Полупроводниковые нитевидные кристаллы: рост и физические свойства

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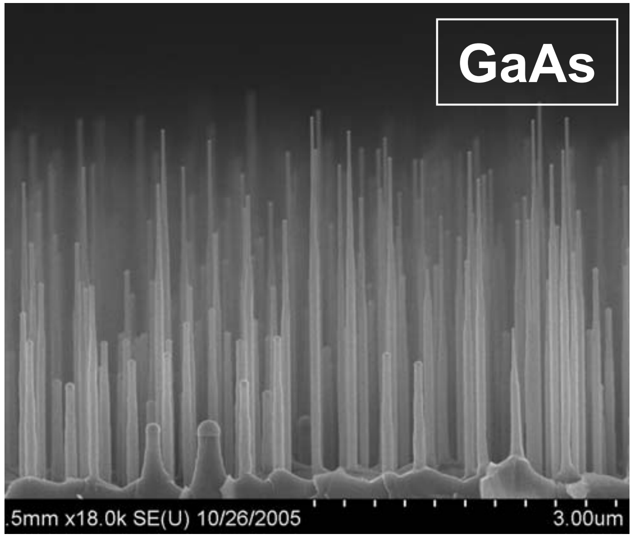
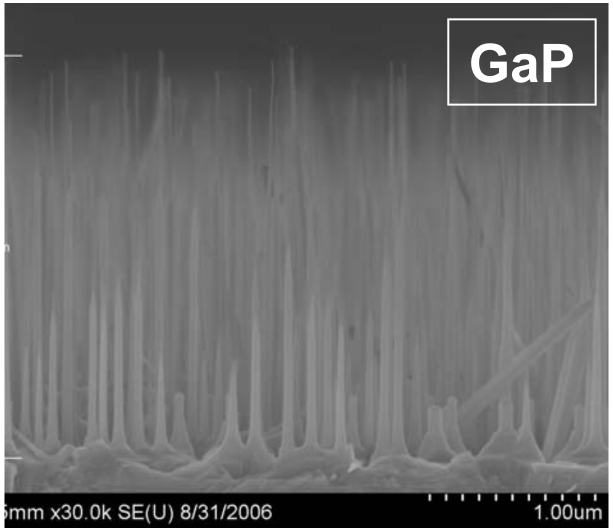
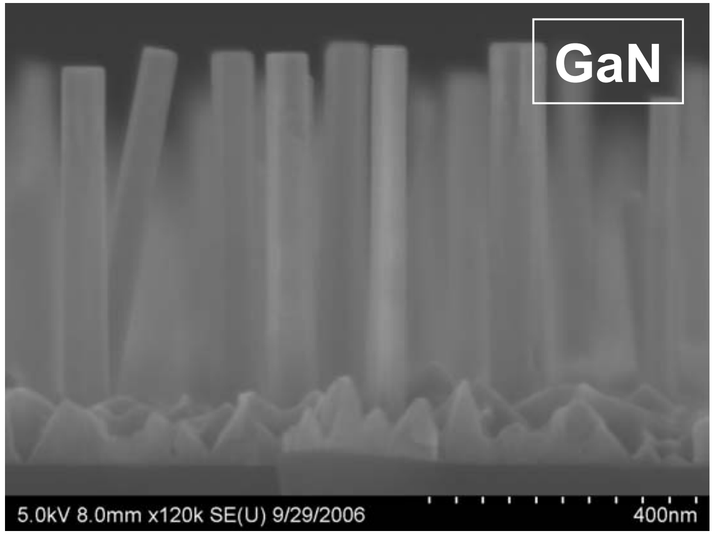
Outline

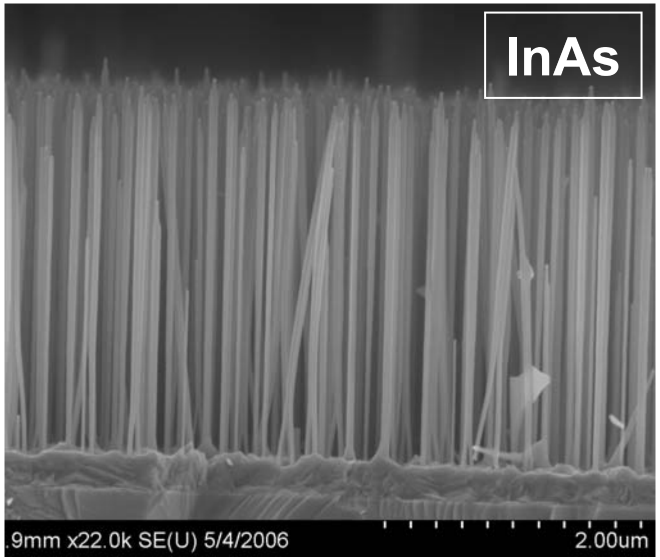
- ❑ Au-assisted MBE growth of GaAs nanowires
- ❑ MBE growth of A3B5 nanowires on silicon
- ❑ InAs, InP nanowires and InP/InAsP/InP heterostructures
- ❑ GaAs quantum dots inside AlGaAs nanowires
- ❑ Photovoltaic properties of p-type GaAs NWs on GaAs(111)B n-type substrate
- ❑ Few other examples of NWs (GaAs NWs on tungsten STM tips)

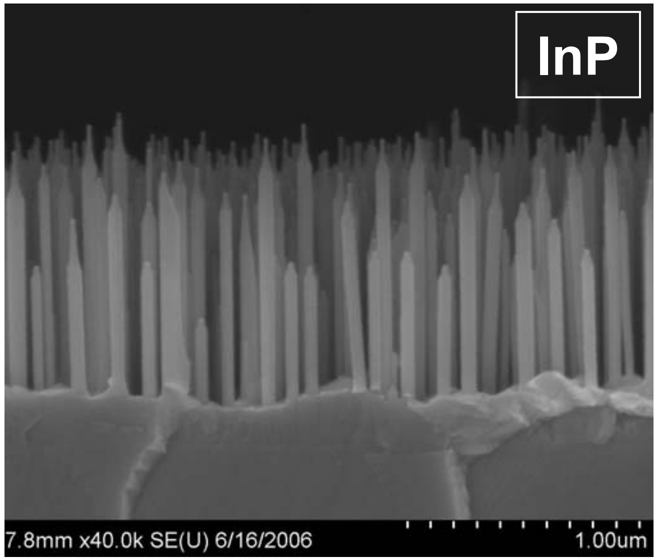
Self-organized III-V nanowires by MBE











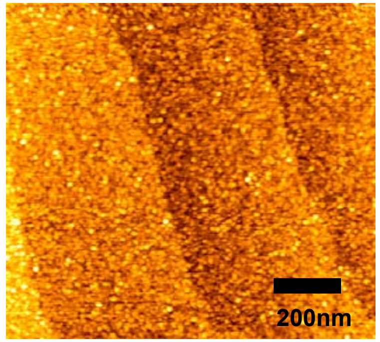
Nanowire parameters

- d from 20 to 200 nm
- h up to 50 μm
- hexagonal cross-section
- density ~$10^6 – 10^{10}$ cm^{-2}

GaAs nanowires

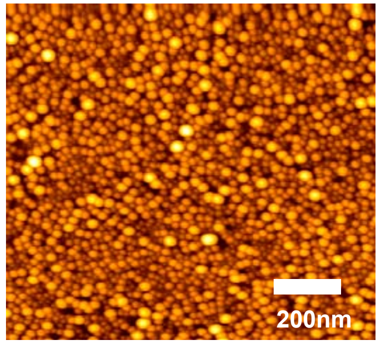
Au assisted nanowire growth

- (111)B oriented substrate
- Buffer layer ~100 nm
- Au deposition in the growth chamber (h up to 1 nm)

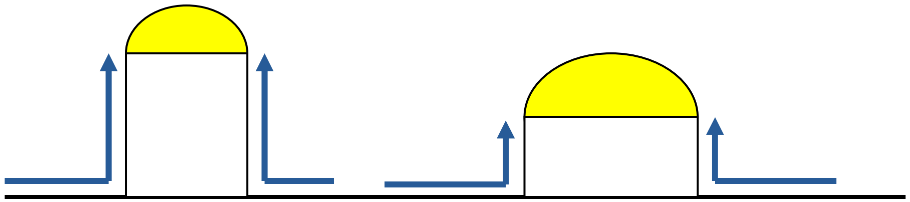


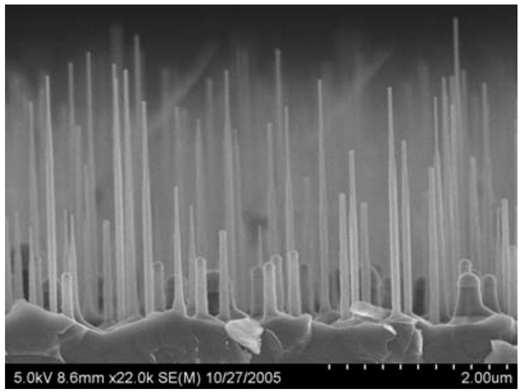
- Annealing ⇒ Au – metal alloying

Droplet size and density depends on h and $T_{annealing}$

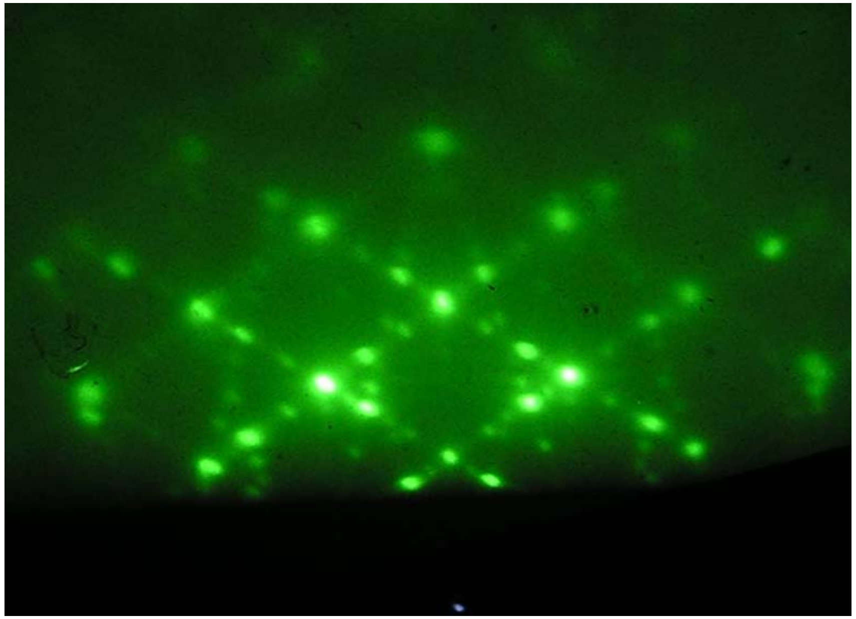


- Nanowire growth (surface diffusion of the species up to the catalyst, super-saturation, precipitation)

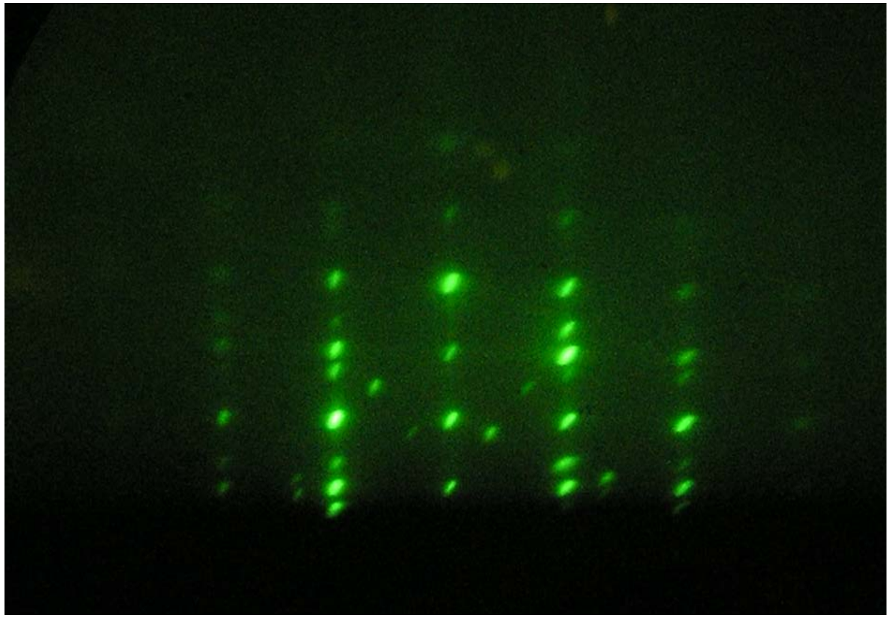




In situ RHEED control



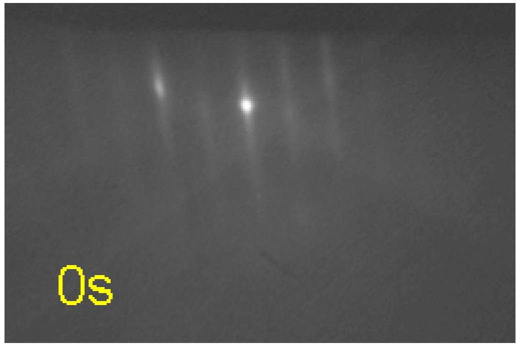
200 nm
GaAs/Si(001)

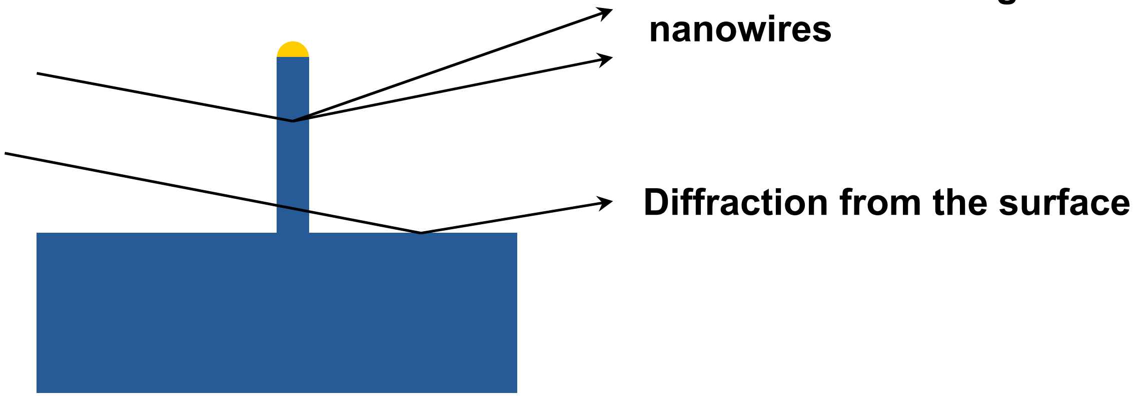


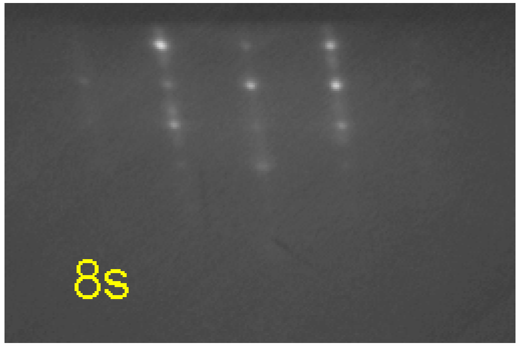
200 nm
GaAs/GaAs(111)B

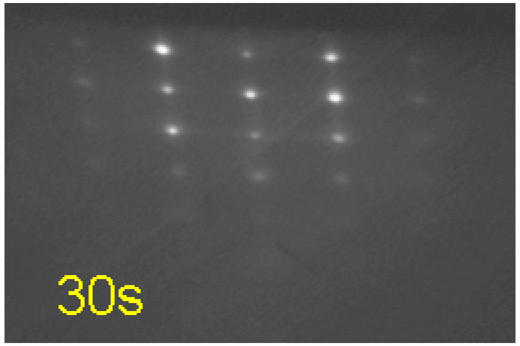
RHEED dynamics: CB to WZ transition

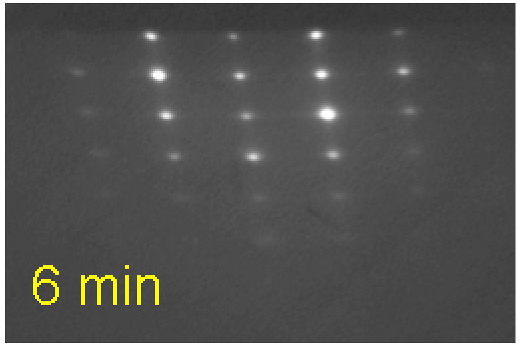
GaAs (111)B + Au
450°C





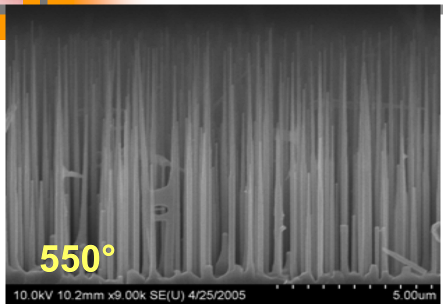


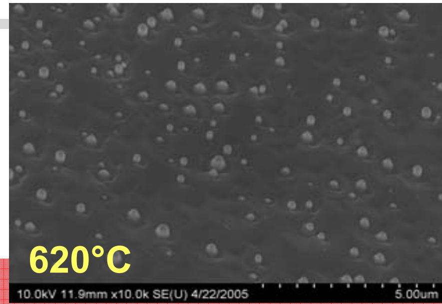


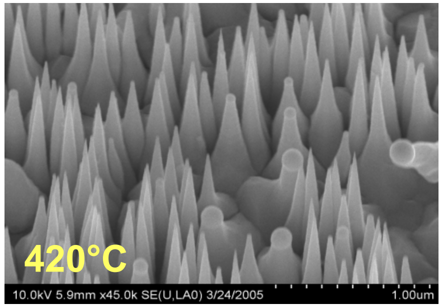


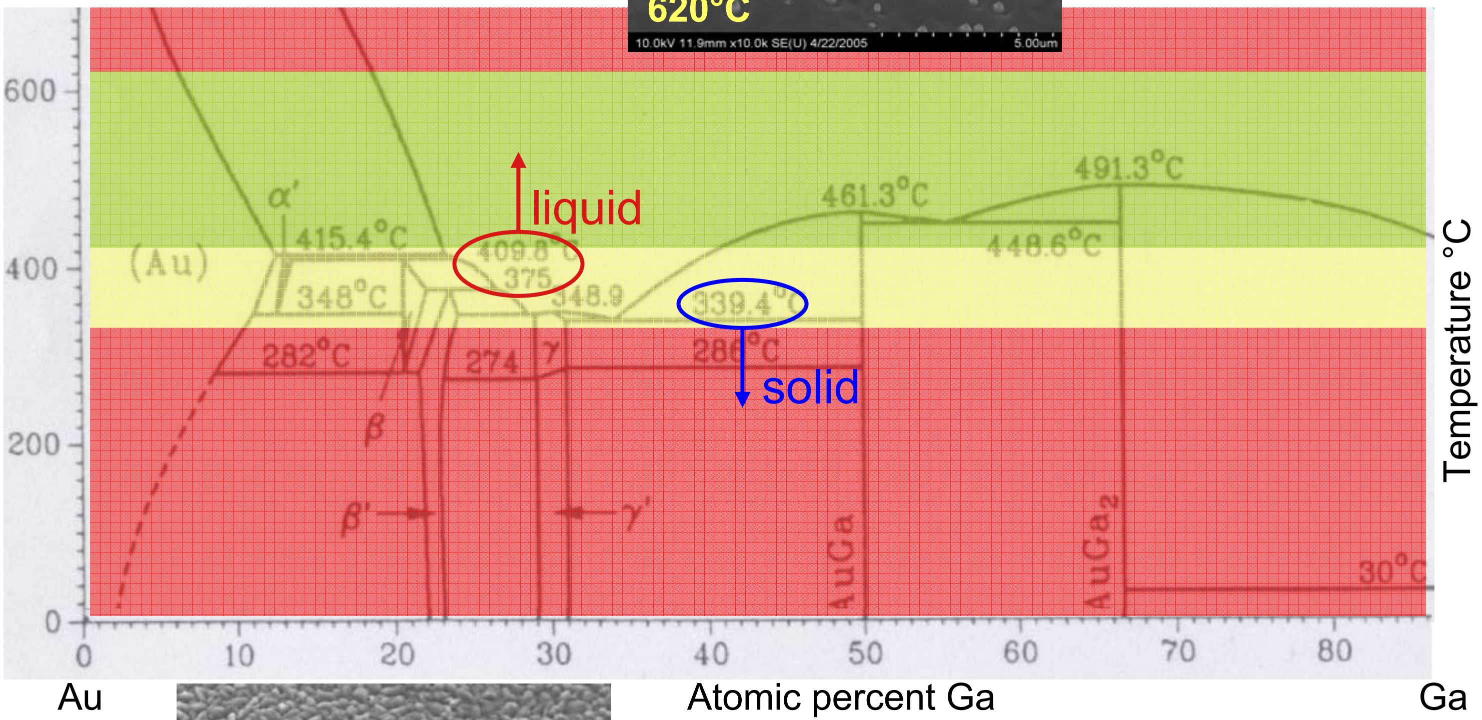
Hexagonal phase

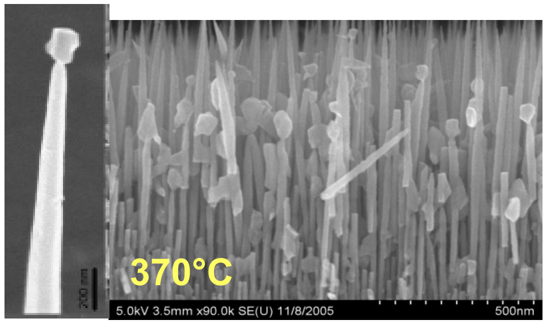
Temperature domain for NW growth

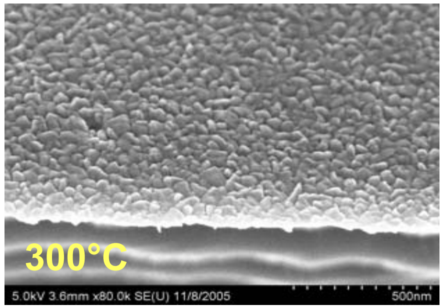








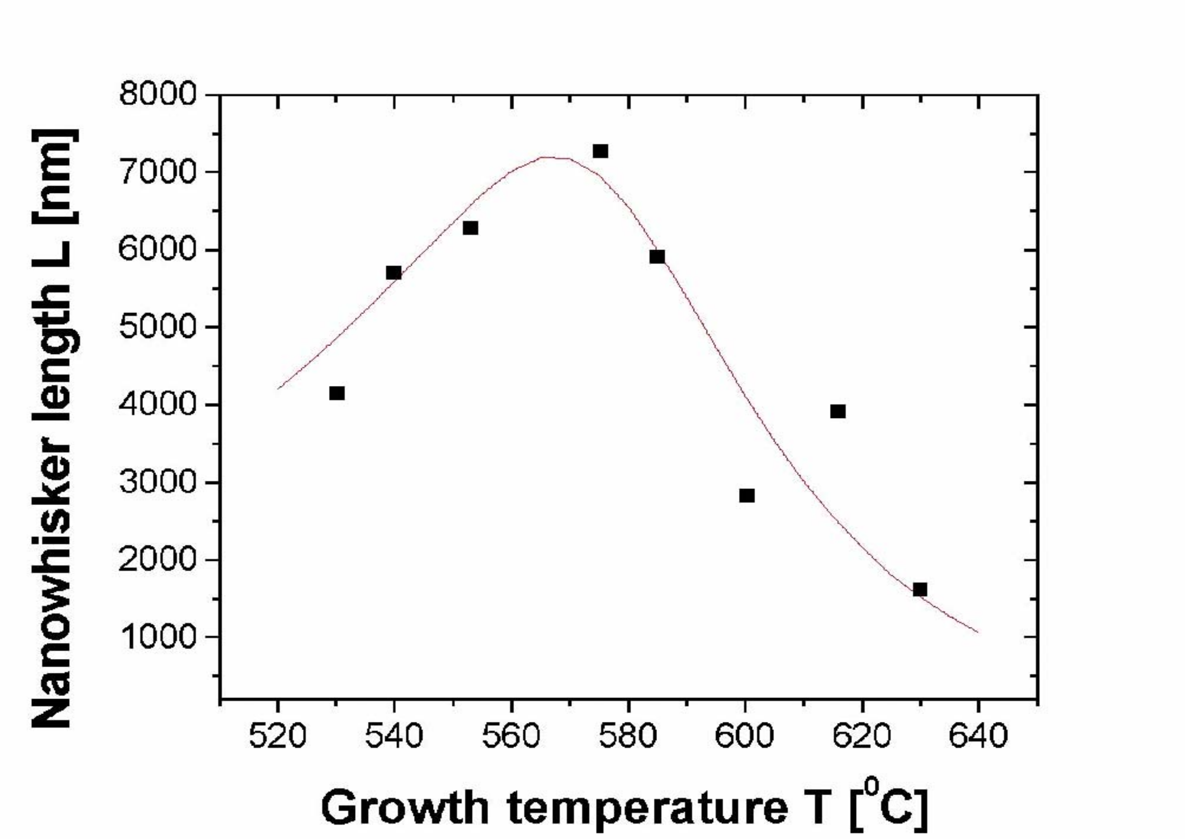




Journal of Crystal Growth, 2007, v.301–302, p.853–856.

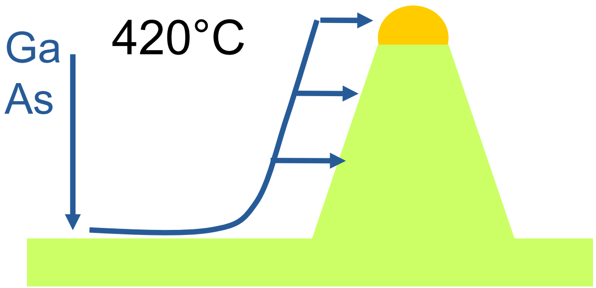
Growth rate with temperature

Temperature domain for regular GaAs nanowires : 410°C – 620°C



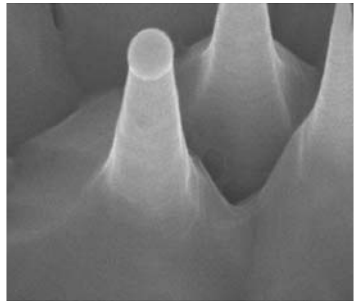
- Nucleation is faster at the liquid/solid interface than at the vapor/solid interface – increase of the growth rate
- Increase of $T_g \Rightarrow$ enhancement of adatom surface migration $\Rightarrow$ higher NW growth rates

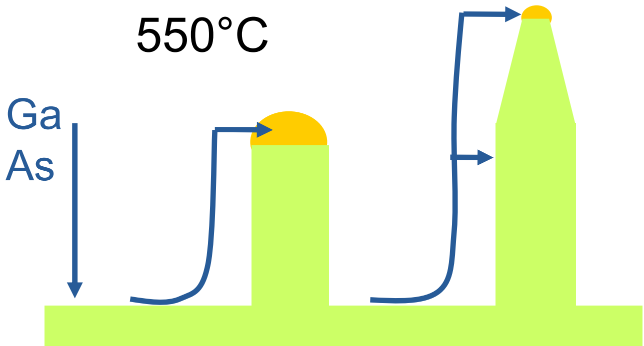
NW morphology with temperature



Nucleation on the sidewalls

Conical shape





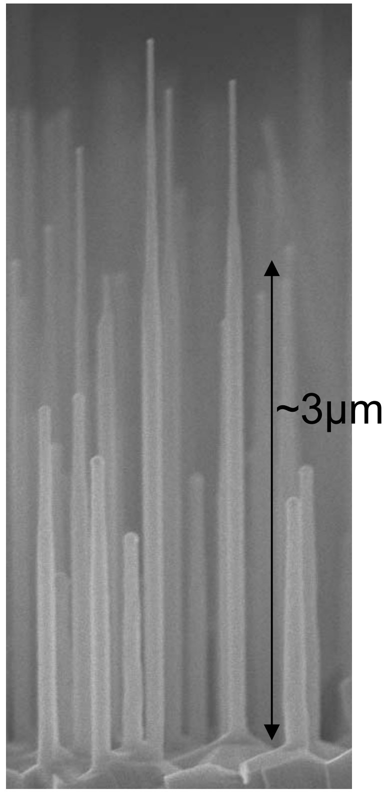
h < λ ⇒ No nucleation on the sidewalls

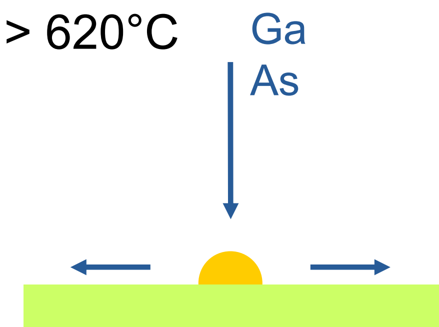
Cylindrical shape

h > λ ⇒

- Possible nucleation on the sidewalls
- Reduction of Ga content in the catalyst

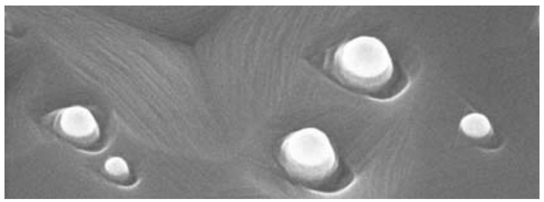
Tapering of the nanowire



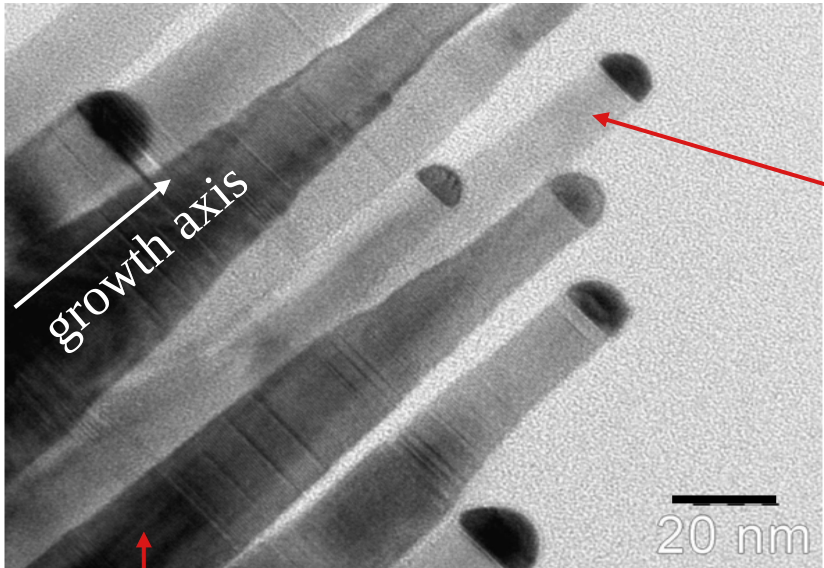


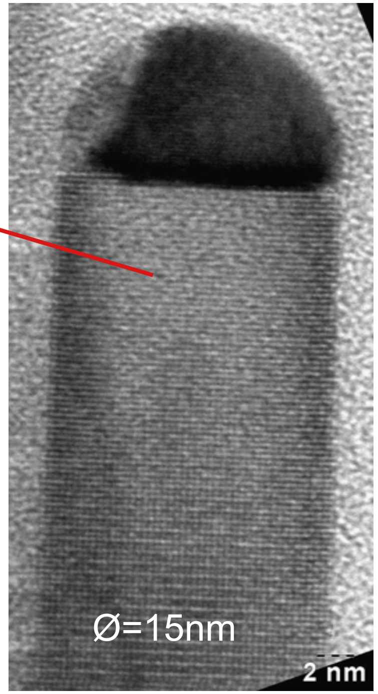
Chemical potential $\mu_{liq} > \mu_{ads}$

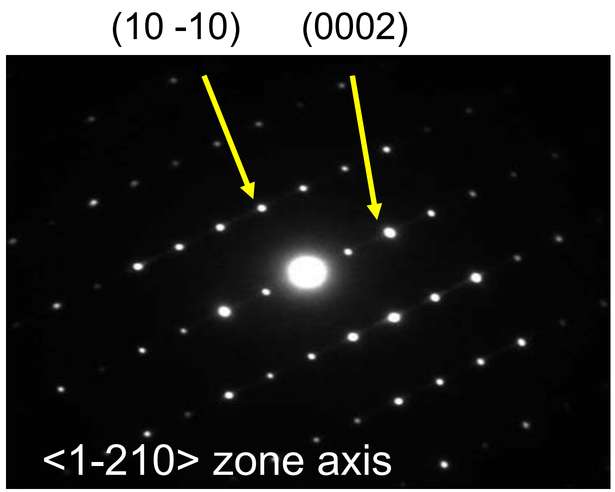
No nanowire growth



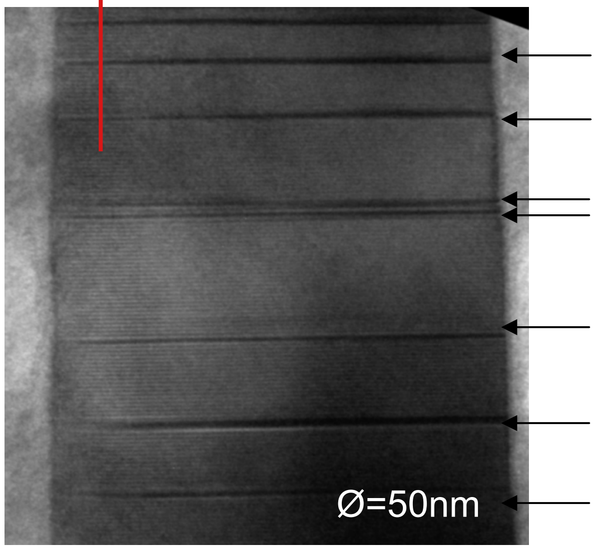
TEM study of crystalline phase







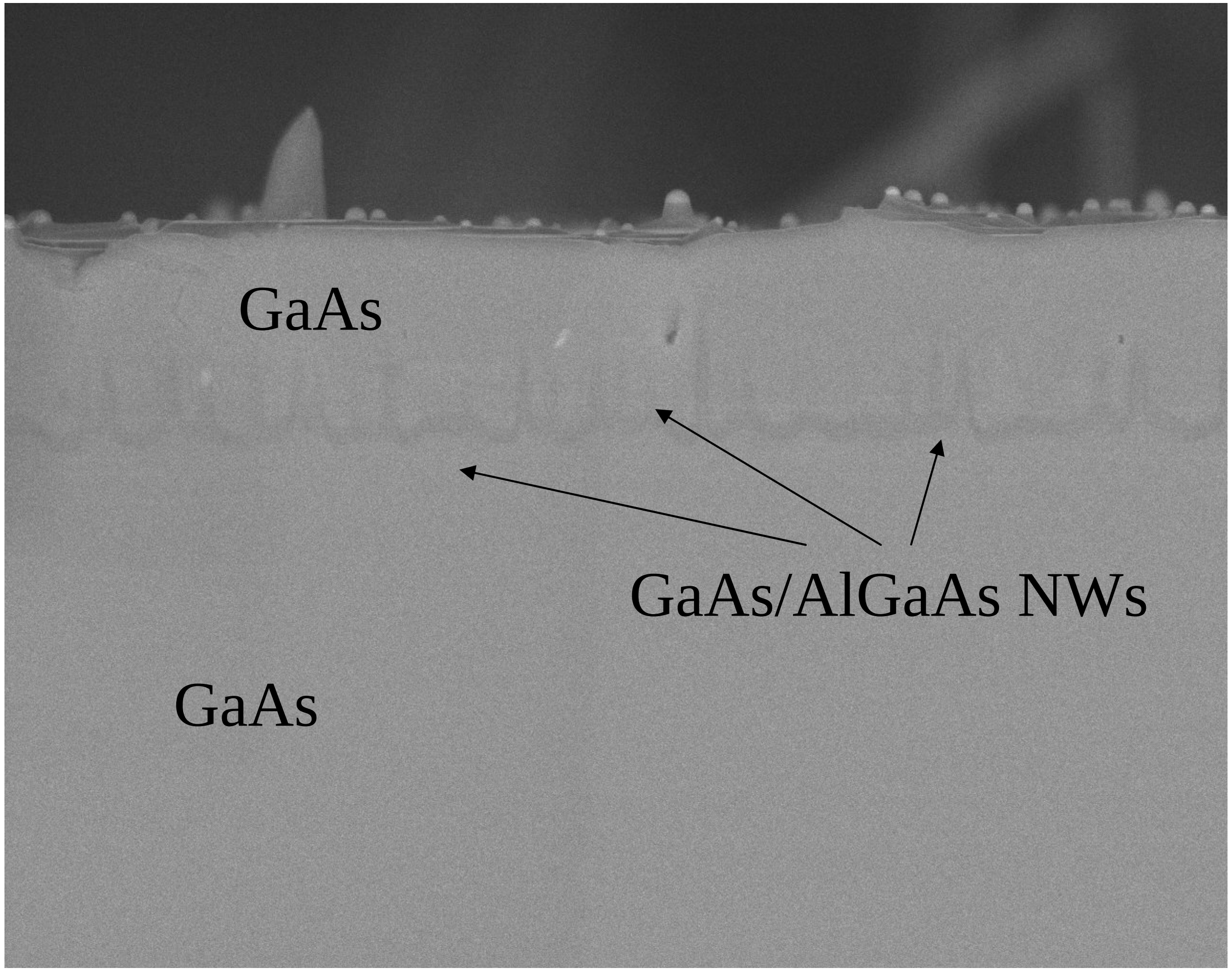
Wurtzite structure
≠ bulk GaAs



Stacking faults (density ↑ when T↓)

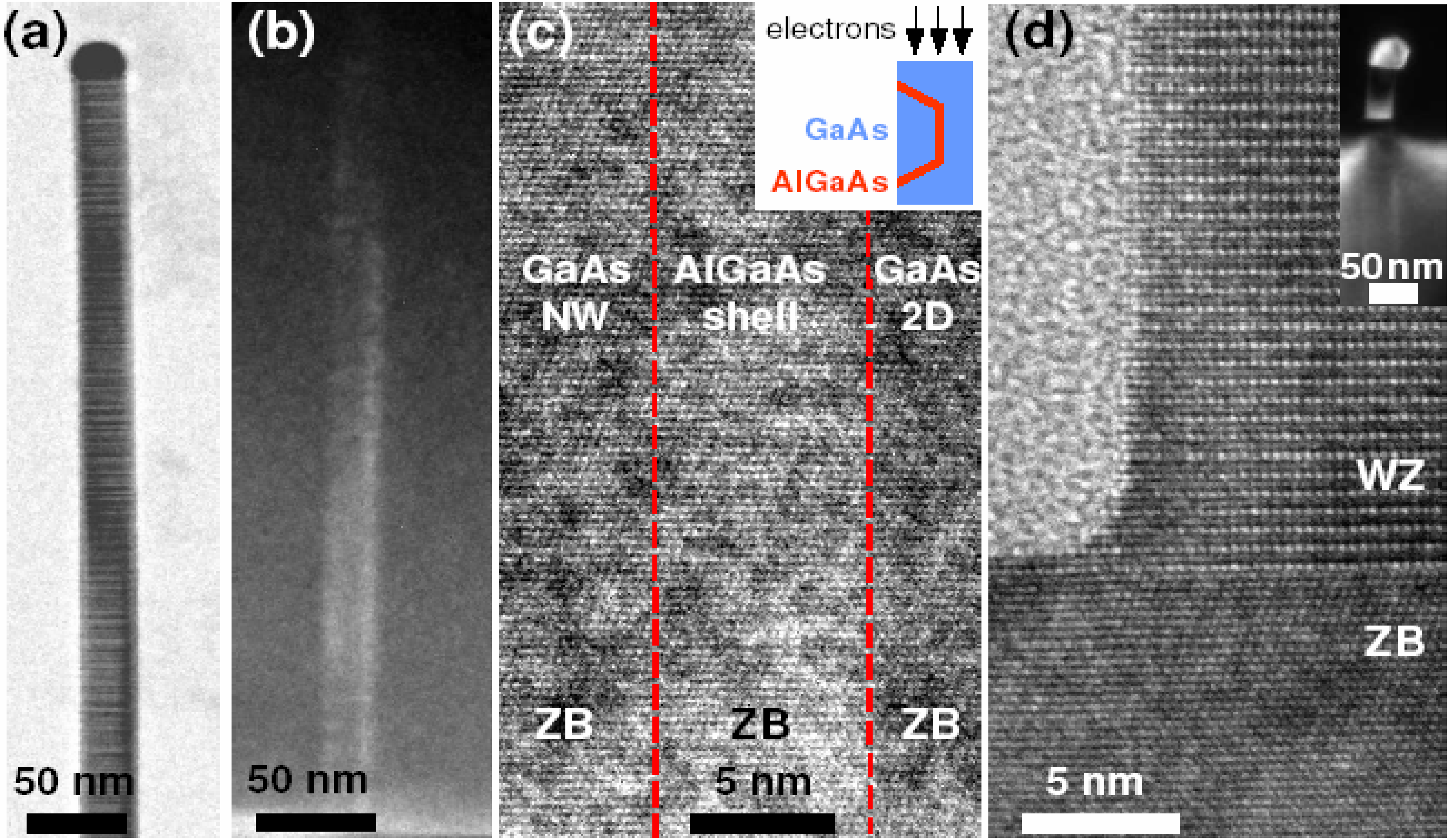
Hexagonal phase is predominant

GaAs/AlGaAs nanowires embedding in GaAs matrix



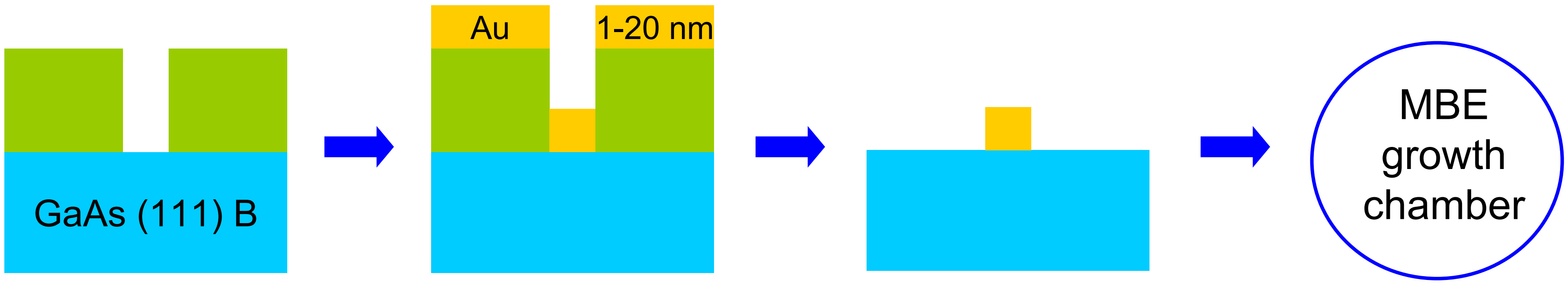
Nano Lett., 2008, v. 8, p.1638-1643

Embedding: WZ to ZB transition, twins disappearance



Ordering of GaAs nanowires using e-beam lithography

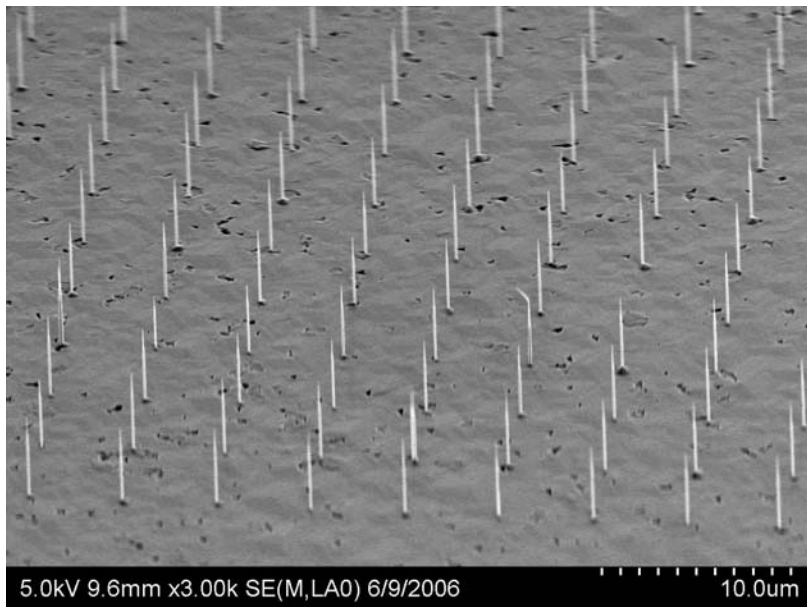
Fabrication procedure



PMMA deposition + e-beam lithography

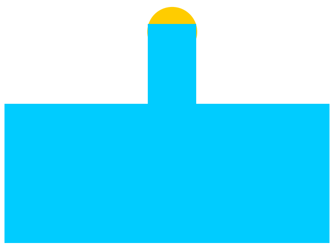
Au deposition

Lift-off

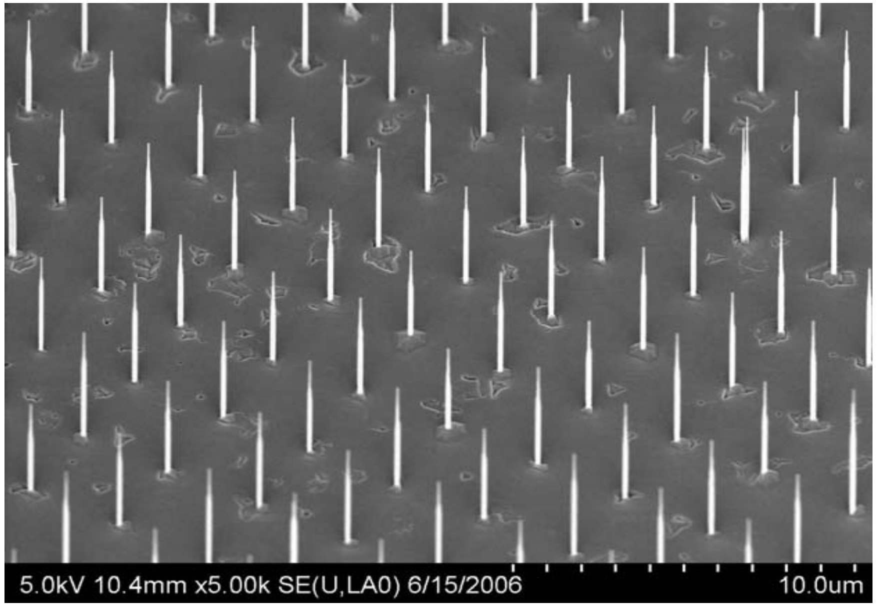


Surface cleaning at 300°C under H plasma

GaAs nanowire growth at 550 °C

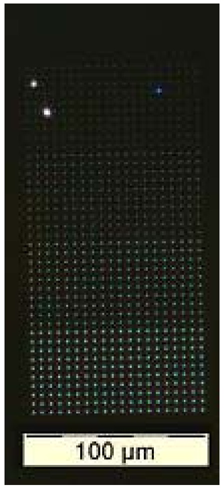


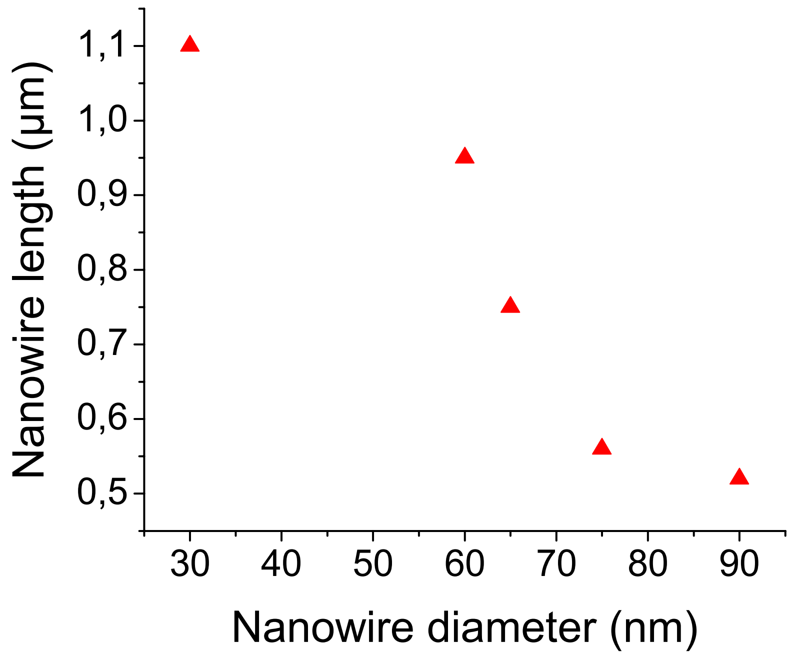
2D Arrays of GaAs nanowires



Step 3µm
Wire length 5µm
Wire diameter 120nm
Tapering after 3-µm height

Mask with different Au dot diameters :
decrease of the nanowire length with diameter

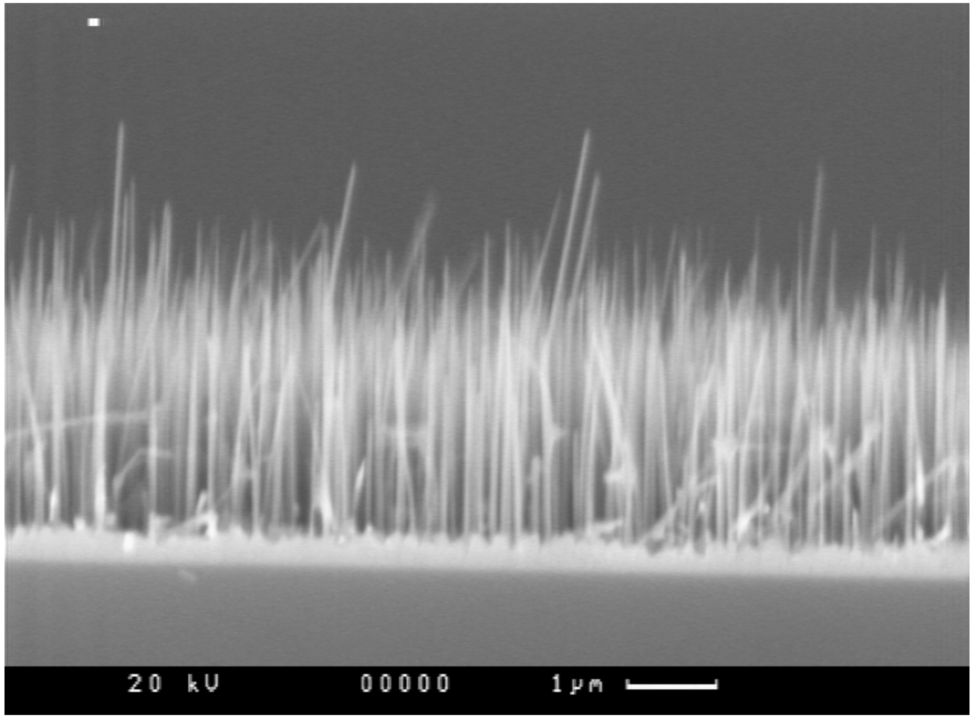


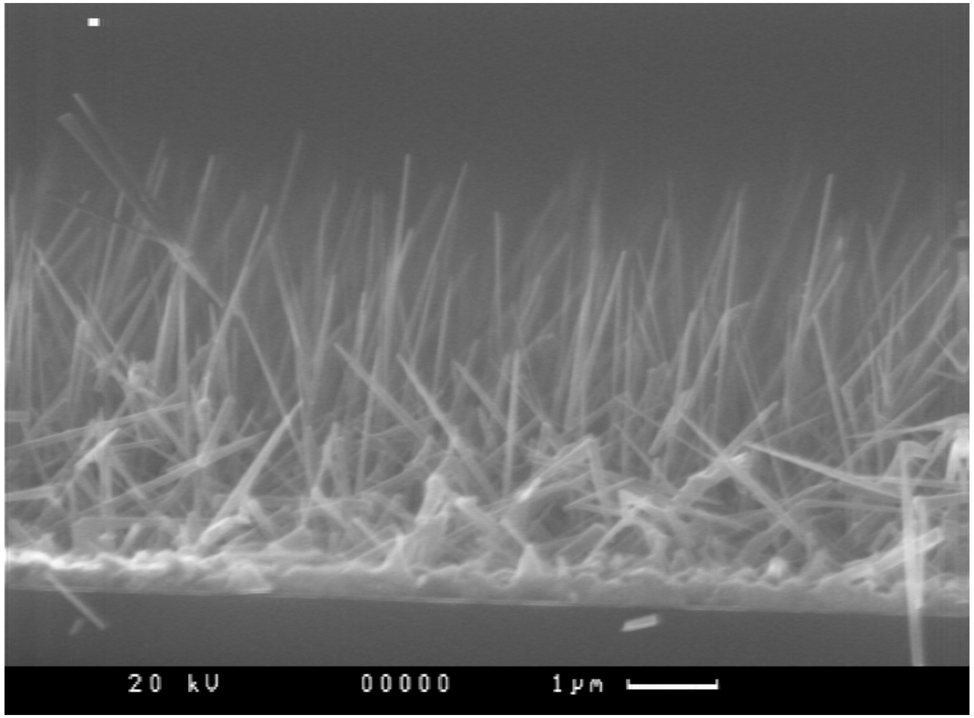


NW growth is fed by surface diffusion

A3B5 nanowires on Si

GaAs NWs on Si: SEM observation

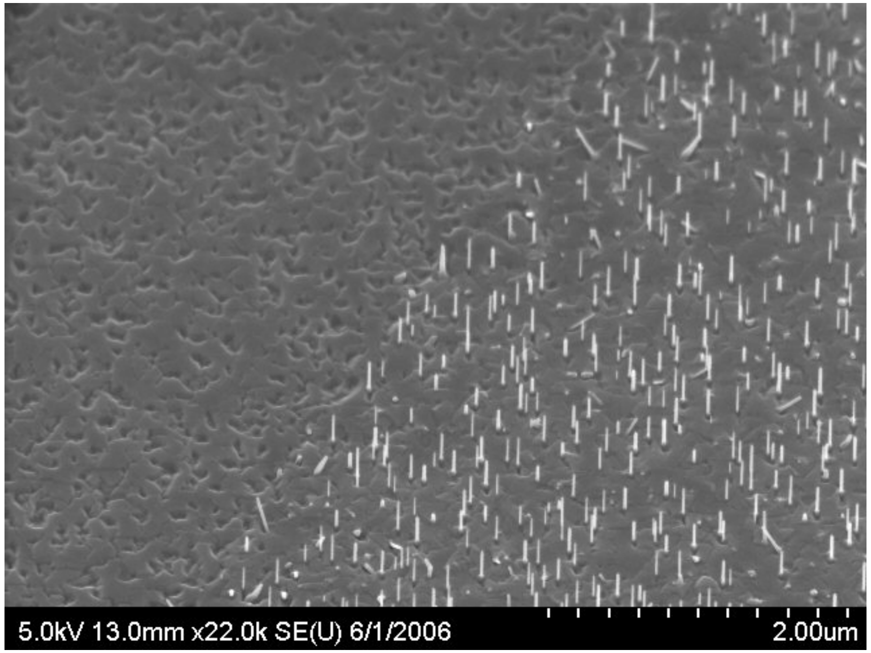




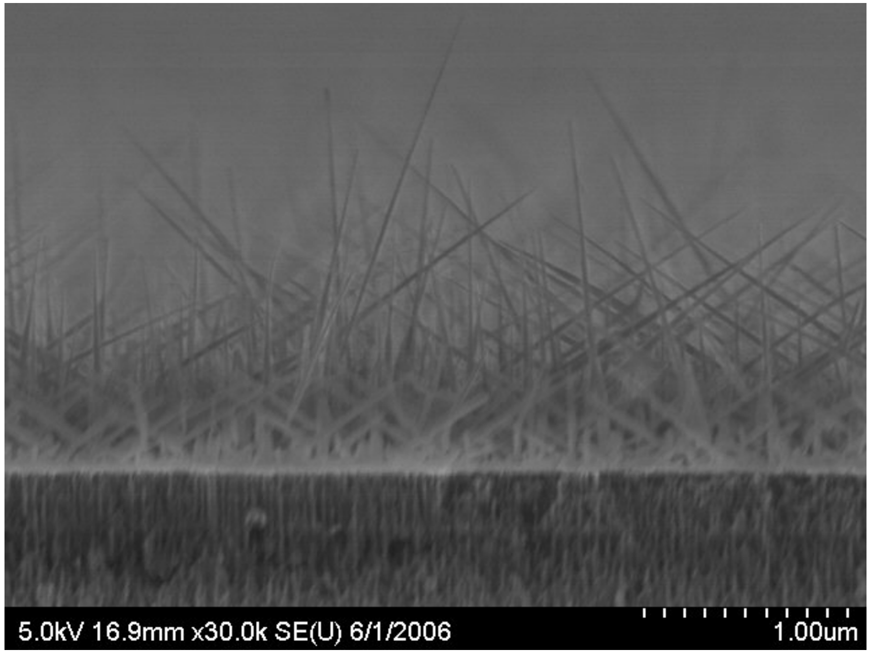
GaAs/Si(111), 700 nm

GaAs/Si(001), 700 nm

GaAs NWs on Si: effect of porosity

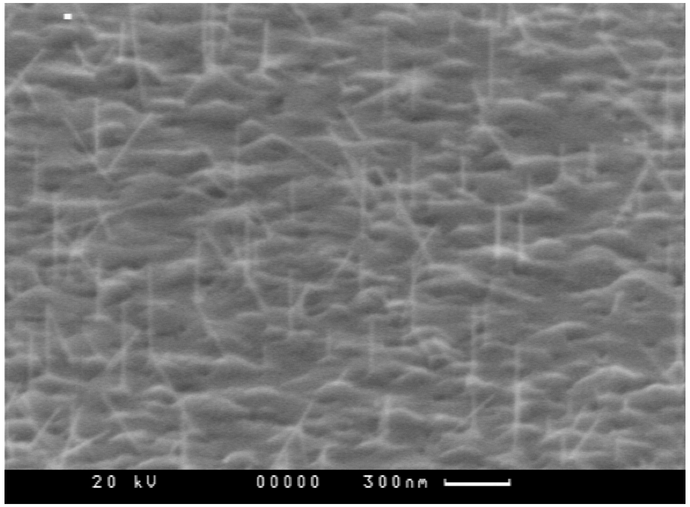


GaAs NWs on Si(111)

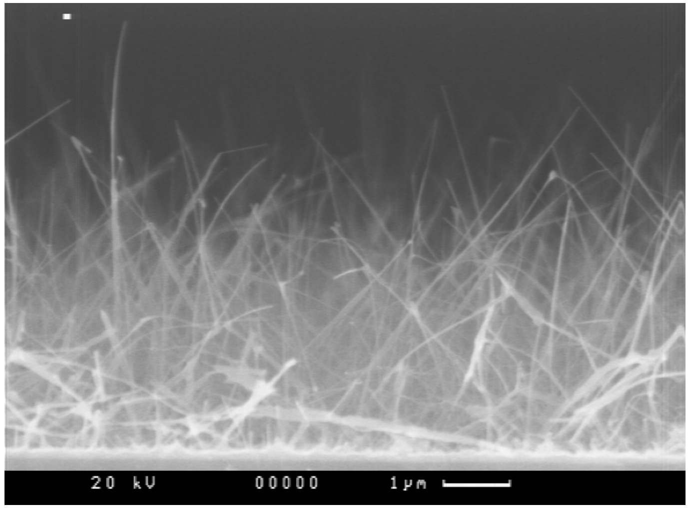


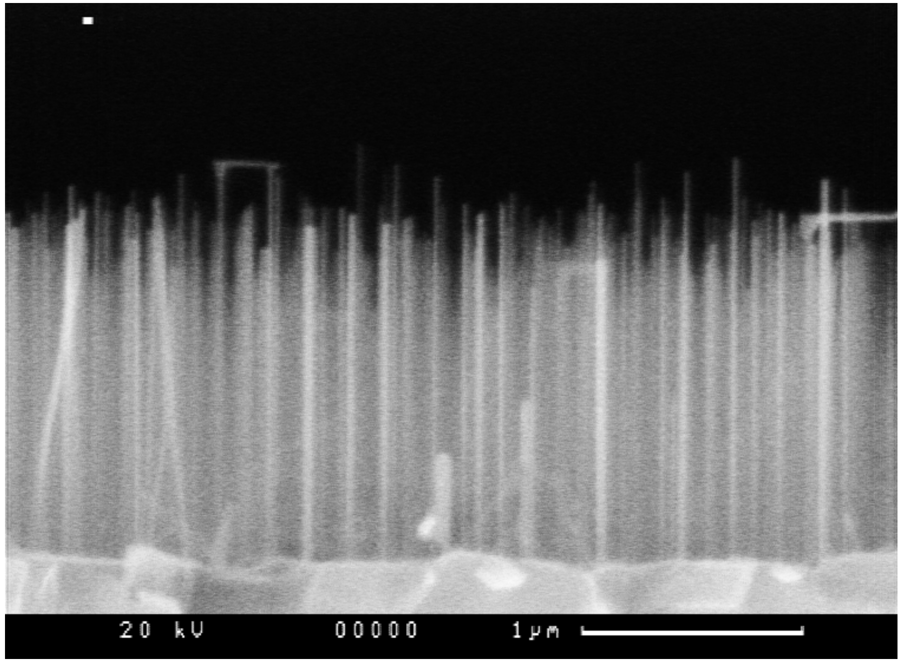
GaAs NWs on Si(001)

InAs NWs on Si(111) and GaAs(111)B



InAs/Si(111)

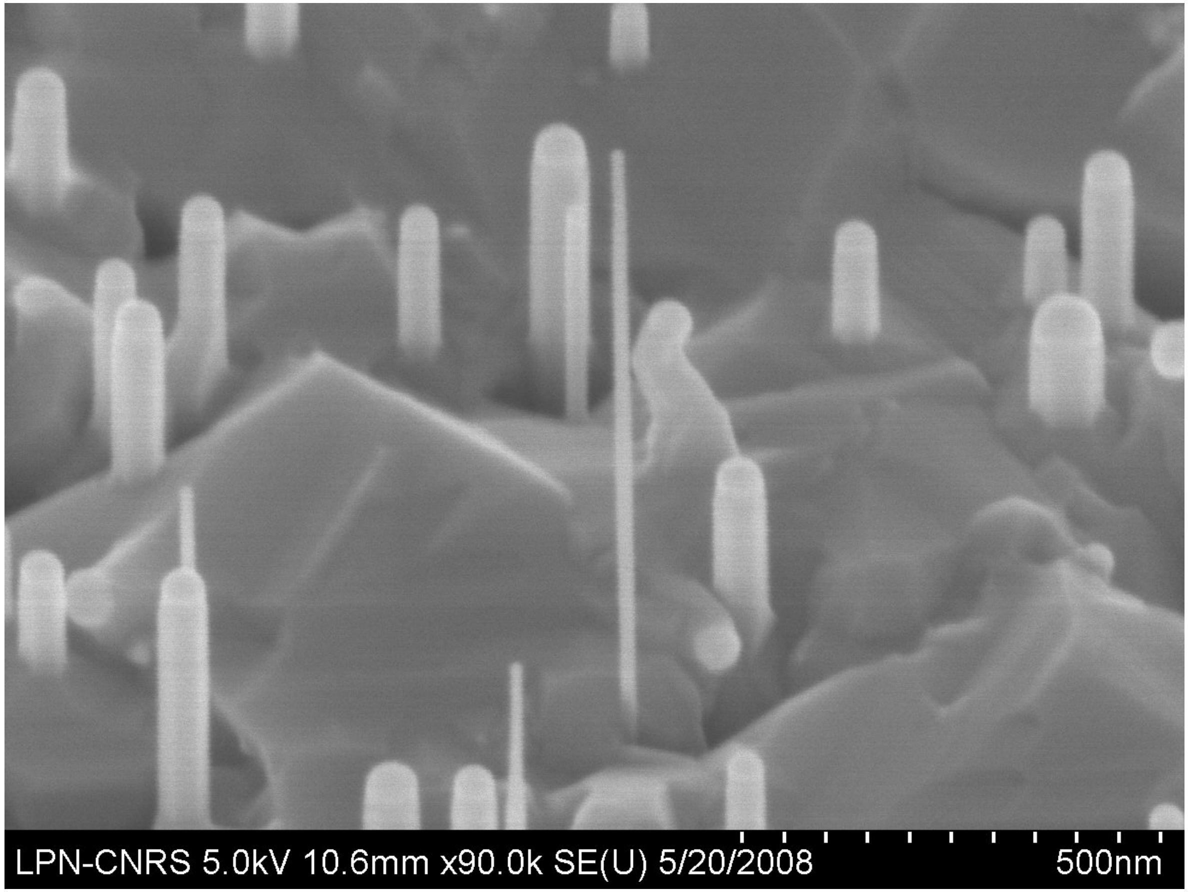




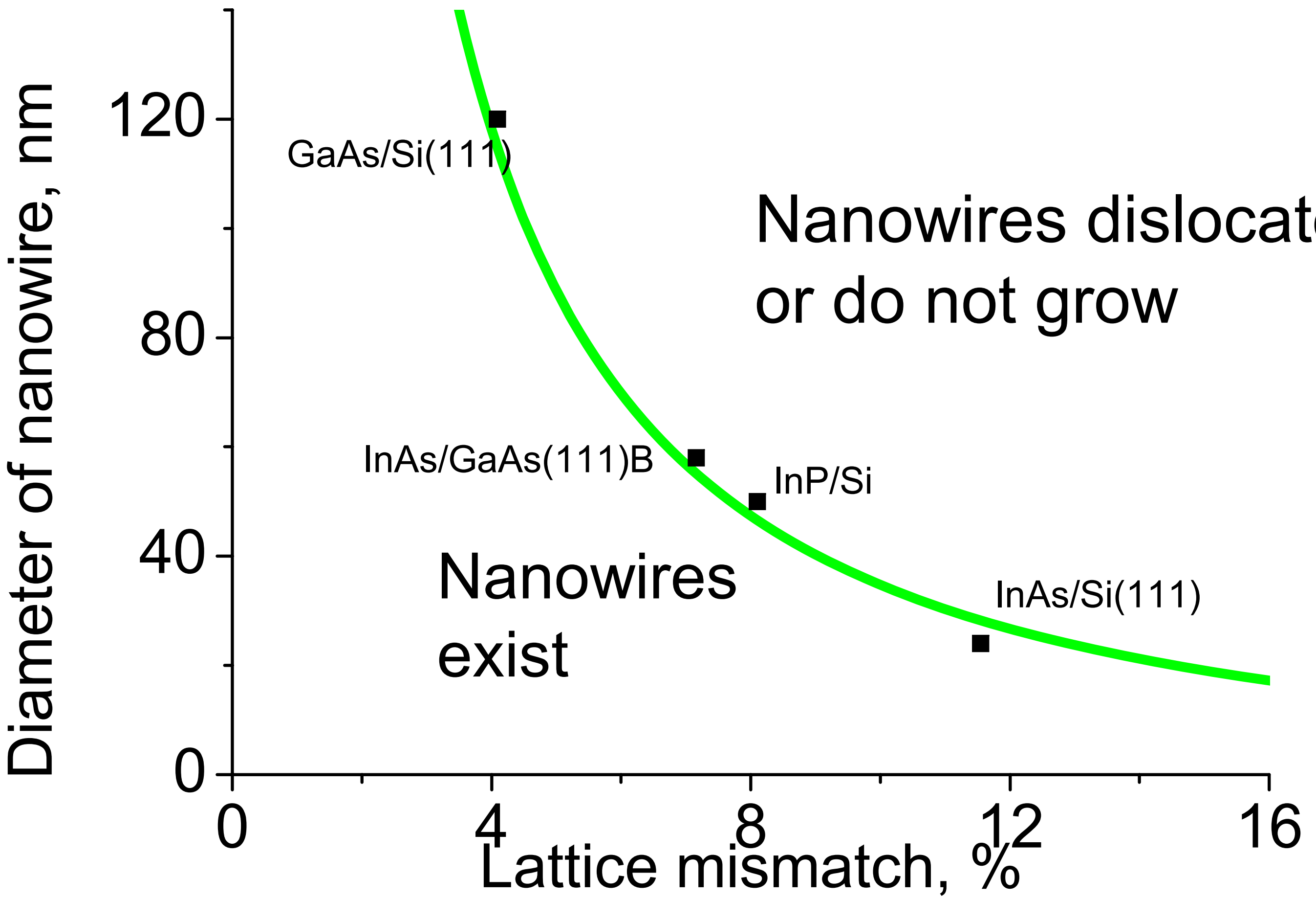
InAs/GaAs(111)B

InAs/Si(001)

InP NWs on Si(111)



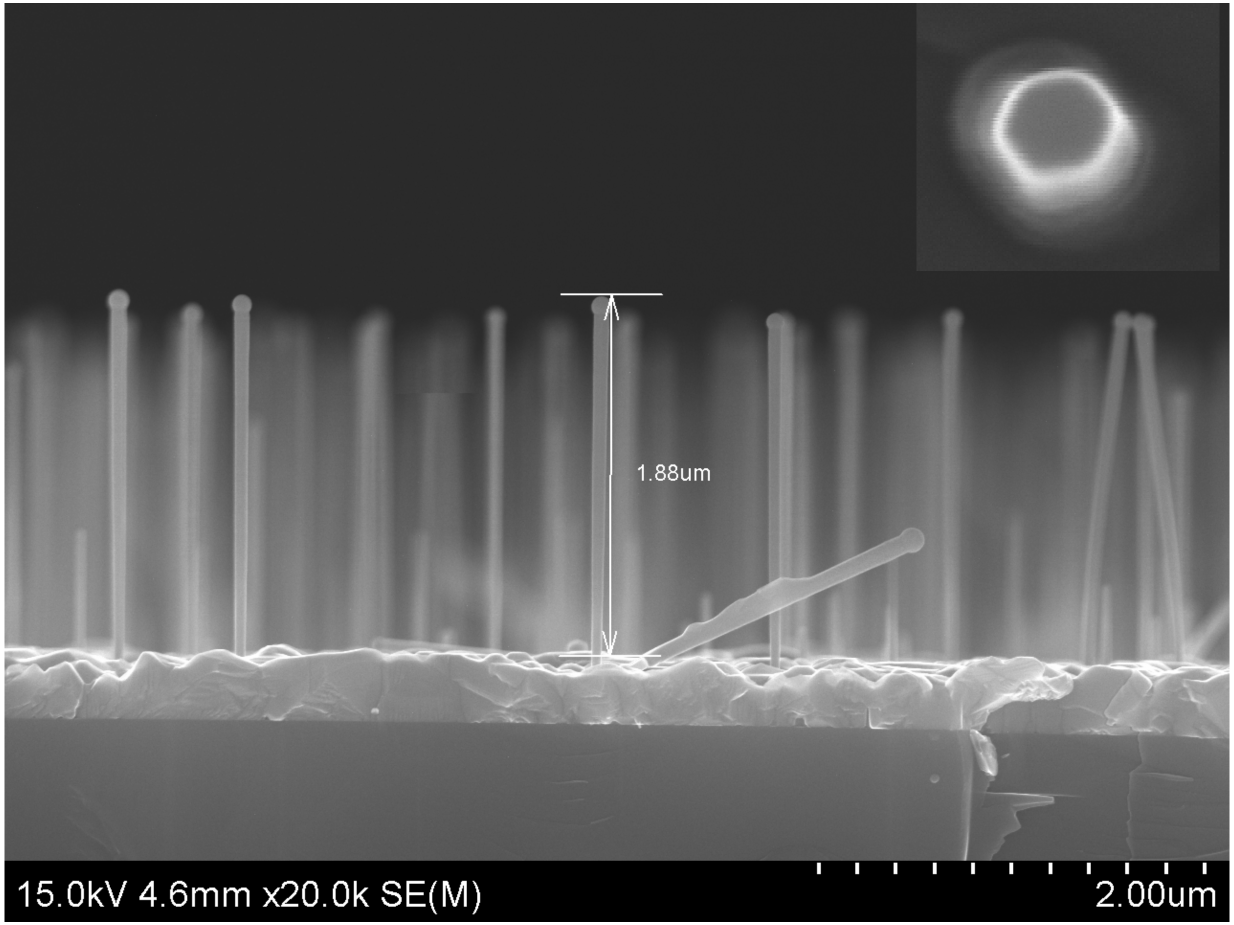
CRITICAL DIAMETER OF A3B5 NANOWIRES



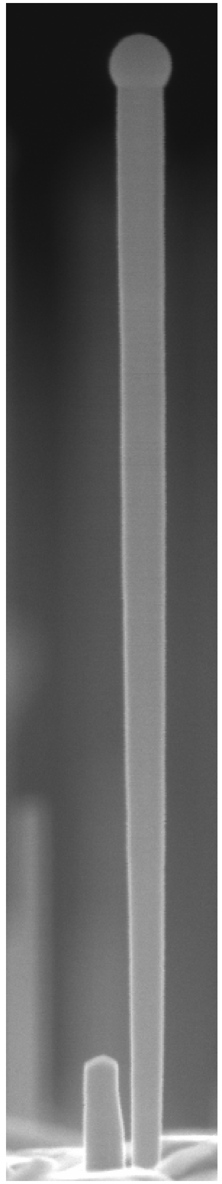
*Phys. Status Solidi RRL **3**, No.4, 112–114 (2009)*

Self-catalysed GaAs NWs on Si(111)

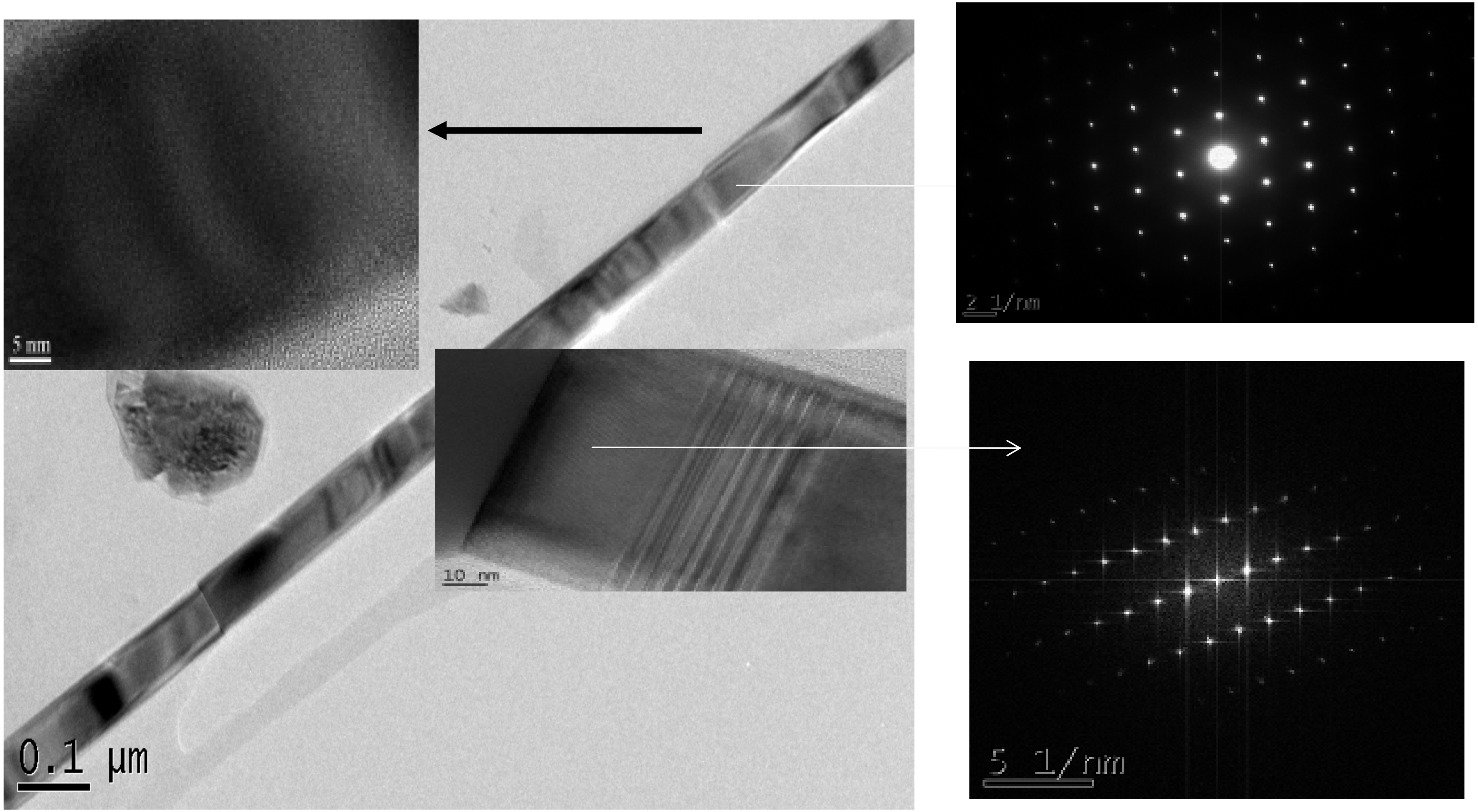
Ga-catalised GaAs/Si(111)



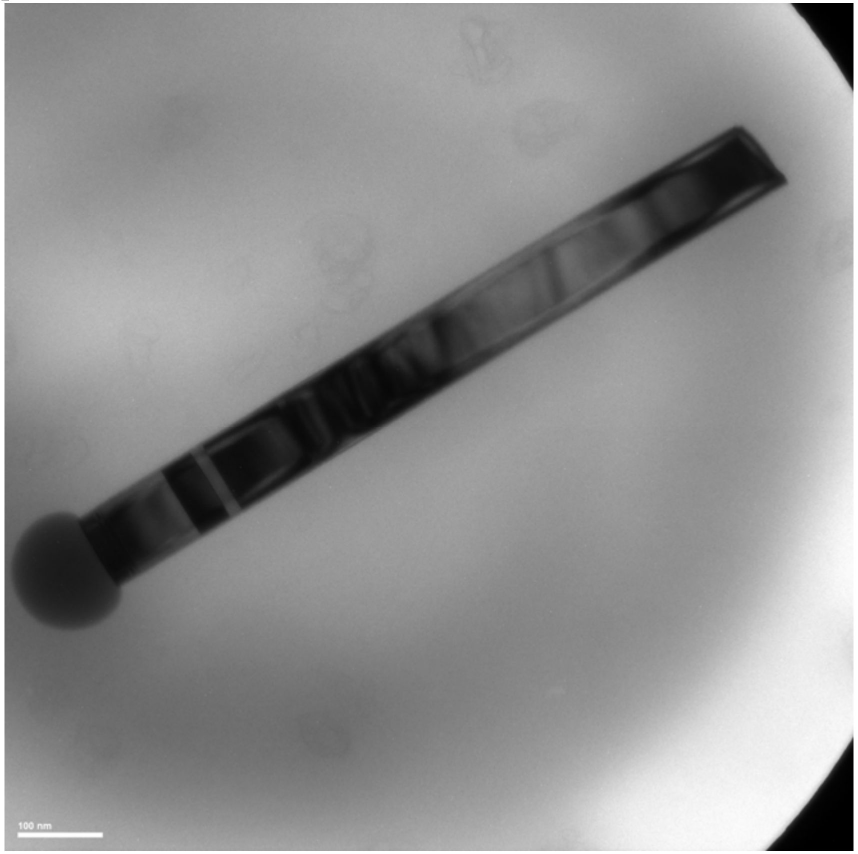
Phys.Rev.B, 2010, v.82, 035302

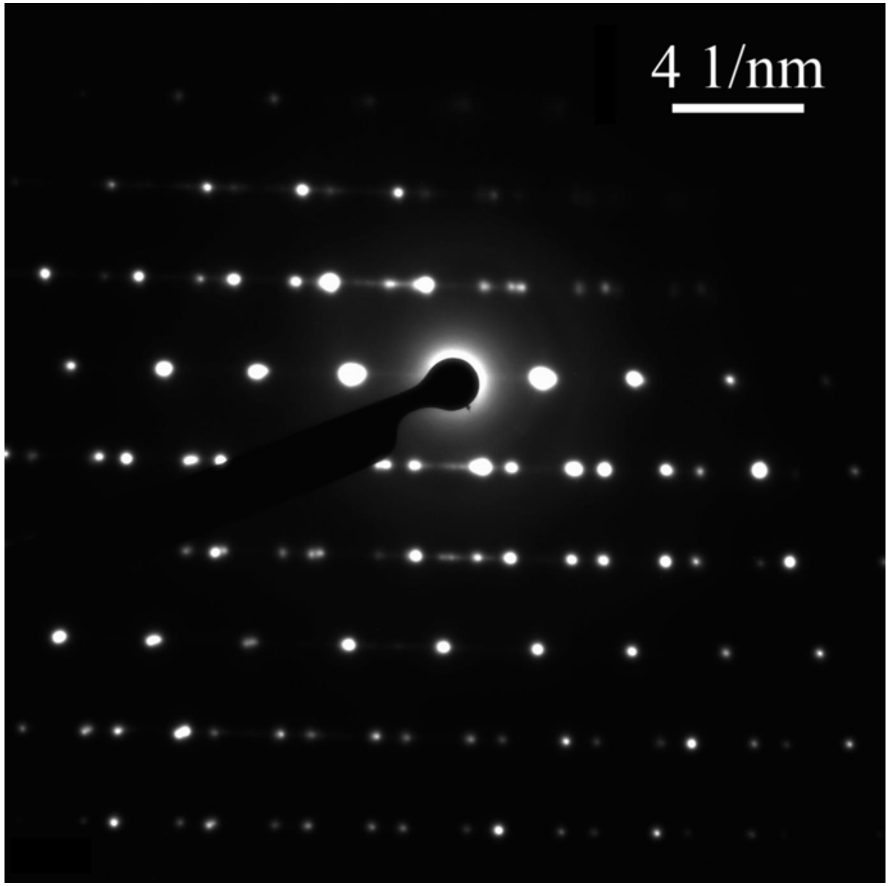


Cubic phase!



Pure cubic phase: approach

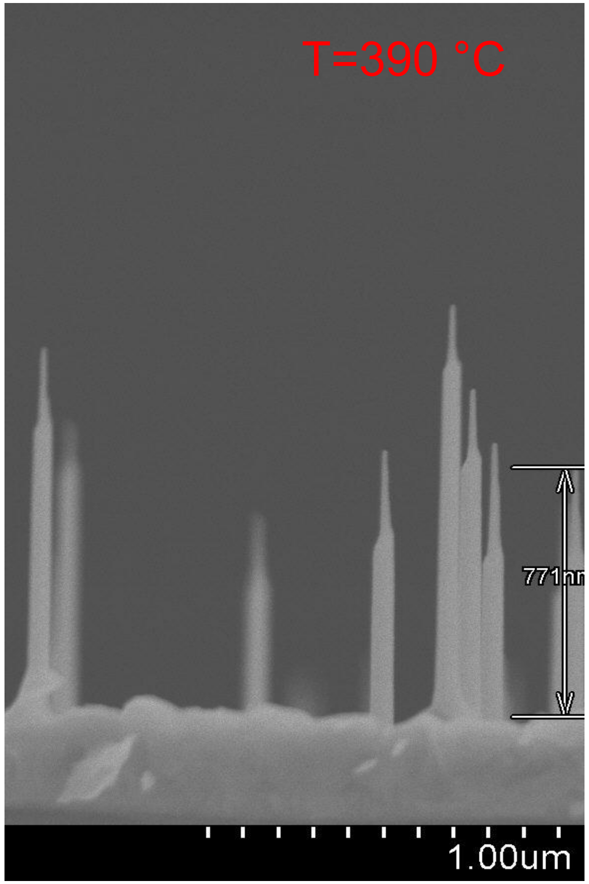


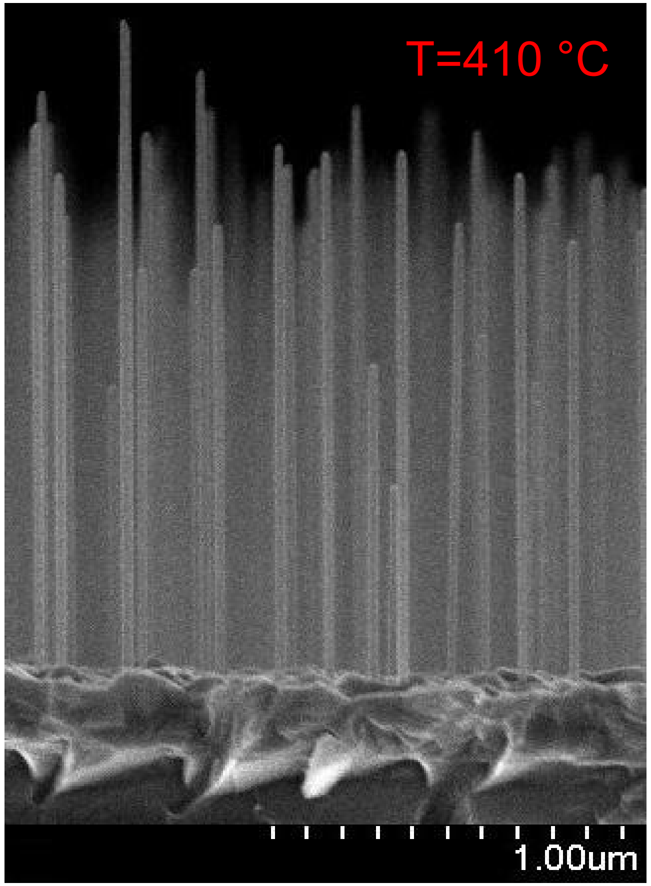


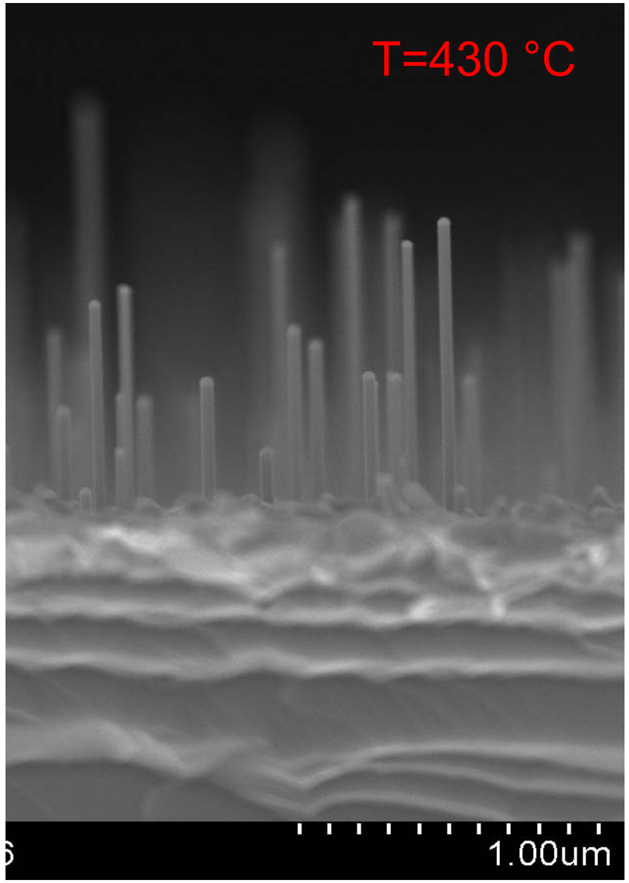
Pure ZB: if stop/reinitiate the growth or end the growth under Ga flux (no As)!

InAs and InP nanowires
InP/InAsP/InP heterostructures

InAs nanowires: morphology



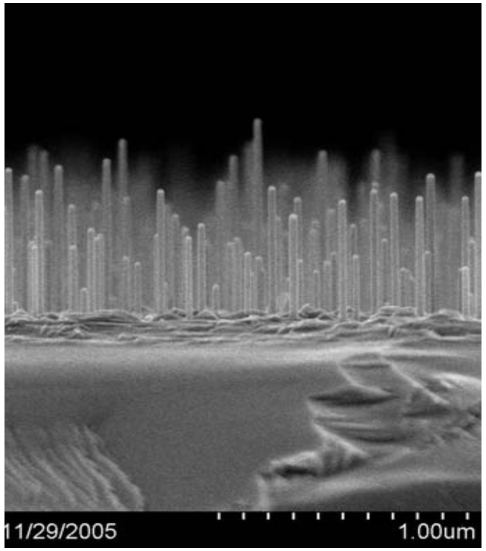




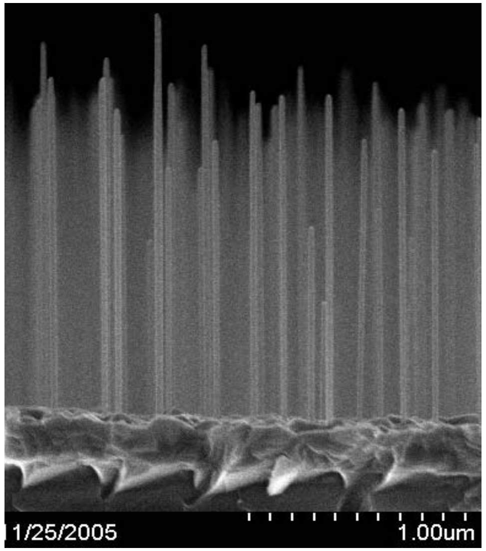
Pencil-like

Cylindrical shape

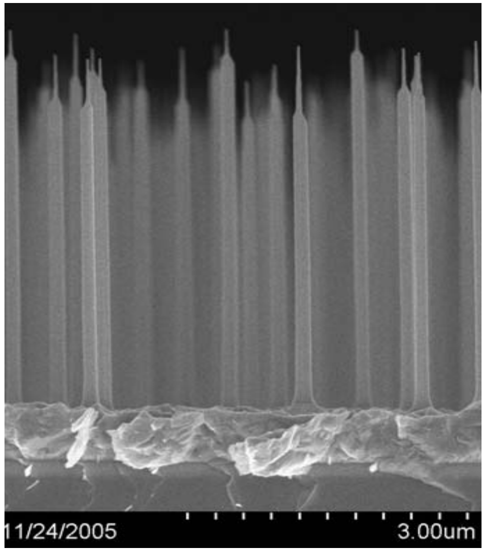
InAs nanowires: growth duration



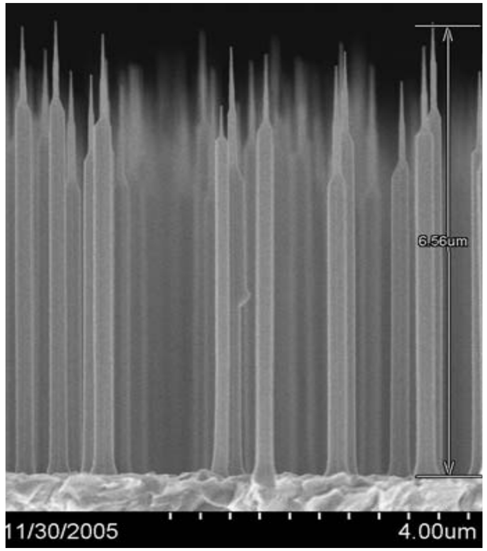
10 min
h~0,35µm
d~30nm



20 min
h~1,5µm
d~40nm

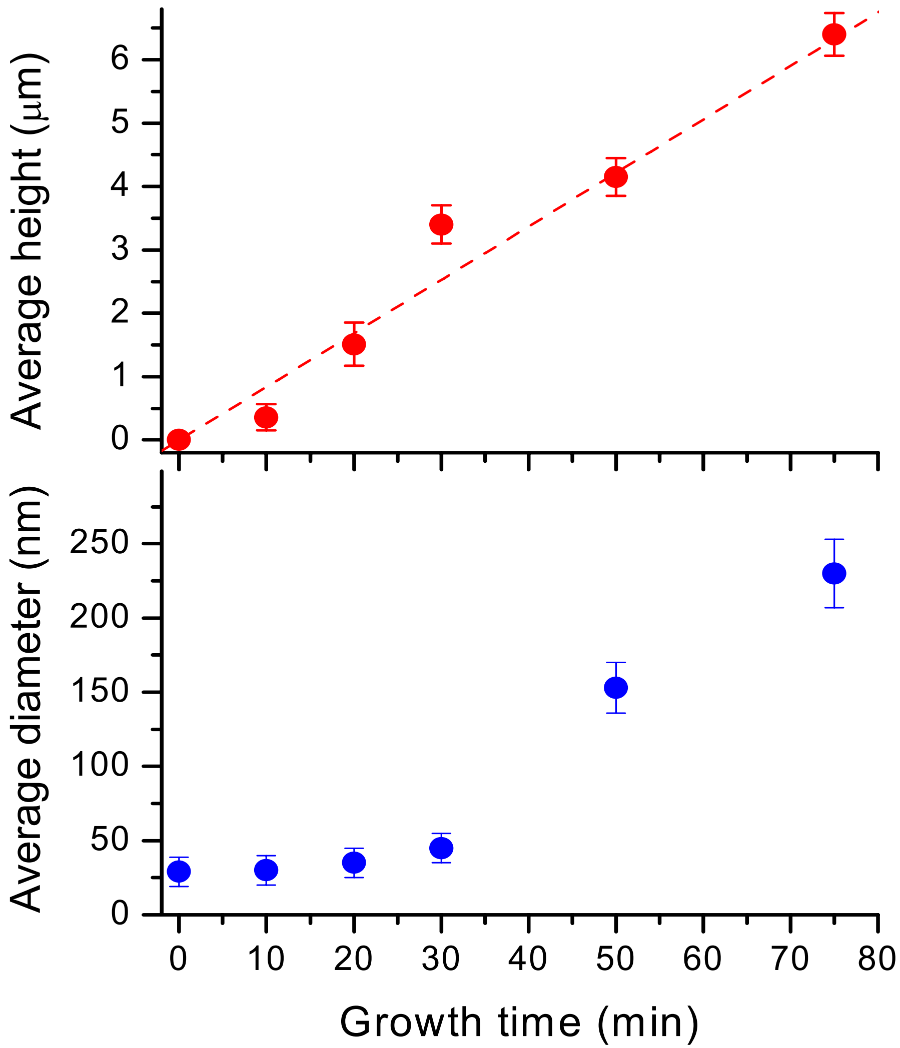


50 min
h~4,2µm
d~150nm



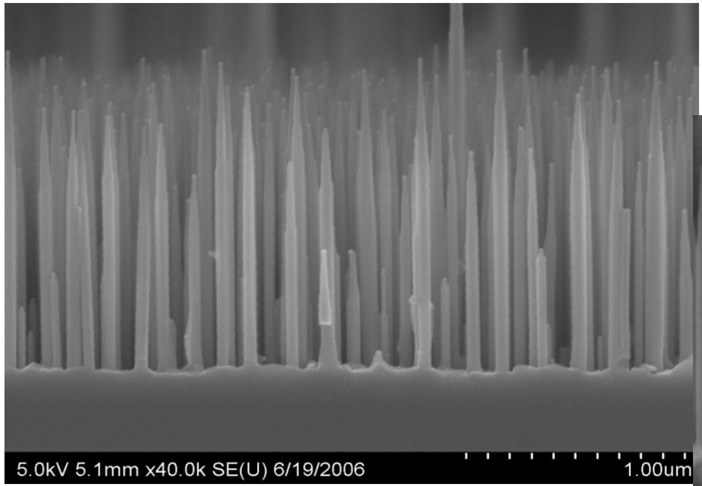
75 min
h~6µm
d~220nm

Axial/lateral growth: effect of growth duration

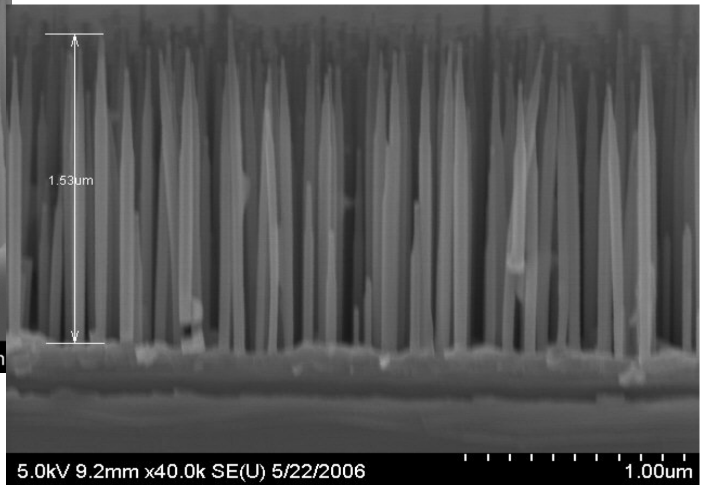


J.Appl.Phys., 2007, v. 102, 094313

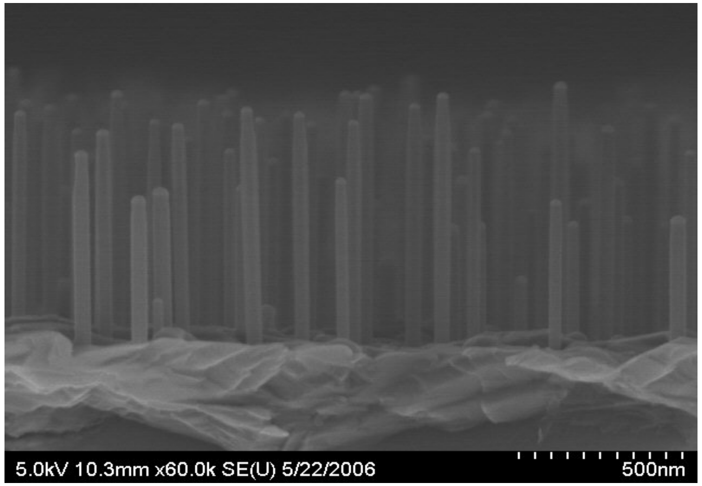
InP nanowires: morphology



T=350 °C

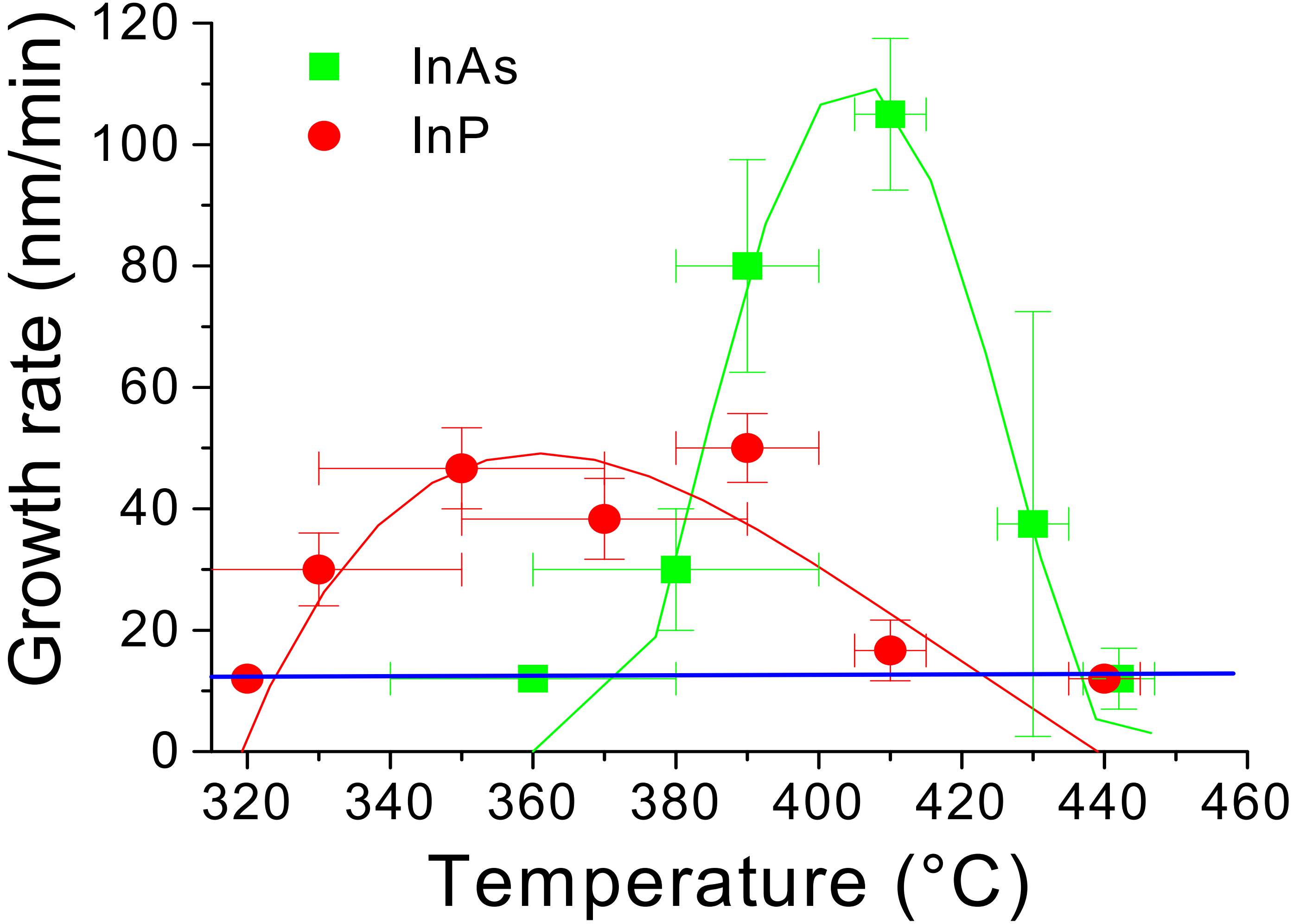


T=390 °C

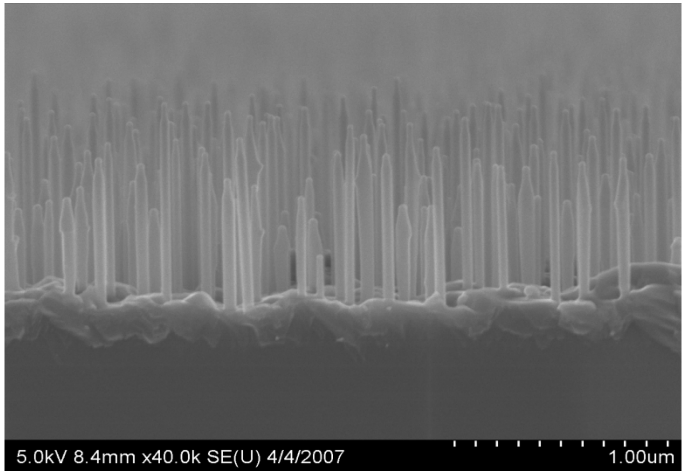


T=410 °C

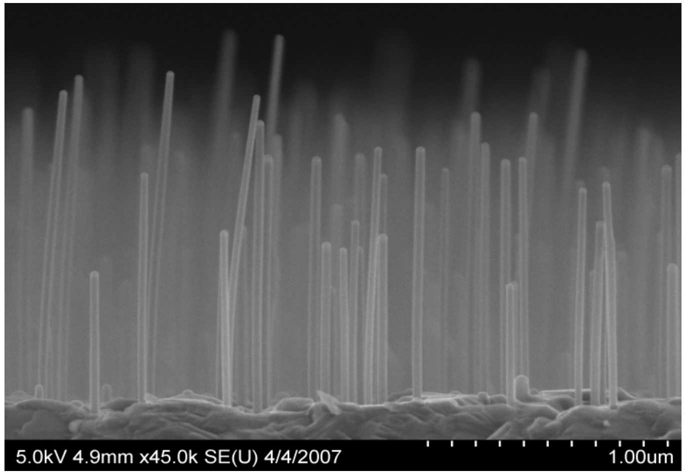
Temperature limits and NWs growth rate



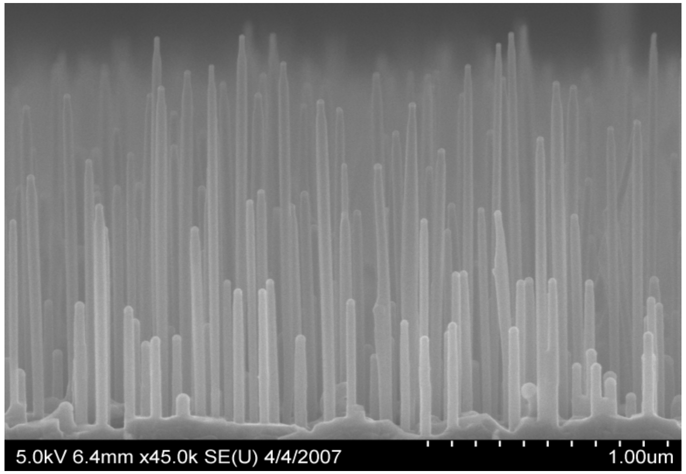
InP/InAsP/InP heterostructures: morphology



390^0C

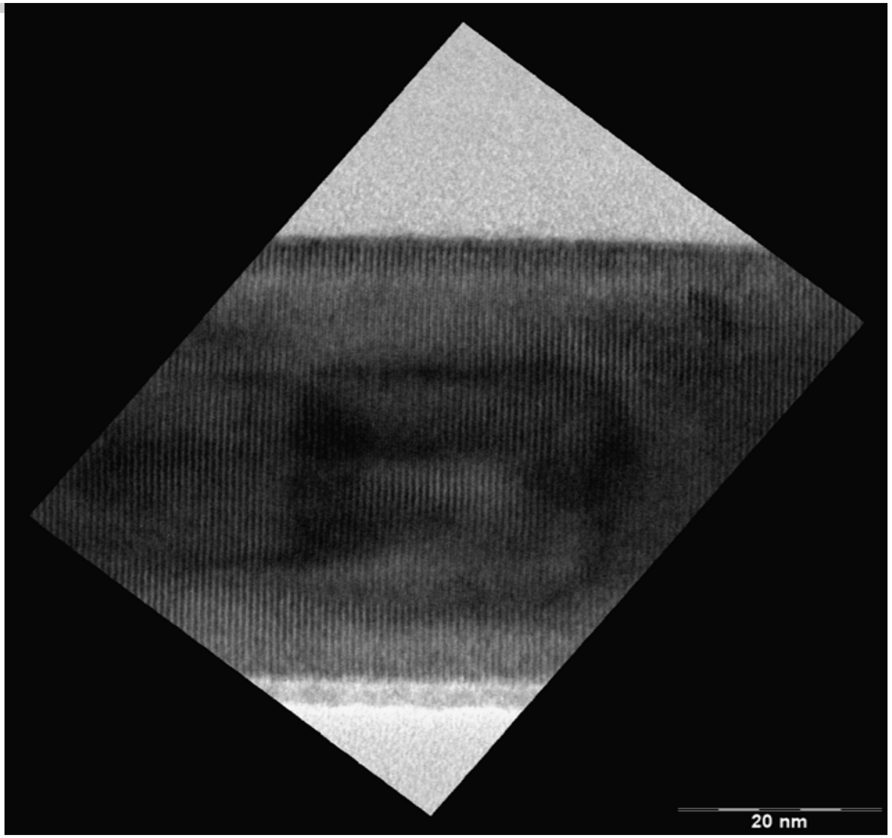


$390^0C + 430^0C$



$390^0C+430^0C+390^0C$

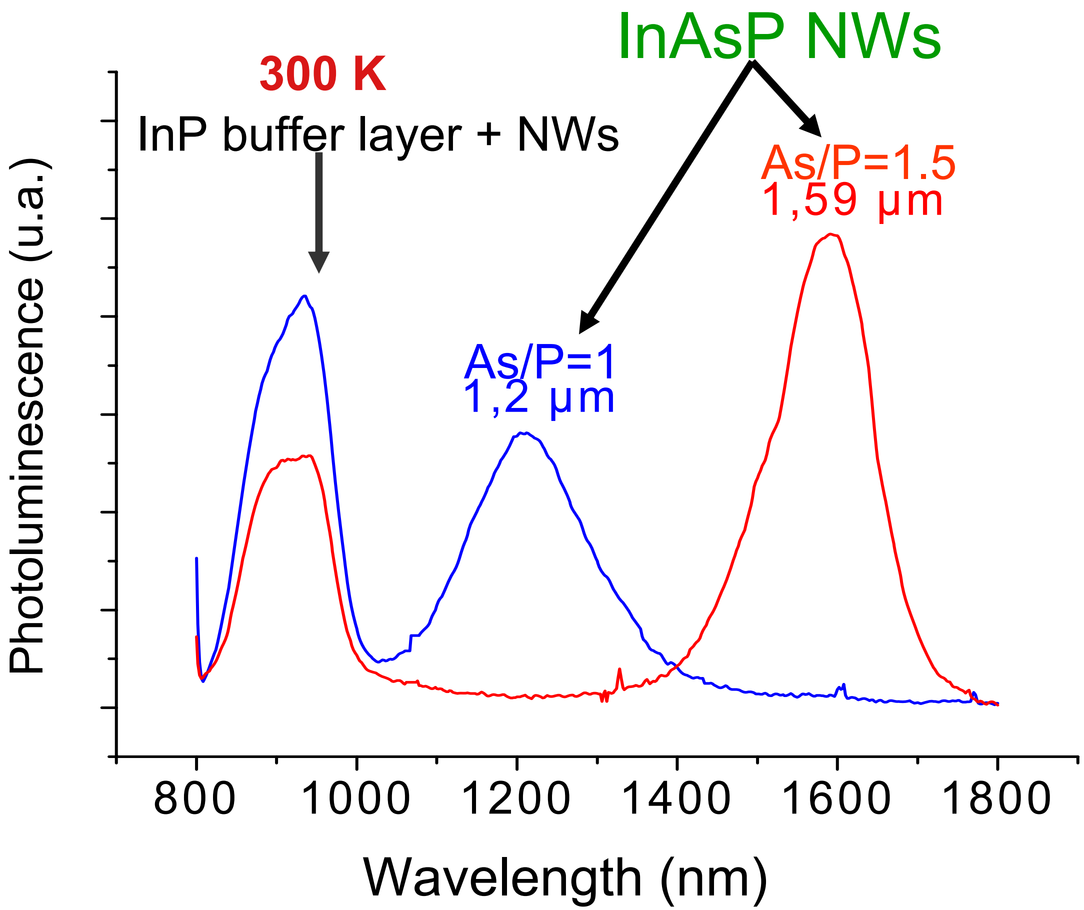
Optimized growth procedure



Three steps procedure

- *Start of InP NW growth at 390°C*
- *Growth of the InP/InAsP/InP heterostructure at 430°C – straight interfaces*
- *Growth of the InP shell at 390°C*

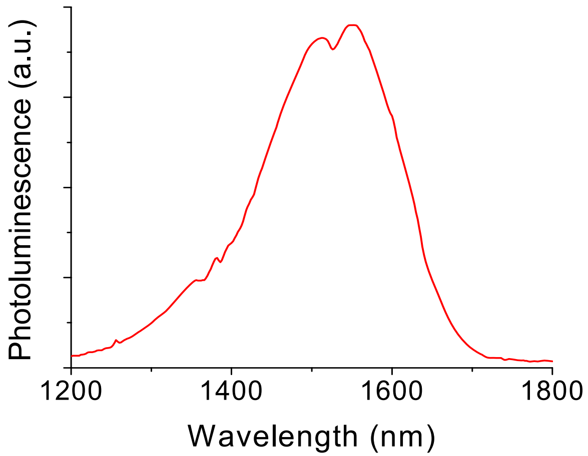
Room-temperature PL of InP/InAsP/InP NWs



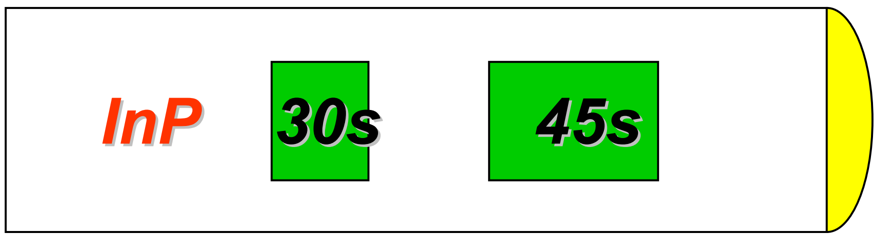
1. **By changing As flux from As/P=1.5 to As/P=1 the PL peak is tuned from 1.2 to 1.6µm – possibility to cover telecom wavelenghts**
2. **FWHM = 150 meV – inhomogeneous broadening is due to the insertion size and composition dispersion**
3. **Positive effect of InAsP embedding – almost no PL signal for NWs without InP shell.**

Macro- and micro-PL of InP/InAsP/InP NWs

Room-temperature macro-PL

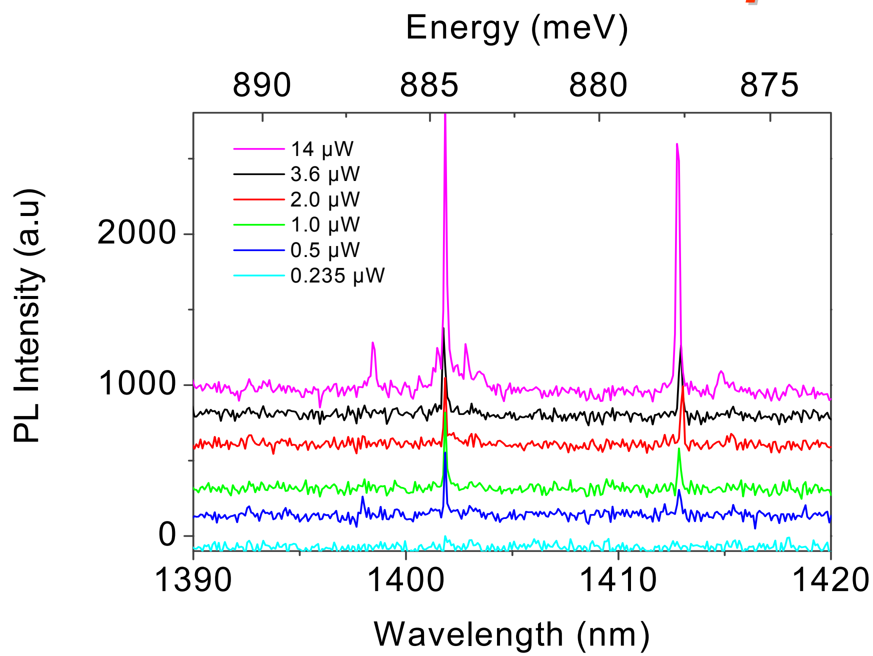


Structure with 2 InAsP segments



Micro-PL at 10K of a single wire

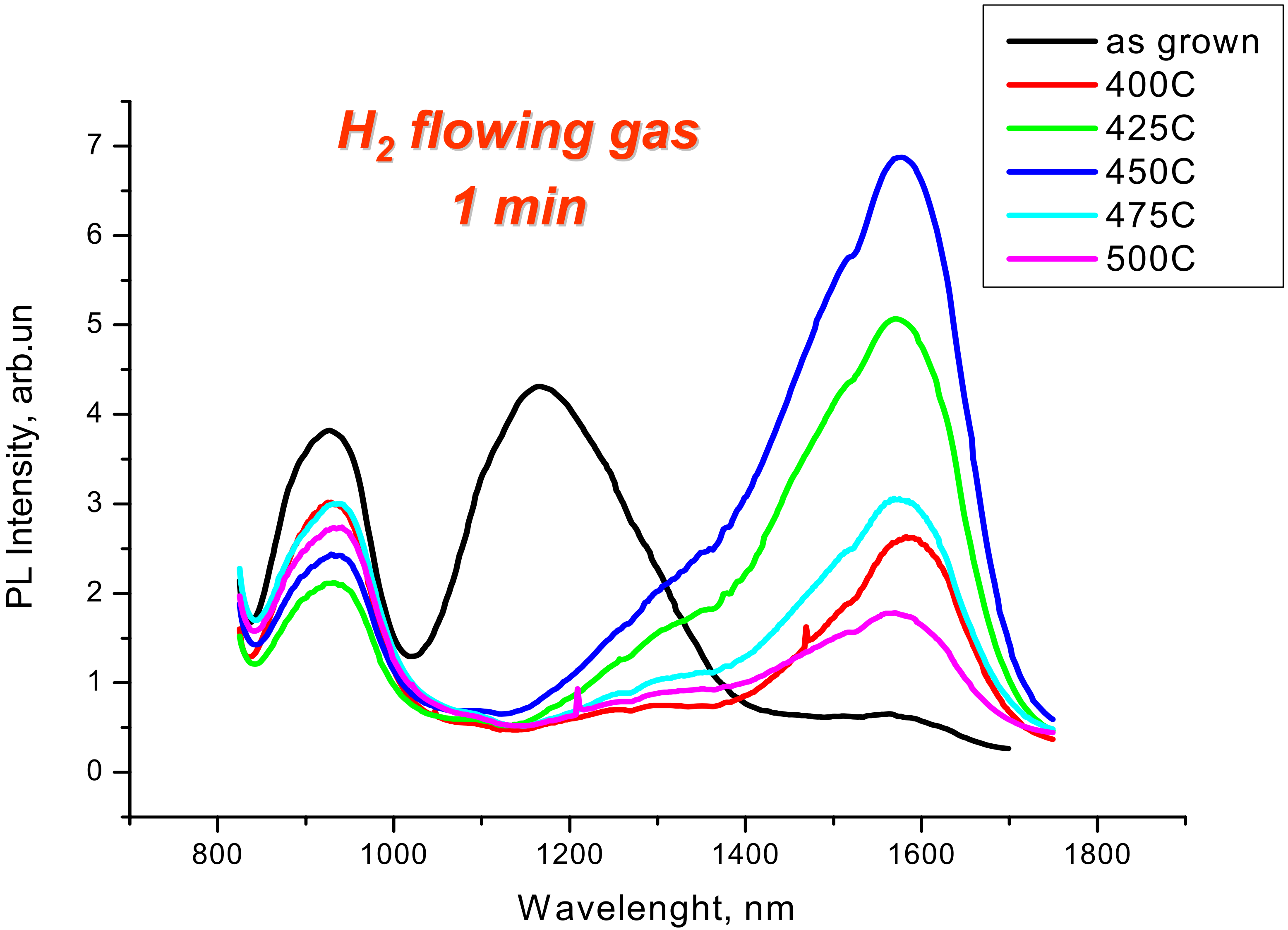
FWHM = 120 μeV



Valery Zwiller
Delft University of Technology

Nano Lett., 2007, v. 7, p. 1500-1504.

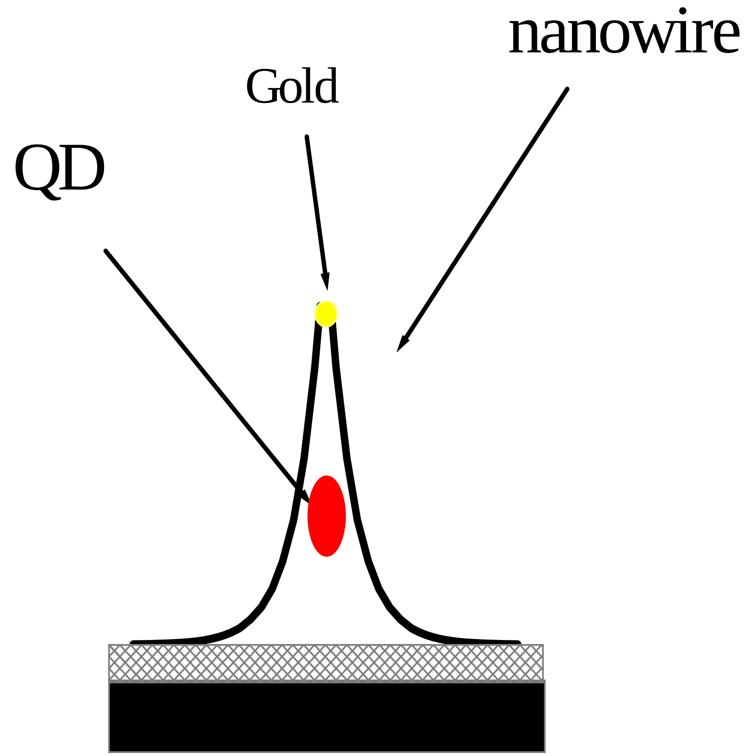
InP/InAsP/InP LT grown NWs: post growth annealing



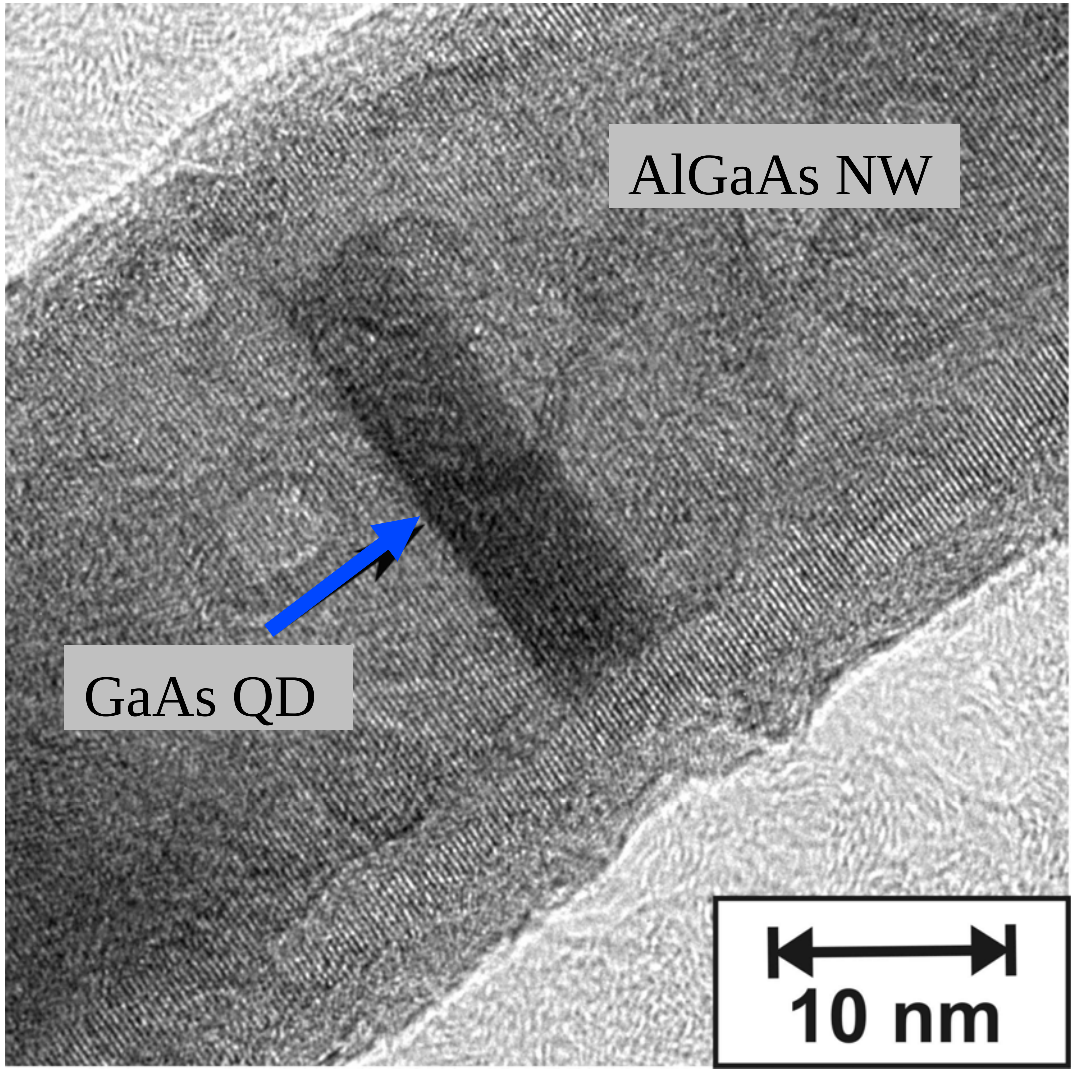
GaAs quantum dots in AlGaAs nanowires

Samples preparation

- AlGaAs NWs were grown on the GaAs (111)B semi-insulating substrate in an MBE system
- Al concentration in NW was 30%, according to the two-dimensional growth rate
- For AlGaAs/GaAs/AlGaAs quantum dot formation, the growth started with 15 min of AlGaAs, and then the Al source was closed for 5 sec in order to form a GaAs segment in each NW.
- The growth was completed with 2 min. deposition of GaAs at 530 °C to avoid oxidation.

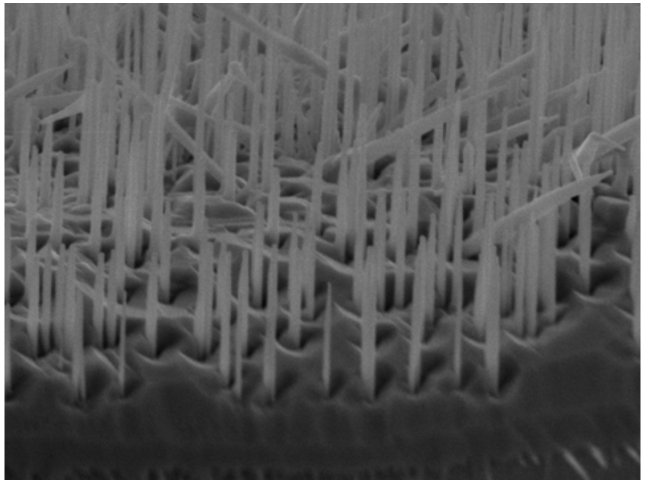


TEM image of GaAs QD in AlGaAs NW

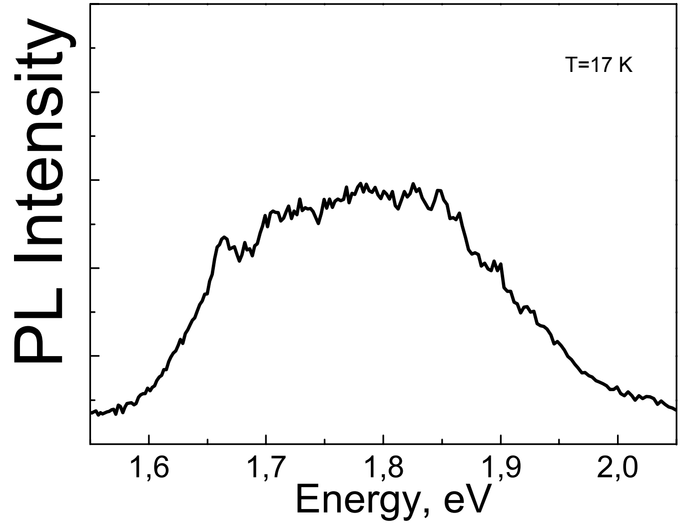


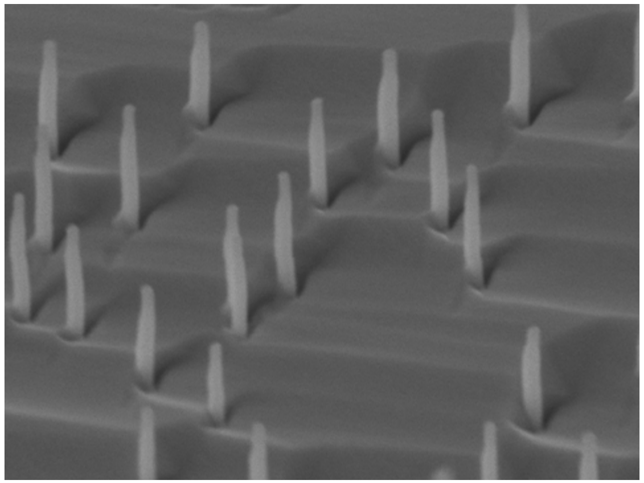
- QD height is 5 nm and diameter is 20-30nm
- Sharp interfaces

Growth at low and high substrate temperature

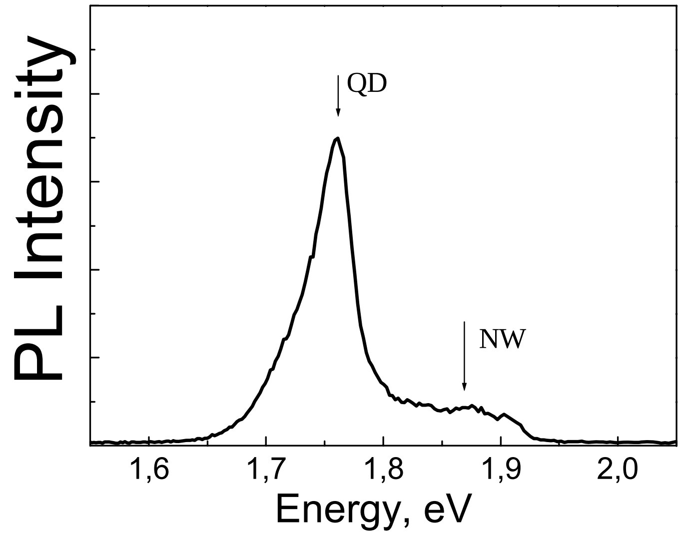


T = 550^{0}C

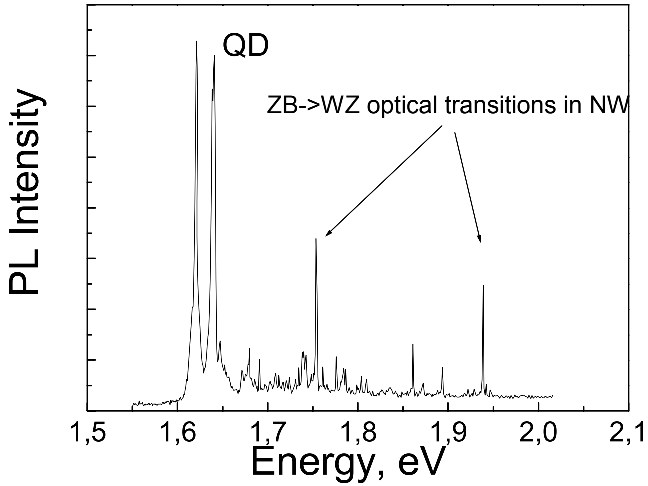


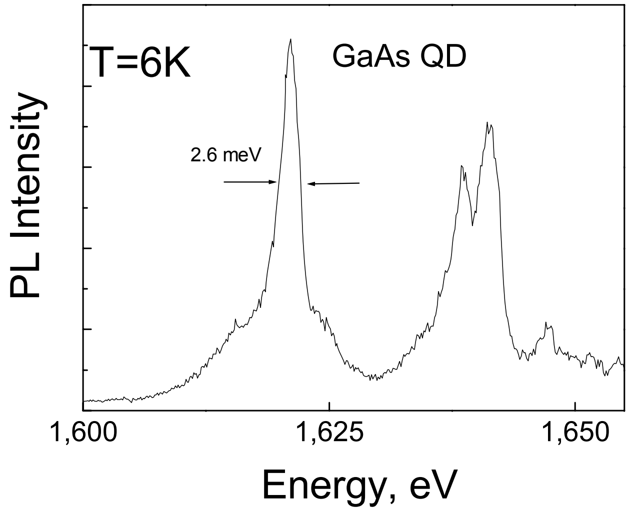


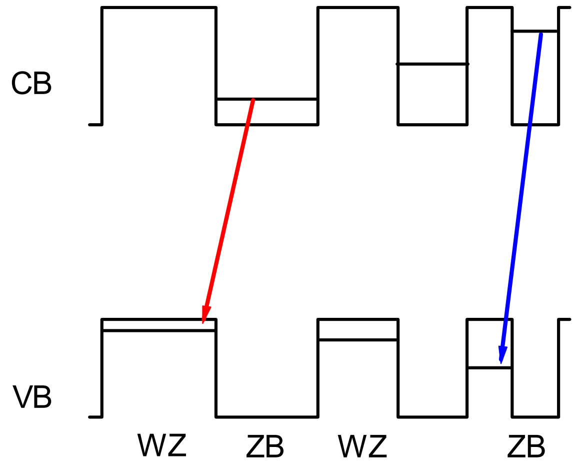
T = 580^{0}C



PL features in AlGaAs/GaAs NW–QD structures

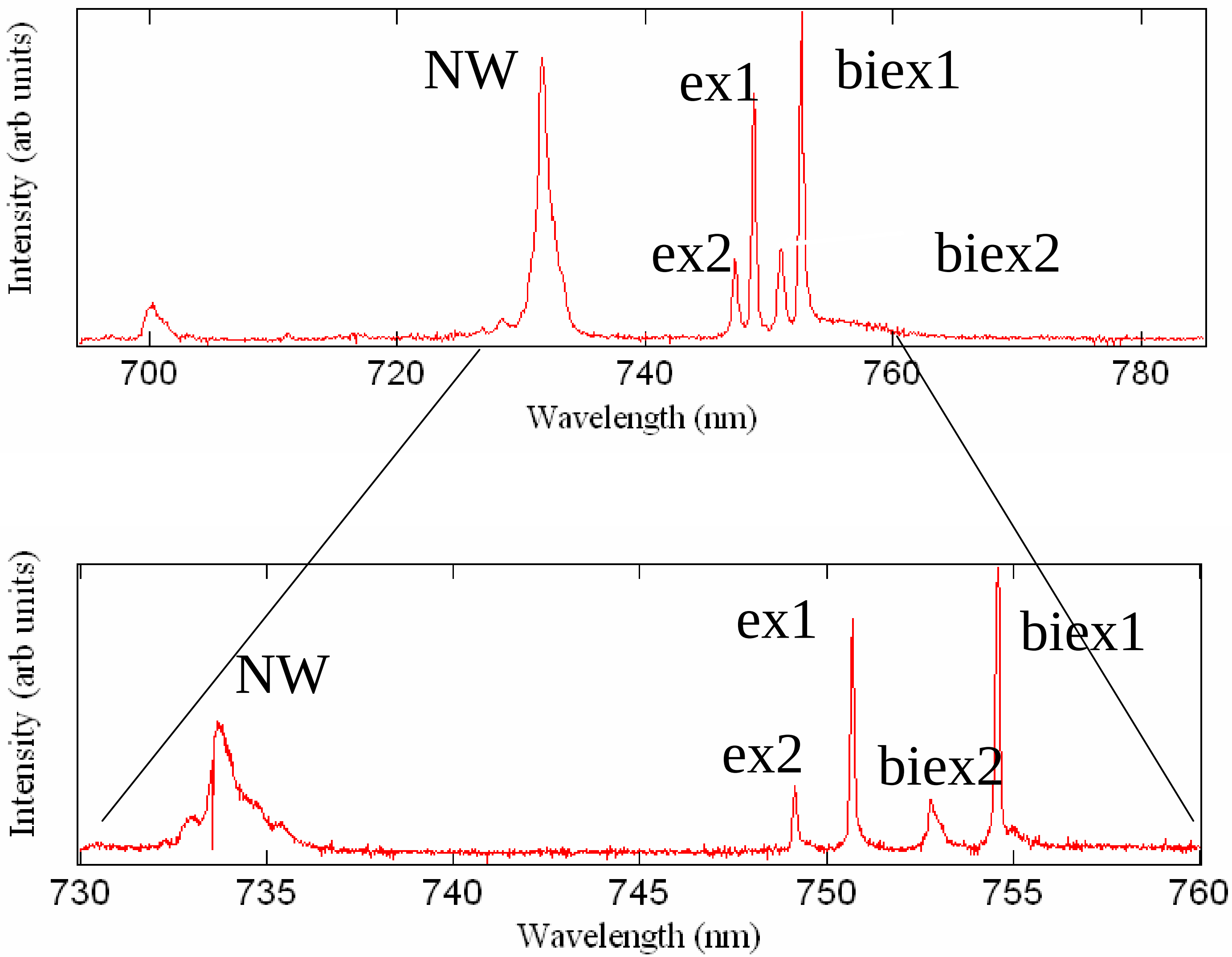




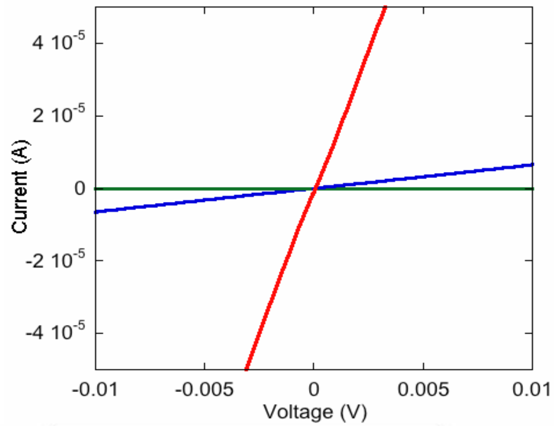


In AlGaAs nanowire, the crystalline structure can switch spontaneously from the zinc-blende (ZB) to the wurtzite (WZ) structure. The alternation in crystalline structure leads to the formation of type -II superlattice along the growth direction and therefore the carrier spectrum become quantized along the axis.

Micro PL of 2 NWs

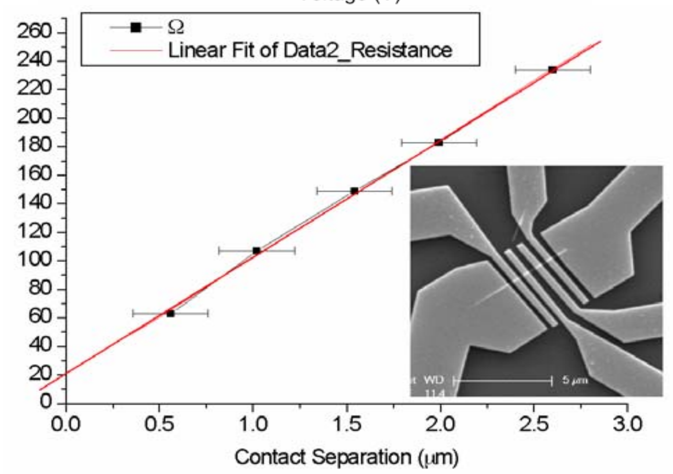


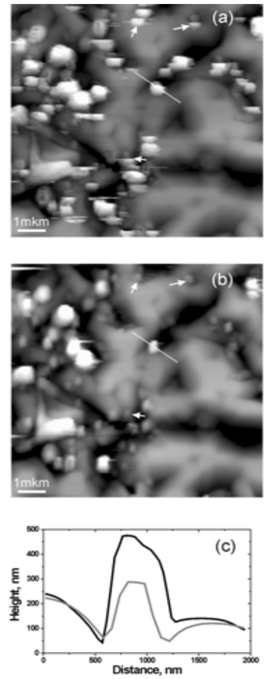
Локальные вольт-амперные характеристики

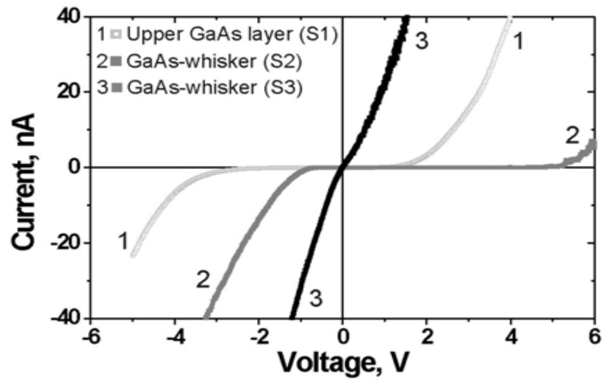


InP:Si

GaAs:Si







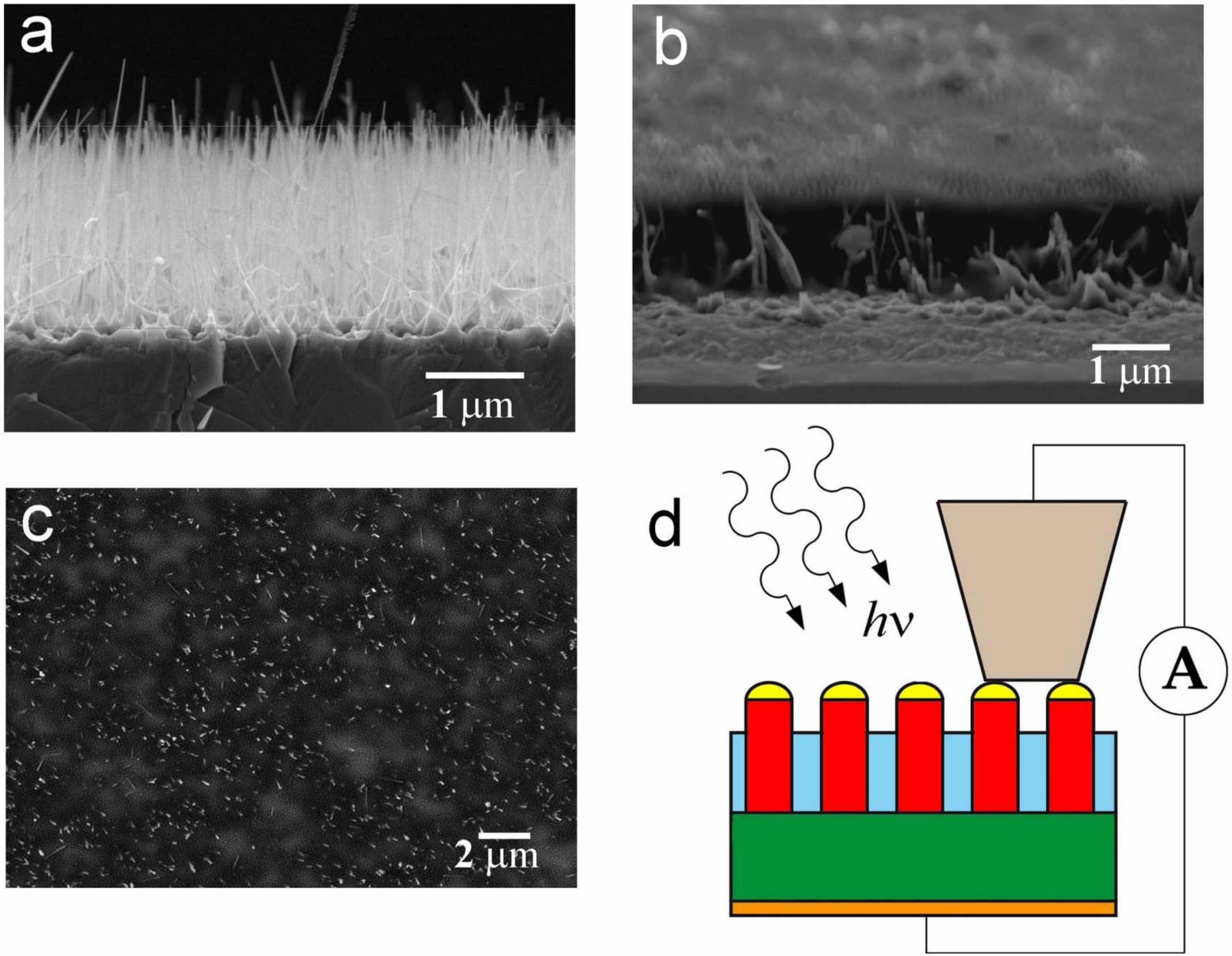
undoped	no conduction
Low Si doping (T_{si}=1040°C)	1.9±0.4×10⁻⁴ Ωcm
Hi Si doping (T_{si}=1150°C)	1.6±0.3×10⁻⁵ Ωcm

Photovoltaic properties of p-type GaAs NWs on GaAs(111)B n-type substrate

Samples description

- MBE growth of GaAs:Be NWs on n-type GaAs(111)
- Back (substrate side) metallic contact by electron-beam deposition of AuGe-30 nm+ Ni/Au 10/150нм
- Filling the space between the NWs with PMMA
- Partial removing of PMMA and the top of NWs in O2 plasma

SEM images taken at different stages of device structure preparation



Measurement details

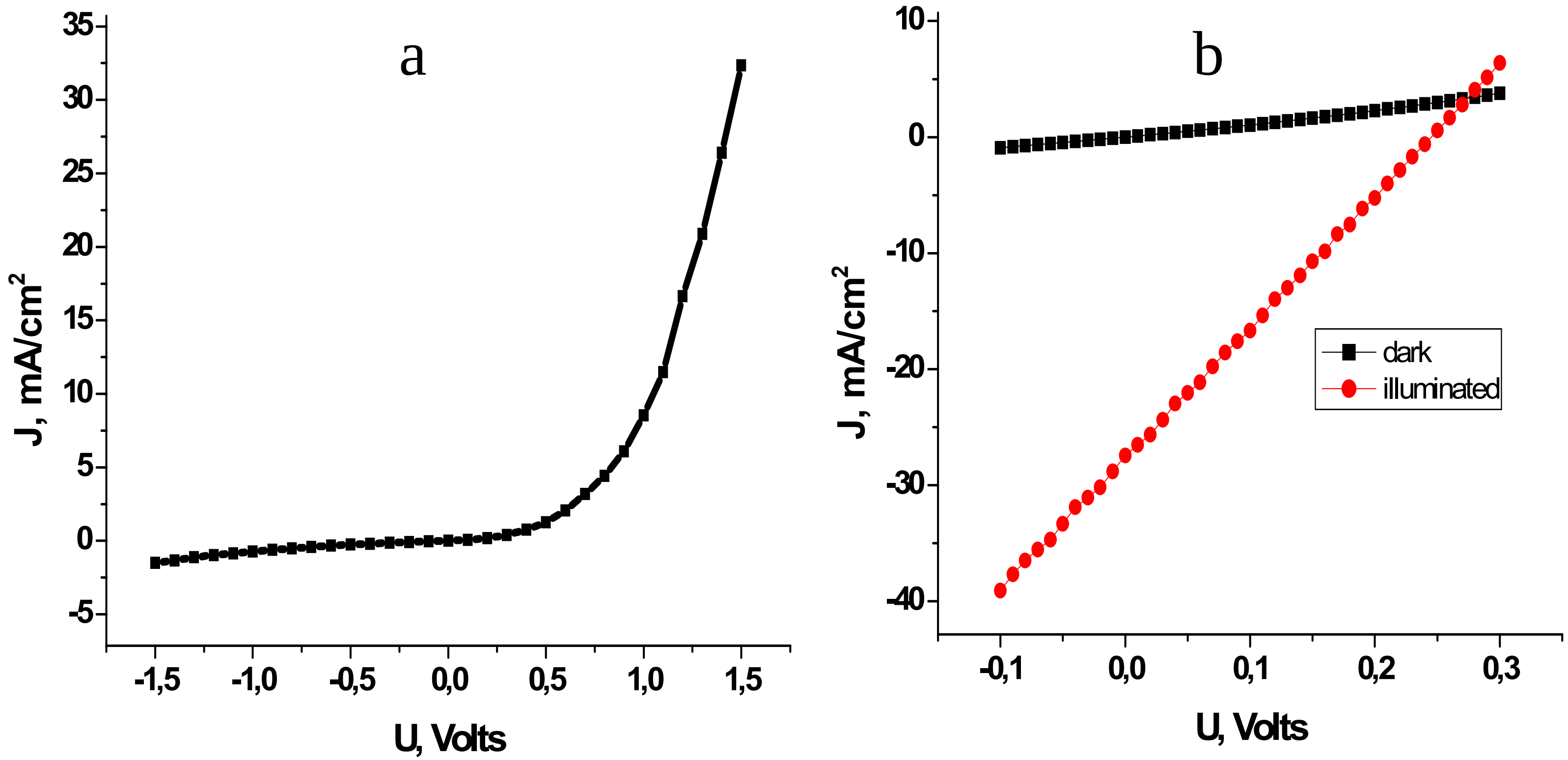
- I-V characteristics are measured using a Keithley 238 source meter. The samples are placed on a copper base from a backside; a metallic sharp tip (D~0.5mm) is used as a top contact to the NWs/PMMA array. The energy conversion efficiency was determined by illuminating the structures using halogen arc-lamp with a calibrated power density of P = 100 mW/cm^2.
- Fill factor (FF) and power conversion efficiency (η) are calculated according to the following equations:

$$FF = V_M J_M / V_{OC} J_{SC}$$

$$\eta = V_M J_M / P$$

V_{OC} and J_{SC} are the open-circuit voltage and short-circuit current and V_M and J_M are the voltage and current density at the maximum power output, respectively, and P is the incident power density

J-V characteristics

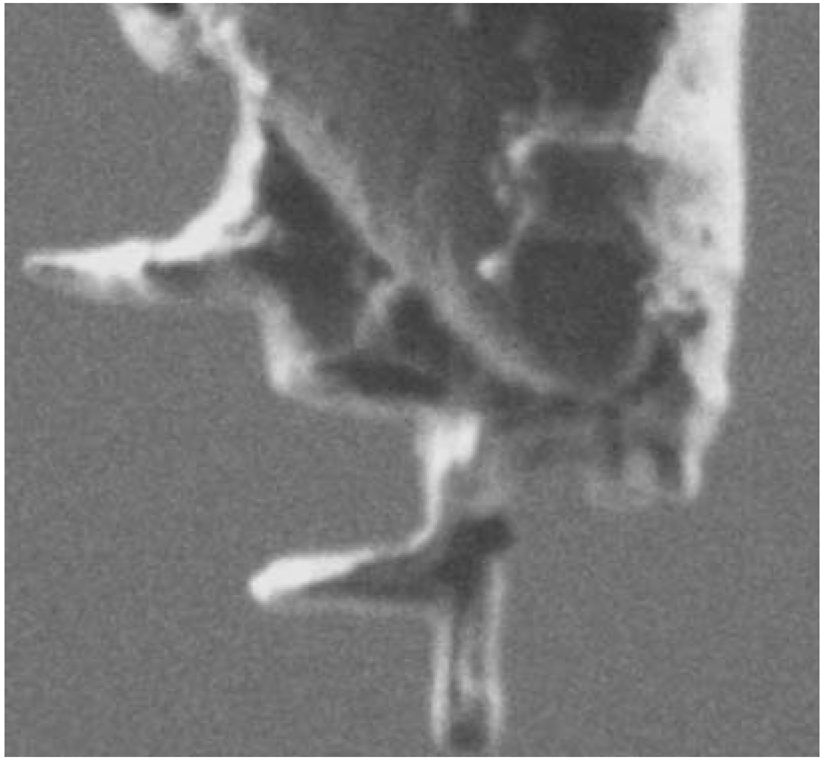


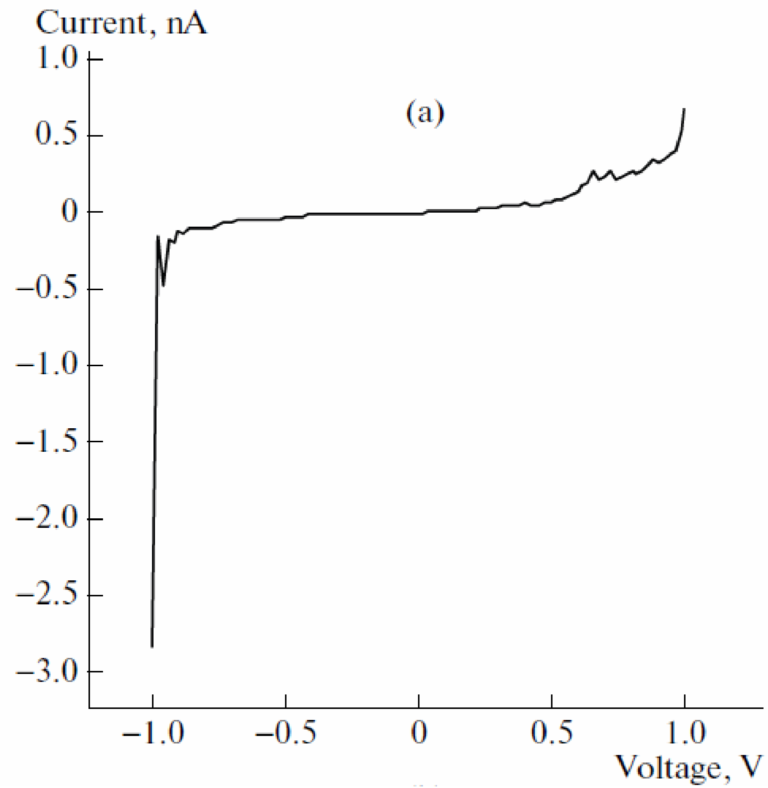
The rectification ratio is greater than 10^2 at ±0.5 V, implying a reasonable p-n junction

Efficiency *vs* NWs array properties

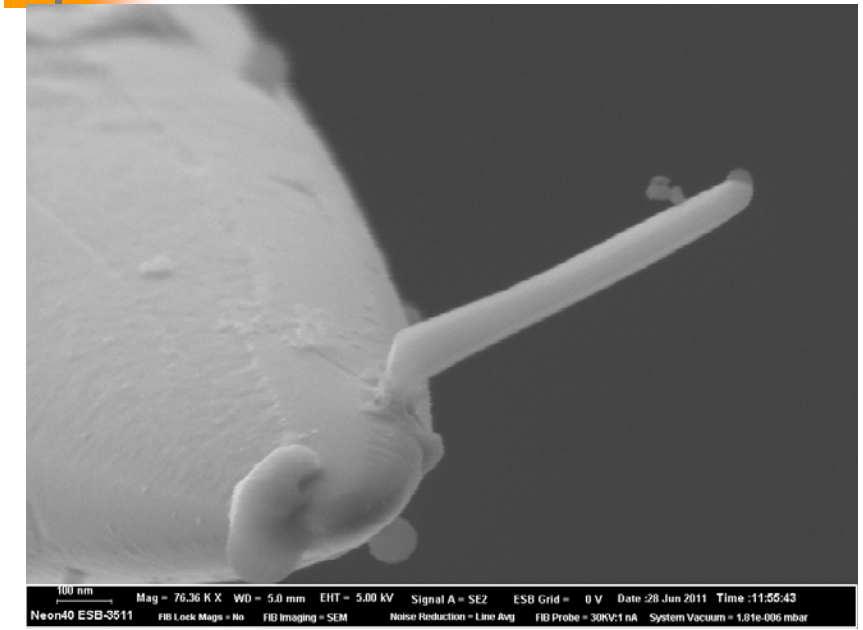
T_s, C	NWs surface density, cm^{-2}	NWs height, mkm	Conversion efficiency, % (FF, %)
520	$1*10^9$	1.7	0.08 (29)
535	$1*10^9$	1.9	0.27 (27)
550	$1*10^9$	2.2	1.65 (25)
580	$5*10^8$	1.7	0.29 (28)

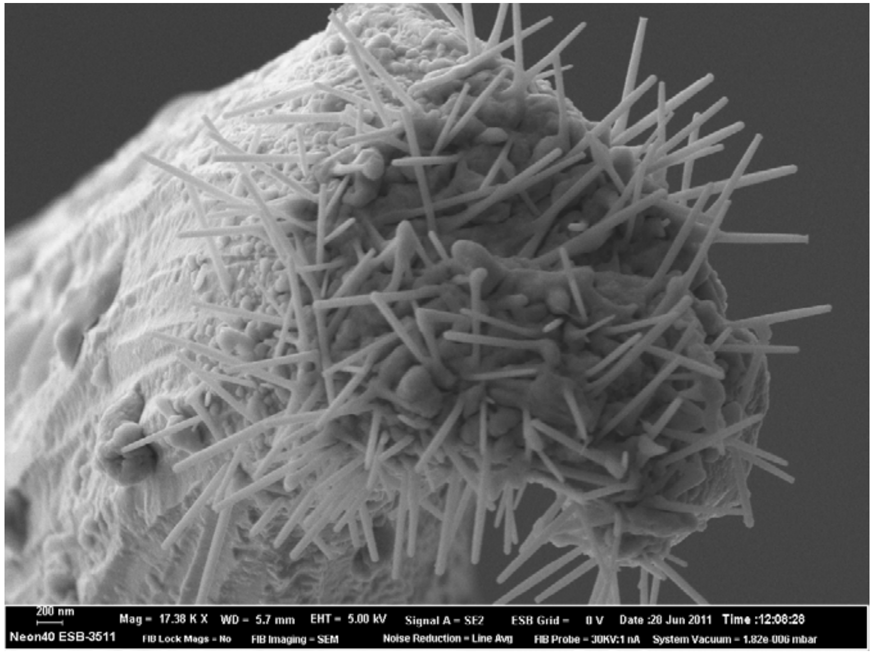
Single NW grown on tungsten tip

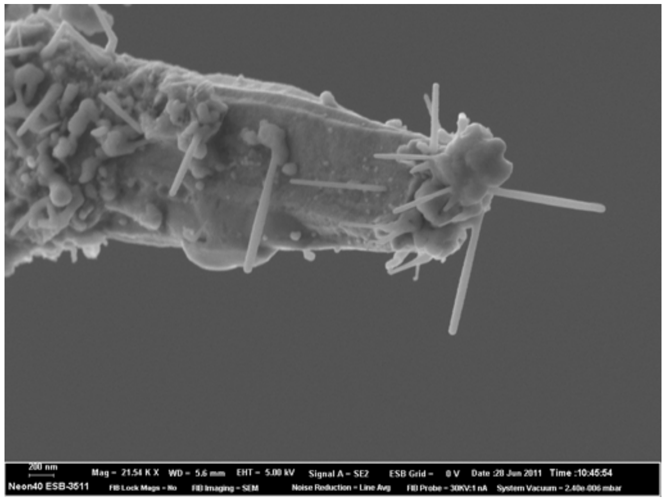


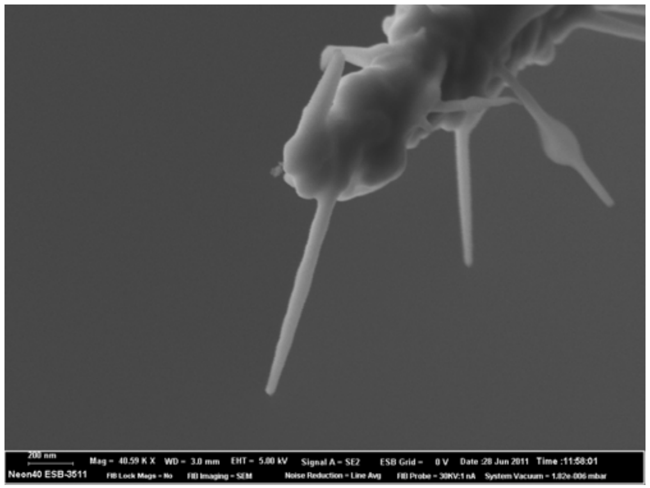


Self catalysed GaAs NW on a STM W tip

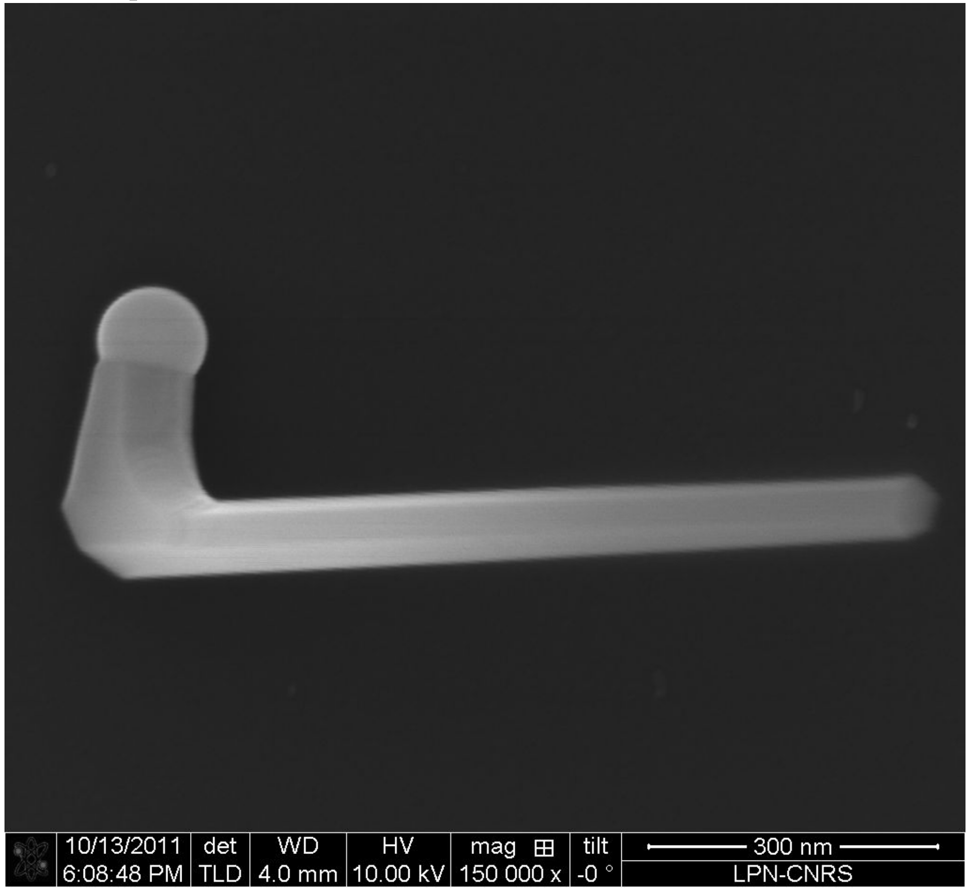


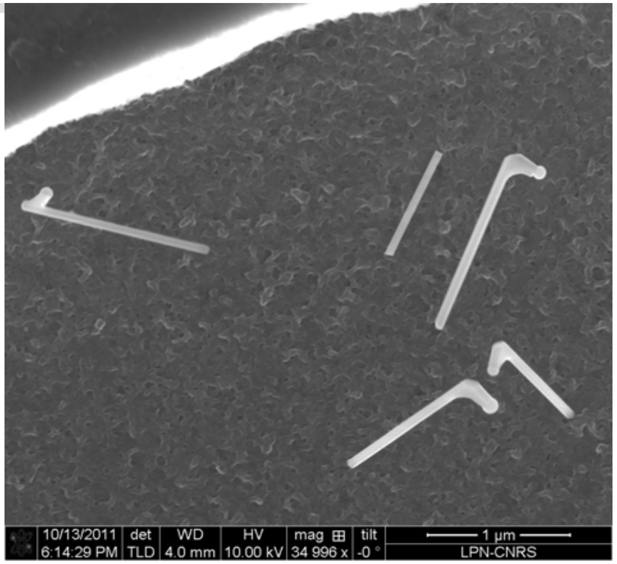


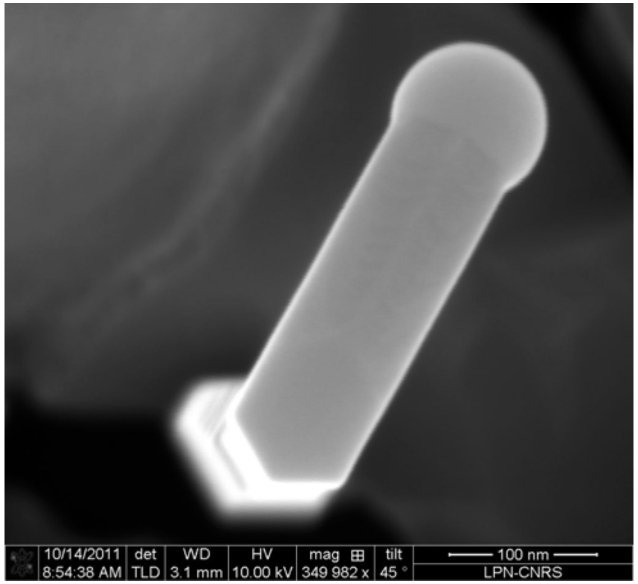




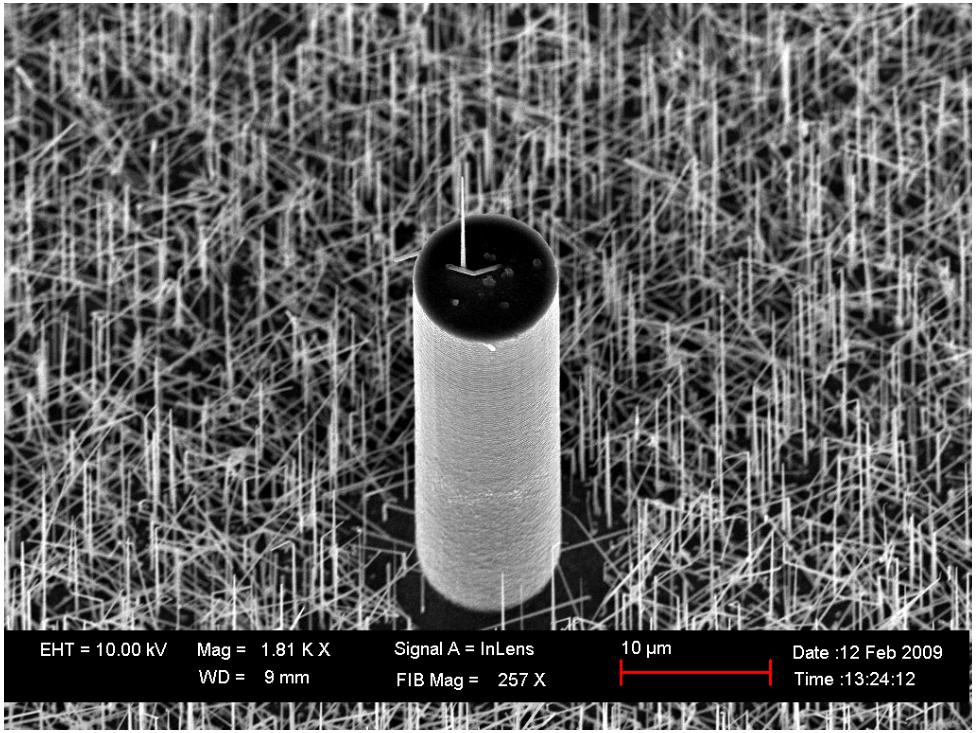
NWs with controllable change of the growth direction

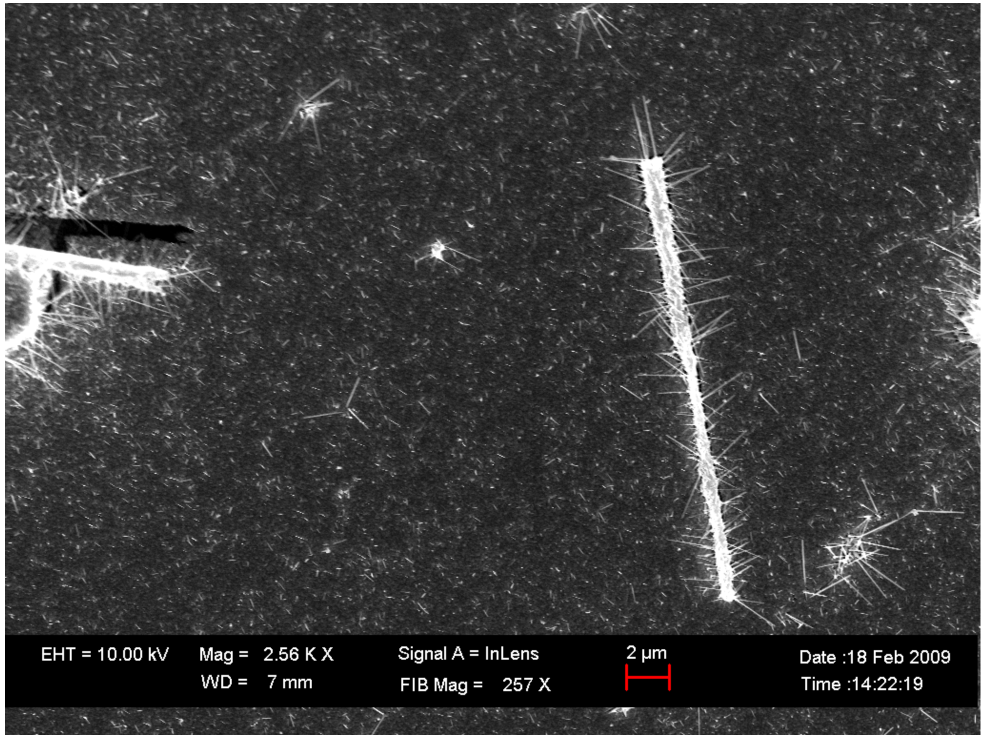






GaAs NWs grown on micro pillars






Спасибо за внимание!