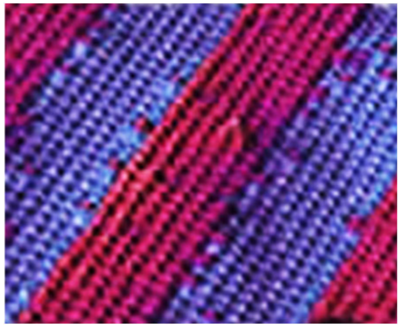
Ganex Summer School - 2025



Growth

Nicolas Grandjean

Institute of Physics
EPFL - Switzerland

nicolas.grandjean@epfl.ch

Growth - Basics

Growth III: fundamentals

Quantum dots: Stranski-Krastanov growth mode, deterministic nucleation

Growth techniques: MOVPE, HVPE, MBE

Growth - Basics

Growth III: fundamentals

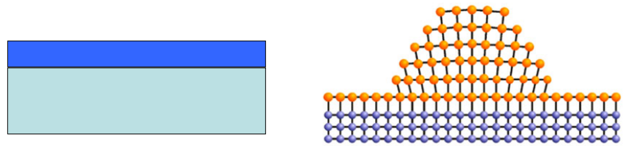
Quantum dots: Stranski-Krastanov growth mode, deterministic nucleation

Growth techniques: MOVPE, HVPE, MBE

Quantum dots

Strain relaxation by elastic deformation of 3D islands

Stranski-Krastanov growth mode



2D 3D

Elastic energy release by relaxation at free-edges

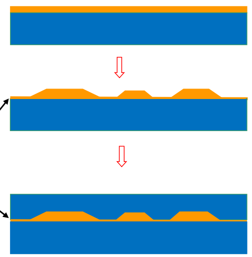
But larger surface free energy

3D island formation: balance between elastic and surface energies

GaN/AlN $\Rightarrow$ 2.5 %
InAs/GaAs $\Rightarrow$ 7.2 %

Quantum dots

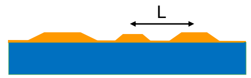
Strain relaxation by elastic deformation of 3D islands



Quantum dots

What is needed for 3D island formation?

- Strain $\Rightarrow$ lattice mismatch must be high enough
- Low surface free energy
- Large surface diffusion length



crude criterion: $\lambda > L$

λ the surface diffusion length and L mean distance between islands

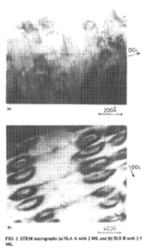
Quantum dots

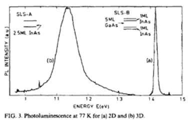
First report of semiconductor quantum dots

Growth by molecular beam epitaxy and characterization of InAs/GaAs strained-layer superlattices

L. Goldstein, F. Glas, J. Y. Marzin, M. N. Charasse, and G. Le Roux
Centre National d'Etudes des Telecommunications, 196 rue de Paris, 92220 France

(Received 26 July 1985; accepted for publication 4 September 1985)





In conclusion, binary InAs/GaAs SLS's have been grown on GaAs substrates. The sharp transition from the 2D nucleation to the 3D was observed by x-ray diffraction, STEM, and photoluminescence. It has been shown that even when In-rich clusters are formed, good crystalline quality material can be obtained. Also, specific and intense photoluminescence is associated with the cluster formation. These kinds of structures are thus proved to be of interest to study low-dimensional (< 2) objects showing good optical properties.

Appl. Phys. Lett. **47**, 1099 (1985)

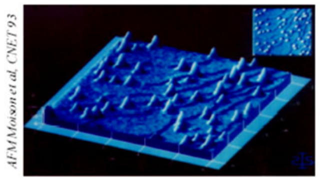
Quantum dots

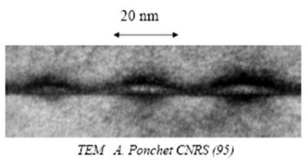
First report of SK-QDs (InAs/GaAs)

Self-organized growth of regular nanometer-scale InAs dots on GaAs

J. M. Moison, F. Houzay, F. Barthe, and L. Leprince
France Telecom, Centre National d'Etudes des Télécommunications Paris B, Laboratoire de Bagneux,[a]
196 Avenue Henri Ravera B.P. 107 F-92225 Bagneux Cedex, France
E. André and O. Vatel
France Telecom, Centre National d'Etudes des Télécommunications, Centre Norbert Segard, Chemin du Vieux Chêne BP 98 F-38243 Meylan Cedex, France

3D growth mode of highly strained InAs on GaAs + overgrowth by GaAs





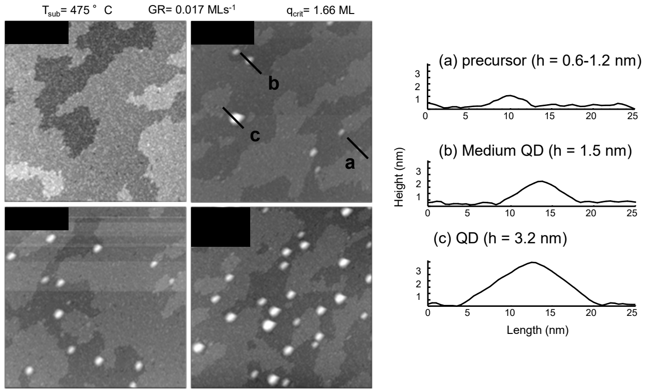
TEM A. Ponchet CNRS (95)

Appl. Phys. Lett. **64**, 196 (1994)

Quantum dots

EPFL

Evolution of InAs QDs by *in vacuo* STM-MBE



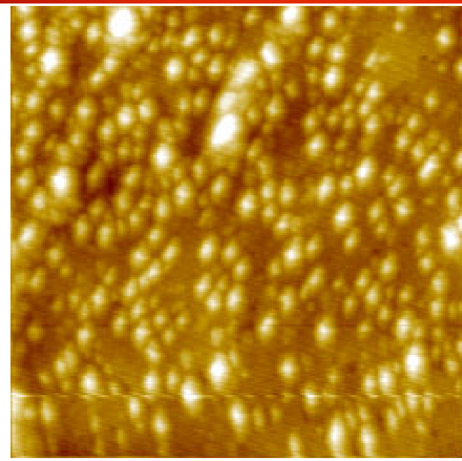
T.J.Krzyzewski, P.B.Joyce, G.R.Bell, and T.S.Jones, Phys.Rev. B 66, 121307 (2002)

9

9

Quantum dots

EPFL



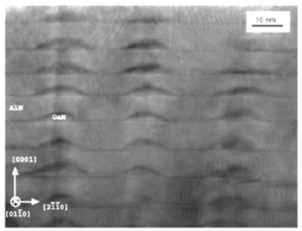
10

10

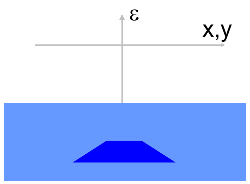
Quantum dots

EPFL

Vertical self-organization

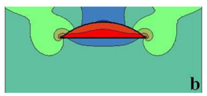


Widmann *et al.*, J. Appl. Phys. <u>83</u>, 7618 (1998)



Tersoff *et al.*, PRL (1995)

Vertical correlation due to QD induced strain field



11

11

Quantum dots

EPFL

Vertical self-organization


PHYSICA E

Composition profiling at the atomic scale in III–V nanostructures by cross-sectional STM

P.M. Koenraad, D.M. Bruls, J.H. Davies, S.P.A. Gill, Fei Long, M. Hopkinson, M. Skolnick, J.H. Wolter

InAs/GaAs QDs

55x55 nm²

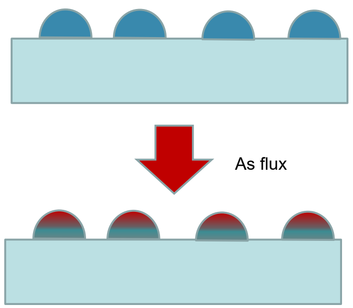
12

12

Quantum dots

Quantum dots without strain: GaAs/AlGaAs

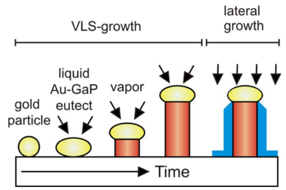
Droplet epitaxy

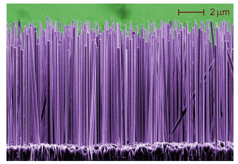


C. Somaschini, S. Bietti, N. Koguchi, and S.Sanguinetti
Appl. Phys. Lett. 97, 203109 (2010)

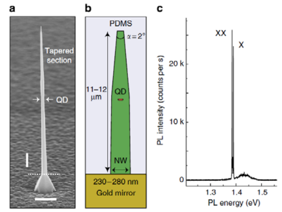
Quantum dots

Quantum dots without strain: nanowires



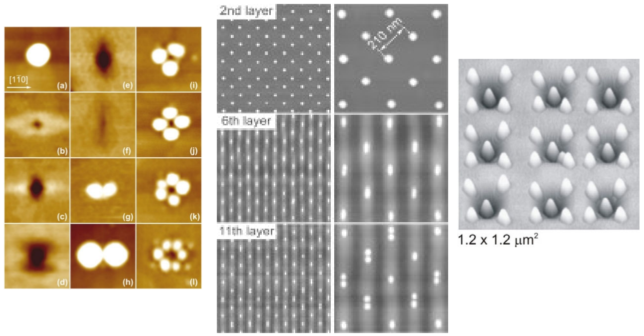


Catalyst-free nanowires (GaN)



Quantum dots

Deterministic nucleation



1.2 x 1.2 μm^2

R. Songmuang, S. Kiravittaya, and O. G. Schmidt
Applied Physics Letters **82**, 2892 (2003)

Growth - Basics

Growth III: fundamentals

Quantum dots: Stranski-Krastanov growth mode, deterministic nucleation

Growth techniques: MOVPE, HVPE, MBE

Growth techniques

EPFL

Main growth techniques:

Chemical

Hydride vapor phase epitaxy (HVPE)

Metal-organics vapor phase epitaxy (MOVPE)

Metal-organics chemical vapor deposition (MOCVD)

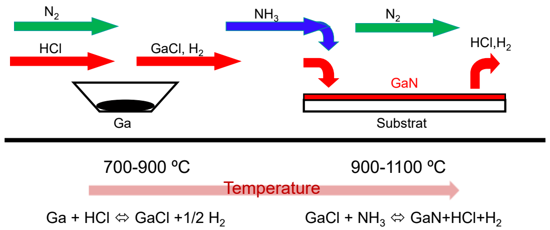
Physical

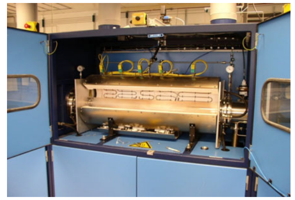
Molecular beam epitaxy (MBE)

Growth techniques

EPFL

Hydride vapor phase epitaxy (HVPE)





Operates near equilibrium:

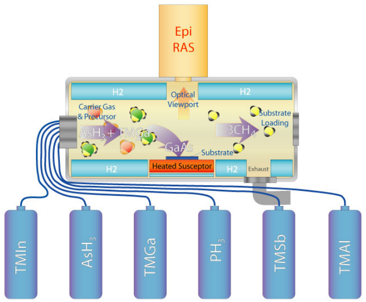
Growth rate > 100µm/h

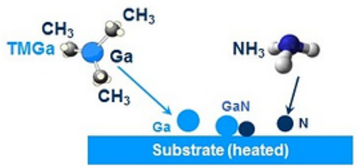
Use for making free-standing GaN substrates

Growth techniques

EPFL

Metal-organic vapor phase epitaxy (MOVPE)



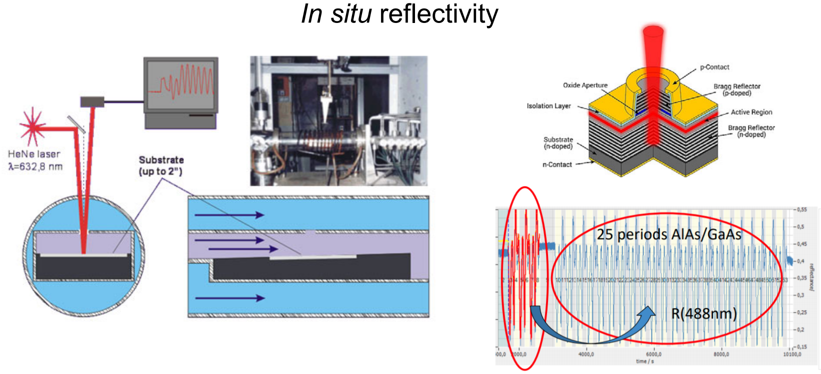


Growth techniques

EPFL

Metal-organic vapor phase epitaxy (MOVPE)

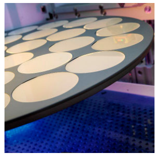
In situ reflectivity



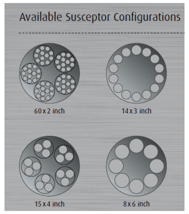
Growth techniques

Metal-organic vapor phase epitaxy (MOVPE)

Production systems



Production systems



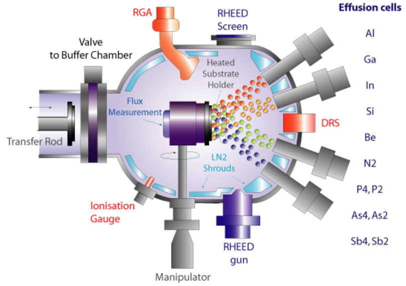
 # wafers per run: 124x4" and 48x6"

GaAs/InP based Optoelectronics and Electronic Devices

GaN blue LEDs (solid state lighting)

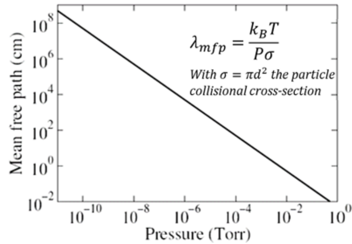
Growth techniques

Molecular Beam Epitaxy (MBE)



Ultra-high vacuum

✓ No interaction between atomic fluxes

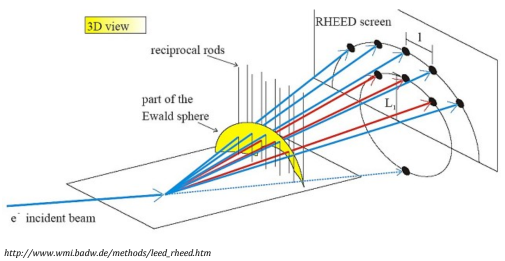


✓ Use of *in situ* electron-beam monitoring (RHEED)

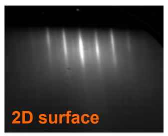
Growth techniques

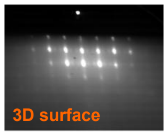
Molecular Beam Epitaxy (MBE)

In situ Reflection High-Energy Electron Diffraction



http://www.wmi.badw.de/methods/leed_rheed.htm

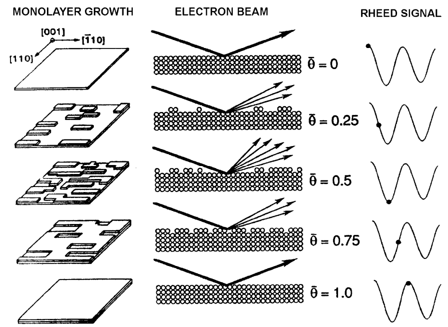




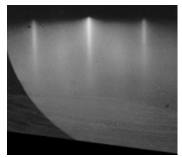
➢ **Surface roughness**

Growth techniques

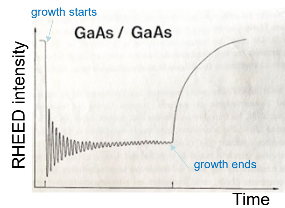
MBE growth: *in situ* monitoring with RHEED



J.H. *Neave*, B.A. *Joyce*, P.J. Dobson, N. Norton. Appl. Phys. A, 31 (1983)



Usually, new 2D-islands tend to appear on large growing 2D-islands
→ **damped oscillations**



Growth techniques

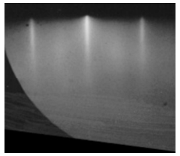
MBE growth: *in situ* monitoring with RHEED

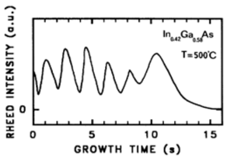

VOLUME 71, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1993

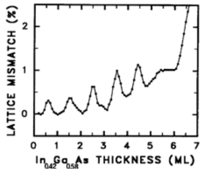
Oscillation of the Lattice Relaxation in Layer-by-Layer Epitaxial Growth of Highly Strained Materials

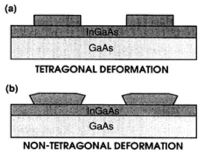
J. Massies and N. Grandjean

Laboratoire de Physique du Solide et Energie Solaire, Centre National de la Recherche Scientifique,









25

25

Growth techniques

Molecular Beam Epitaxy (MBE)

Research

- Up to 4" wafers
- II-VI, III-V (As, P, Sb, N), Oxides, SiGe, etc…

Production

- Up to 5 × 8" or 8 × 6" wafers
- Mainly for GaAs-based HEMTs & HBTs
- Opportunities for VCSELs

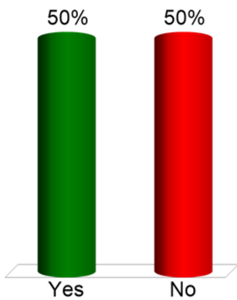
26

26

Questions

The critical thickness for plastic relaxation depends on the growth conditions

A. Yes
B. No



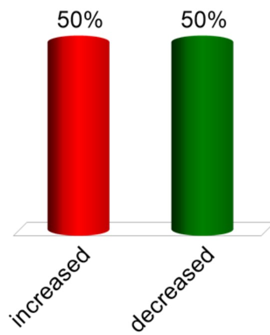
27

27

Questions

To promote the formation of SK-dots the surface energy should be

A. increased
B. decreased



28

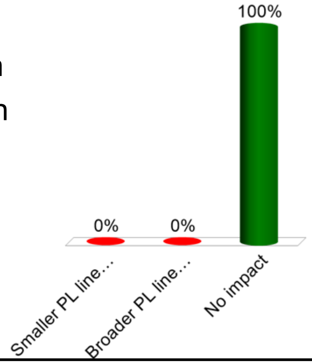
28

Questions

EPFL

A quantum well with diffused interfaces, with respect to perfectly sharp ones, exhibits a

A. Smaller PL linewidth
B. Broader PL linewidth
C. No impact

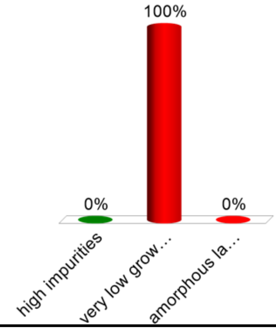


Questions

EPFL

MOVPE is usually not well suited for low growth temperature process because of

A. high impurities
B. very low growth rate
C. amorphous layer

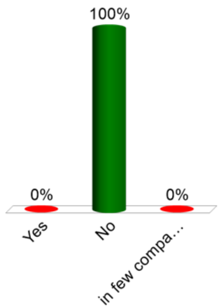


Questions

EPFL

MBE is used for the production for blue LEDs

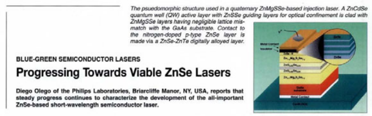
A. Yes
B. No
C. in few companies



Questions

EPFL

II-VIs ((Zn,Cd)(S,Se)) have been investigated for blue LEDs and blue lasers but eventually abandoned. Why?



The psuedomorphic structure used in a quaternary ZnMgSSe-based injection laser. A ZnCdSe quantum well (QW) active layer with ZnSSe guiding layers for optical confinement is clad with ZnMgSSe layers having negligible lattice mismatch with the GaAs substrate. Contact to the nitrogen-doped p-type ZnSe layer is made via a ZnSe-ZnTe digitally alloyed layer.

BLUE-GREEN SEMICONDUCTOR LASERS

Progressing Towards Viable ZnSe Lasers

Diego Olego of the Philips Laboratories, Briarcliffe Manor, NY, USA, reports that steady progress continues to characterize the development of the all-important ZnSe-based short-wavelength semiconductor laser.

A. Too expensive
B. Toxicity
C. Other