Semiconductor Nanowires: Opportunities & Challenges

Albert Davydov   Metallurgy Division

Outline:

- NW research in our Division
- Nano-LEDs case study:
  - Design: Core-shell vs. Axial Heterostructures
  - Growth: VLS vs. VS (nucleation, phase diagrams, defects)
  - Quantum Discs: InGaN phase separation, strain, defects
- Summary

Acknowledgement

Denis Tsvetkov, Sergiy Krylyuk – GaN and Si CVD growth

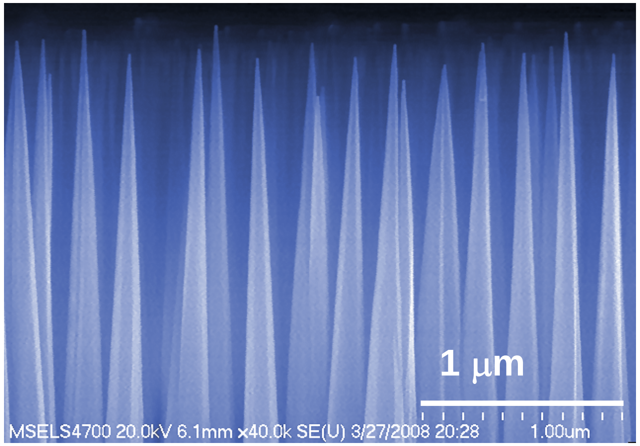
Kris Bertness (Boulder) – GaN MBE growth

Igor Levin, Vladimir Oleshko – TEM

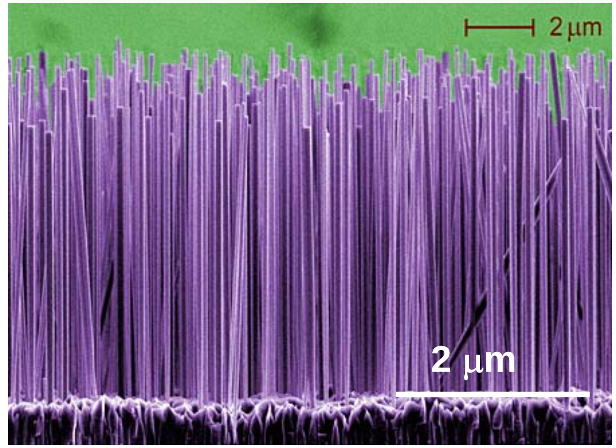
Abhishek Motayed – nanodevices

John Schlager, Norman Sanford (Boulder) – opt. spectroscopy

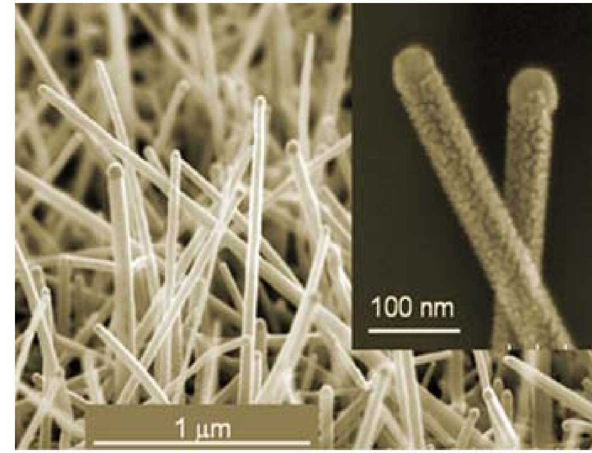
Semiconductor NW Growth at NIST



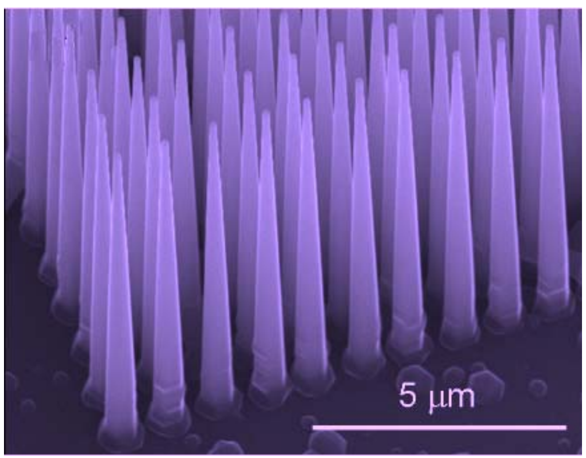
AlN by HVPE (D. Tsvetkov)



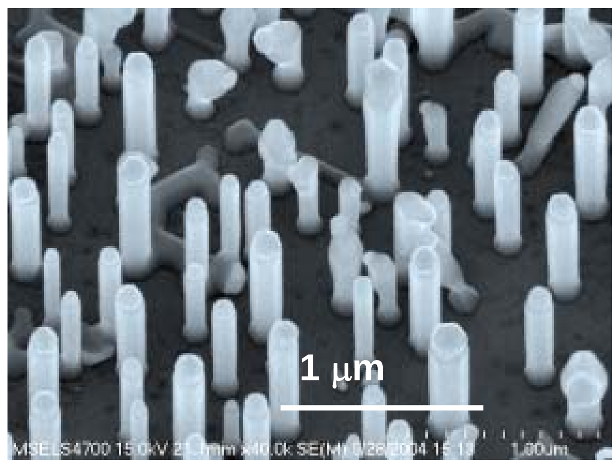
GaN by MBE (K. Bertness)



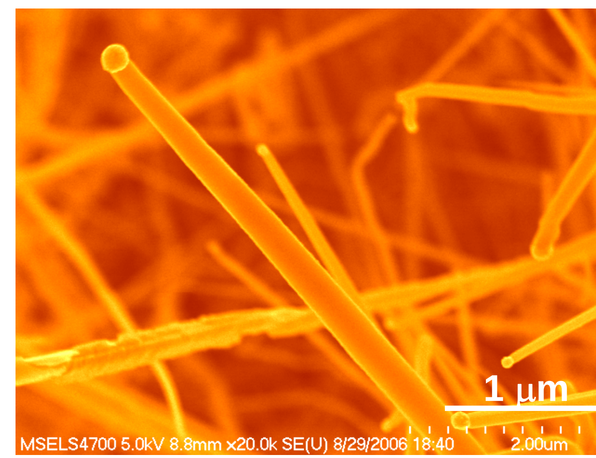
GaN by HVPE (D. Tsvetkov)



Si by CVD (S. Krylyuk)



ZnO by CVD (B. Nikoobakht)

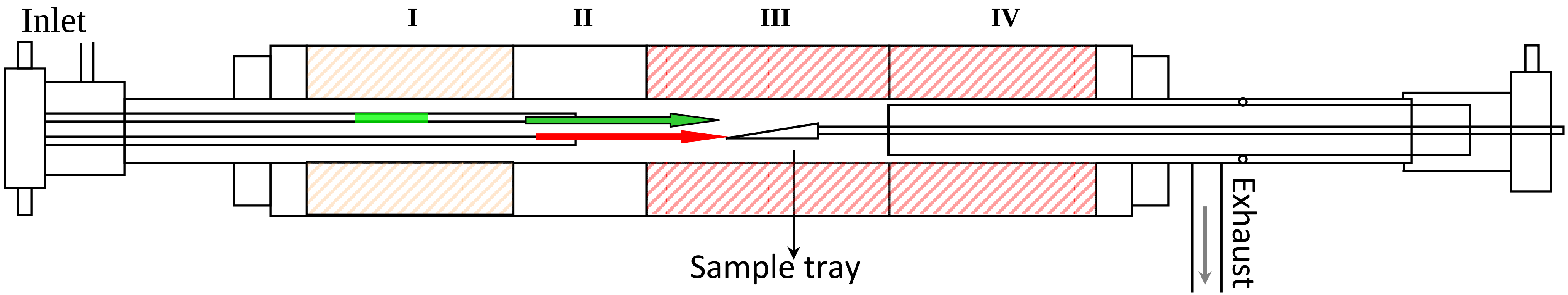


SiC by sublimation (S. Sundaresan)

Key Issues:

- uncontrolled NW dimensions, orientation and defects
- lack of metrology: new measurements & models needed

HVPE Systems for GaN and Si NW Growth



Halide Vapor Phase Epitaxy: $Al^s + HCl^v \rightarrow AlCl_x^v$ + NH_3^v → AlN^s

System Features:

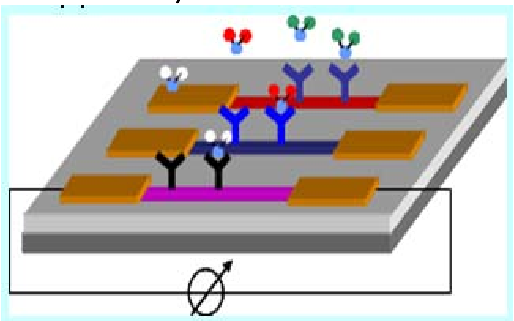
- Variable pressure (3 mTorr – 760 Torr)
- Fast growth interruption
- Growth of alloys (AlGaN, InGaN) and heterostructures (GaN/AlN, GaN/AlGaN etc.)
- *In situ* n- and p- doping

T_g=700°C - 1050°C; P=450 torr;

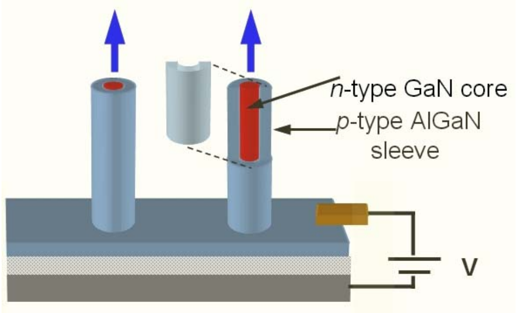
t = 20s – 90 min; V/III = 20-30 (VS) & 0.3-1 (VLS)

Motivation: NWs for Optoelectronics, PV, batteries, sensors

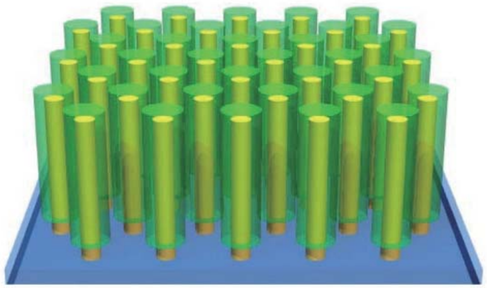
Bio-/chemi- sensors



LEDs, lasers, detectors

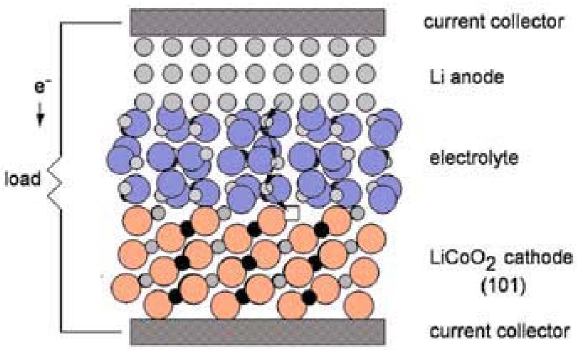


Photovoltaics

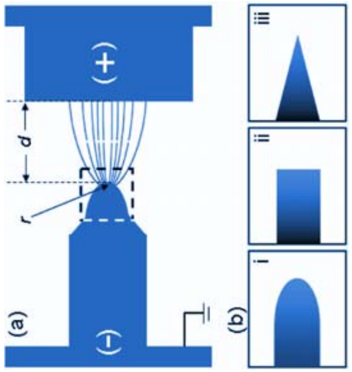


[09Fan]

Li-ion batteries



Field-emitters



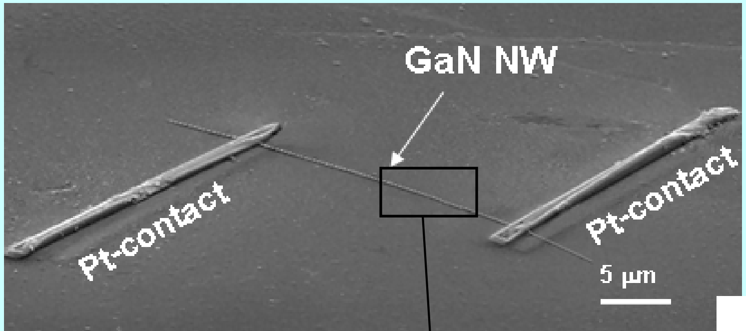
[08Fan]

Advantages of NW arrays over thin-film devices:

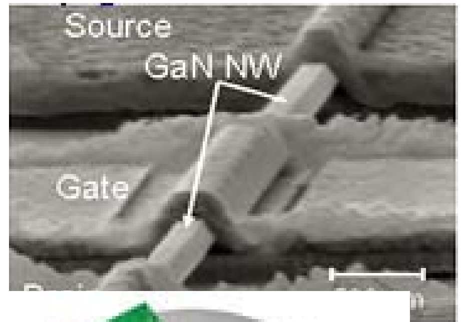
- high efficiency (no defects, high surface/volume ratio)
- high selectivity (multiple materials and/or devices on a single chip)
- new types of devices (quantization effects)

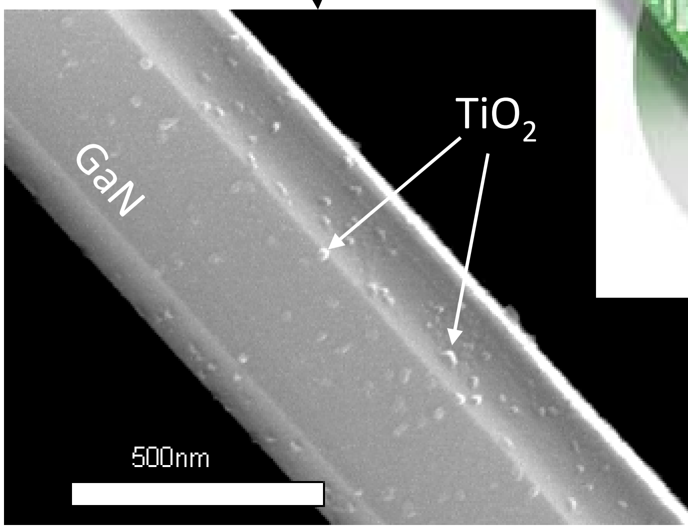
GaN NW Gas Sensors (Chemiresistors)

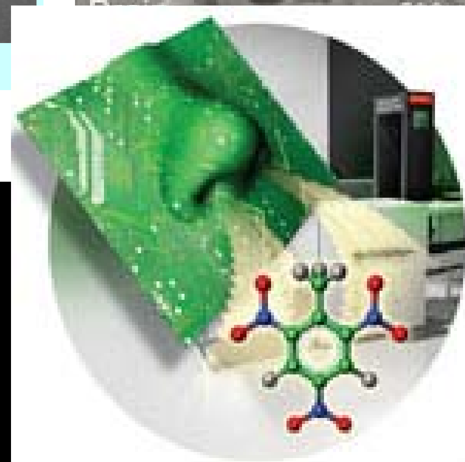
Abhishek Motayed, Geetha Aluri

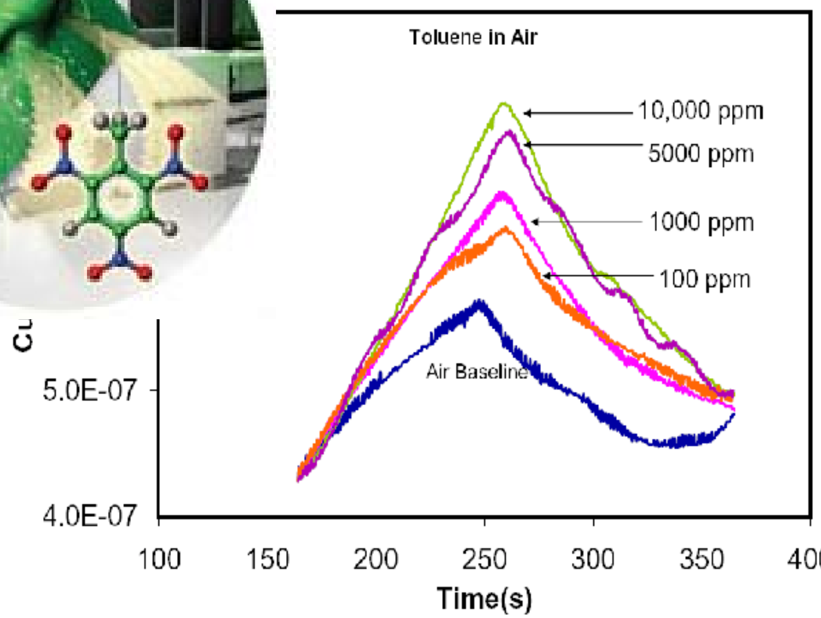


A. Motayed et al., JAP 100, 24306 (2006)

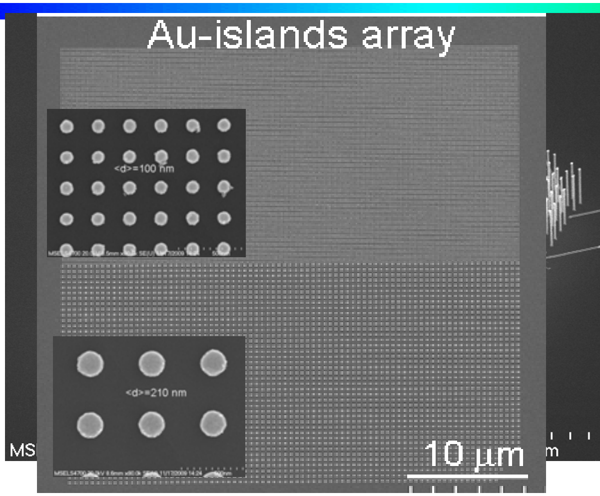


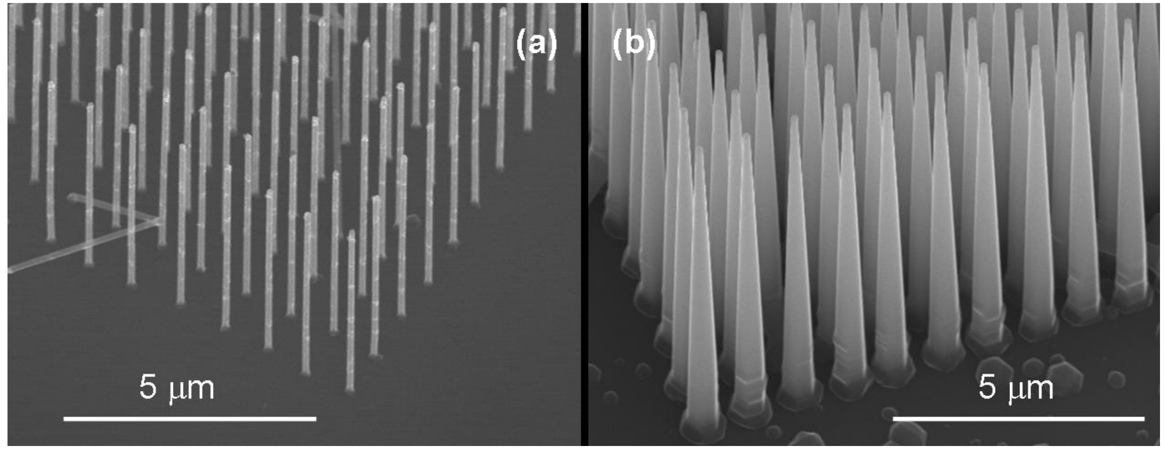


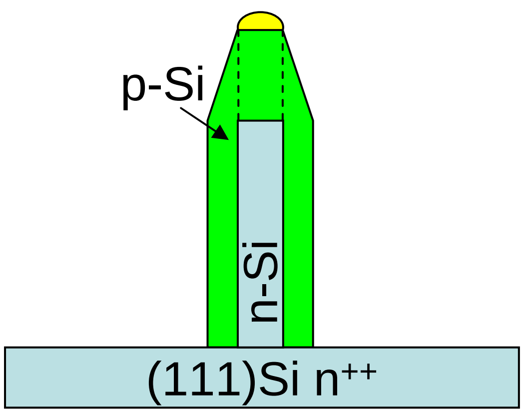




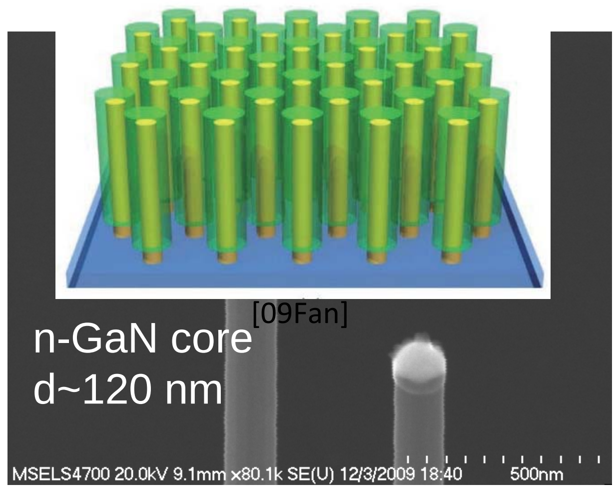
Si NW Photovoltaics

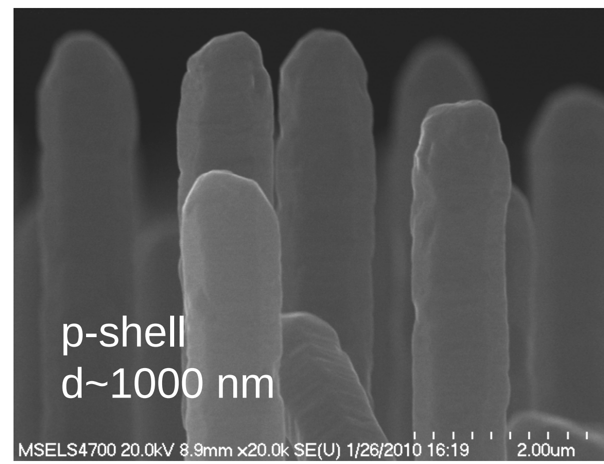




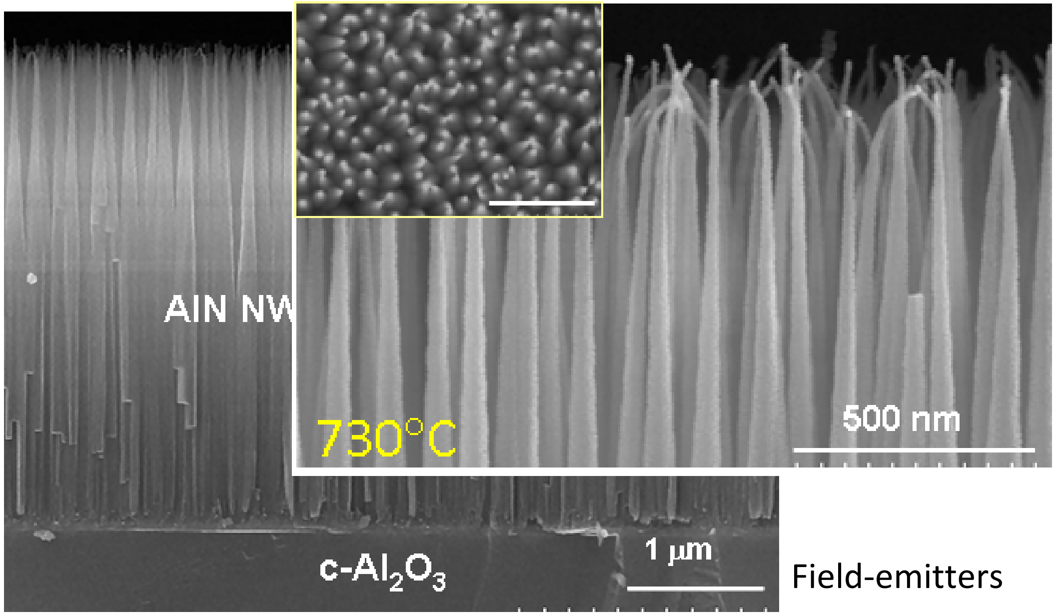


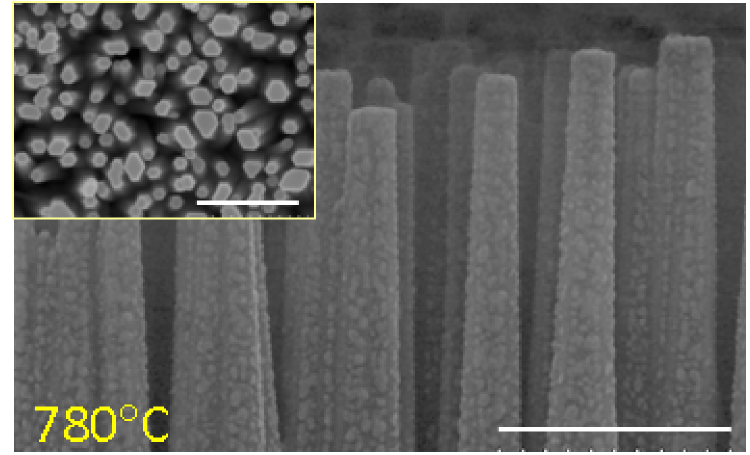
Photovoltaics





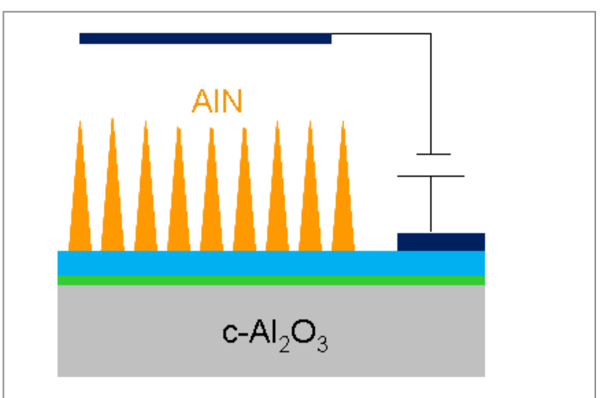
AlN and Si NW Field-Emitters

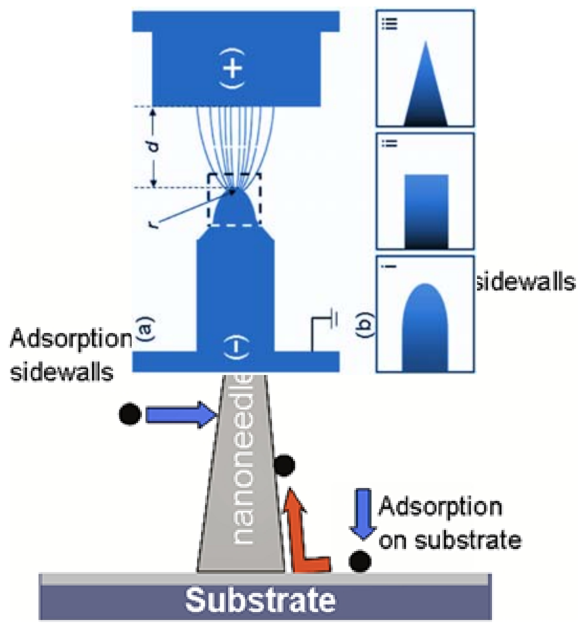




Field-emitters

Schematic AlN NW Field-Emitter



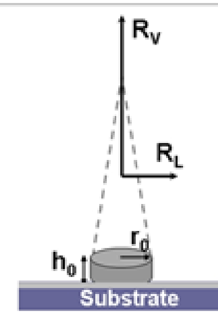


Cone height: $\mathbf{h = h_0 + R_V \cdot t}$

Cone radius: $\mathbf{r = r_0 + R_L \cdot t}$

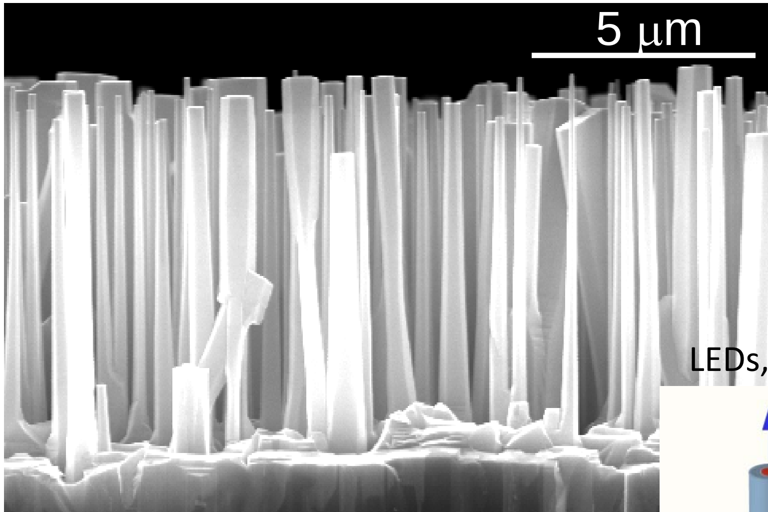
$\mathbf{h_0} = \mathbf{r_0} \sim 2$ nm

$\mathbf{R_V} \sim 200$ nm/min; $\mathbf{R_L} \sim 2$ nm/min

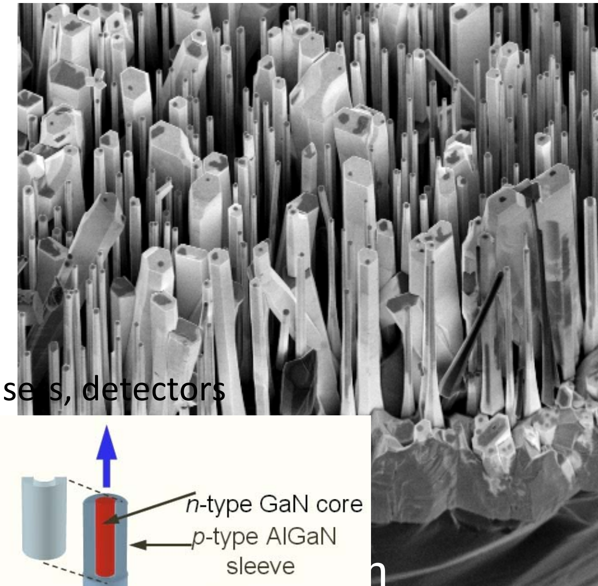


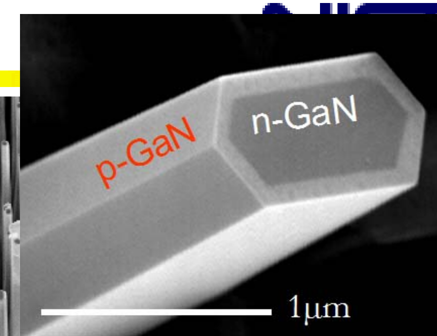
n/p Core-Shell GaN NWs for LEDs

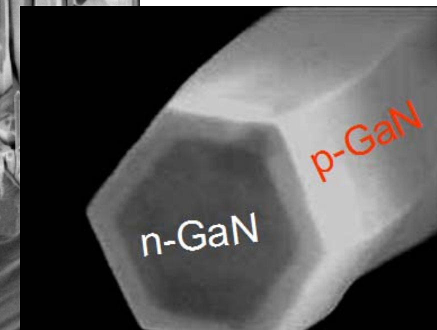
IMS program w/Boulder



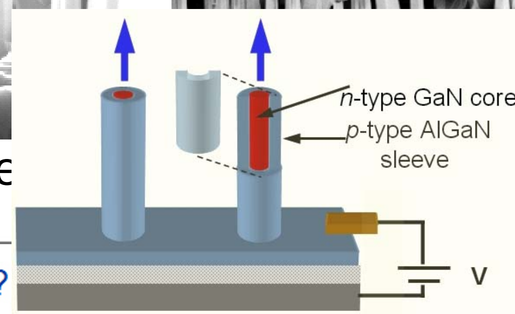
HVPE p-shells over n-core

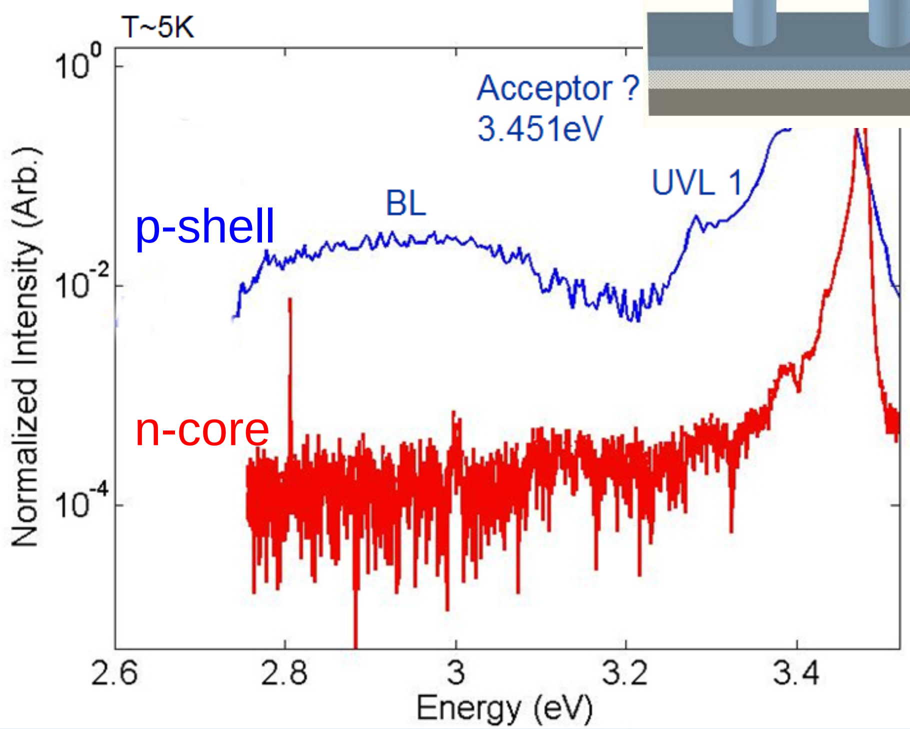


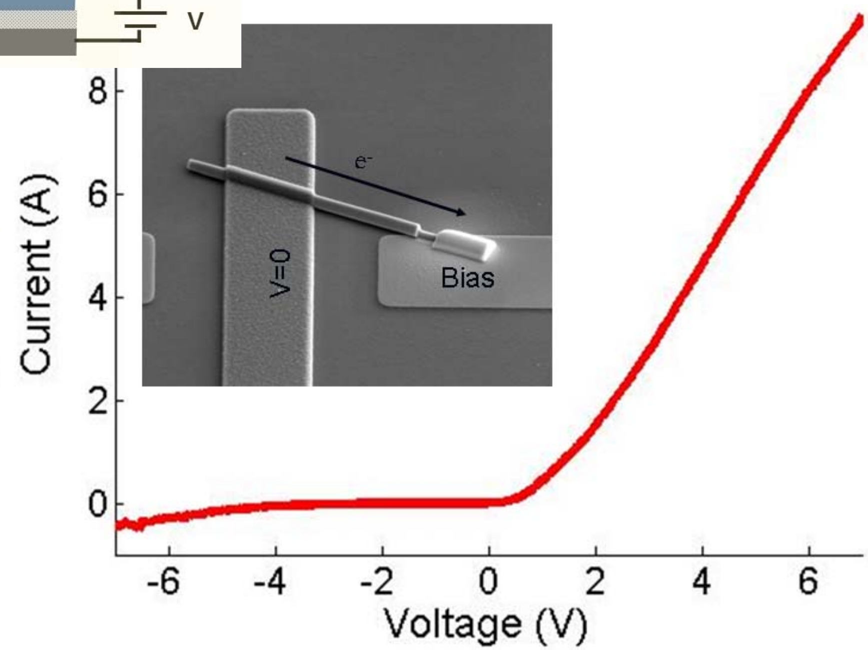




LEDs, lasers, detectors

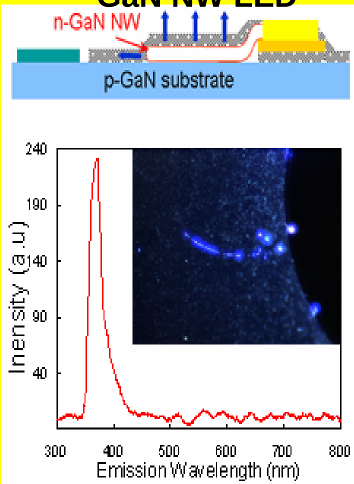






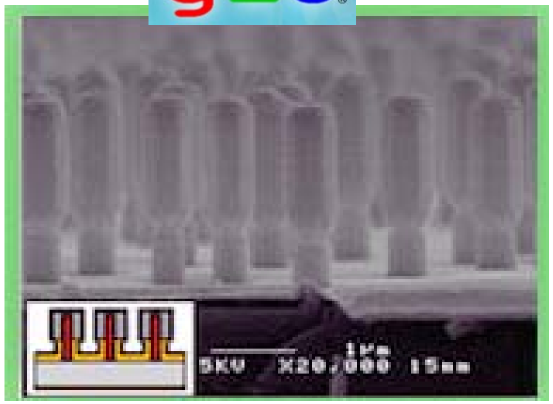
GaN NW LEDs

GaN NW LED

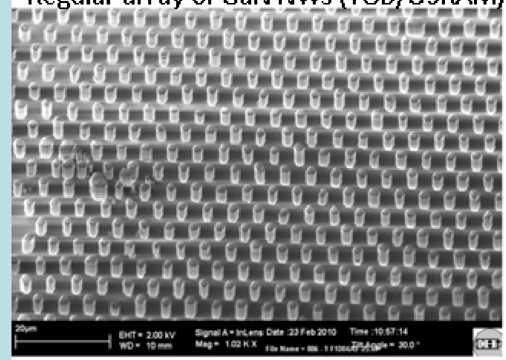


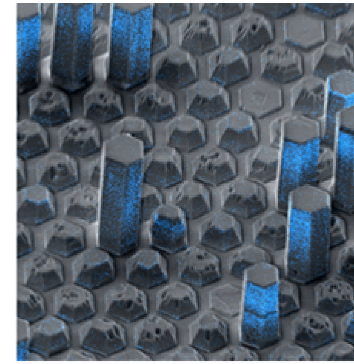
APL (2007) 90, 183120

glō

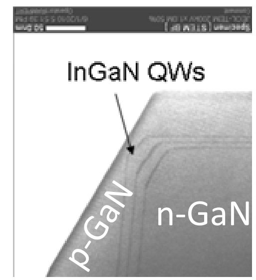


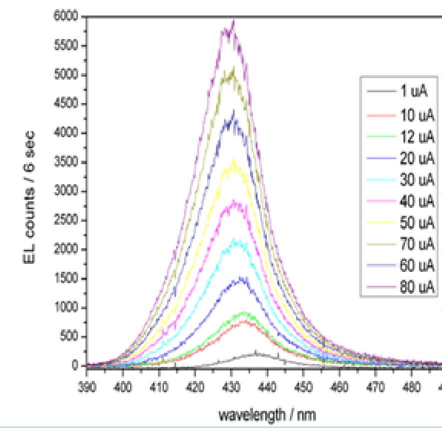
Regular array of GaN NWs (TUB/OSRAM)





emission wavelength 400 nm

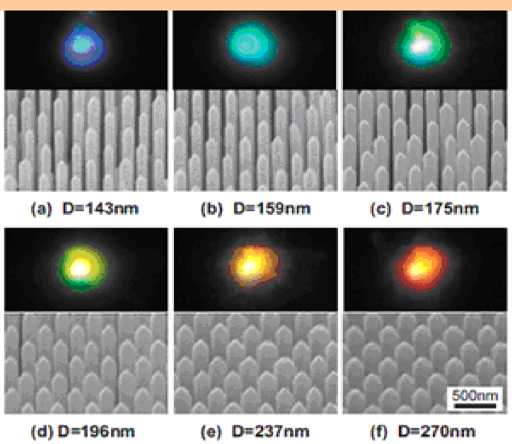




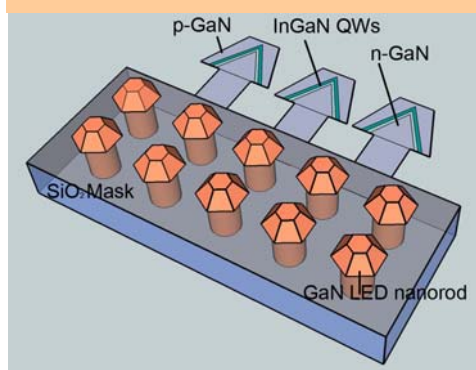
Technische Universität Braunschweig

OSRAM Opto Semiconductors

PL from InGaN/GaN NWs [10Kishino]

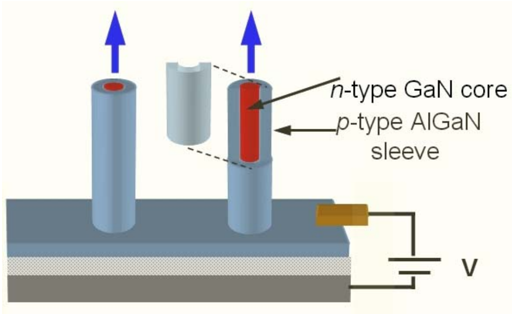


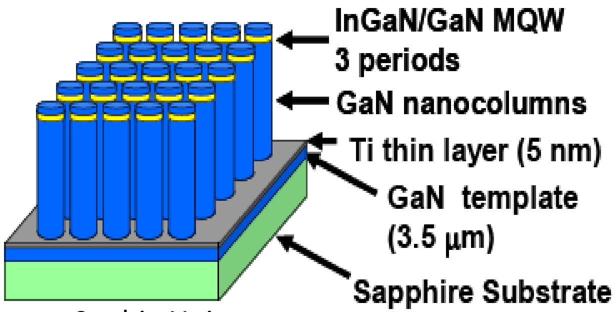
Schematic NW array LED [10Kim]



GaN NW LEDs: case study

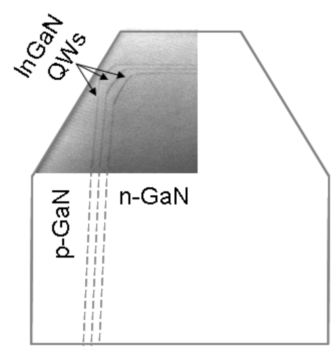
LEDs, lasers, detectors



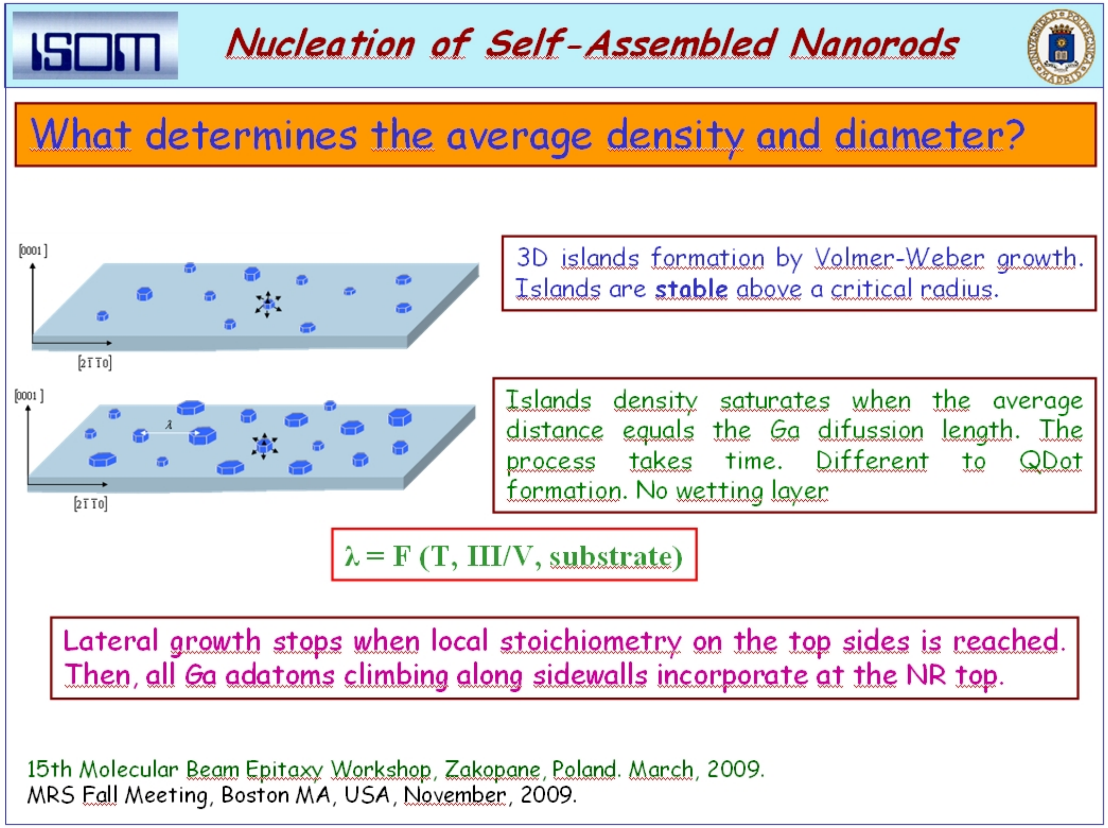


Sophia Univ.

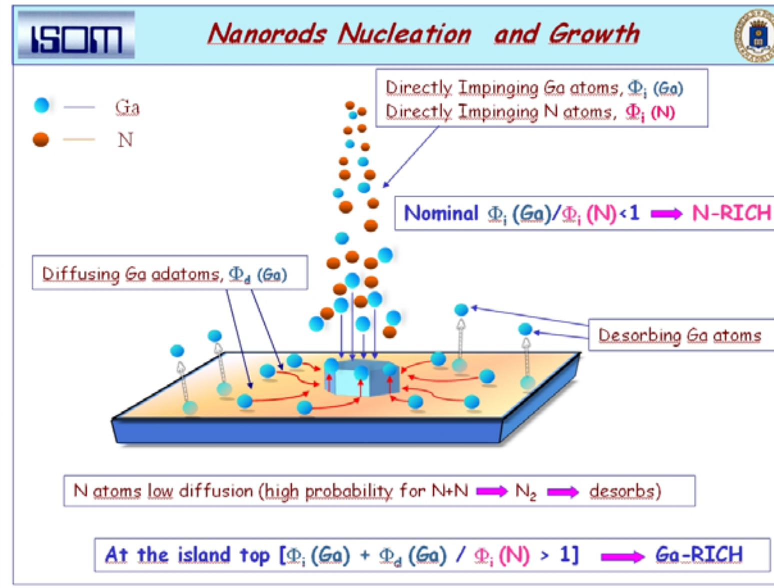
- Design: Core-shell vs. Axial Heterostructures
- Growth: VLS vs. VS
  - phase diagrams; nucleation, defect formation, competition
- Quantum Disks:
  - strain, InGaN phase separation, defects



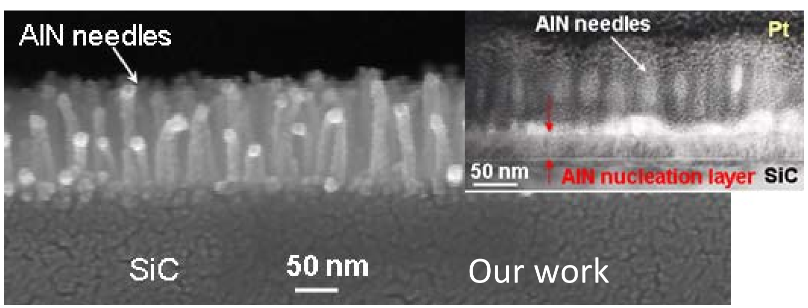
VS Growth Status: well understood?



Courtesy Enrique Colleja



M. Knelangen et al., Nanotechnology 21, 245705 (2010)
V. Consonni et al, Phys. Rev. B81, 085310 (2010)



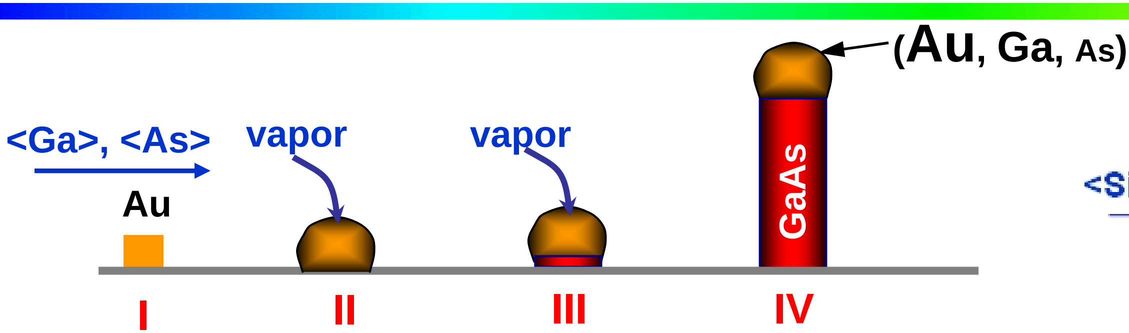

PHYSICAL REVIEW B 79, 241308(R) (2009)

Large anisotropic adatom kinetics on nonpolar GaN surfaces: Consequences for surface morphologies and nanowire growth

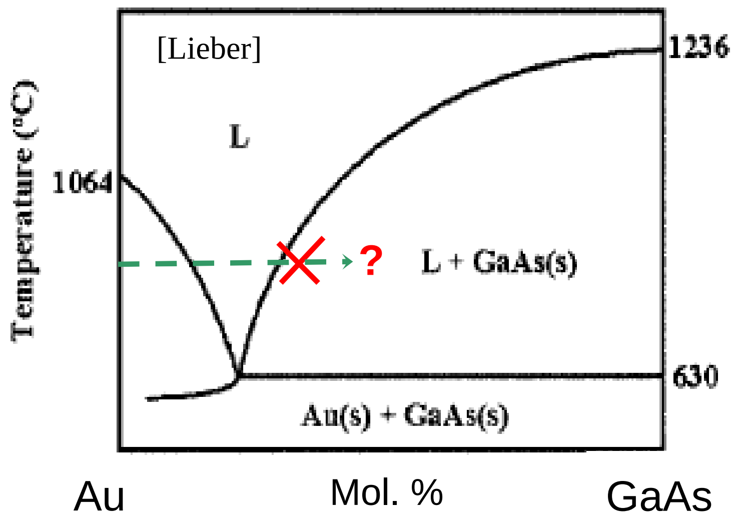
Liverios Lymperakis* and Jörg Neugebauer

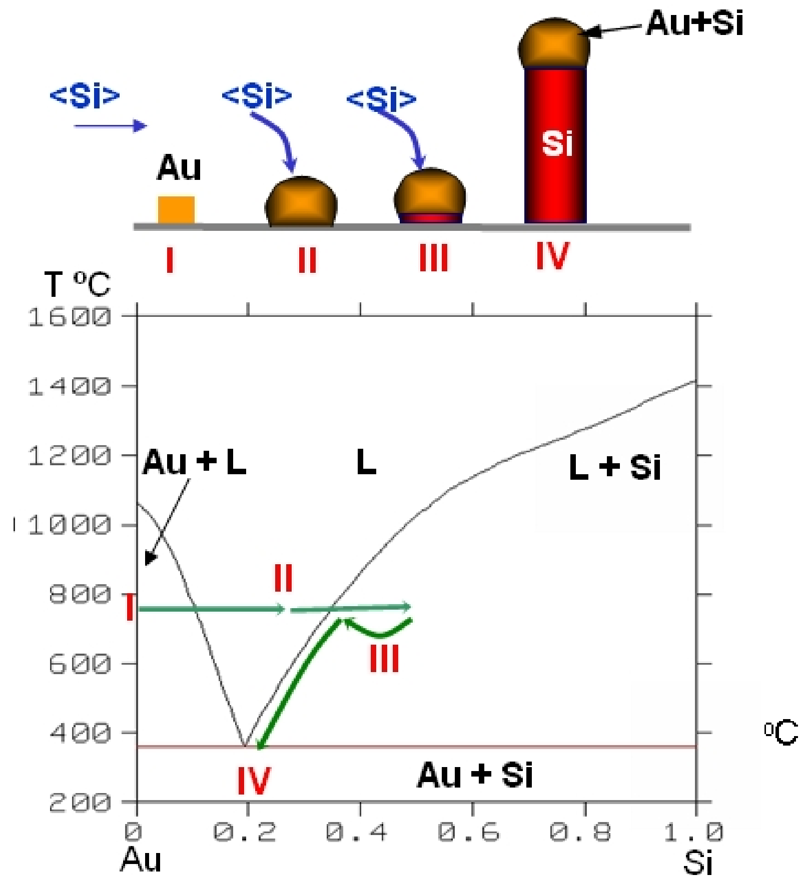
- Spontaneous formation of wetting layer: not understood yet (no modeling)?

VLS status: misuse of phase diagrams for compounds



Does VLS path lie in the Au-GaAs binary?





- Growth path can not be traced on the Au-GaAs section:

  Not possible to:
  - define growth temperature or trace compositions
  - choose metal for catalyst

Need ternary diagram!

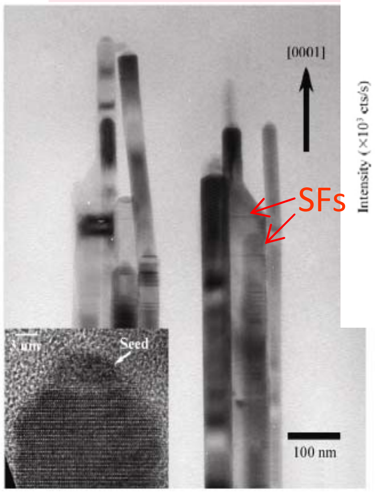
- Thermodynamic description of VLS growth for **compounds** is needed

Effect of VLS and VS Growth on Defects

Nano Res (2010) 3: 528–536
DOI 10.1007/s12274-010-0013-9
Research Article

Direct Comparison of Catalyst-Free and Catalyst-Induced GaN Nanowires

Caroline Chèze[1,†] (✉), Lutz Geelhaar[1,†], Oliver Brandt[1], Walter M. Weber[2,†], Henning Riechert[1,†], Steffen Münch[3], Ralph Rothemund[3], Stephan Reitzenstein[3], Alfred Forchel[3], Thomas Kehagias[4], Philomela Komninou[4], George P. Dimitrakopulos[4], and Theodoros Karakostas[4]



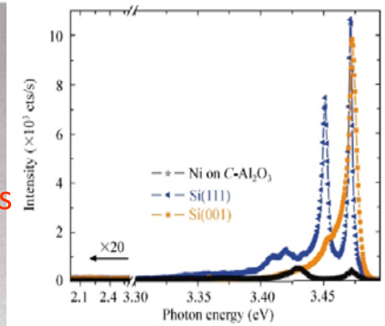
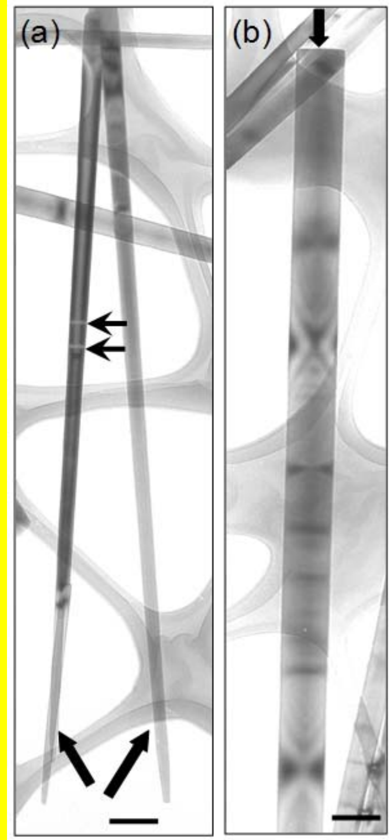
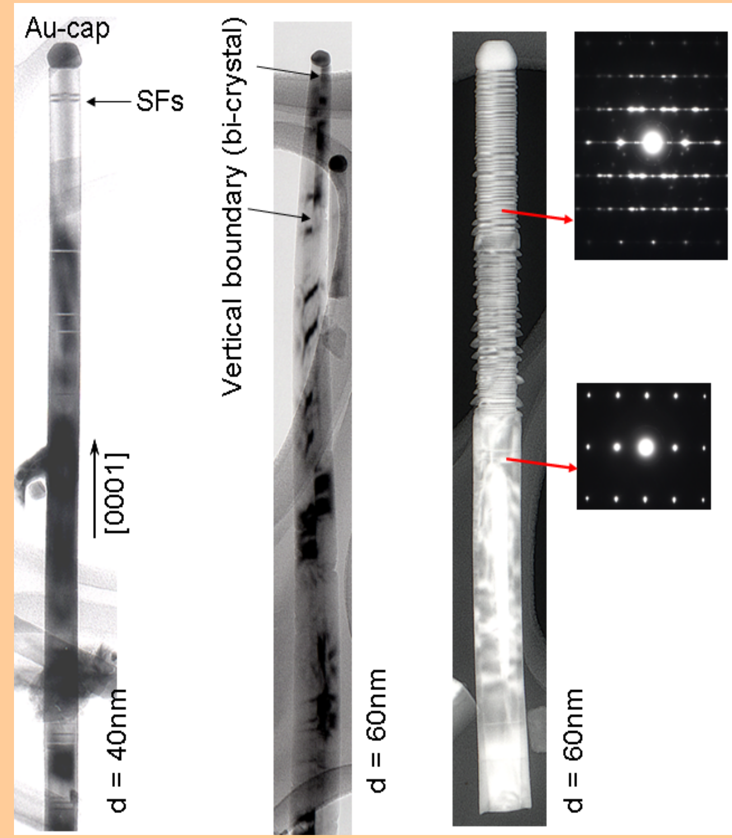


Figure 3 Cross-sectional TEM image along the ⟨11$\bar{2}$0⟩ zone axis of the catalyst-induced NWs showing basal SFs within the NWs. The inset depicts a high-resolution TEM image of the tip of a NW revealing the crystalline seed particle of the catalyst

VS growth (MBE) NIST



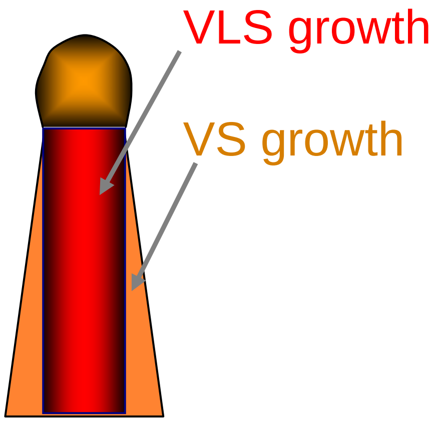
VLS growth (HVPE) NIST



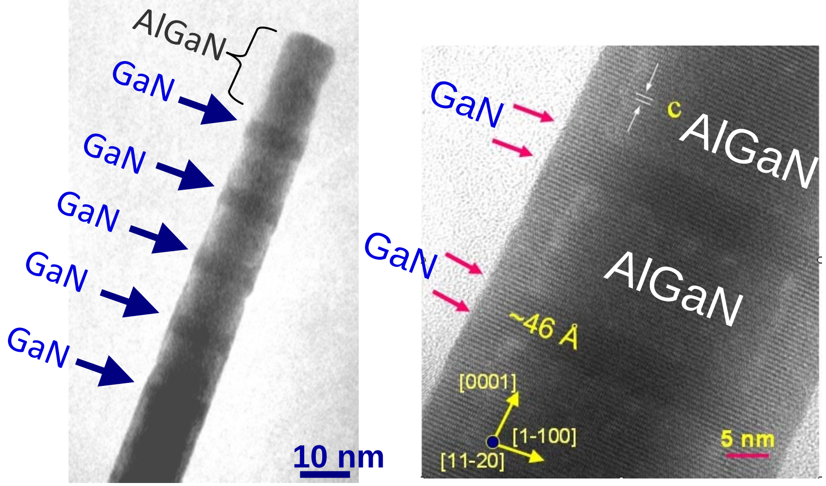
TEM: courtesy of Igor Levin

- Higher density of extended defects in VLS NWs: growth instabilities at the L/S interface?
- Contamination of NWs with catalyst (indirect evidence, PL): inside matrix or/and on sidewalls?

Competition of VS vs. VLS Growth



AlGaN/GaN QDs (Courtesy E. Calleja)



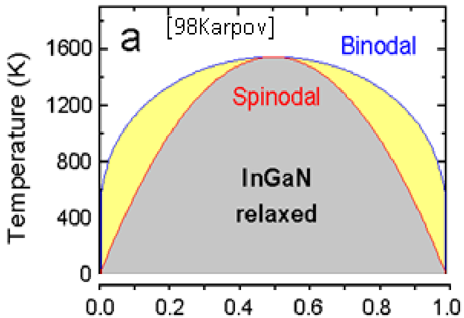
J. Ristic et al., Phys. Rev. B68, 125305 (2003)

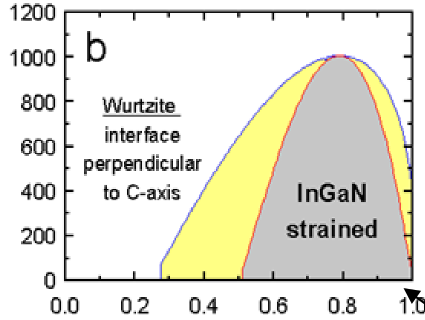
Complications:

- Heterostructure integrity
- Doping inhomogeneity
- Unified model to explain morphology?

Quantum Discs (QDs): InGaN phase separation, strain, defects

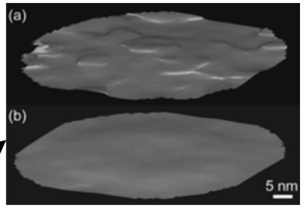
Effect of biaxial strain during layer growth



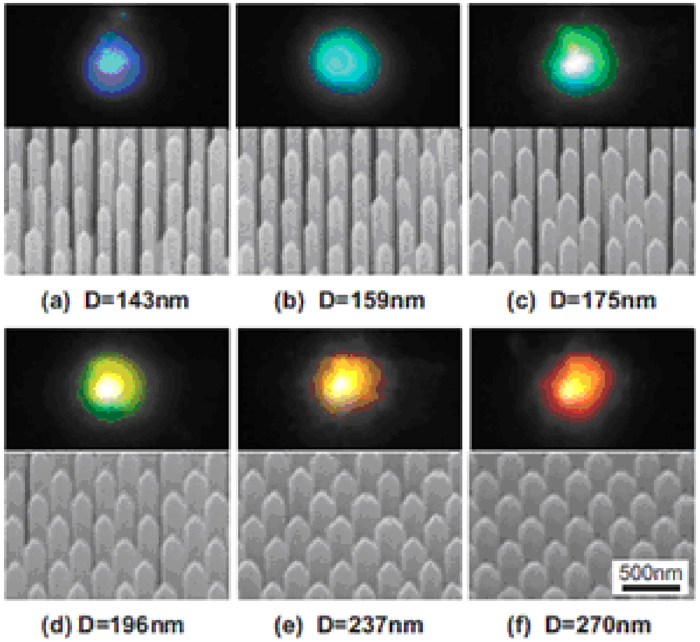


- Higher In incorporation due to residual stress in QDs

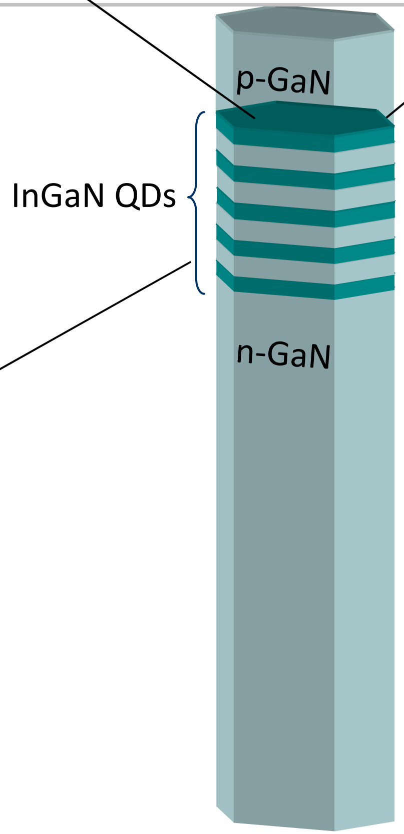
[10 Oliver]



[10Kishino]



In incorporation – function of NW diameter!



[09 Gu]

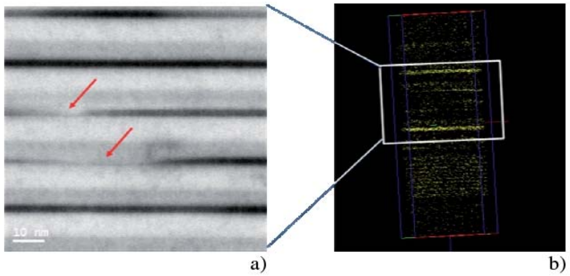


Figure 2 (online colour at: www.pss-rapid.com) (a) STEM-BF image of InGaN based MQWs and (b) 3D atom map obtained from the APT analysis, showing the discontinuity of the InGaN active layers.

- QD inhomogeneity – strain related?
- Charge localization effects in InGaN NWs

Summary

Modeling opportunities:

- VS growth:
  - understanding wetting layer formation (Stranski-Krastanov?)
  - defect formation
- VLS growth:
  - thermodynamic description of ternary systems
  - combine with VS model
  - explain NW morphologies and defects
- Core-shell and axial heterostructures:
  - strain and its relaxation – effect on morphology and composition
  - doping issues
- Surface states and their effect on opto/electronic properties