Epitaxy of quantum nanostructures

Quantum dots and nanowires

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Outline

1. Introduction

2. Island growth on a bulk substrate – Stranski-Krastanov quantum dots

3. Free-standing nanowires (NWs) – The homogeneous case

   Growth mechanisms, thermodynamics, kinetics

4. Heterostructures and quantum insertions in NWs

   Compositional heterostructures, interface sharpness, strain relaxation

   Polytypism, interface morphology and crystal phase heterostructures

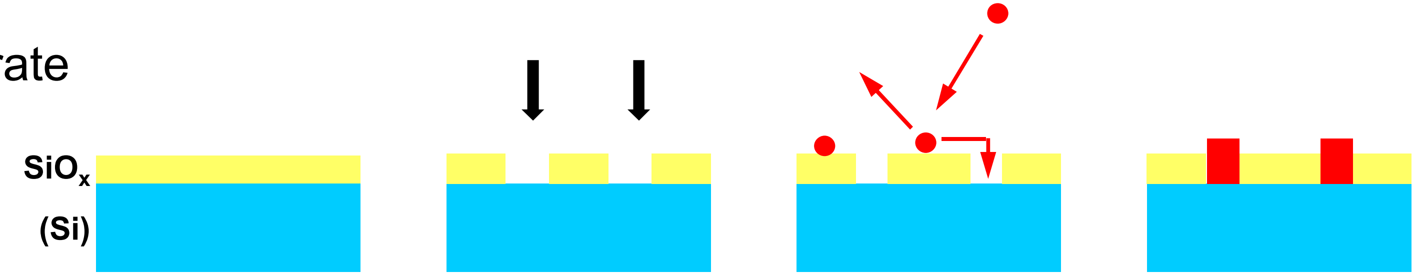
5. Nucleation and growth statistics

Epitaxy of nanostructures is challenging

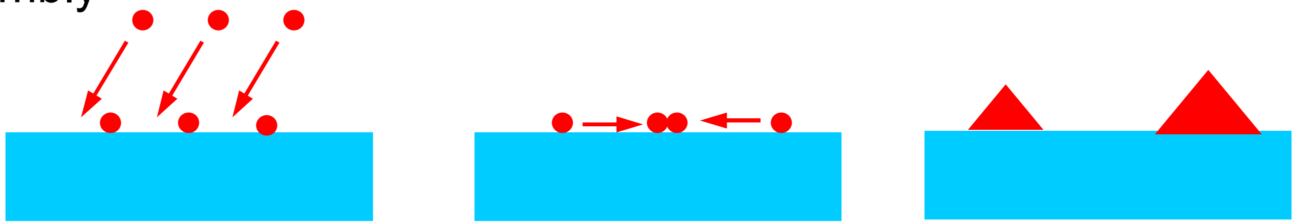
Epitaxy was developed to produce **uniform planar (2D) structures**

- Retain structural quality, epitaxial match, monolayer (ML) control
- Fight lateral uniformity

❑ Masked substrate

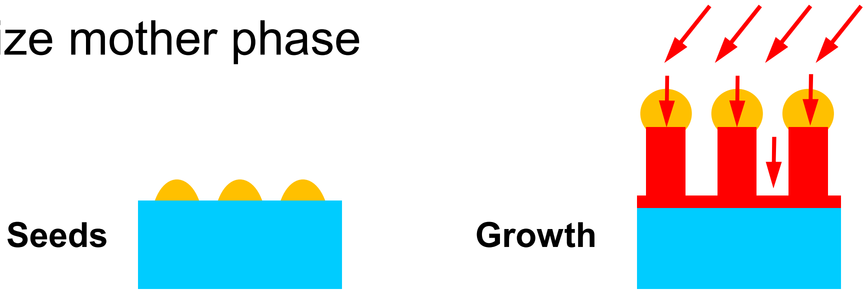


❑ Self-assembly



islands, QDs

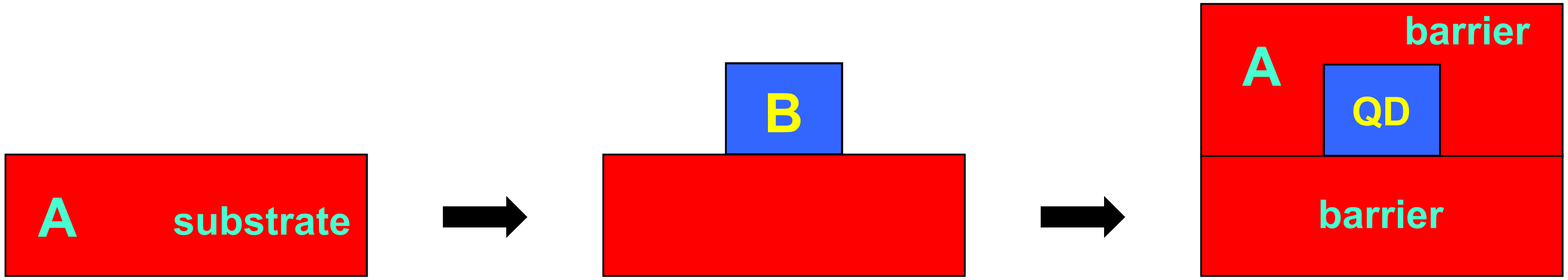
❑ Use nanosize mother phase



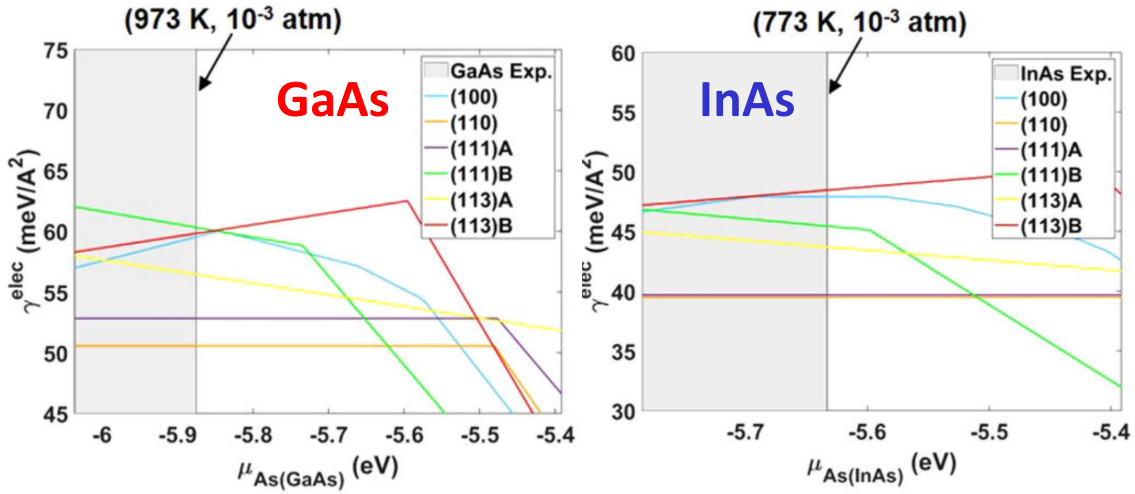
Droplet epitaxy

Nanowires (NWs)

Self-organization via 3D growth



	E_g (eV)	Cohesive energy (kcal/mol)
InAs	0.36	-124
GaAs	1.42	-136
AlAs	3.01	-156



Yeu, Han, Park, Hwang, Choi, Sci. Rep. 9, 1127 (2019)

3D growth of B on A if

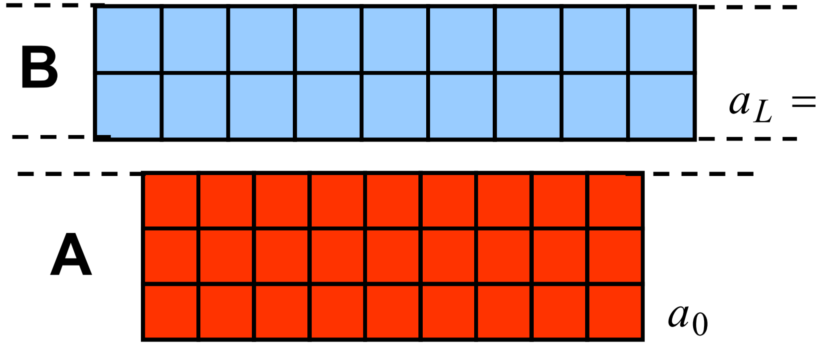
$$\Phi = \gamma_B - \gamma_A + \gamma_{AB} > 0$$

Not likely

Lattice-mismatched planar (2D) heterostructures

thin layer

thick substrate



$a_L = a_0(1+\varepsilon_0)$

$\varepsilon_0 = \Delta a / a$

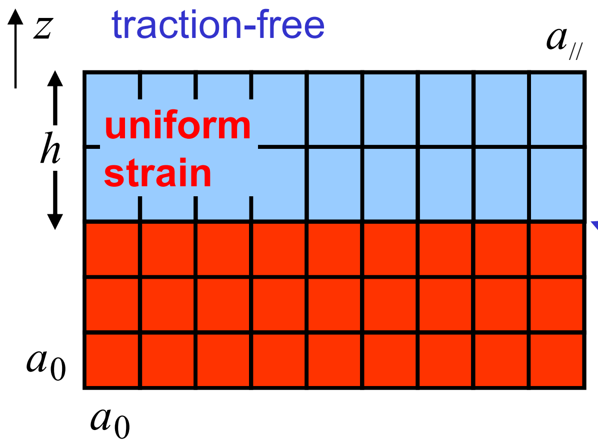
intrinsic strain or misfit

	a (nm)
InAs	0.606
GaAs	0.565
AlAs	0.566

In

Ga

Coherent elastic relaxation



$a_{//} = a_0 < a_L$

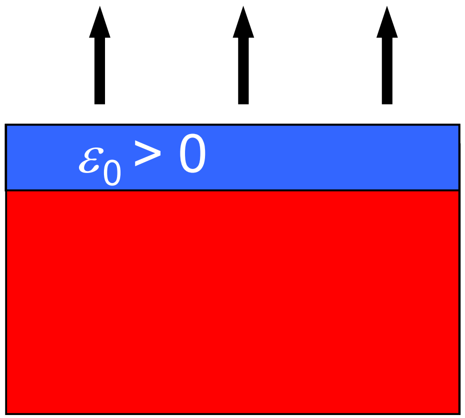
$a_\perp > a_L$

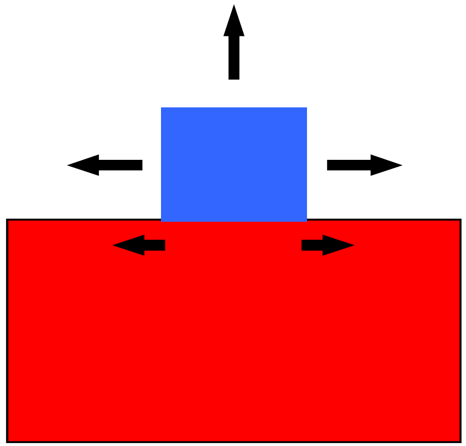
coherency (no extended defects)

3D growth induced by strain relaxation

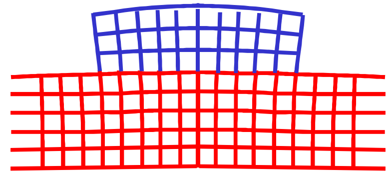
Coherent island on substrate

2D layer on substrate

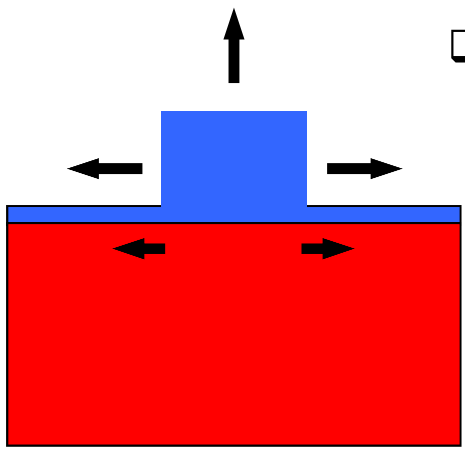




Volmer-Weber (1930s)



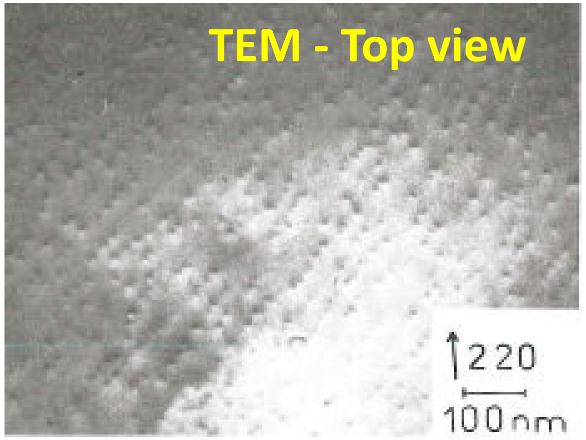
- ❑ Elastic energy decreased
- ❑ Surface energy increased

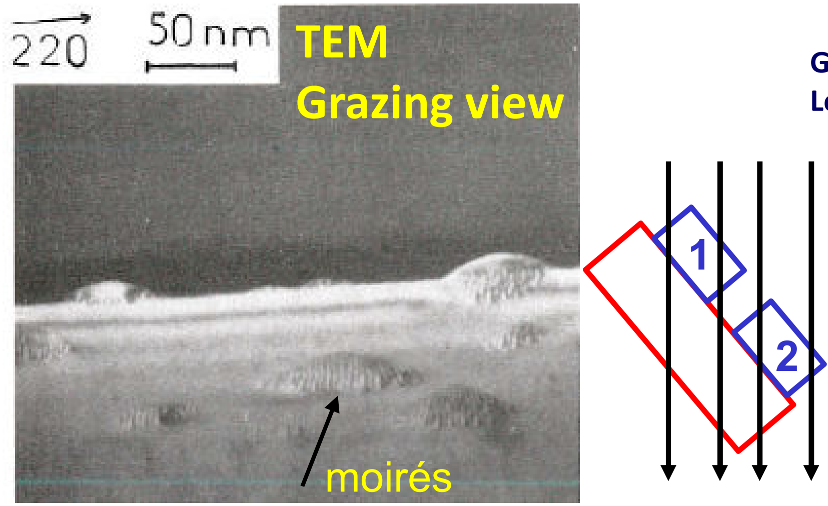


Stranski-Krastanow (SK) (1938)

Early observations of SK growth in semiconductors

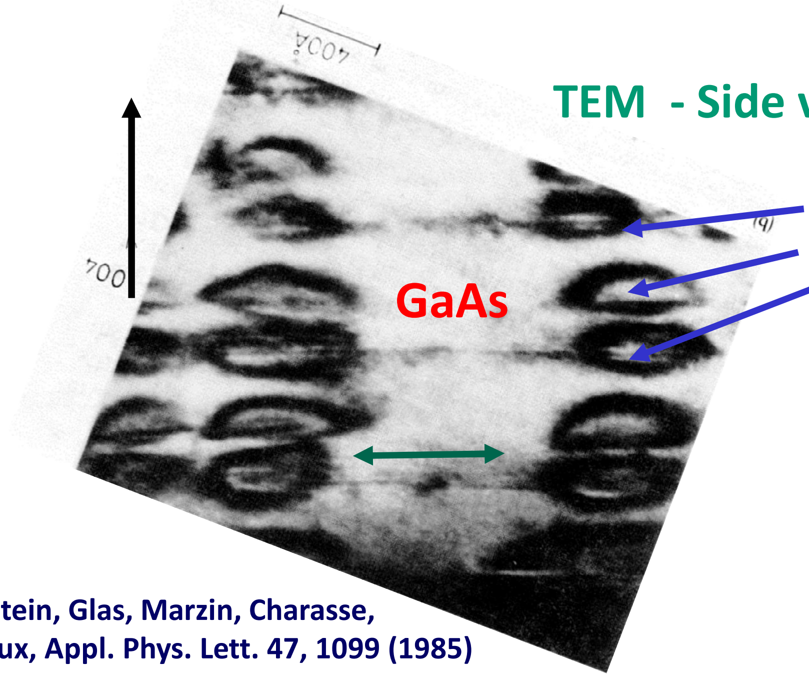
InAs islands on GaAs substrate



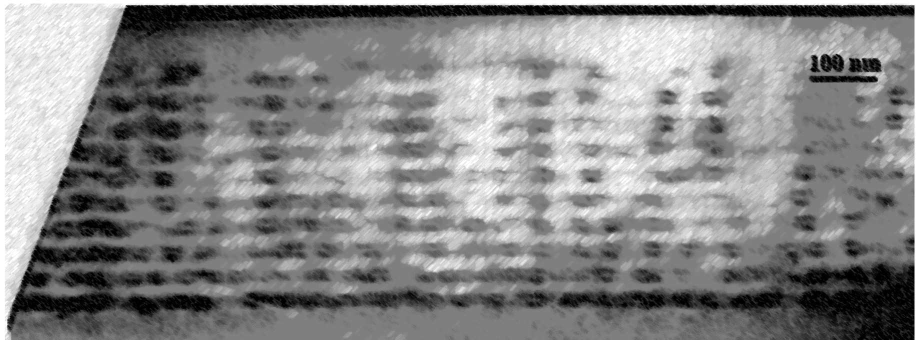


Glas, Guille, Hénoc, Houzay, IOP Conf. Ser. No 87 (1987)

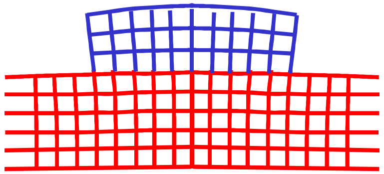
Lateral and vertical self-organization

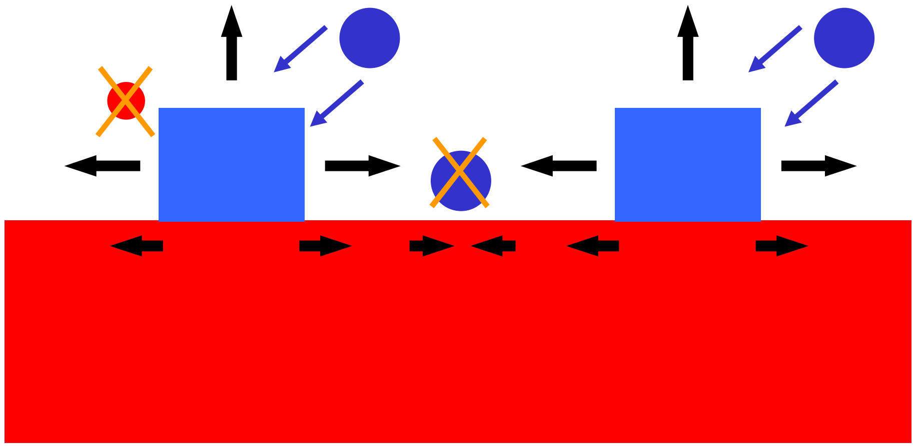


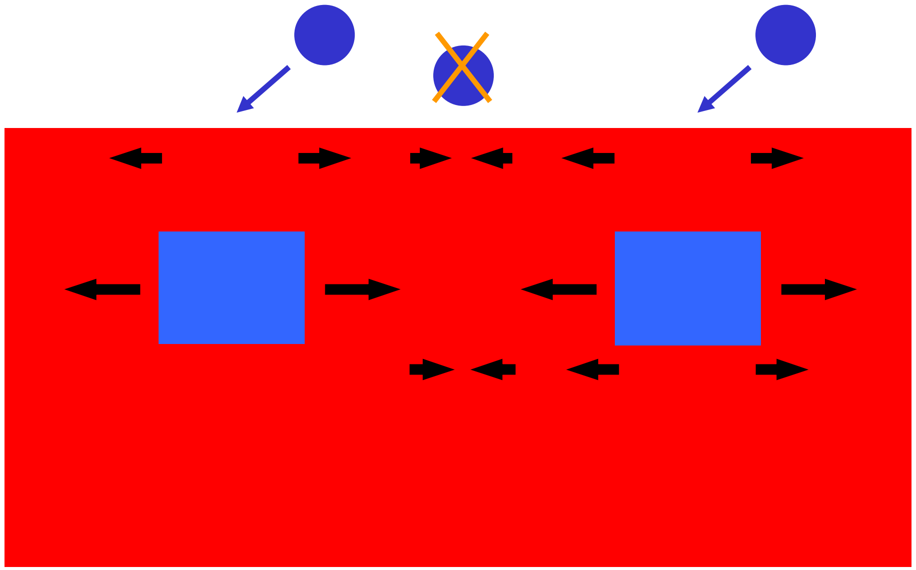
Goldstein, Glas, Marzin, Charasse, Le Roux, Appl. Phys. Lett. 47, 1099 (1985)



Lateral and vertical self-organization



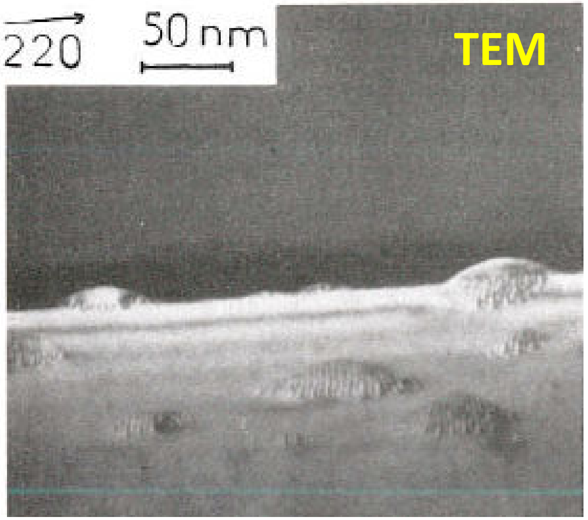


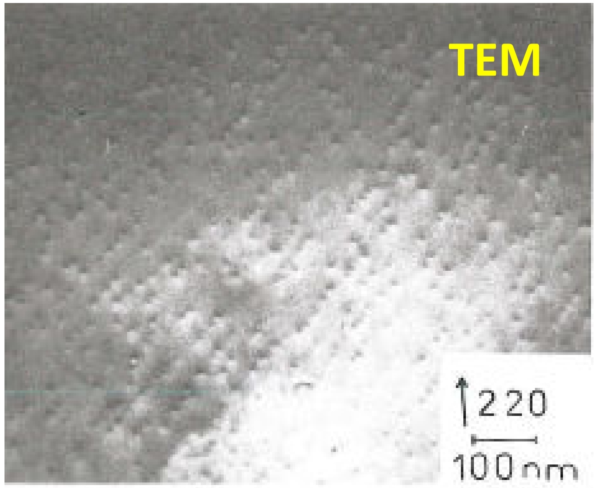


Issues with SK self-assembly

Random nucleation →

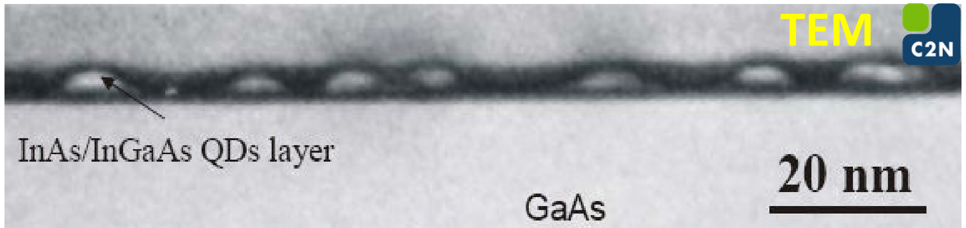
- ❑ Island location not controlled
- ❑ Size distribution
- ❑ Inhomogeneous strain





Glas, Guille, Hénoc, Houzay, IOP Conf. Ser. No 87 (1987)

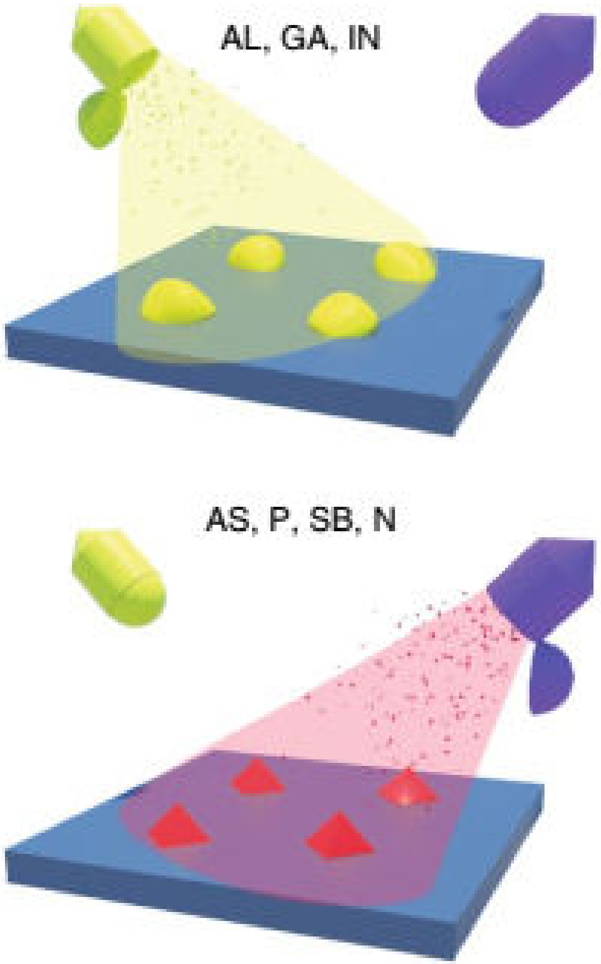
Courtesy G. Patriarche



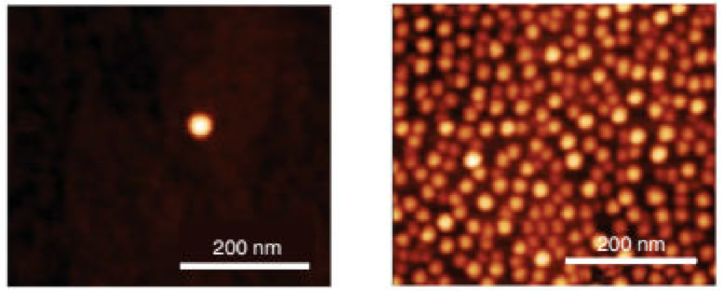
- ❑ Alloying (2D layer, capping layer)
- ❑ Need strain, *i.e.* lattice mismatch

	E_g (eV)	a (nm)
GaAs	1.42	0.565
AlAs	3.01	0.566

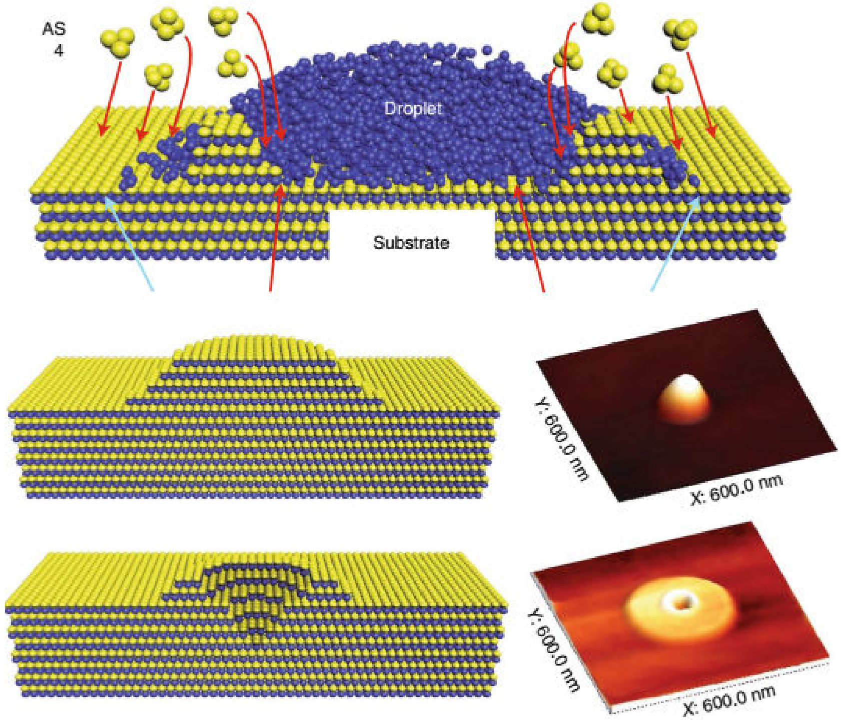
Droplet epitaxy – Island growth without lattice mismatch



❑ Density control

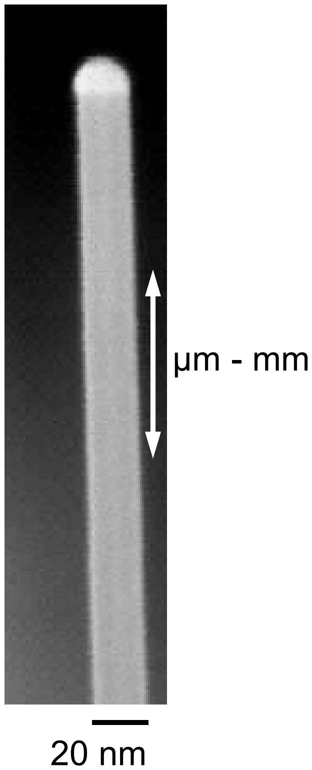


❑ Geometry control

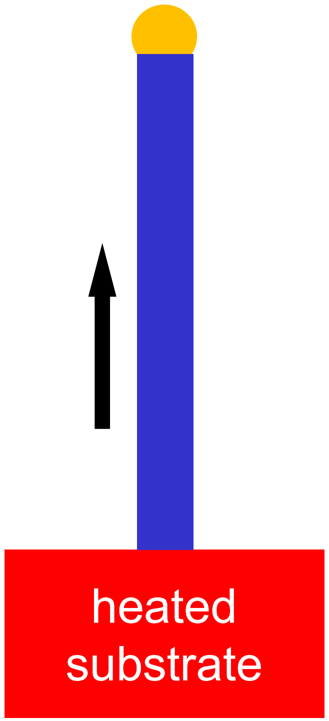


Gurioli, Wang, Rastelli, Kuroda, Sanguinetti, Nat. Mater. 18, 799 (2019)

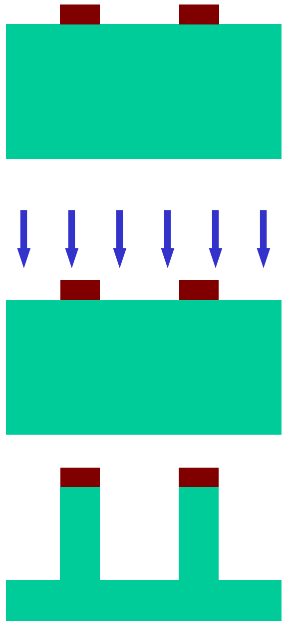
Free-standing epitaxial nanowires (NWs)

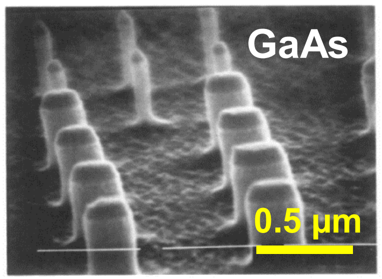


'Vertical'
Bottom-up

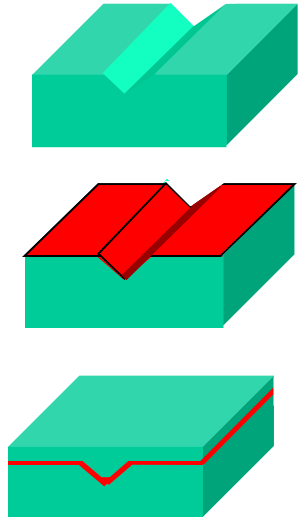


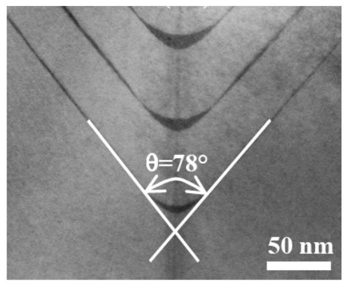
~~Top-down~~





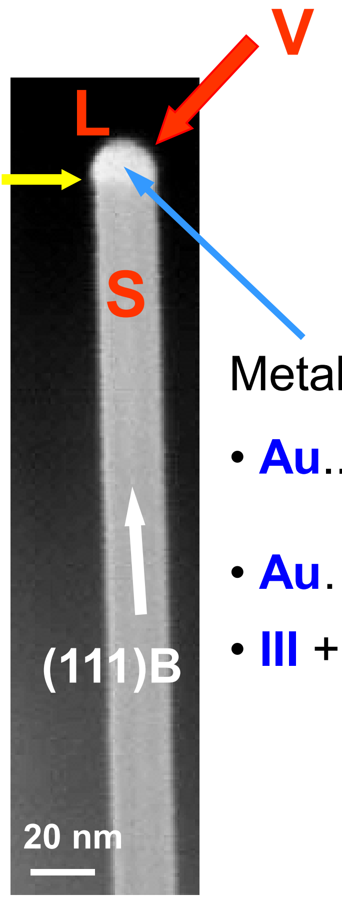
~~'Horizontal'~~





VLS, VSS, self-catalyzed, catalyst-free...

Vapor - Liquid - Solid (VLS)

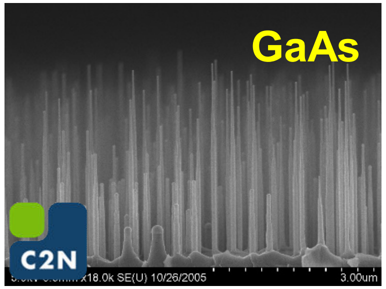


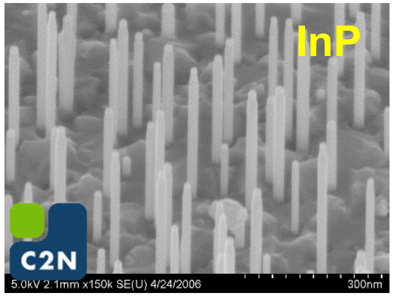
Metal **catalyst** droplet

- **Au**...+ Si (Ge….)
- **Au**… + III,V…
- **III** + V (self-catalyzed)

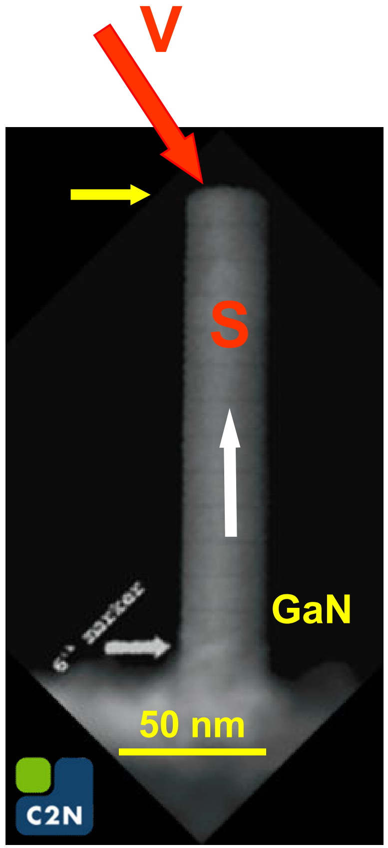
- **Vapor species transferred to Solid via Liquid**
- **New solid forms at the L-S interface**
- **Catalyst particle 'defines' NW diameter**

Catalyzed growth
VLS, VSS





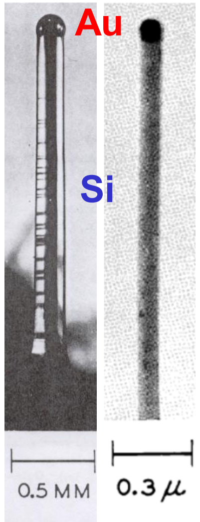
Catalyst-free
VS



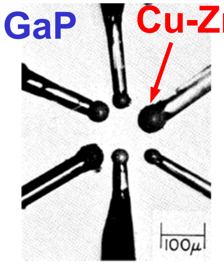
Oehler, Cattoni, Scaccabarozzi, Patriarche, Glas, Harmand, Nano Lett. 18, 701 (2018)

A short history of NW growth

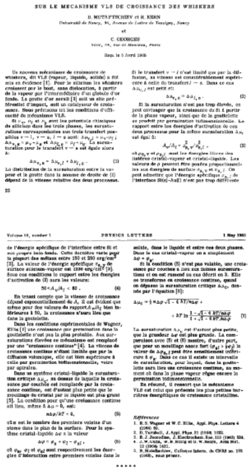
1964	1965	1965	1970s	1992-6	~ 2000	2005
Wagner, Ellis *Bell Labs*	Holonyak *Univ. Illinois*	Mutaftschiev, Kern, Georges *France*	Givargizov, Chernov *Moscow*	Hiruma *Hitachi*	Samuelson *Lund* Lieber *Harvard* Yang *Berkeley*	Ross, Tersoff *IBM*
VLS Si wires (whiskers)	III-V wires by VLS	1st theory of VLS		**Nano**wires Heterostructures Polytypism		*in situ* TEM

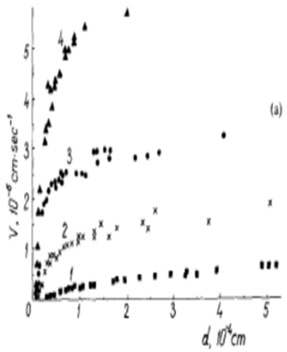


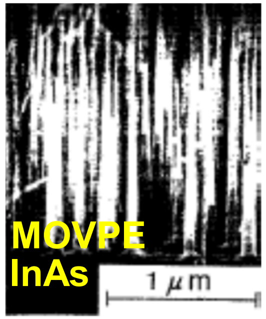
ampoule

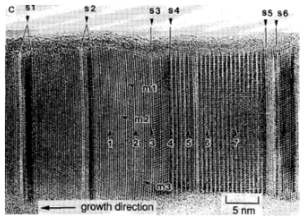


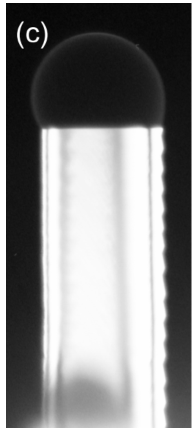
ampoule



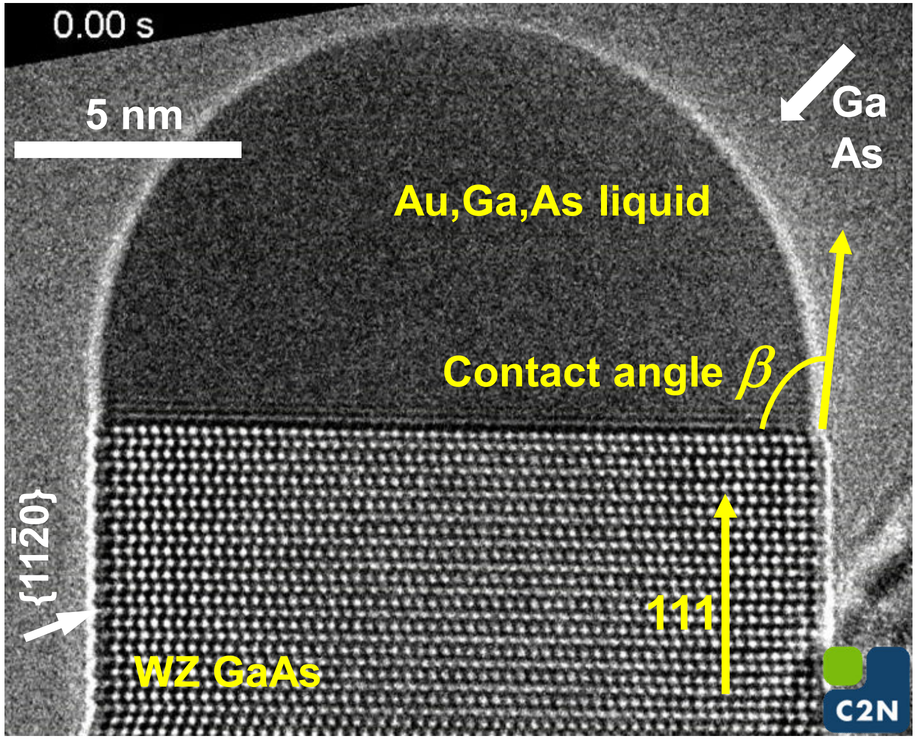




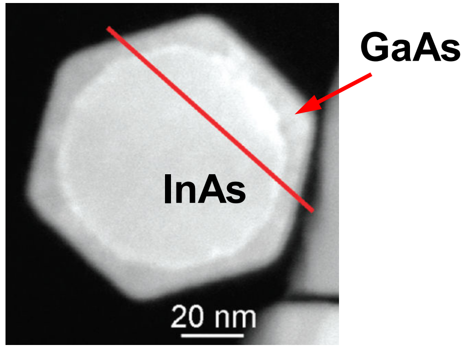




1D crystals with hexagonal cross-section



Oriented single crystal



Popovitz-Biro, Kretinin, Von Huth, Shtrikman, Cryst. Growth Des. 11, 3858 (2011)

Often: axisymmetric models

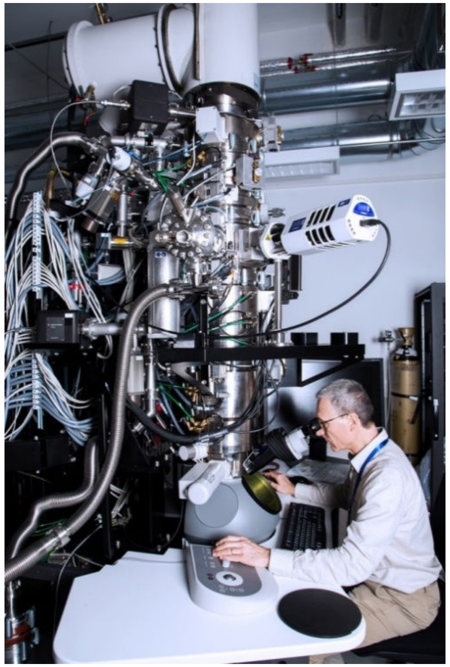
Growth in a TEM - The NanoMAX instrument

NanoMAX

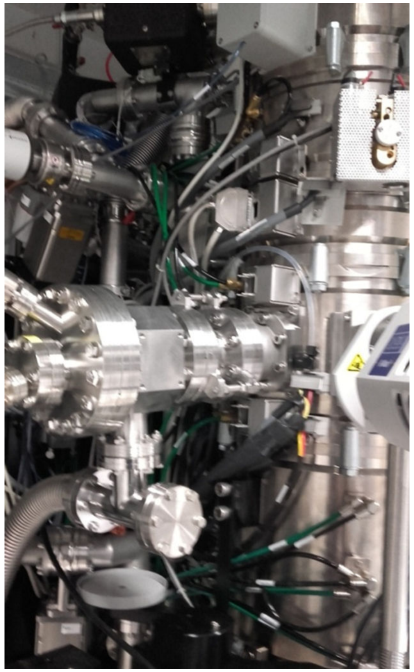
"Seeing the nanostructures growing atom by atom"

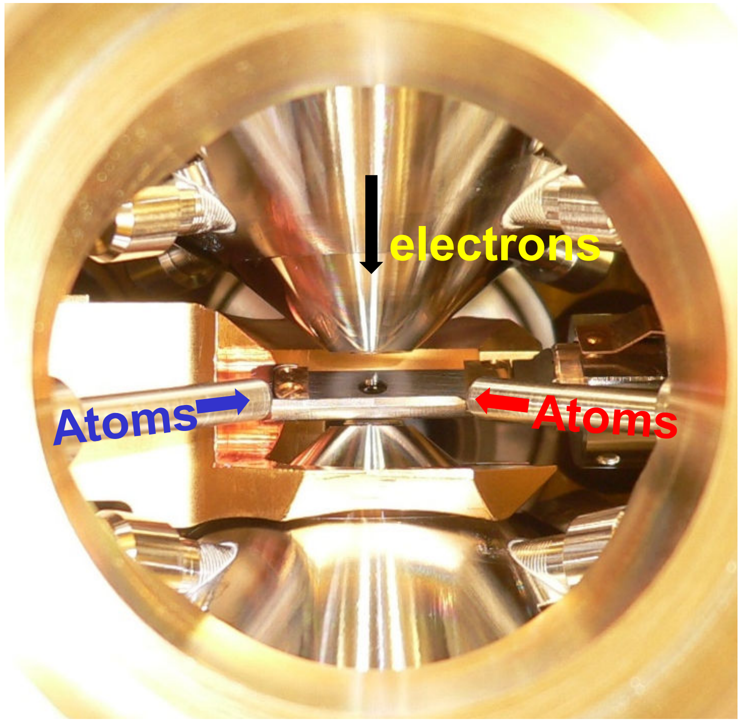
MBE, (MO)CVD…

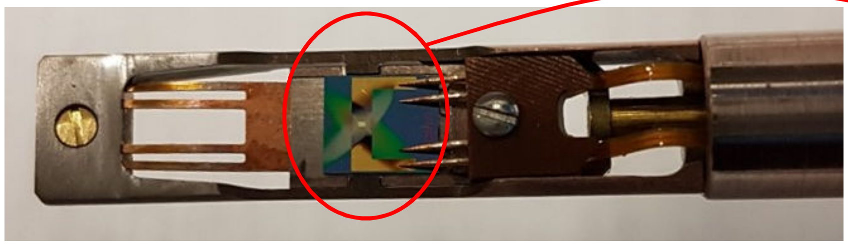
ETEM

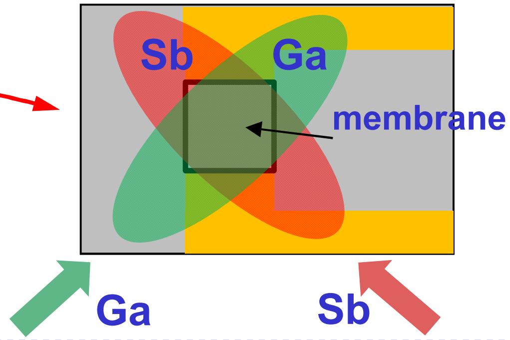


MBE sources



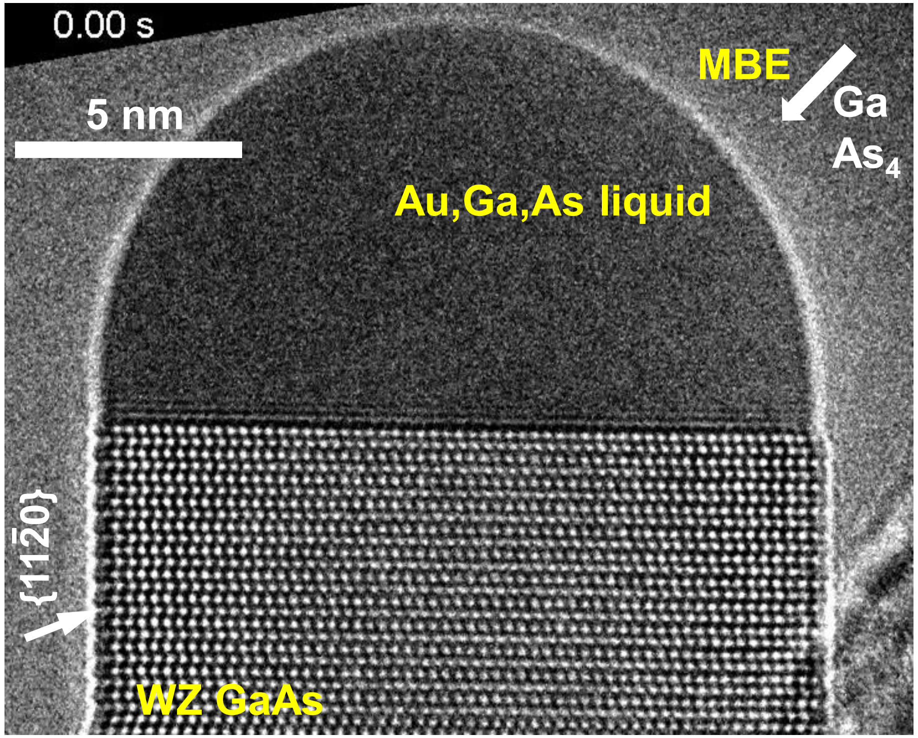






In situ NW growth

NanoMAX
"Seeing the nanostructures growing atom by atom"



Courtesy J.-C. Harmand, G. Patriarche (C2N)

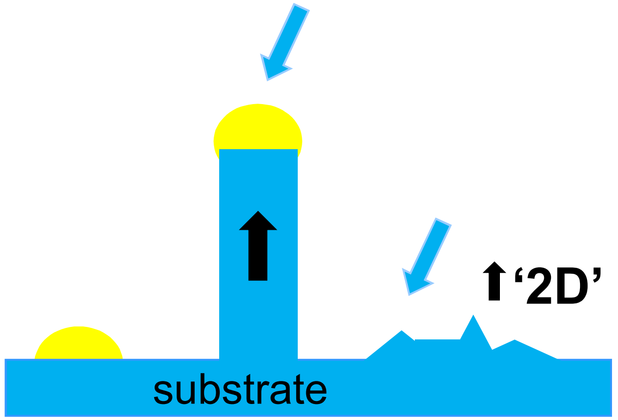
- **Oriented single crystal**
- **Epitaxial growth**
- **Monolayer (ML) by ML growth**

1 ML = 2 atomic planes
III+V, or Si+Si

The droplet as seed and catalyst

- initiates local growth
- conserved during growth
- promotes axial nanowire growth

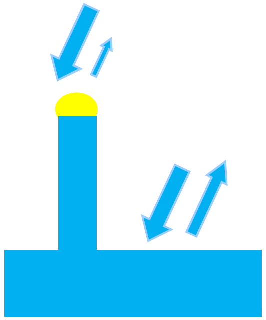
NW **competes** with "non-activated" surface



❑ CVD, MOVPE, CBE: constituents brought by gas molecules

Catalyst may promote precursor **decomposition**

chemical catalyst



❑ MBE: constituents brought as atoms or simple molecules

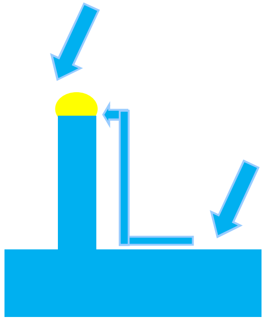
Si, Ga, In ... As_2, As_4 ... No chemical reaction needed

sticking coefficient of group-III atom = 1 on non-activated surface

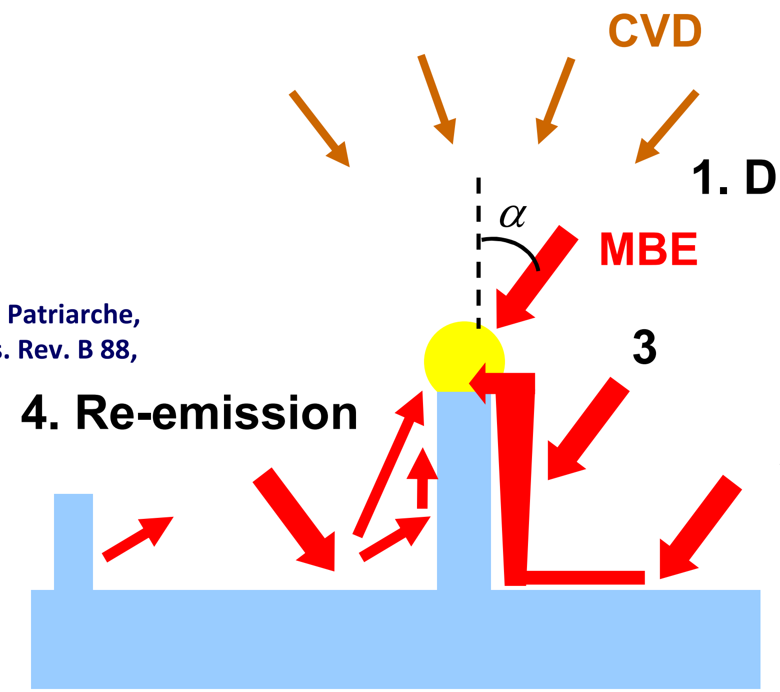
Transport of matter to the catalyst

Catalyst promotes **incorporation** of atoms in NW

physical catalyst



The droplet as collector - Material pathways



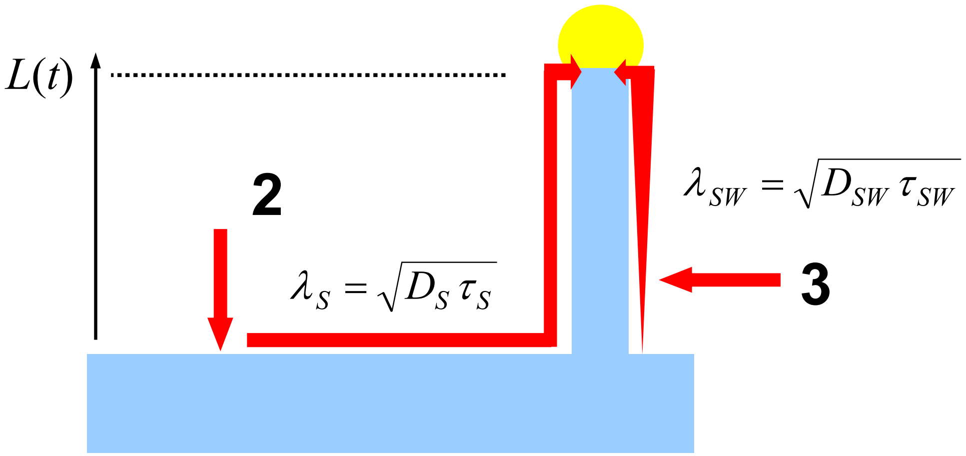
Glas, Phys. Stat. Sol. (b) (2010)

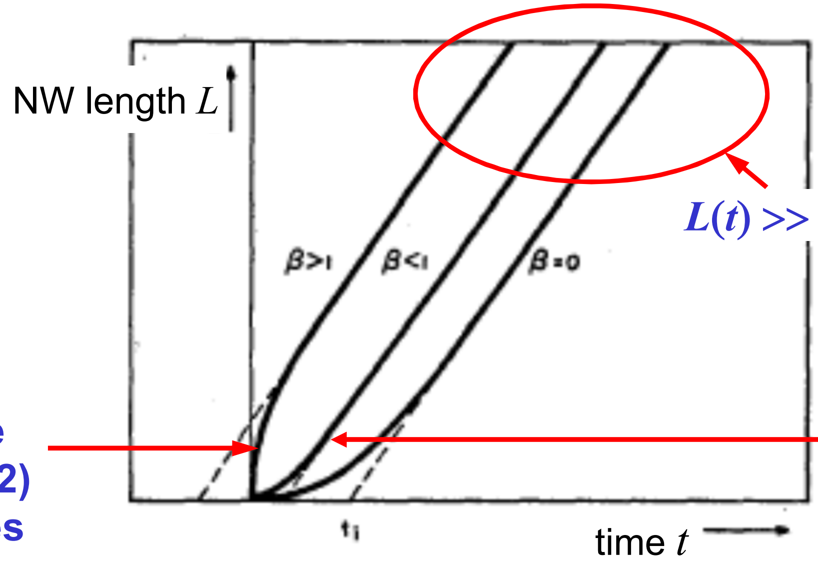
Glas, Ramdani, Patriarche, Harmand, Phys. Rev. B 88, 195304 (2013)

Tchernycheva et al., J. Appl. Phys. 102, 094313 (2007)
Plante and LaPierre, J. Appl. Phys. 105, 114304 (2009)
Dubrovskii et al., Phys. Rev. B 80, 205305 (2009)

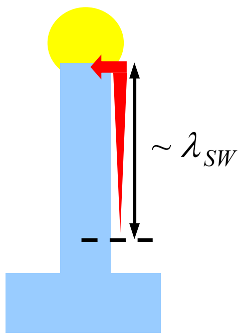
- Growth rate varies with time
- Possible radial growth on the sidewalls

Nonlinear growth





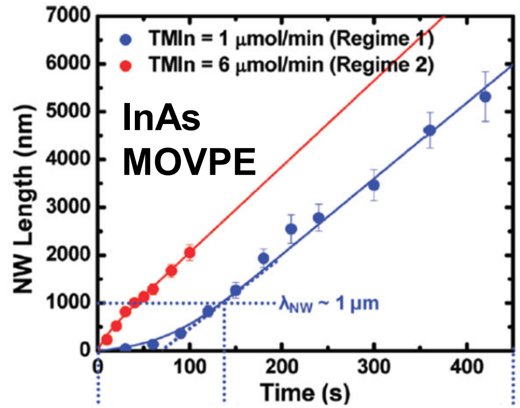
$L(t) >> \lambda_{SW}$



λ_S **large substrate contrib. (2) dominates**

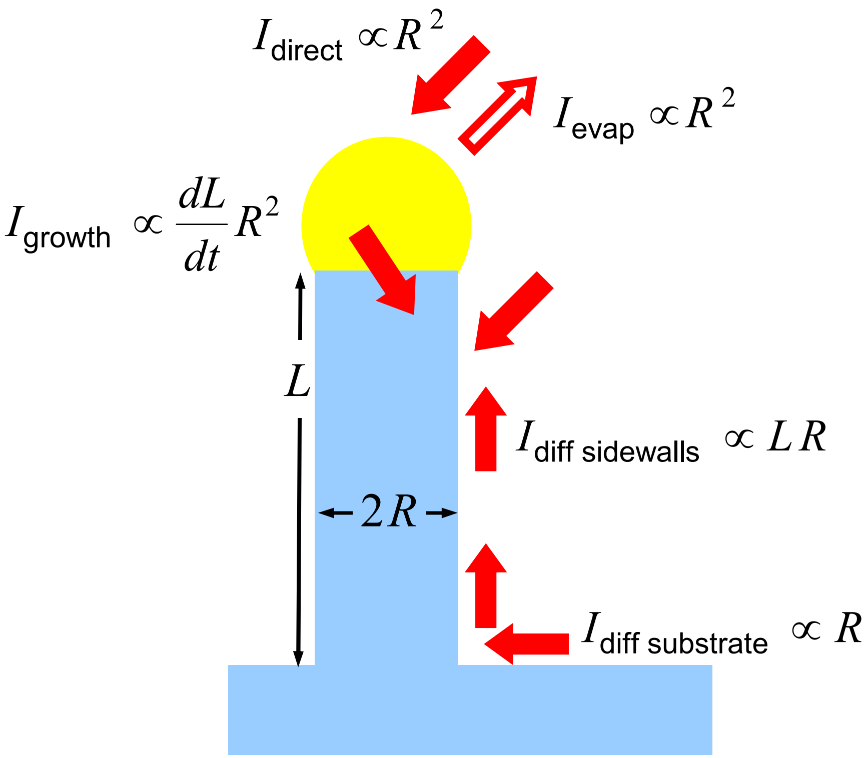
λ_{SW} **large sidewall contrib. (3) dominates**

Ruth and Hirth, J. Chem. Phys. 41, 3139 (1964)

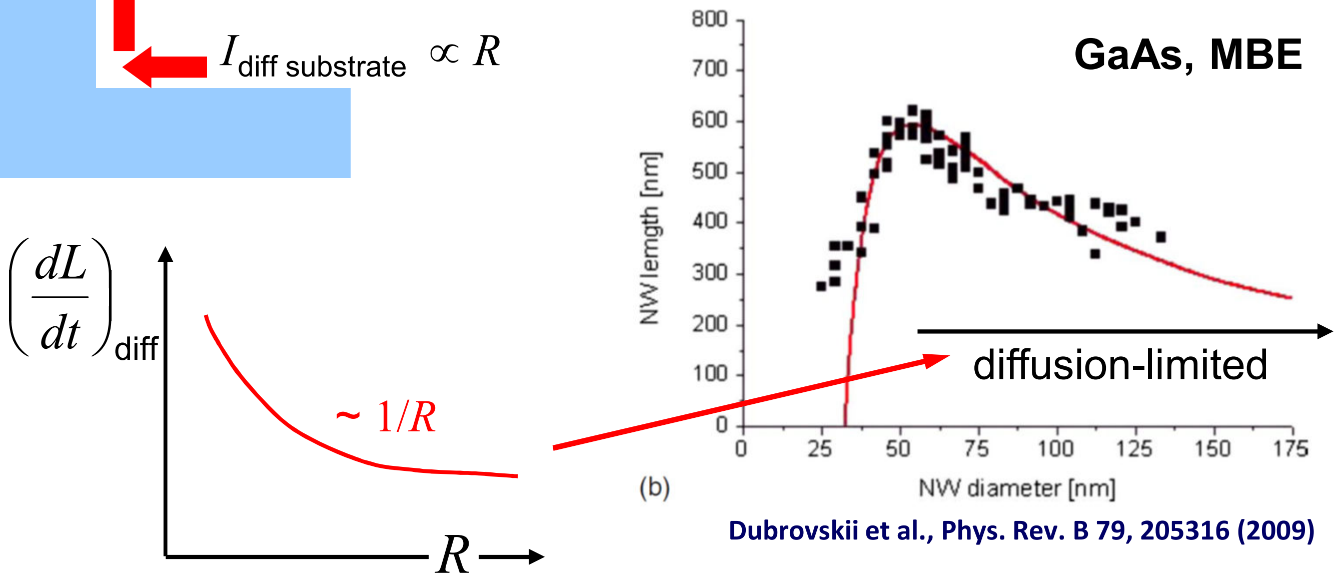


Dayeh, Yu, Wang, Nano Lett. 9, 1967 (2009)

Length/radius dependence



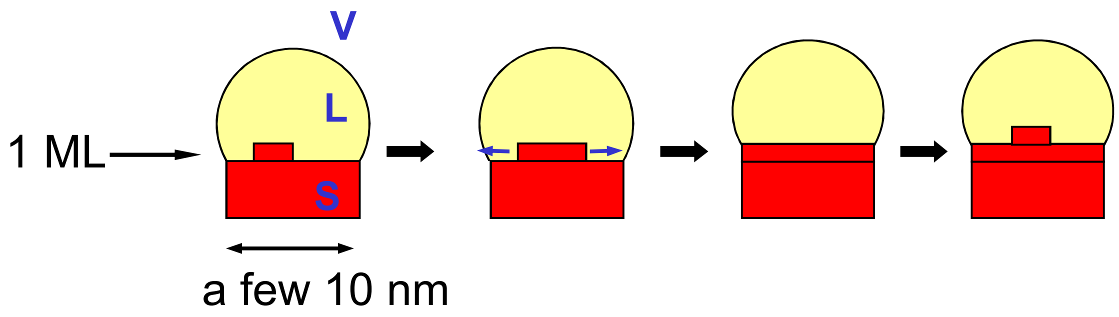
$$\frac{dL}{dt} = A + \frac{B}{R}$$



Dubrovskii et al., Phys. Rev. B 79, 205316 (2009)

Vapor-Liquid-Solid (VLS) nanowire growth and nucleation

- VLS growth proceeds **layer by layer**



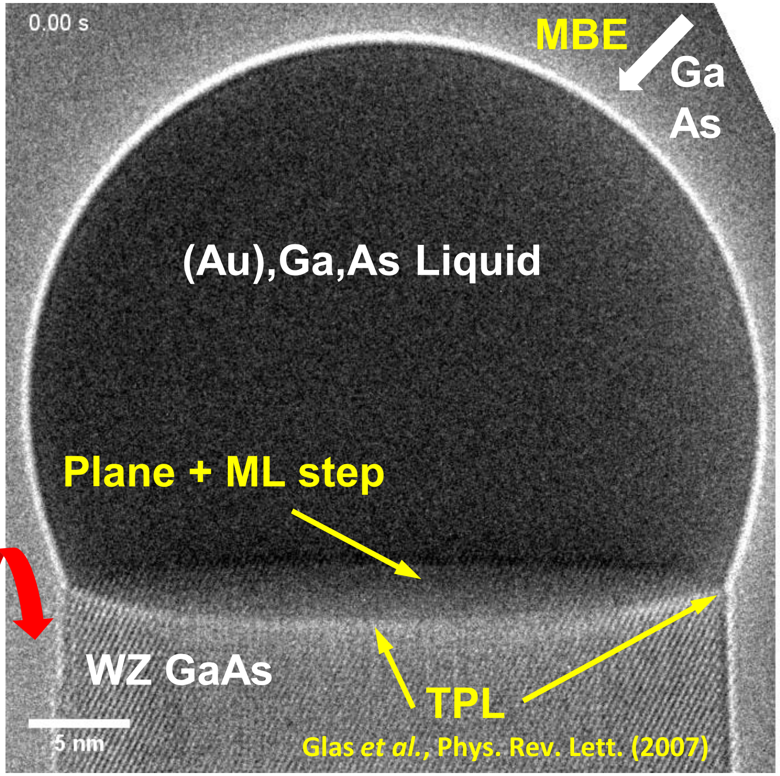
- Each ML starts growing on a bare flat facet

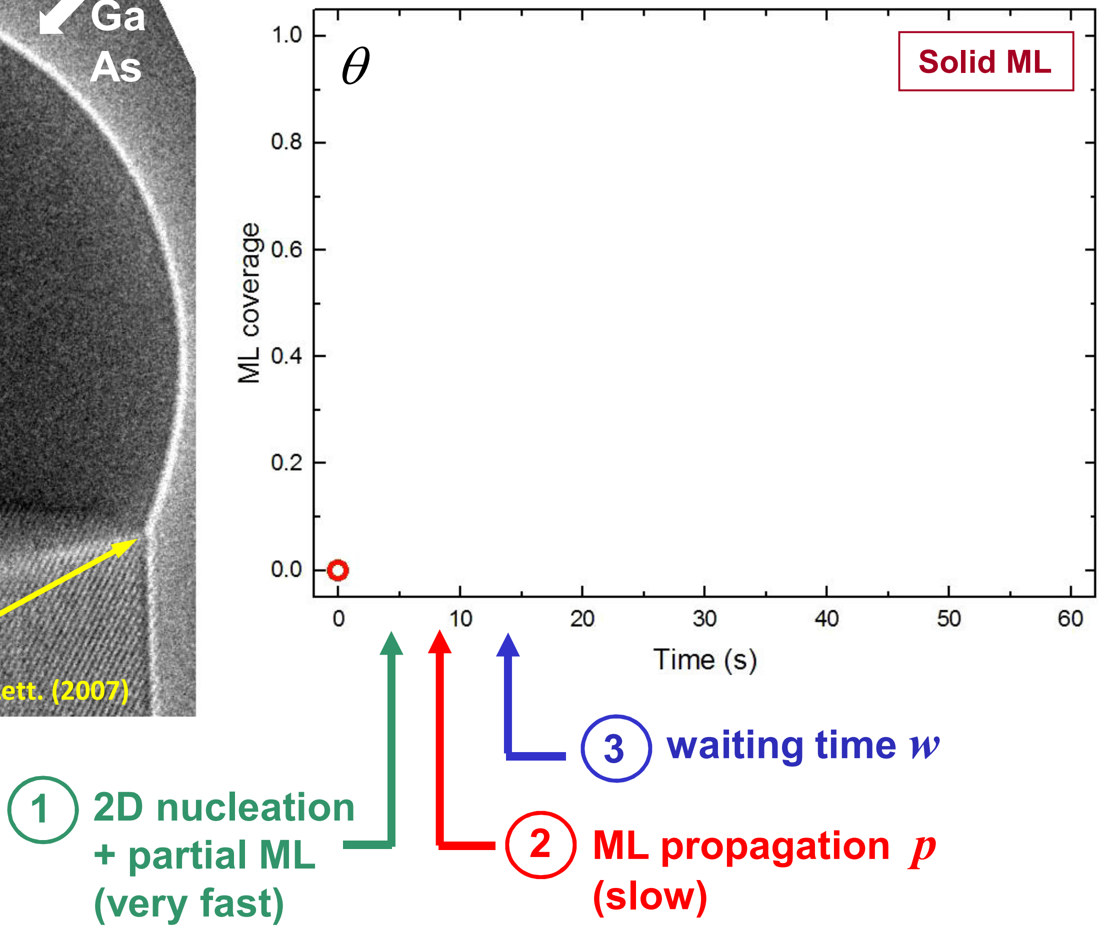
  At least one new 2D nucleus is needed for each ML

- If top facet is narrow enough, one nucleus is enough

  1 ML $\leftrightarrow$ 1 nucleation event **Mononuclear** regime

Experiments confirm 2D nucleation for each ML





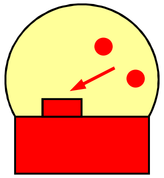
MBE in NanoMAX

"Seeing the nanostructures growing atom by atom"

Harmand, Patriarche, Glas, Panciera, Florea, Maurice, Travers, Ollivier, Phys. Rev. Lett. 121, 166101 (2018)

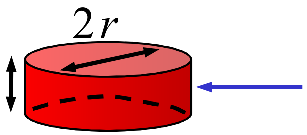
Glas, Panciera, Harmand, Phys. Status Solidi RRL 16, 2100647 (2022)

Nucleation in Vapor-Liquid-Solid (VLS) nanowire growth



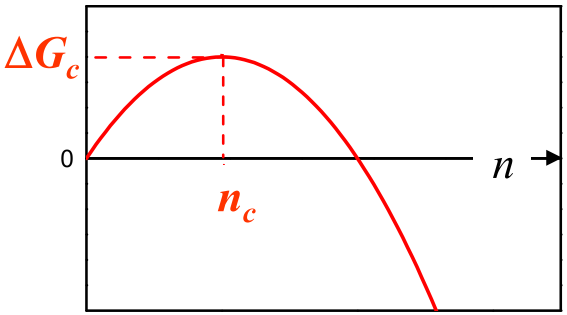
$$\Delta\mu = \mu_{\mathrm{L}} - \mu_{\mathrm{S}} > 0$$

$h = 1$ ML



γ lateral facet (step, edge)

$$\Delta G = -n\,\Delta\mu + b\,n^{1/2}\,\gamma$$



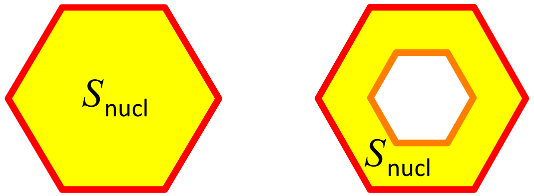
$$n_c \sim \frac{\gamma^2}{\Delta\mu^2} \qquad r_c \sim \frac{\gamma}{\Delta\mu} \qquad \Delta G_c \sim \frac{\gamma^2}{\Delta\mu}$$

- 2D nucleation rate

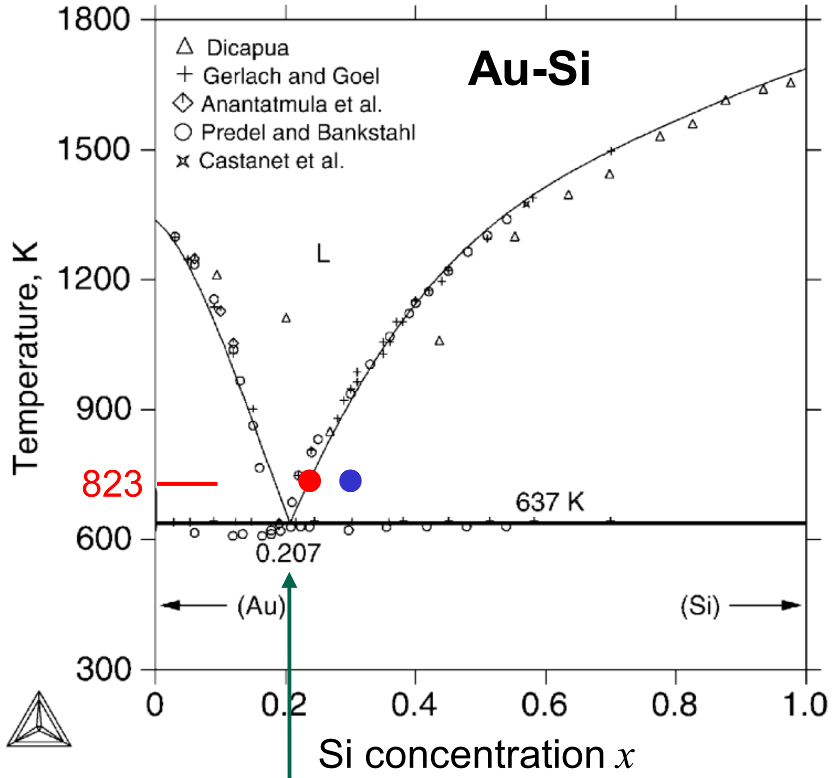
$$J_{\mathrm{nucl}} \sim \exp\left[-\frac{\Delta G_c}{k_B T}\right]$$

- Nucleation probability

$$P_{\mathrm{nucl}} = J_{\mathrm{nucl}}\ S_{\mathrm{nucl}}$$

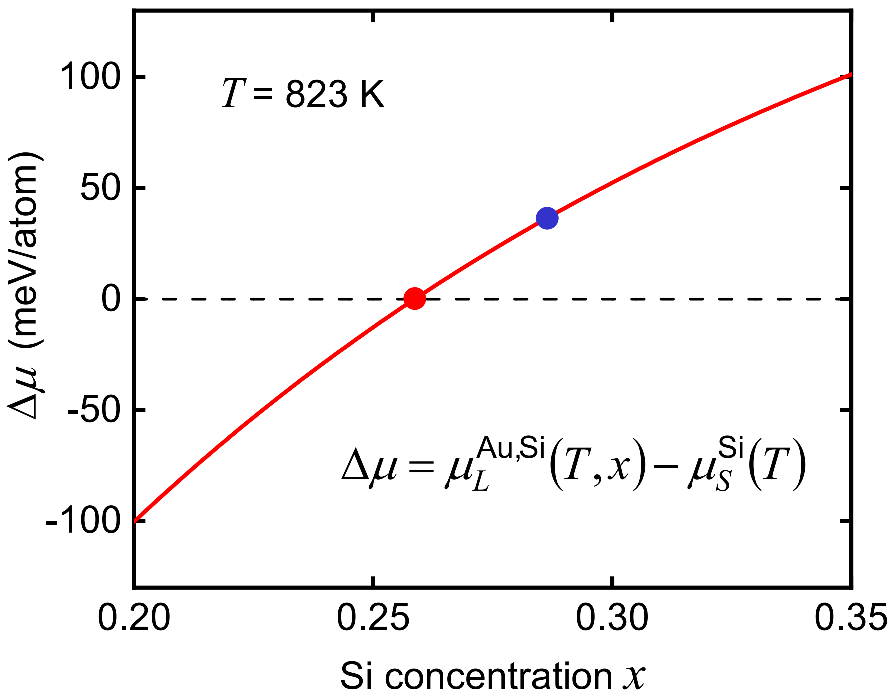


Chemical potentials for VLS growth of elemental NWs



eutectic

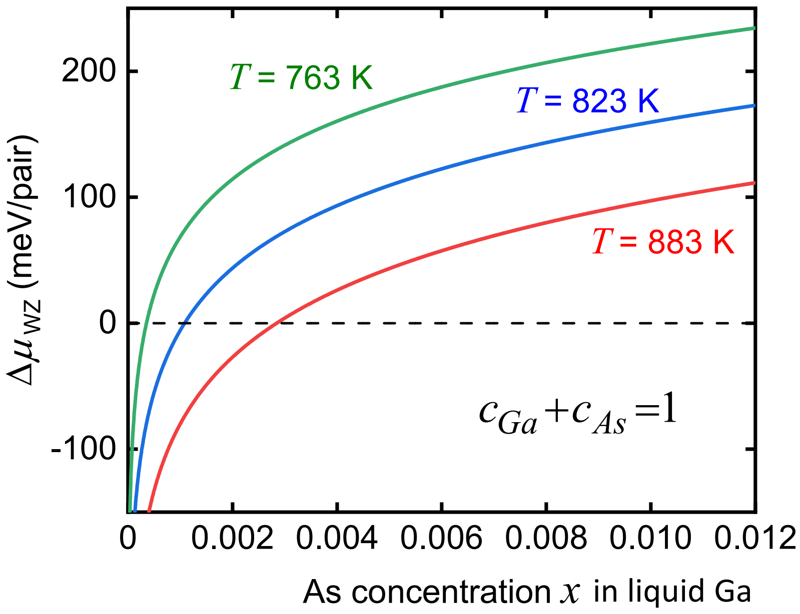
Meng, Liu, Liu, Jin,
J. All. Comp. 431, 292 (2007)



Calculated using thermodynamic data from
Dinsdale, CALPHAD 15, 317 (1991)
Chevalier, Thermochim. Acta 141, 217 (1989)

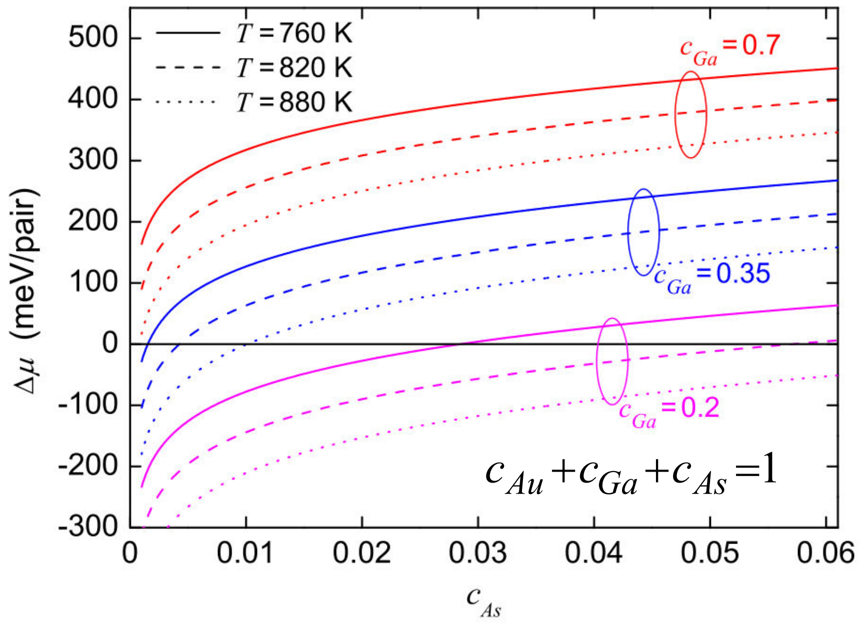
Chemical potentials for VLS growth of III-V compound NWs

Self-catalyzed GaAs (Ga,As)



Calculated using thermodynamic data from
Dinsdale, CALPHAD 15, 317 (1991)
Ansara et al., CALPHAD 18, 177 (1994)

Au-catalyzed GaAs (Au,Ga,As)

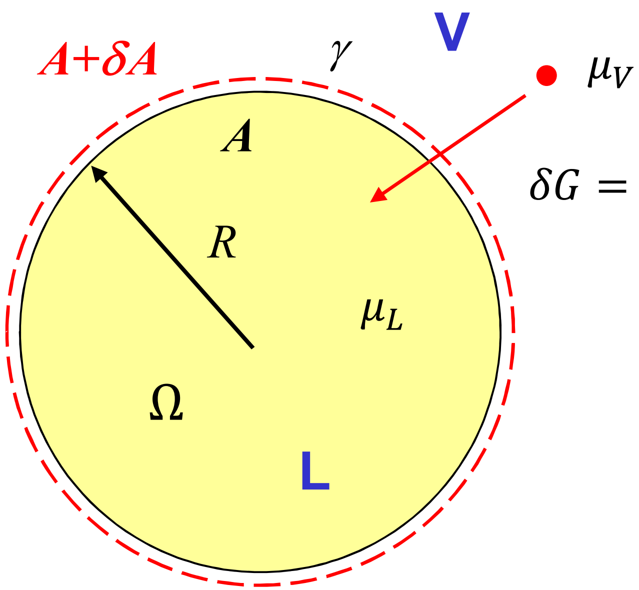


Glas, J. Appl. Phys. 108, 073506 (2010)

$$\Delta\mu(x,T) \approx k_B T \ln\left(x / x_{eq}\right)$$

Very low group V (As, P) concentration in Liquid

Finite phases - Gibbs-Thomson effect (1)



$$\delta G = \mu^L - \mu^V$$

$$\Omega = 4\pi R^3/3 \qquad d\Omega = 4\pi R^2 dR$$

$$A = 4\pi R^2 \qquad dA = 8\pi R\, dR = 2\, d\Omega / R$$

Infinite liquid $\quad \mu^L = \mu^{L\infty} \quad \delta G = \mu^{L\infty} - \mu^V$

Droplet $\quad \delta G = \mu^{L\infty} - \mu^V + \gamma\,\delta A = \mu^L - \mu^V \longrightarrow \mu^L = \mu^{L\infty} + \gamma\,\delta A$

$$\delta A = \frac{2\omega}{R} \longrightarrow \mu^L = \mu^{L\infty} + \frac{2\gamma\omega}{R}$$

Gibbs-Thomson

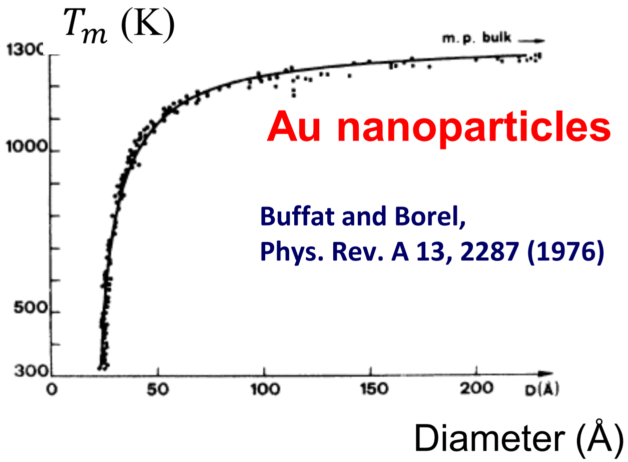
$$\mu_{GT} = \frac{2\gamma\omega}{R}$$

Gibbs-Thomson effect (2)

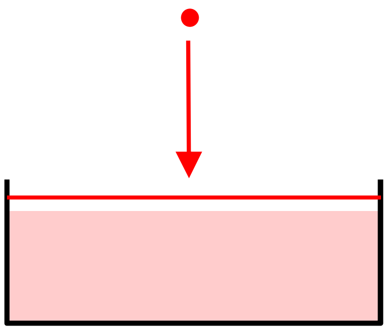
- Lowering of the melting temperature of nanoparticles

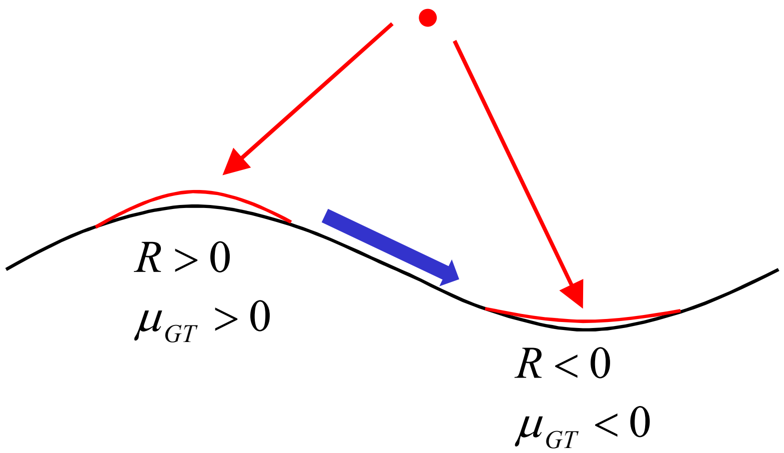
$$\mu^S = \mu^{S\infty} + \frac{2\gamma_S\,\omega_S}{R}$$

$$\mu^L = \mu^{L\infty} + \frac{2\gamma_L\,\omega_L}{R}$$



- GT effect relates to curvature, not size

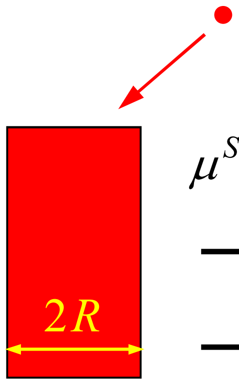




$$\mu_{GT} = \gamma\,\omega\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

GT effect and NW growth

- Early theories

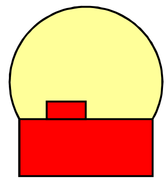


$\mu^S > \mu^{S\infty}$

→ supersaturation ↓ when R ↓

→ growth rate ↓ when R ↓

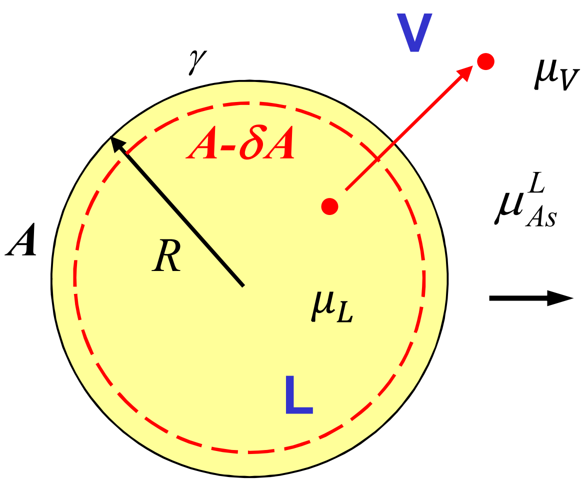
- Nucleation



$$\Delta G = -n\,\Delta\mu + b\,n^{1/2}\,\gamma$$

$$\Delta\mu = \mu_L - \mu_S^{\infty}$$

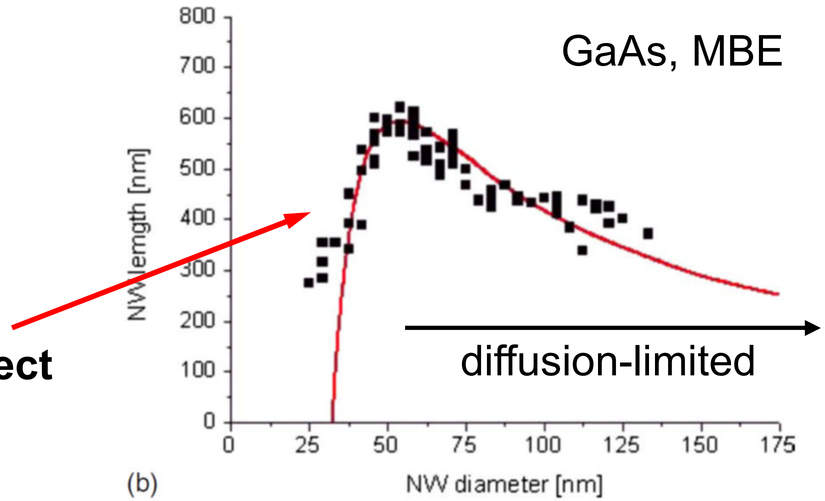
→ growth rate ↑ when R ↓ **?**



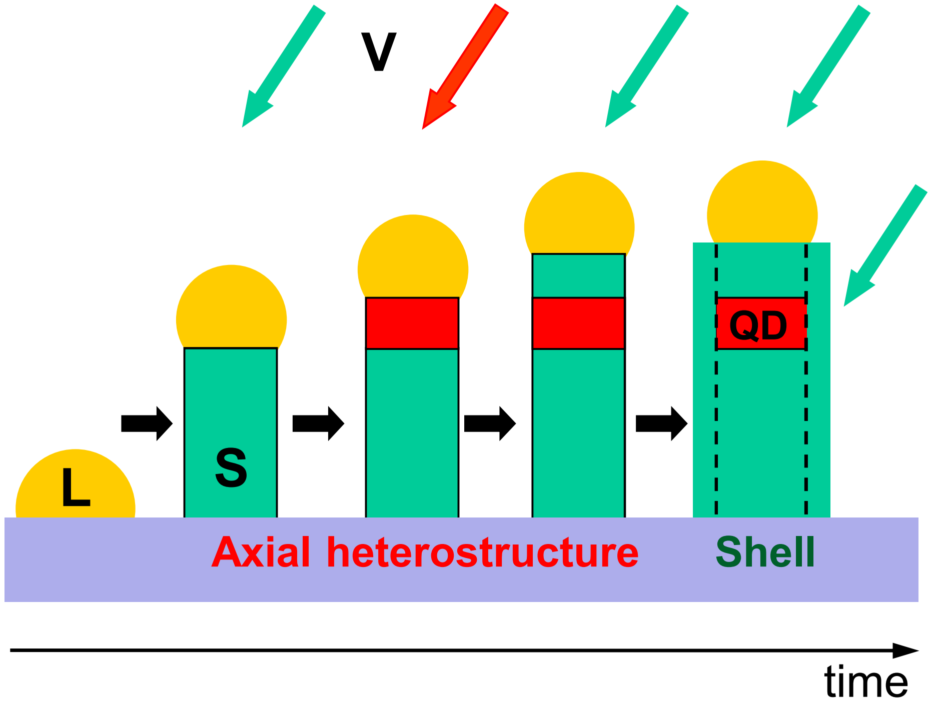
μ_{As}^{L} ↑ when R ↓

→ desorption ↑

Kelvin effect



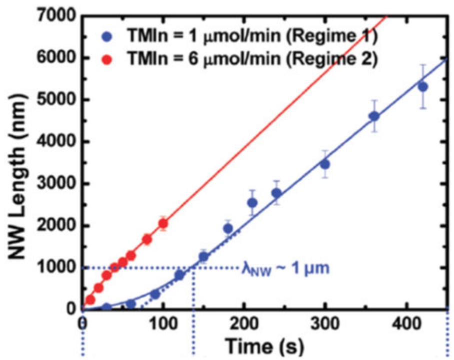
Quantum size insertions in NWs



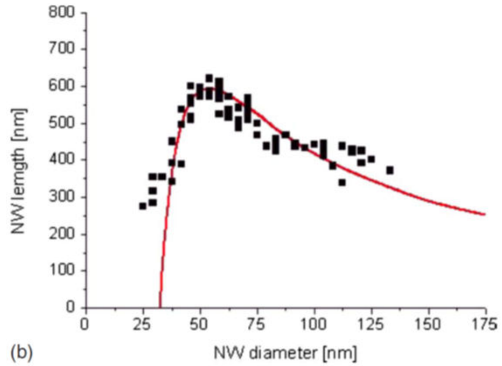
- no strain needed
- size control
- position control

However, growth rate depends

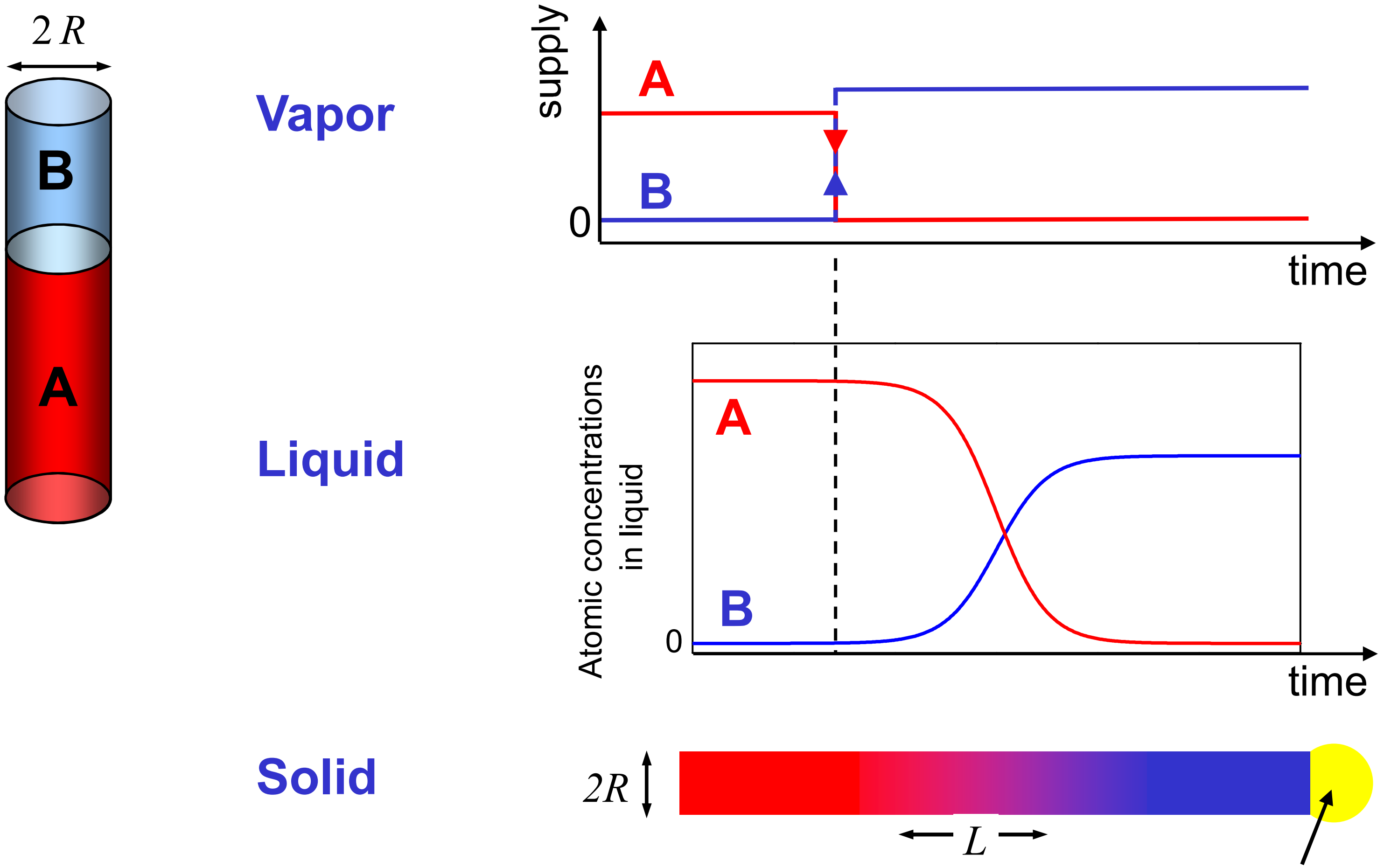
on NW length



and radius



Axial hetrostructures - The reservoir effect in VLS growth



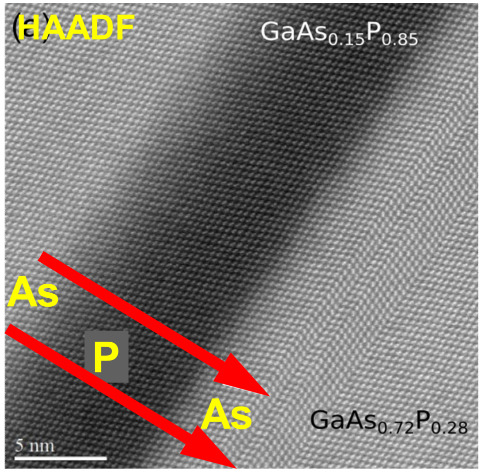
graded interface $N \sim LR^2$ $N \sim cR^3$ $\longrightarrow$ $L \sim cR$

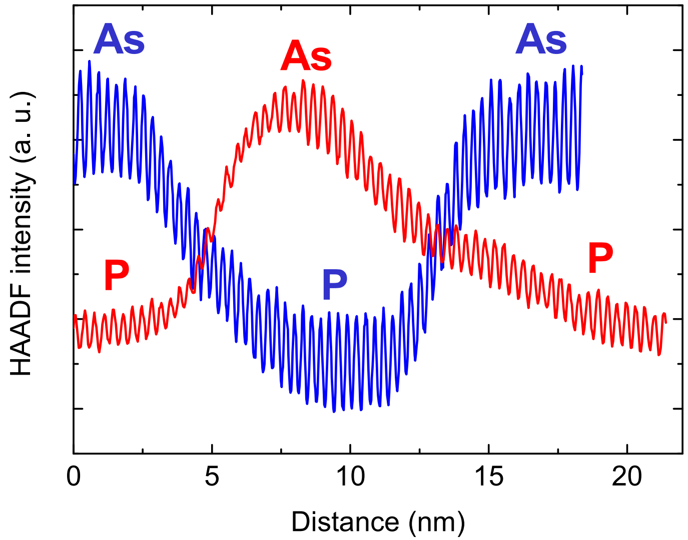
- **Si** ↔ **Ge**
- group III commutation in III-Vs: **Ga**As ↔ **In**As, **Ga**As ↔ **Al**As ...

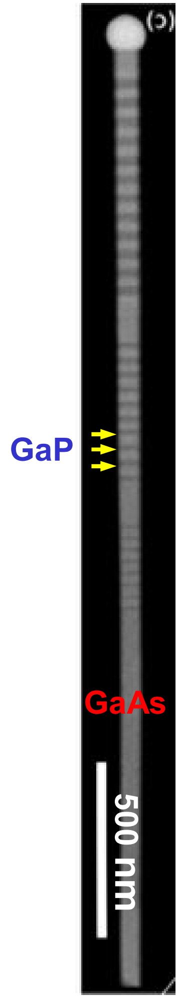
Circumventing the reservoir effect

Commute elements with low solubility: group V elements

ML resolution

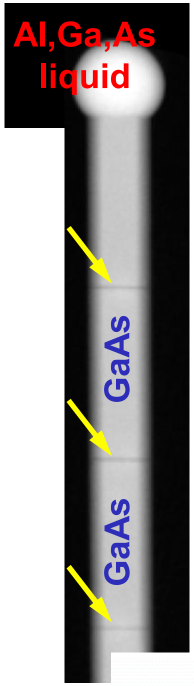


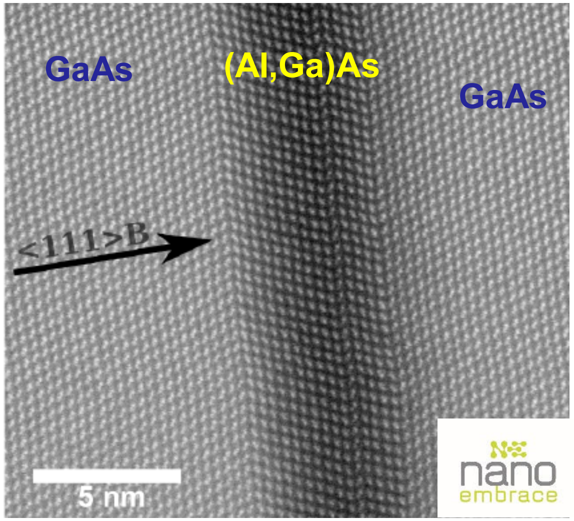




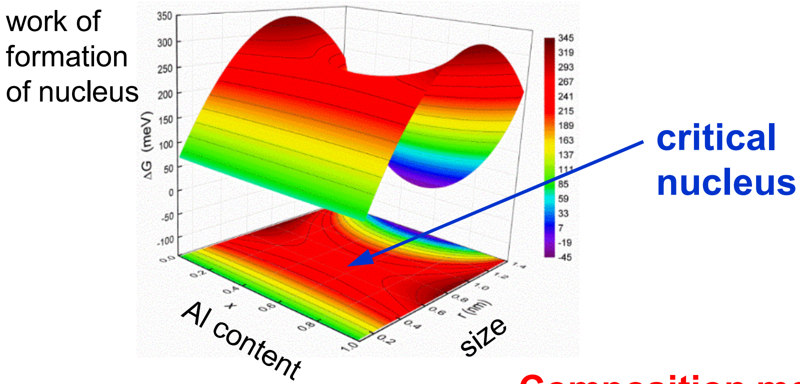
Priante, Patriarche, Oehler, Glas, Harmand, Nano Lett. 15, 6036 (2015)

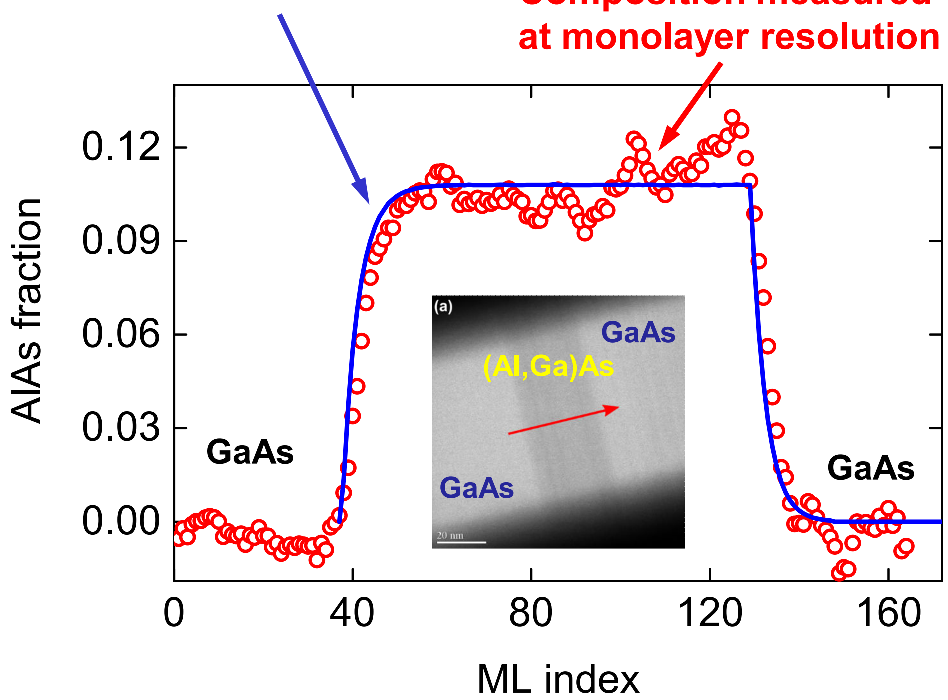
Sharp interfaces even when commuting group III!

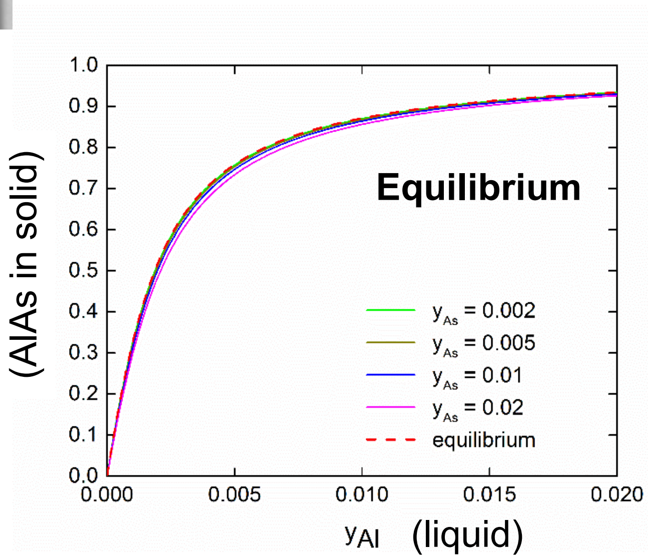




Atomic resolution STEM



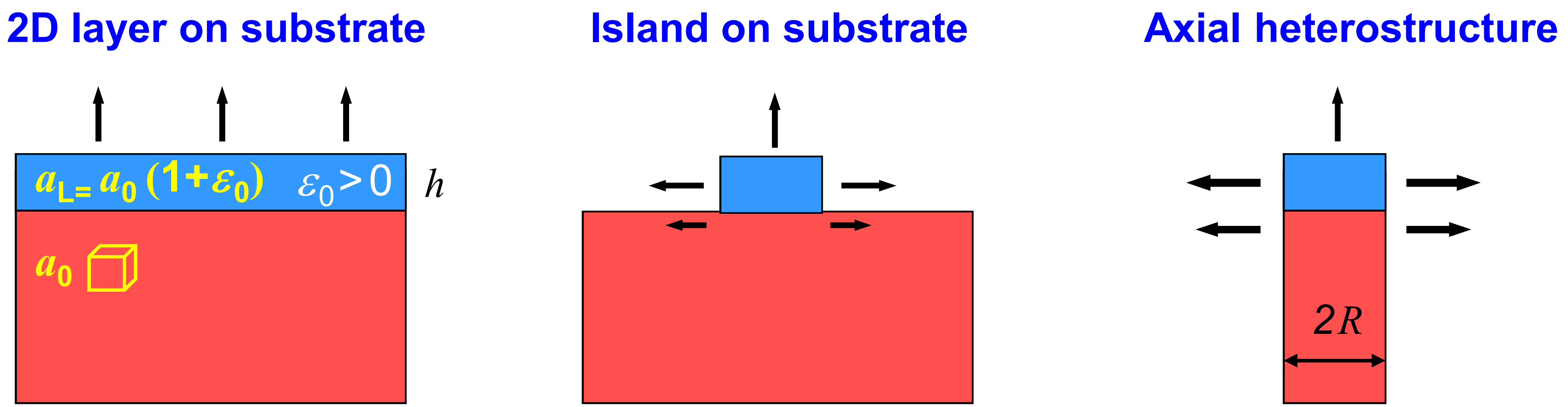


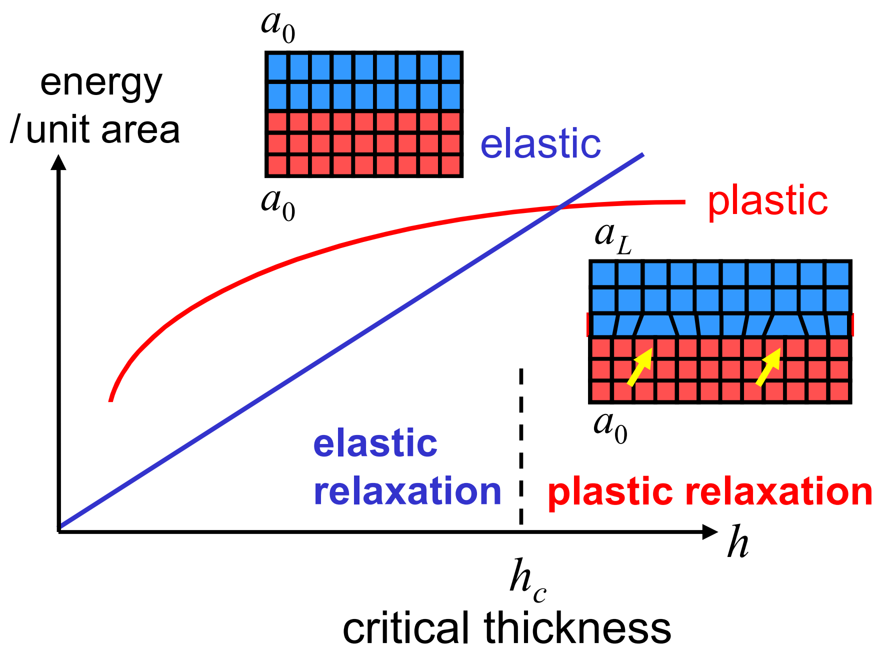


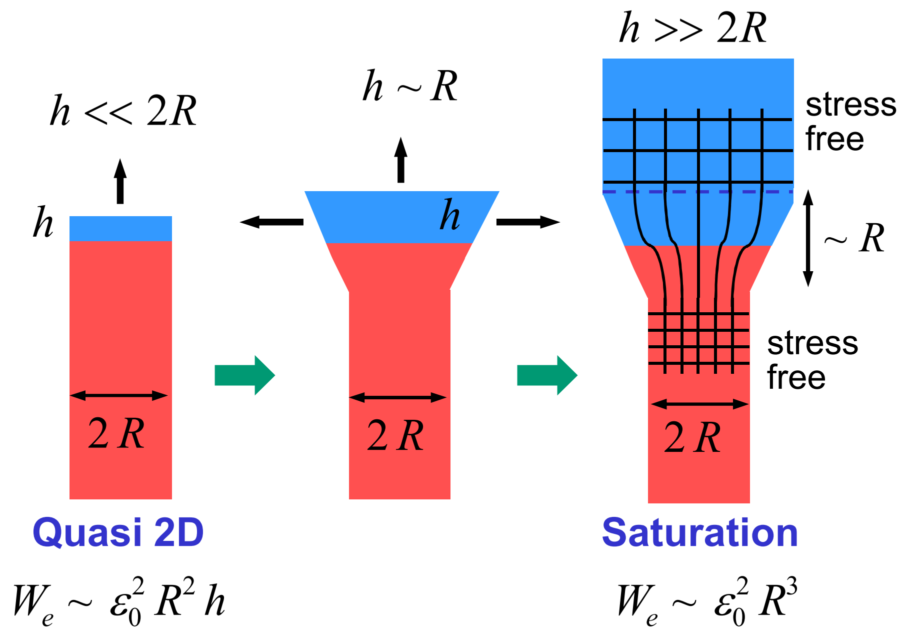
Priante, Glas, Patriarche, Pantzas, Oehler, Harmand, Nano Lett. 15, 1917 (2016)

Glas, Cryst. Growth Des. 17, 4785 (2017)

Strain relaxation in 1D axial heterostructures

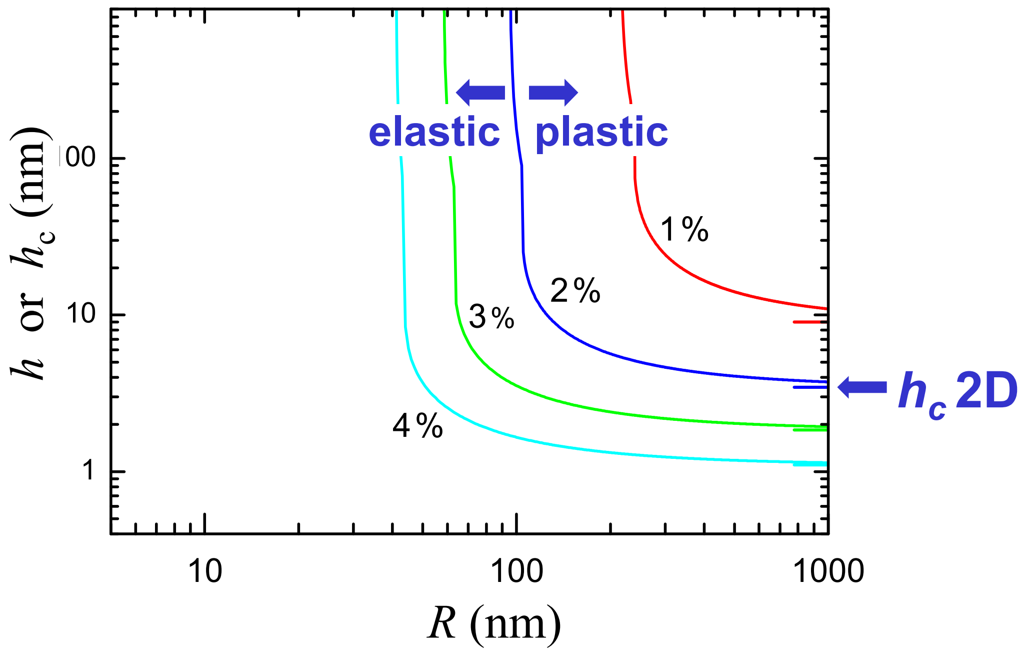


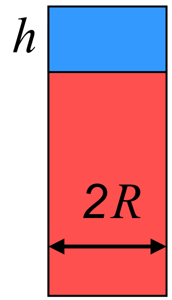




Critical thickness and critical radius

Radius-dependent critical thickness

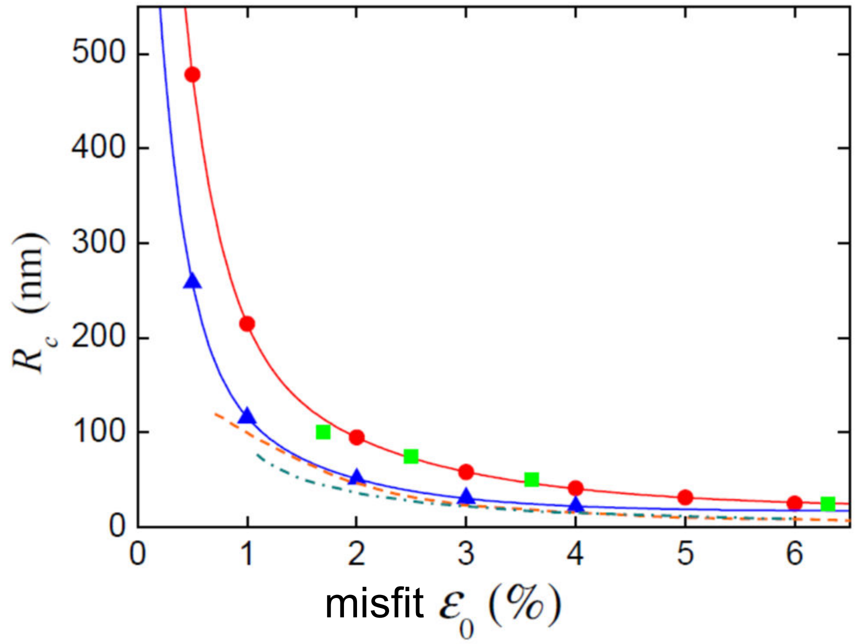




Glas, Phys. Rev. B 74, 121302(R) (2006)

Glas, Chapter 2 in: Semiconductor nanowires I: Growth and theory, Academic Press, Burlington (2015)

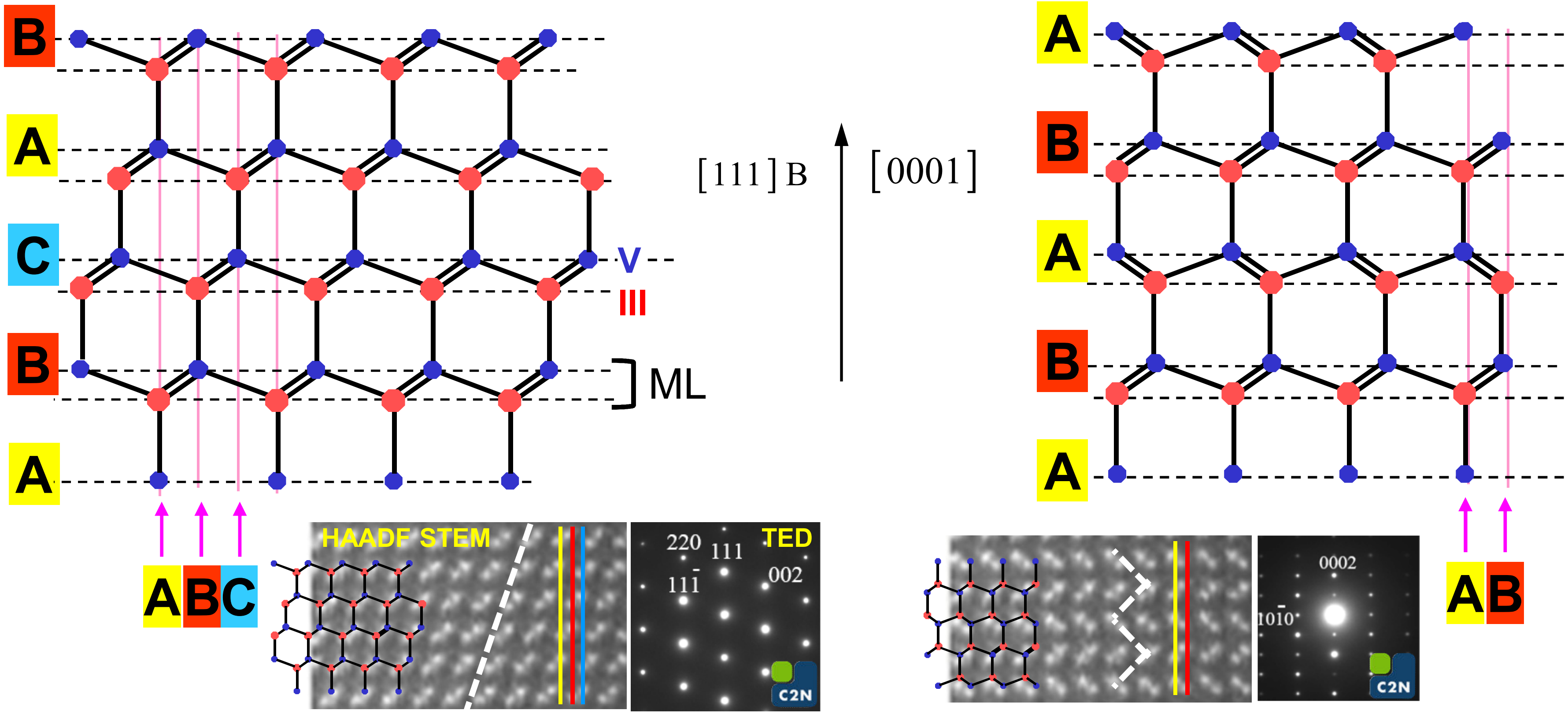
Critical radius



Polytypism in III-V NWs

Cubic (fcc)
zinc blende ZB
(sphalerite)

Hexagonal
wurtzite WZ

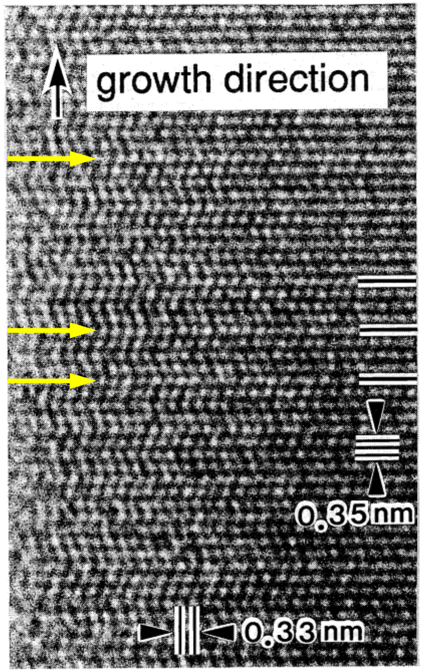


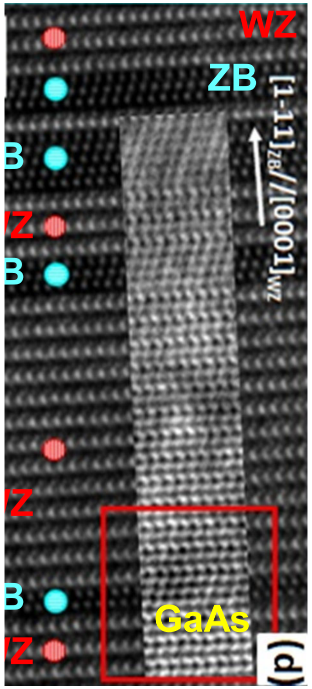
G. Patriarche

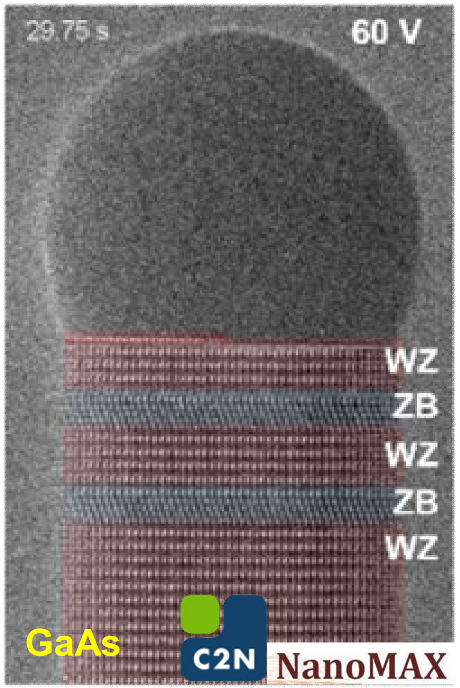
Polytypism in NWs - Compounds vs elemental

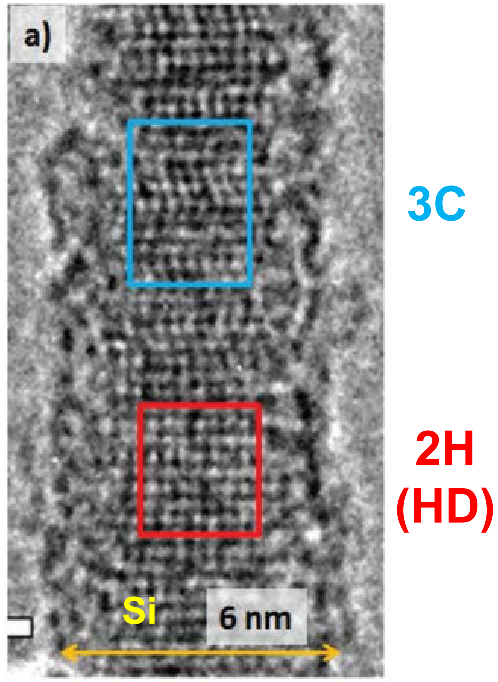
Very common in III-V NWs — **Very rare in Si,Ge…**

unintentional — **intentional**









Koguchi, Kakibayashi, Yasawa, Hiruma, Katsuyama, Jpn. J. Appl Phys. 31, 2061 (1992)

Spirkoska, Arbiol, Gustafsson, Conesa-Boj, Glas, Zardo, Heigoldt, Gass, Bleloch, Estrade, Kaniber, Rossler, Peiro, Morante, Samuelson, Abstreiter, Fontcuberta i Morral, Phys. Rev. B 80, 245325 (2009)

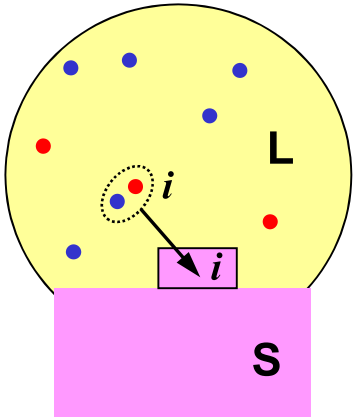
Yu, Saidov, Erofeev, Hassebi, Wei, Renard, Vincent, Glas, Mirsaidov, Panciera Submitted (2025)

Tang, Maurice, Fossard, Florea, Chen, Johnson, Foldyna, Yu, Roca i Cabarrocas, Nanoscale 9, 8113 (2017)

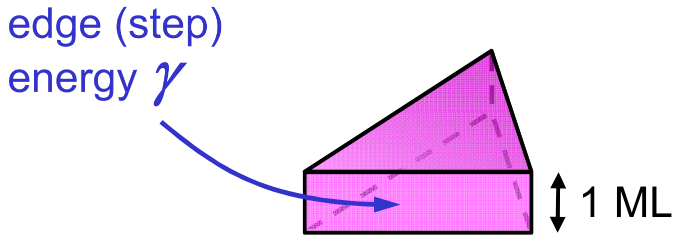
Never found in III-V bulk, layers, quantum dots…

2D nucleation and kinetic competition

ML ‘structure’ is selected at nucleation

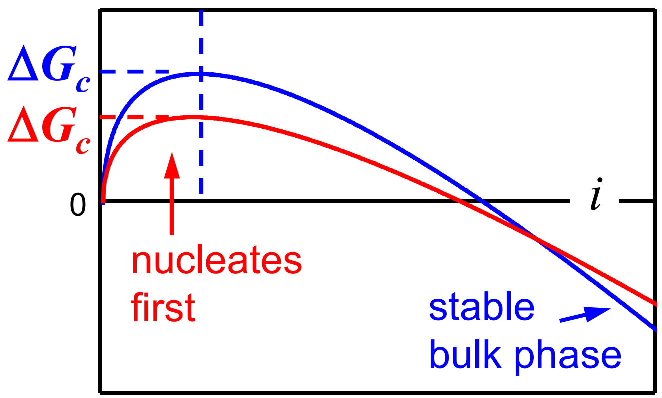


$$\Delta\mu = \mu_L - \mu_S \geq 0$$



Work of formation of 2D cluster $\Delta G = -i\,\Delta\mu + a\,i^{1/2}\gamma$

$$\Delta G_c = \frac{a^2}{4}\frac{\gamma^2}{\Delta\mu}$$



$$P_{\text{nucl}} \sim \exp\left(-\Delta G_c / k_B T\right)$$

cf. Ostwald's step rule (1897)

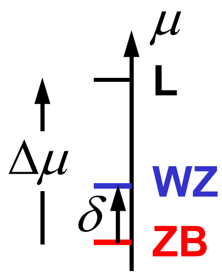
Glas, Harmand, Patriarche, Phys. Rev. Lett. 99, 146101 (2007)

Zinc blende (ZB) - Wurtzite (WZ) competition in III-V NWs

Glas, Harmand, Patriarche, Phys. Rev. Lett. 99, 146101 (2007)

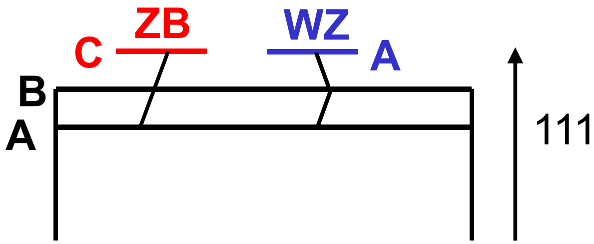
$$\Delta G_c^{ZB} = \frac{a^2}{4}\frac{\gamma_{ZB}^2}{\Delta\mu}$$

$$\Delta G_c^{WZ} = \frac{a^2}{4}\frac{\gamma_{WZ}^2}{\Delta\mu - \delta}$$



$\delta \approx 24$ meV/pair for GaAs

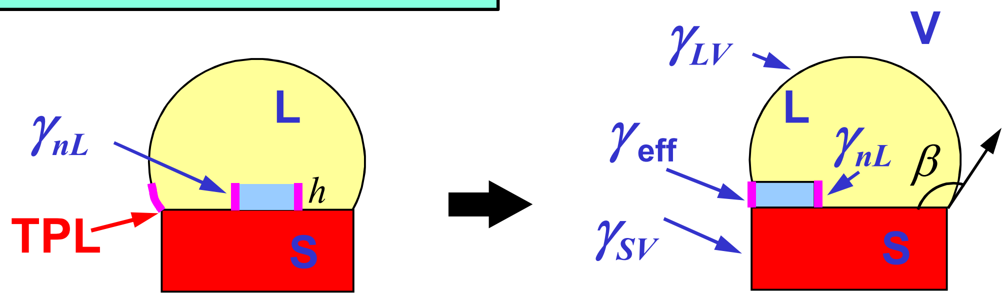
Yeh, Lu, Froyen, Zunger, Phys. Rev. B 46, 10086 (1992)



$$\Delta G_c^{WZ} - \Delta G_c^{WZ} = \frac{a^2}{4}\frac{\left(\gamma_{WZ}^2 - \gamma_{ZB}^2\right)\Delta\mu + \gamma_{ZB}^2\delta}{\Delta\mu\left(\Delta\mu - \delta\right)}$$

< 0 requires $\gamma_{WZ} < \gamma_{ZB}$

1. Nucleation at the triple phase line (TPL)



$$\gamma_{eff} = \gamma_{SV} - \gamma_{LV}\sin\beta < \gamma_{nL}$$

3. $\Delta\mu > \Delta\mu^* \approx \frac{\gamma_{ZB}}{\gamma_{ZB} - \gamma_{WZ}}\frac{\delta}{2}$ Growth

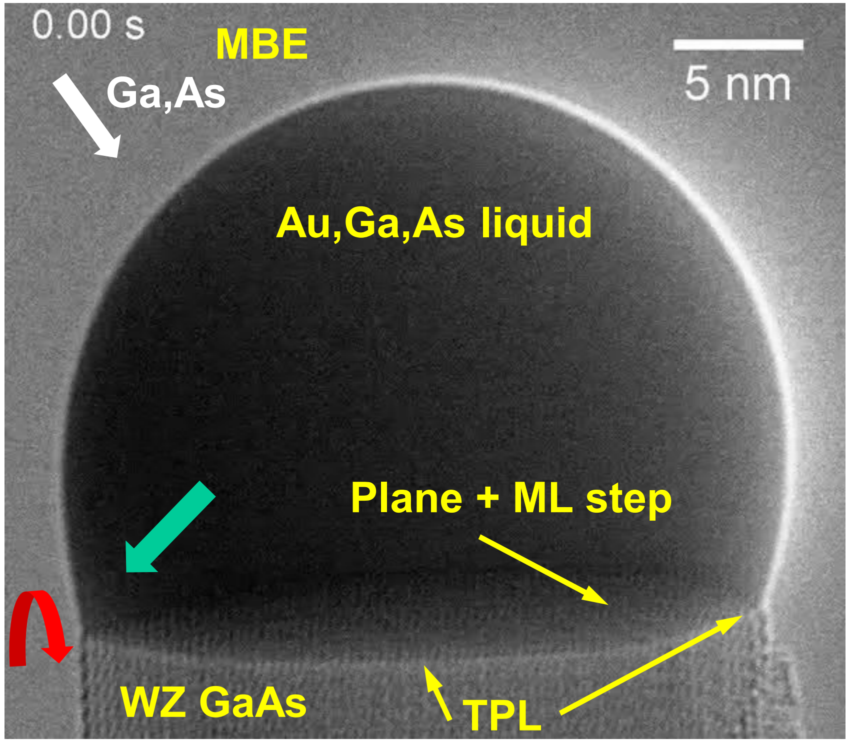
2. $\gamma_{SV}^{WZ} < \gamma_{SV}^{ZB}$ Material

Magri, Rosini, Casetta, Phys. Status Solidi C 7, 374 (2010)

Pankoke, Kratzer, Sakong, Phys. Rev. B 84, 075455 (2011)

WZ nucleation at the TPL (corner) confirmed!

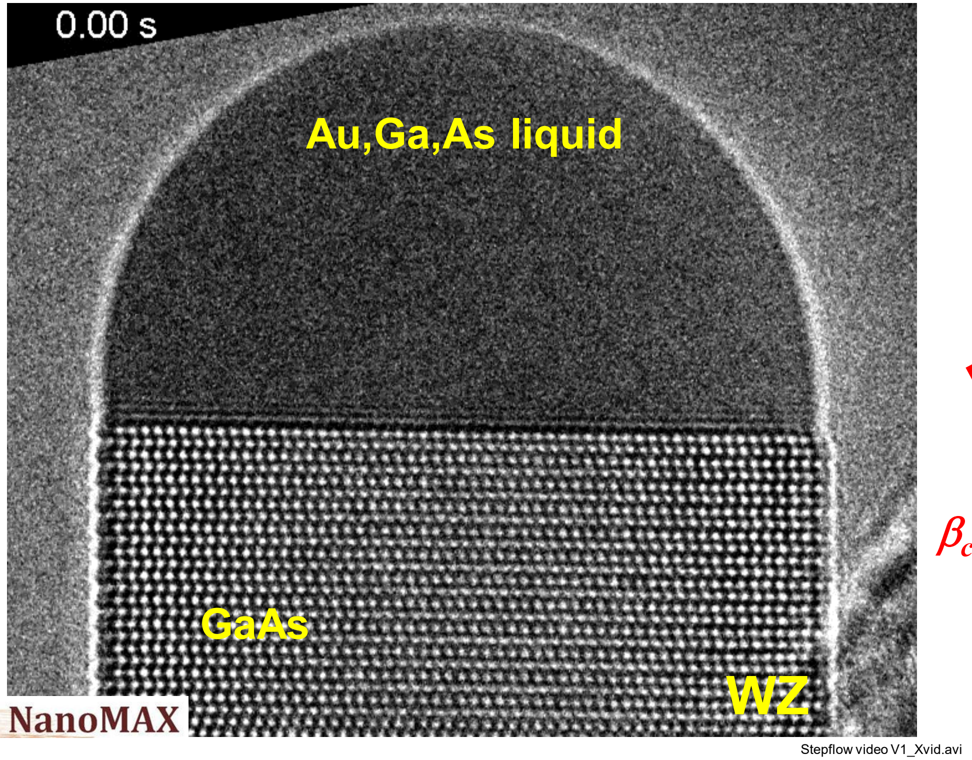
NanoMAX
"Seeing the nanostructures growing atom by atom"

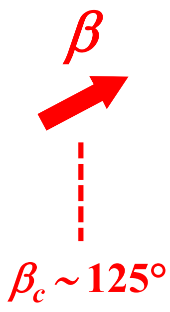


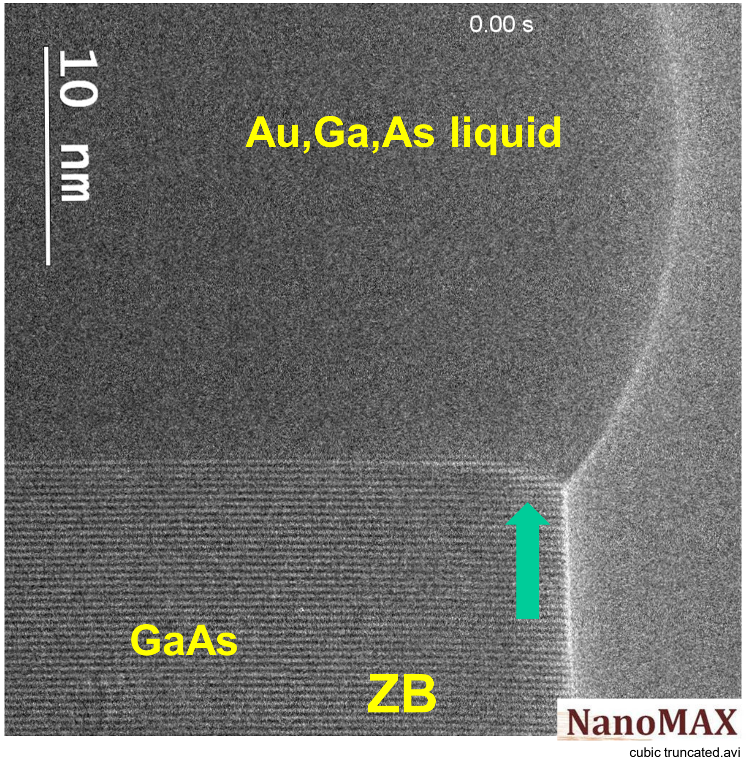
Harmand, Patriarche, Glas, Panciera, Florea, Maurice, Travers, Ollivier, Phys. Rev. Lett. 121, 166101 (2018)

Confirmed (in writing) by Marnauza, Tornberg, Martensson, Jacobsson, Dick, Nanoscale Horiz. 8, 291 (2023)

Two interface morphologies, governed by contact angle







Intermediate contact angle

$100° \leq \beta \leq 125°$

Planar SL interface

Hexagonal WZ

Slow ML growth (step flow)

Large contact angle

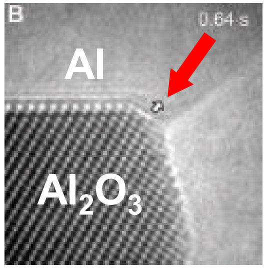
$\beta \geq 125°$

Truncated SL interface

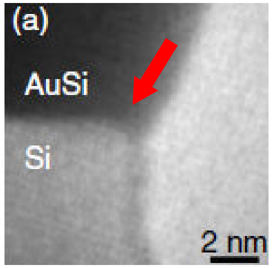
Cubic ZB

Oscillation + fast ML growth

Origin of interface truncation

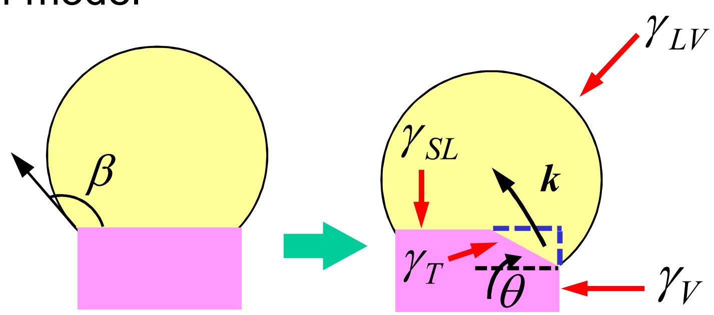


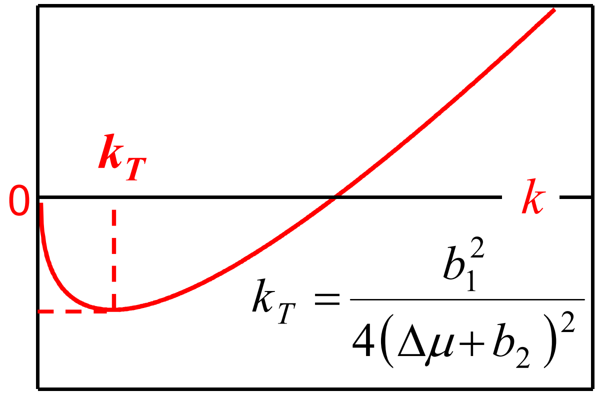
Oh, Chisholm, Kauffmann, Kaplan, Luo, Rühle, Scheu, Science 330, 489 (2010)



Wen, Tersoff, Hillerich, Reuter, Park, Kodambaka, Stach, Ross, Phys. Rev. Lett. 107, 025503 (2011)

'Tersoff model'





$$\Delta G^T = k\,\Delta\mu \;+\; b_1 k^{1/2} + b_2 k$$

volume interfaces

If $b_1 < 0$, planar interface is **unstable**

$$b_1 \propto \Delta\gamma = \frac{\gamma_T}{\sin\theta} - \gamma_{SL}\cot\theta - \gamma_V + \gamma_{LV}\sin\beta$$

'Equilibrium truncation' $k_T \leftrightarrow \Delta\mu$ **No growth**

Jacobsson, Panciera, Tersoff, Reuter, Lehmann, Hofmann, Dick, Ross, Nature 531, 318 (2016)

Dynamical truncation $\Delta\mu$ varies during ML cycle

Dubrovskii, Glas, Cryst. Growth Des. 24, 9660 (2024)

Interface geometry/crystal phase selection: An open question

Exp: Interface morphology and crystal structure change simultaneously at $\beta_c^{\text{exp}} \sim 125°$

"Contact angle determines crystal structure"

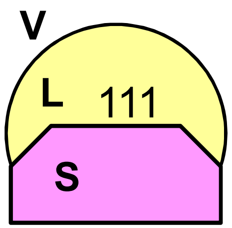
Interface truncation at large β

(Tersoff model)

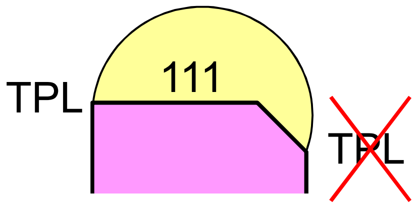
$$\Delta\gamma(\beta) = \gamma_T / \sin\theta - \gamma_{SL} \cot\theta - \gamma_V + \gamma_{LV} \sin\beta$$

$$\Delta\gamma = 0 \longrightarrow \beta_c^T$$

Truncation all around?



No TPL

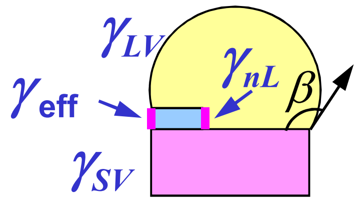


No WZ

(2007 LPN model)

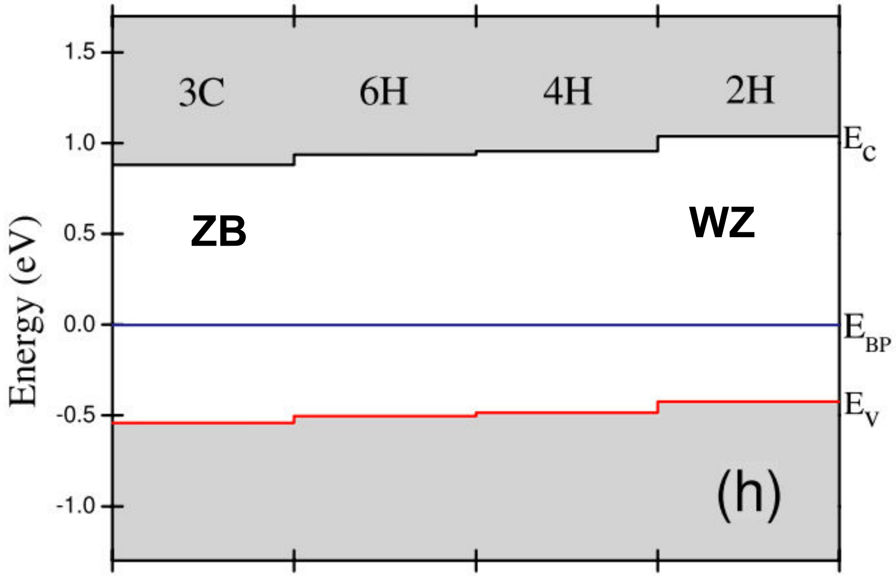
$$\gamma_{\text{eff}}(\beta) = \gamma_{SV} - \gamma_{LV} \sin\beta$$

$$\gamma_{\text{eff}} = \gamma_{nL} \longrightarrow \beta_c^{TPL}$$



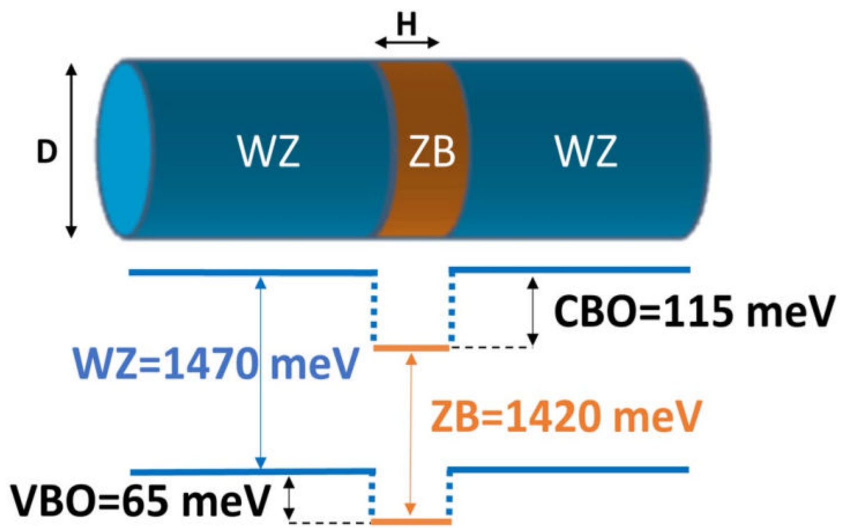
Crystal phase quantum dots (CPQDs)

GaAs



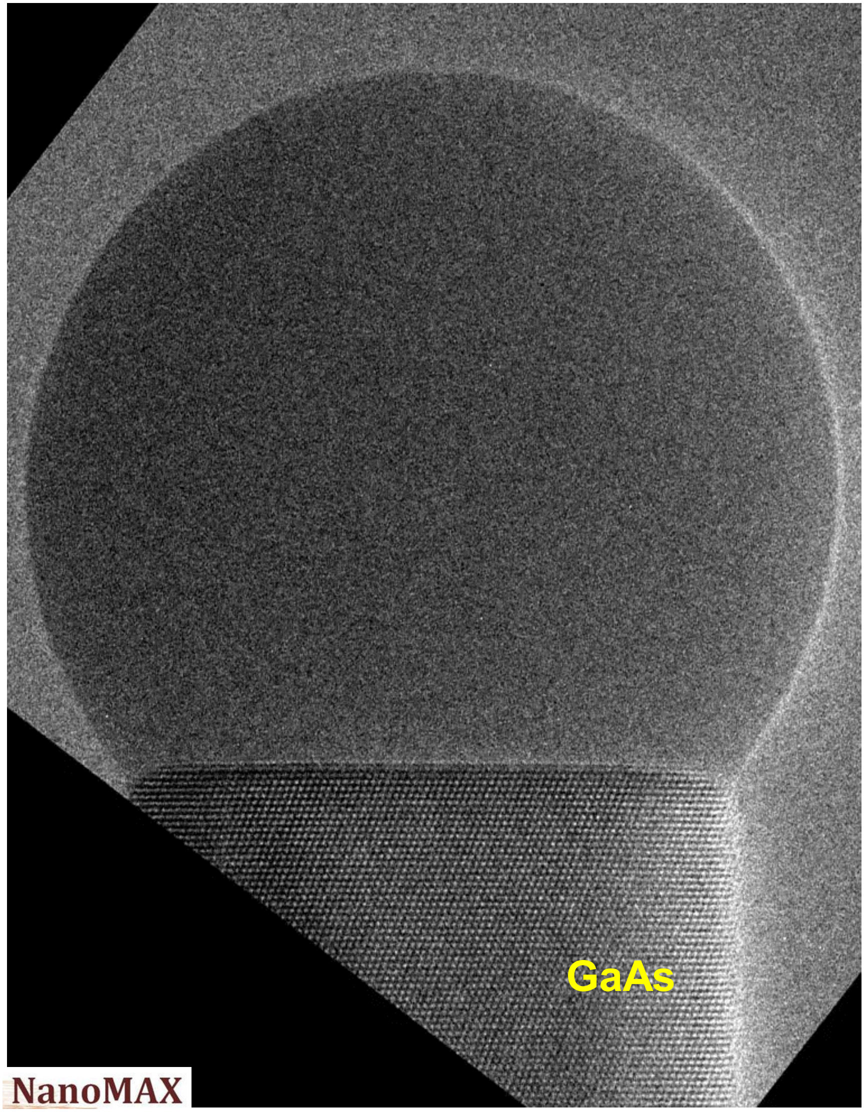
Bechstedt, Belabbes, J. Phys.: Condens. Matter 25, 273201 (2011)

InP



Patera, Zielinski, Sci. Rep. 12, 15561 (2022)

Structural control via contact angle



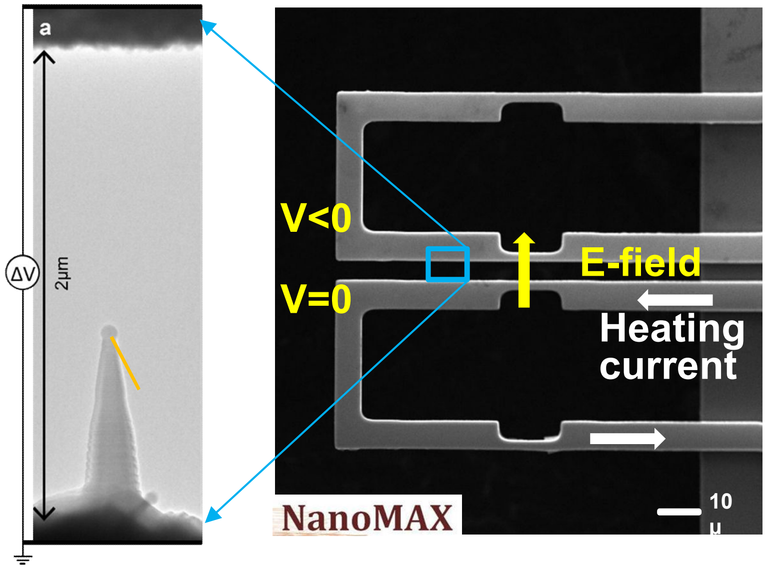
Ga on / Ga off

Relatively slow

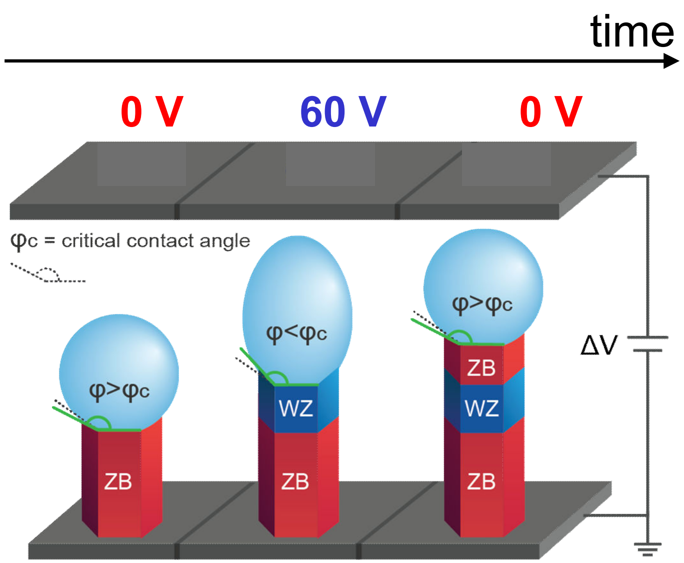
Nam Hong's PhD (2023-2026)

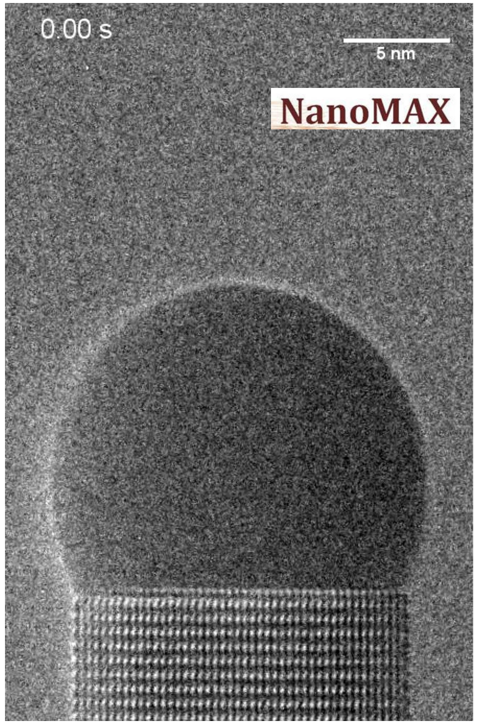
Courtesy J.-C. Harmand, G. Patriarche, F. Panciera

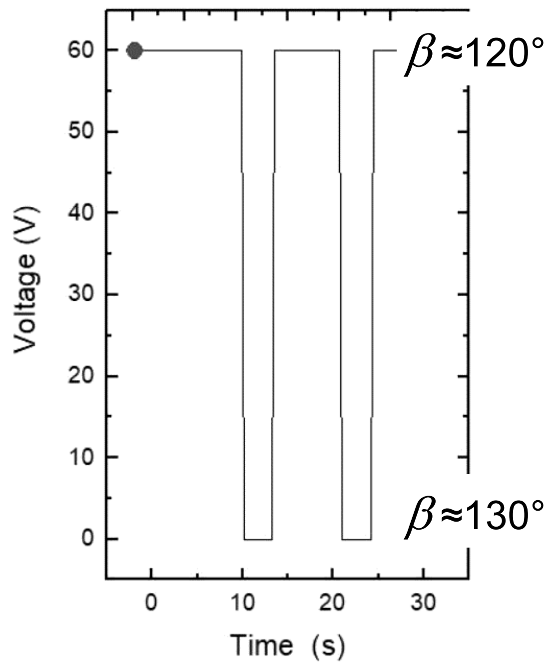
Structural control using electric field



See Qiang Yu's (Chad) poster

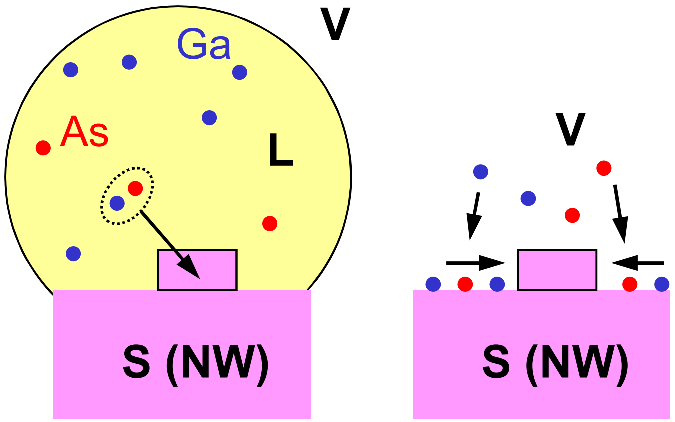






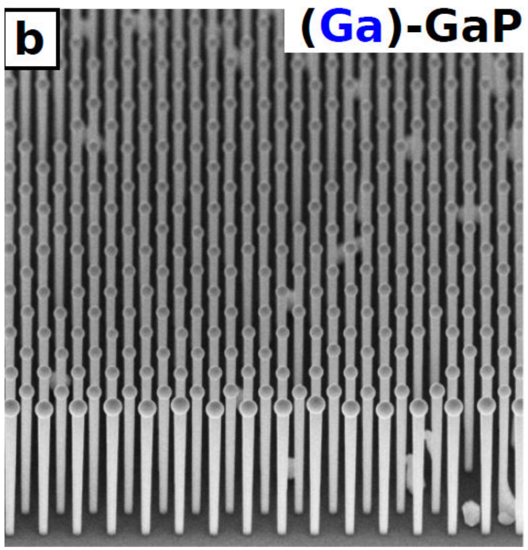
Yu, Saidov, Erofeev, Hassebi, Wei, Renard, Vincent, Glas, Mirsaidov, Panciera, Submitted (2025)

Why bother about the statistics of nucleation and growth?

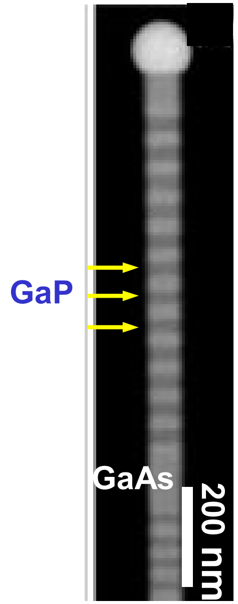


- Monolayer (ML) by ML growth
- Each ML stems from a single 2D **nucleation** event

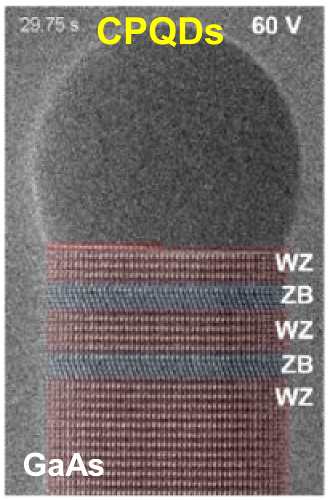
→ intrinsic randomness



A. Scaccabarozzi
F. Oehler
A. Cattoni



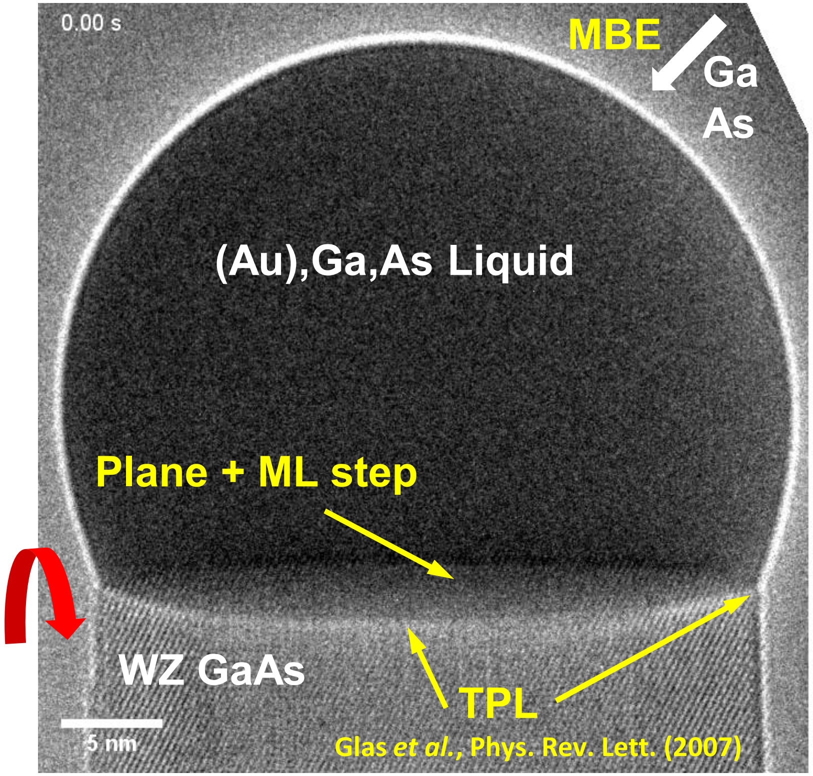
G. Priante

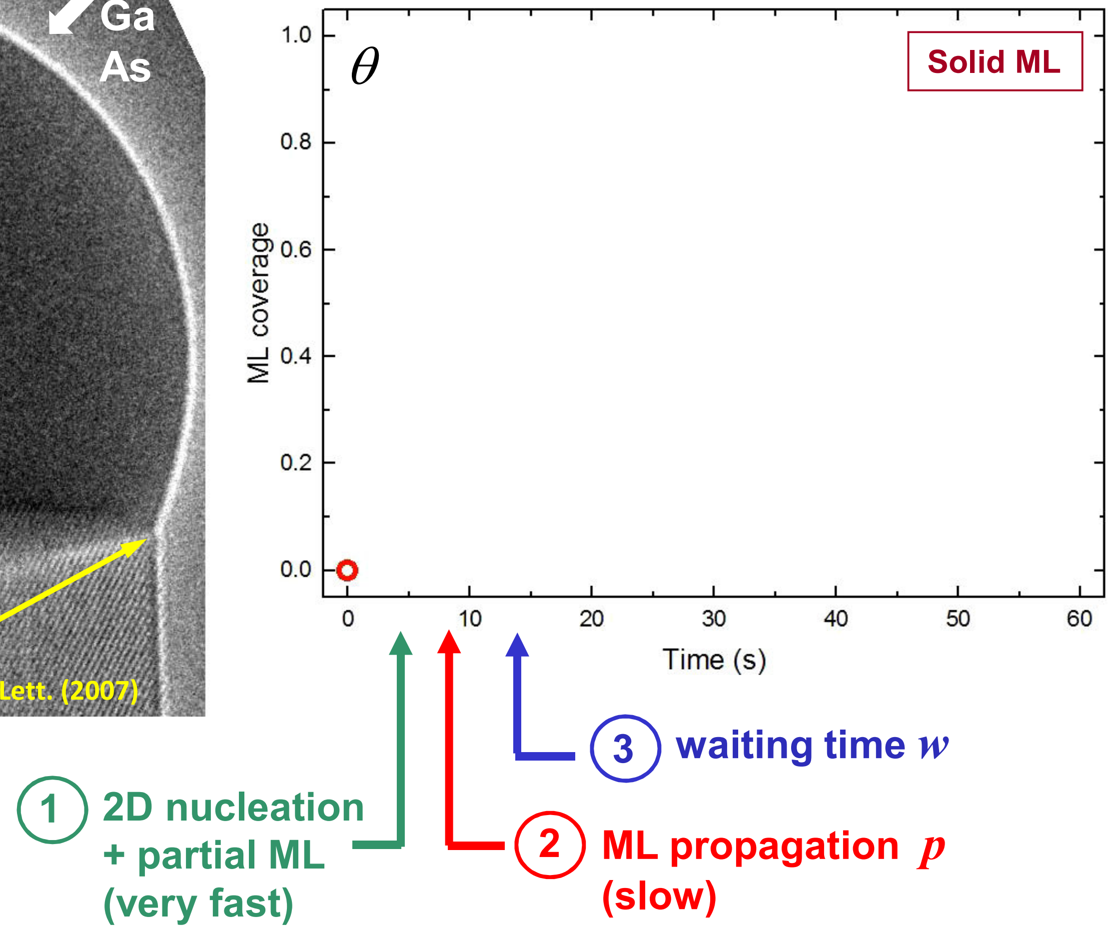


NanoMAX

F. Panciera
Qiang Yu

Planar solid-liquid interface - The 3 stages of ML formation



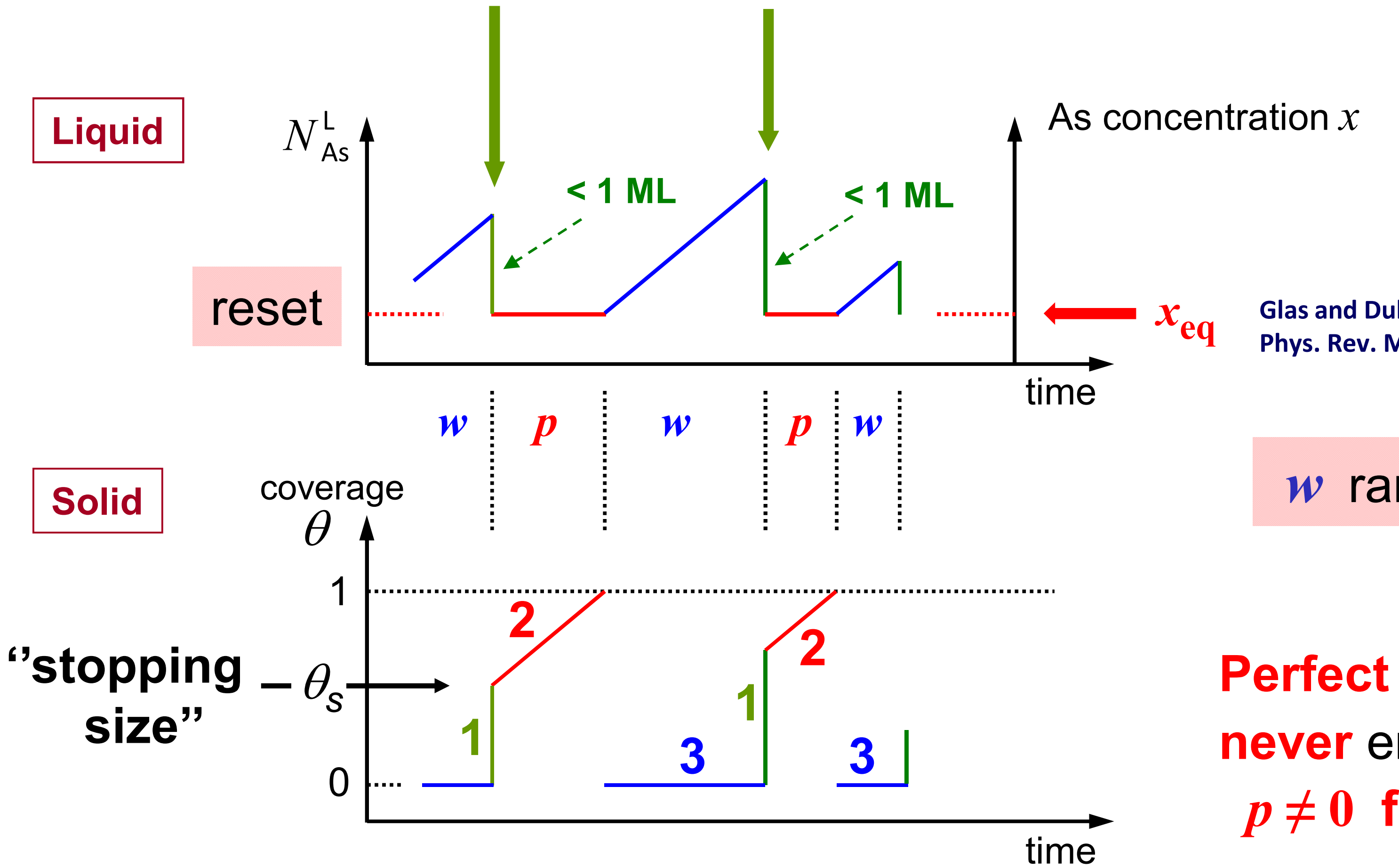


Harmand, Patriarche, Glas, Panciera, Florea, Maurice, Travers, Ollivier, Phys. Rev. Lett. 121, 166101 (2018)

Glas, Panciera, Harmand, Phys. Status Solidi RRL 16, 2100647 (2022)

The incomplete monolayer (IML) regime

Not enough As available in liquid at nucleation to build a complete ML



Glas and Dubrovskii, Phys. Rev. Mater. 4, 083401 (2020)

w random

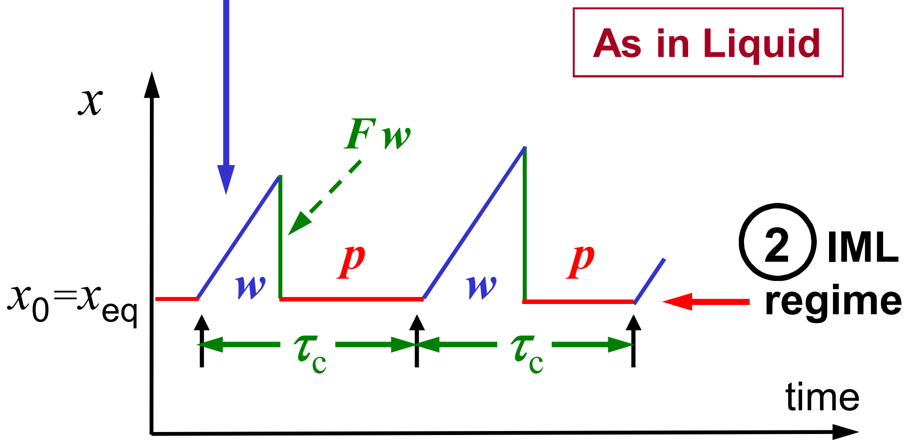
Perfect IML regime:
never enough As
$p \neq 0$ **for all MLs**

Glas, Panciera, Harmand, Phys. Status Solidi RRL 16, 2100647 (2022)

Deterministic growth in the IML regime at low temperature

① No As desorption from liquid (low T)

$$x = x_0 + F w$$

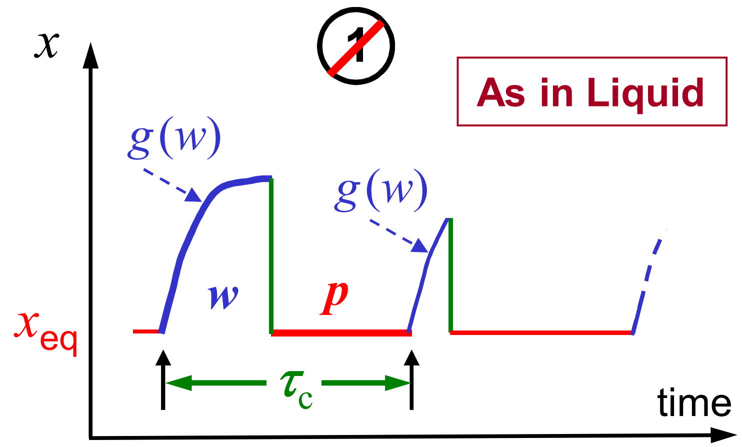


$$F w + F p = x_{ML}$$

$\tau_c = w + p$ is the same for each ML

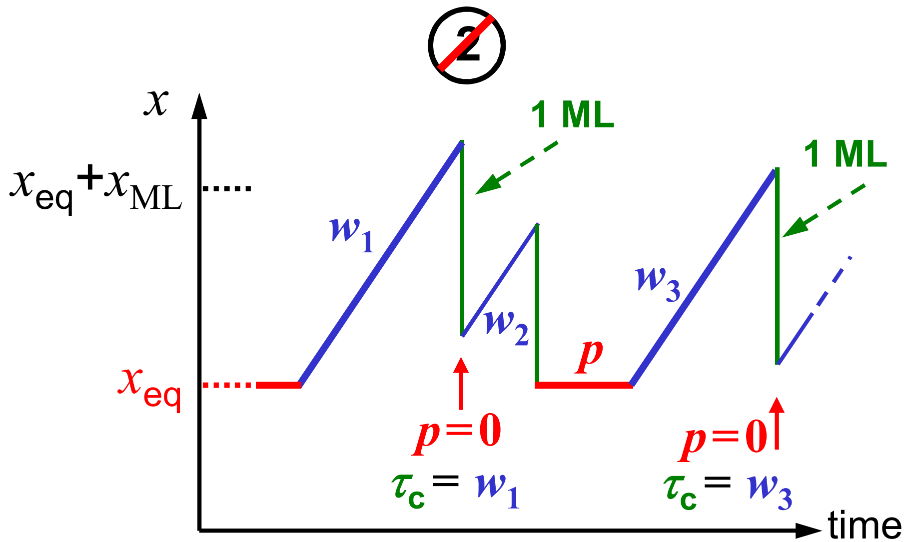
Self-regulated growth

Glas, Panciera, Harmand, Phys. Status Solidi RRL 16, 2100647 (2022)



$$g(w) + F' p = x_{ML}$$

τ_c varies between MLs

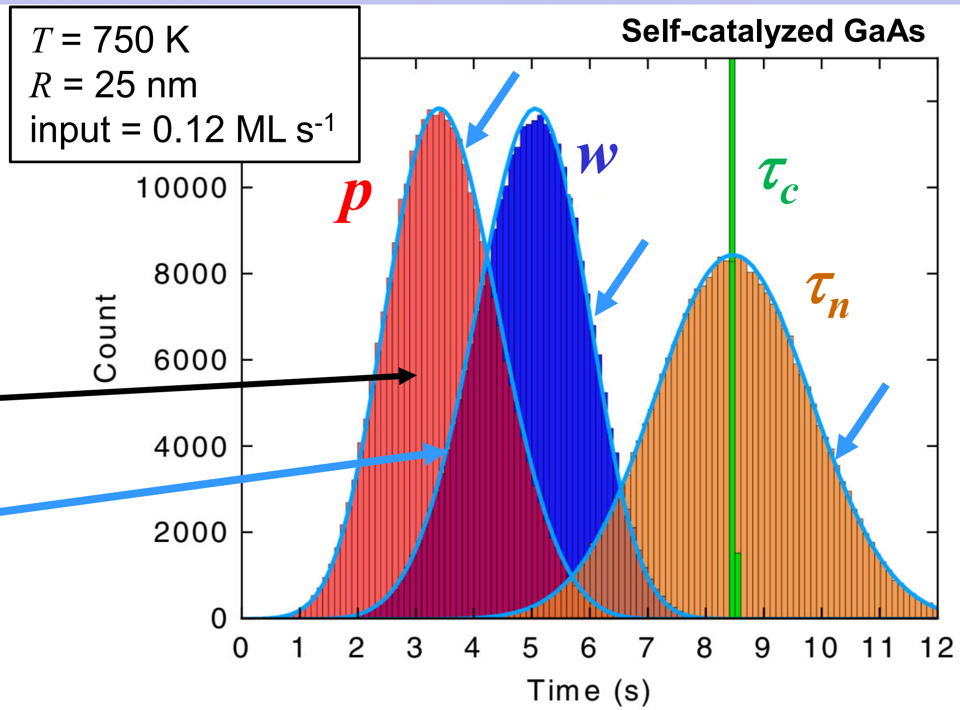


Simulations and analytical calculations - *In situ* experiments

- 2D nucleation rate

$$J_n(x,T) = A(T)\ x \sqrt{\frac{\Delta\mu}{k_B T}} \exp\left[-\frac{K\ \gamma_e^2}{k_B T\ \Delta\mu(x,T)}\right]$$

- Numerical growth simulations



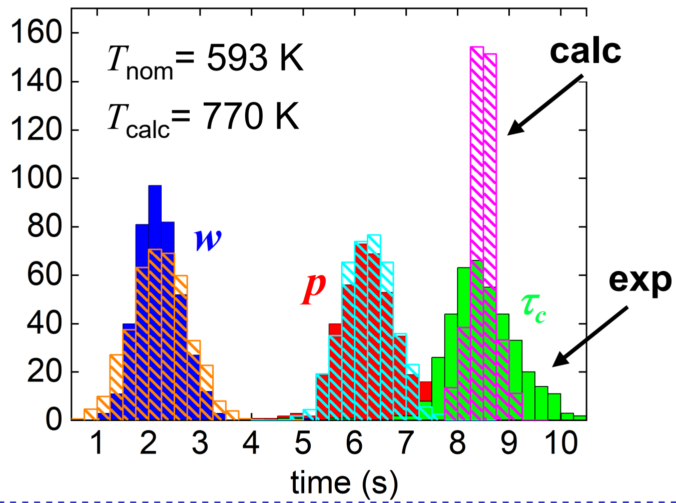
- Analytical calculations

1. **No As desorption**
2. **IML regime**
3. $\Delta\mu \approx \alpha_\mu k_B T\ \ln(x/x_{eq})$

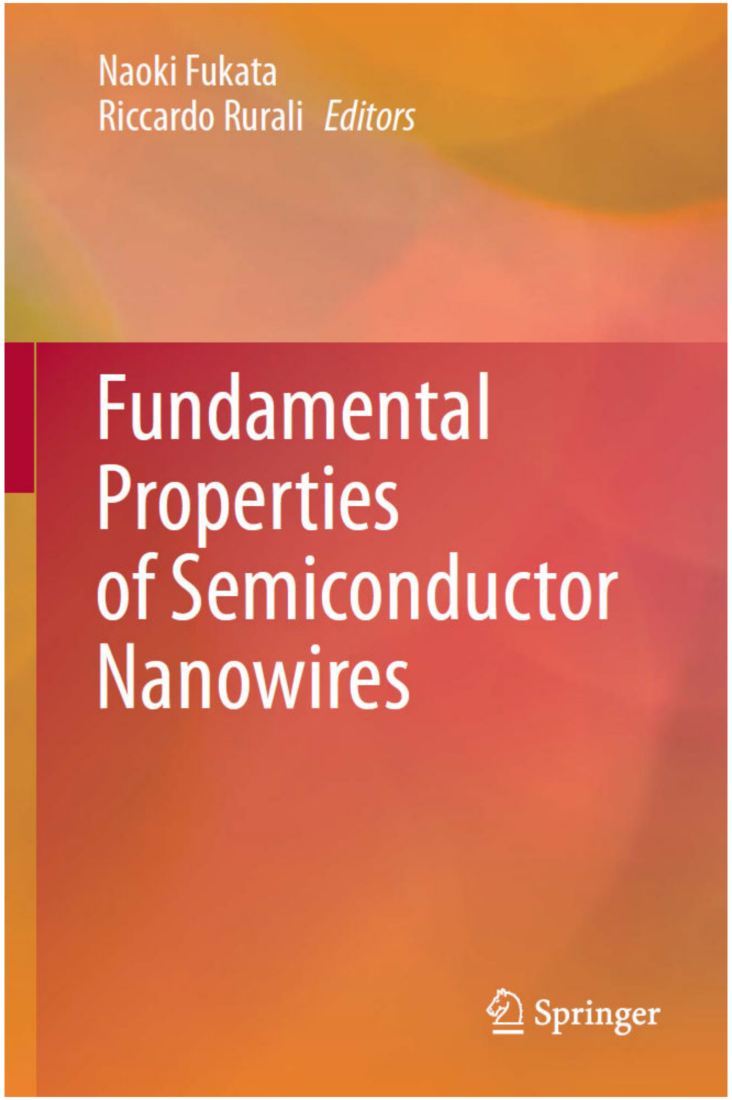
NanoMAX
"Seeing the nanostructures growing atom by atom"

Self-regulation is observed…

but not (yet) the quasi-deterministic regime



Glas, Panciera, Harmand, Phys. Status Solidi RRL 16, 2100647 (2022)



Vapor–Liquid–Solid Growth of Semiconductor Nanowires

Vladimir G. Dubrovskii and Frank Glas

Abstract We discuss the growth of semiconductor nanowires, with an emphasis on the vapor–liquid–solid growth of III–V nanowires. Special attention is paid to modeling of growth and the resulting morphology, crystal phase, composition, nanowire heterostructures, and statistical properties within the nanowire ensembles. We give a general overview of the vapor–liquid–solid growth of nanowires by different epitaxy techniques and the bases for nanowire growth modeling. We discuss the role of surface energetics in the formation of GaAs nanowires, which has an important impact on the nanowire morphology and crystal phase. A detailed description of the nanowire growth kinetics is presented, including the transport-limited growth, chemical potentials, nucleation and growth of two-dimensional islands, and self-consistent growth models combining the material transport equations with the nucleation rate. The nanowire length and diameter distributions are considered along with the methods for narrowing them to sub-Poissonian values. Ternary III–V nanowires and heterostructures based on such nanowires are discussed, including the relaxation of elastic stress at the free sidewalls and the sharpening of the heterointerfaces. We consider polytypism of III–V nanowires and possibilities to control their crystal phase by tuning the growth parameters.

Keywords III–V nanowires · Vapor–liquid–solid growth · Nucleation · Growth modeling

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N. Fukata and R. Rurali (eds.), *Fundamental Properties of Semiconductor Nanowires*,
https://doi.org/10.1007/978-981-15-9050-4_1