Nanowire Fabrication and Assembly

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March 20th, 2012

What to learn today?

1. Introduction to nanowire

2. Nanowire fabrication

- VLS/CVD
- Solution phase
- Template assisted
- Electrospinning

3. Nanowire assembly

- Magnetic assembly
- DEP assembly
- Surface tension based assembly
- Langmuir–Blodgett technique
- others

4. Lab session (Perry Hall 301)

1. Introduction to Nanowires

Nanowire

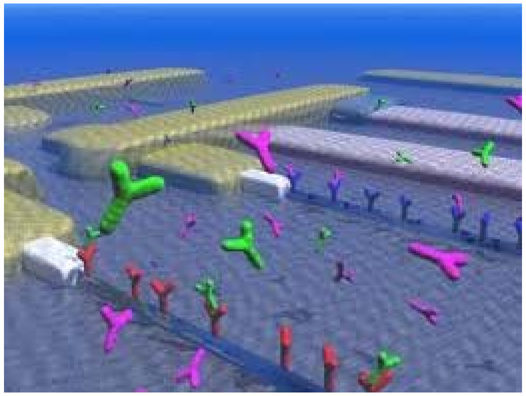
A *nanowire* is an extremely thin wire with a diameter on the order of a few nanometers or less.

" They represent the smallest dimension for efficient transport of electrons and excitons, and thus will be used as interconnects and critical devices in nanoelectronics and nano-optoelectronics." (C. M. Lieber, Harvard)

General attributes & desired properties

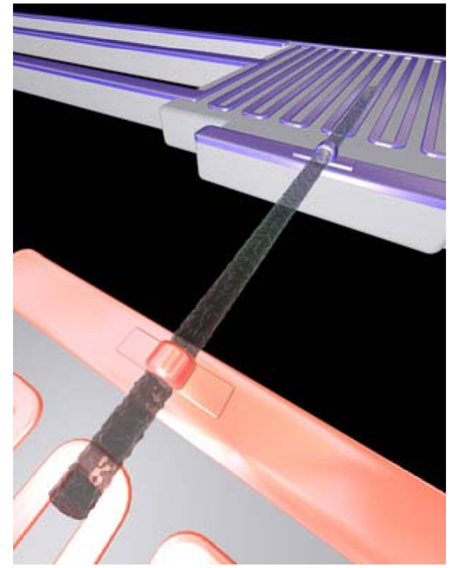
- Diameter – tens of nanometers
- Single crystal formation –common crystallographic orientation along the nanowire axis
- Minimal defects within wire
- Minimal irregularities within nanowire arrays

What a "Nanowire" can do?



Nanowire-based Biosensor

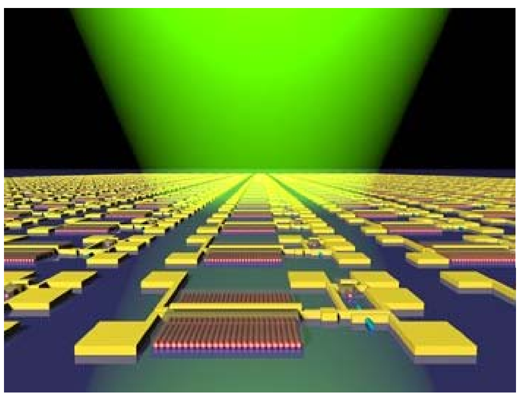
http://biosingularity.com/2007/02/02/breakthrough-in-nanodevice-synthesis-revolutionizes-biological-sensors/



Nanowire Thermoelectric Converter

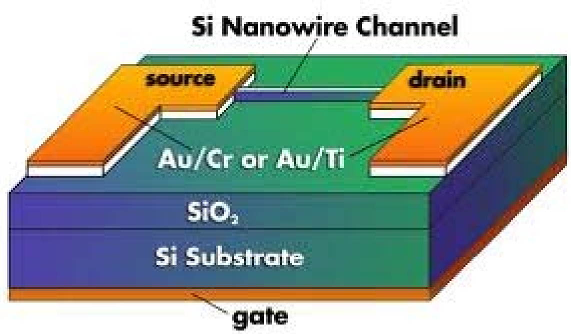
http://spectrum.ieee.org/energy/renewables/silicon-nanowires-turn-heat-to-electricity

Nanowire



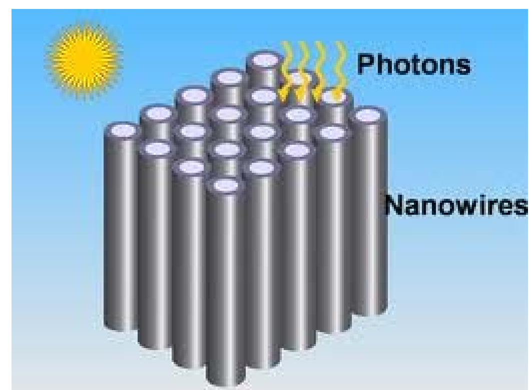
Nanowire circuit

http://www.lbl.gov/publicinfo/newscenter/features/2008/MSD-nanowire-circuit.html



Nanowire Transistor

http://www.nist.gov/public_affairs/techbeat/tb2005_0630.htm



Nanowire Solar Cell

http://spie.org/x26848.xml

Arts of Nanowire

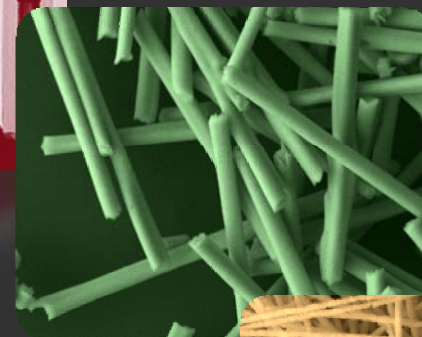
Ge-Catalyzed ZnO Nanowire Forest

ZnO Nanowire Comb

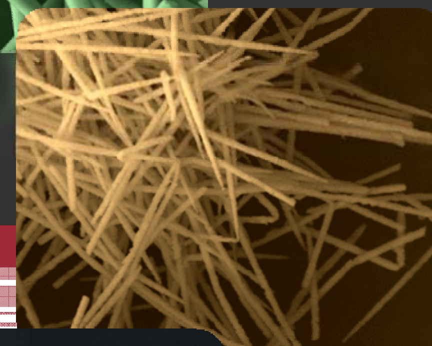
Ga-Catalyzed SiO2 Nanowire Assembly

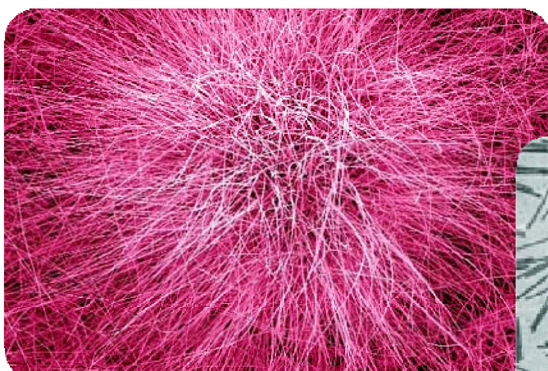
ZnO Nanowire Flower

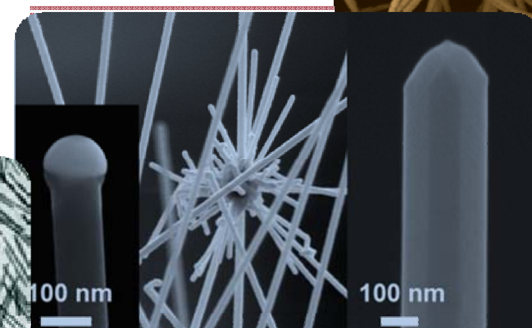
Z. L. Wang, Small, 2006, 2(11)　　Z. Pan *et al, Nano Lett.*, **2003**, *3* (9)　　http://pubs.acs.org/doi/pdfplus/10.1021/nl0343203



2. Nanowire Fabrication







Ways of growing 1-D nanostructures

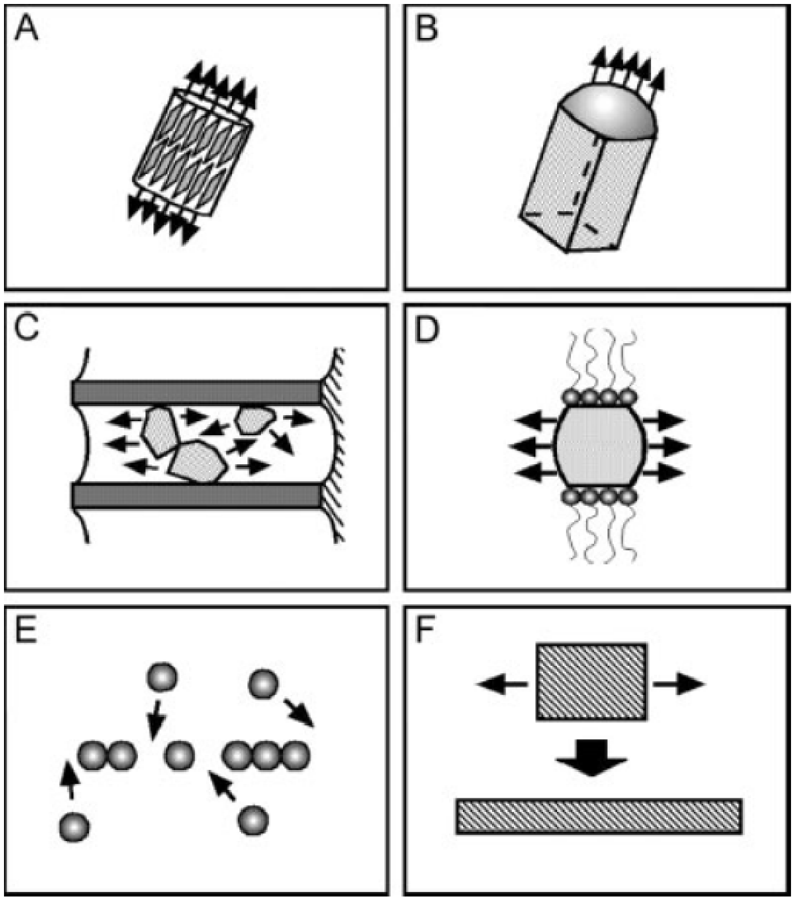
Guide along a preferred crystal direction

Confinement by liquid droplet

Hard template directed

Soft template directed

Self-assembly



Top-down

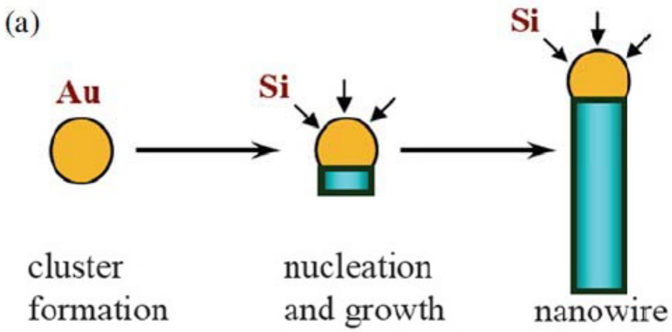
A) Dictation by the anisotropic crystallographic structure of a solid
B) Confinement by a liquid droplet as in the vapor-liquid-solid (VLS) process
C) Direction through the use of a template
D) Kinetic control provided by a capping reagent (soft-template)
E) Self-assembly of 0-D nanostructure
F) Size reduction of a 1-D microstructure

Y. Xia *et al*, Adv. Mater. 2003, 15, No. 5

Nanowire Fabrication Method

- Vapor phase growth
  - CVD (chemical vapor deposition)/VLS (vapor-liquid-solid)
- Liquid phase growth
  - Soft template: surfactant assisted
  - Hard template: Electroplating
- Electrospinning

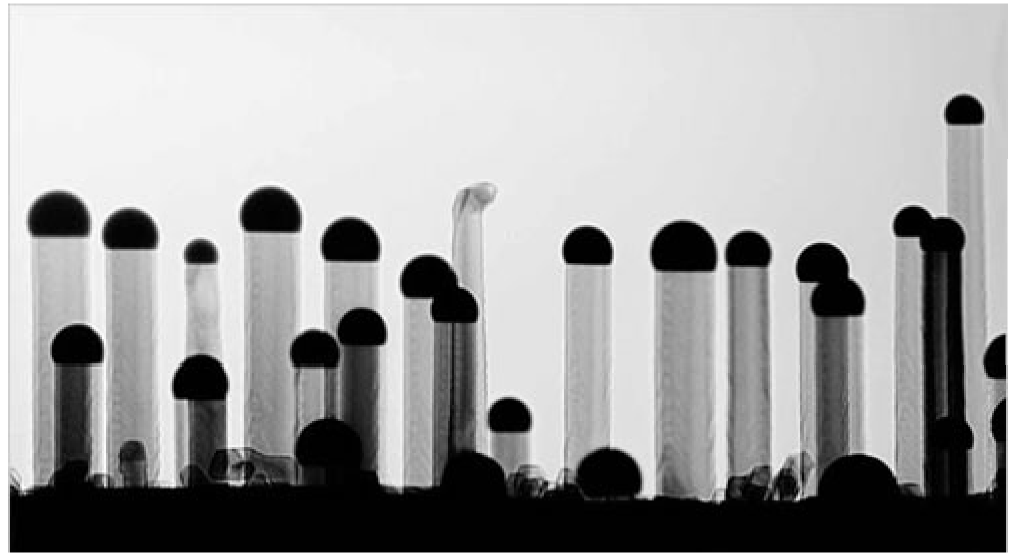
Vapor phase growth



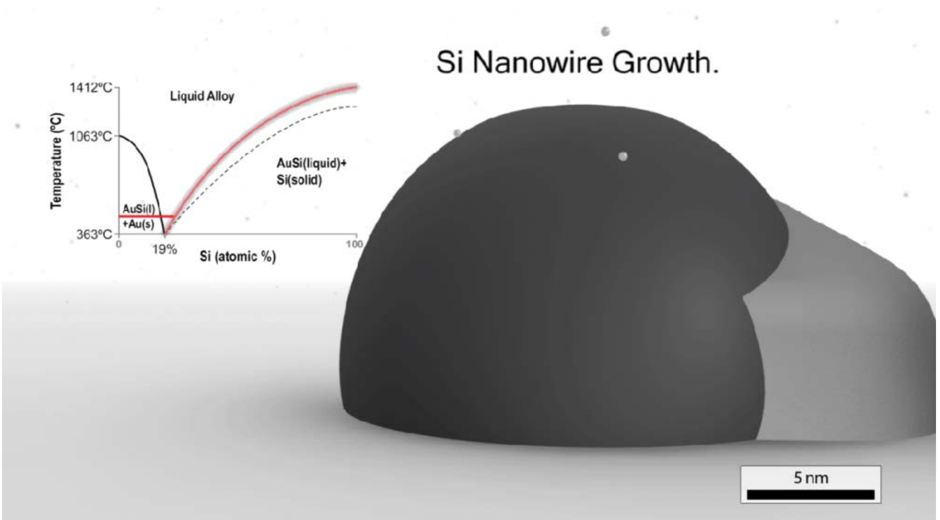
$Si_2H_6 \rightarrow Si + H_2$

$Si + Au \rightarrow SiAu$ alloy

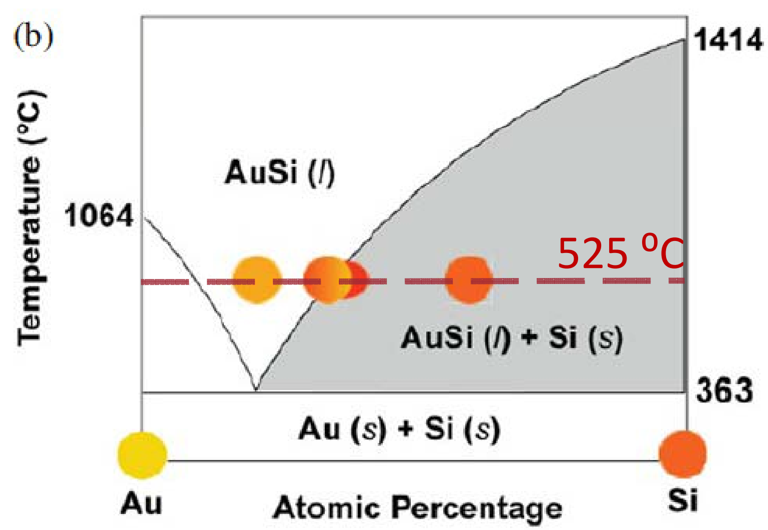
Supersaturation



S. Kodambaka *et al*, Phys. Rev. Lett. 96, (2006)

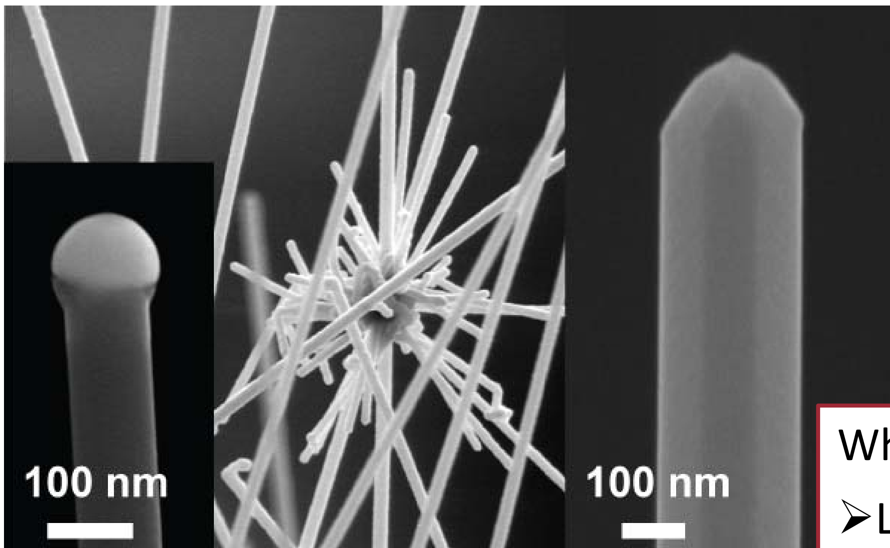


J. Phys. D: Appl. Phys. 39 (2006)



CVD

Chemical vapor deposition (CVD) is a chemical process used to produce high-purity, high-performance solid materials.



Catalyst: Au

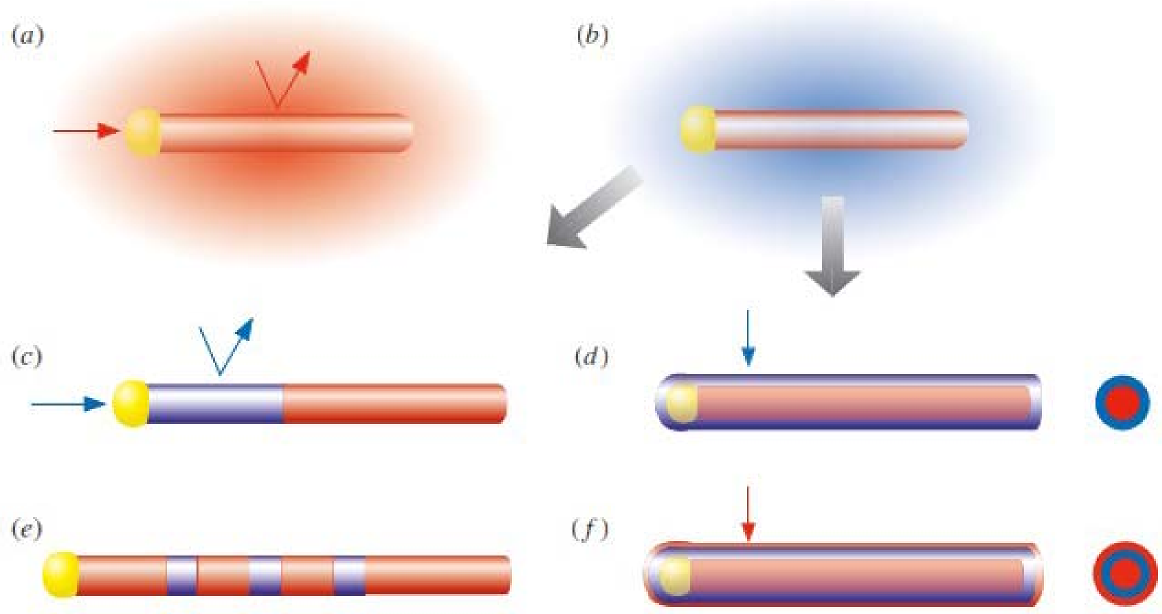
Nanowire: Si

Why CVD?

- Low temperature and low cost
- Adaptable to wide variety of structures
- Low defect density
- Rapid growth
- Direct growth on substrates
- Scalable to large areas and reactor volumes

http://www.chem.unc.edu/people/faculty/cahoon/group/

Heterostructure Nanowires



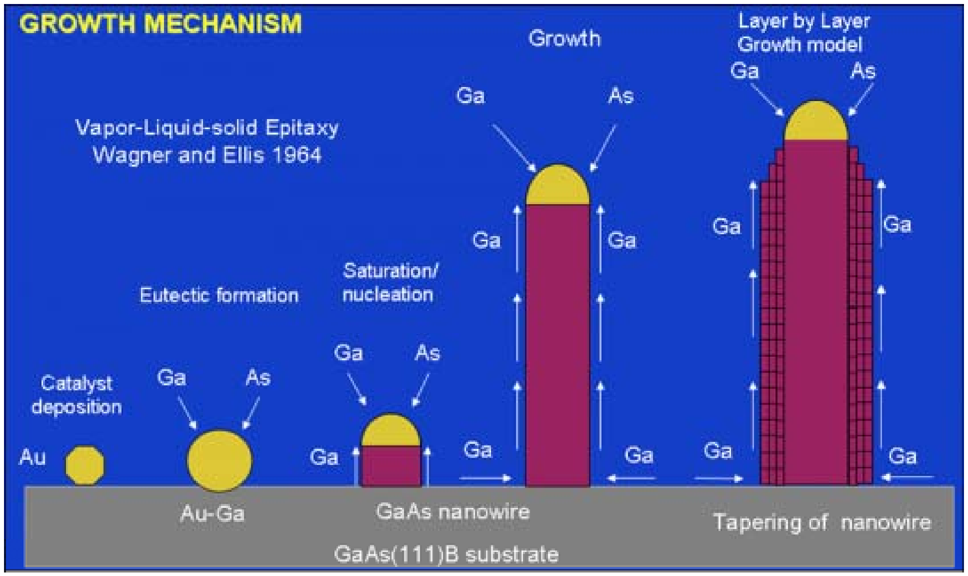
(a) Preferential reactant incorporation at the catalyst (growth end) leads to 1D axial growth.

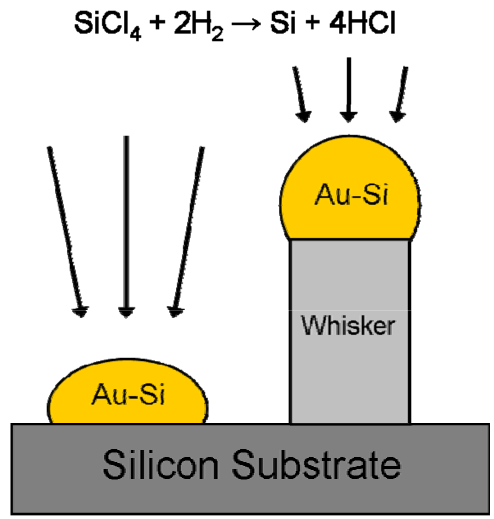
(b) A change in the reactant leads to either (c) axial heterostructure growth or (d) radial heterostructure growth depending on whether the reactant is preferentially incorporated (c) at the catalyst or (d) uniformly on the wire surface.

Alternating reactants will produce (e) axial superlattices or (f) core-multi-shell structures

Phil. Trans. R. Soc. Lond. A 362, 1247, (2004)

VLS (Vapor-Liquid-Solid)





➢Produce crystalline nanowires of some semiconductor materials.

➢Requires a catalyst, such as Au, Pt.

➢Control: turning off the source can adjust the final length of the nanowire; switching sources can create compound nanowires with super-lattices of alternating materials.

Real Video of Nanowire growth

***In situ* TEM video**

Au catalysed Si nanowire nucleation at 590°C.

The nominally 2nm thick Au film supported on a SiO_x membrane is initially exposed to ~1.3×10^{-4}mbar Si_2H_6 .

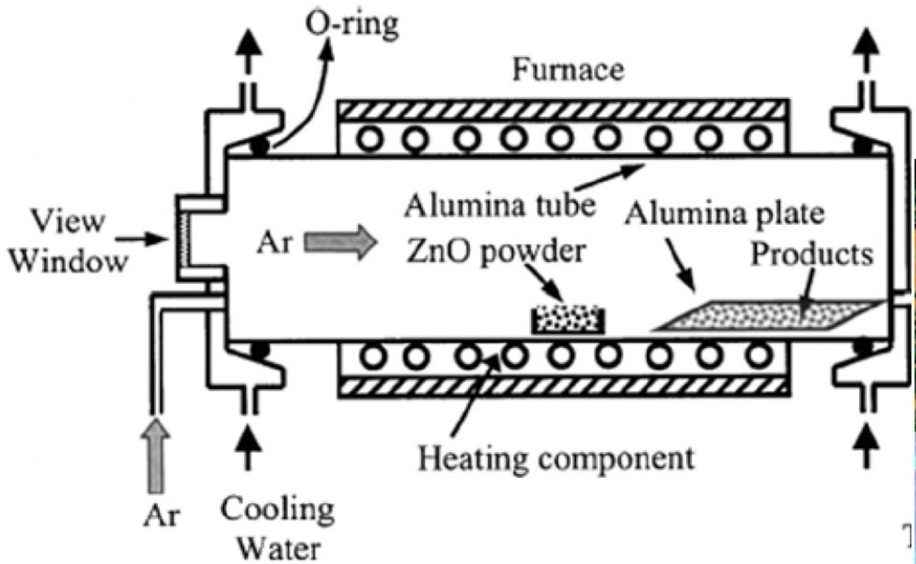
After ~108 s the disilane pressure was increased to ~5×10^{-3} mbar.

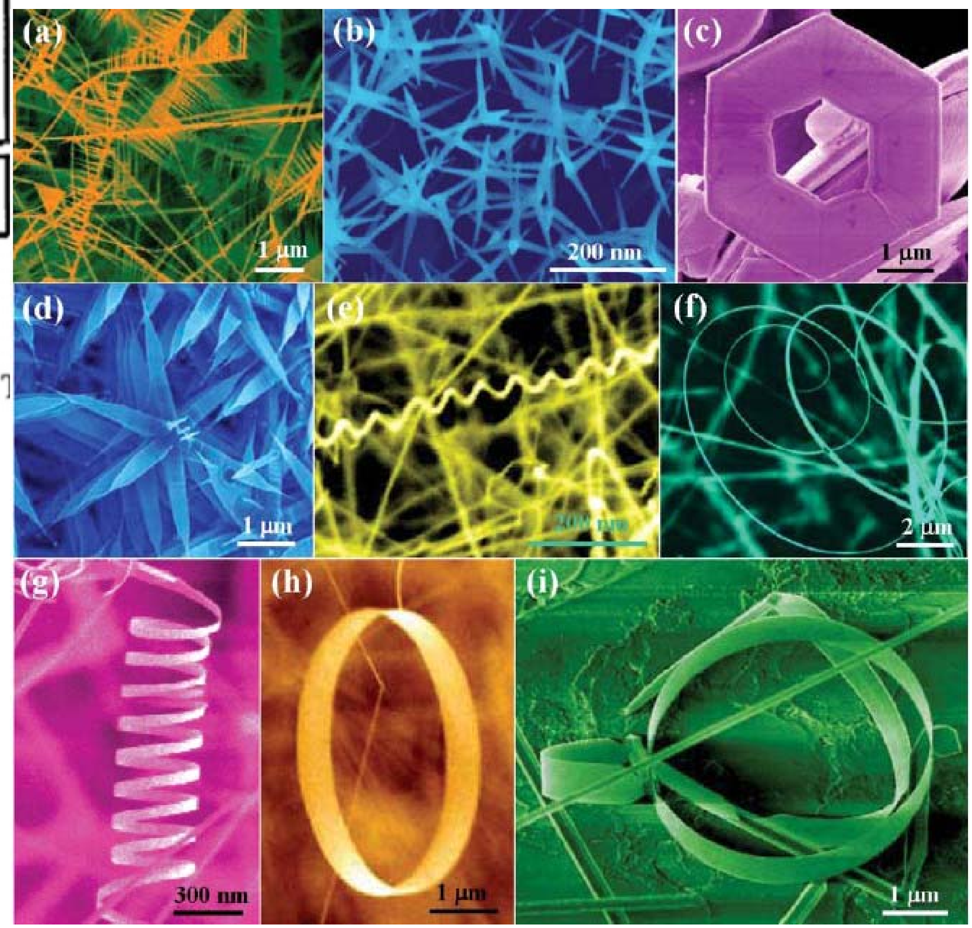
Three important stages:

1. Preparation of the catalyst
2. Nucleation
3. Growth

S. Hofmann *et al*, Nature Materials 7, 372 - 375 (2008)

Thermal evaporation and condensation





ZnO morphologies depends on:

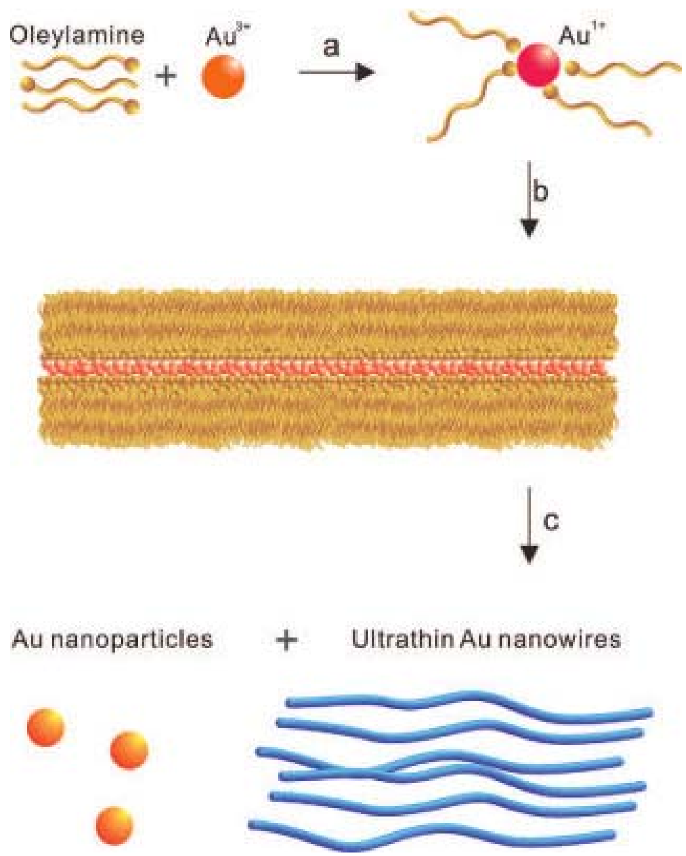
- Source material
- Substrate temperature
- Argon flow rate
- Coating thickness

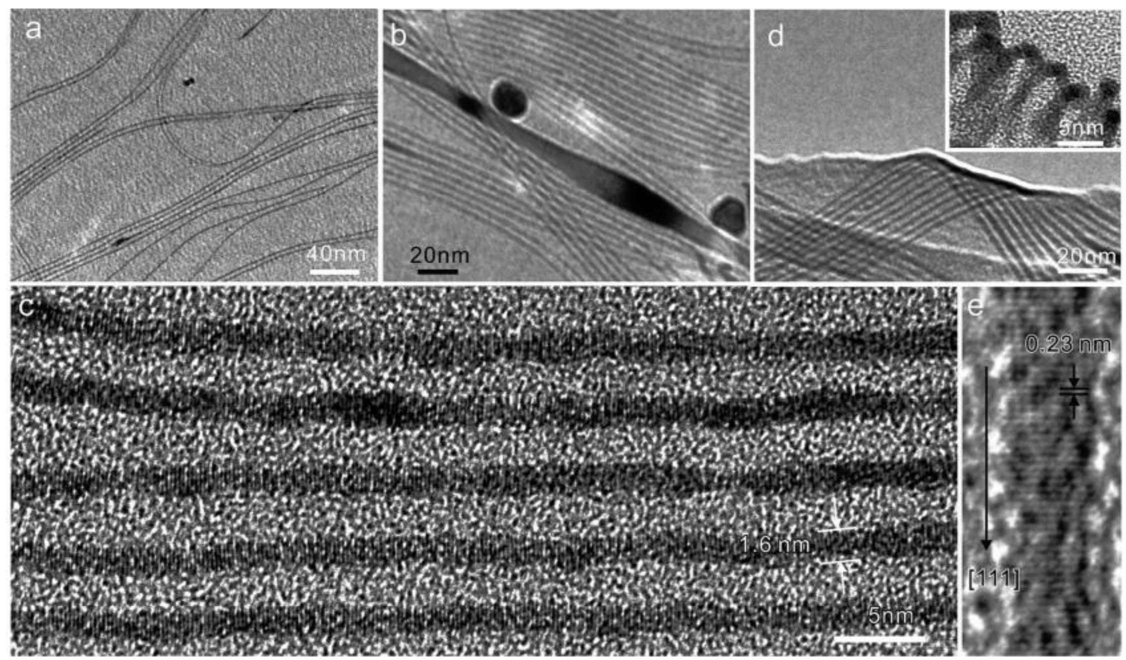
Wang, *J. Materials chemistry* 15: 1021, 2004

Adv. Funct. Mater. 2003, 13, No. 1

Liquid Phase Growth

Chemical Reduction Method-Soft template

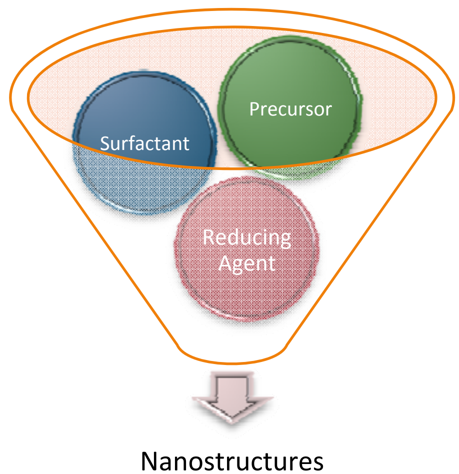




(a-d) TEM images of the ultrathin Au nanowires (<2 nm); (e) HRTEM image of an individual Au nanowire showing the (111) lattice planes

Z. Huo *et al*, *Nano Lett.*, 2008, 8 (7) http://pubs.acs.org/doi/full/10.1021/jp0516846

Chemical Reduction Method



1. Precursor

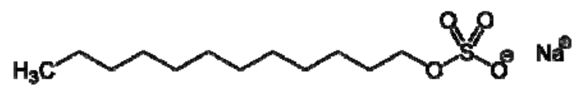
is a compound that participates in the chemical reaction that produces another compound.

- Salt: $HAuCl_4$, $AgNO_3$, $CuSO_4$…

2. Surfactant

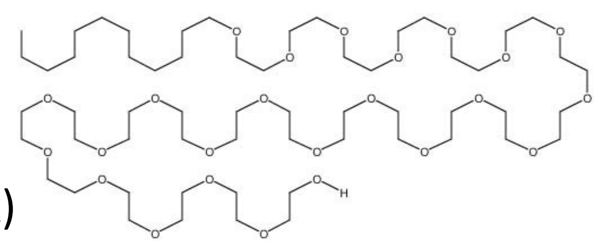
-usually organic compounds that are amphiphilic, containing both hydrophobic groups (their tails) and hydrophilic groups (their heads).

- SDS (Sodium dodecyl sulfate), anionic surfactant



- CTAB (Cetrimonium bromide), cationic surfactant

- Polyoxyethylene (HO-$(CH_2CH_2O)_n$-H), nonionic surfactant

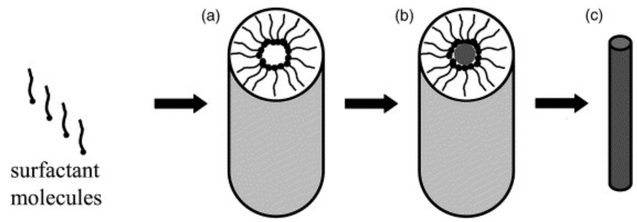


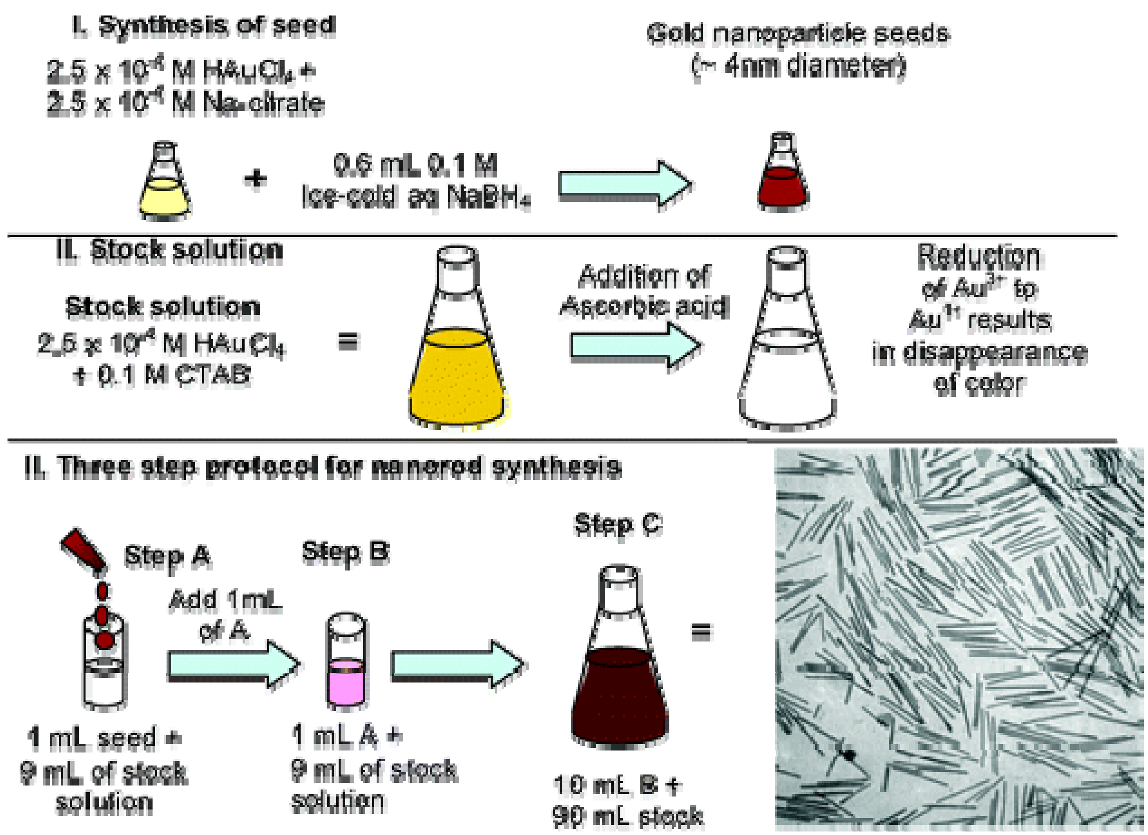
3. Reducing agent

-is the element or compound in a reduction-oxidation (redox) reaction that donates an electron to another species.

- Phosphite, $NaBH_4$, …

Chemical Reduction Method





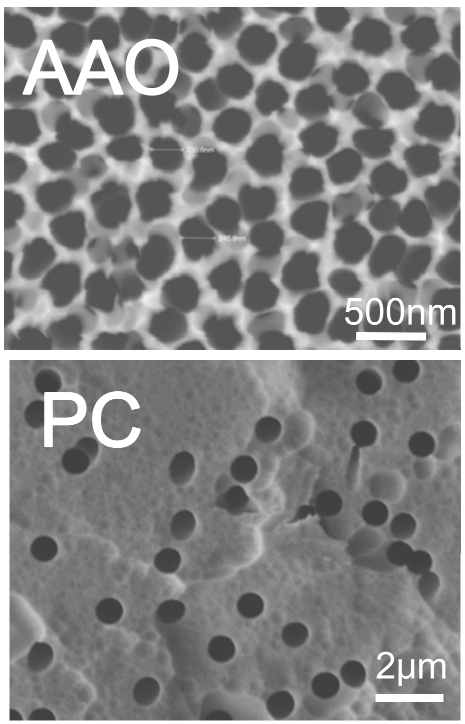
C. J. Murphy *et al*, *J. Phys. Chem. B*, 2005, 109 (29)

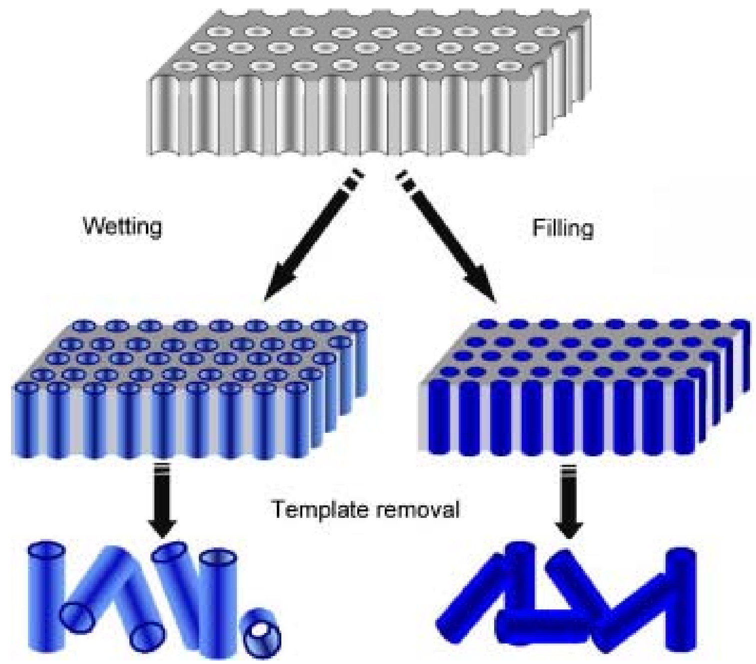
Electroplating-hard template assisted

Electrochemical deposition

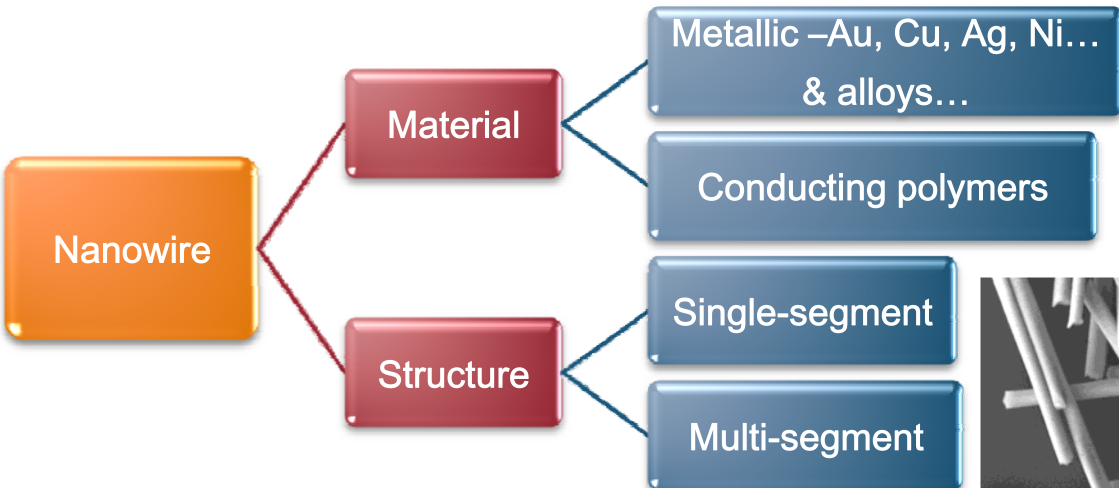
- Ensures fabrication of electrically continuous wires since only takes place on conductive surfaces
- Applicable to a wide range of materials
- Very high aspect ratios may be achieved

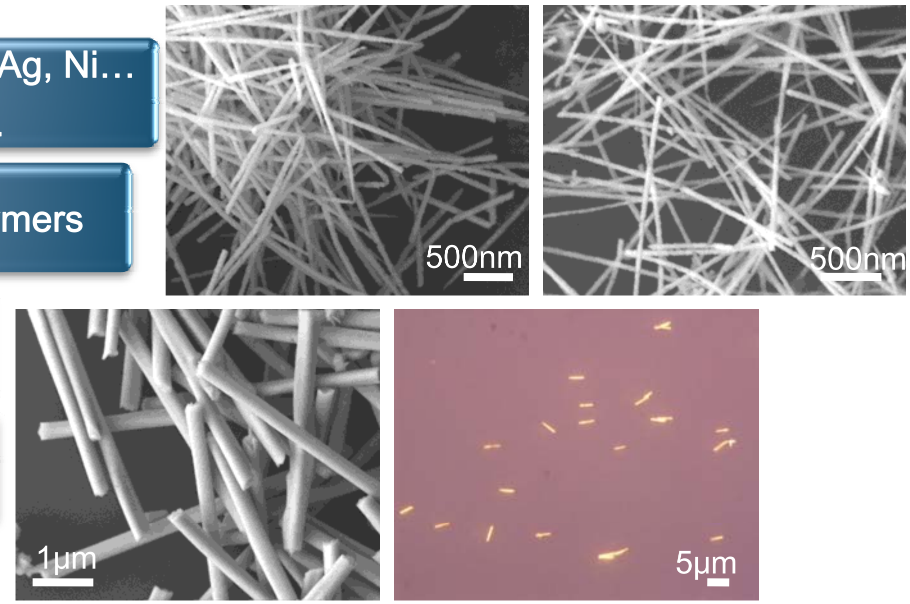
Hard Template: AAO (anodic aluminium oxide) or PC (polycarbonate) membrane.



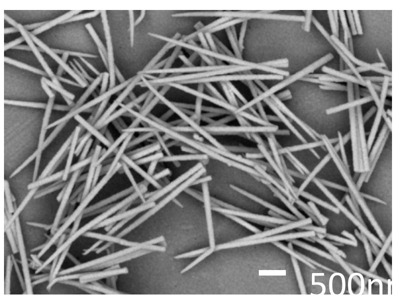


Electrodeposition

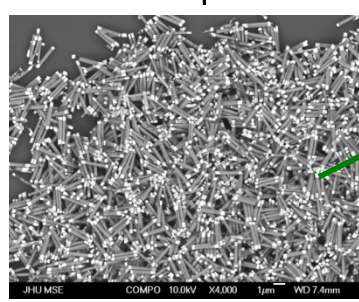




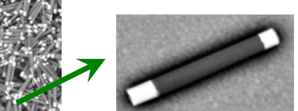
Nanowires with one- and multi-component segments



One-component nanowires
(gold nanowires, d=50nm)



Multi-component nanowires

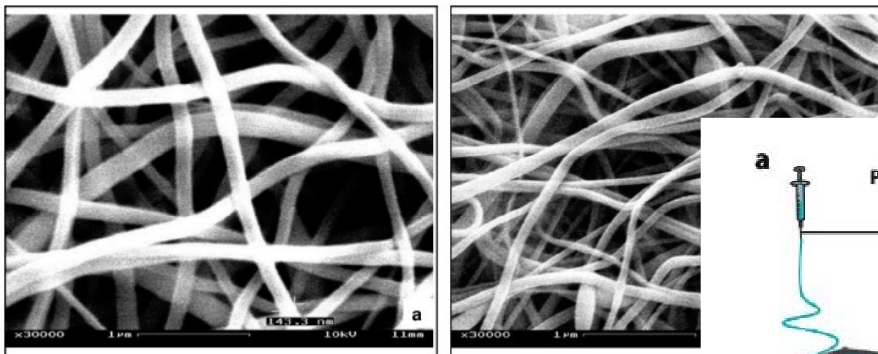


Gold-Nickel-gold
(d=200nm)

Gu, Ye, Gracias. *Journal of Materials (JOM)* **2005**, *57*, 60-64

Electrospinning

Electrospinning Setup



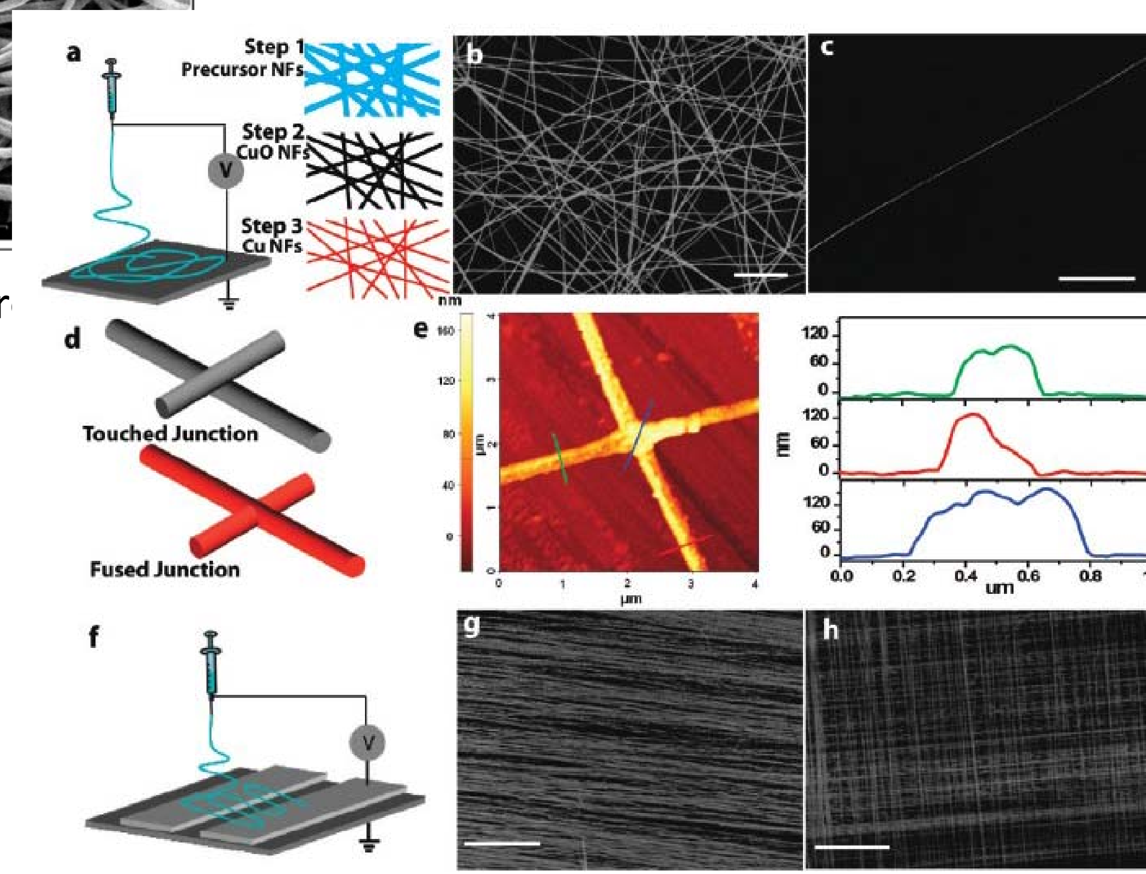
PVP/H_2PtCl_6 composite nanowir

Nano Lett., 2009, 9 (4), pp 1307–1314

Easily form thin film

Polymer fibers

Polymer + Salt Precursor

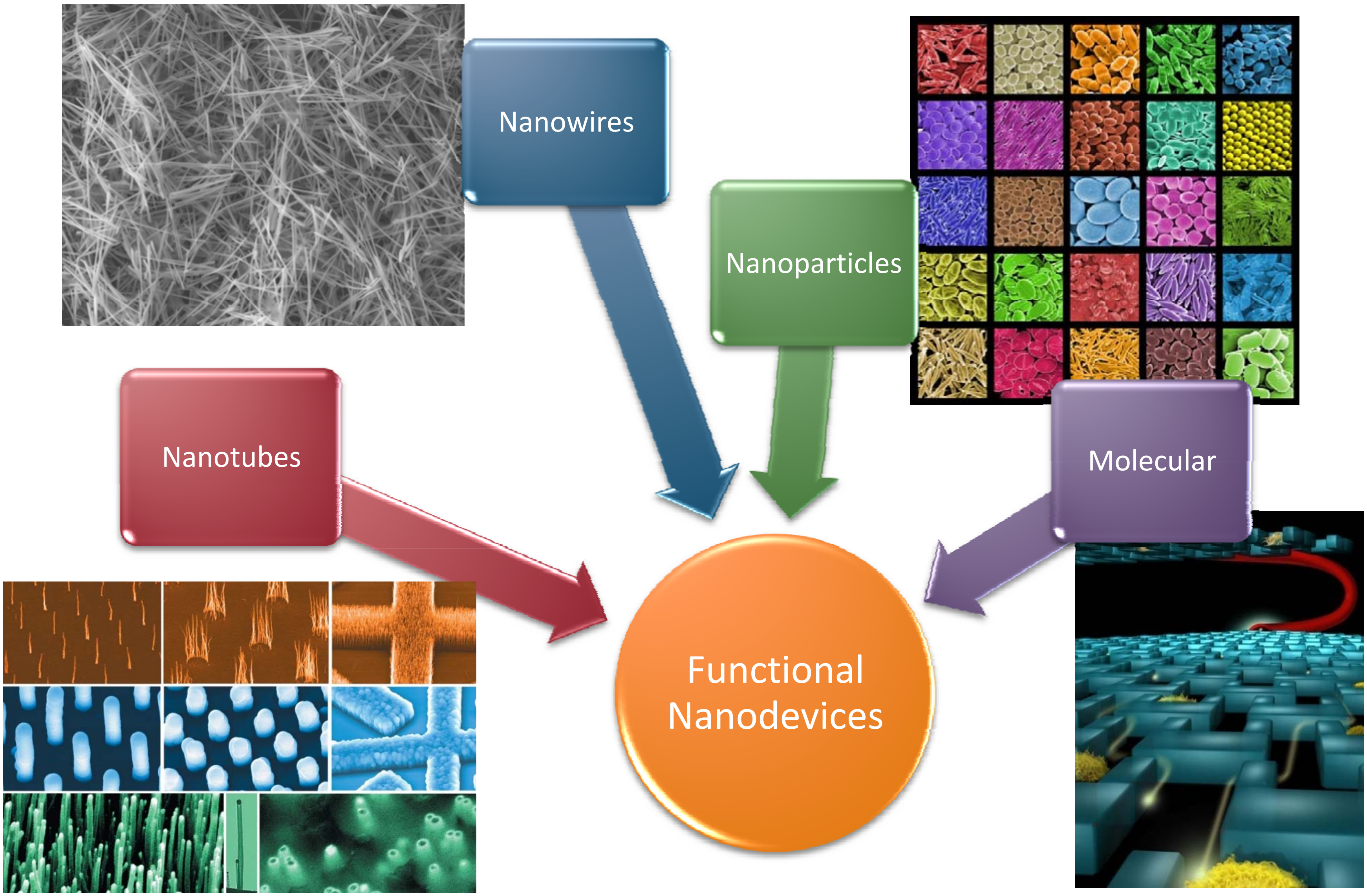


$PVA/CuAc_2$ composite fibers

Nano Lett., 2010, 10, pp 4242-4248

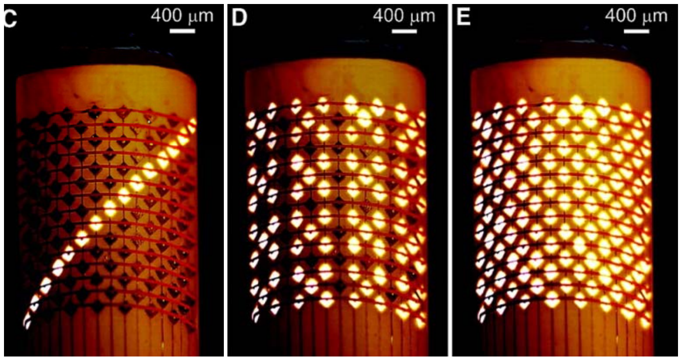
3. Nanowire Assembly

Why do we study “assembly”?



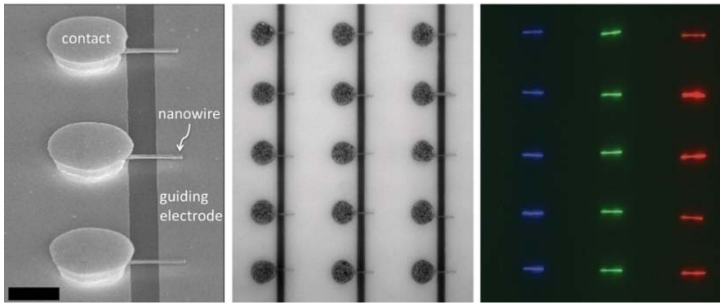
Methods of Self-assembly

- Electro-static self-assembly (ESA)
- Fluidic self-assembly (FSA)
- Gravity driven self-assembly
- Molecular self-assembly
- Solder based assembly
- Magnetic forces assisted self-assembly
- Dielectrophoresis assembly (DEP)
- DNA assisted assembly
- Langmuir–Blodgett



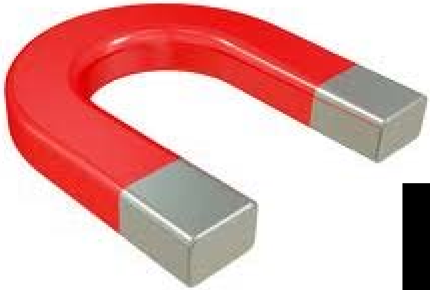
Solder-based assembly to integrate device segments onto nonplanar substrates.
Jacobs et al. Science, 2000, Vol. 296

Integrated LEDs

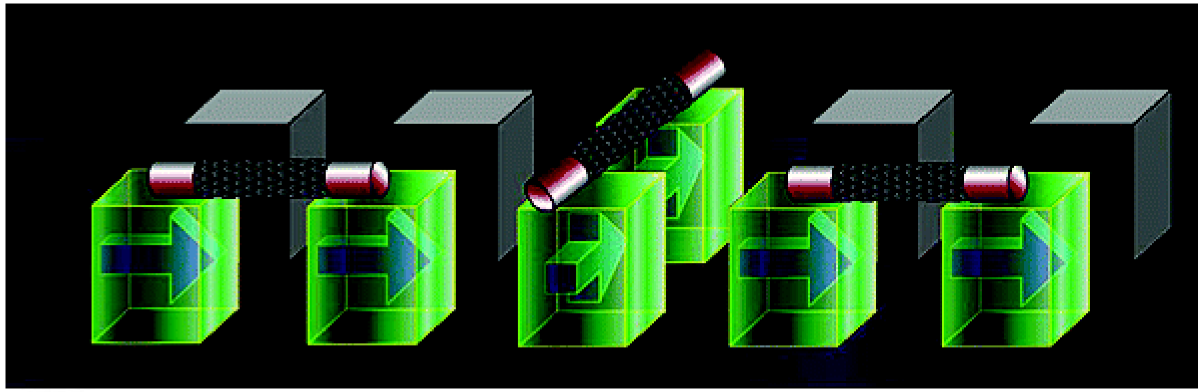


Programmed assembly of DNA-Coated Nanowire Devices.
Thomas et al. Science, 2009, Vol. 323

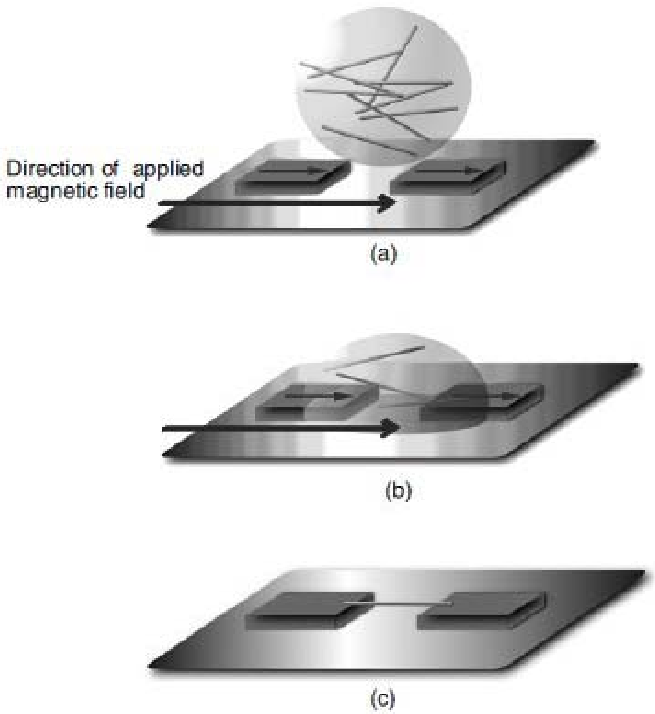
Biomaterial Devices

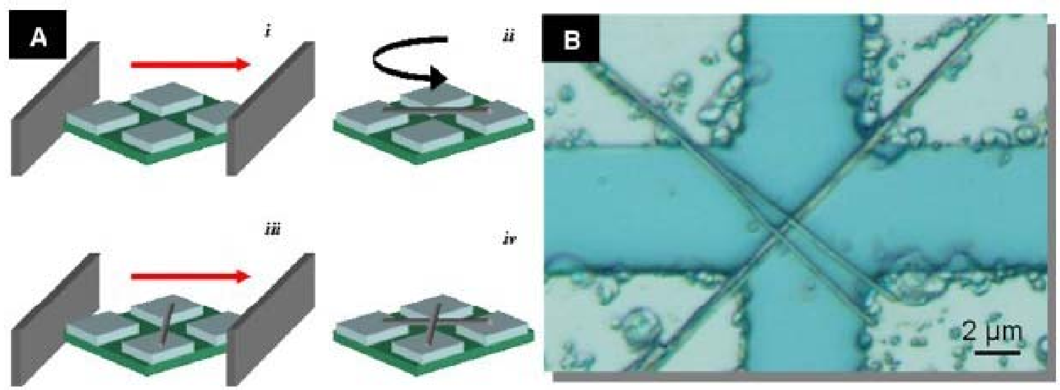


Magnetic Assembly



Only magnetic materials can be assembled!
Fe, Ni, Co





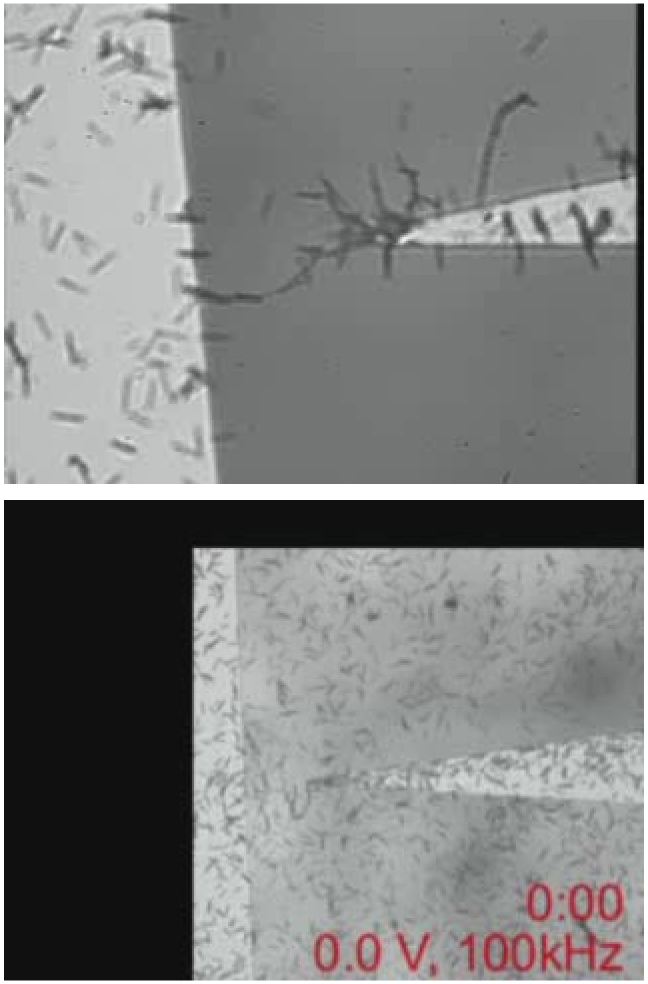
Carlos M H. *et al* 2007 *Nanotechnology* **18** 205305

Bongyoung Yoo *et al* 2006 *Nanotechnology* **17** 2512

Carlos M H. *Chem. Mater.*, 2005, 17 (6), pp 1320–1324

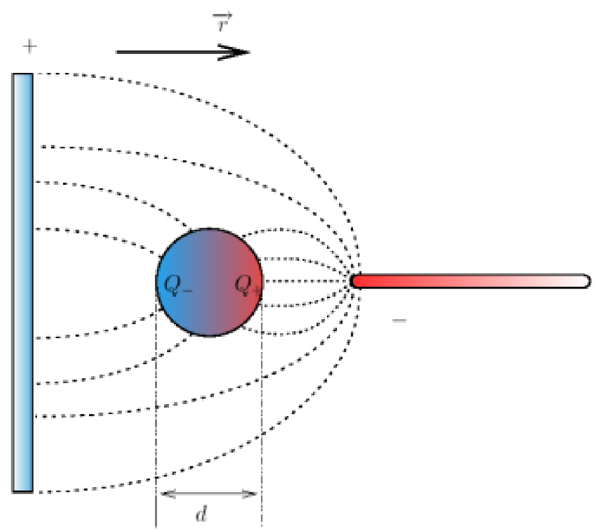
Electrical field-assisted assembly

Vedio: Dielectrophoresis Assembly



Appl. Phys. Lett. **88**, 233118 (2006)

Dielectrophoresis (or **DEP**) is a phenomenon in which a force is exerted on a dielectric particle when it is subjected to a non-uniform electric field.

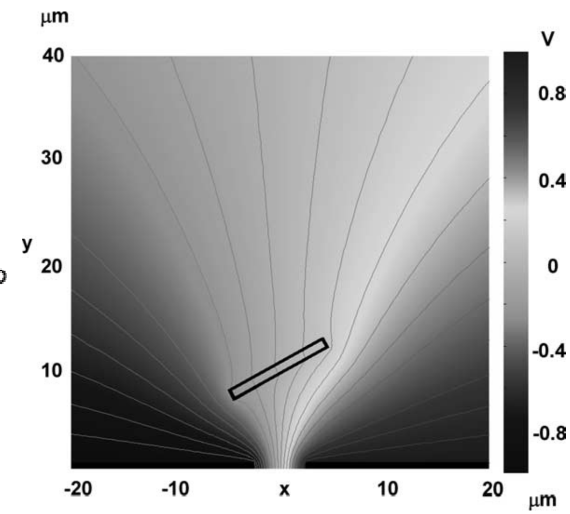


$$F_{cylinder} = \pi a^2 L \frac{\epsilon_1[\epsilon_2 - \epsilon_1]}{\epsilon_2 + \epsilon_1} \nabla |E|^2$$

E-magnitude of the electrical field

$\mathcal{E}_1$-dielectric constant of the cylinder

$\mathcal{E}_2$-dielectric constant of the medium



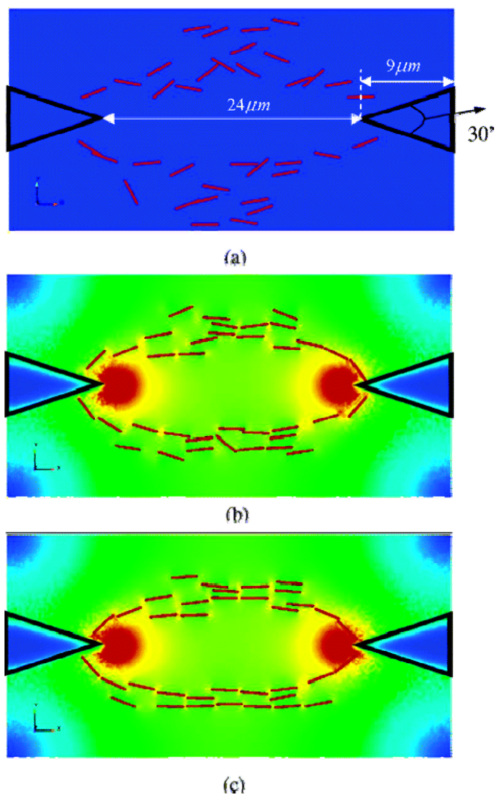
Finite element simulation

http://matthieu.lagouge.free.fr/elecstq/dep.xhtml

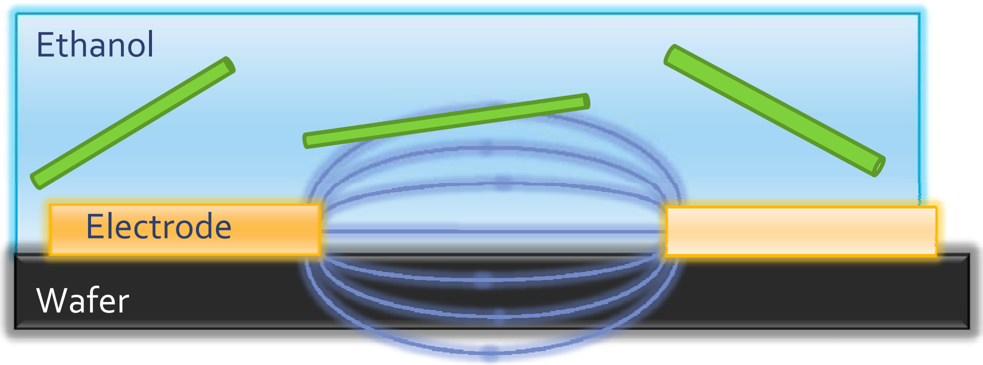
H.A. Pohl*, New York, 1978*

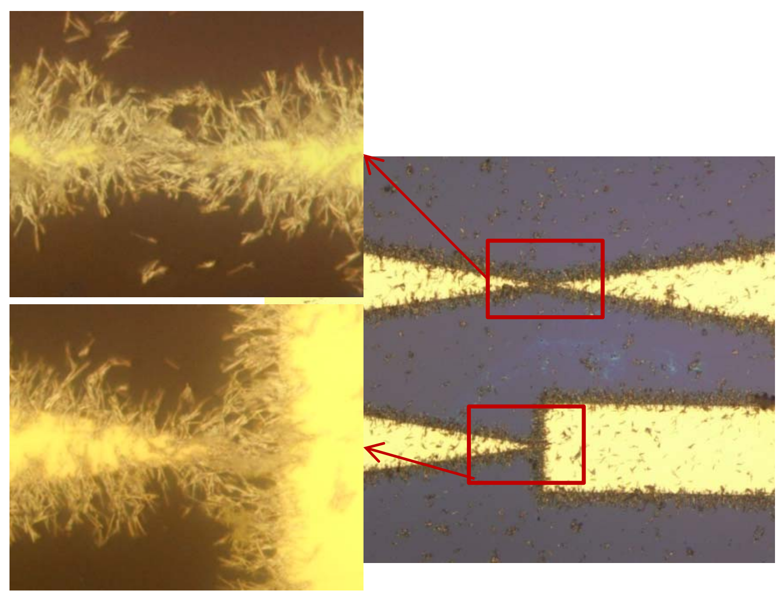
Evoy S *et al. Microelectron. Eng.2004*

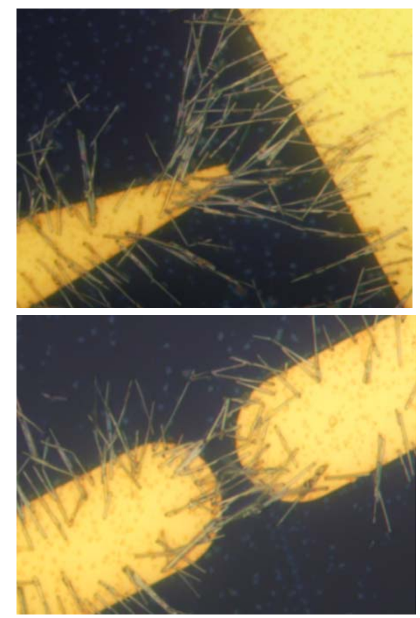
DEP – 2D Assembly



Sequential images of 3 μm-long NWs lining up between triangular-shaped electrodes





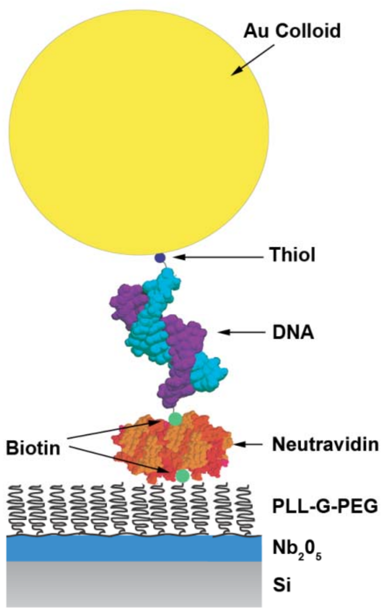


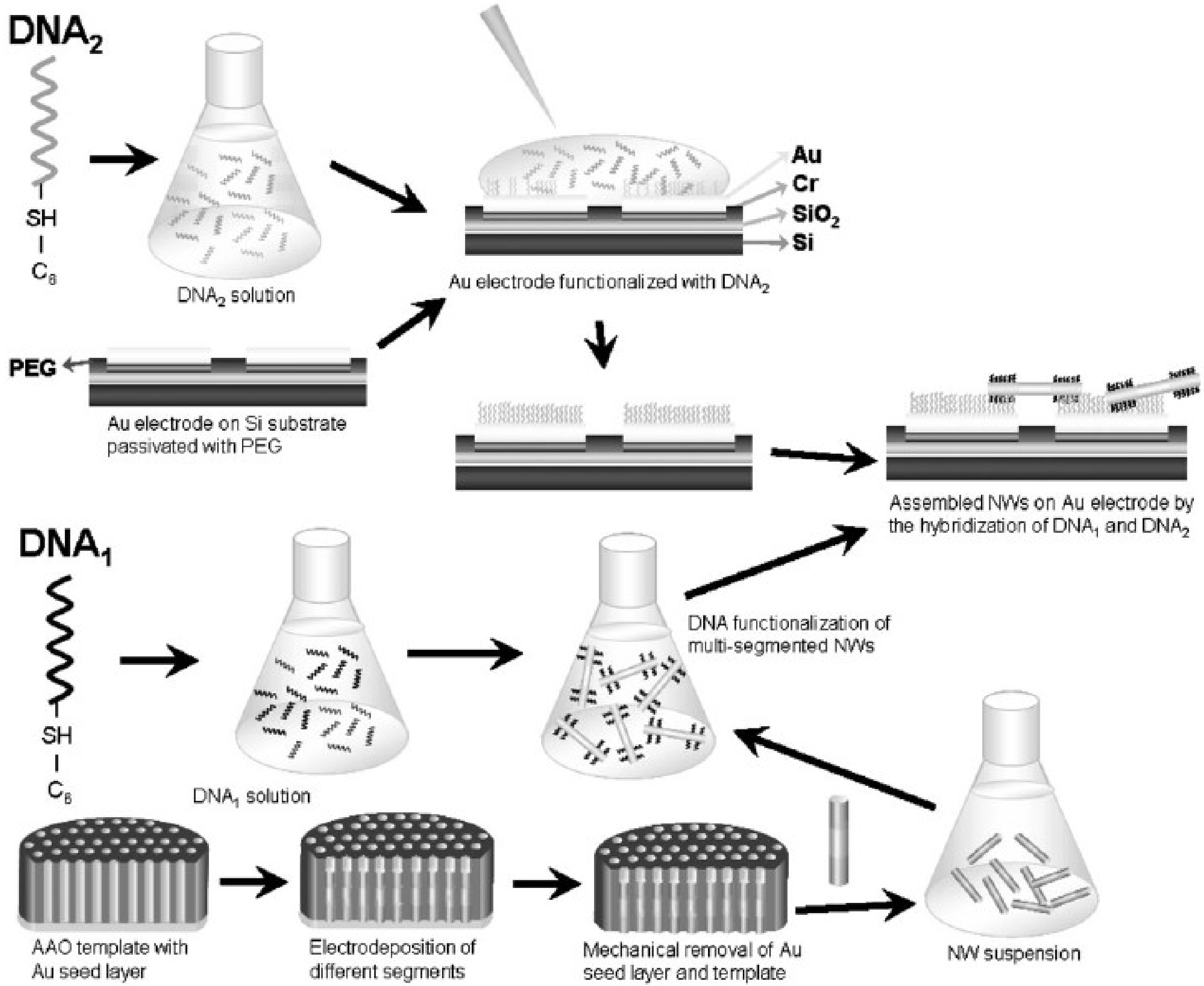
Left: Tin (Sn) nanowires DEP aligned

Right: Indium (In) nanowires DEP aligned

J. Phys. Chem. B, 2006, 110 (29)

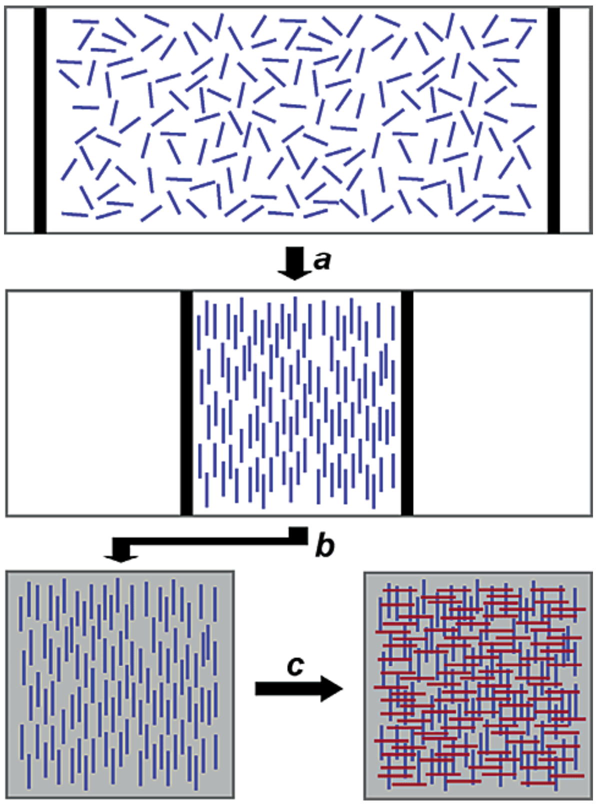
DNA assisted nanowire assembly





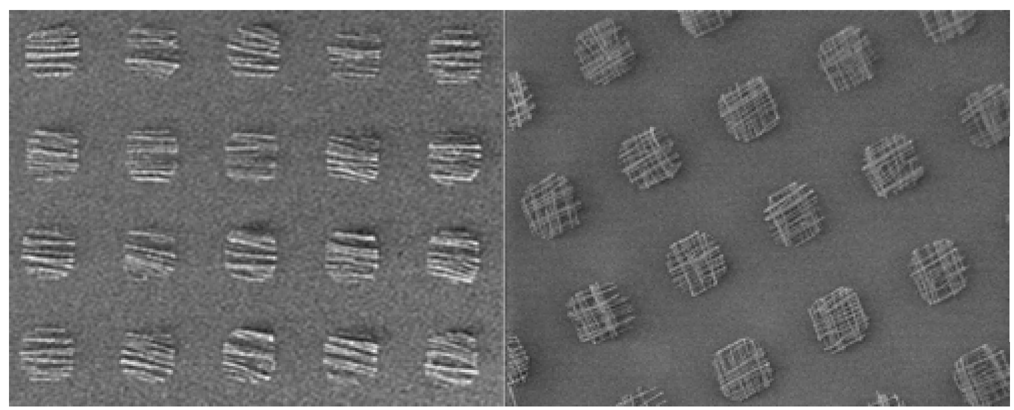
J. Lee*, et al, Electroanalysis* 19, (2007)

Langmuir–Blodgett technique



NWs (blue lines) in a monolayer of surfactant at the air–water interface are

(a) compressed on a Langmuir–Blodgett trough to a specified pitch.
(b) The aligned NWs are transferred to the surface of a substrate to make a uniform parallel array.
(c) Crossed NW structures are formed by uniform transfer of a second layer of aligned parallel NWs (red lines) perpendicular to the first layer (blue lines)



D. Whang *et al, Nano Letters*, 2003, 3 (9)

Video of Ag nanowire in a LB trough

http://pubs.acs.org/doi/full/10.1021/nl0345062#references

4. Lab Session I: Electrodeposition of Nanowires in Nanoporous Templates

Location:

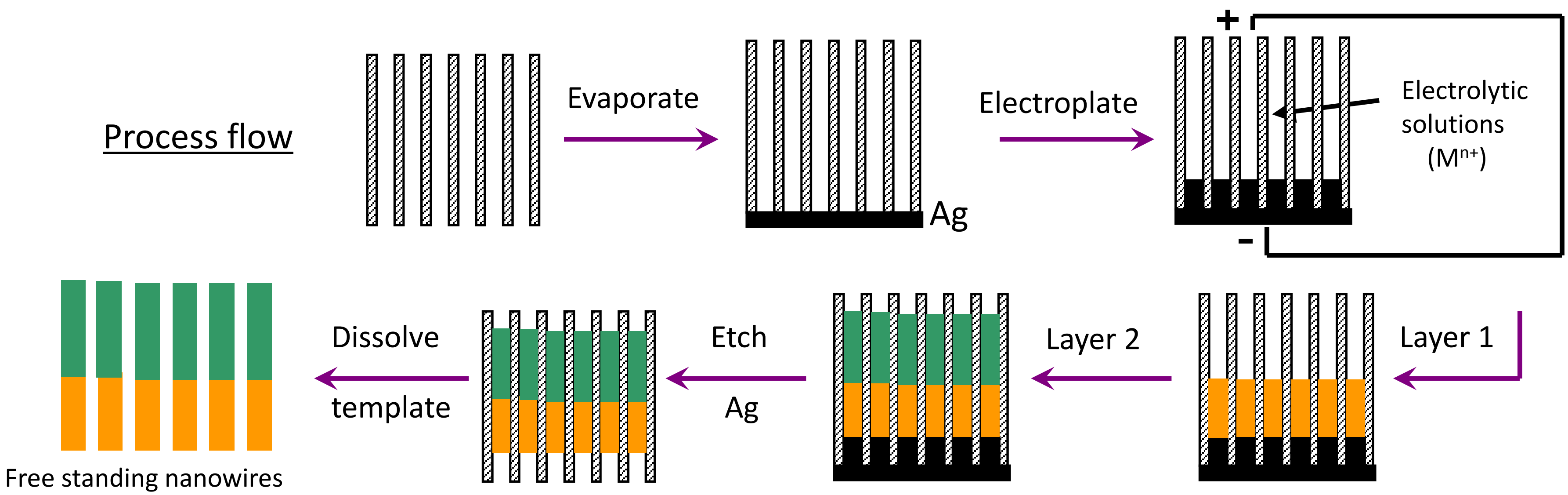
Engineering Building 301

What to know?

Lab safety!

Total Experiment time: 45 min

Multi-segment nanowire fabrication steps



Experiment Setup

Gold nanowire fabrication

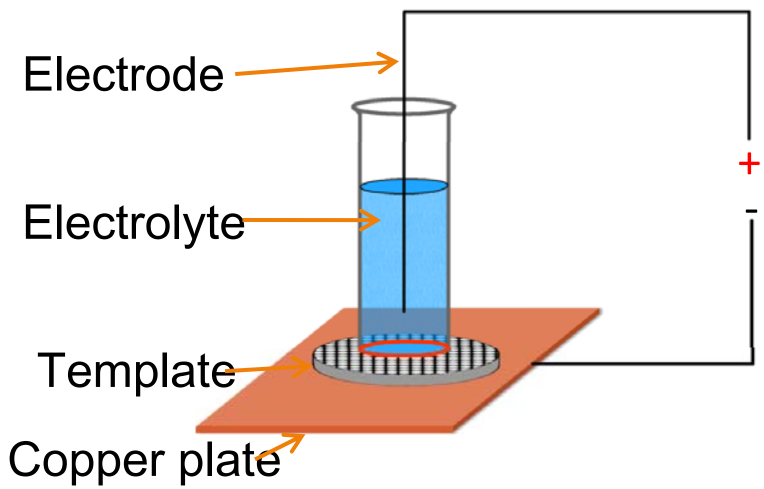
$Au^{+} + e \rightarrow Au$

Current control

Current Density:

Ag- 0.5~1 mA/cm^2

Au- 1~2 mA/cm^2



Ag etching: 6M HNO_3

Template dissolve: 2M NaOH

Nanowire Cleanning: DI Water& Ethanol

Homework-Lab report
Due date: Apr. 3rd 2013

Laboratory reports should be typed and in the format listed below:

- Lab title
- Lab summary
- Objectives
- Design
- Implementation
- Results and discussions
- Conclusion

Thanks