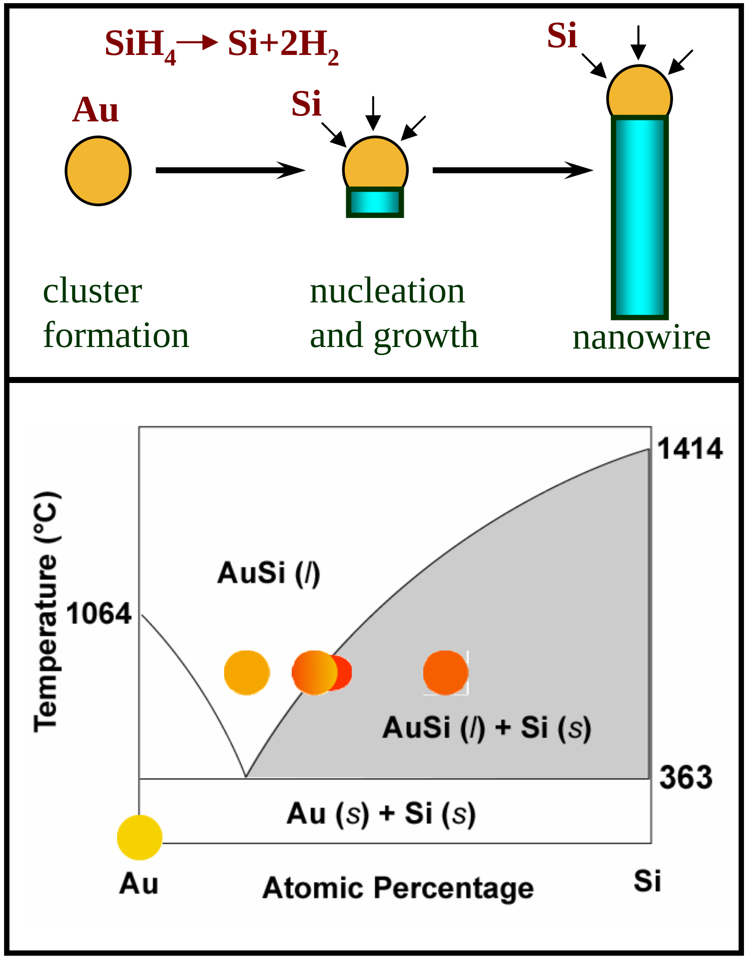
Semiconductor Nanowires I: Growth, assembly, non-electronic applications

11/03/2005

VLS growth of semiconductor nanowirs

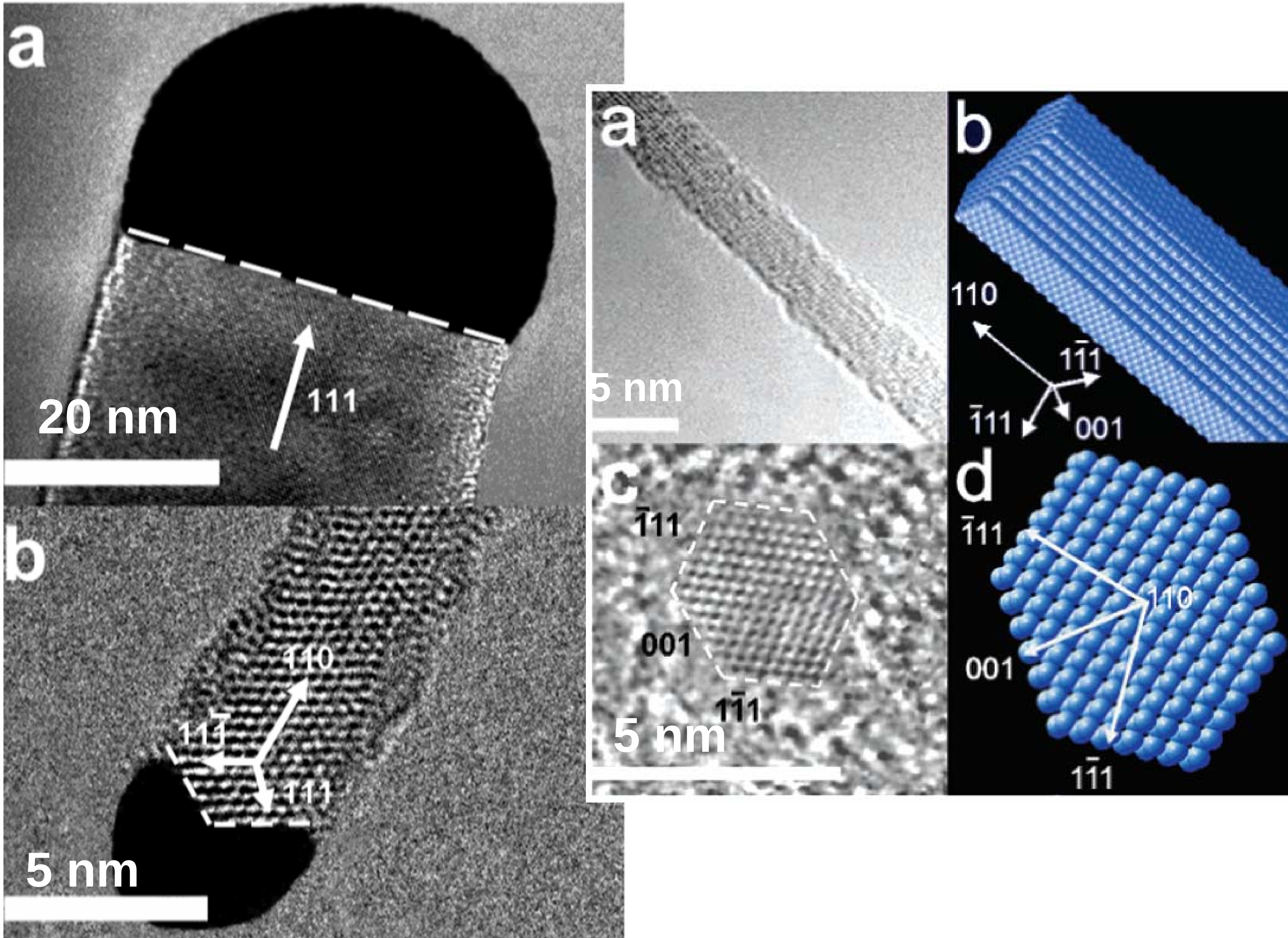


Vapor-Liquid-Solid (VLS) growth process

- Decomposition of precursors (vapor phase) via catalyst particles
- Liquid alloy droplet formation above the Eutectic temperature
- Supersaturation of the liquid droplet resulting in solid phase growth
- Diameter controlled by the catalyst particle size

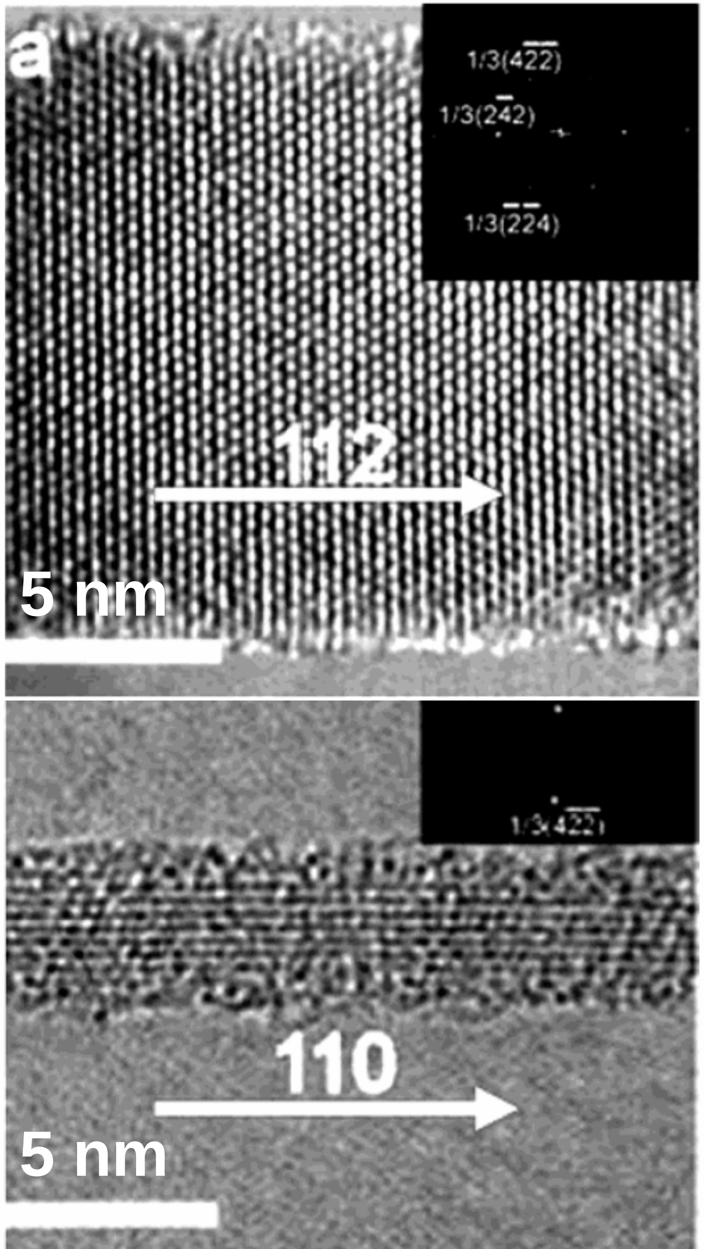
VLS growth of semiconductor nanowirs

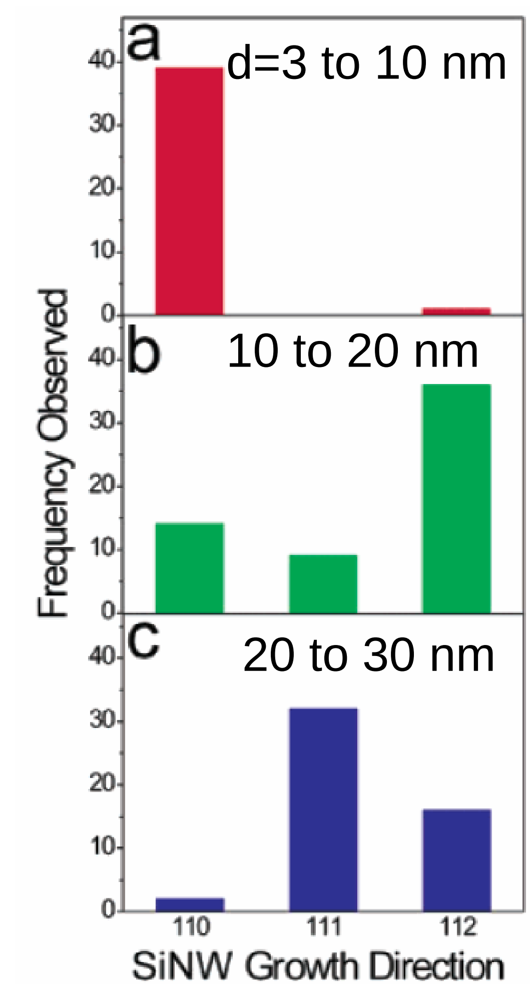
Y. Wu, Nano Lett. **4**, 433 (2004)



VLS growth of semiconductor nanowirs

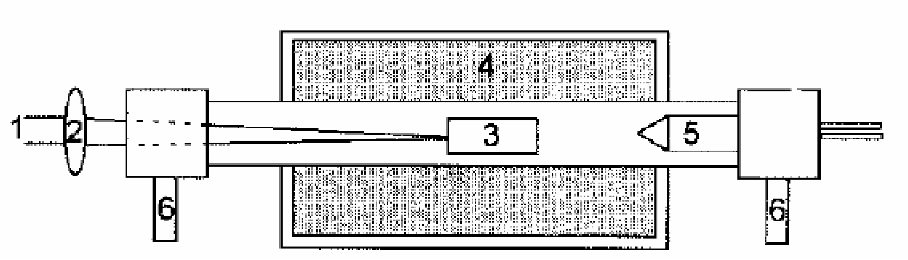
Y. Wu, Nano Lett. **4**, 433 (2004)



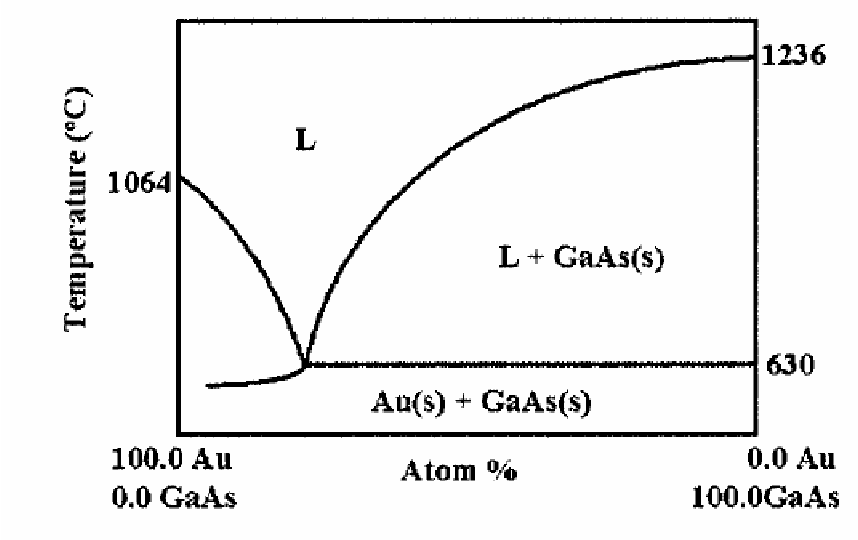


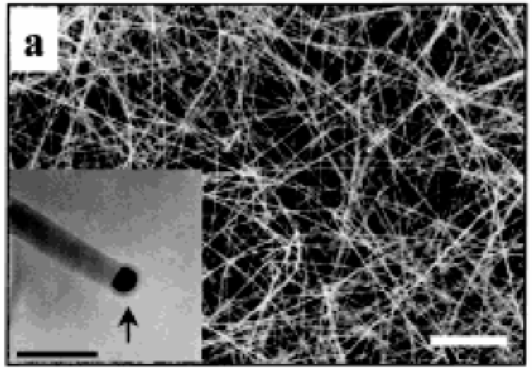
Growth direction at different diameters

Growth of compound nanowires with laser-assisted catalytic growth



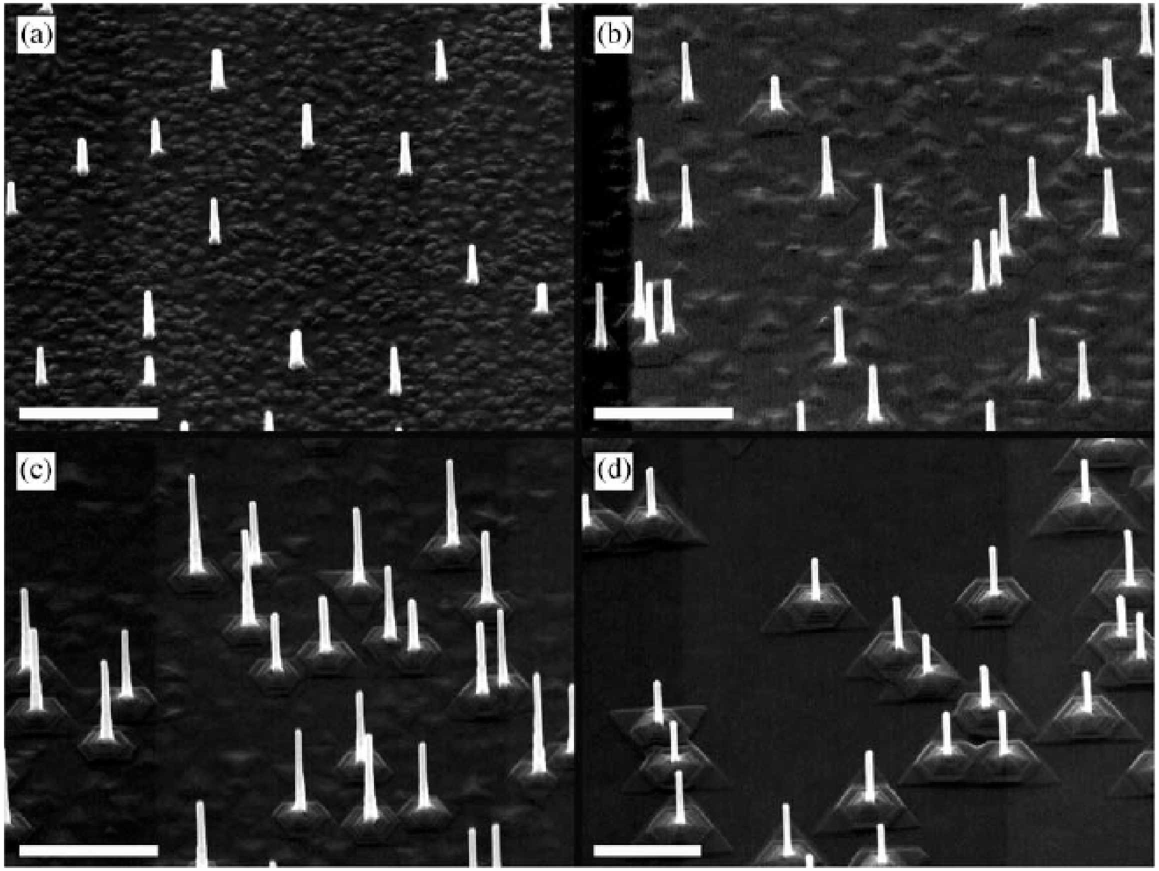
Target: solid compound material + Au mixture

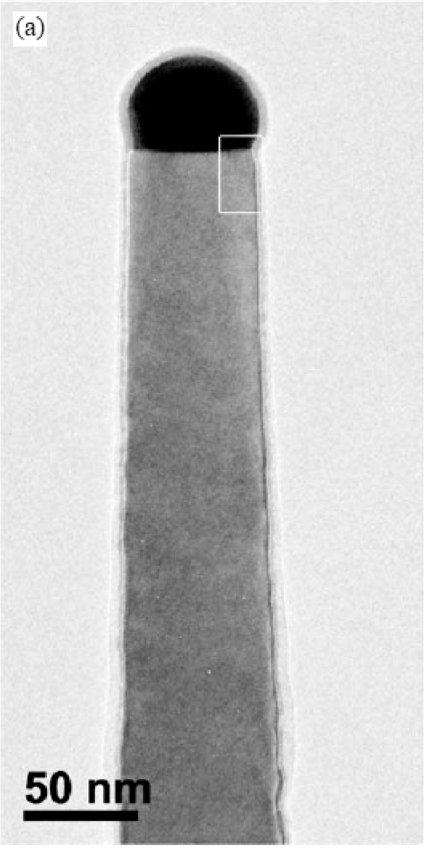




L+S phase above certain temperature

Growth of compound nanowires via MOCVD



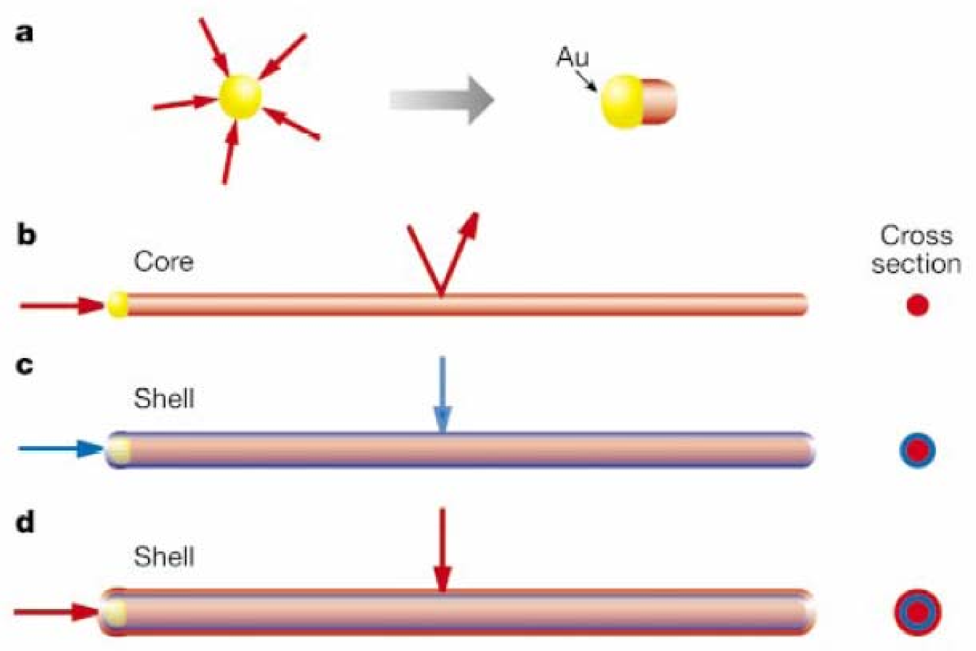


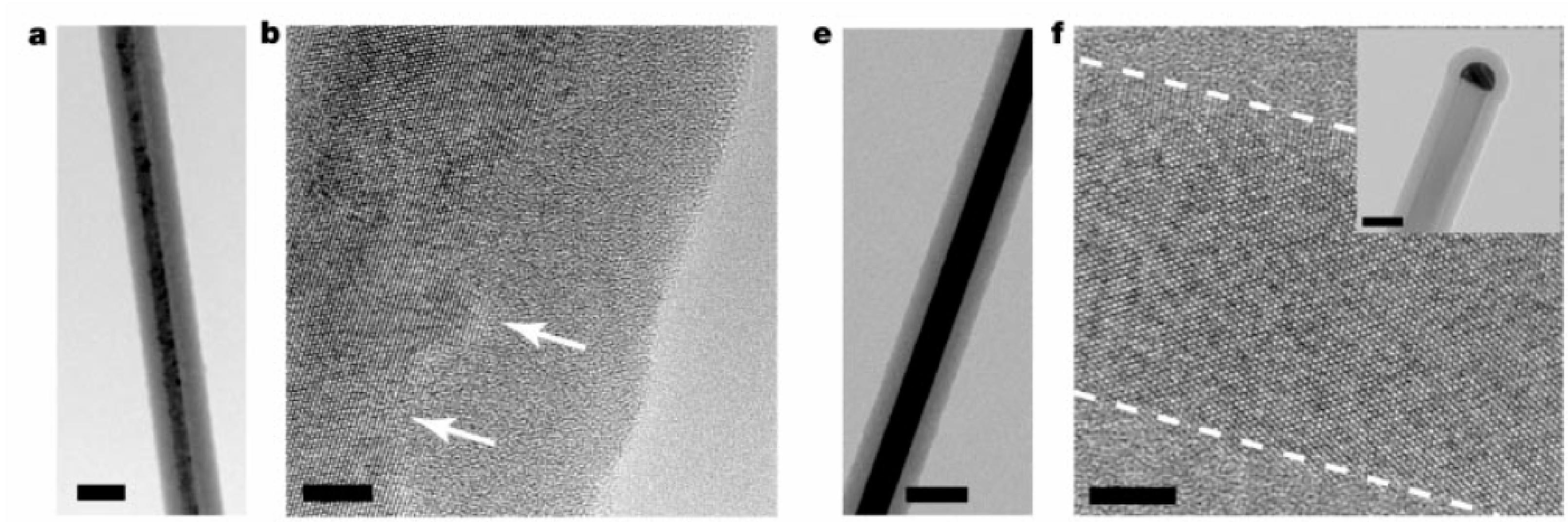
TMG+NH3

Tapering due to direct radial deposition

Core/shell radial heterostructures

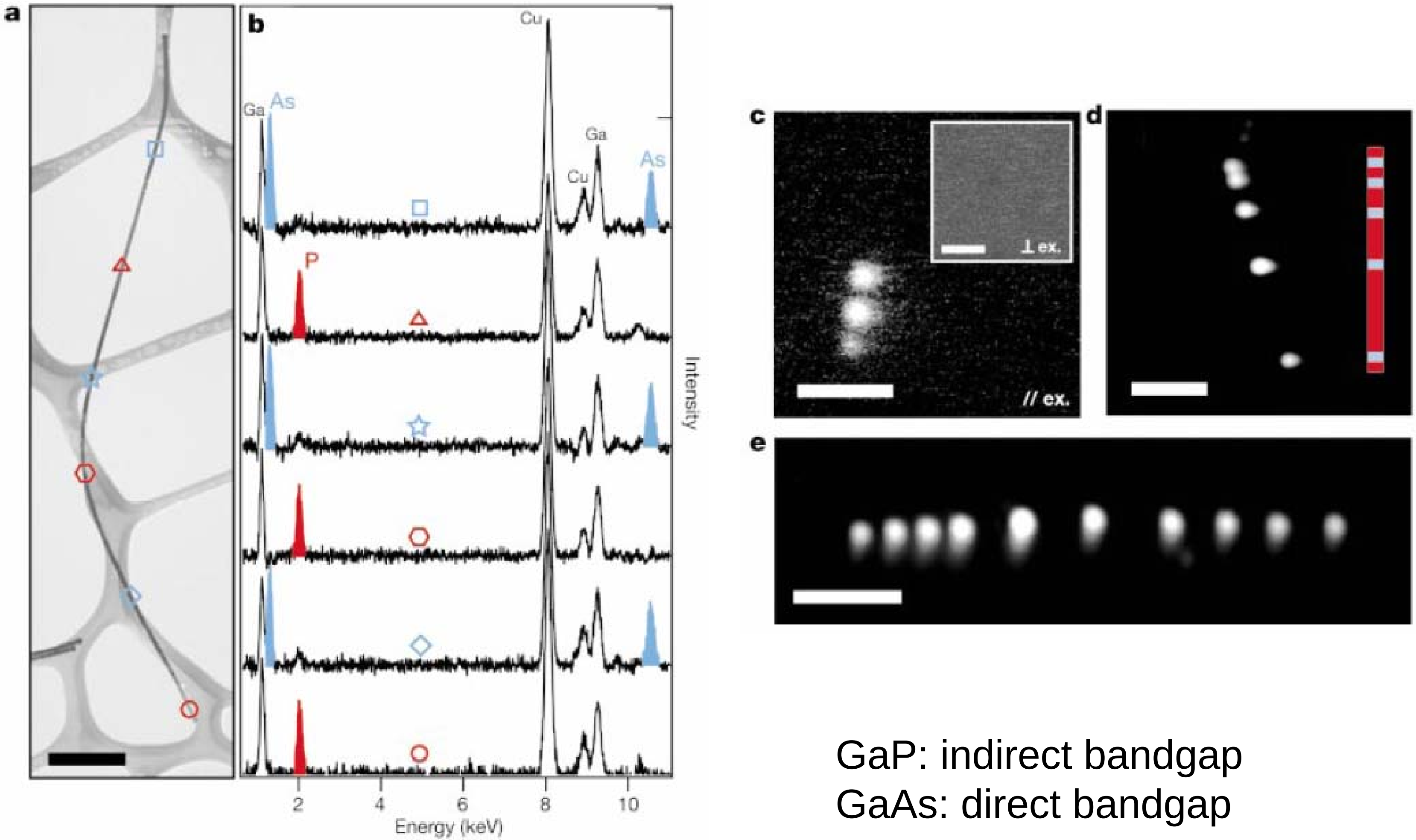
Lauhon, Nature **420**, 57 (2002)





Core/shell radial heterostructures

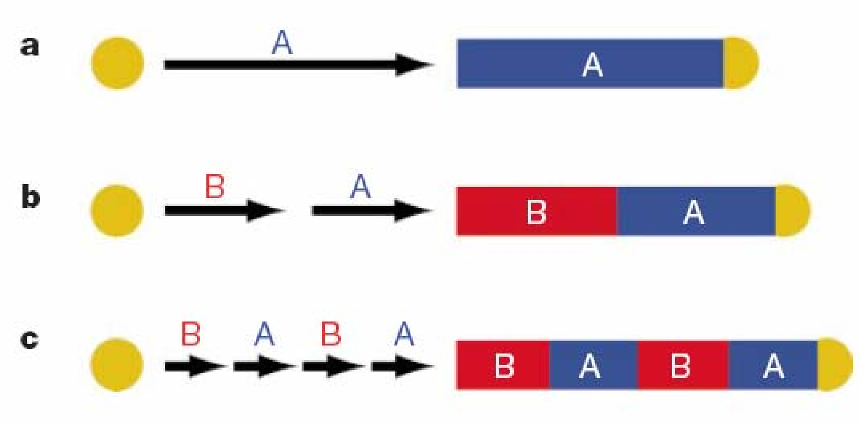
Gudiksen, Nature 415, 617-620 (2002).

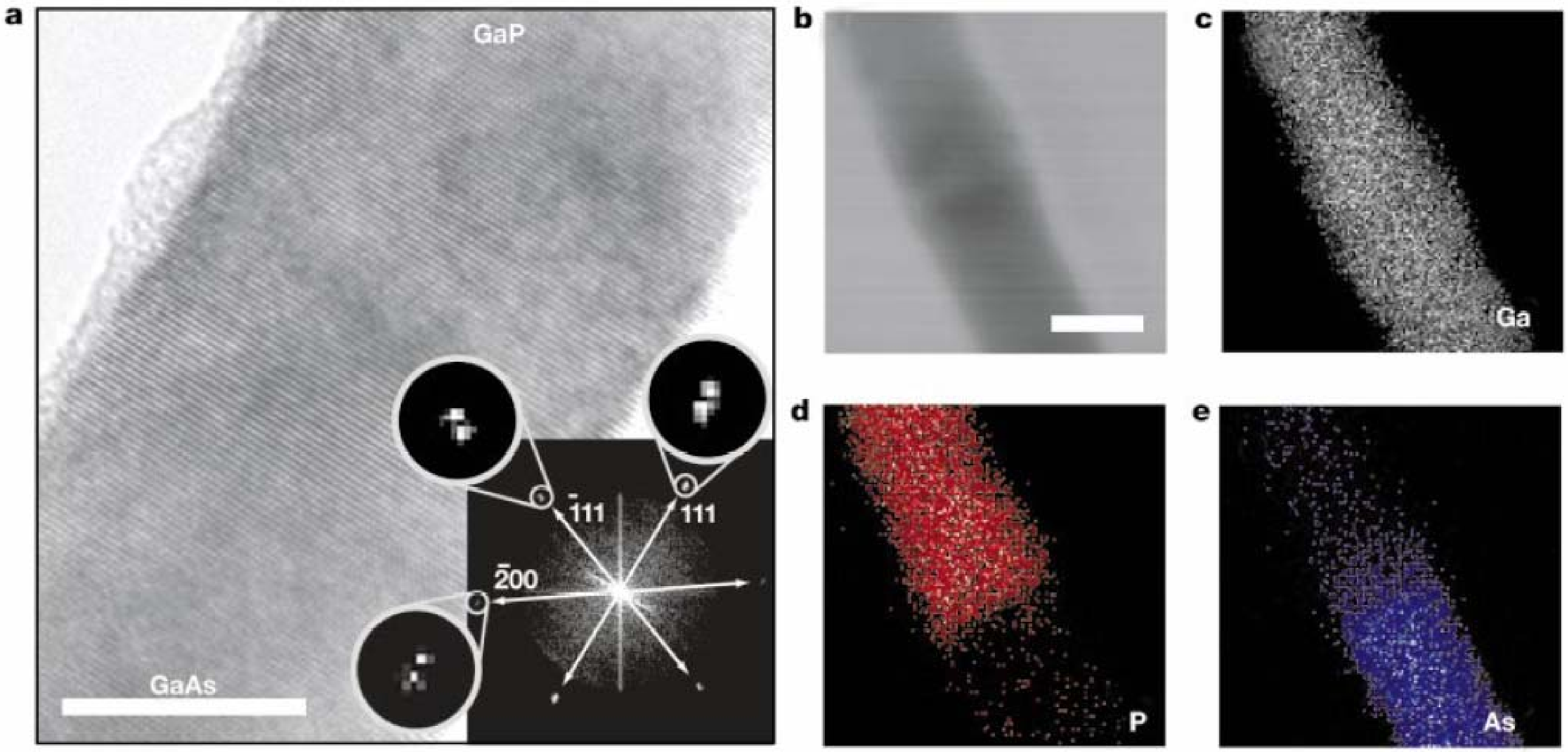


GaP: indirect bandgap
GaAs: direct bandgap

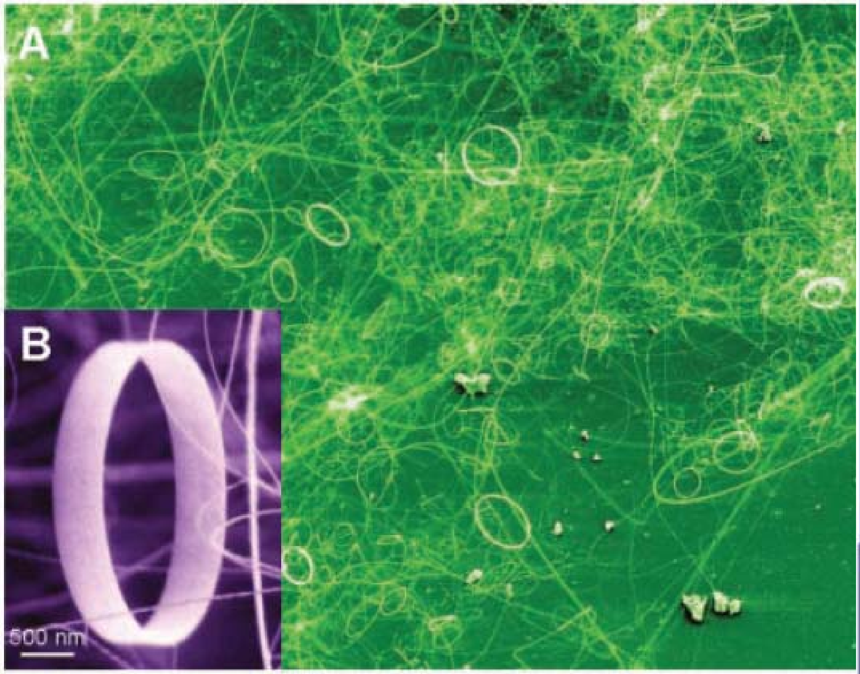
Nanowire axial heterostructures

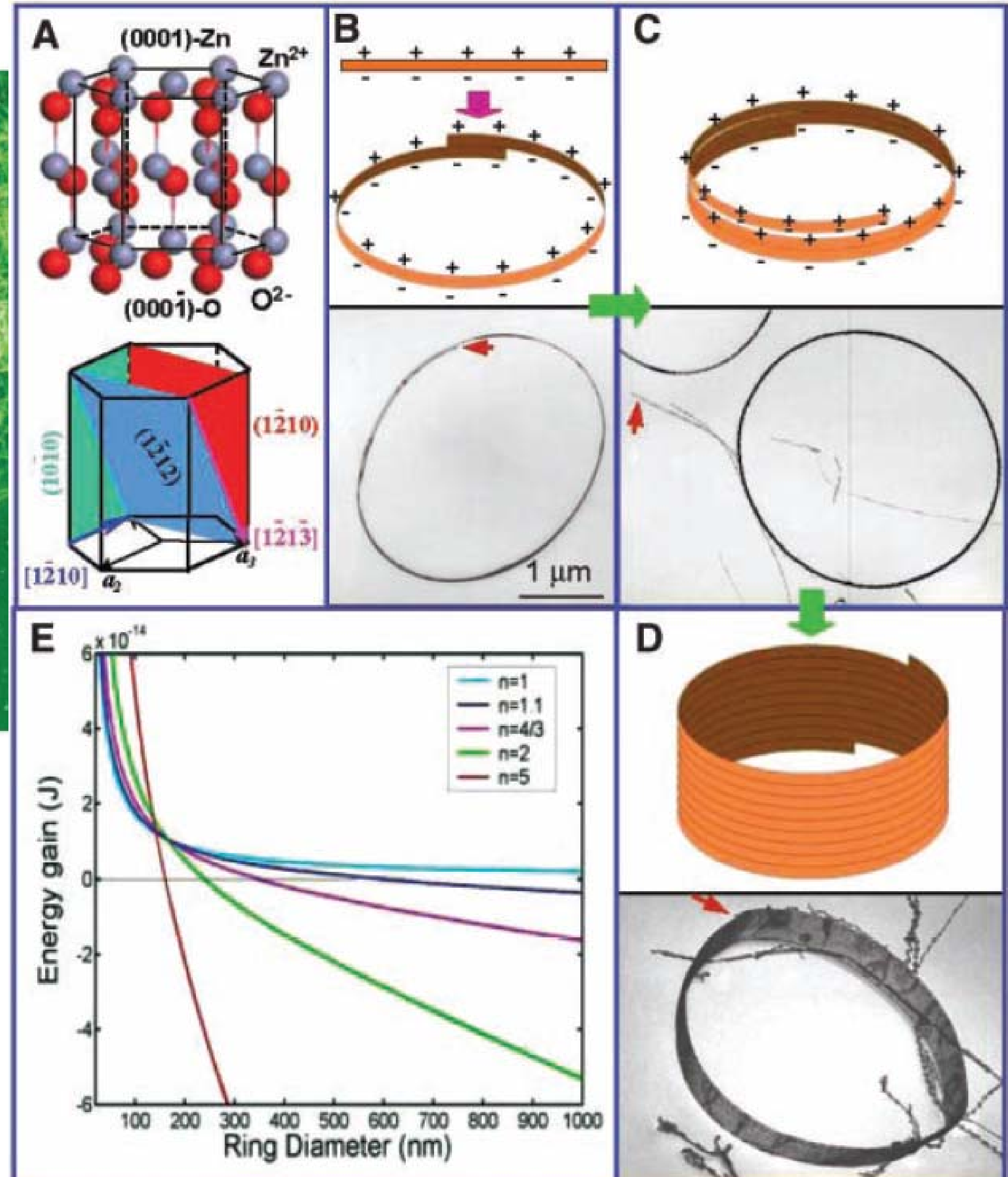
Gudiksen, Nature 415, 617-620 (2002).





Thermal evaporation and self-assembly formation of nanowires



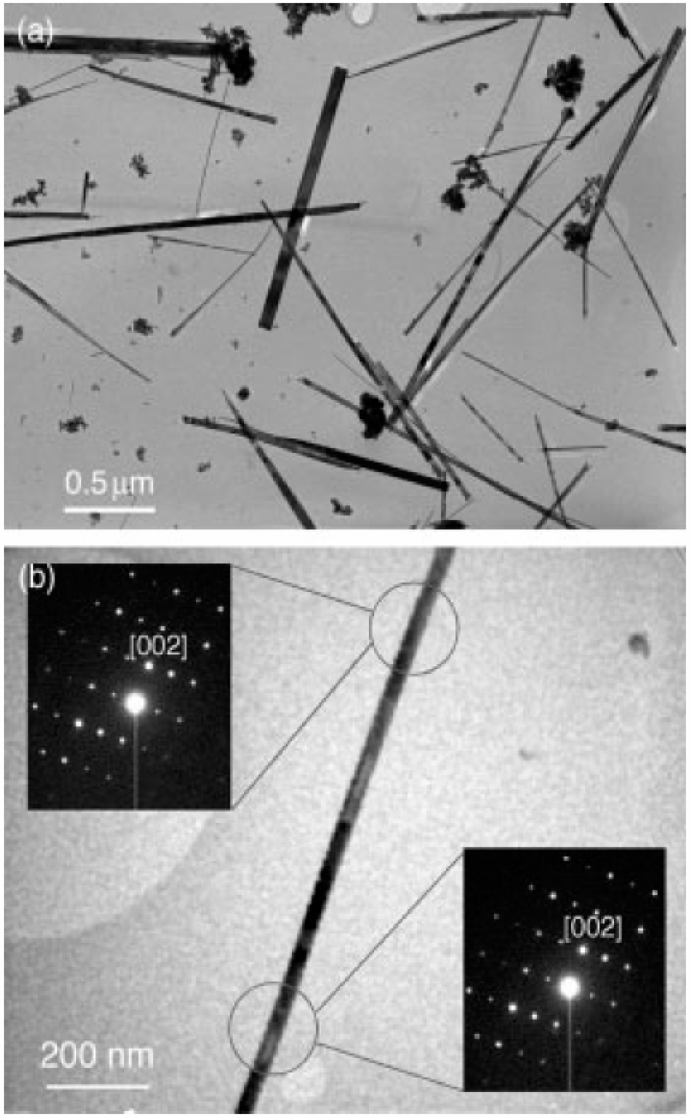


Thermal evaporation of ZnO
Nanowires and nanorings collected at cold finger
Formation of nanowires, nanorings due to self-assembly

Kong, Science, **303**, 1348 (2004)

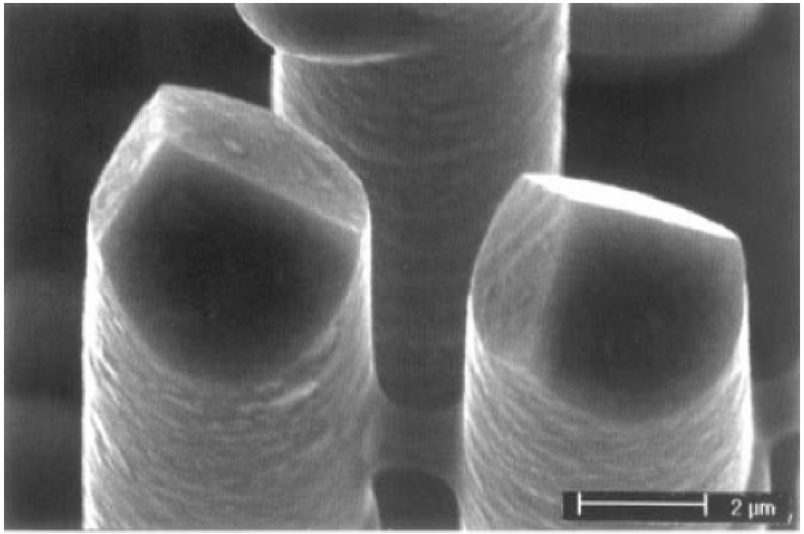
Solution based nanowire growth

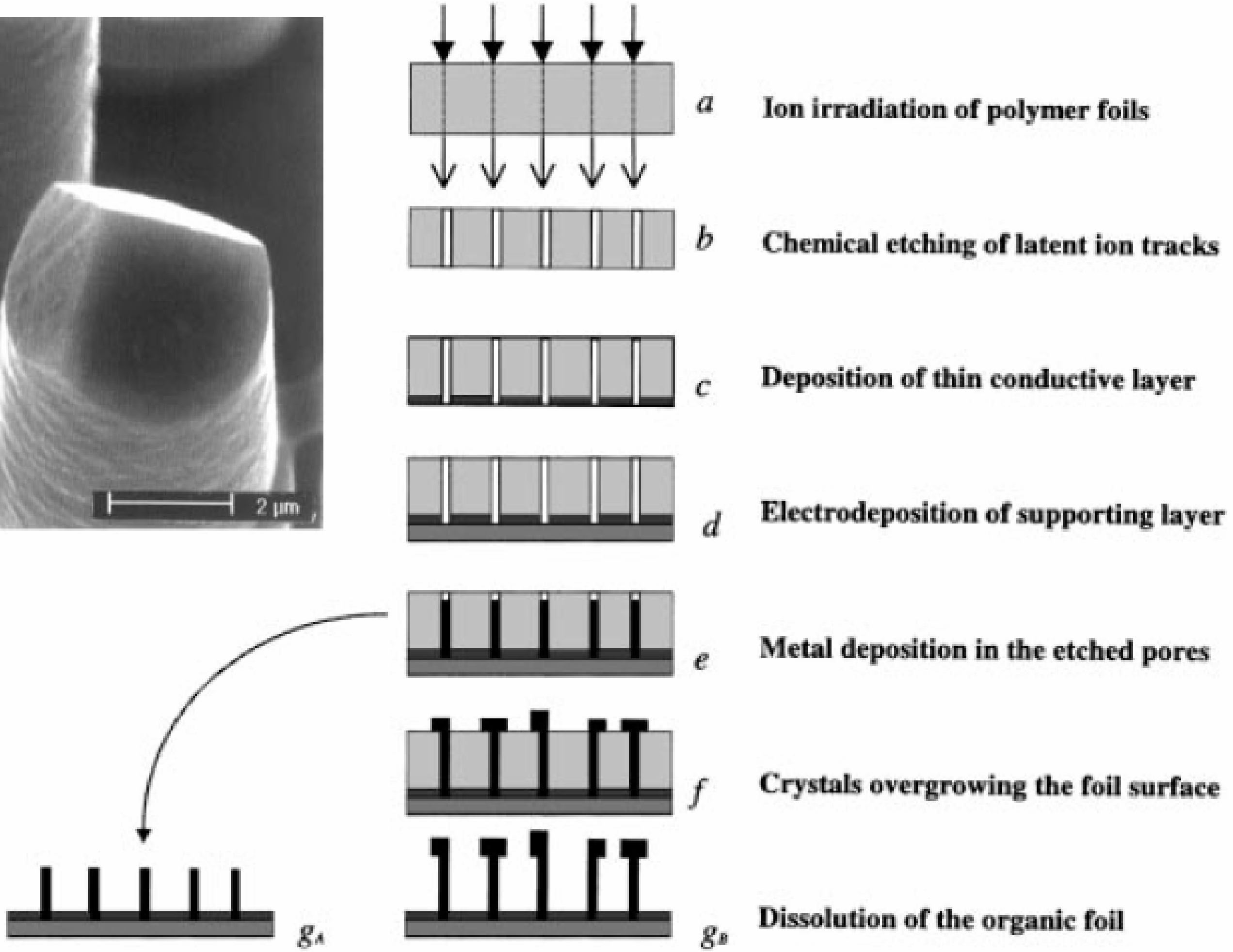
Solution phase decomposition of bimetallic precursors



Urban, Adv. Mater. **15,** 423 (2003)

Electroplating with polymer or anodized alumina membranes

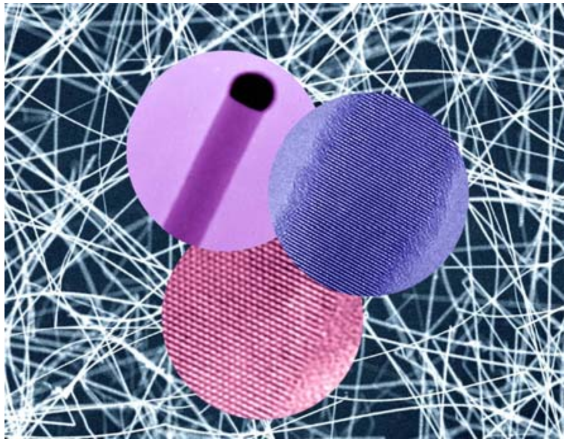


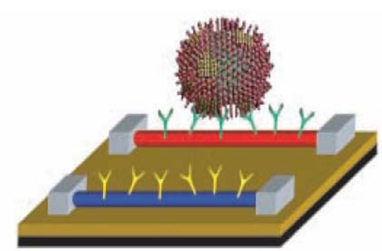


Dobrev, Appl. Phys. A, **69**, 233 (1999)

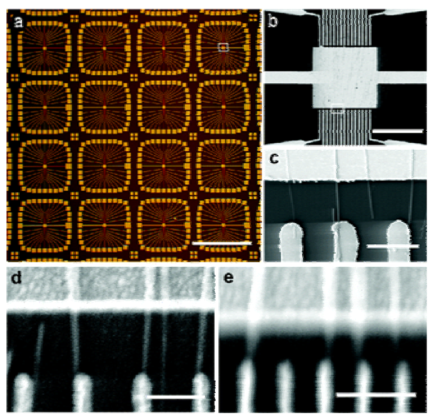
Separation of growth and device fabrication processes

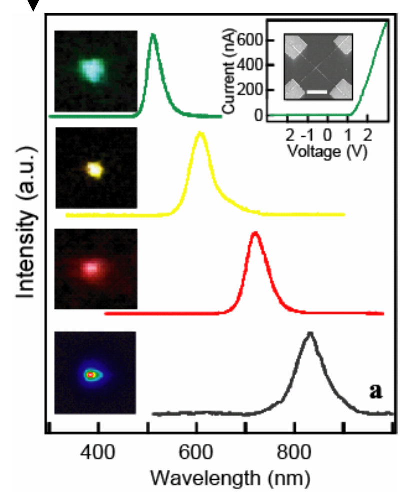
d ~ 10 nm
L ~ 20 μm

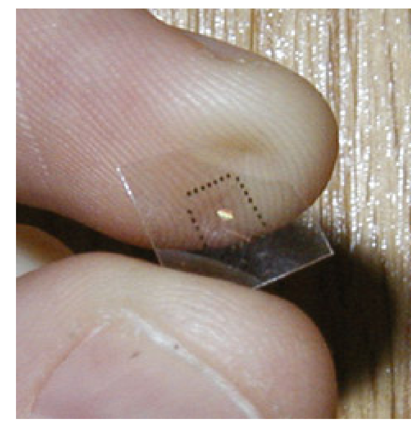




Single virus detection



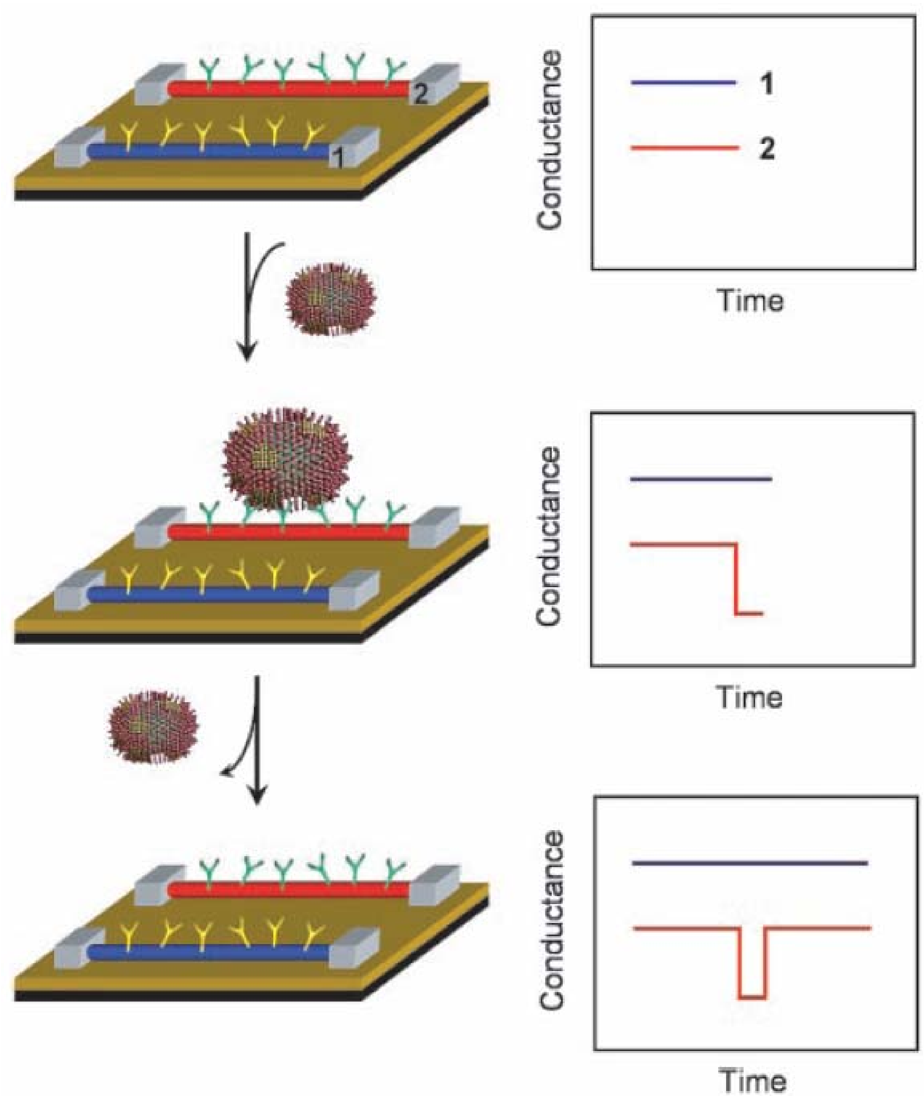




By separating the high temperature synthesis from assembly and device fabrication a diverse set of materials can be integrated together on a common platform.

Nanowire biosensors

F. Patolsky, PNAS **101**, 14017 (2004).



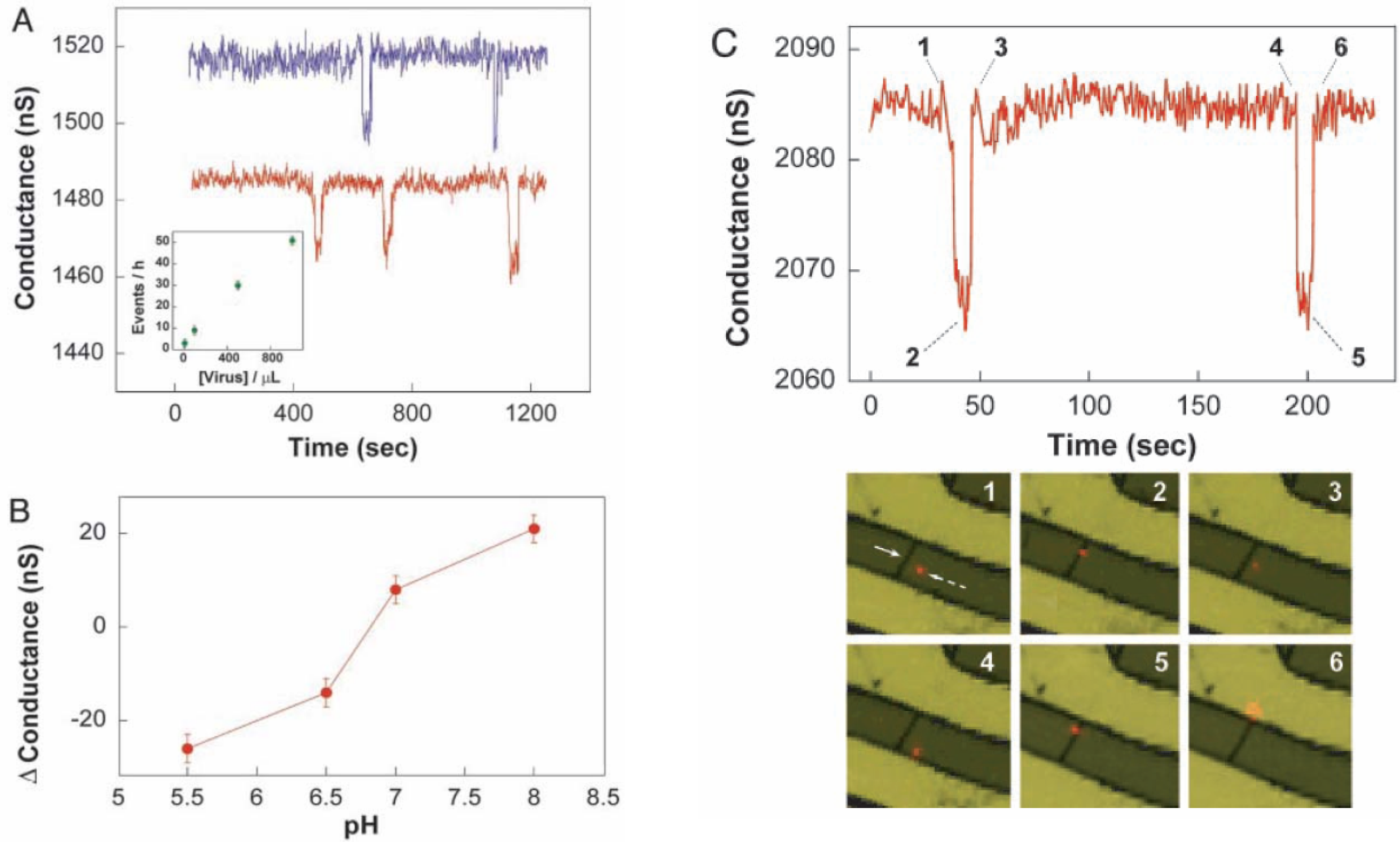
- Wire surface functionalized by antibody (ab-A)

- Virus A specifically binds to ab-A

- Conductance of the nanowire changes due to the local gating effect.

Nanowire biosensor

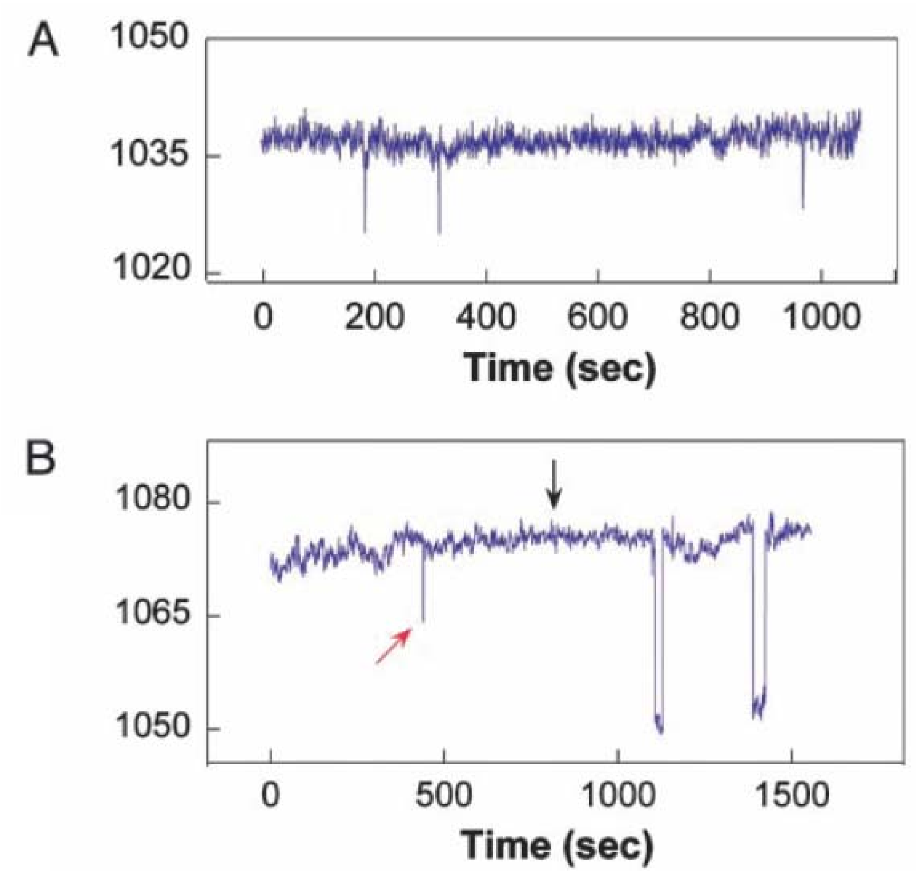
F. Patolsky, PNAS **101**, 14017 (2004).

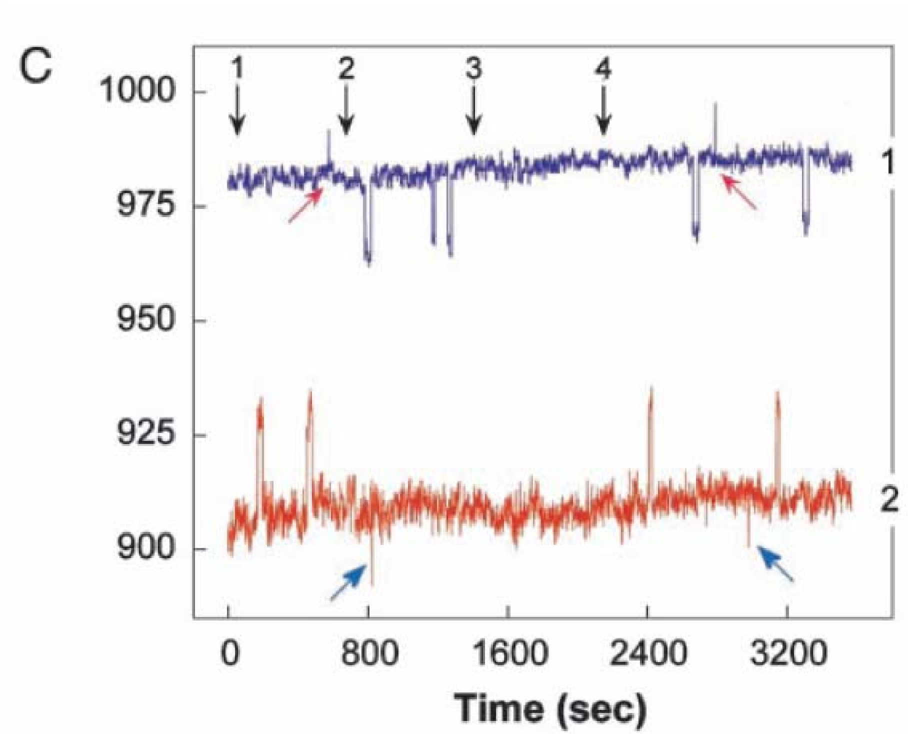


Single virus binding signals

Nanowire biosensor

F. Patolsky, PNAS **101**, 14017 (2004).



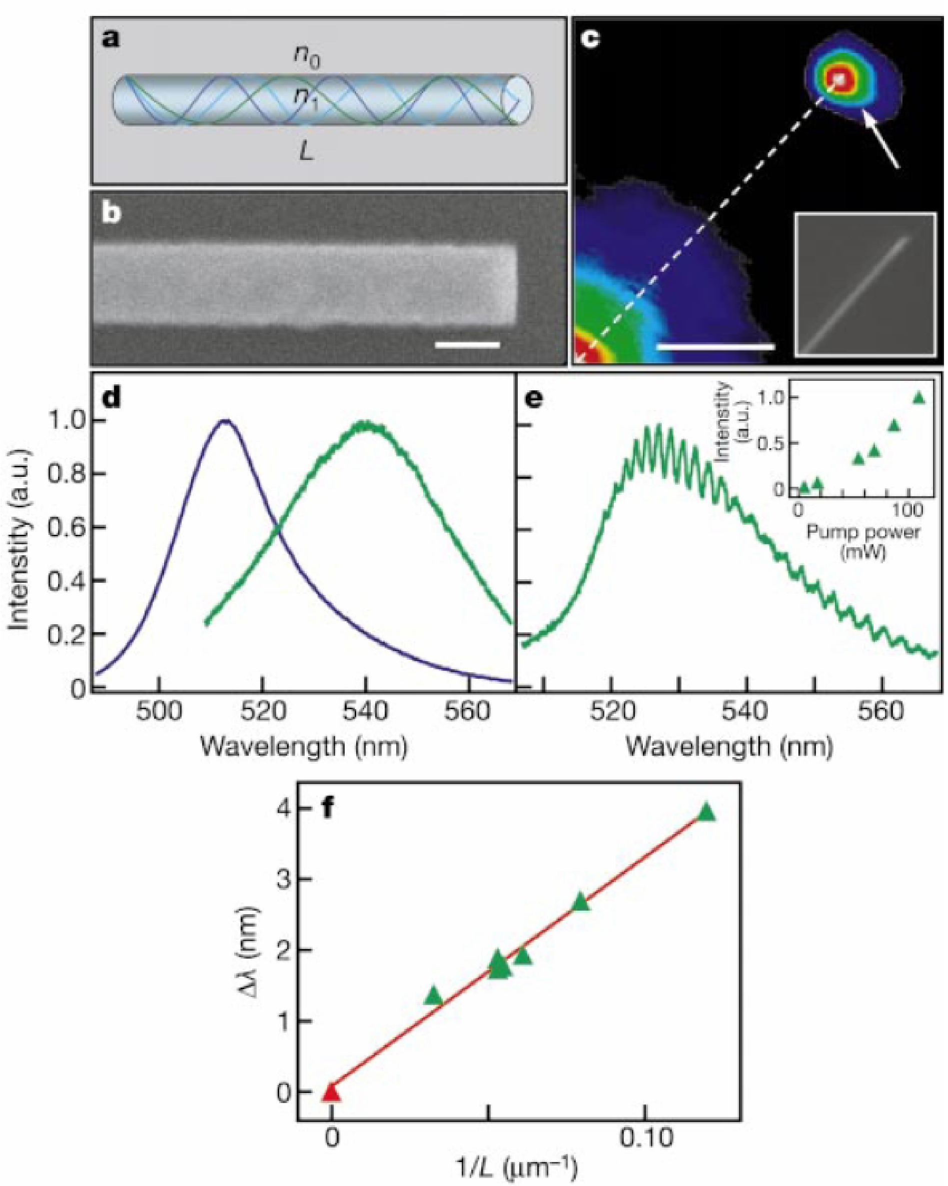


selectivity

Multiplexing detection

Nanowire optics

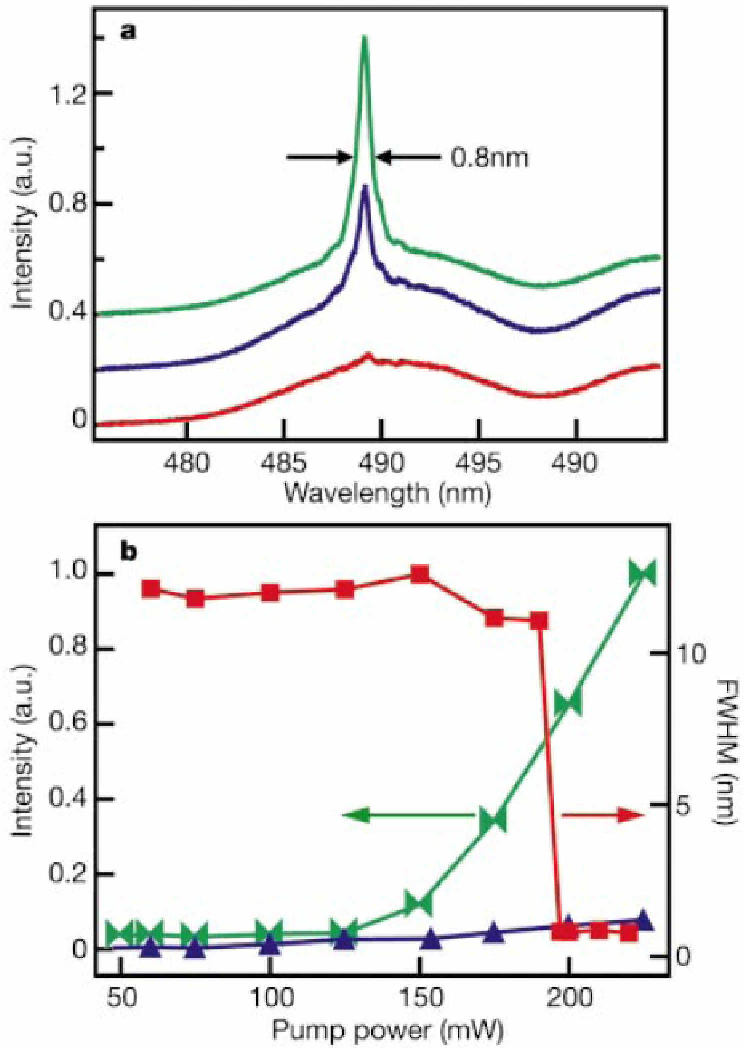
Duan, Nature **421**, 241 (2003)



- •ZnS nanowire as optical waveguide
- •Fabry-Perot interference due to reflection at the two ends, discrete cavity modes
- •End emission vs. body emission

Lasing via optical carrier injection

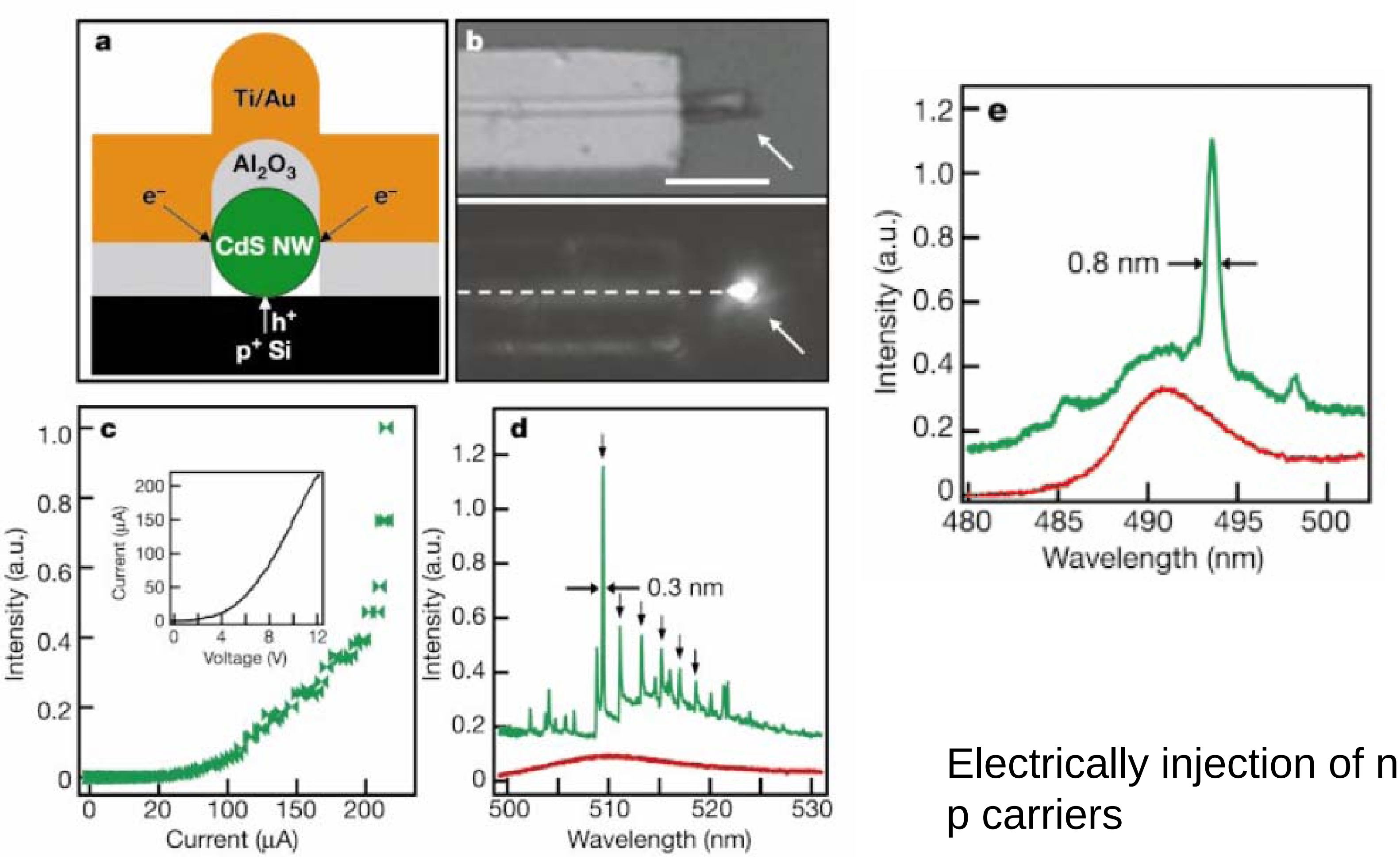
Duan, Nature **421**, 241 (2003)



- •Amplified spontaneous emission in the ZnS nanowire medium (superlinear vs. pump power)
- •Lasing occurs soon above threshold

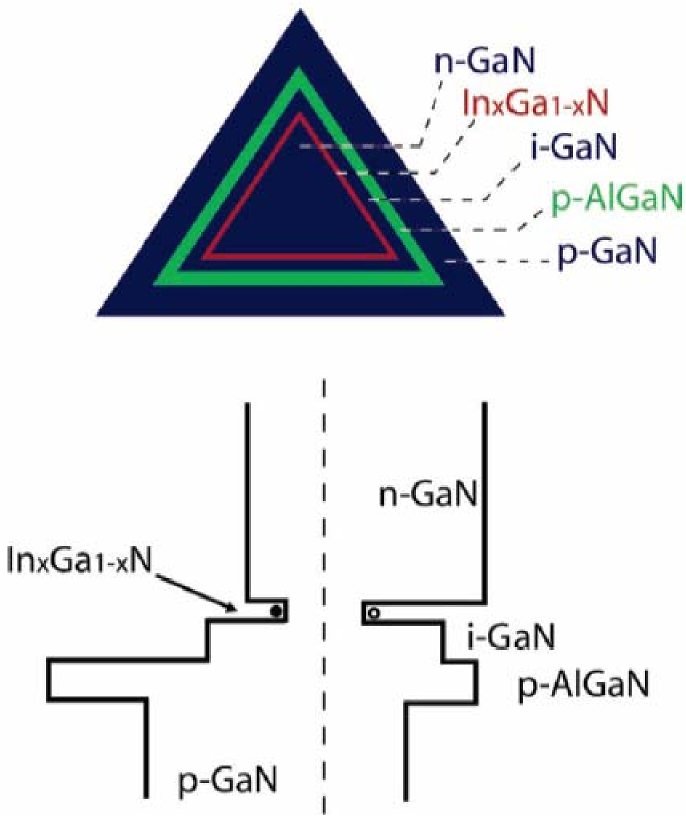
Lasing via electrical carrier injection

Duan, Nature **421**, 241 (2003)

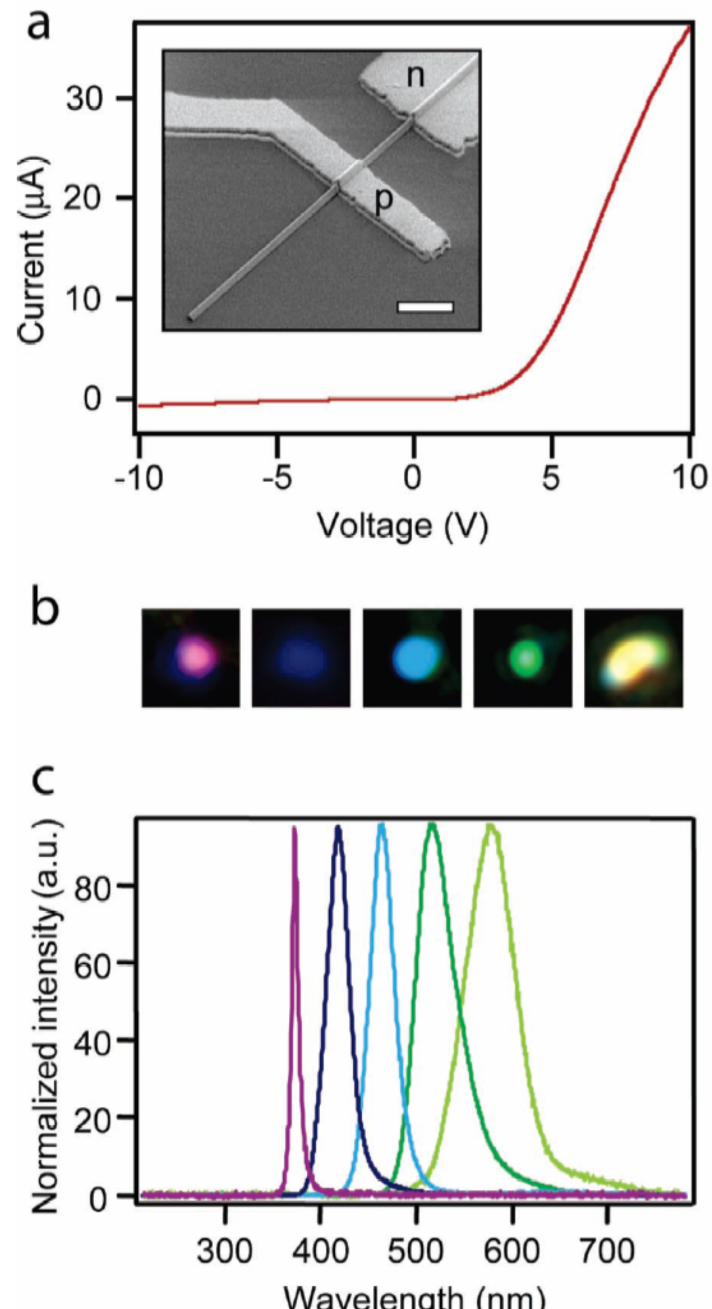


Electrically injection of n, p carriers

Core/multishell nanowire LED



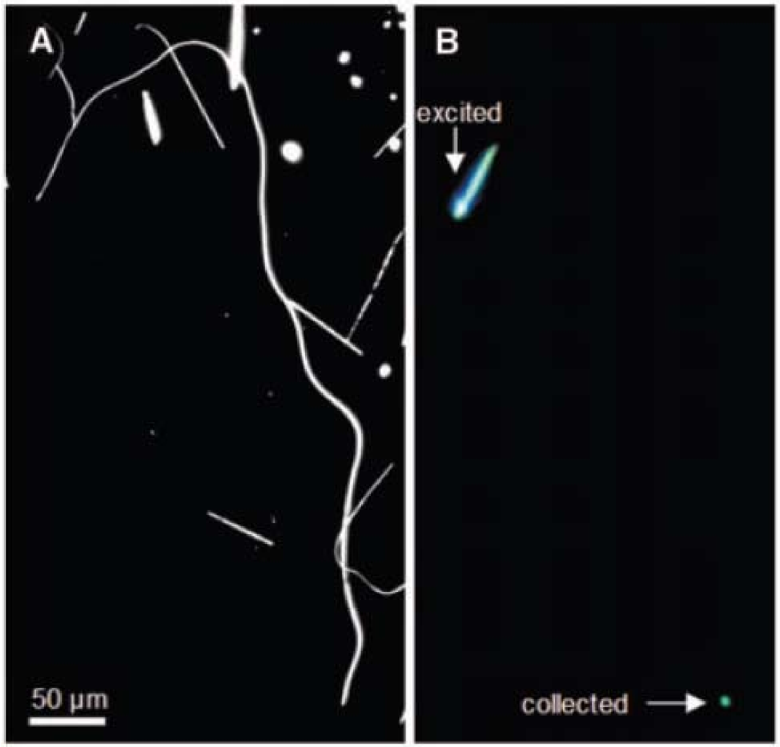
Band gap of the InGaN quantum well can be tuned by In/Ga ratio

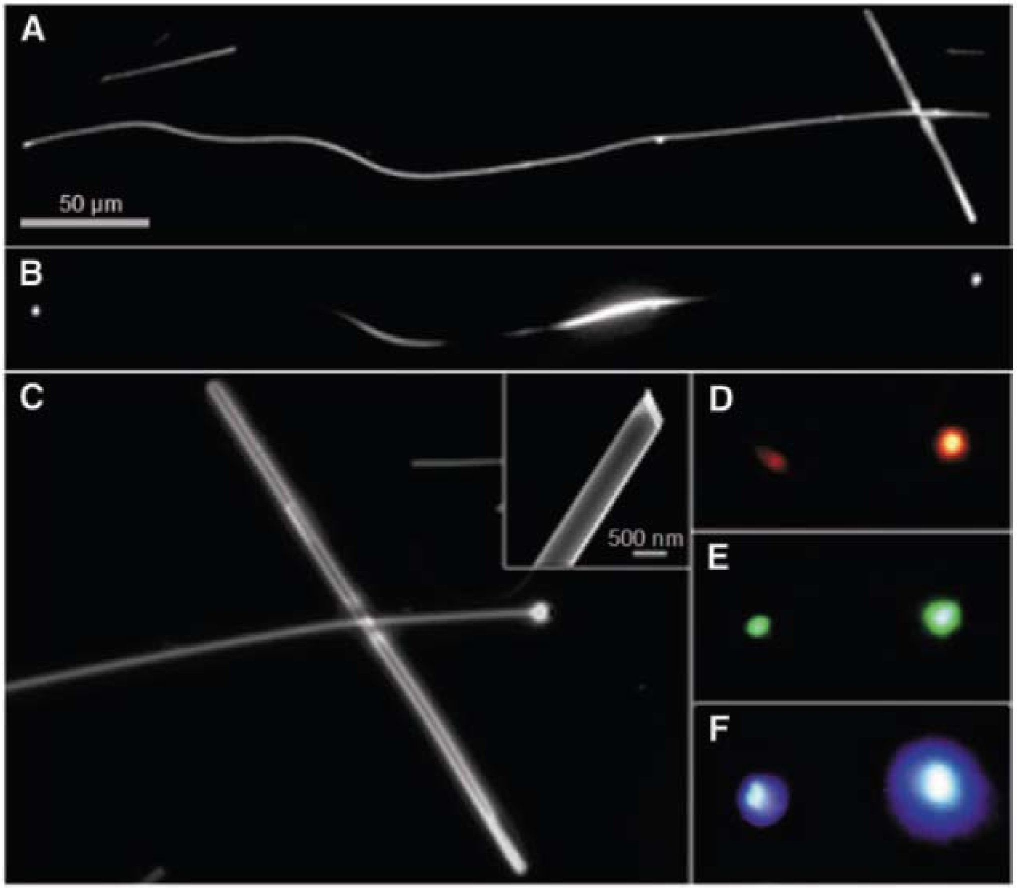


Qian, Nano Lett. ASAP, (2005)

Nanowire (nanoribbon) waveguide

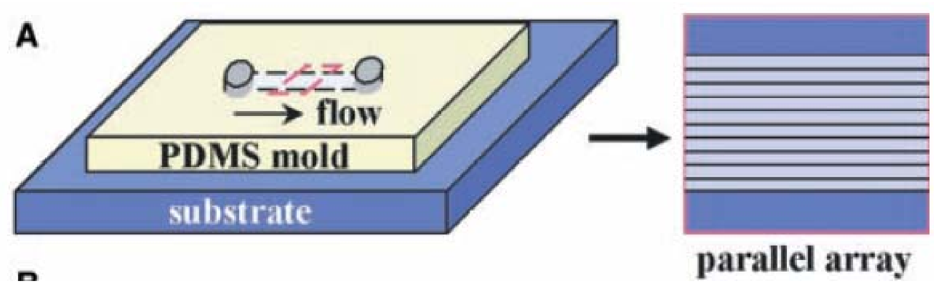
Law, Science, **305**, 1269, (2004)



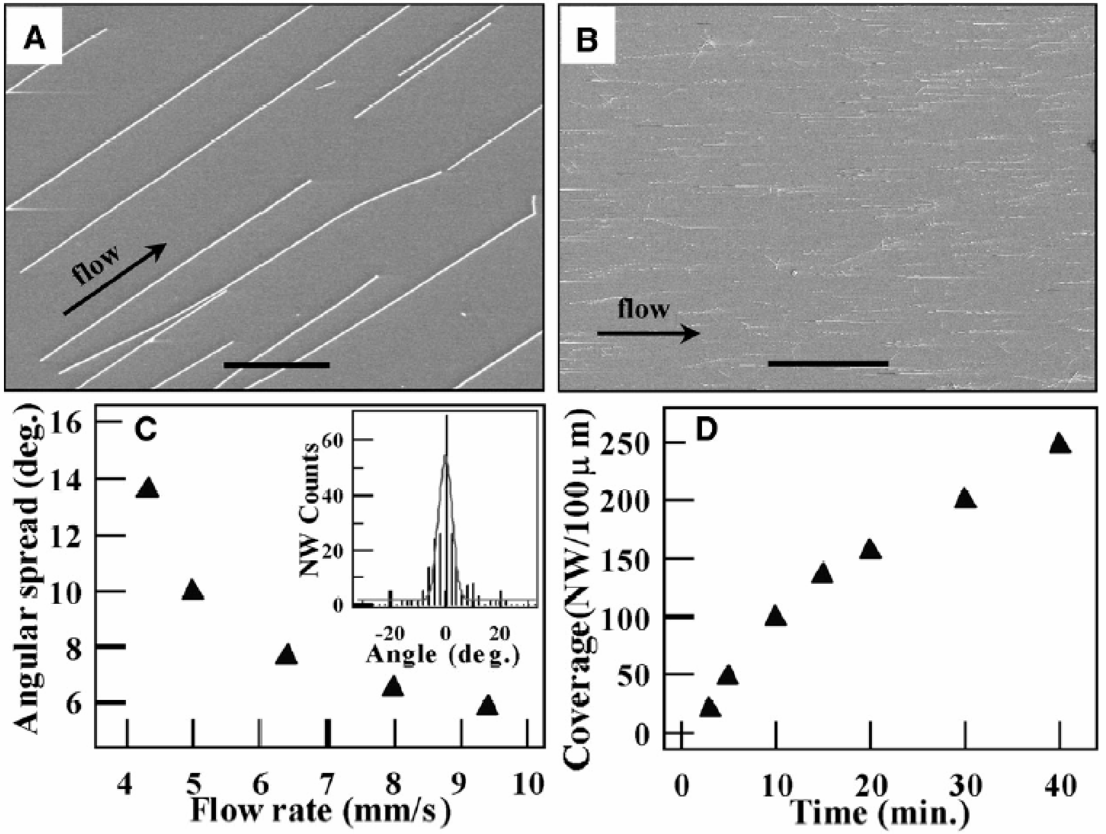


mm long SnO_2 nanoribbon waveguides

Assembly of nanowires via flow alignment

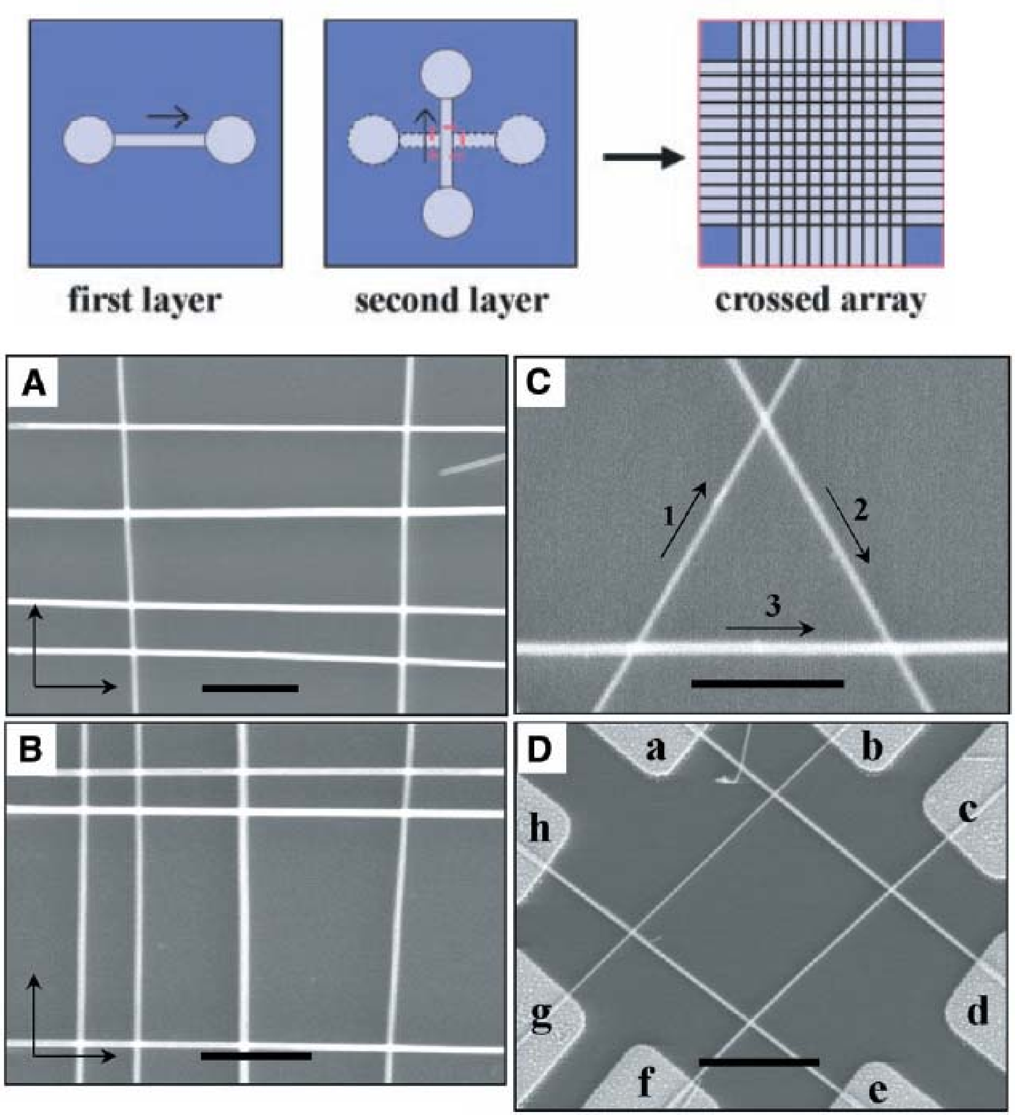


Analogous to flowing logs of wood down the river



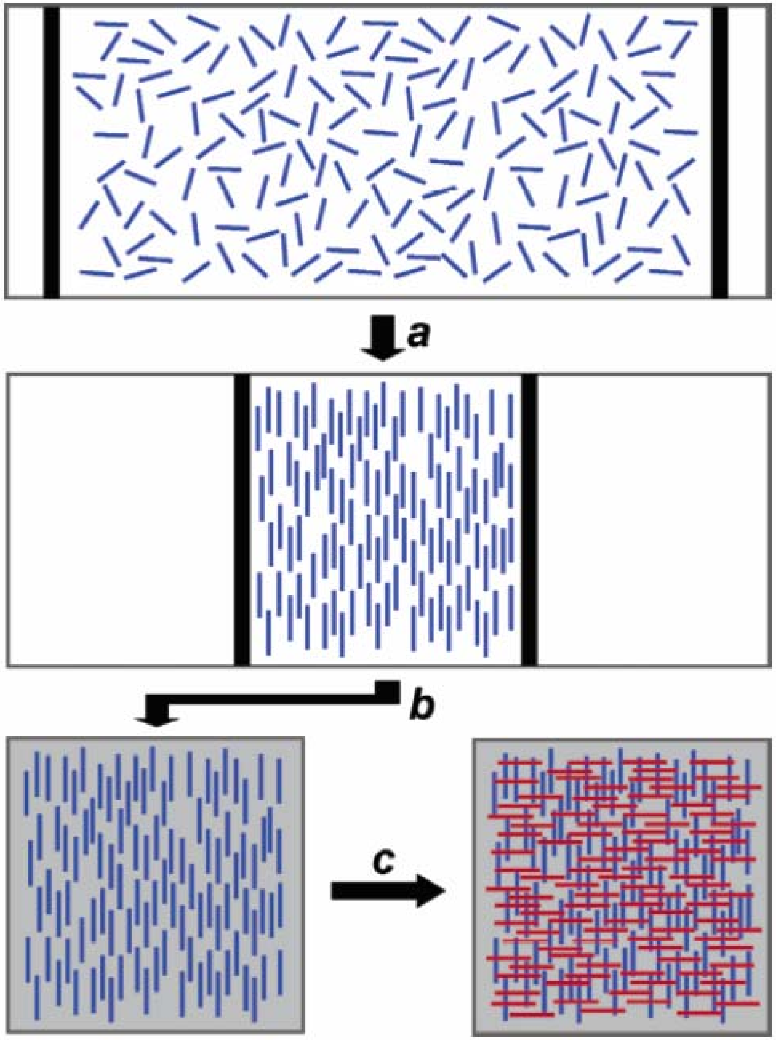
Assembly of nanowires via flow alignment

Y. Huang, Science **291**, 630 (2001).



Assembly of nanowires via Langmuir-Blodgett technique

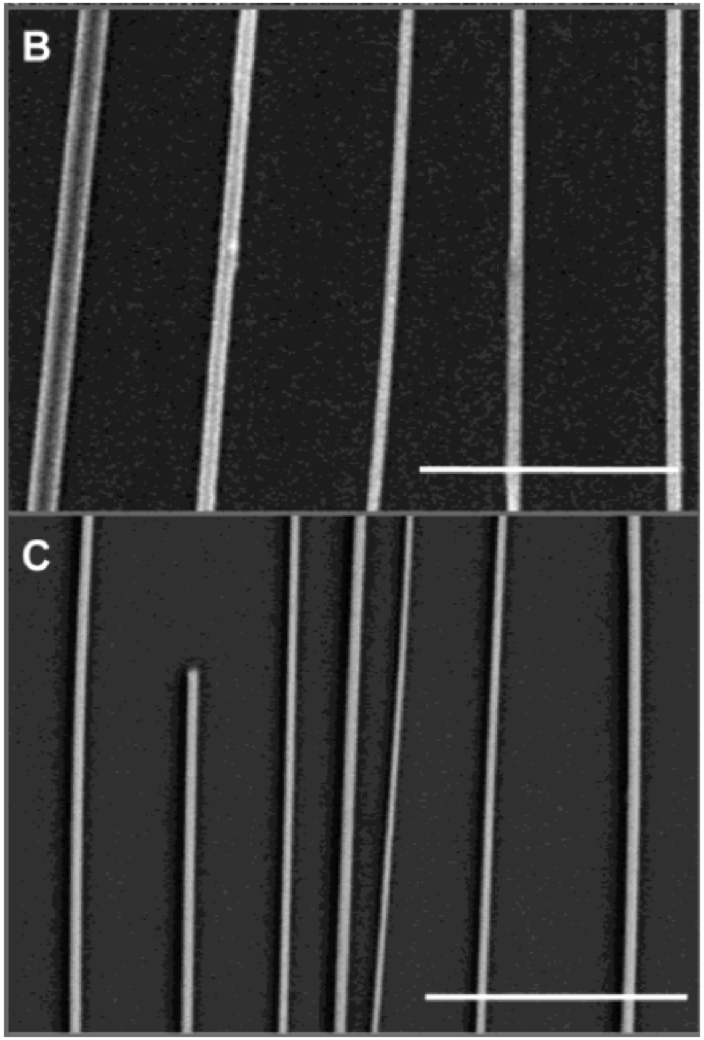
Whang, Nano Lett. **3**, 1255 (2003).

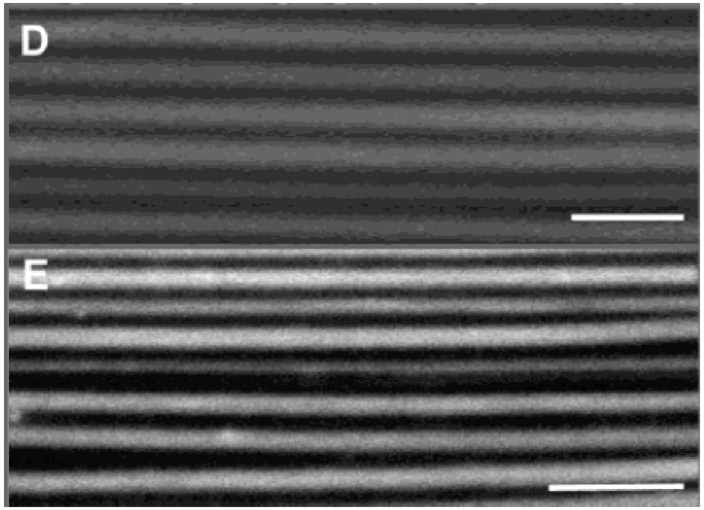


- Nanowires forming a film at the air/liquid interface
- Squeezing the film by the two impedances causes the wires to align with the impedance
- Large scale assembly possible

Assembly of nanowires via Langmuir-Blodgett technique

Whang, Nano Lett. **3**, 1255 (2003).

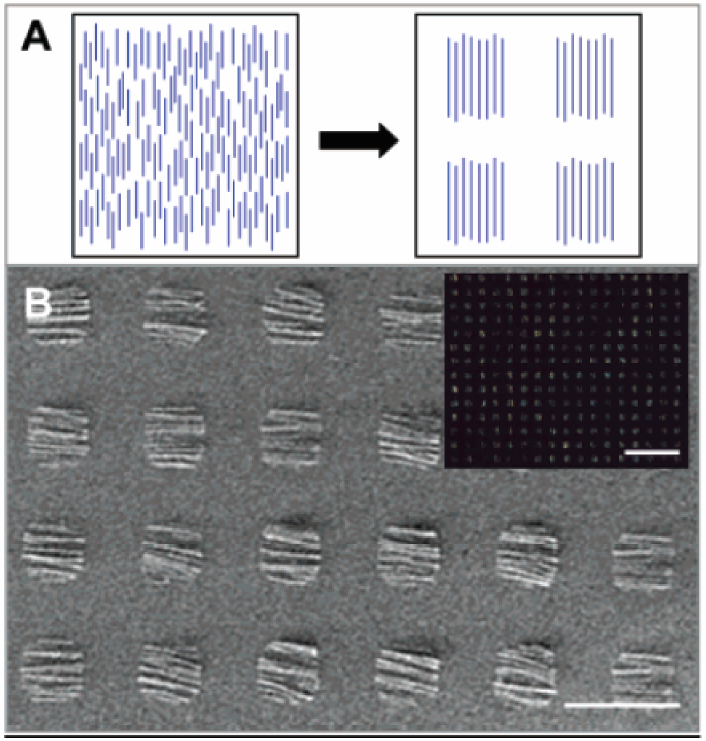


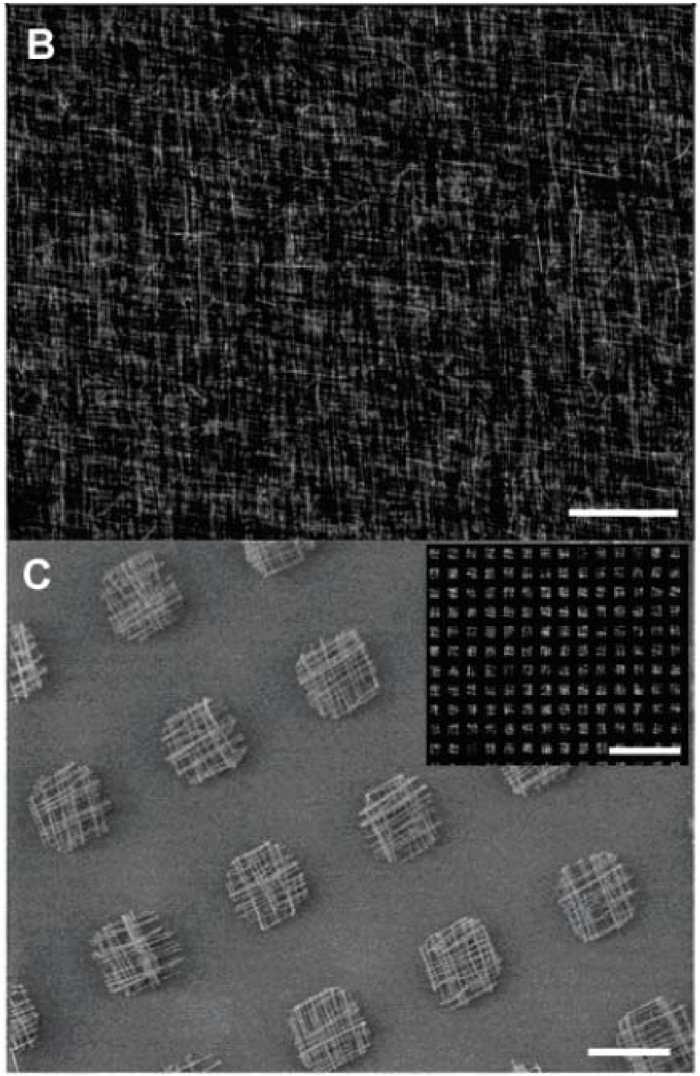


Control the spacing by controlling pressure between the impedances

Assembly of nanowires via Langmuir-Blodgett technique

Whang, Nano Lett. **3**, 1255 (2003).

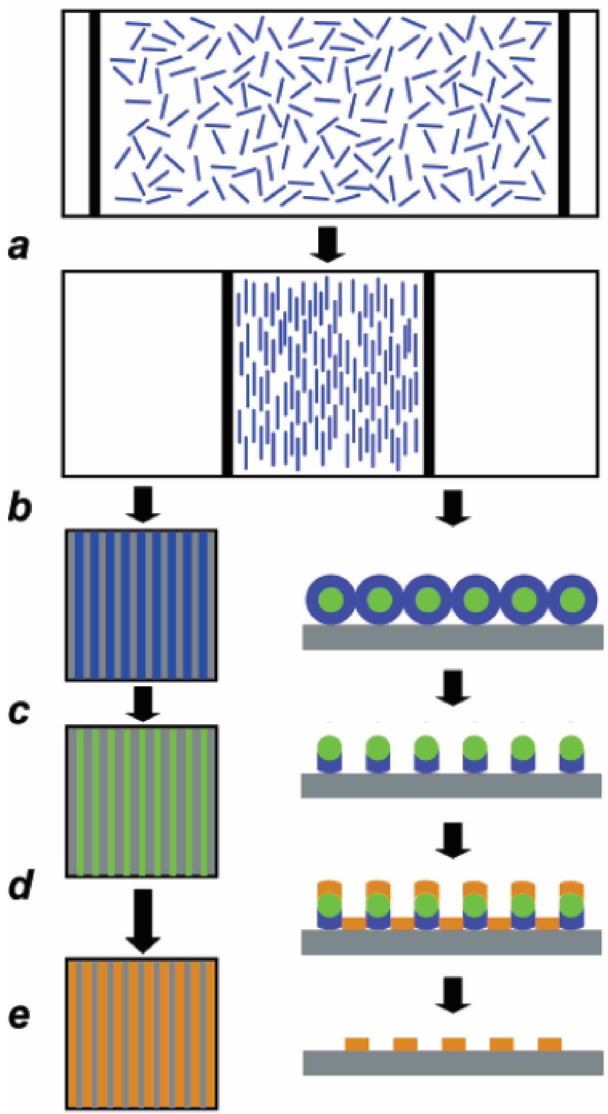


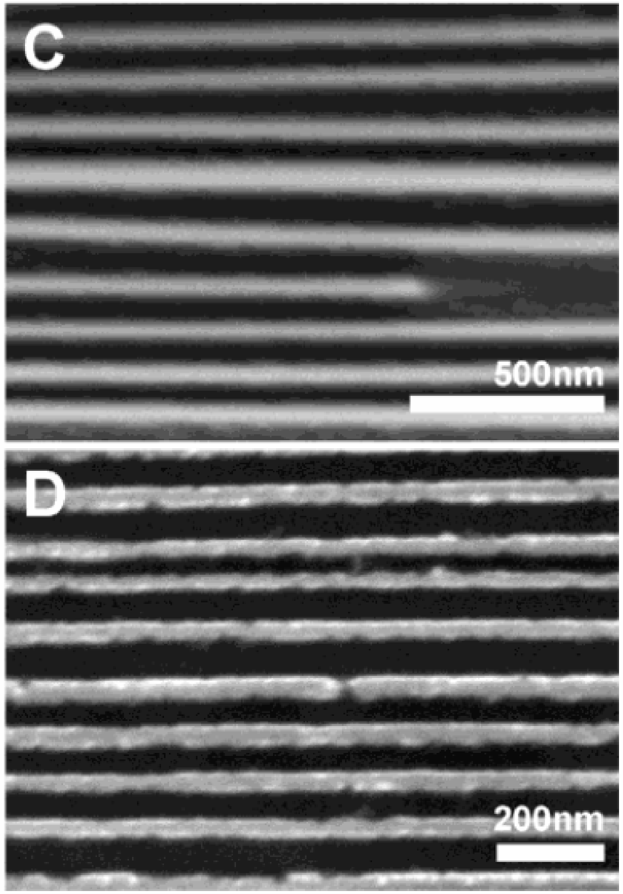


Pattern formation by selectively removing excess wires

Assembly of nanowires via Langmuir-Blodgett technique

Whang, Nano Lett. **3**, 951 (2003).

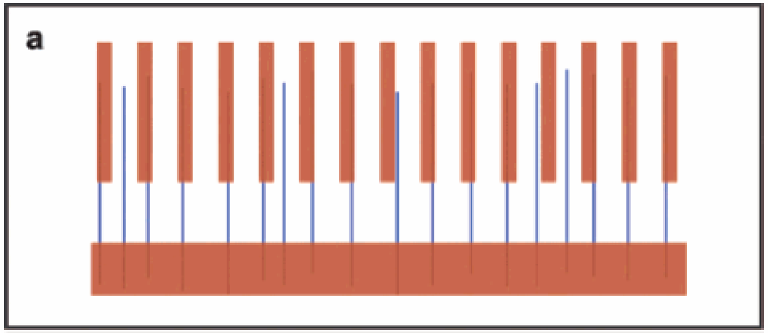


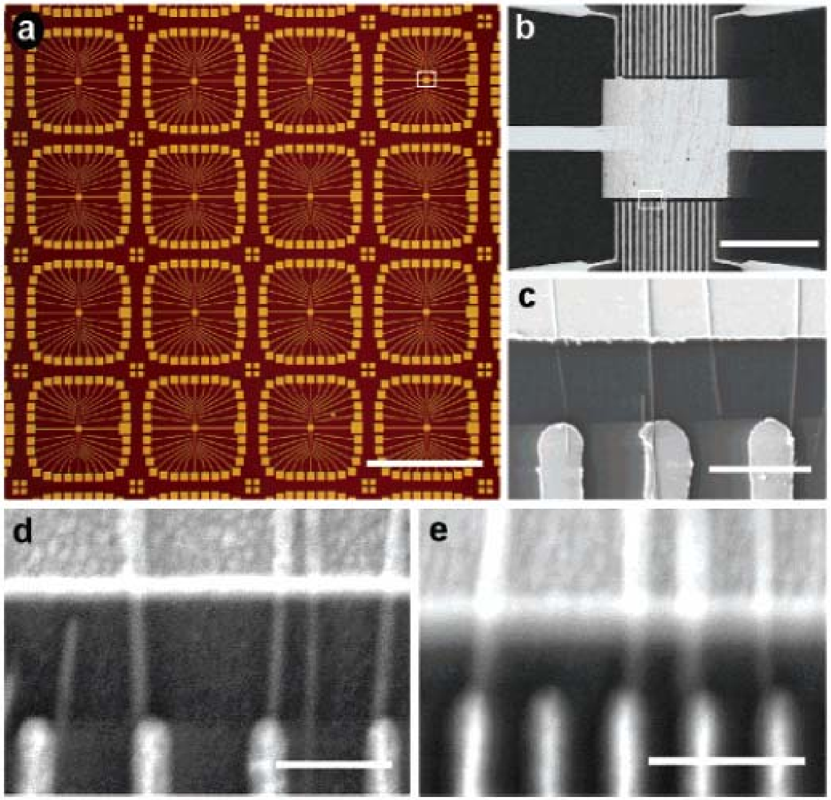


Spacing can also be controlled via a sacrificial shell layer

Assembly and integration

Jin, Nano Lett. **4**, 915 (2004)

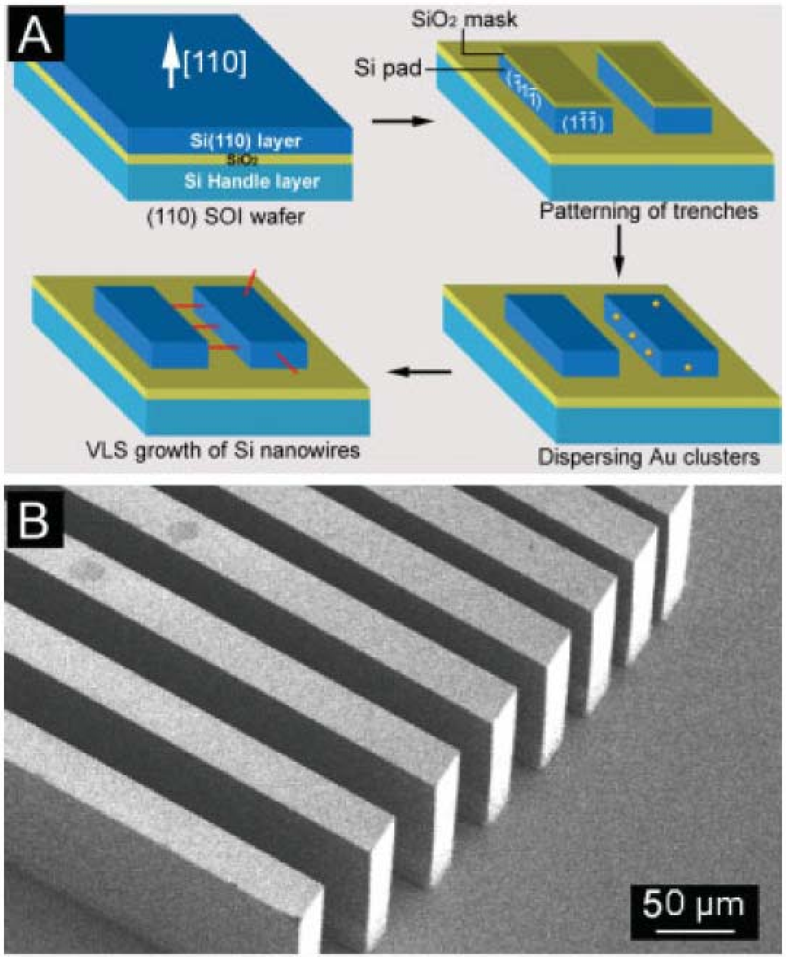


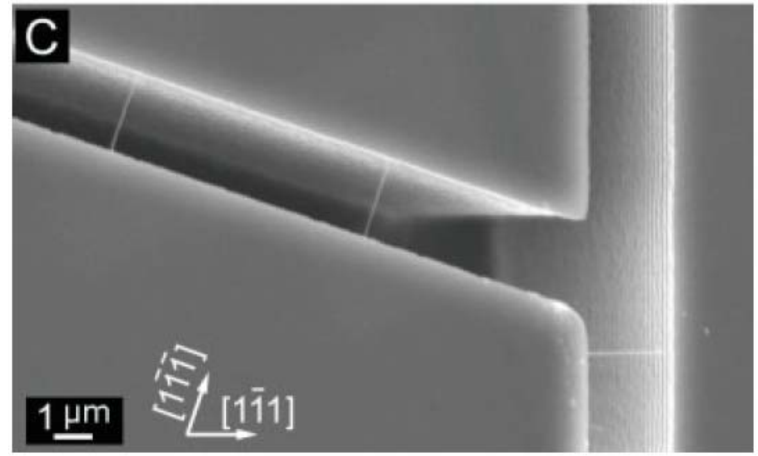


Large scale application may be realized without registration

Si nanowires directly bridging contacts

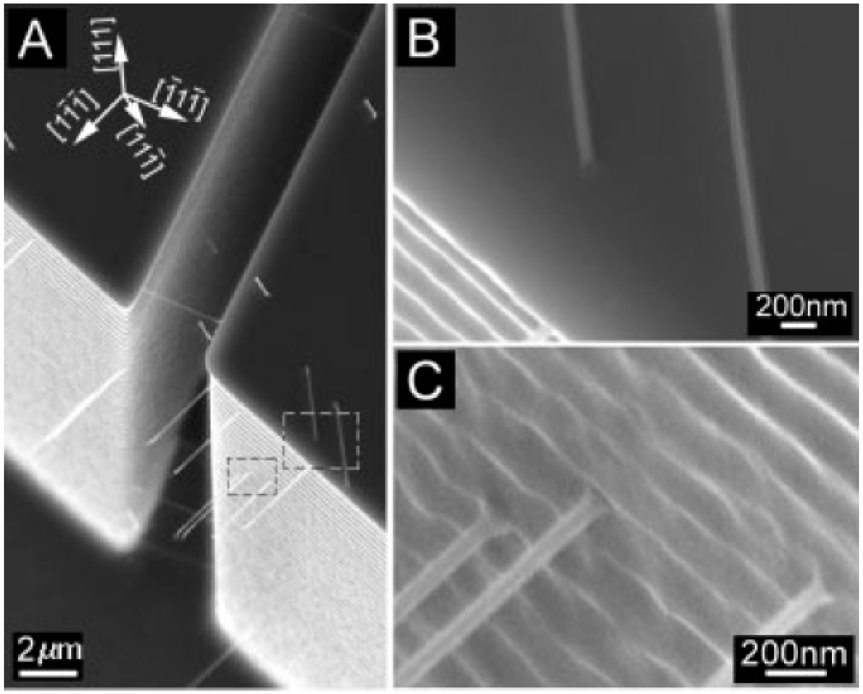
He, Adv. Mater. **17**, 2098 (2005)

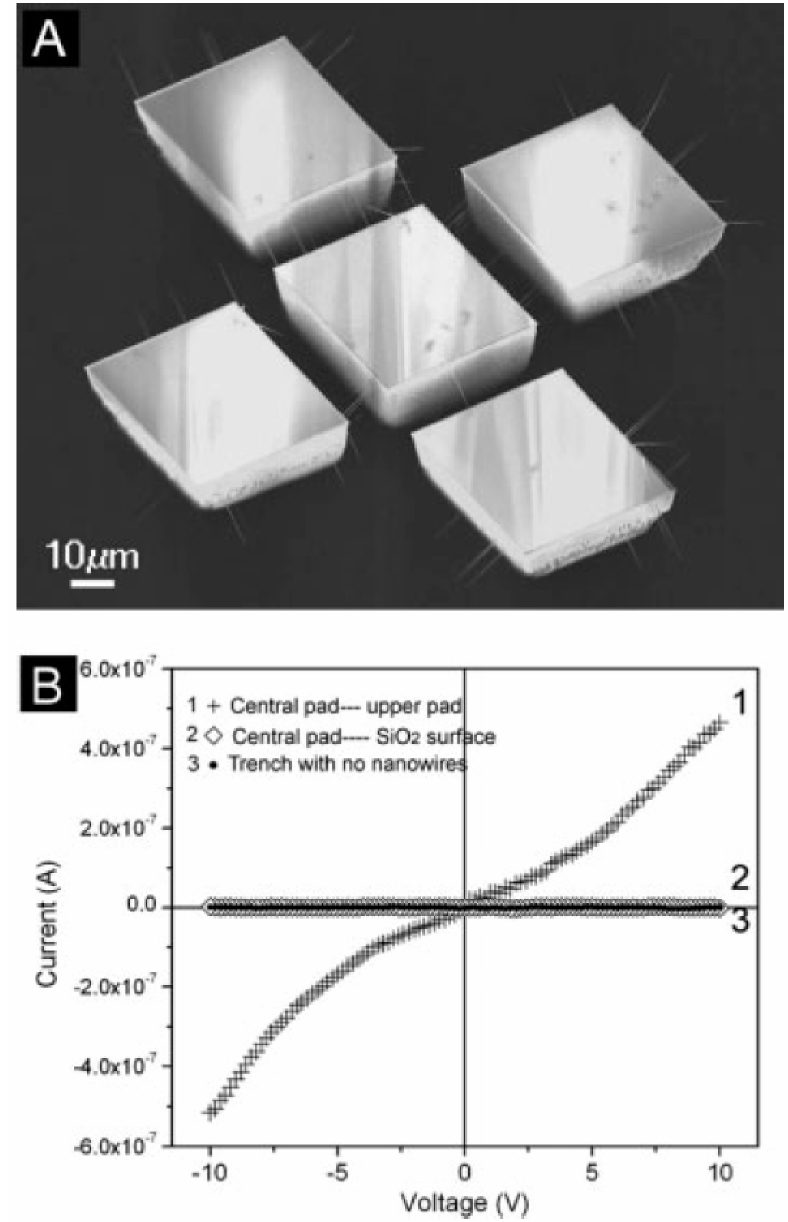




Si nanowires can be epitaxially grown on Si <111> surface

Si nanowires directly bridging contacts

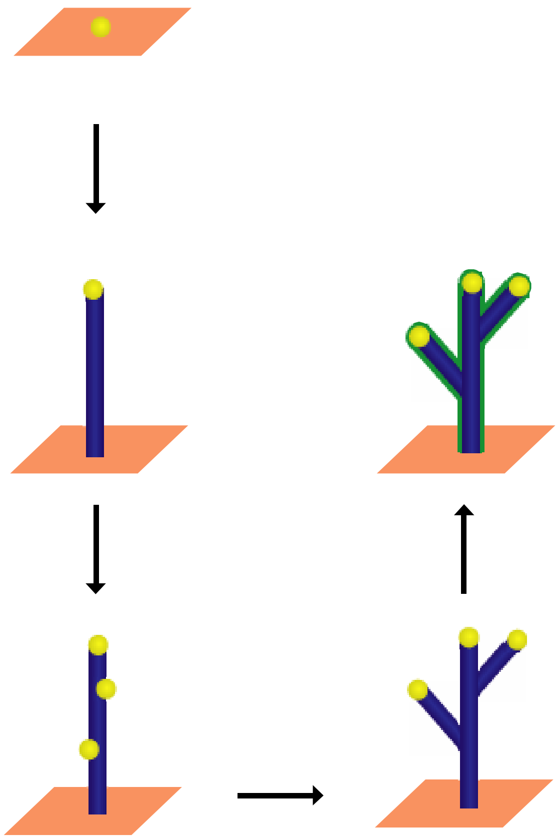


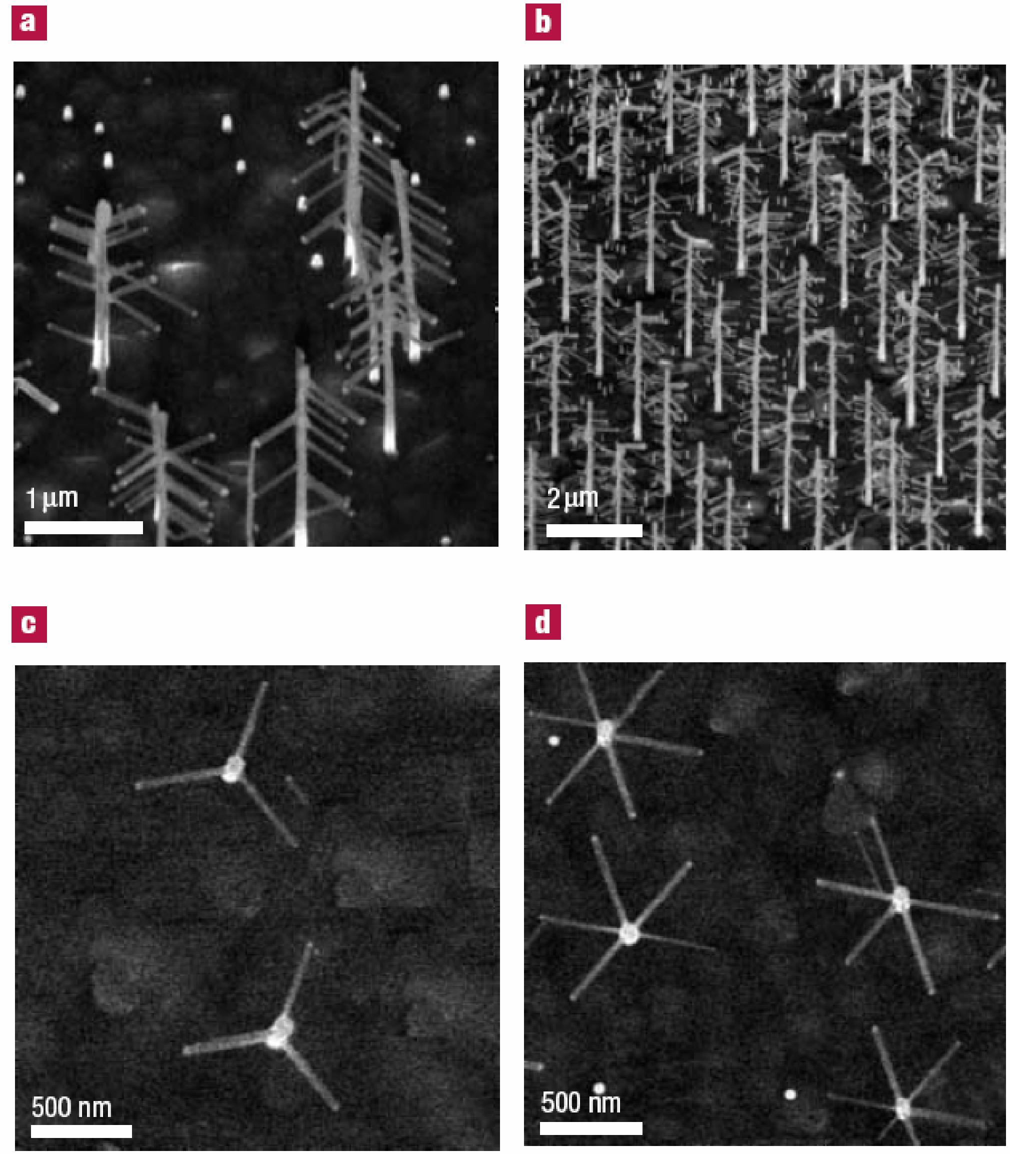


He, Adv. Mater. **17**, 2098 (2005)

Dick, Nature Mater **3**, 380 (2004)

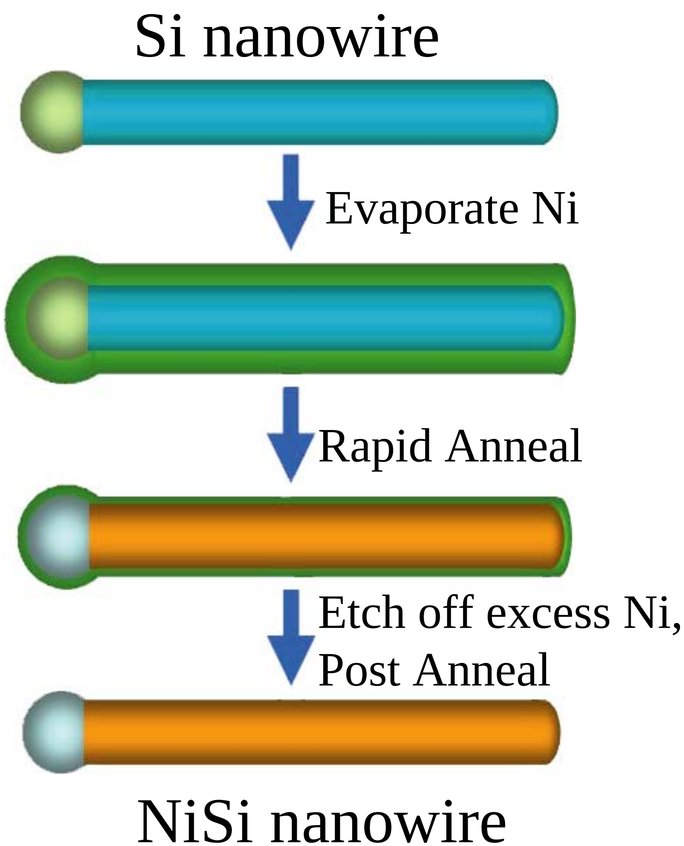
Branched nanowires



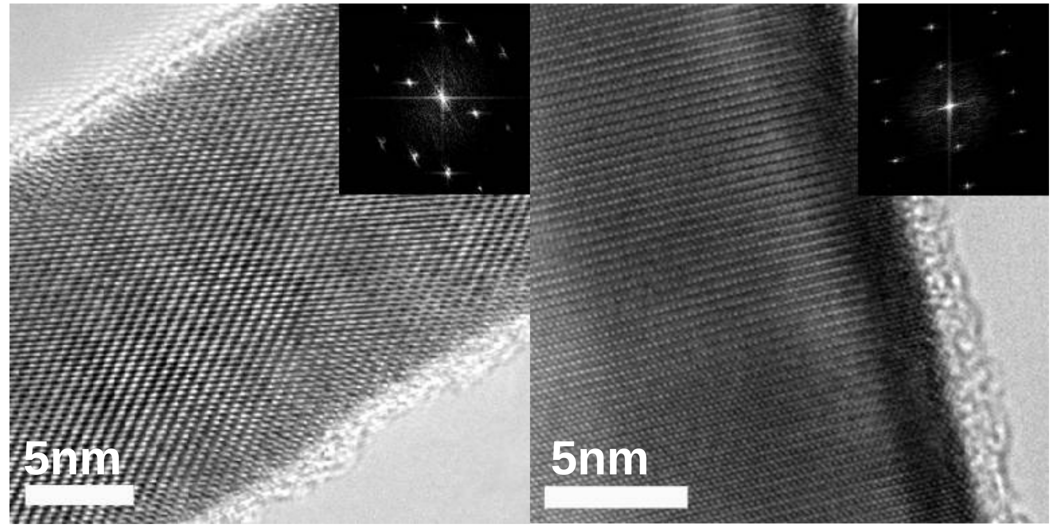


GaP nanowires via VLS and MOCVD

Fabrication of single crystalline metallic nanowires from SiNWs

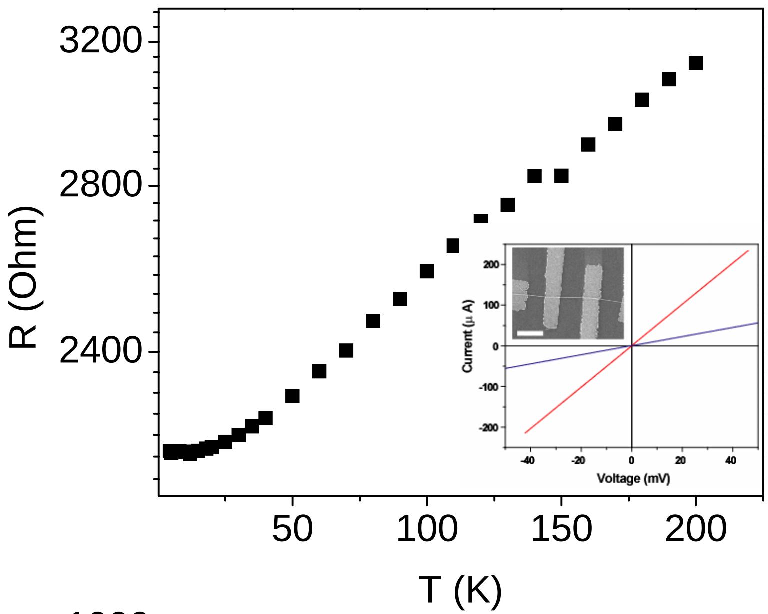


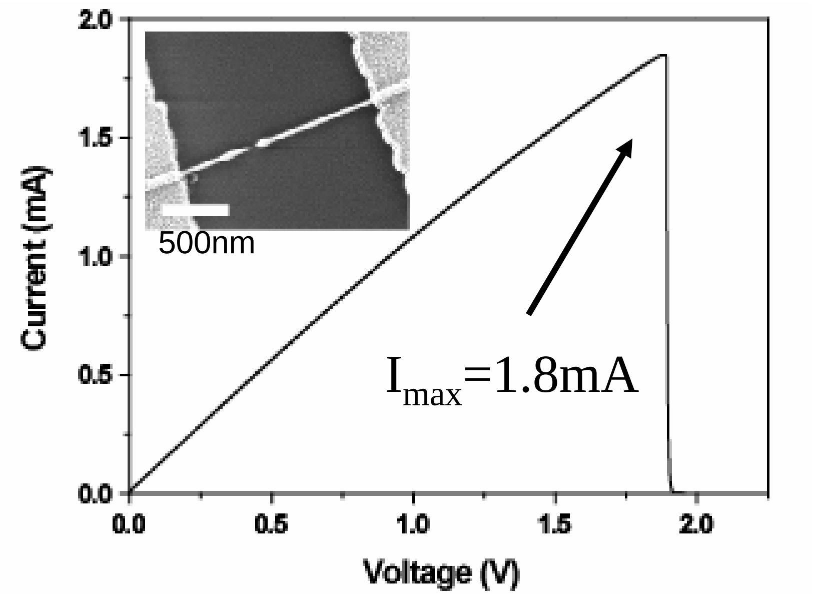
$Si + Ni \rightarrow NiSi$

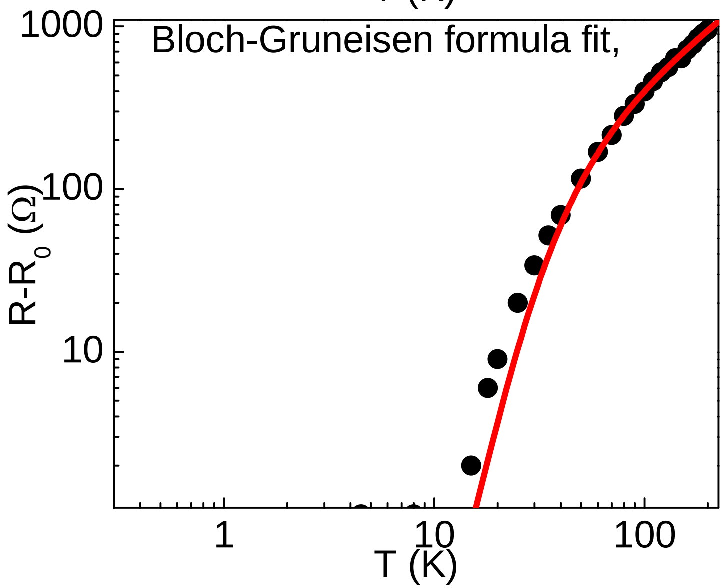


- Single Crystal
- NiSi 1:1 phase confirmed by EDS
- Diameter control inherited from Si nanowire

Pure NiSi Nanowires: Transport Measurement





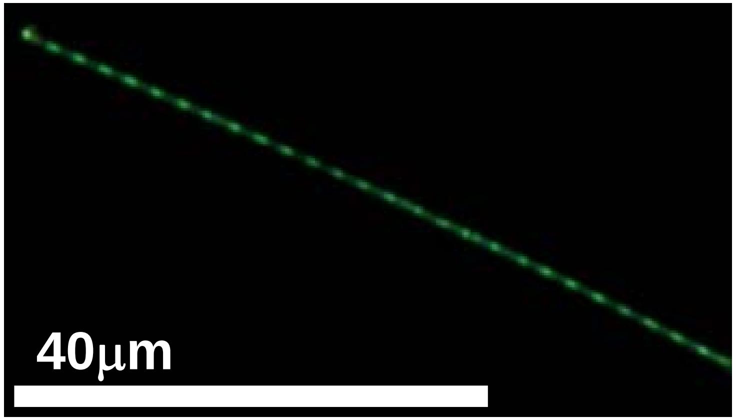


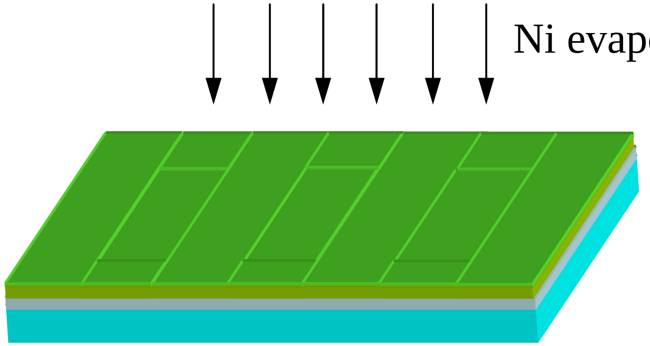
- Metallic
- Low resistivity: 9.5 μΩ·cm
- Diffusive transport, electron phonon scattering dominates
- Very High J_{max}: 3×10^8 A/cm^2 due to elimination of grain boundaries (electromigration)

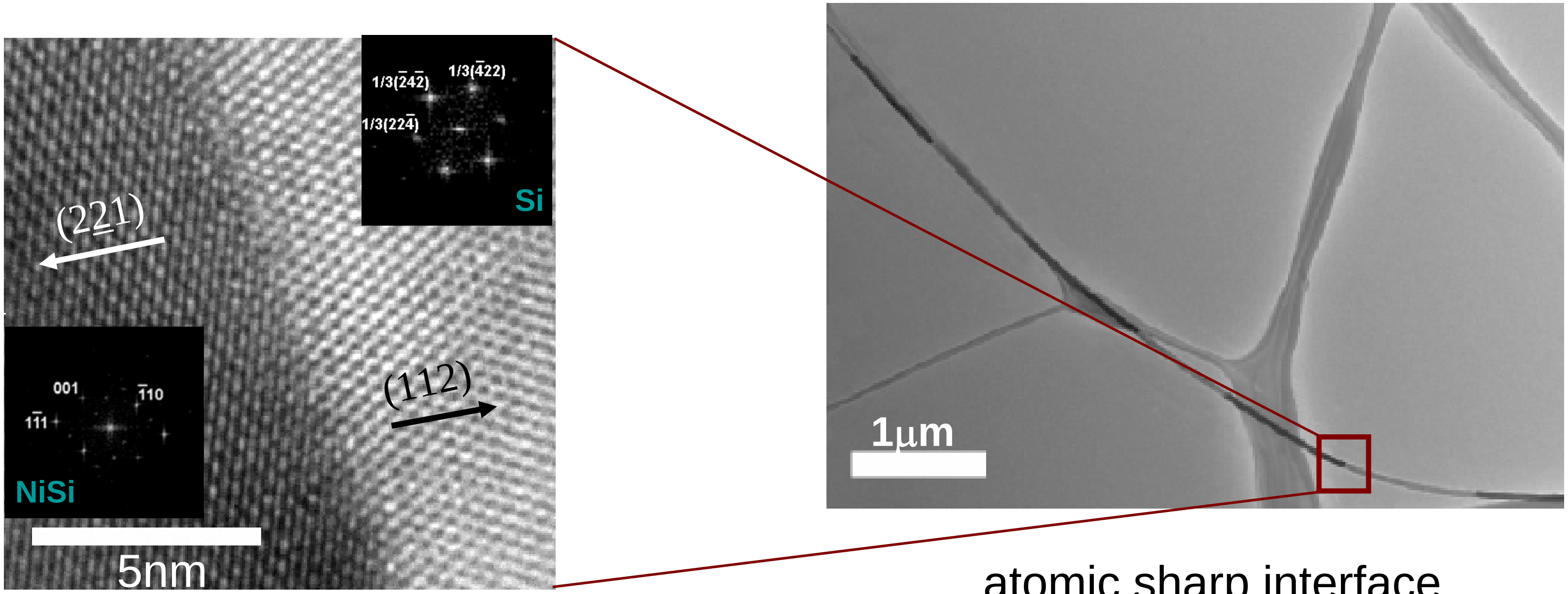
Compare: Metallic Carbon Nanotube:

$J_{max}=1\times10^9$ A/cm^2

NiSi/Si Nanowire Heterostructure

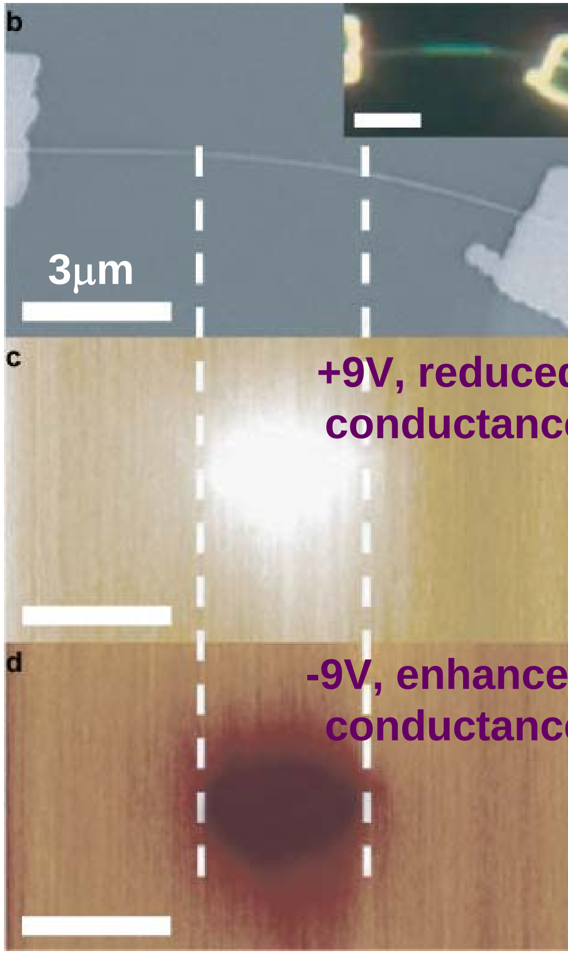




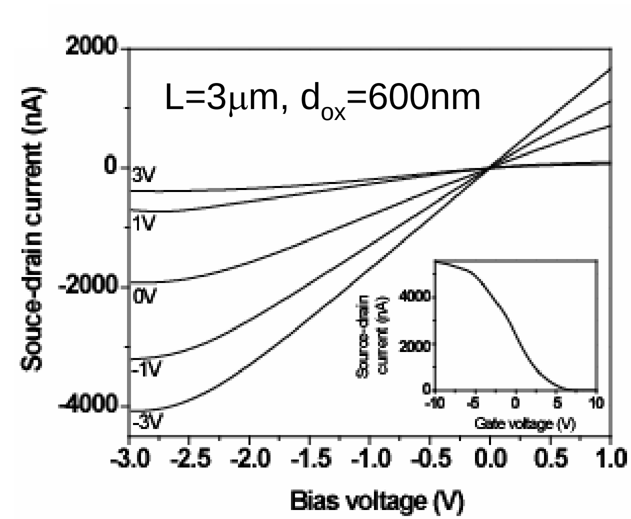


atomic sharp interface

Integrated NiSi/Si/NiSi FET Devices

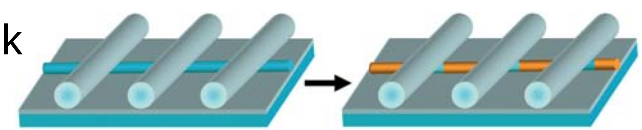


Gate response only observed on p-Si

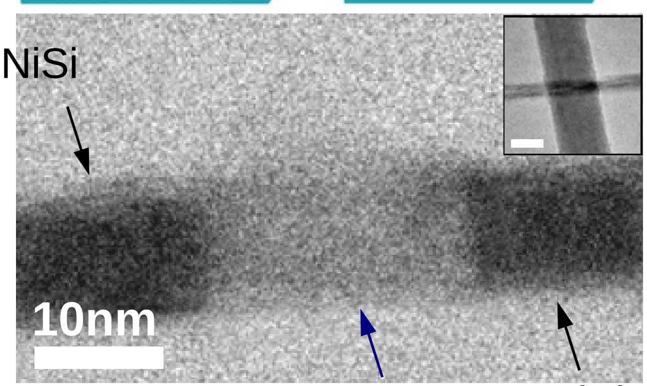


g_m=275nS @ -1V bias; μ=325cm^2/Vs

NW mask



NiSi

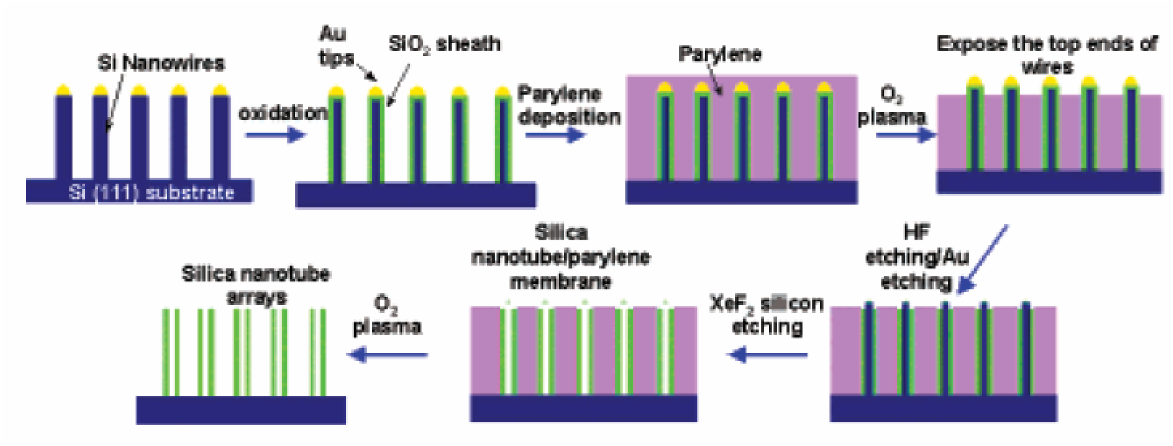


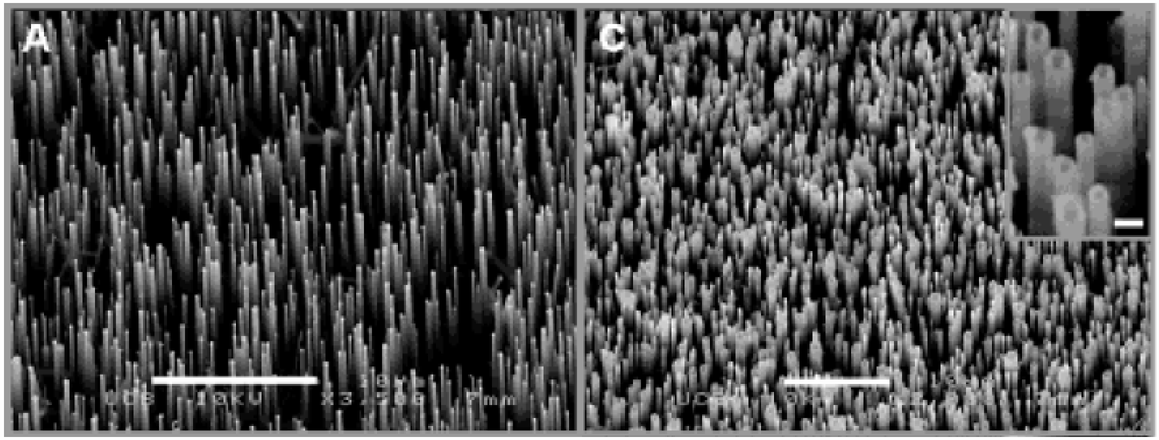
Si

NiSi

Nanowires as temperatures

Fan, J. Am. Chem. Soc. **125**, 5254, (2003)



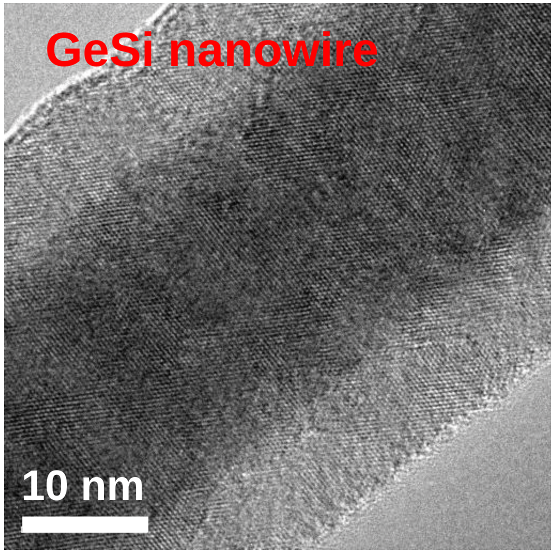


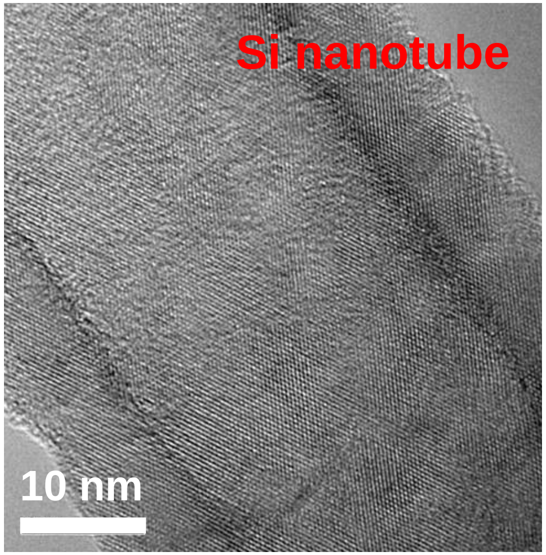
Si as template

From SiO_2/Si core/shell structure, resulting in SiO_2 nanotubes

Single-crystalline Si naotubes

Timko, et al, unpublished

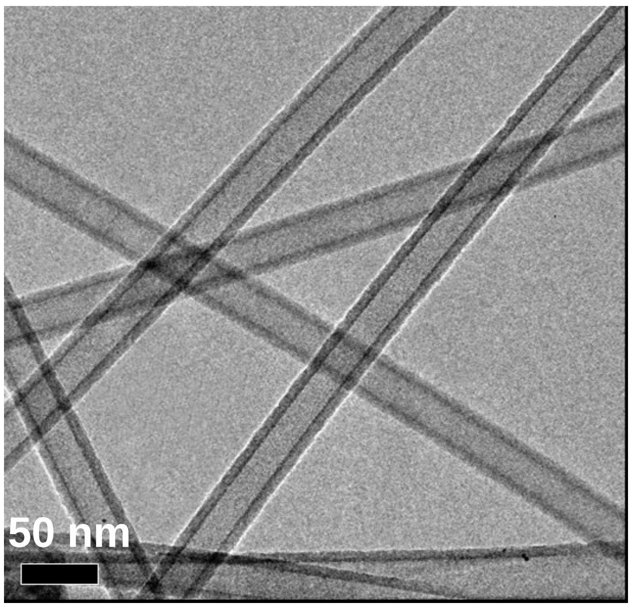


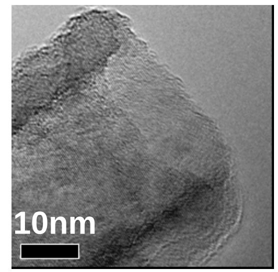


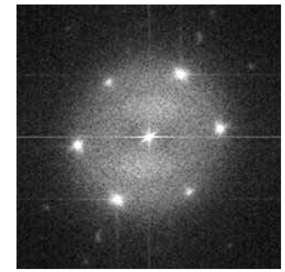
Ge core as template
Si tubes obtained from the Ge/Si core/shell nanowires

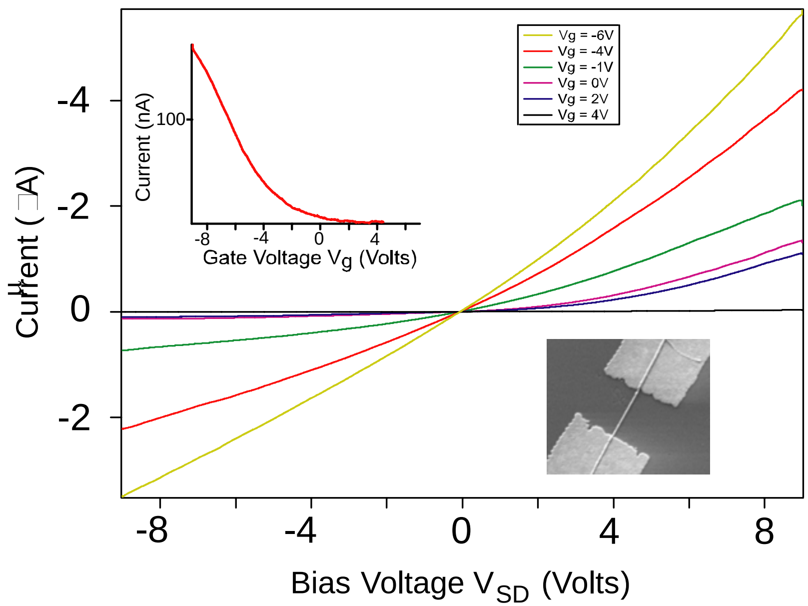
Single-crystalline Si naotubes

Timko, et al, unpublished

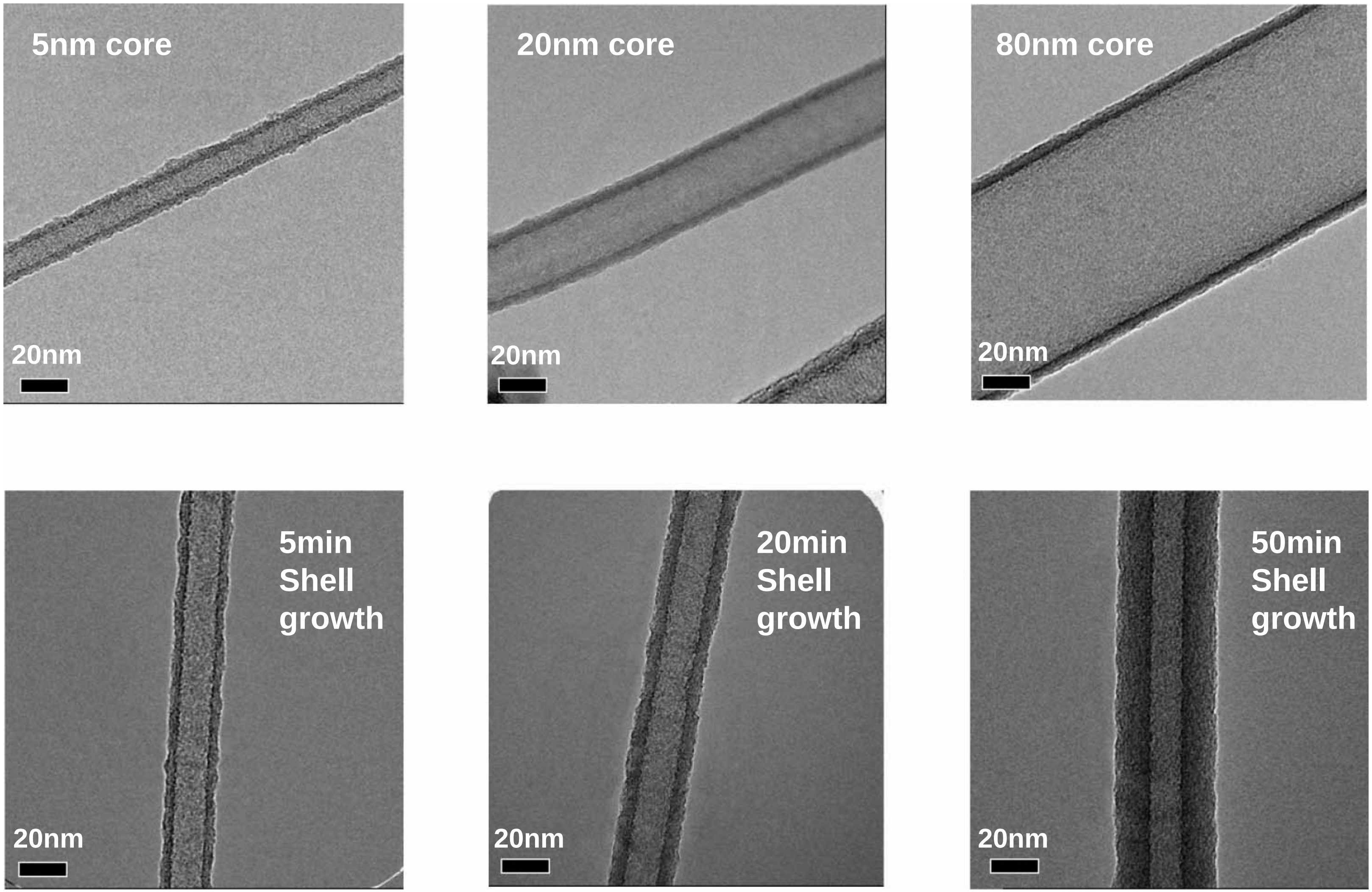




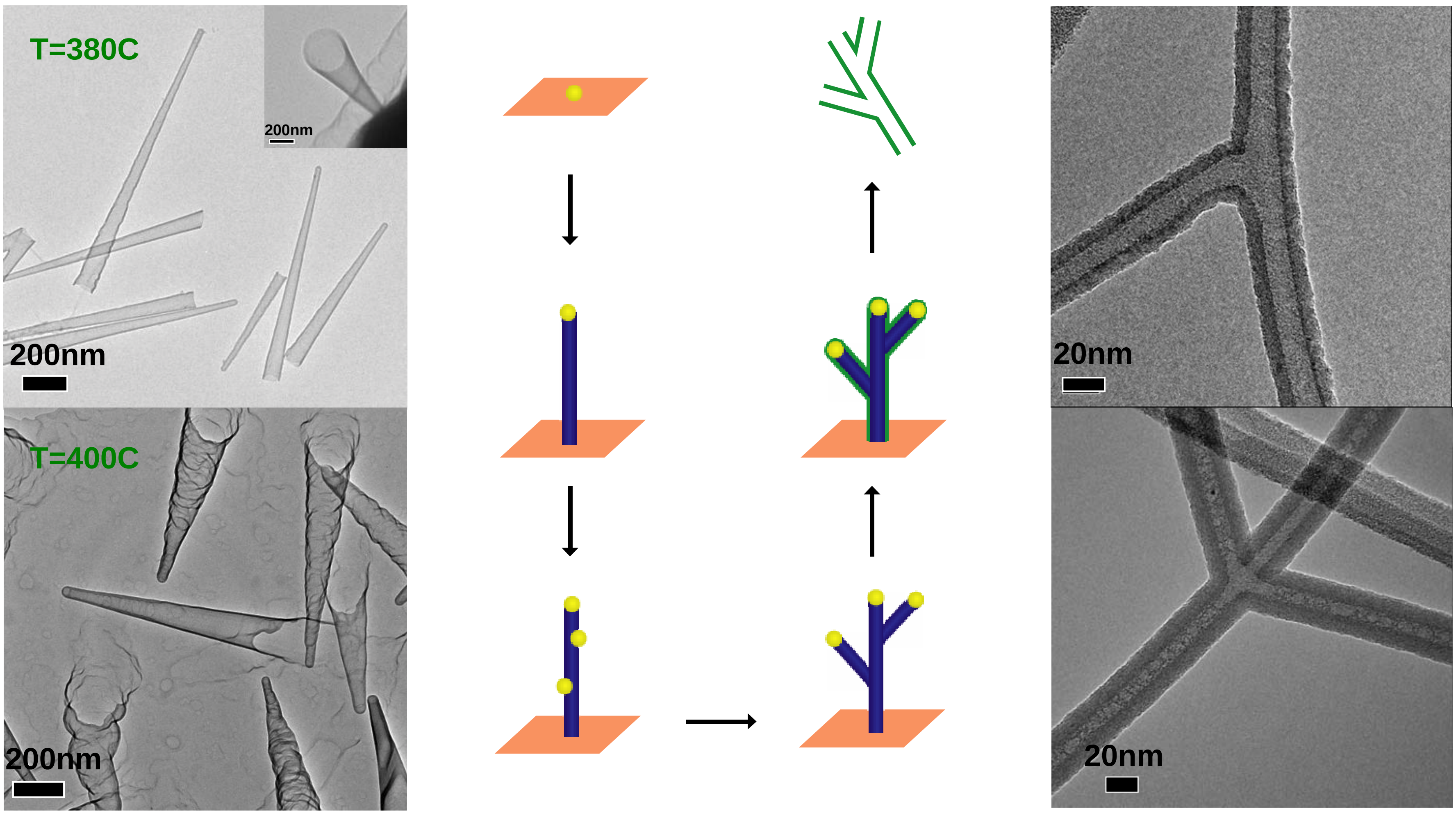




Diameter and Wall Thickness Control



Variations of Si Nanotubes

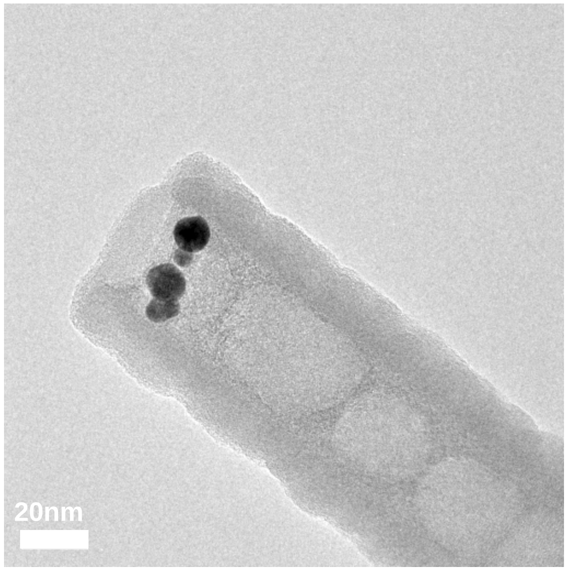


Si cones

Si nanotube networks

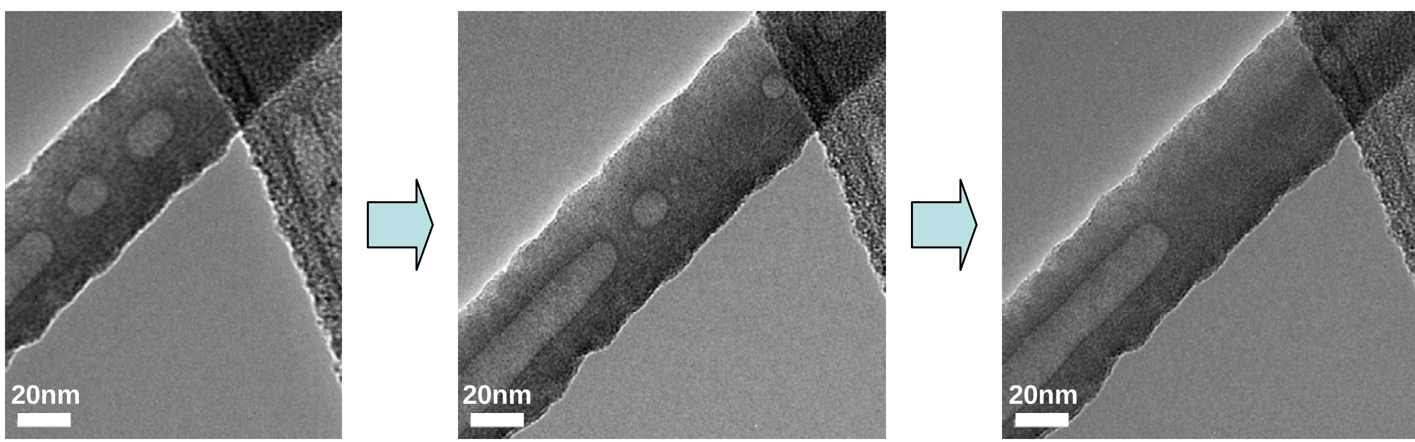
Nanofluidics with Si nanotubes

Timko, et al, unpublished



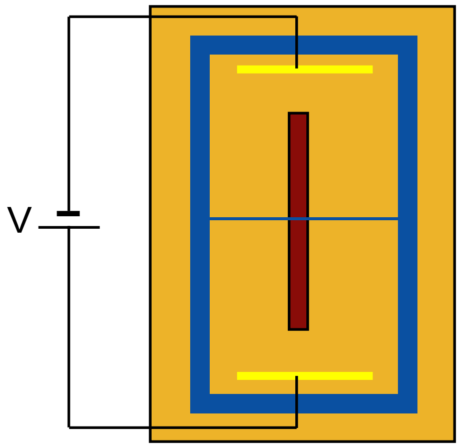
Nanoparticles inserted inside
Si nanotubes

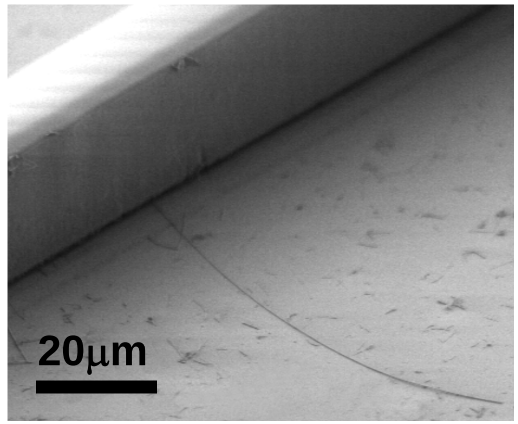
Trapped gas bubbles

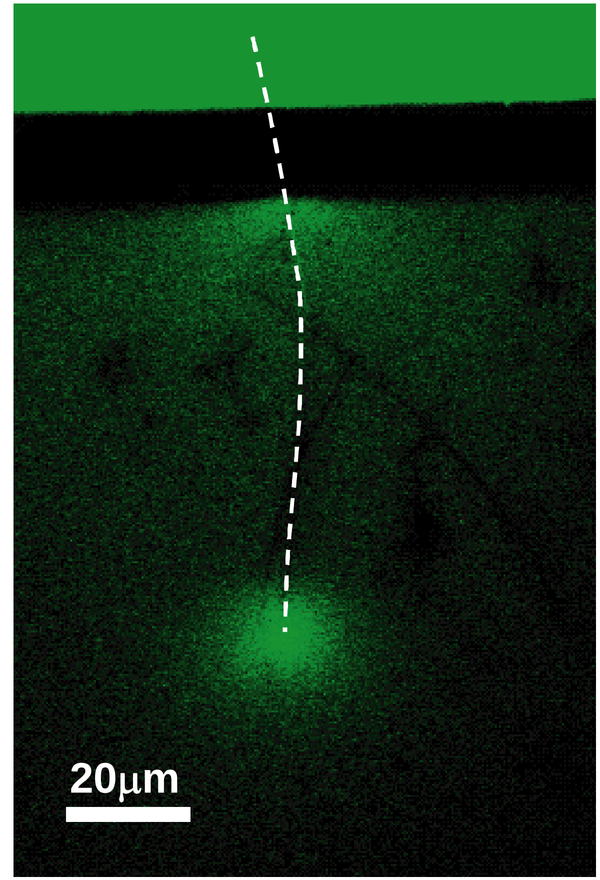


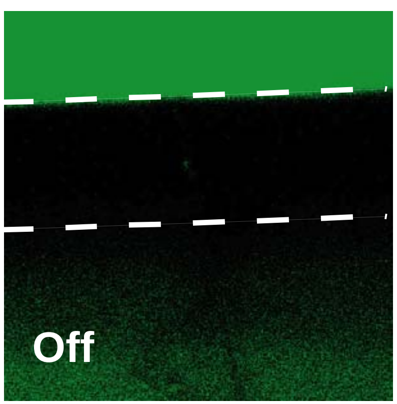
Nanofluidics with Si nanotubes

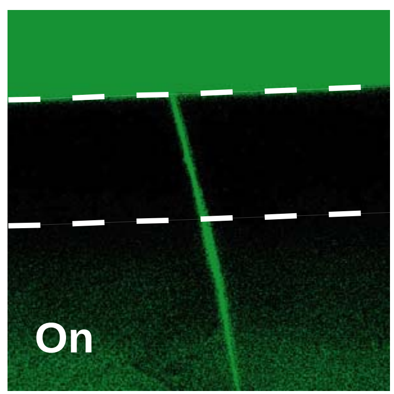
Timko, et al, unpublished











Electro-osmosis

- Fluidic properties at the nanoscale
- DNA stretching
- Bio-sensing