# Nanoscale Imaging and Illumination of Semiconductor Nanowires

**Lincoln J. Lauhon**

Department of Materials Science and Engineering

Materials Research Center

NORTHWESTERN
UNIVERSITY

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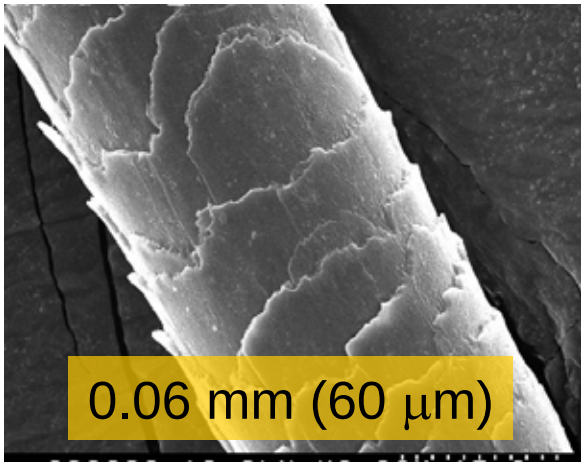
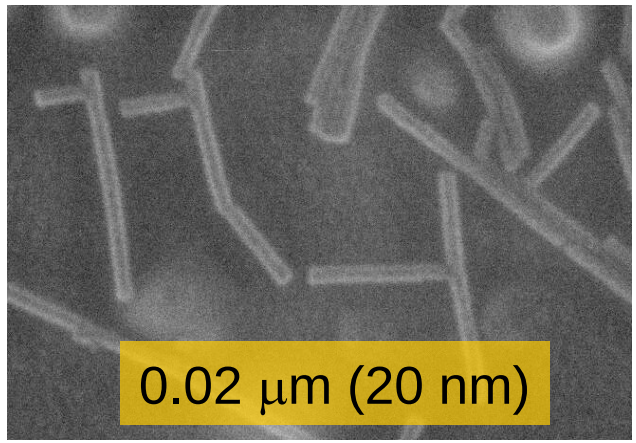
# Nanomaterials

***How small is NANO?***

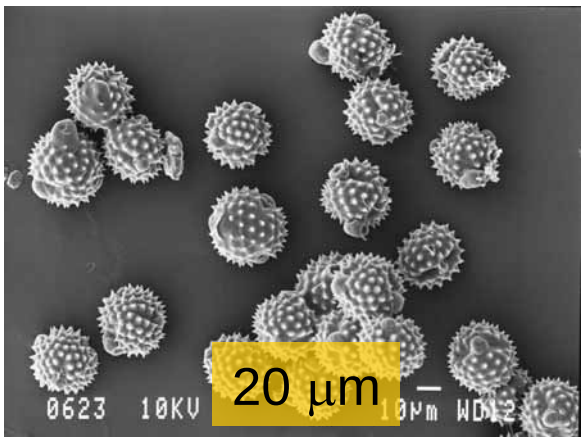
***human hair***



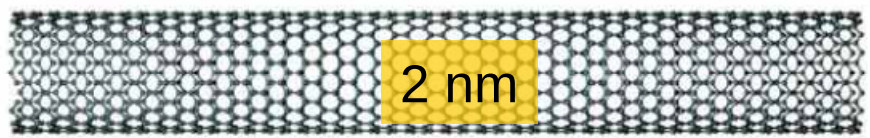

***virus***



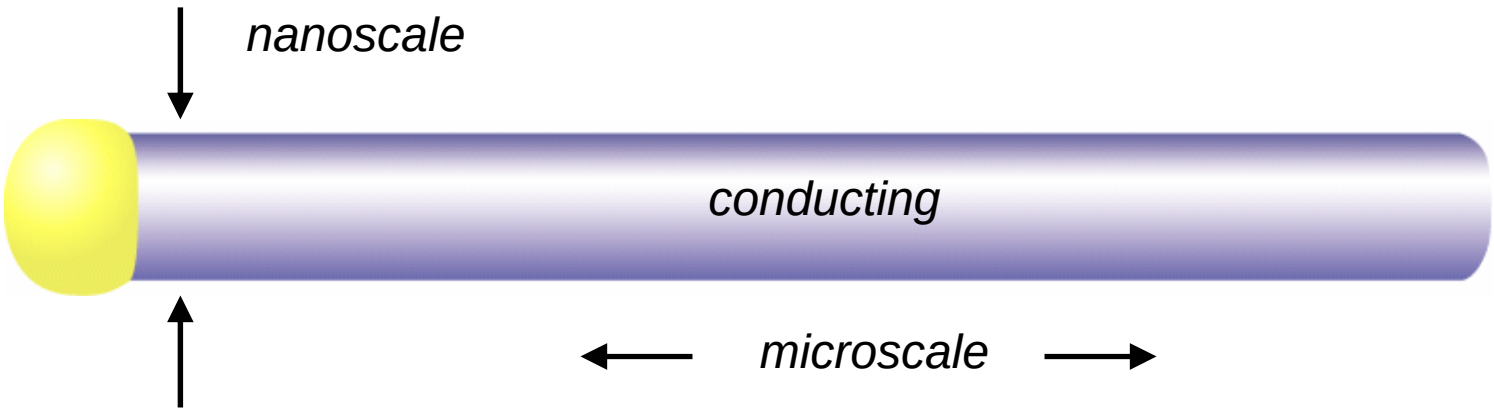

***pollen grain***




***carbon nanotube***



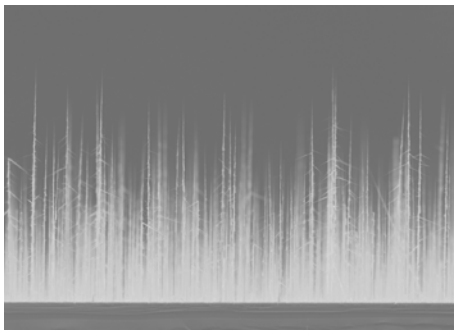
# What are Nanowires?

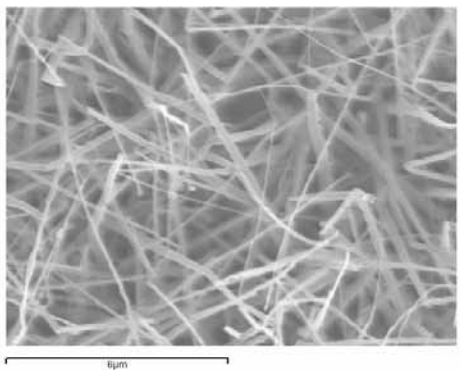



- Nanoscale diameters
- Microns in length
- Interesting electrical properties

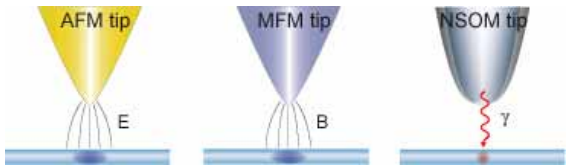
# Semiconductor Nanowire Research

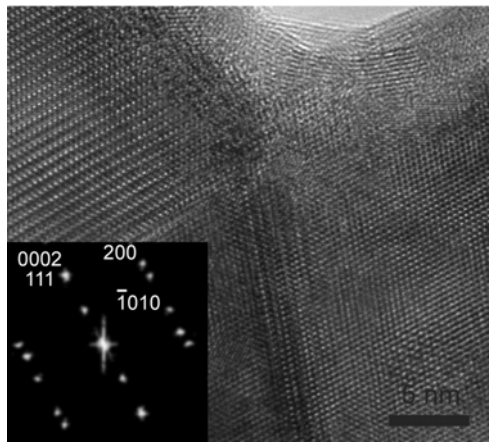
## Nanowire Synthesis



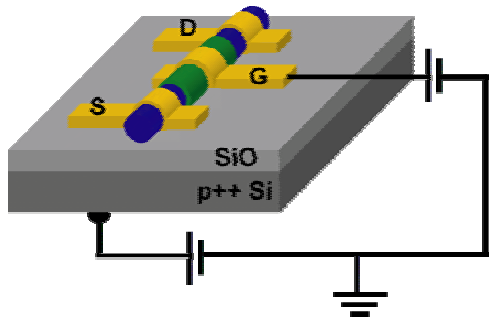


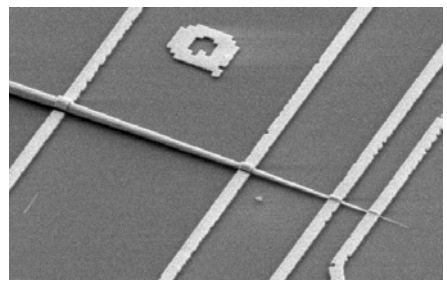
## Nanoscale Characterization




## Nanowire Devices



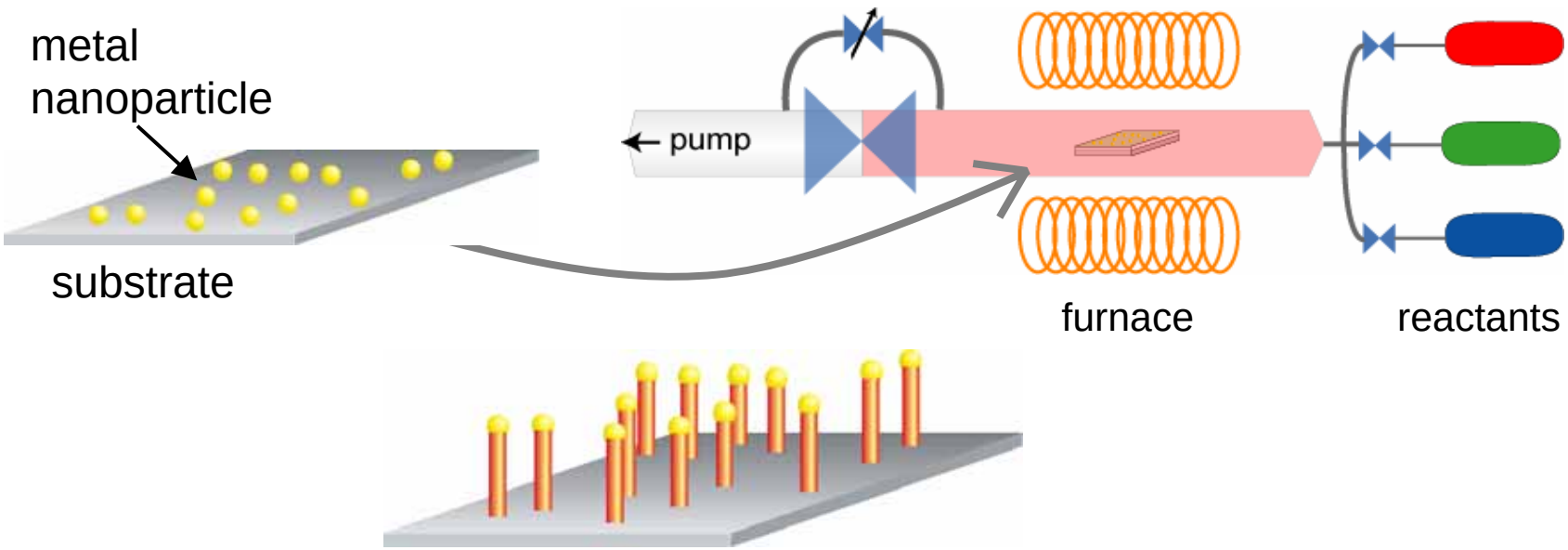
*New materials* + *New properties* → *New technology*

# Nanowire Imaging and Illumination

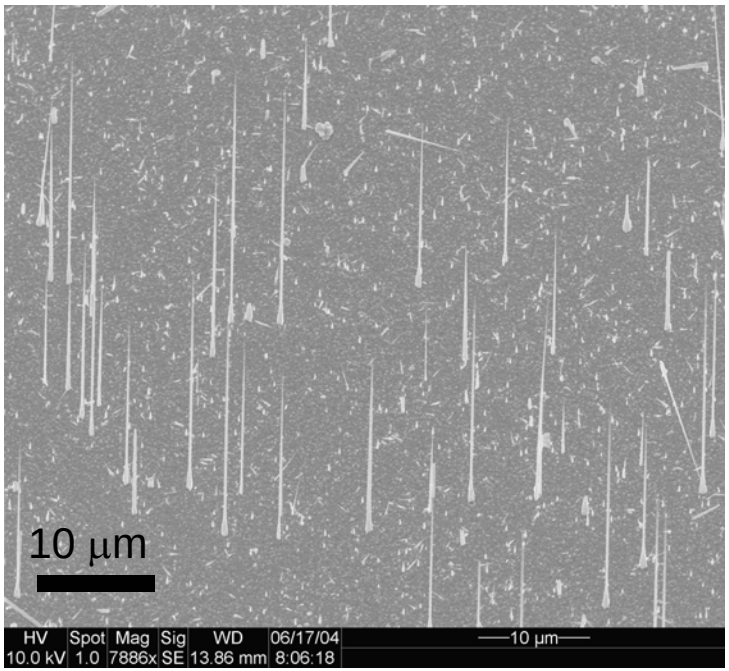
*For today's presentation...*

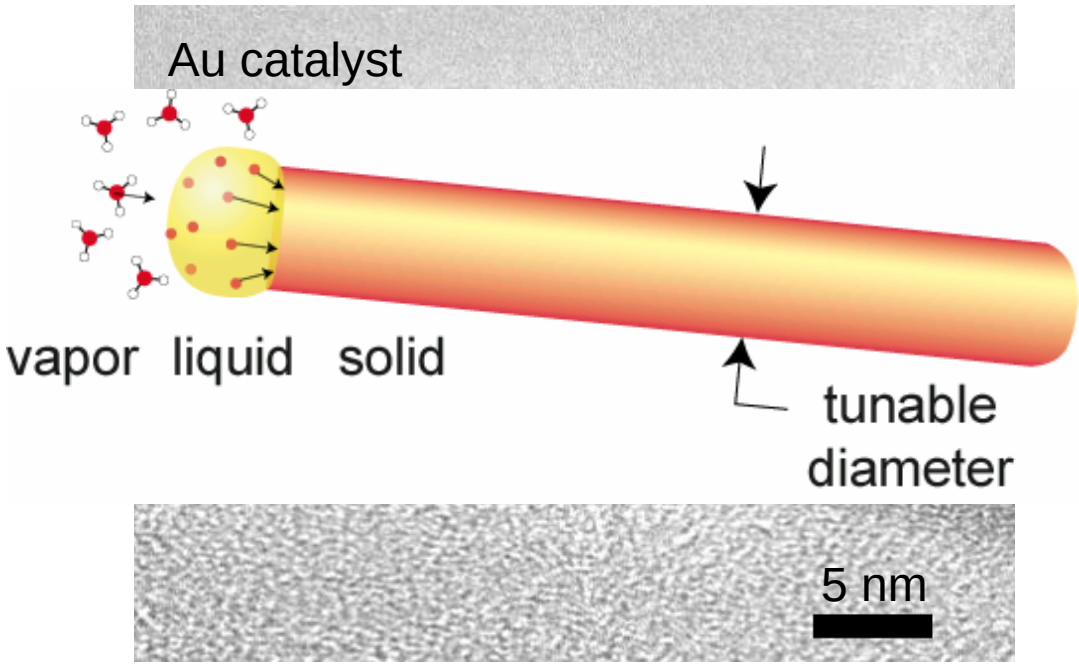
- Making small things (*synthesis*)
- Visualizing nanoscale structure (*imaging*)
- Measuring properties at nanoscale (*illumination*)

# Nanowire Synthesis

# InAs Nanowire Growth

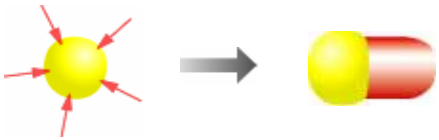


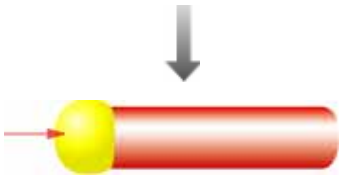

InAs-NW on GaAs(111)

Au-catalyzed InAs-NW

# Nanowire Heterostructures



1-d growth nucleation



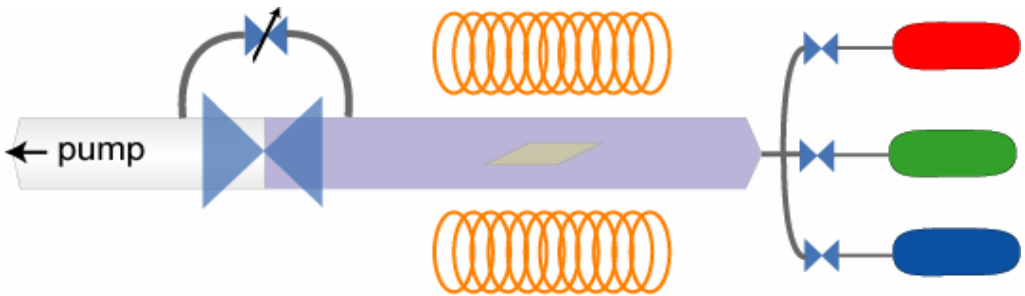
VLS (axial) growth

VLS

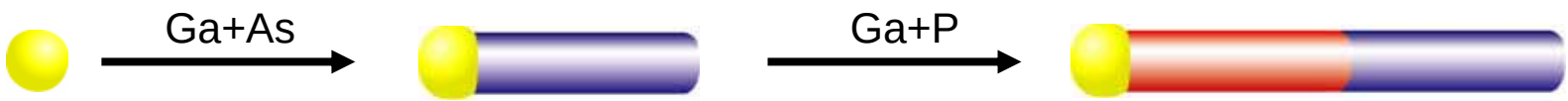
axial heterojunction

VS

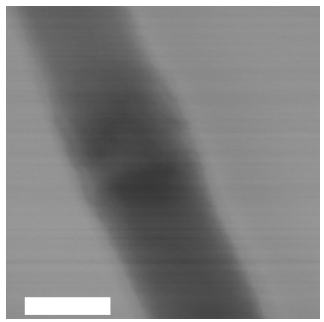
core-shell structure



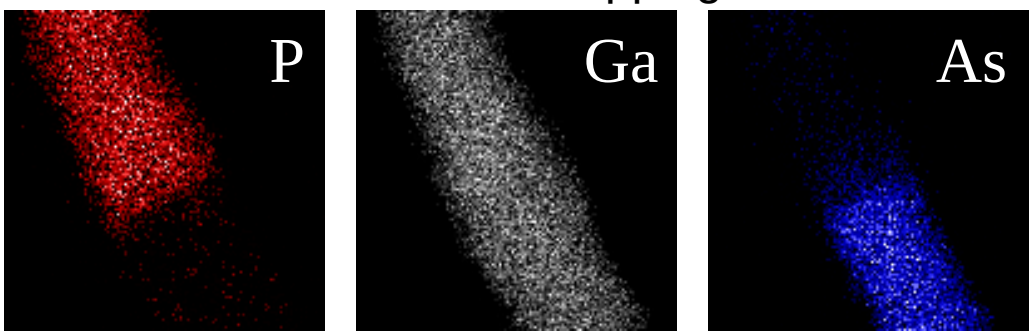
# Intrawire Heterojunction



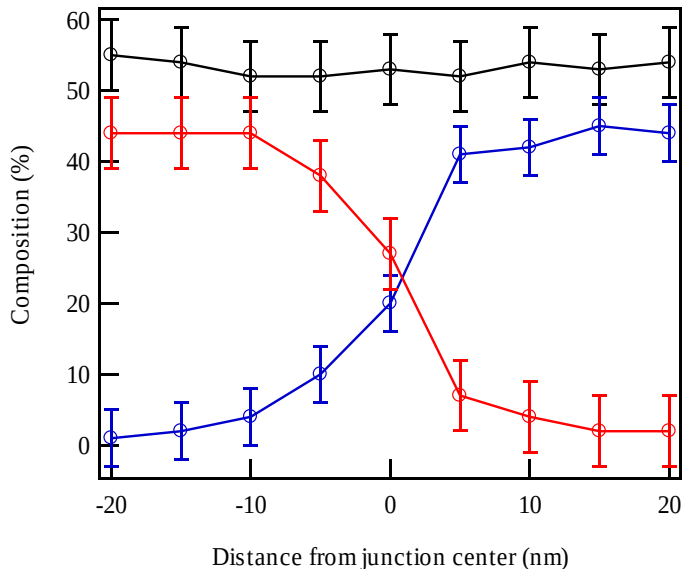

TEM Image



Elemental Mapping

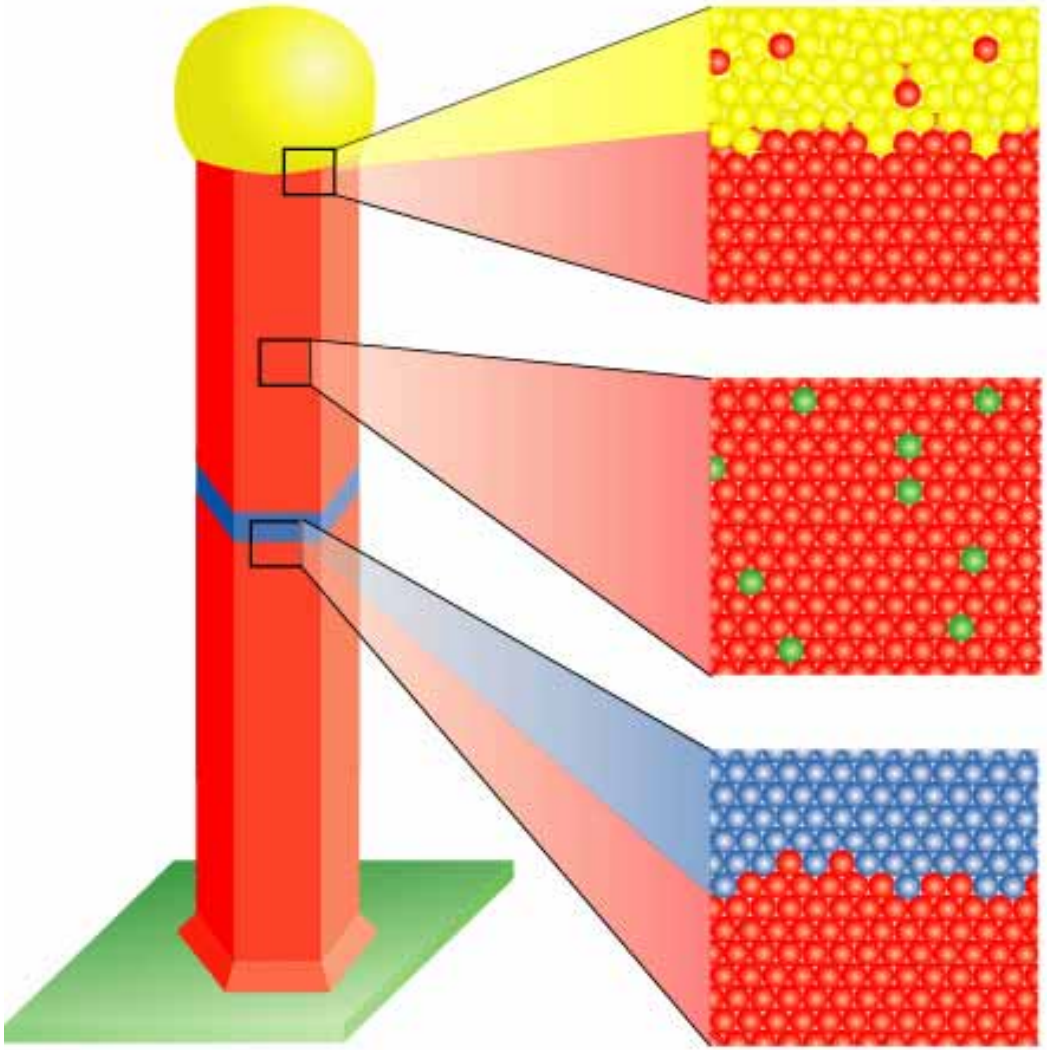



Composition Profile




Gudiksen, M.S., Lauhon, L.J., Wang, J., Smith, D.C., Lieber, C.M. *Nature* **415**, 617 (2002).

# Nanoscale Composition Visualization

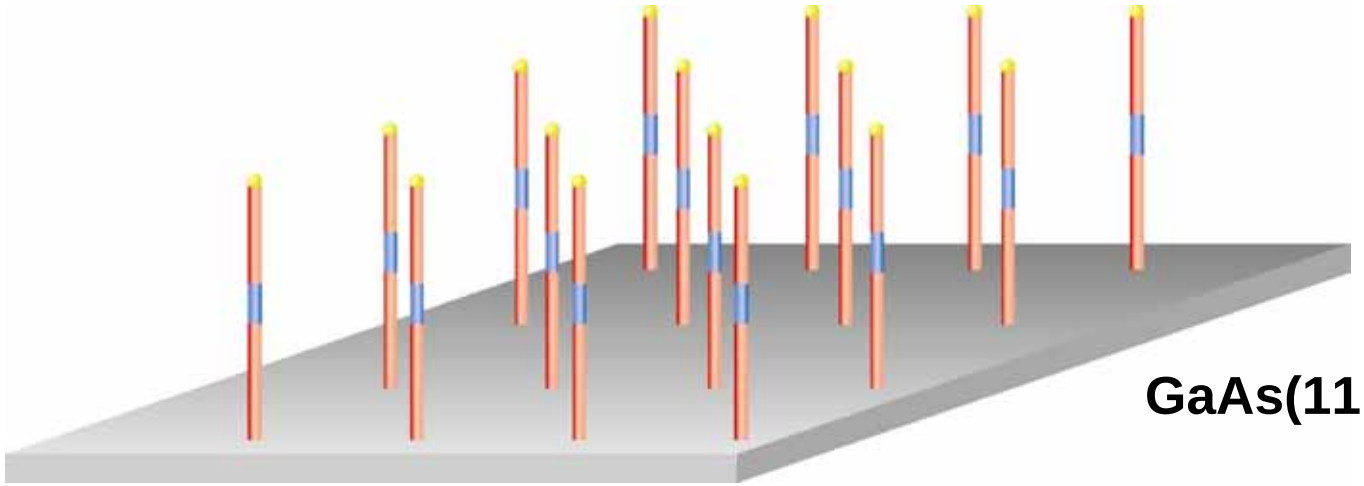


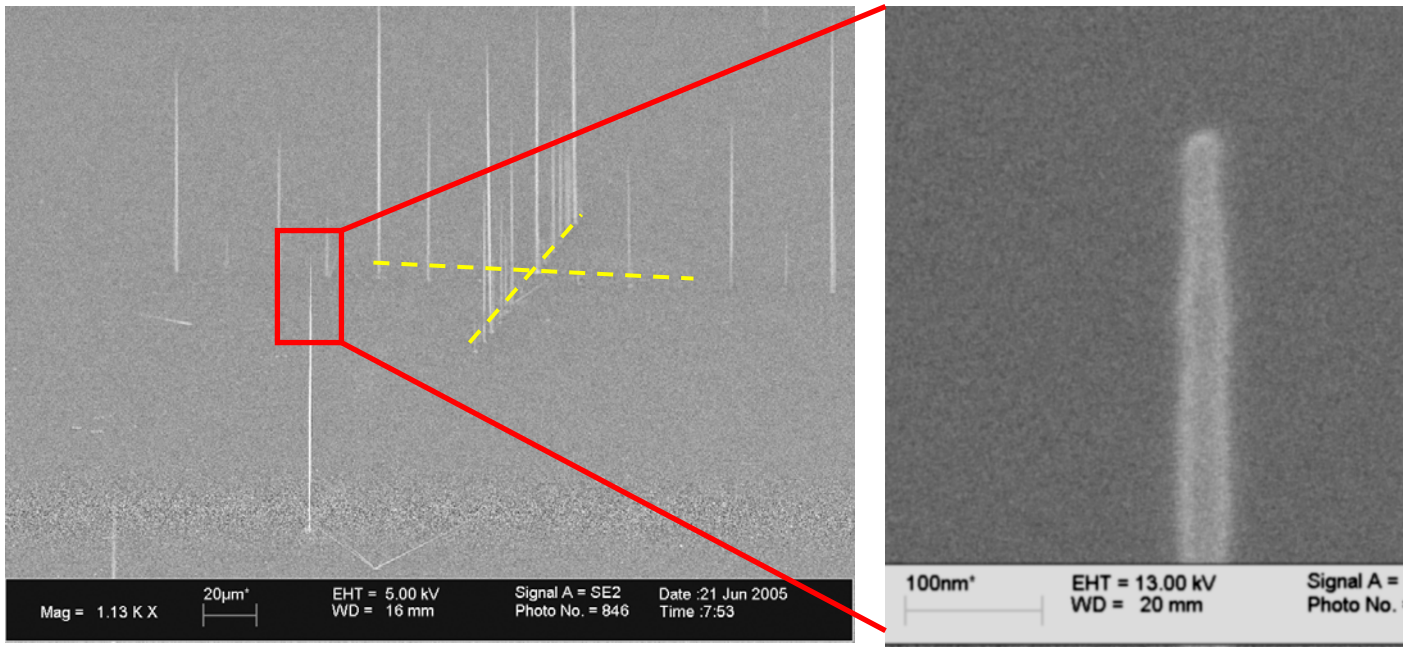
Catalyst-Solid Interface

Dopant Level & Distribution

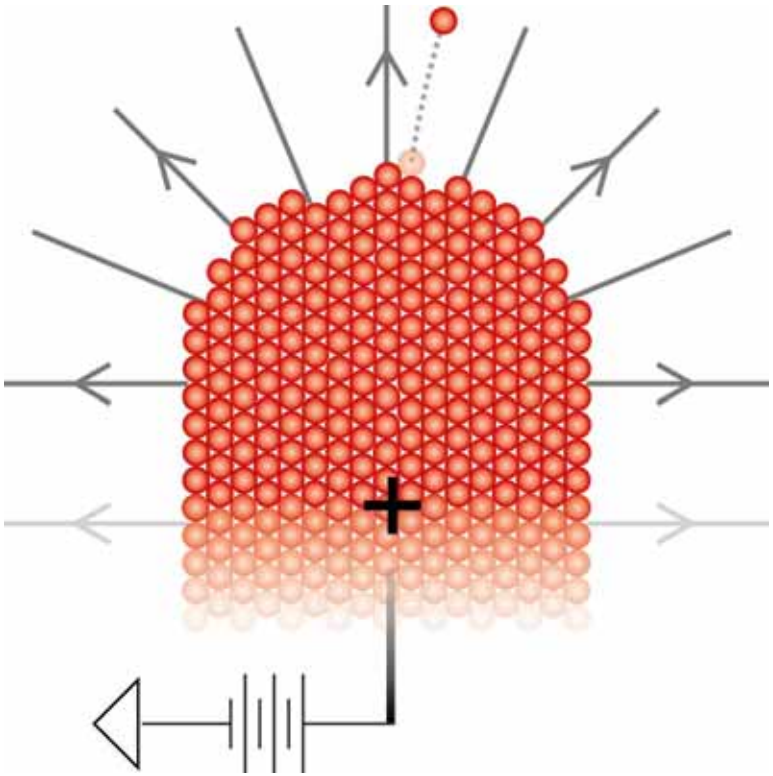
Interfacial Abruptness

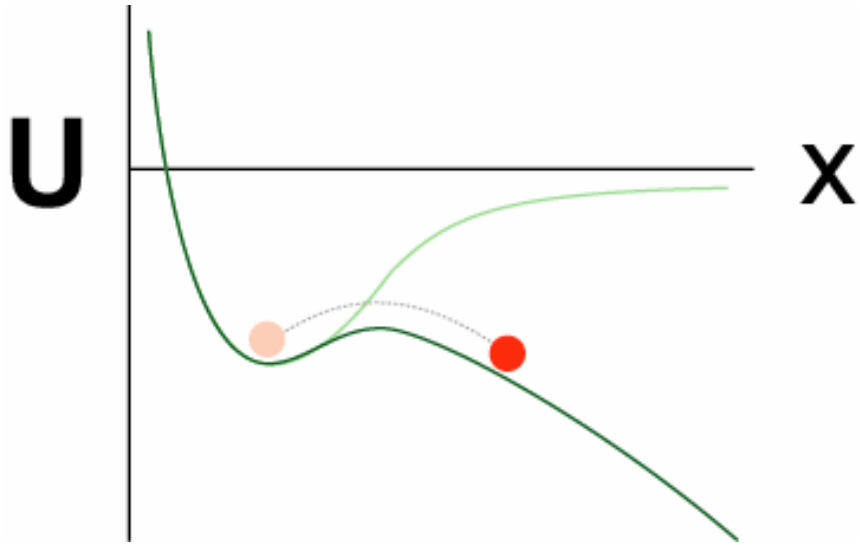
# Nanowire Array Growth



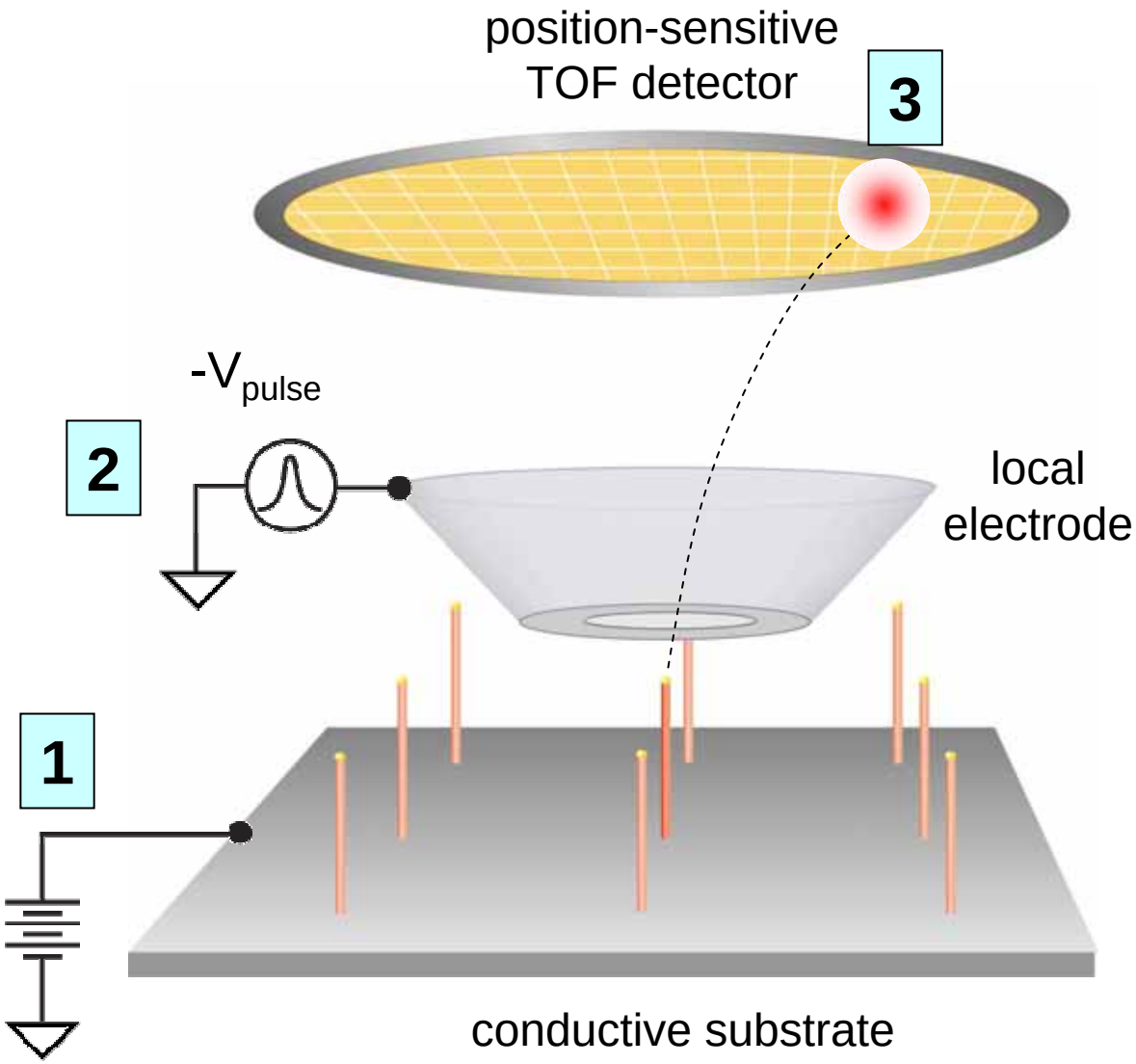



# Field Evaporation

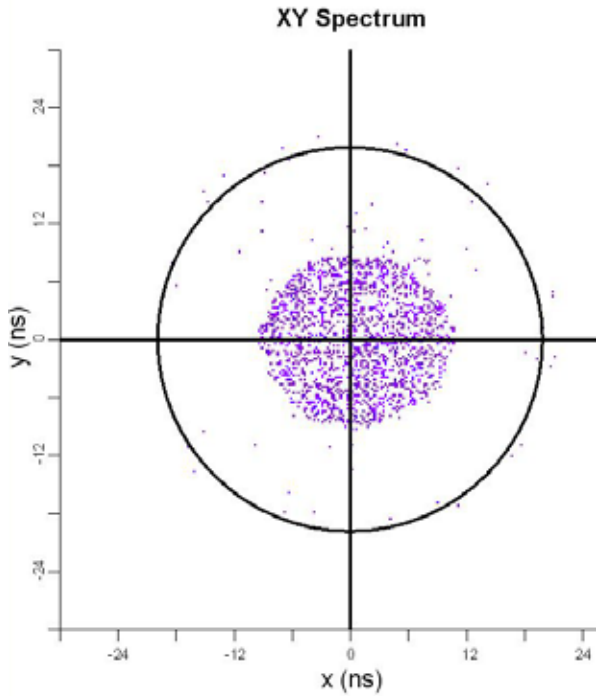




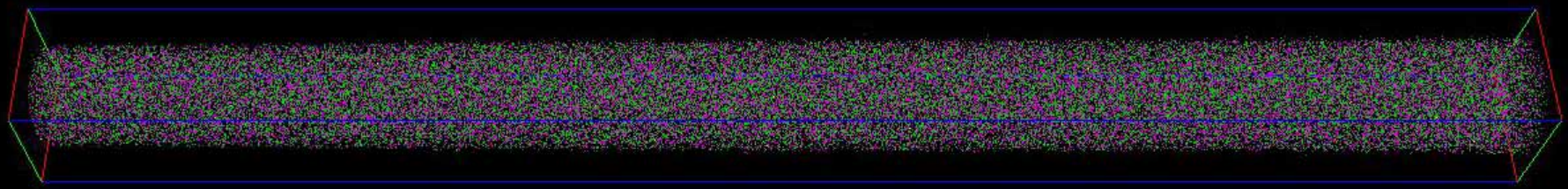
# Atom Probe Tomography




Detector Output



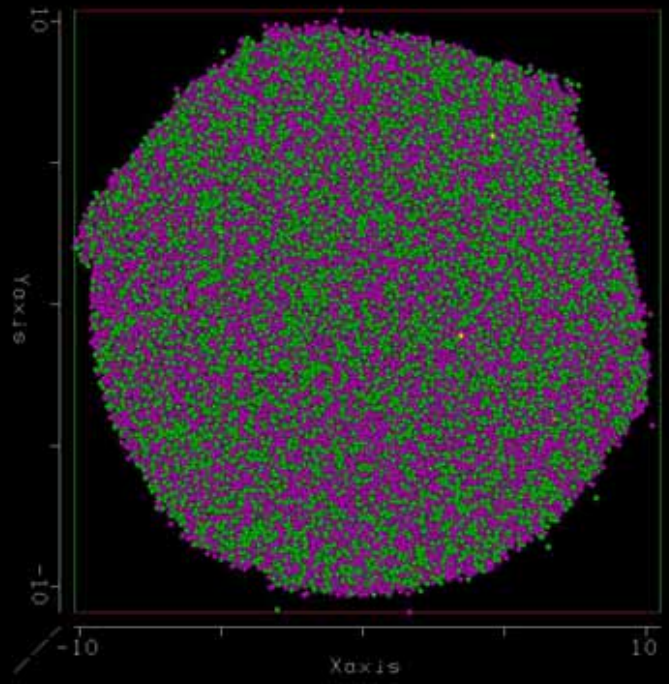
# Nanowire Reconstruction



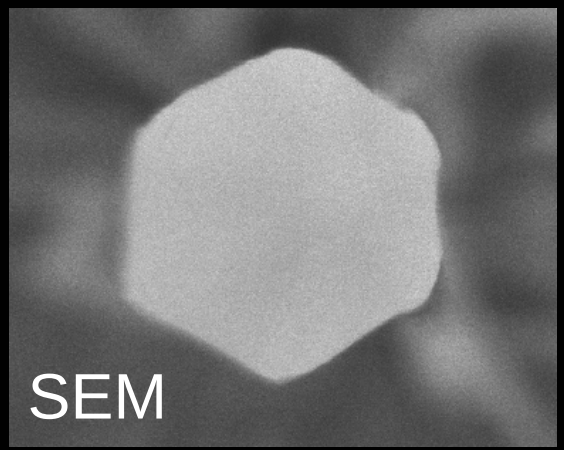
Side View: 300 x 22 x 22 nm$^3$ 5% of atoms

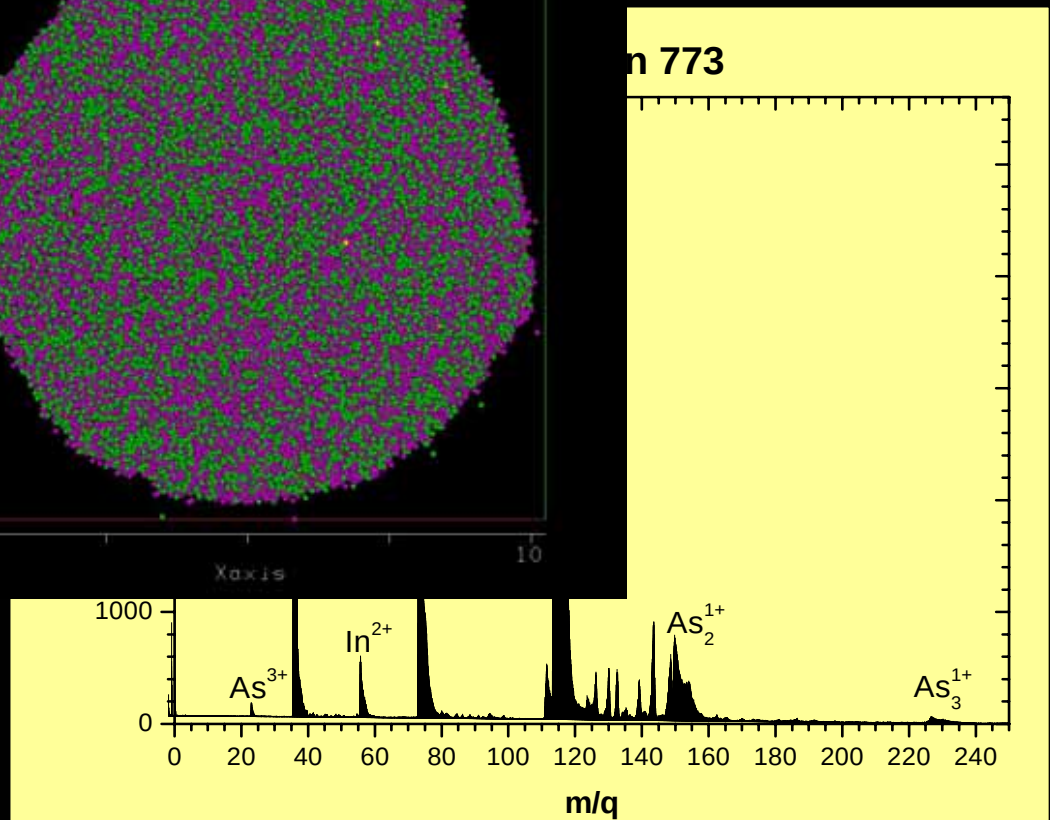
In

As

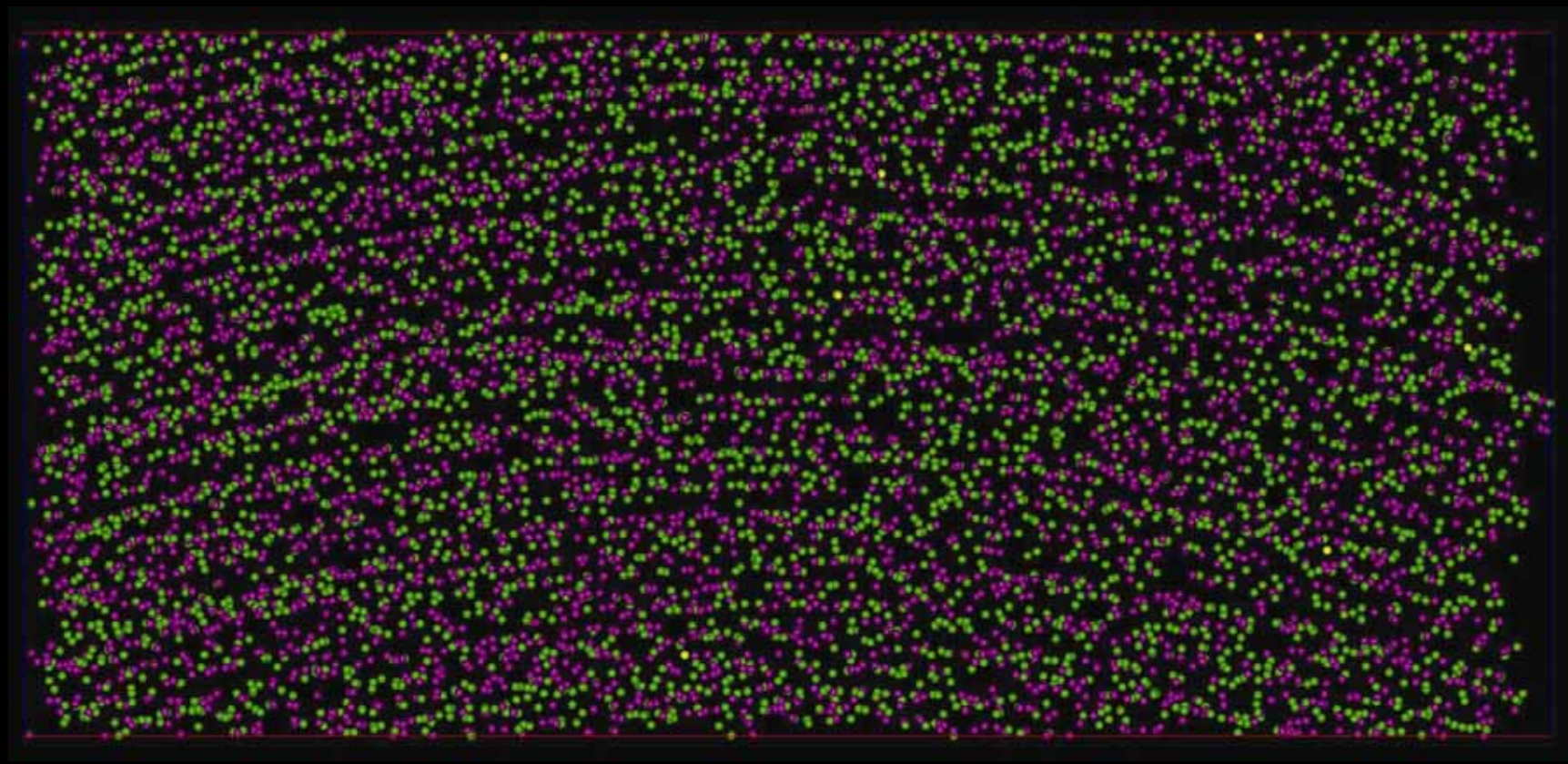



End View: 22 x 24 nm$^2$



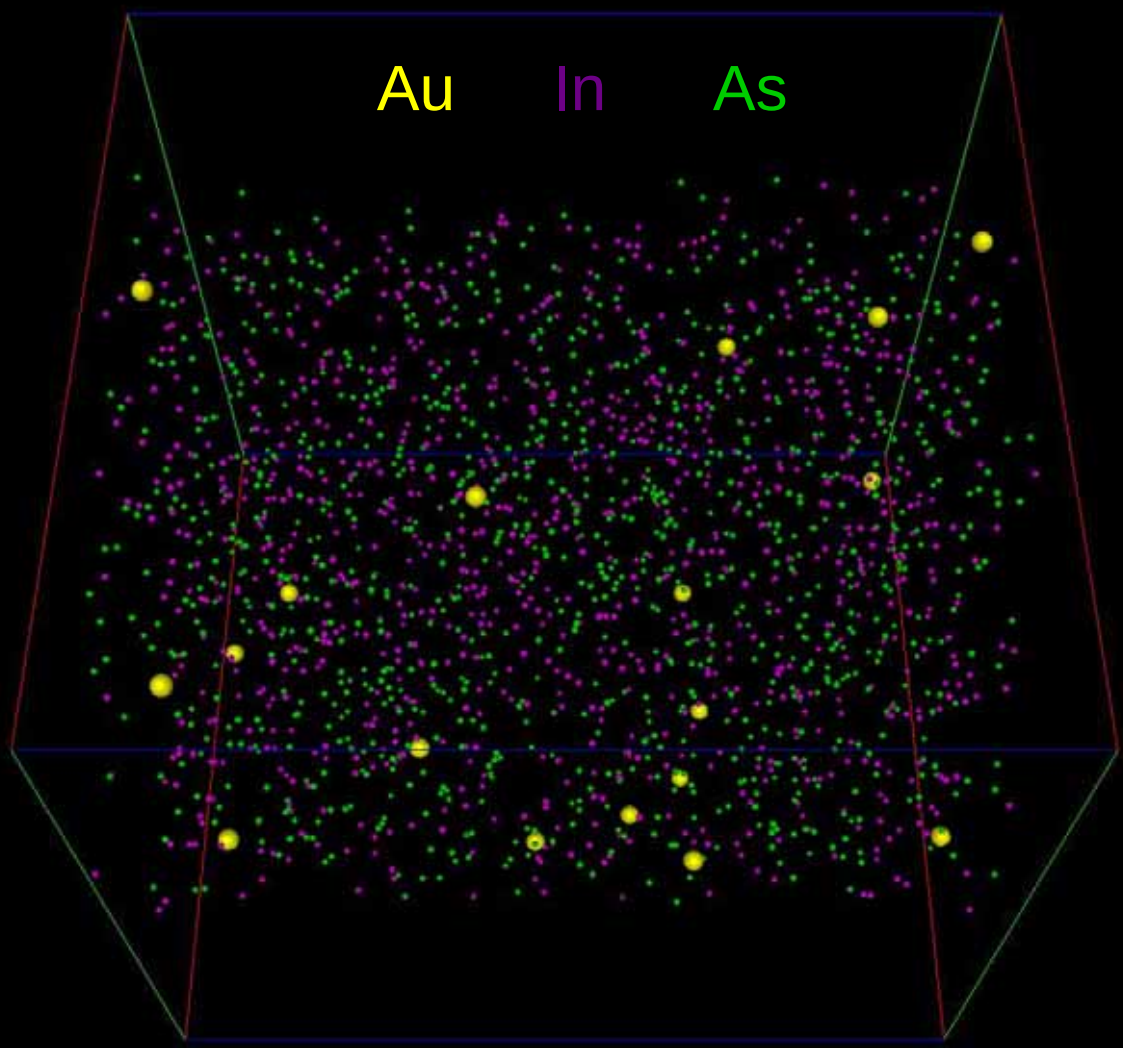
# Resolved Atomic Planes



10 nm

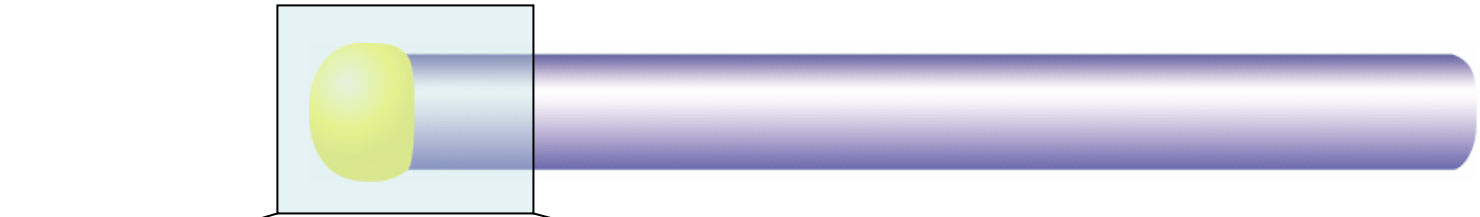
23 nm

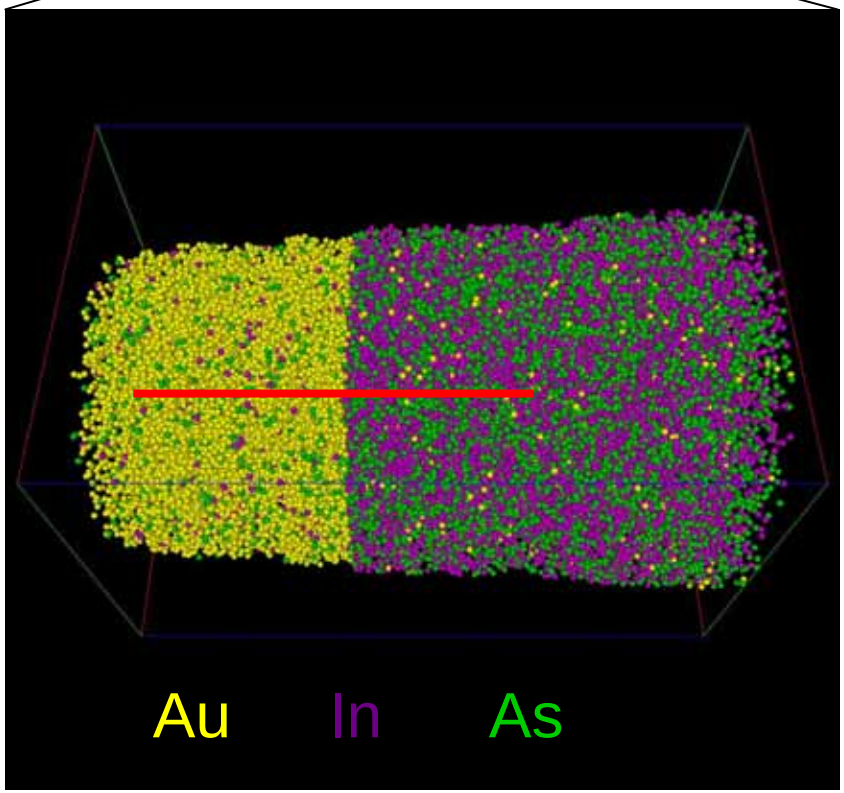
# Single Impurity Imaging

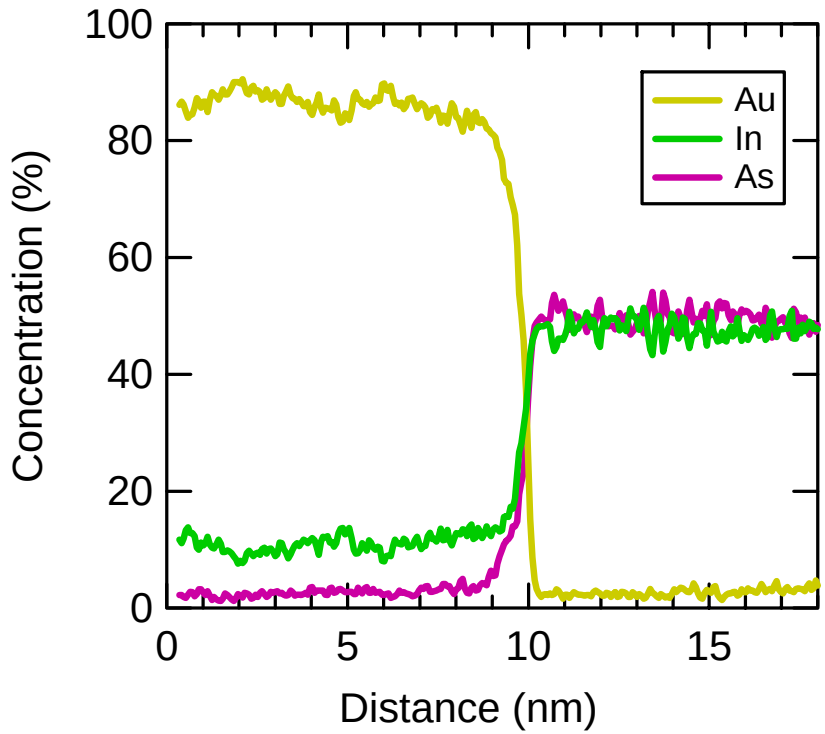



15 x 15 x 20 $nm^3$, 100% of Au, 2 % of In, As atoms

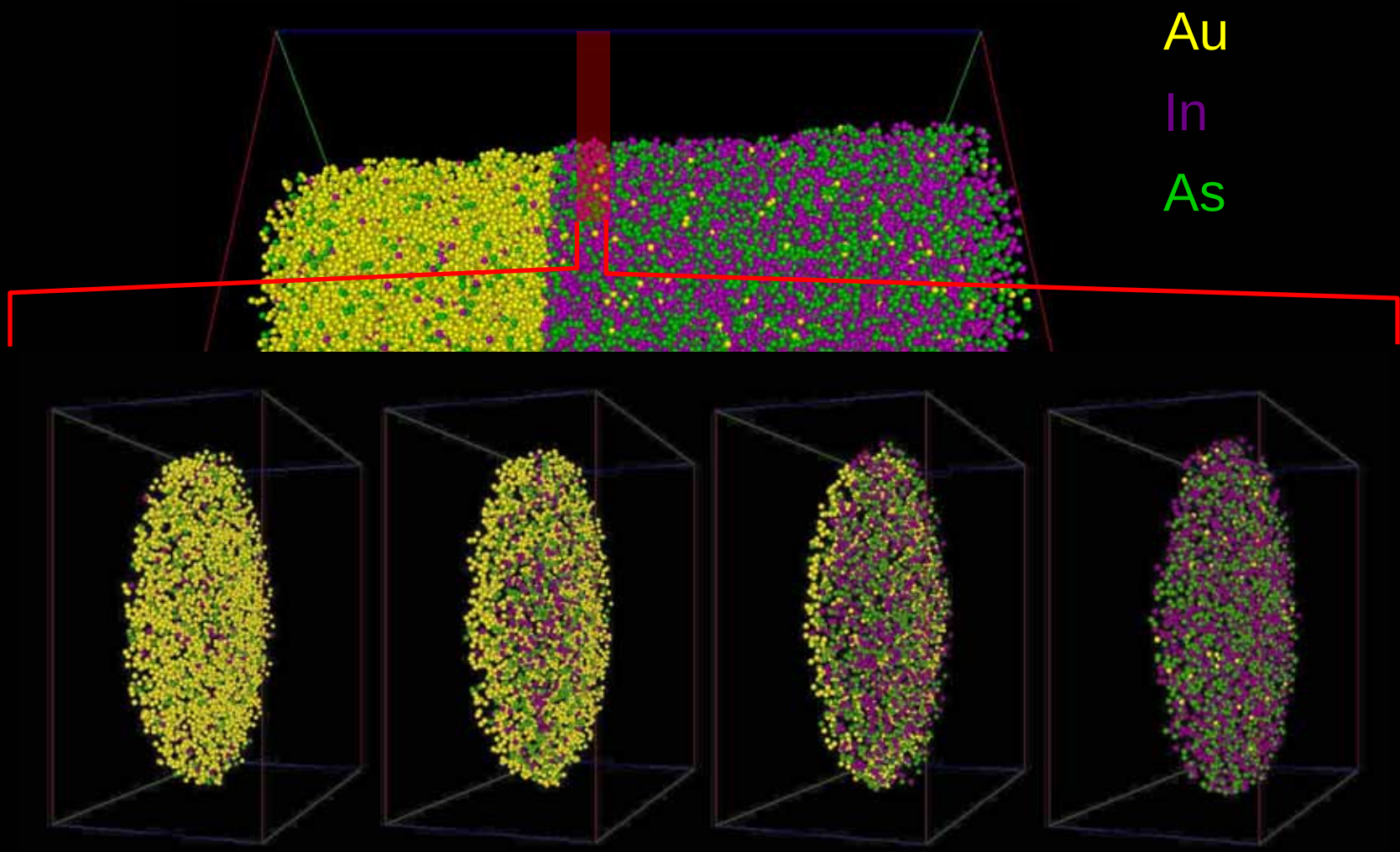
# Catalyst-Nanowire Interface (1-d)





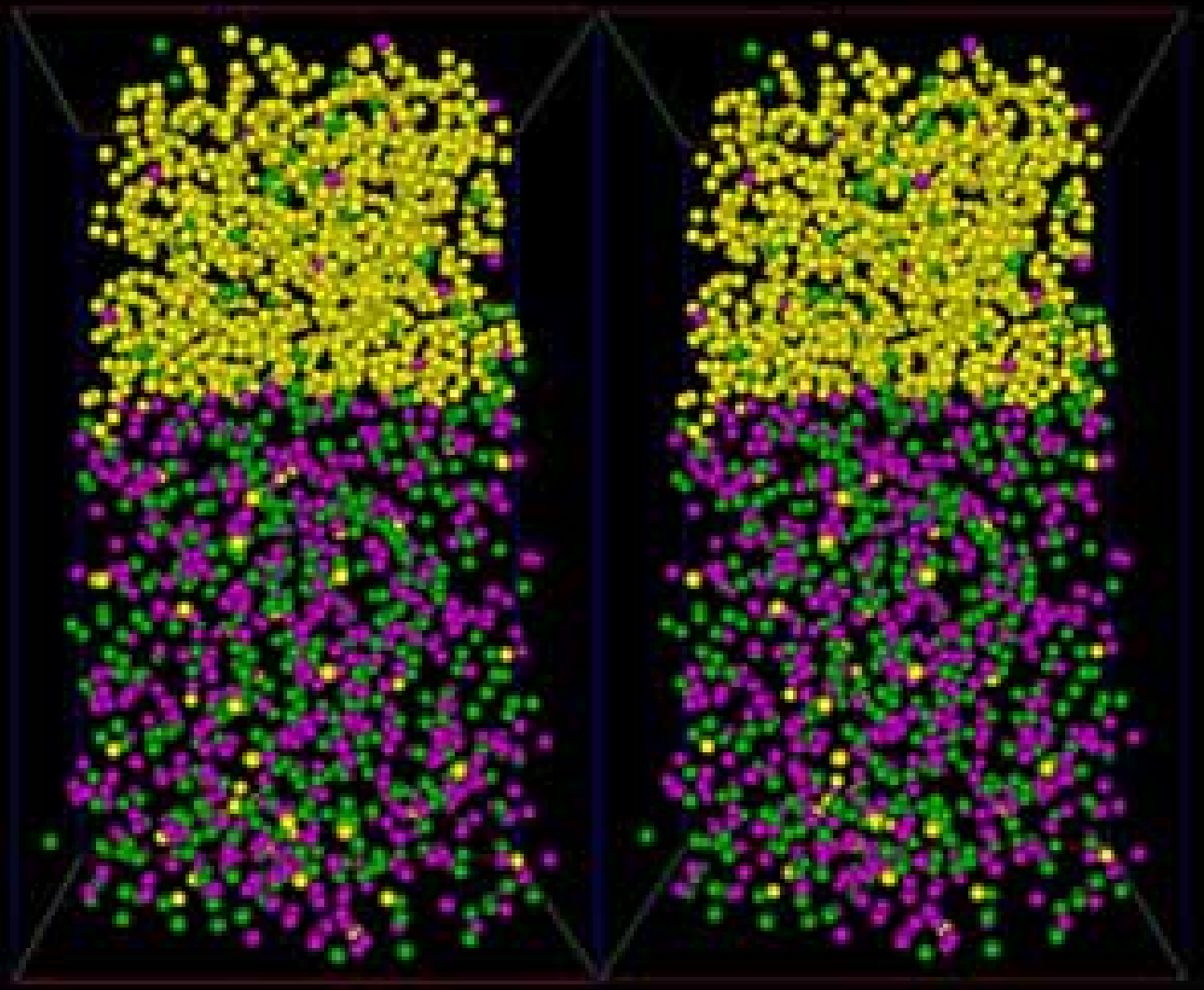



# Catalyst-Nanowire Interface (3-d)



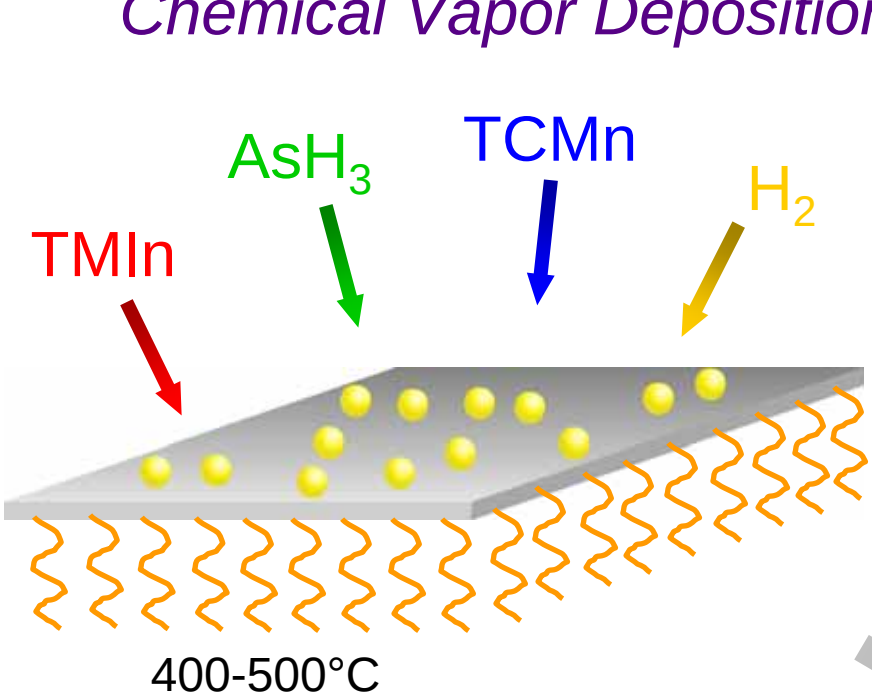

Perea et al, in preparation.

# Catalyst-Nanowire Interface (3-d)

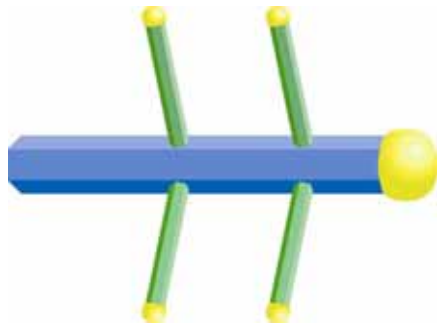


# Hierarchical Nanowire Structures

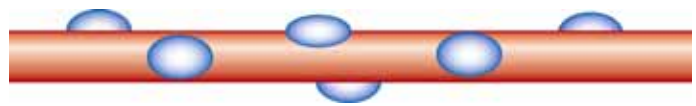
*Chemical Vapor Deposition*




*core-shell nanowire*



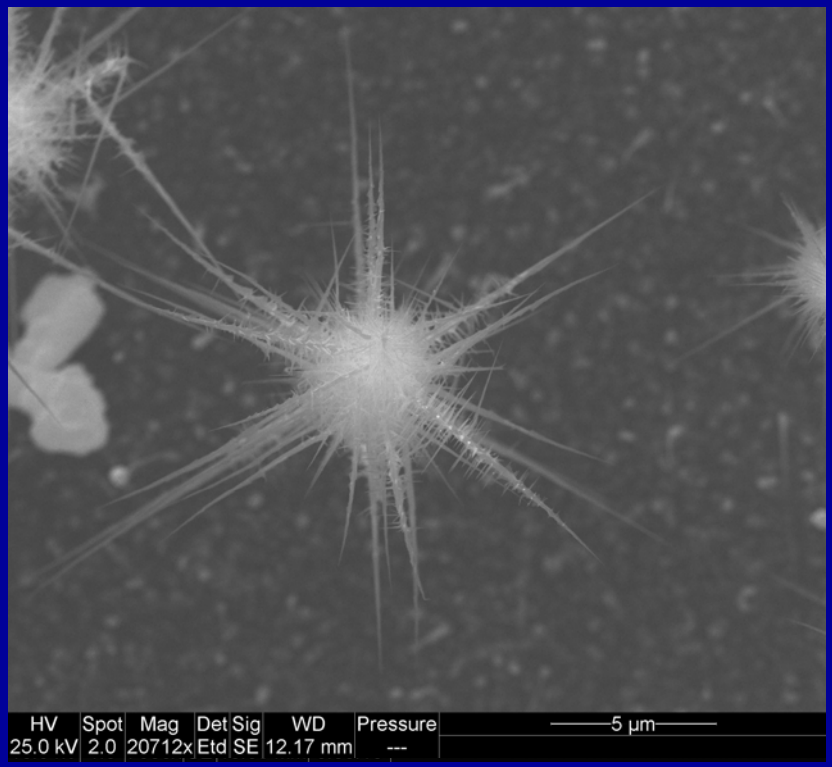
*dendritic nanowire*

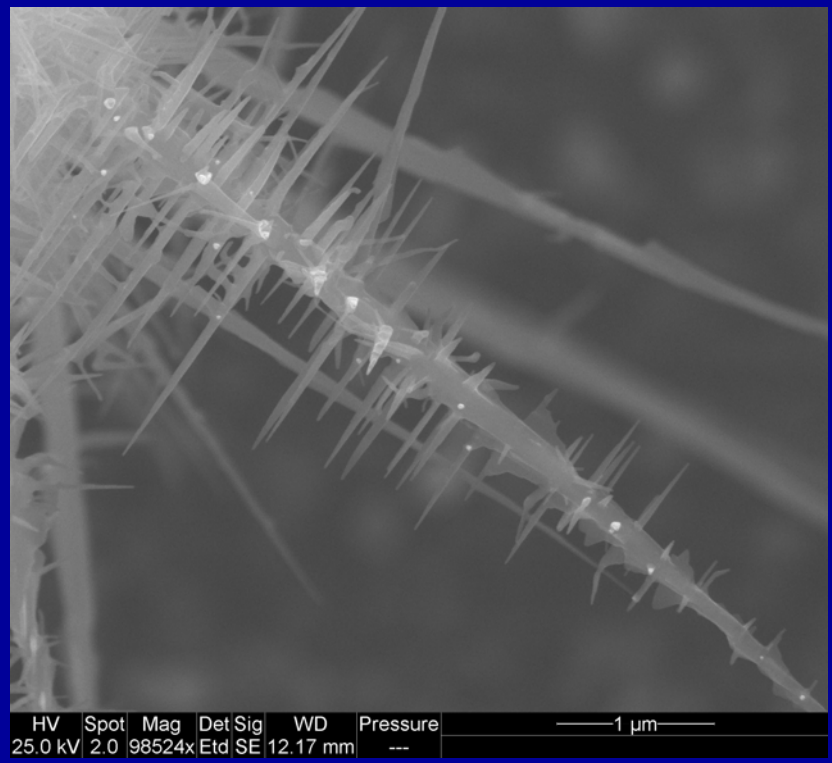


*SAQD-nanowire*

- Horizontal reactor, graphite susceptor
- Growth temperature: 400-500°C
- Sources: $AsH_3$, TMIn, and TCMn
- $H_2$ carrier gas at 1 atm
- V/III typ. 6:1

# Effect of TCMn: Continuous Flow



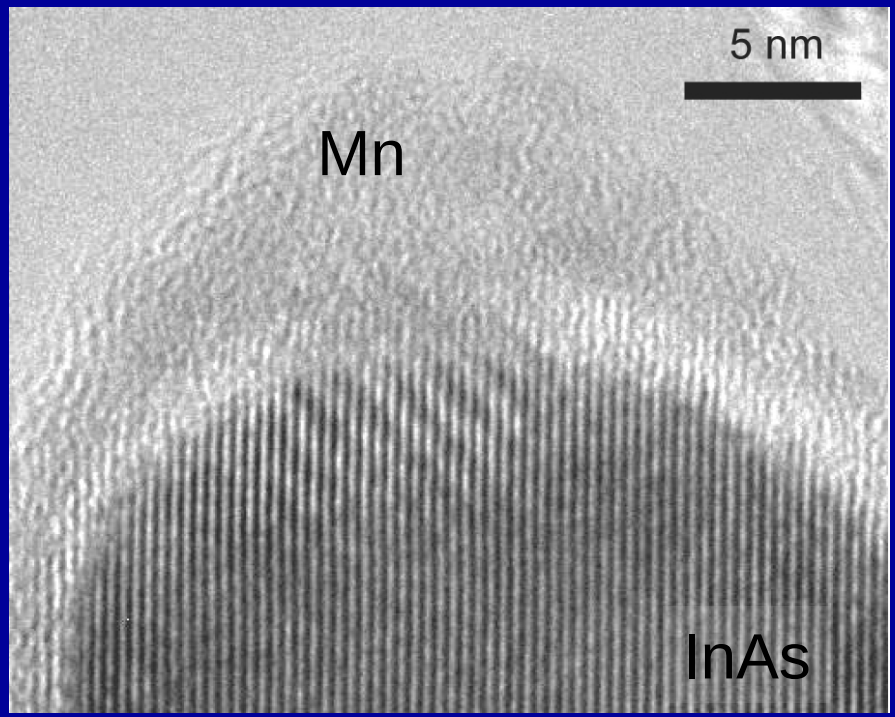




10 min InAs growth → + 10 min w/TCMn*

*Continuous TCMn flow produces continuous branching*

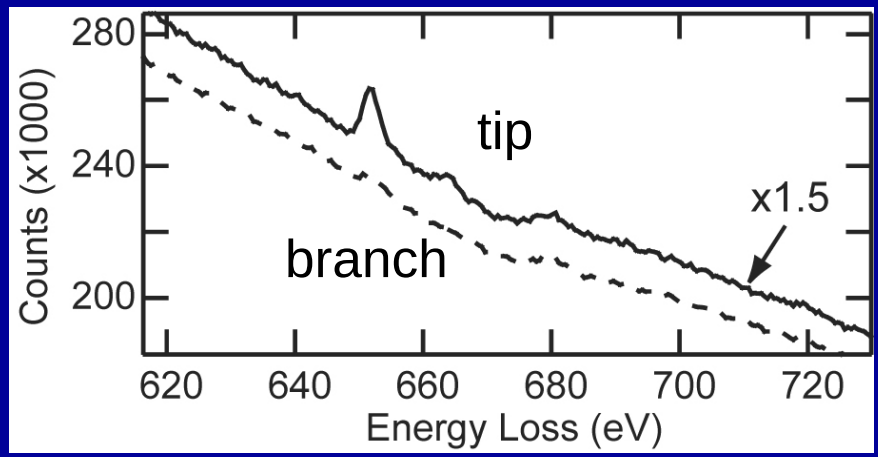
*tricarbonyl(methycyclopentadienyl) manganese

# Where is the Manganese?

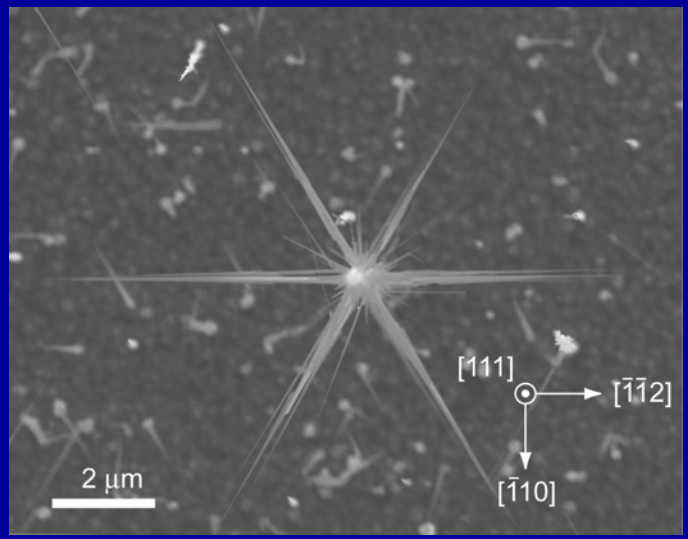


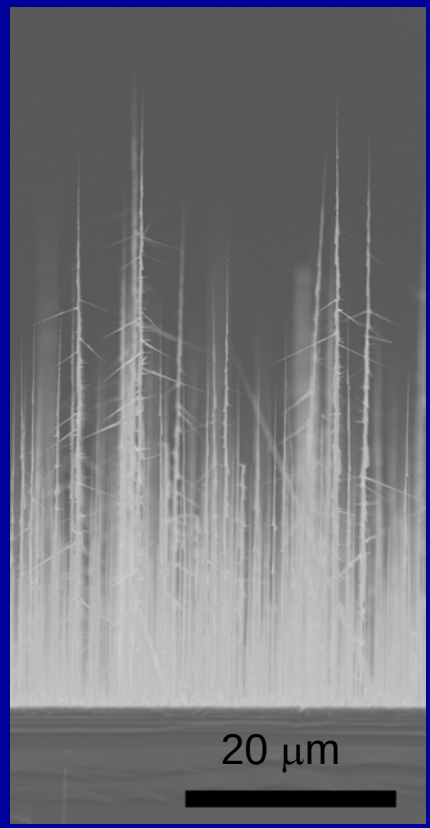

*EELS suggests Mn at branch tips*

EELS spectra



# Controlled Catalyst Formation

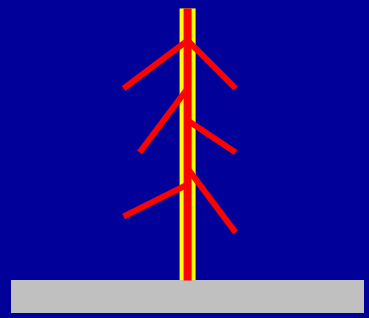


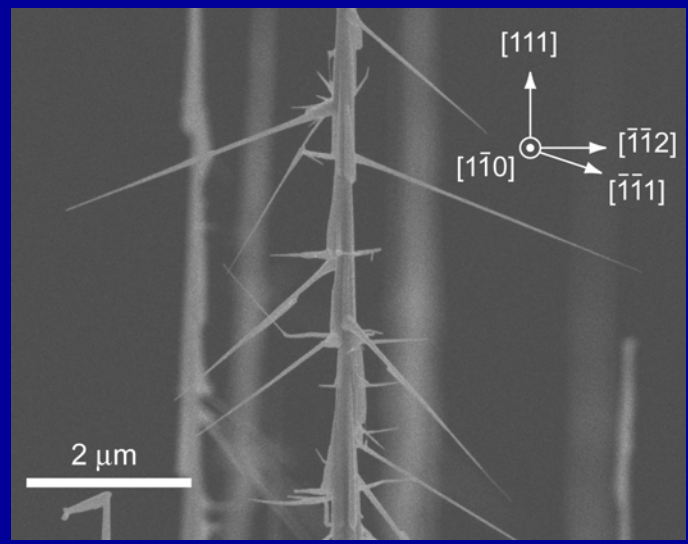




**(1) 5 min InAs**

**(2) 30 sec InAs + TCM**

**(3) 5 min InAs**



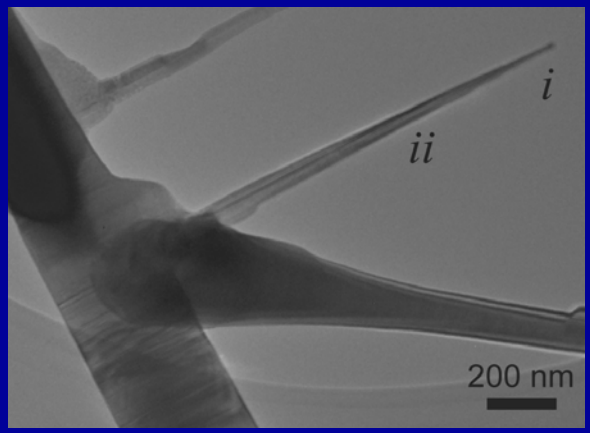


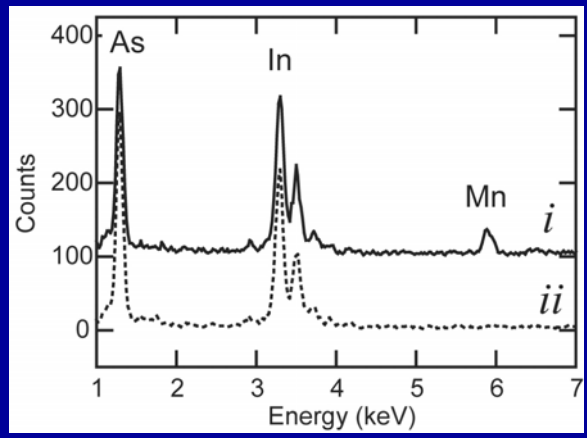

Au-mediated InAs growth perpendicular to GaAs(111)

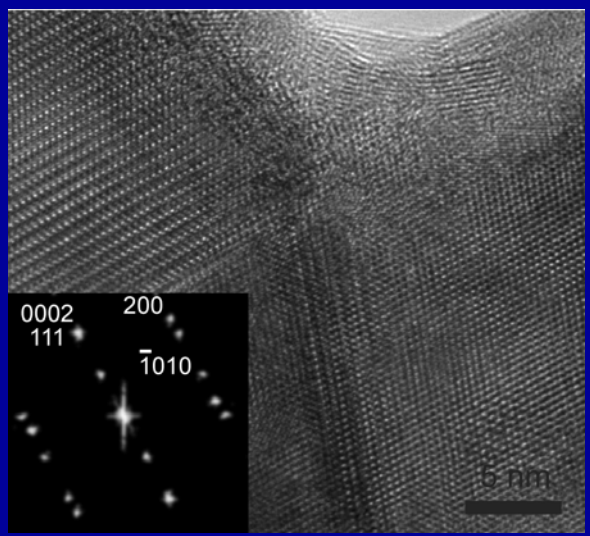
Mn mediated InAs branch growth

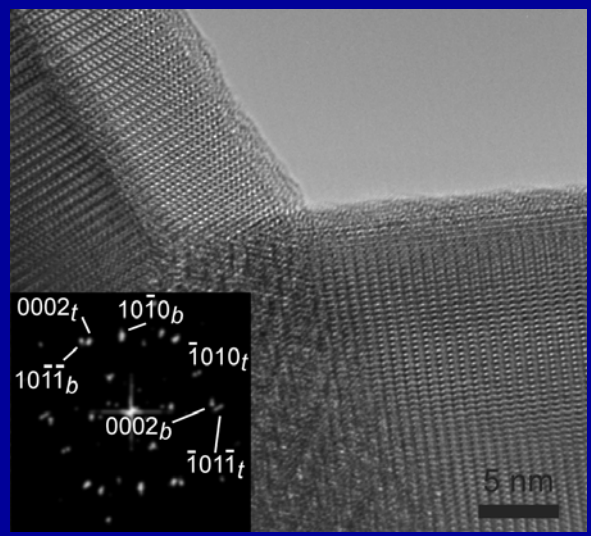
SJM109 TMIn:TCMn 50:1

# Epitaxial Branch Growth



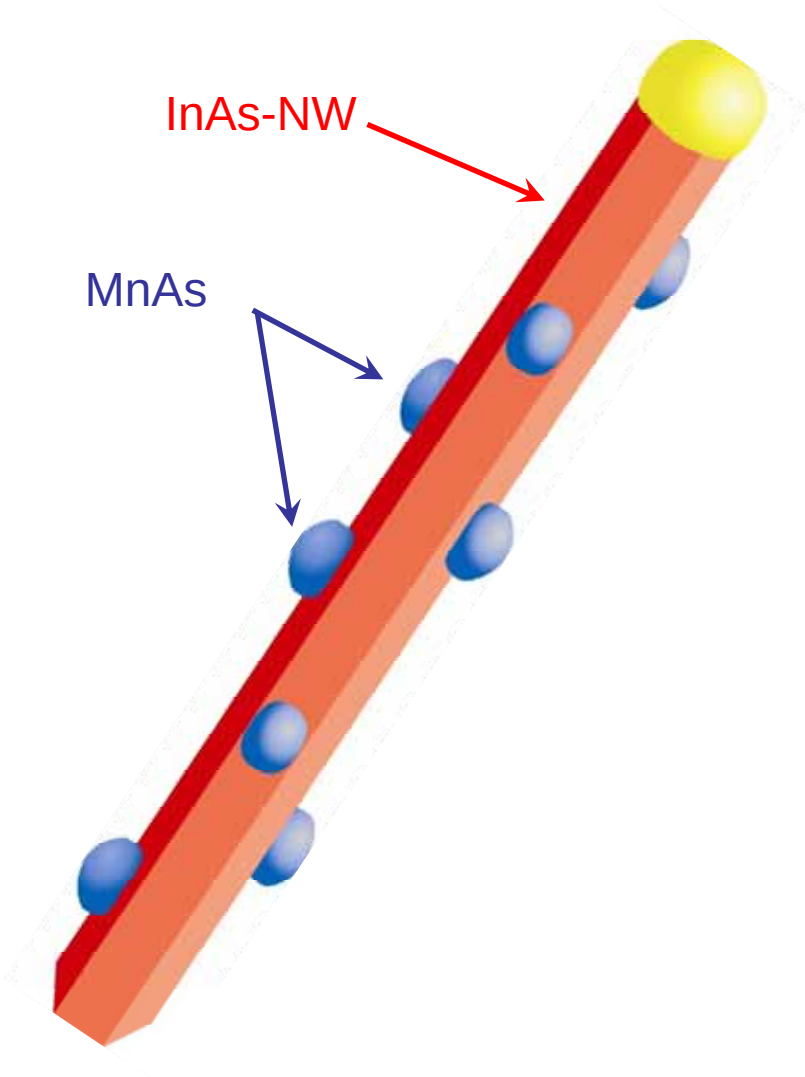

*Registry with 'trunk' is maintained by branch.*

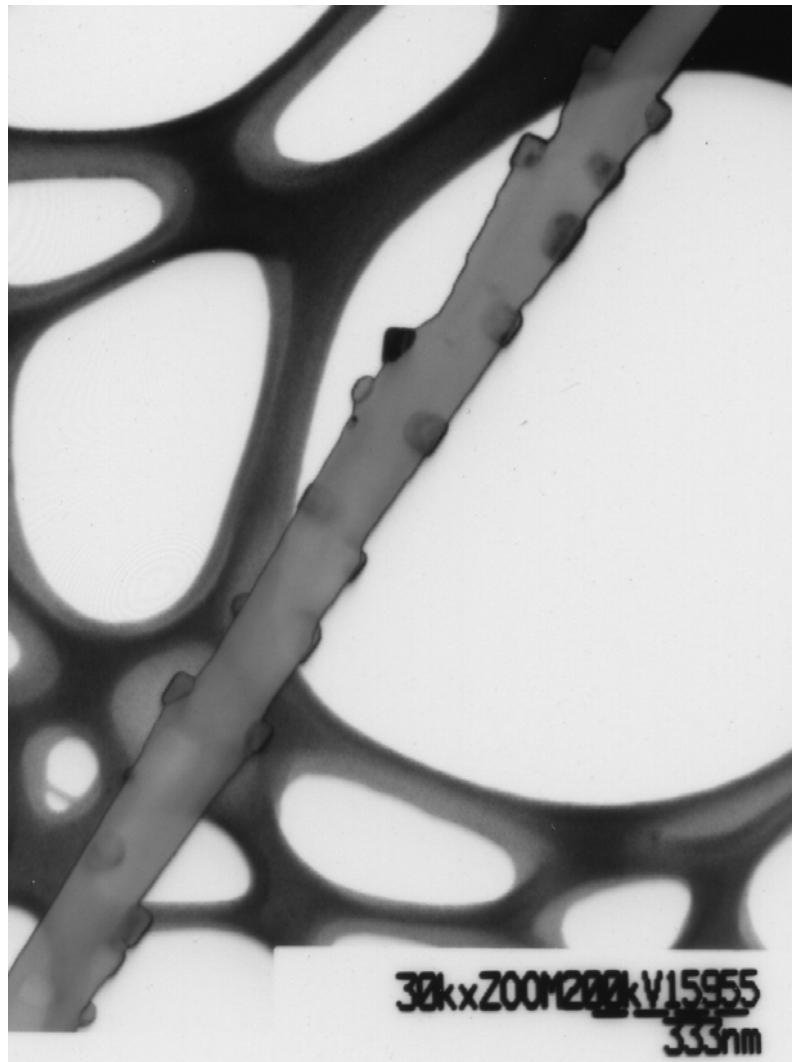
S.J. May, J. G. Zheng, B. W. Wessels, L.J. Lauhon, *Advanced Materials* **17**, 598 (2005)

# Manganese Self-Assembly

- Mn self-assembly leads to nucleation of new branches and dendritic growth
- Vapor-phase catalyst deposition is well-controlled
- Could be used to form other nanostructures, e.g. *self-assembled quantum dots*.

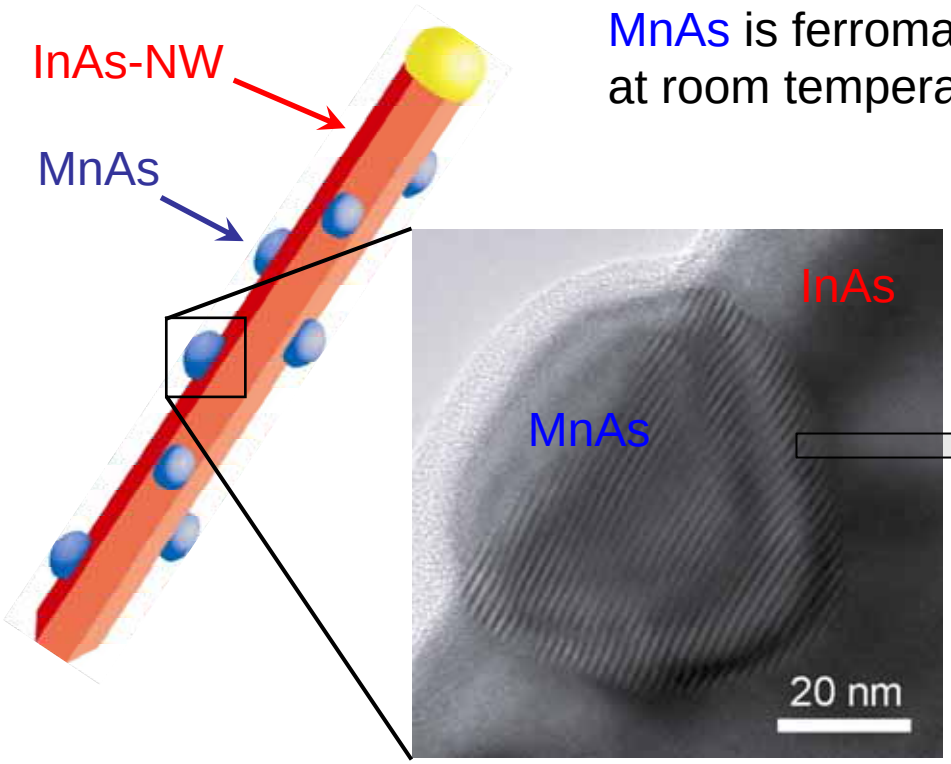
# MnAs SAQD on Nanowires



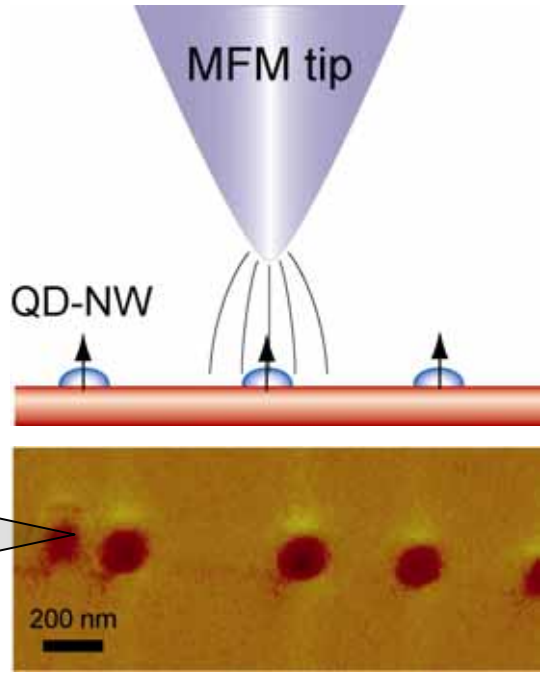



# QD-NW Hybrid Structures

*Self-assembled MnAs quantum dots on InAs nanowires*




MnAs is ferromagnetic at room temperature.



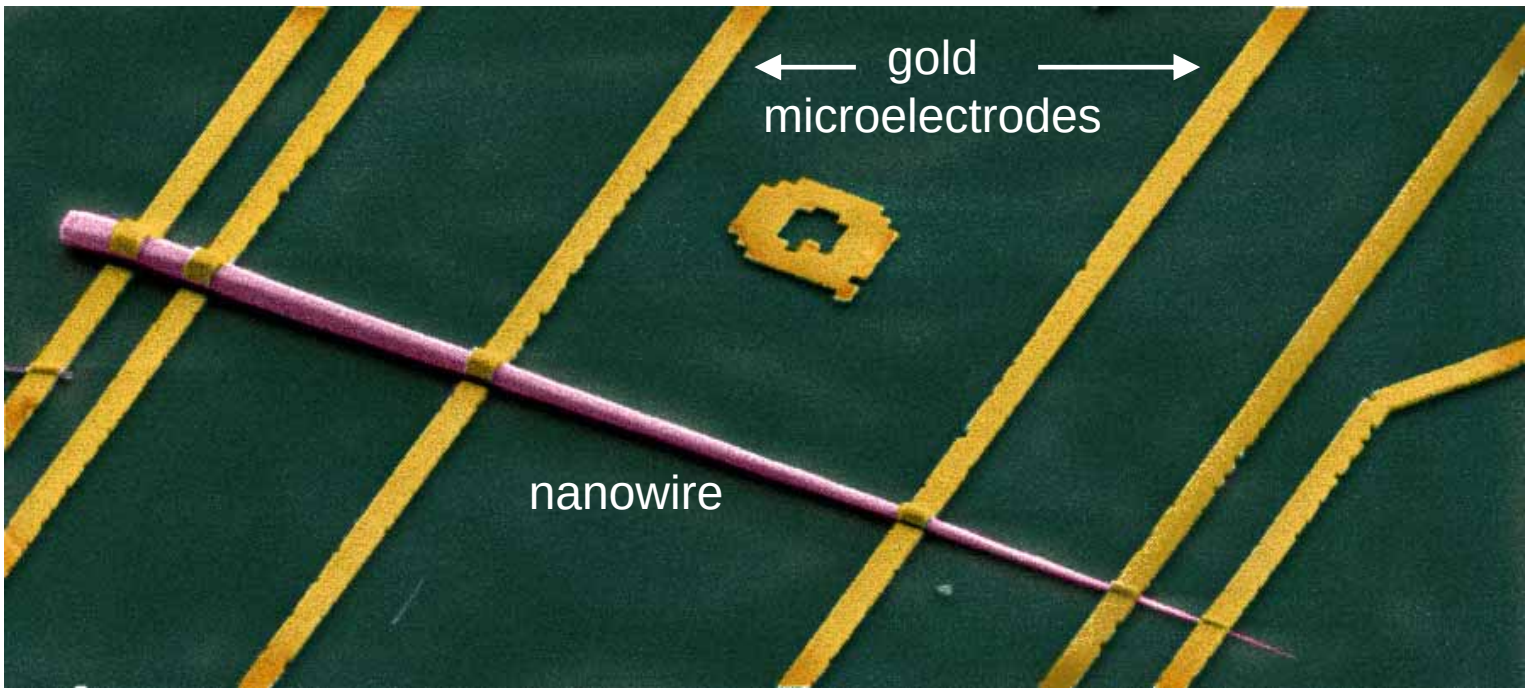

QD-NW Applications:

- Spin-injection into 1-d conductor
- 'Bit' flipping → discrete MR states

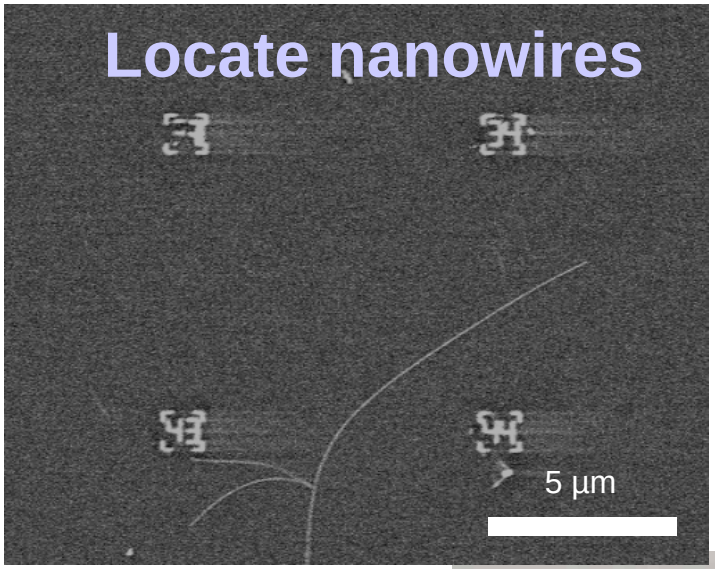
Ramlan et al, in preparation.

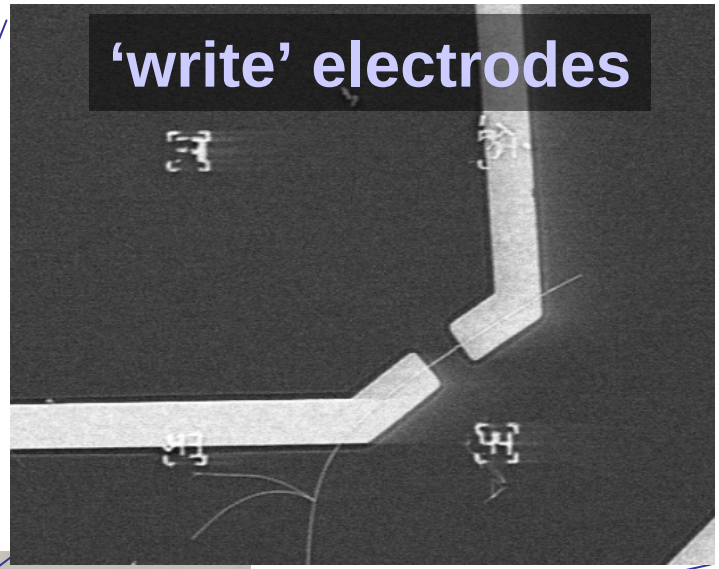
# Nanowire Electronic Devices

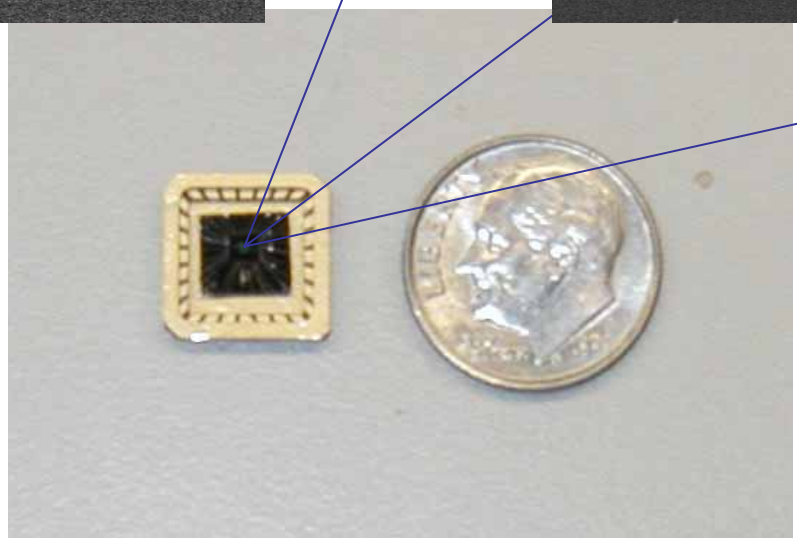
*Fabrication of metal microelectrodes enables the electrical properties of nanowires to be measured.*



# Nanowire Device Fabrication



# Summary

- Metal nanoparticles initiate ‘self-assembly’ of a variety of nanowire structures.
- Nanowire structure and composition can now be analyzed in 3-d, atom-by-atom.
- Scanned probe techniques allow nanoscale properties to be ‘illuminated’.

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