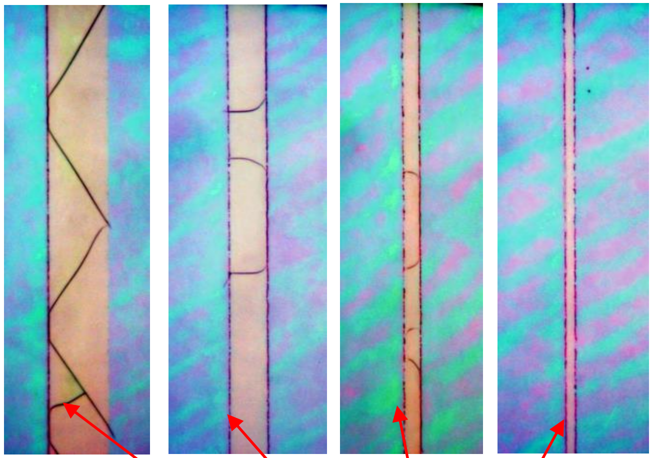
Elimination of cracking and bowing



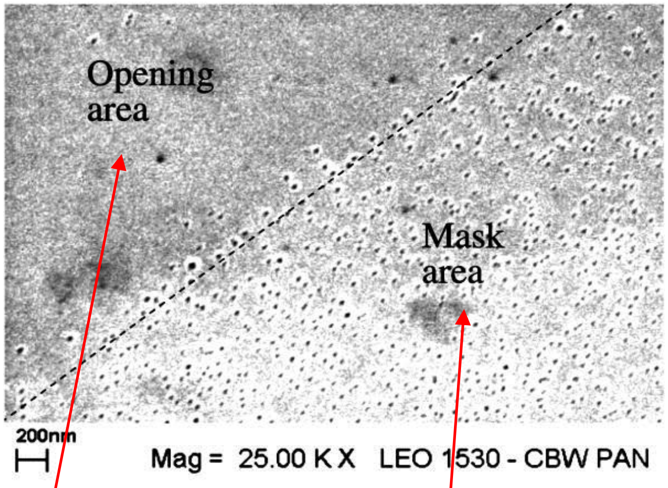
AlGaN 27%
220 nm



No maskAlN



With mask 15   10   5   3   μm



Density of defects: **window<10^6/cm2** **on mask 10^{10}/cm2**

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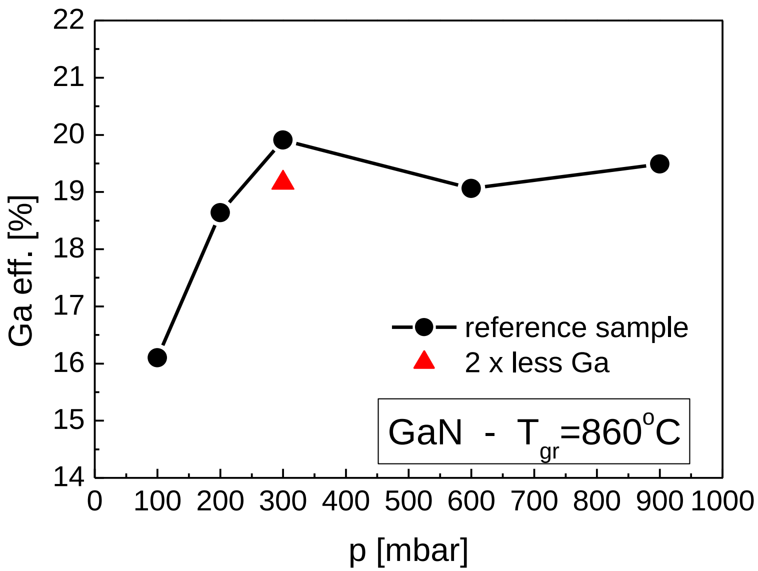
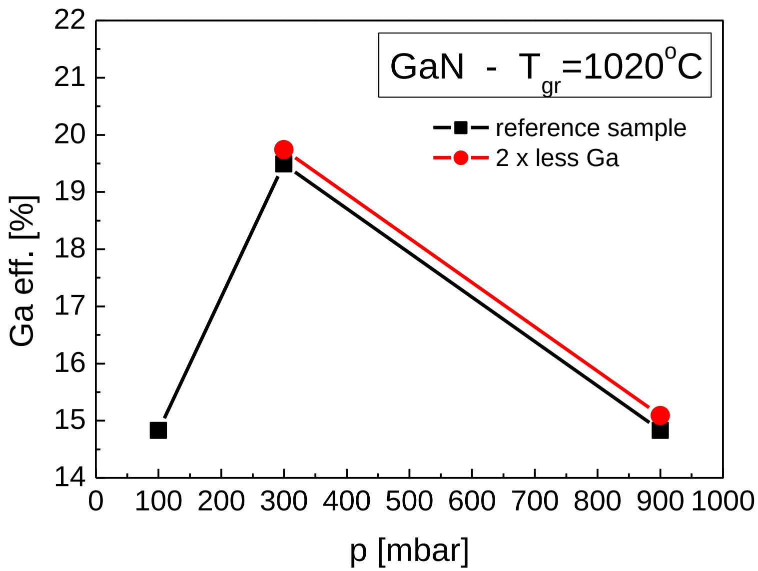
Efficiency of Ga incorporation into GaN in HM

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



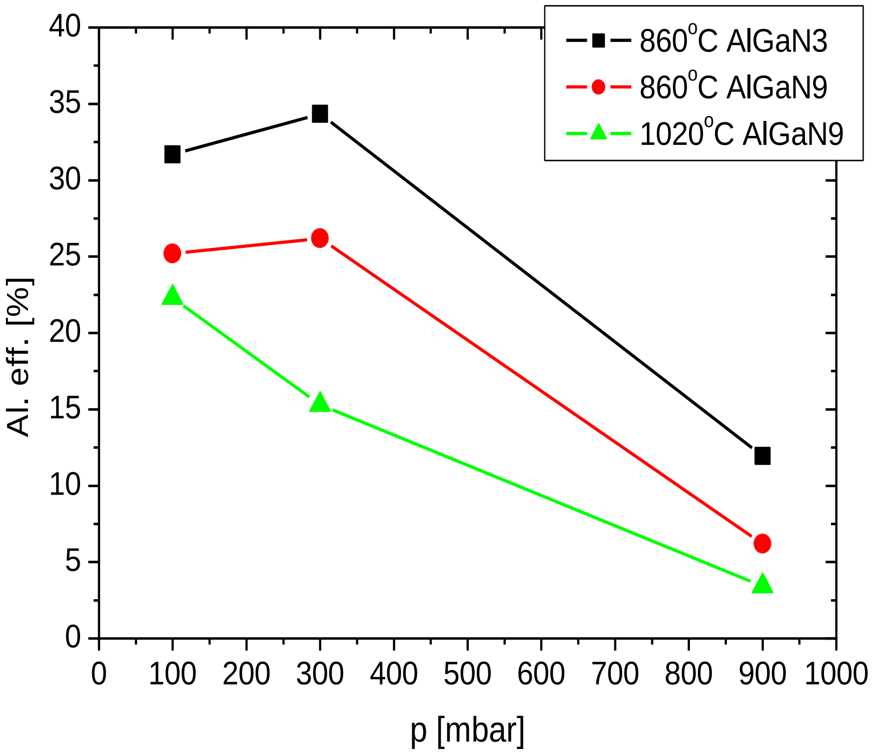


At low pressure, the Ga atoms are blown away from the surface.

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



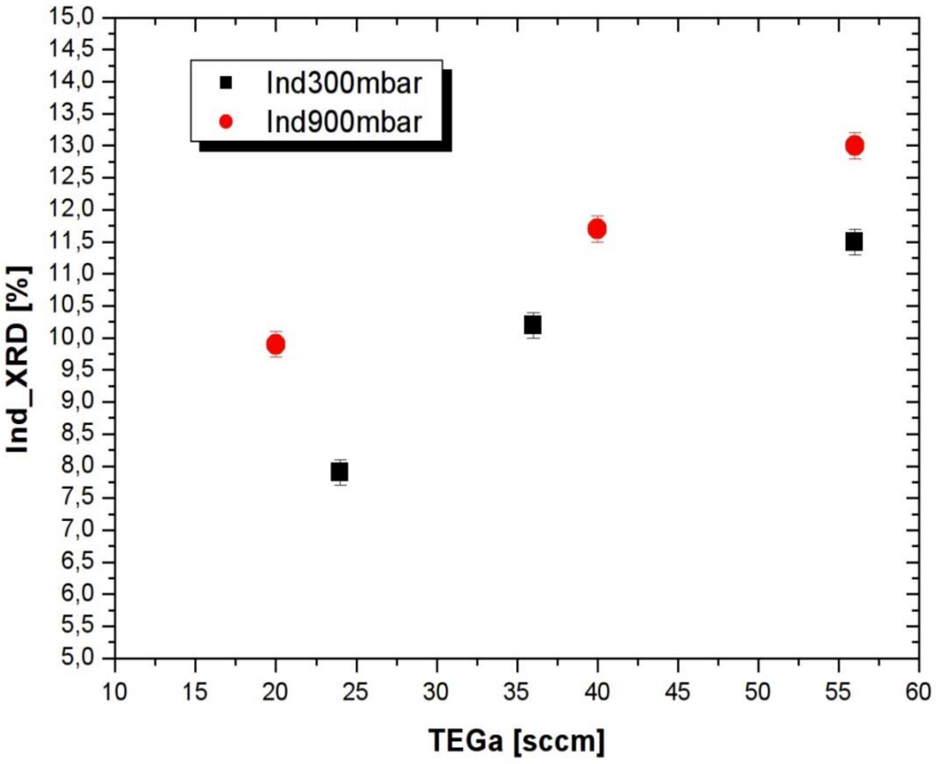
Efficiency of Al incorporation falls down with TMAl flow increase

Prereactions rate higher than in the case of GaN

More prereactions at high temperature and pressure

3 sccm of TMAl
9 sccm of TMAl

Efficiency of In incorporation into InGaN versus TEGa flow

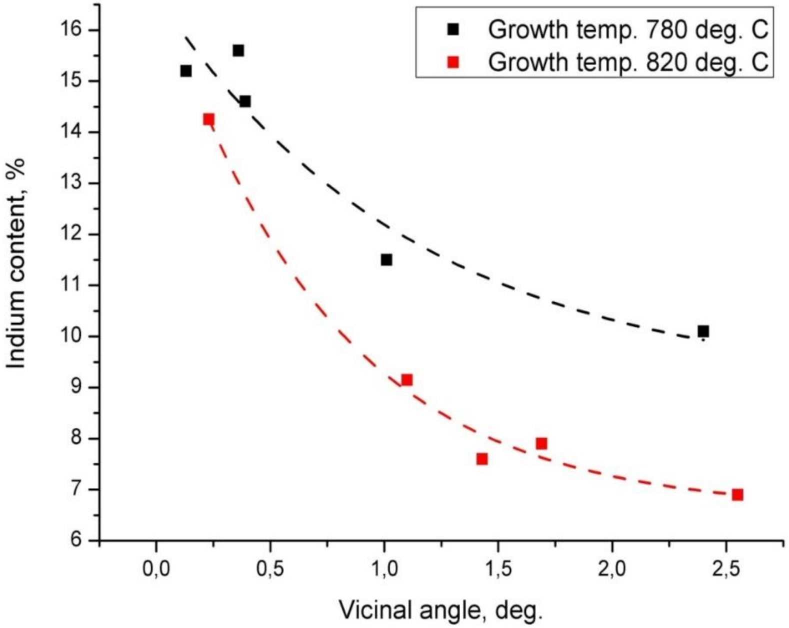


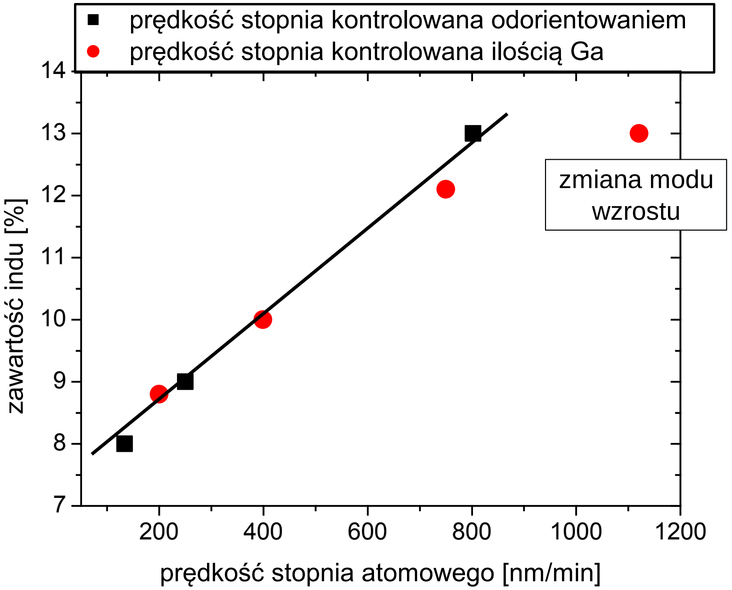
More Ga source in the gas phase, but more In in InGaN solid phase.

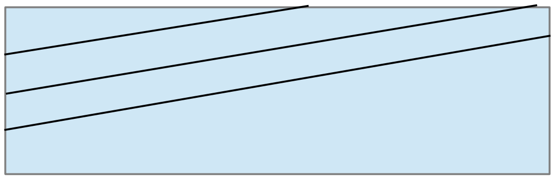
More indium at elevated pressure (not for every reactor!)

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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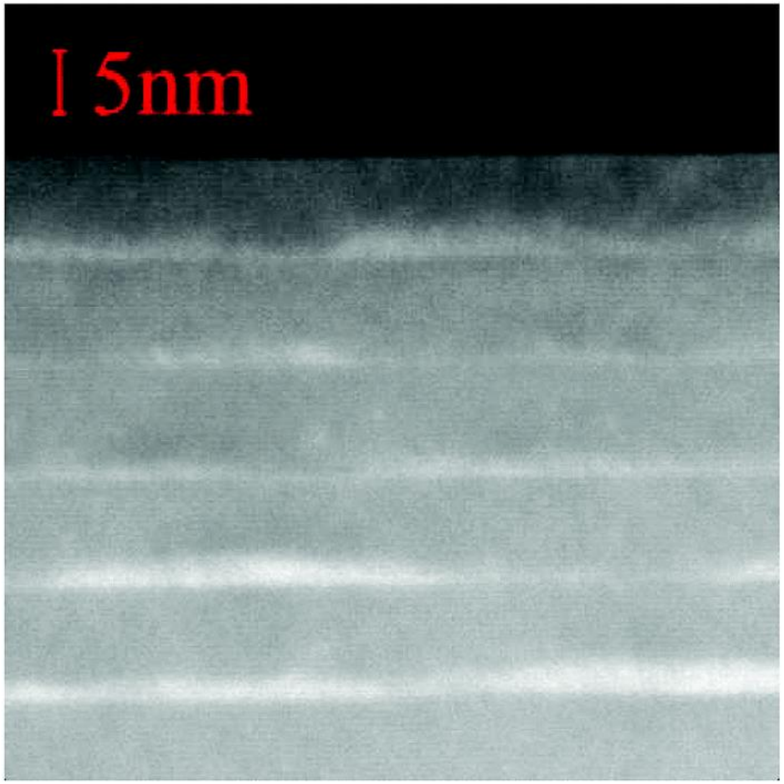
As grown InGaN QWs



Indium fluctuations

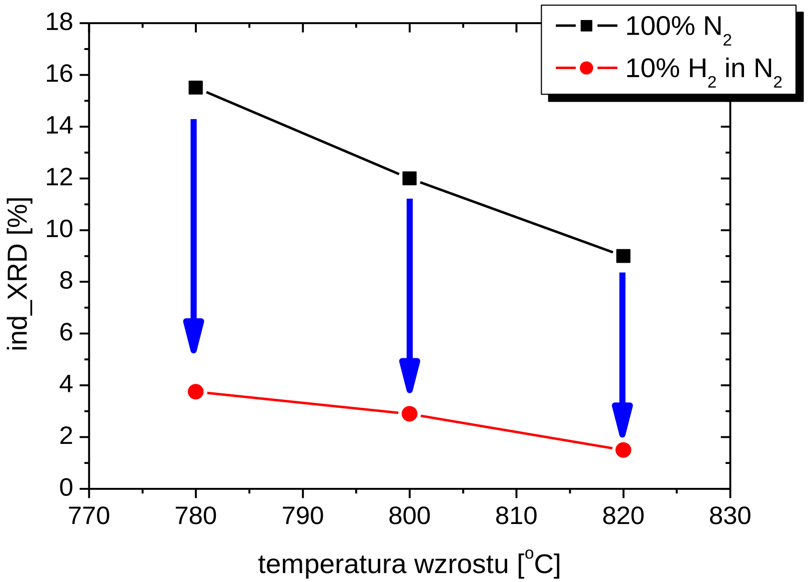
QW thickness fluctuations

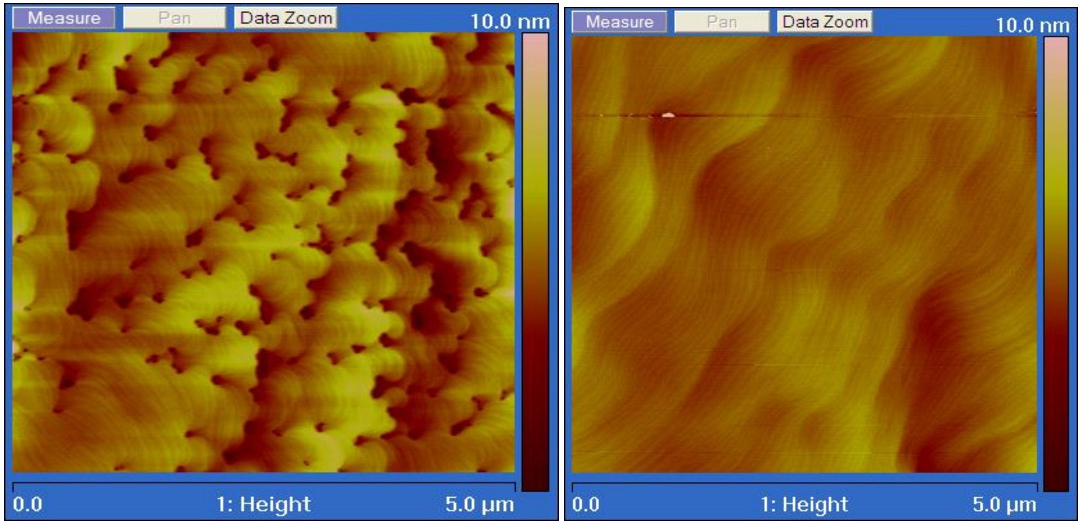
Acceptable for LEDs
Not for LDs

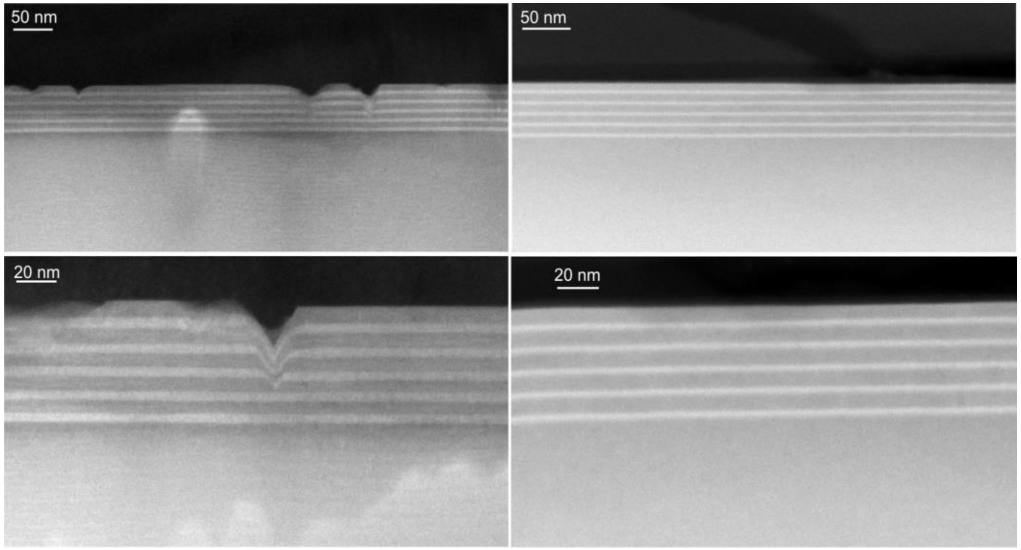
Examples of MOVPE growth: InGaN Quantum Wells

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

Influence of hydrogen used in the carrier gas





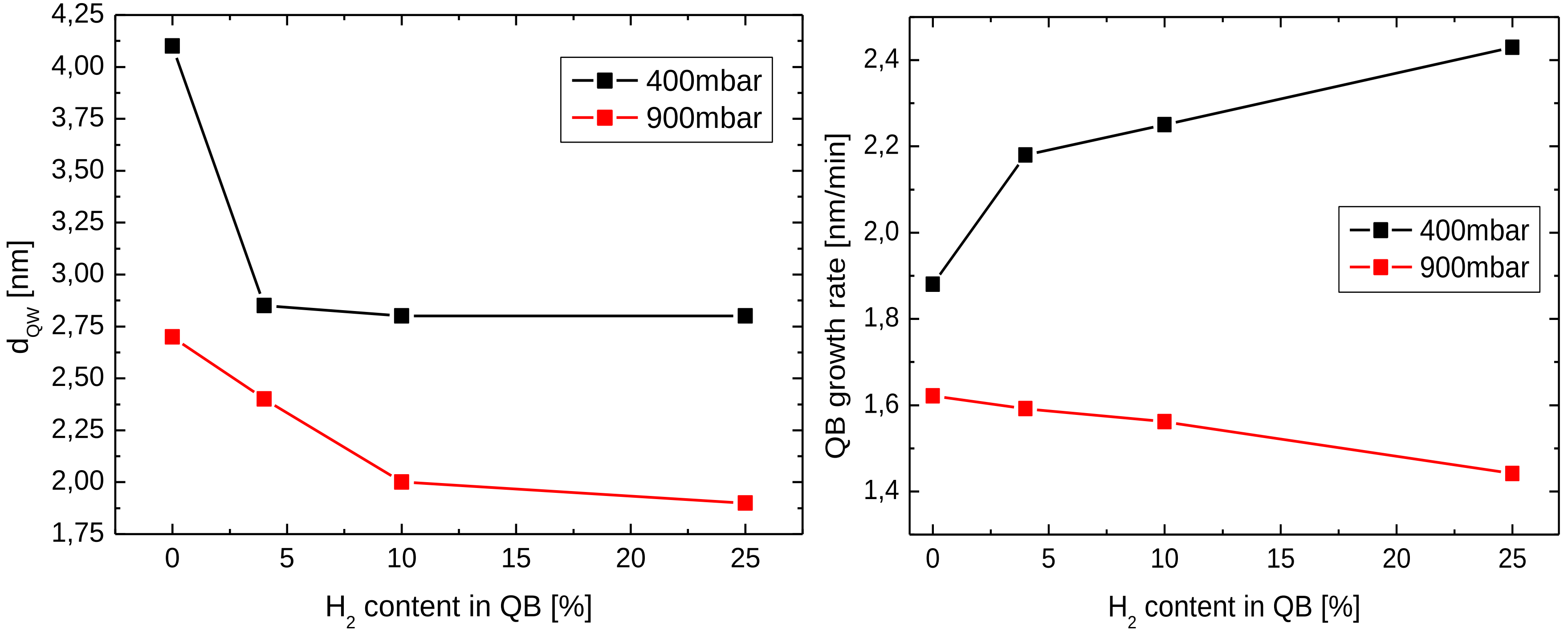


We use hydrogen for growing the QBs- but with special care

No H2 in N2

2% of H2 in N2

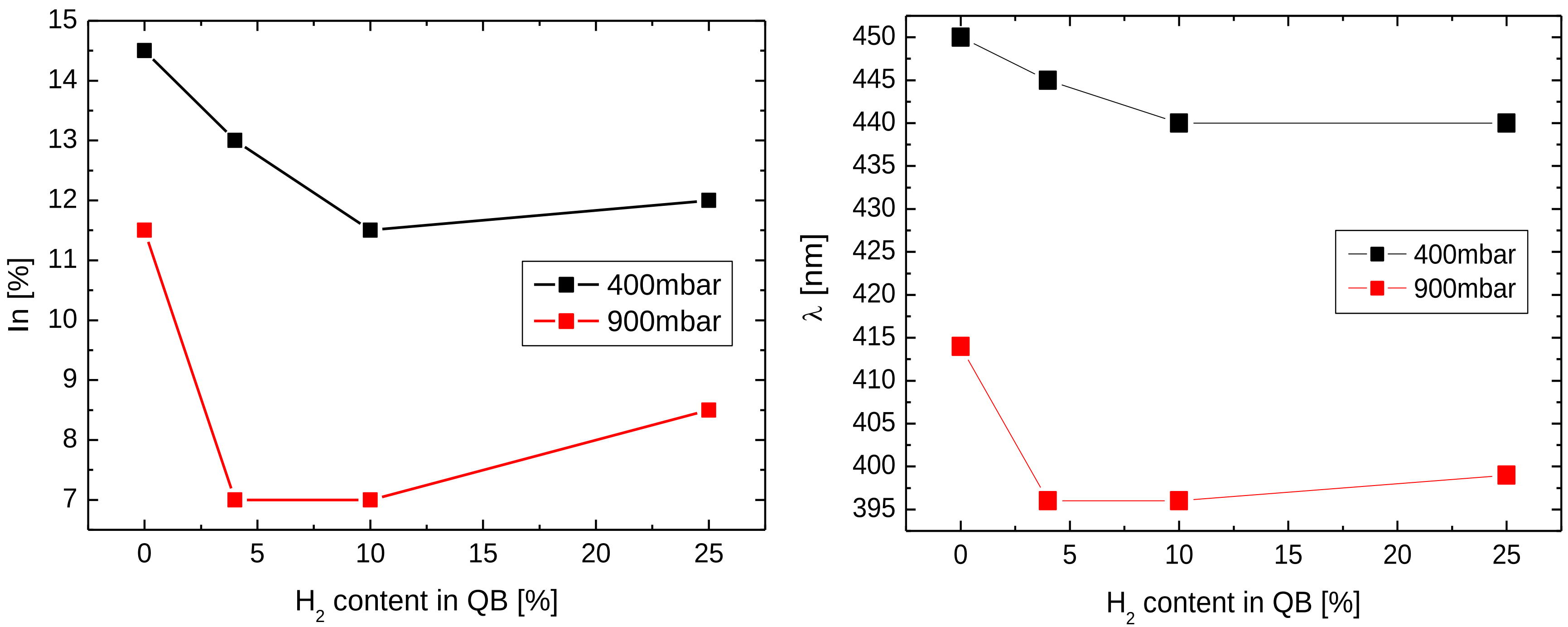
Influence of hydrogen used in the carrier gas during GaN barrier growth in CCS



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, deacreses 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

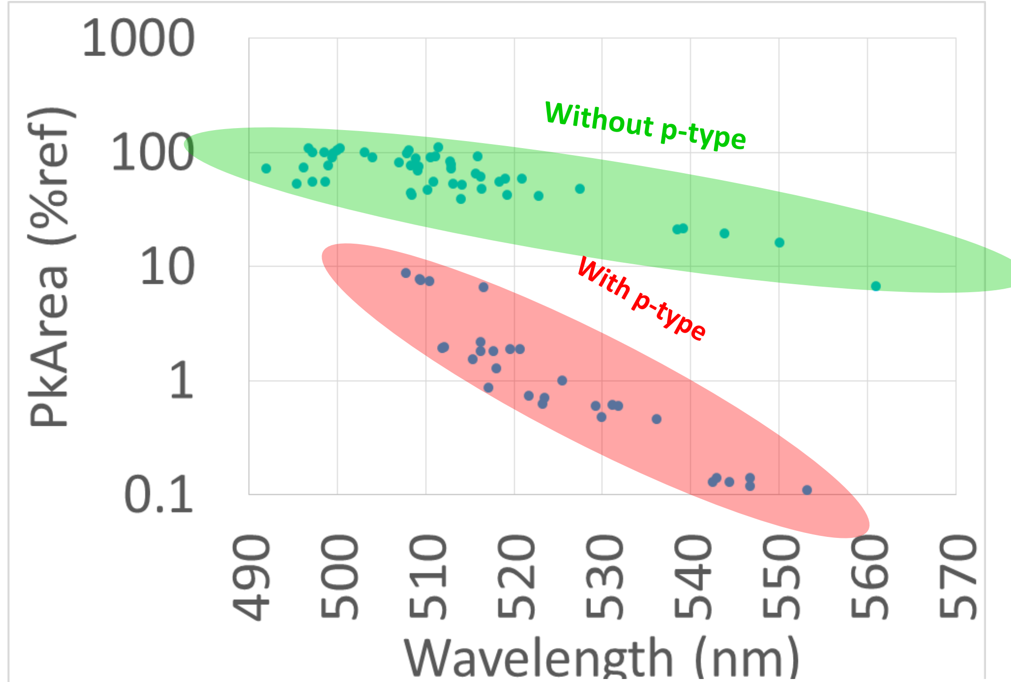
Growth temperatures of the laser diode structure

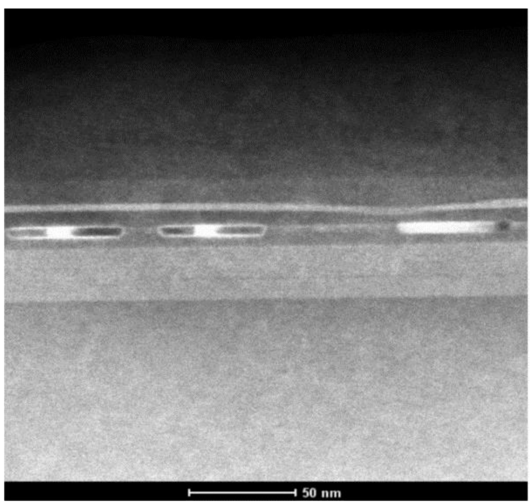
GaN:Mg	T_{Gr} = XXXX°C
AlGaN:Mg	
GaN:Mg	
EBL - AlGaN:Mg	
Cap – GaN	
Cap – GaN	T_{Gr} QW < 740°C T_{Gr} QB > 740°C For In content > 15%
QW - InGaN	
QB – GaN	
InGaN	
GaN	T_{Gr} = 1000°C
AlGaN:Si	
GaN:Si	
Substrate	

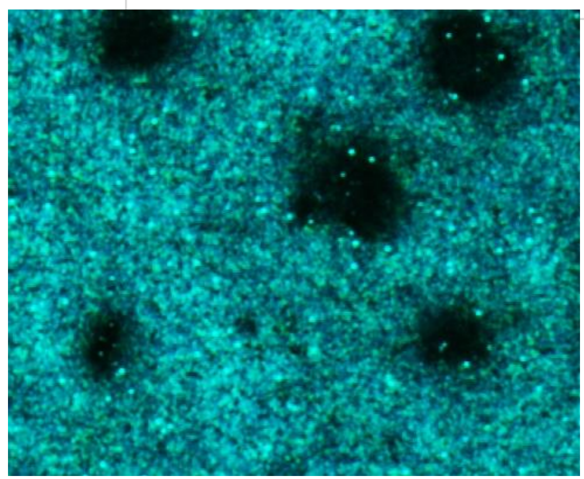
To obtain good p-type XXXX should be as high as possible (above 900°C).

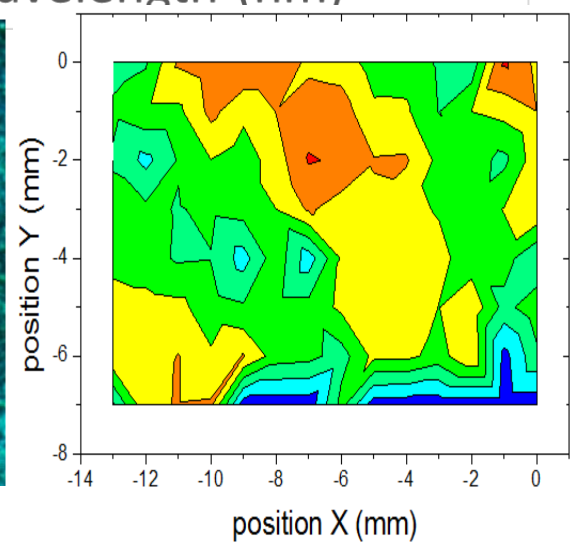
At high temperatures, InGaN QWs change

InGaN MQW decomposition









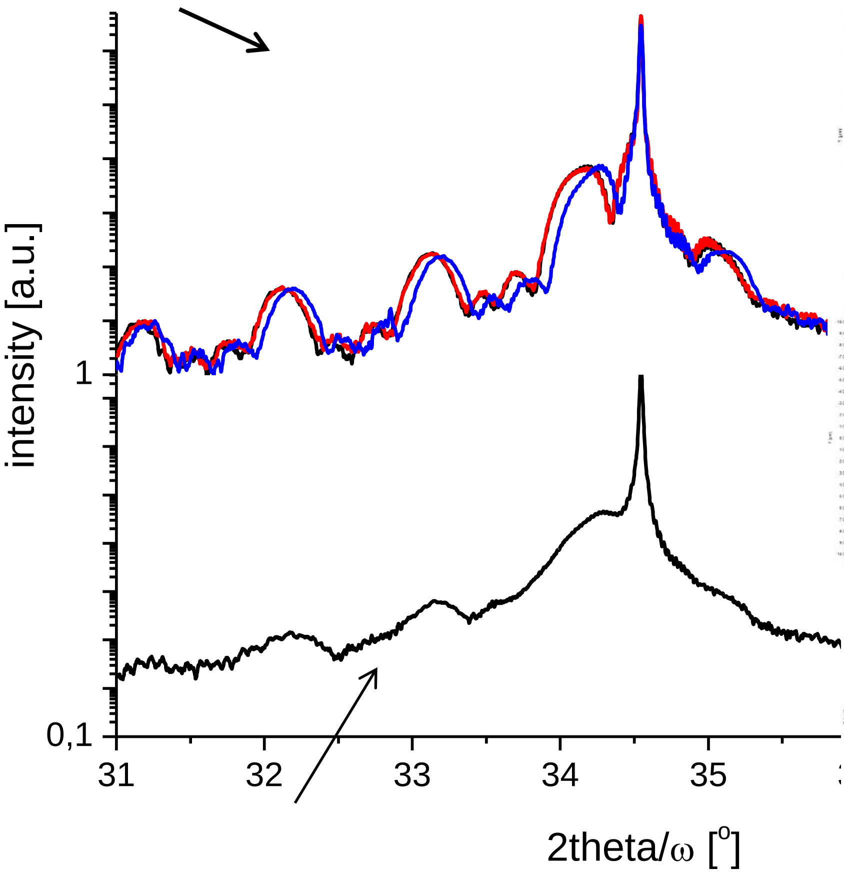
TEM: nanometer scale, Fluorescent microscopy: micrometers, MicroPL: milimieters

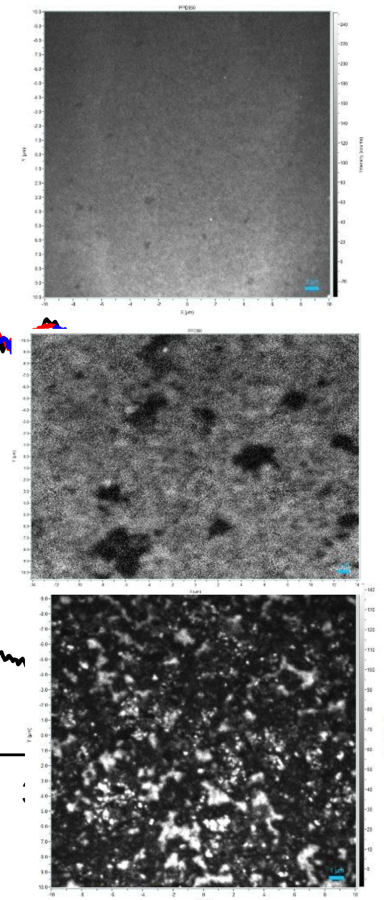
Changes of the MQWs during p-type growth at high temperature: samples on sapphire

HR-XRD measurements of LED structures:

CL

XRD:





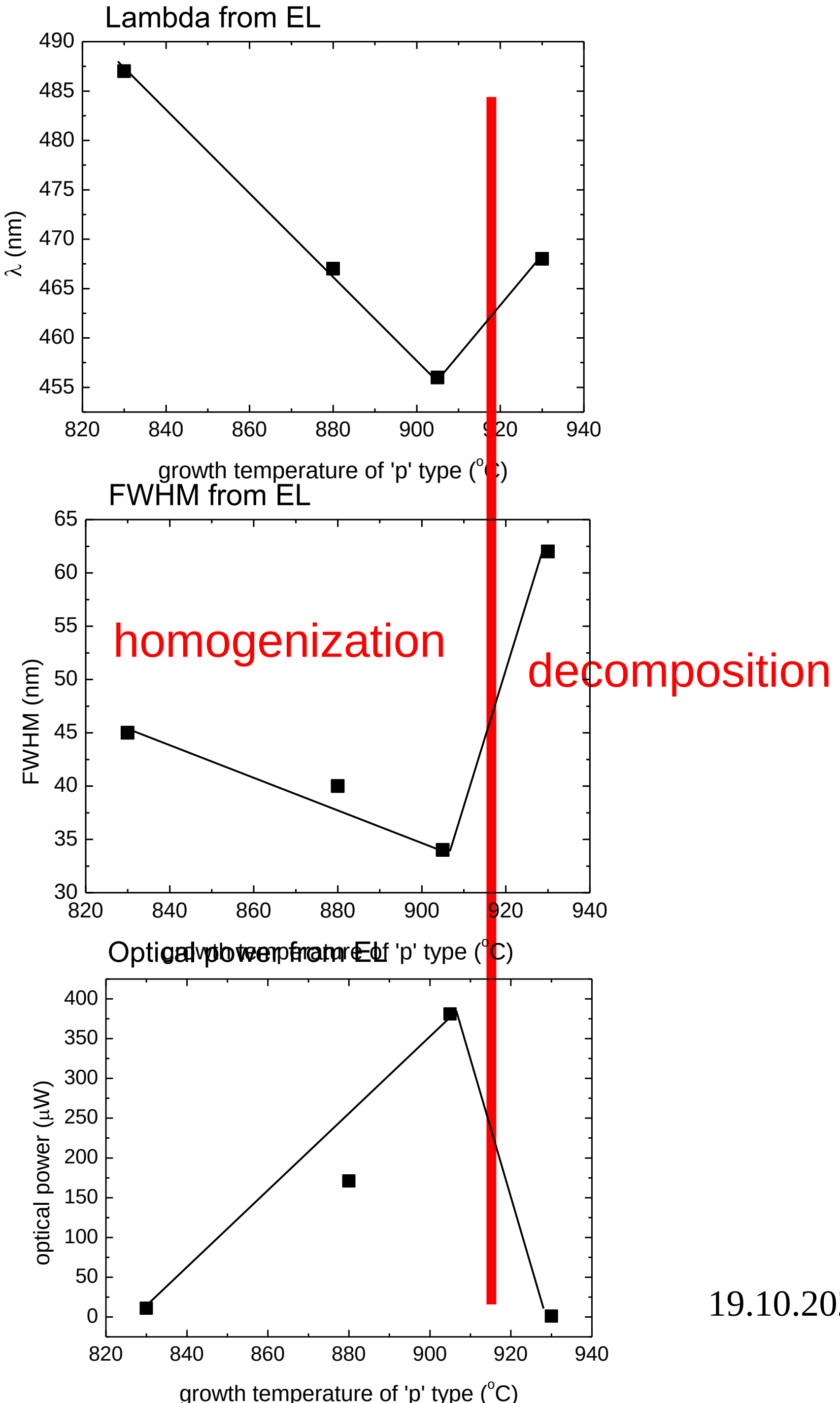
T=830°C In – 18%

T=880°C In – 18%

T=905°C In – 16%

T=930°C In – ?

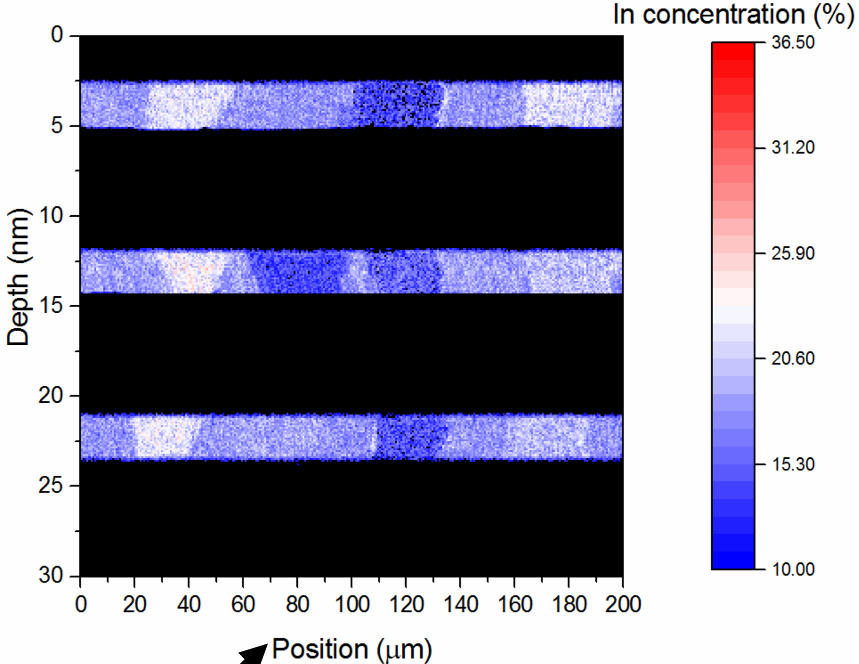
At high temperature satellite peaks becomes much more broader and disappear : QWs degradation occurs



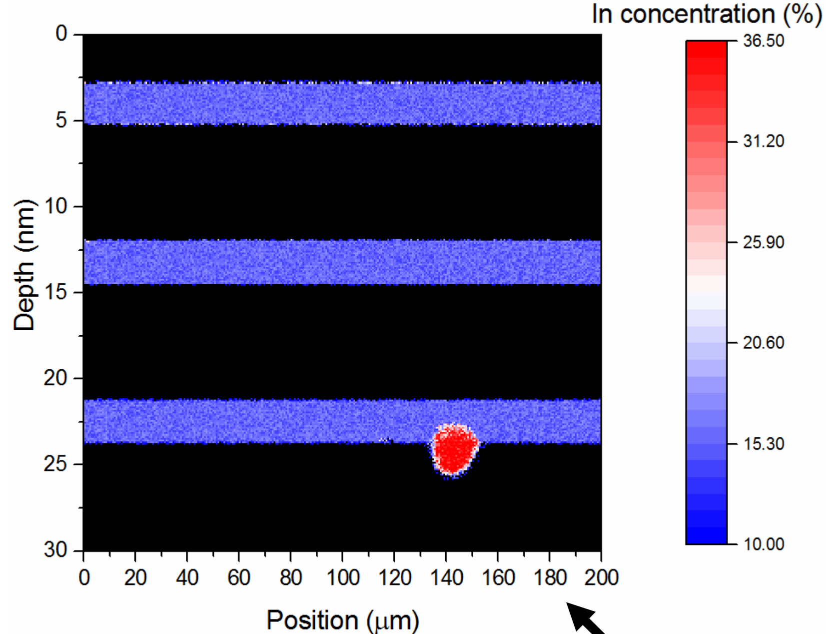
For samples on sapphire (high dislocation density) we are able to homogenize InGaN QWs by growing p-type at high temperature.

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

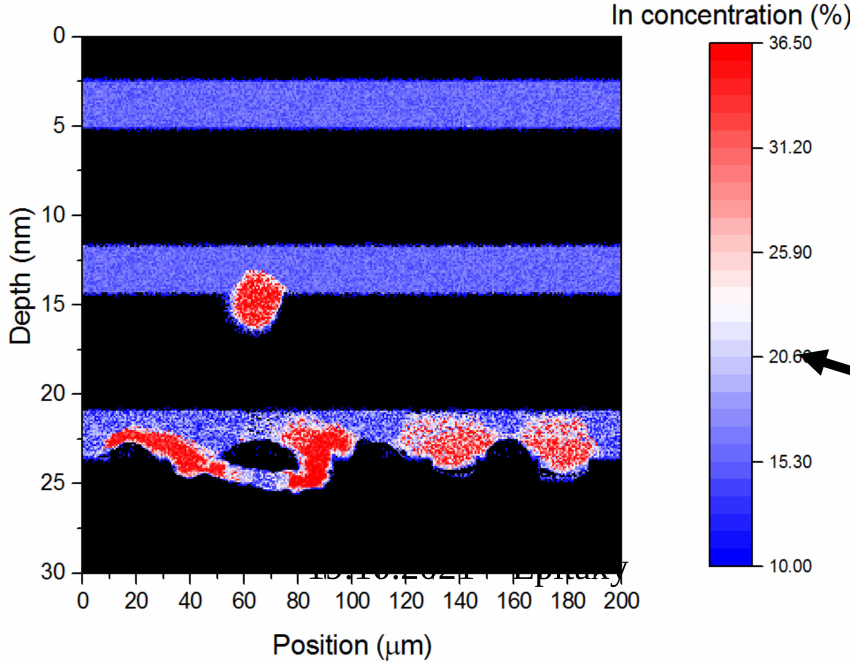
SIMS data of In-content



as grown

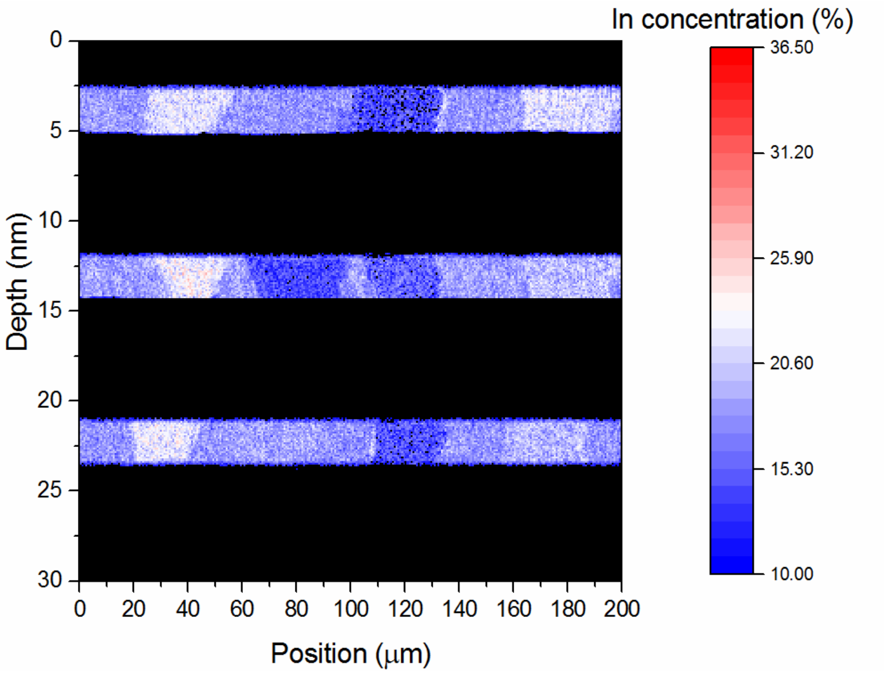


Homogenized 905°C

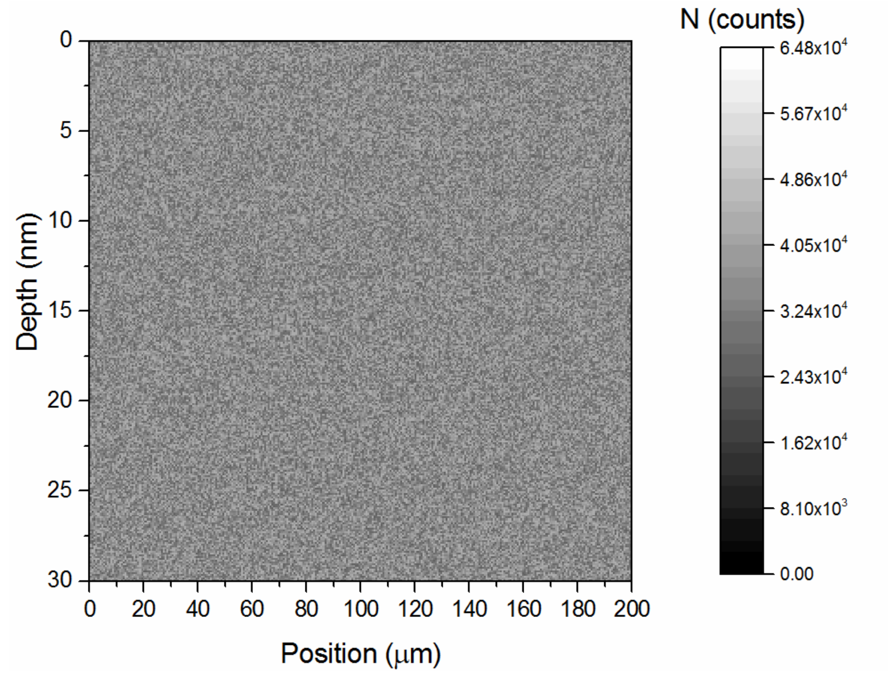


Decomposed 930°C

as grown



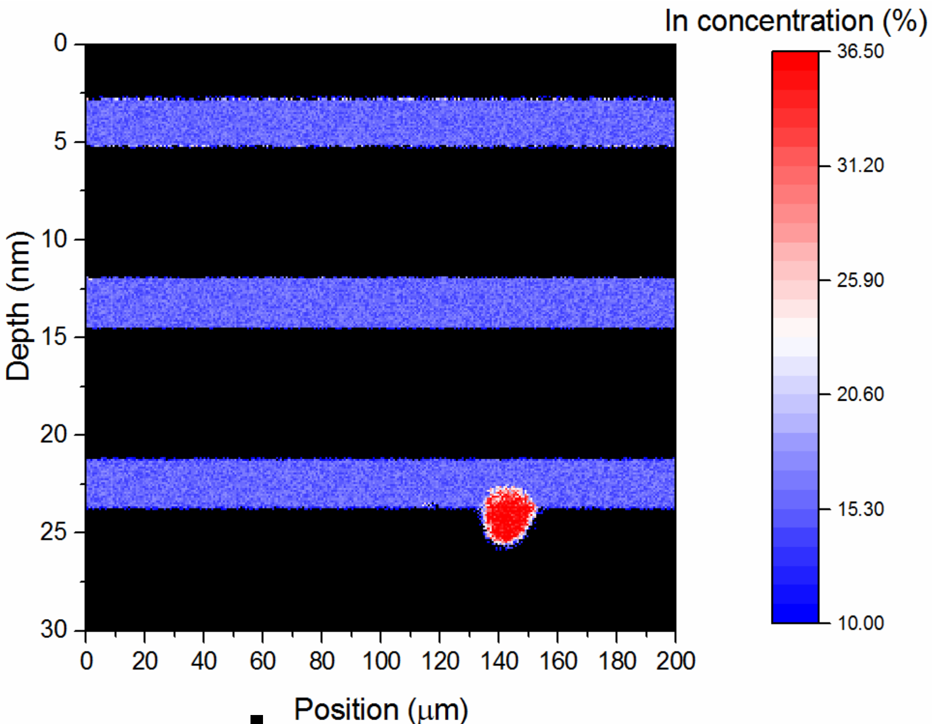
In concentration (%)
36.50
31.20
25.90
20.60
15.30
10.00
Depth (nm)
0
5
10
15
20
25
30
0 20 40 60 80 100 120 140 160 180 200
Position (μm)



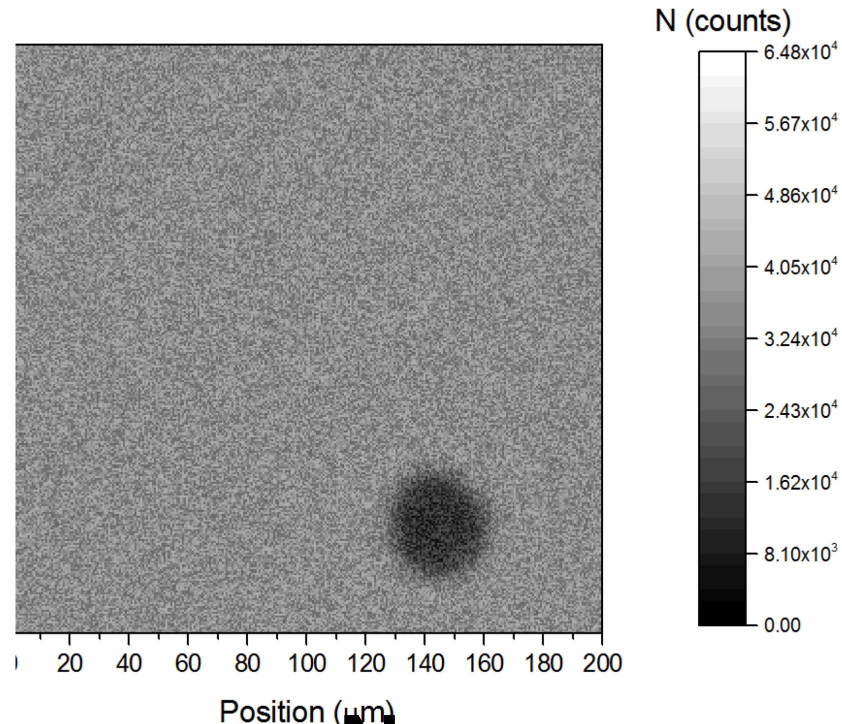
N (counts)
6.48x10⁴
5.67x10⁴
4.86x10⁴
4.05x10⁴
3.24x10⁴
2.43x10⁴
1.62x10⁴
8.10x10³
0.00
Depth (nm)
0
5
10
15
20
25
30
0 20 40 60 80 100 120 140 160 180 200
Position (μm)

In **N**

homogenozed

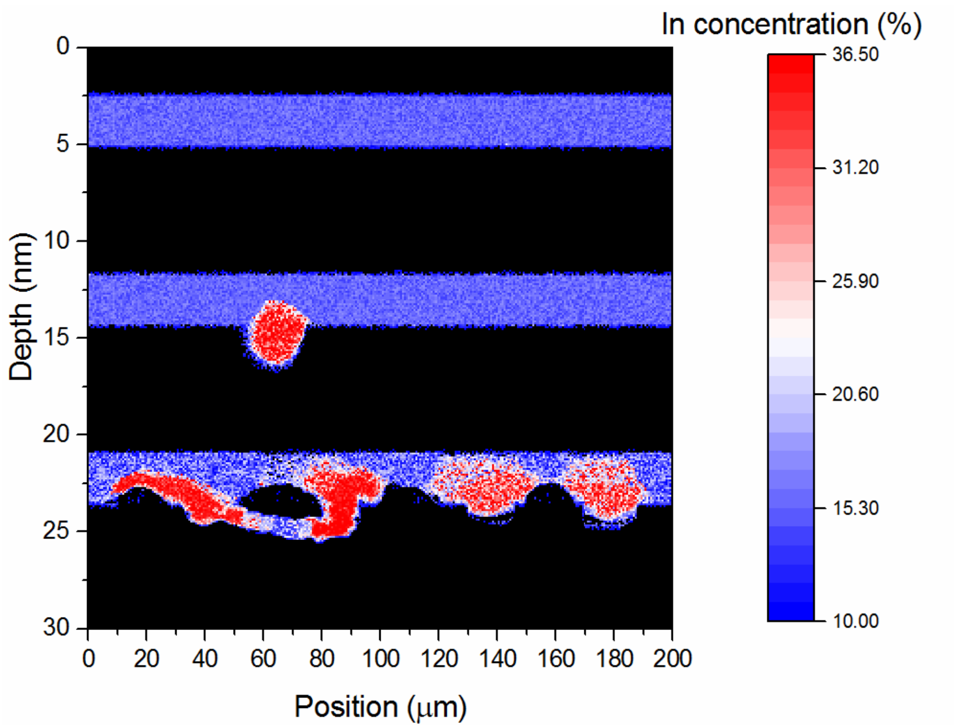


In

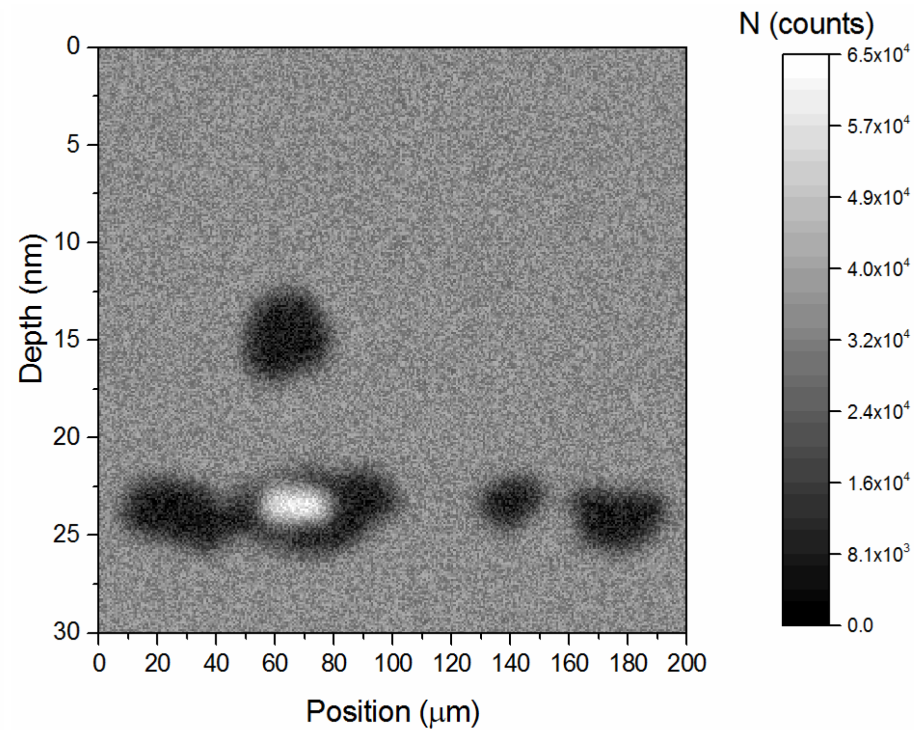


N

decomposed

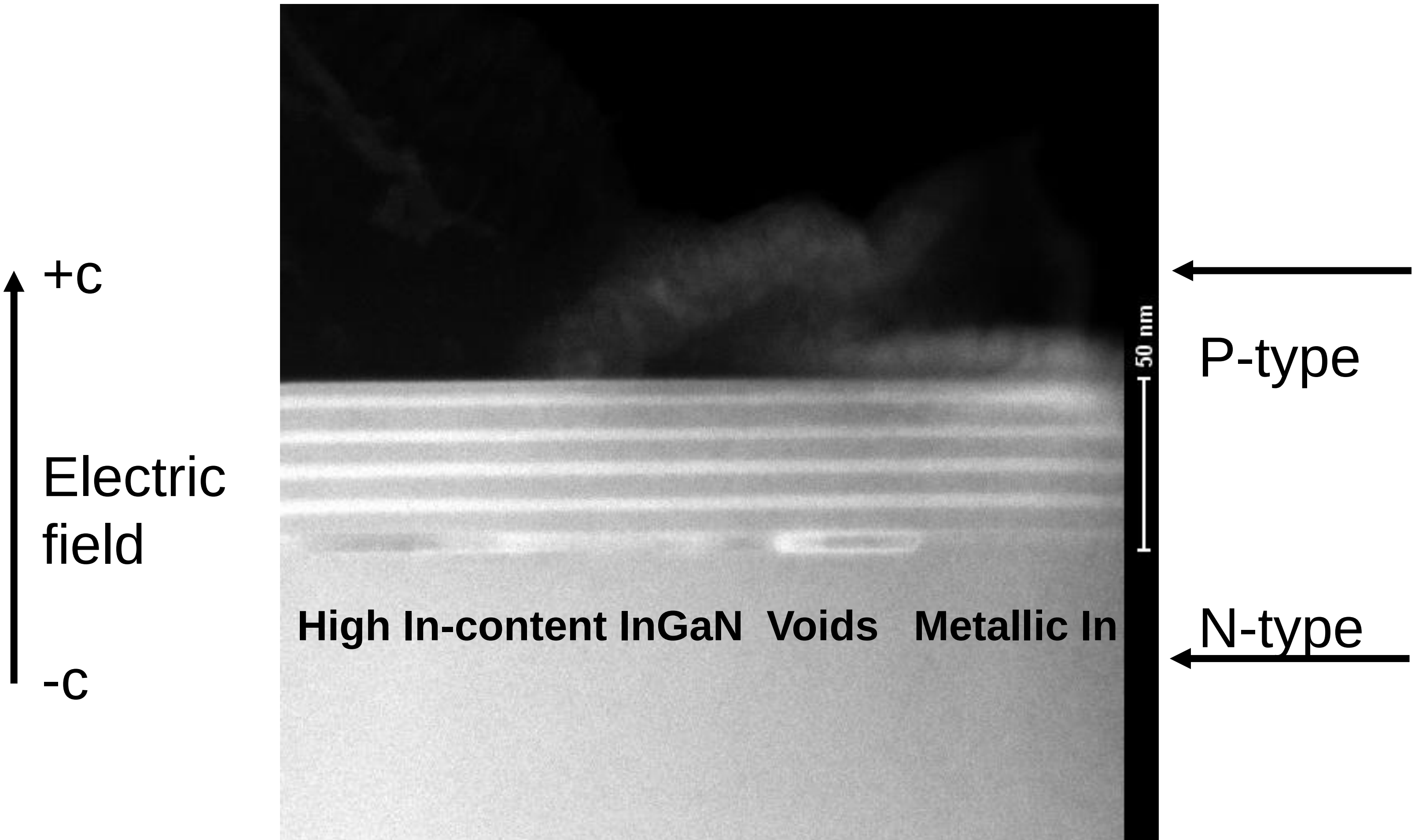


In



N

Why does the decomposition start from the first QW?



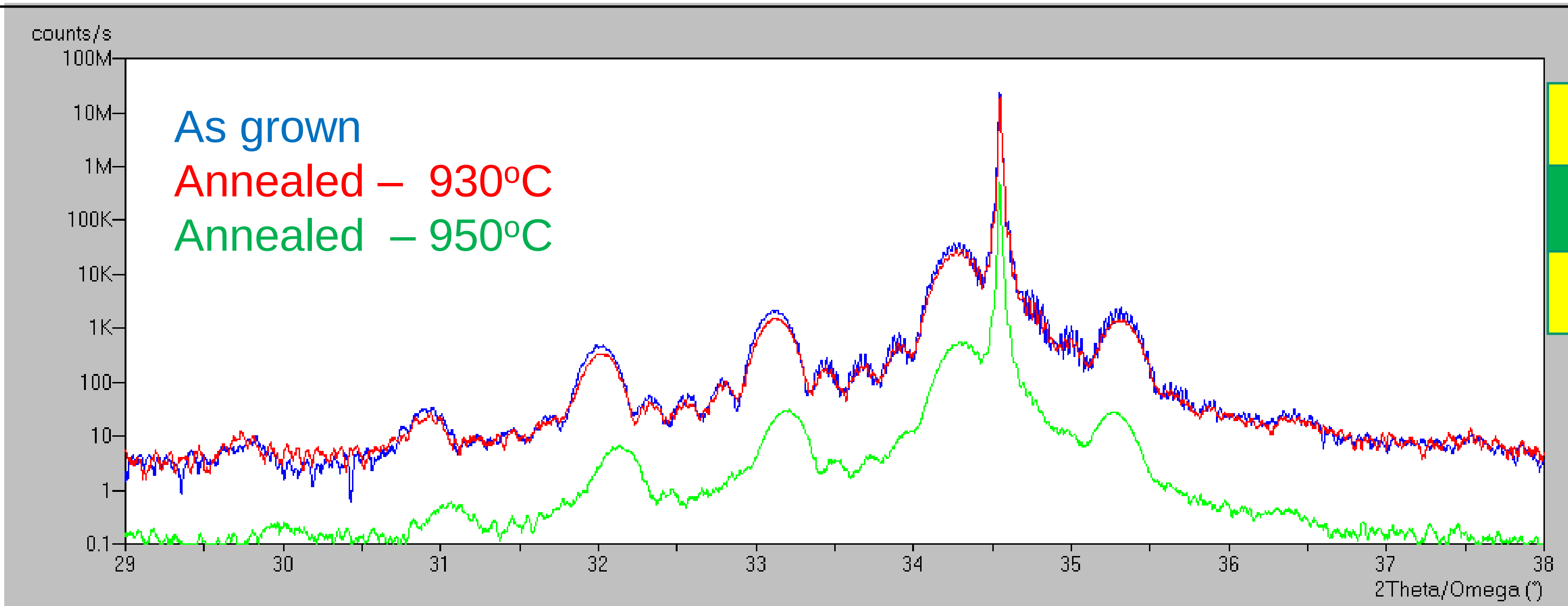
Diffusion of vacancies?

In GaN:Si we have more Ga-vacancies

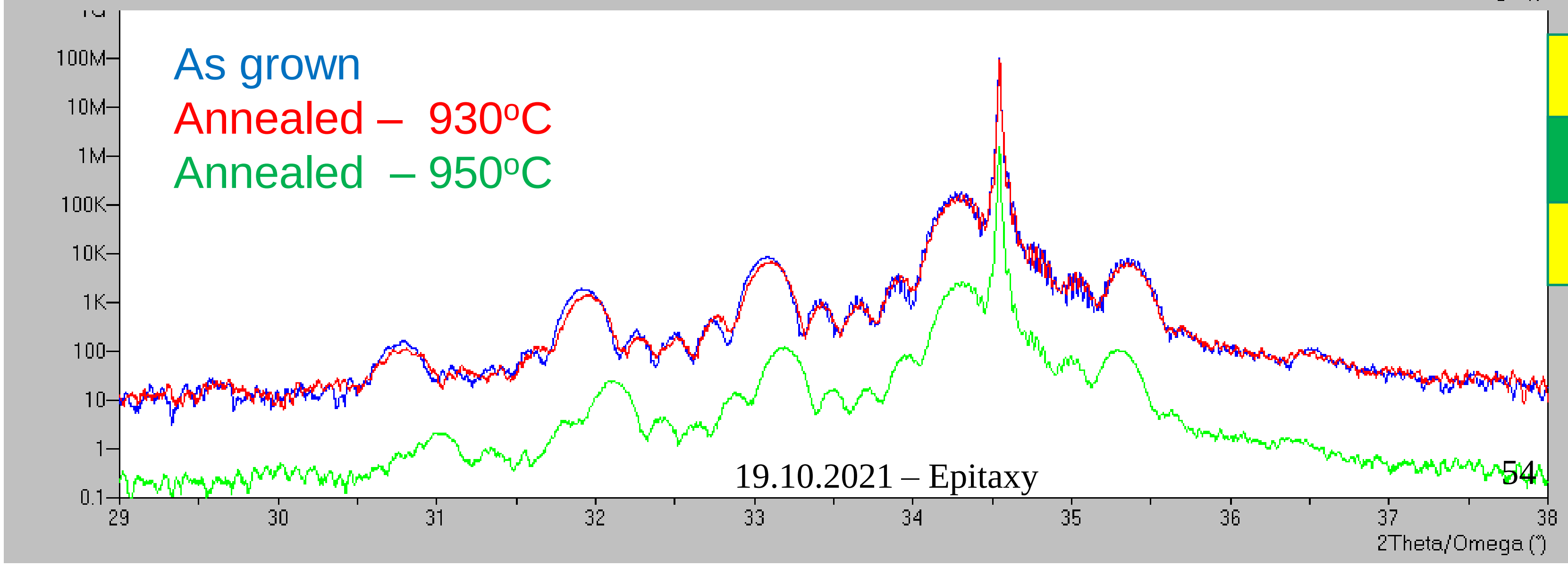
In GaN:Mg we have more N-vacancies

Diiferent doping below and above the InGaN/GaN MQWs

5QWs - (460 nm) - 17%In



GaN:**Si**
5QWs
GaN:**Si**

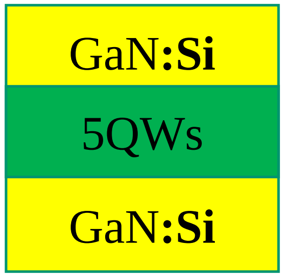


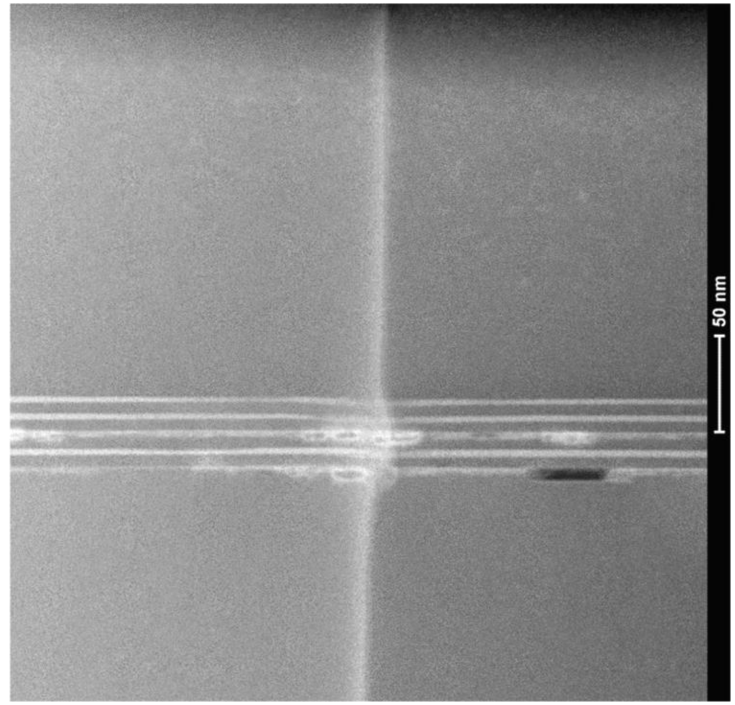
GaN:**Mg**
5QWs
GaN:**Mg**

After annealing at 950ºC

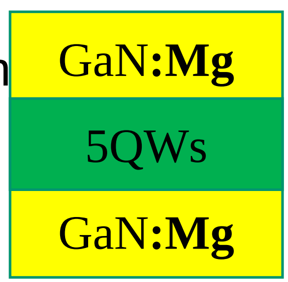
No decomposition from the top

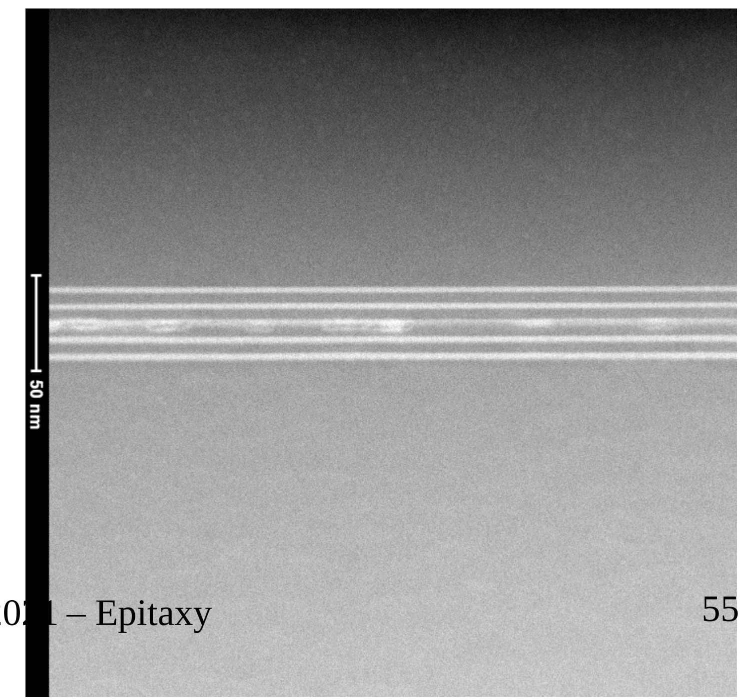
Electric field driven diffusion? Yes!





No decomposition above and below GaN:Mg

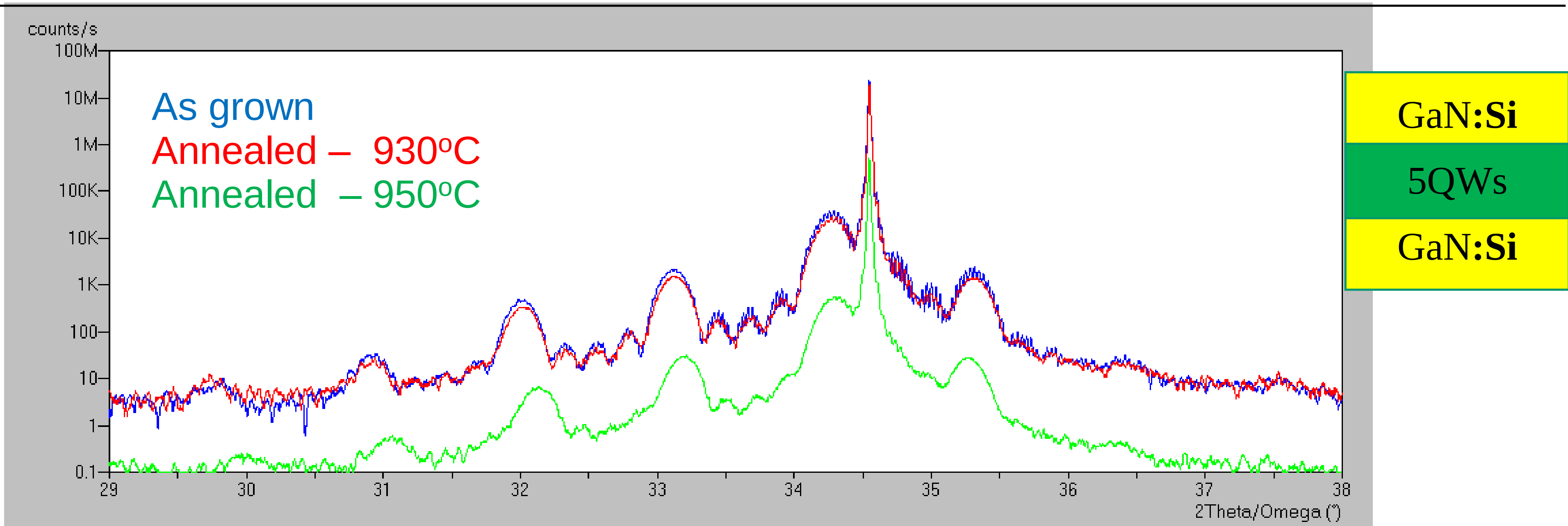


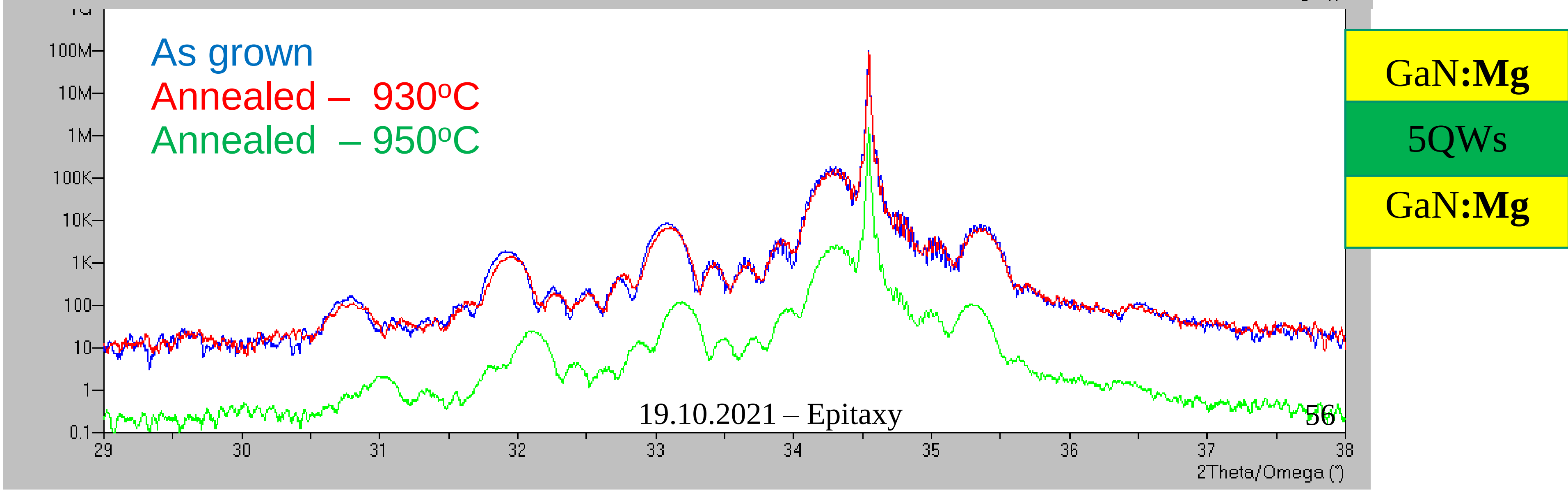


Ga-vacancies? Yes!

Diiferent doping below and above the InGaN/GaN MQWs

5QWs - (460 nm) - 17%In

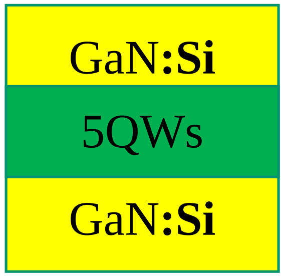


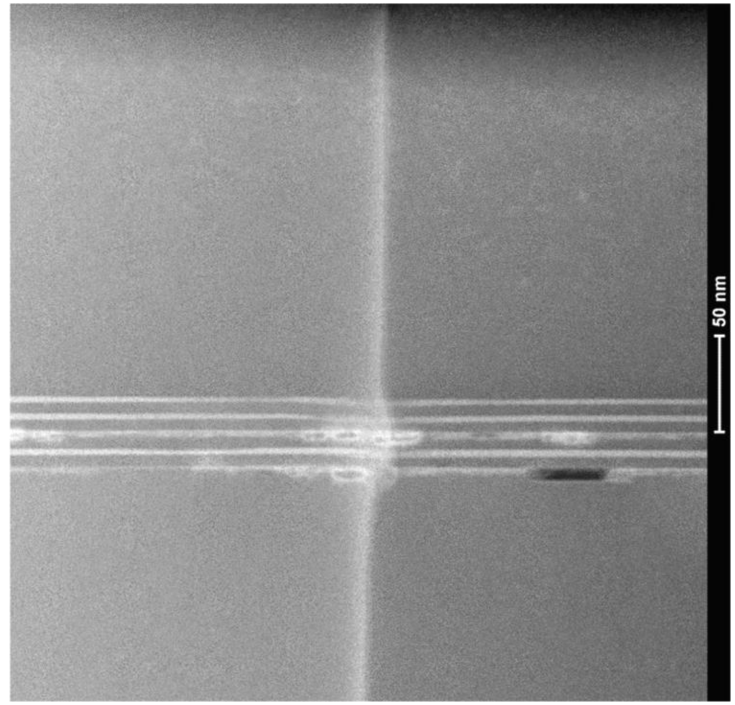


After annealing at 950°C

No decomposition from the top

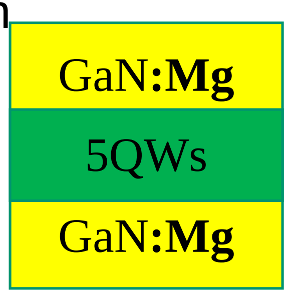
Electric field
driven diffusion?
Yes!

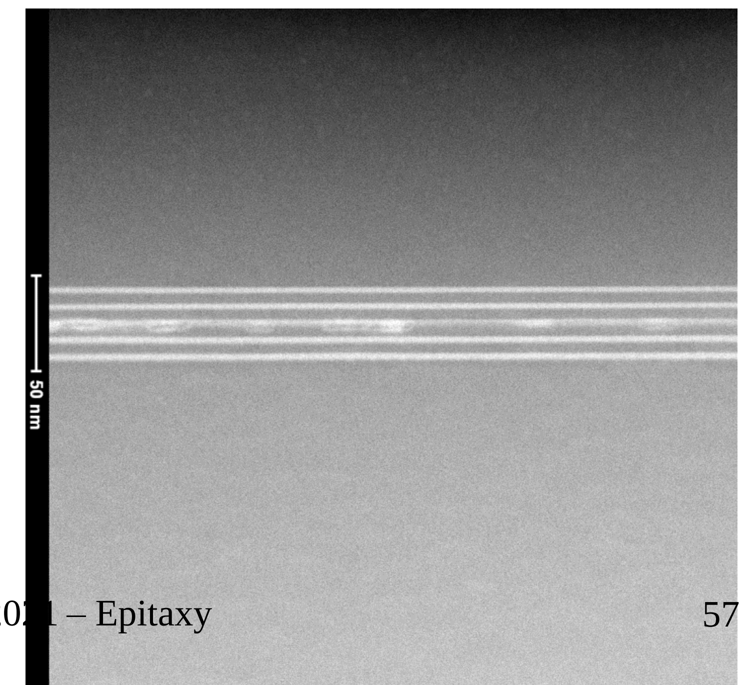




No decomposition
above and below
GaN:Mg

Ga-vacancies?
Yes!

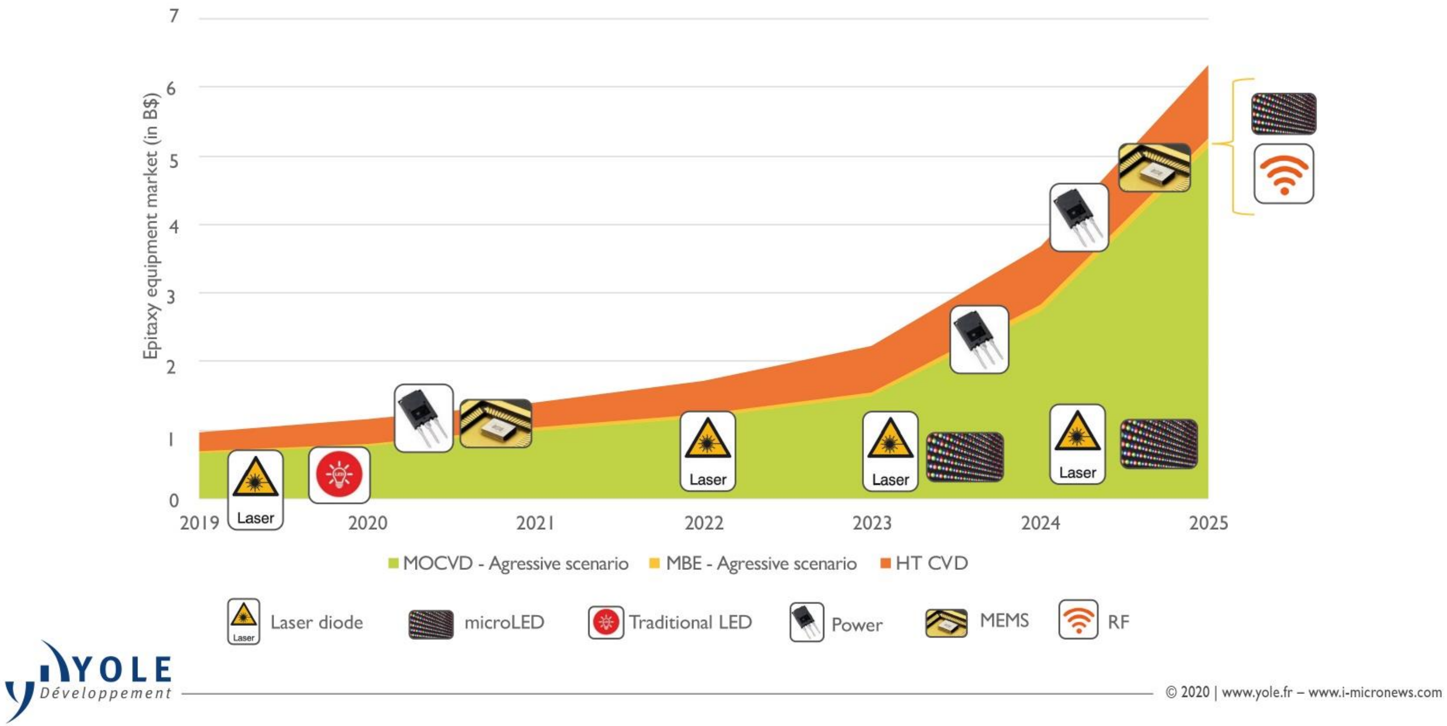




Thank you for your attention!

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.