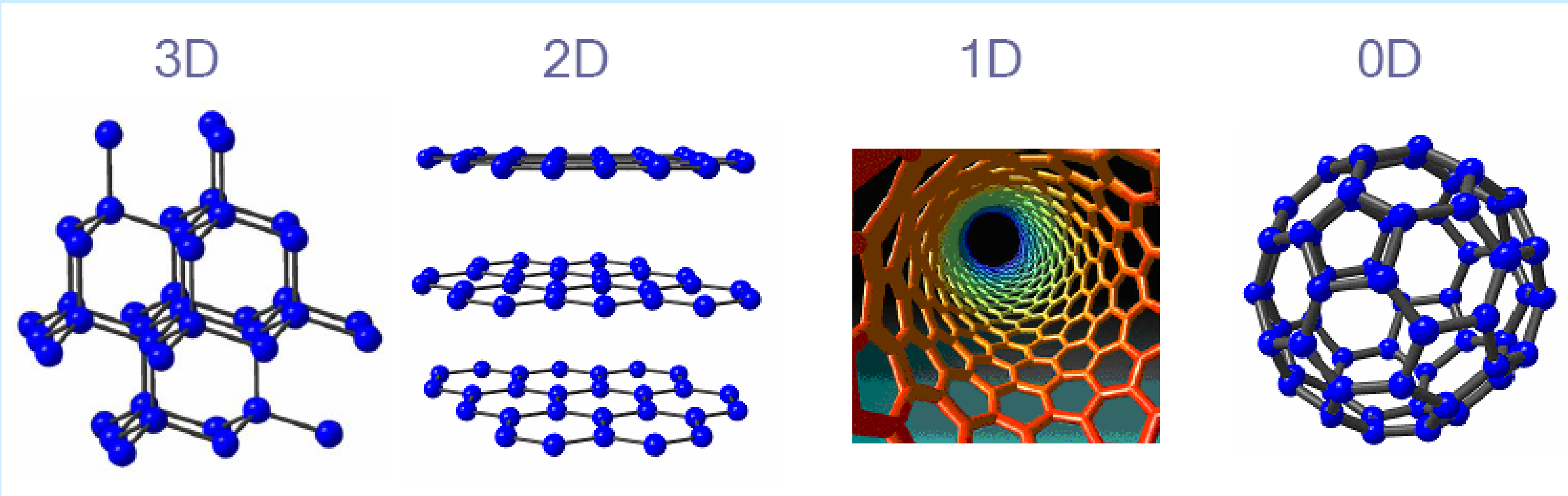
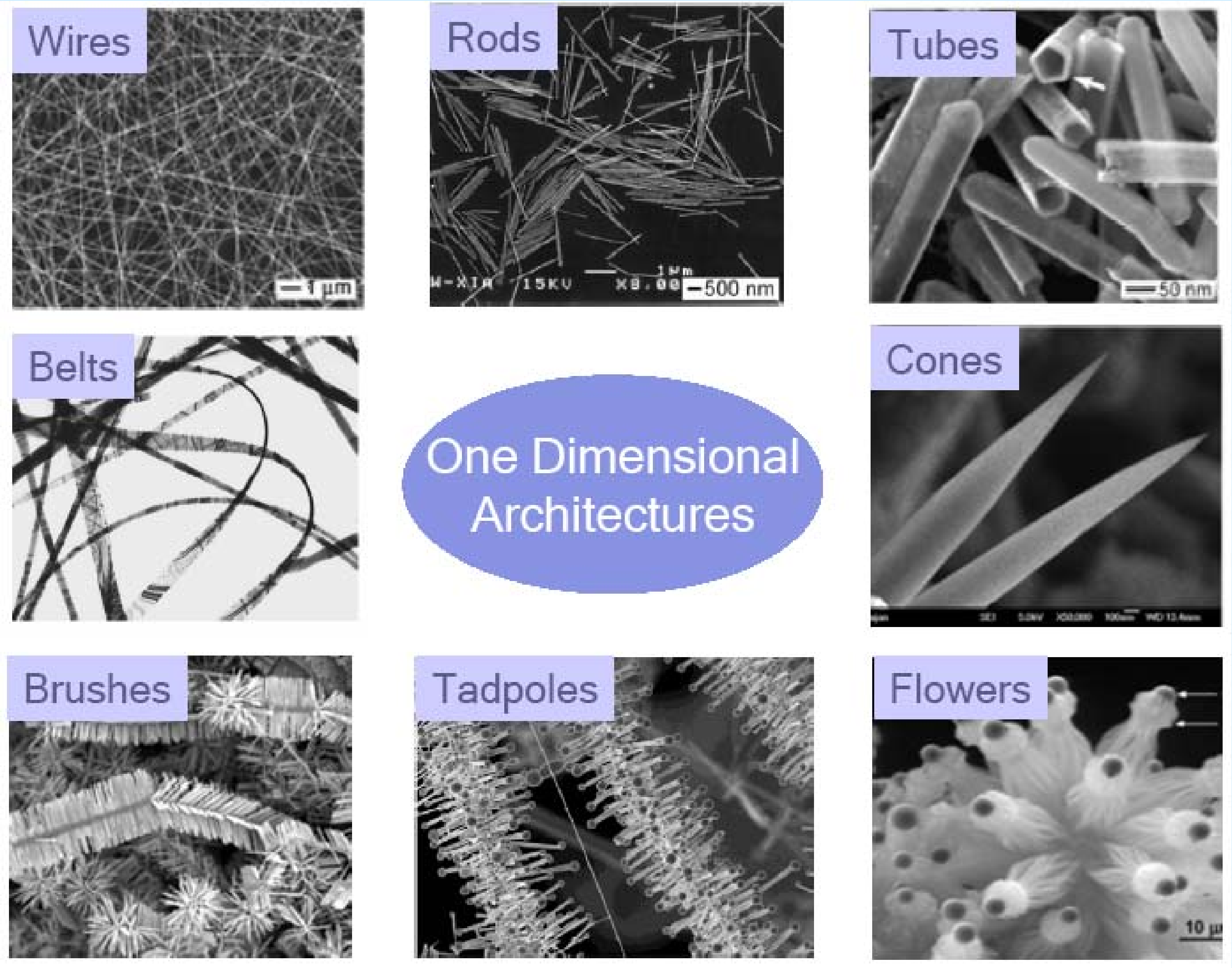
# Dimension-Properties Interplay

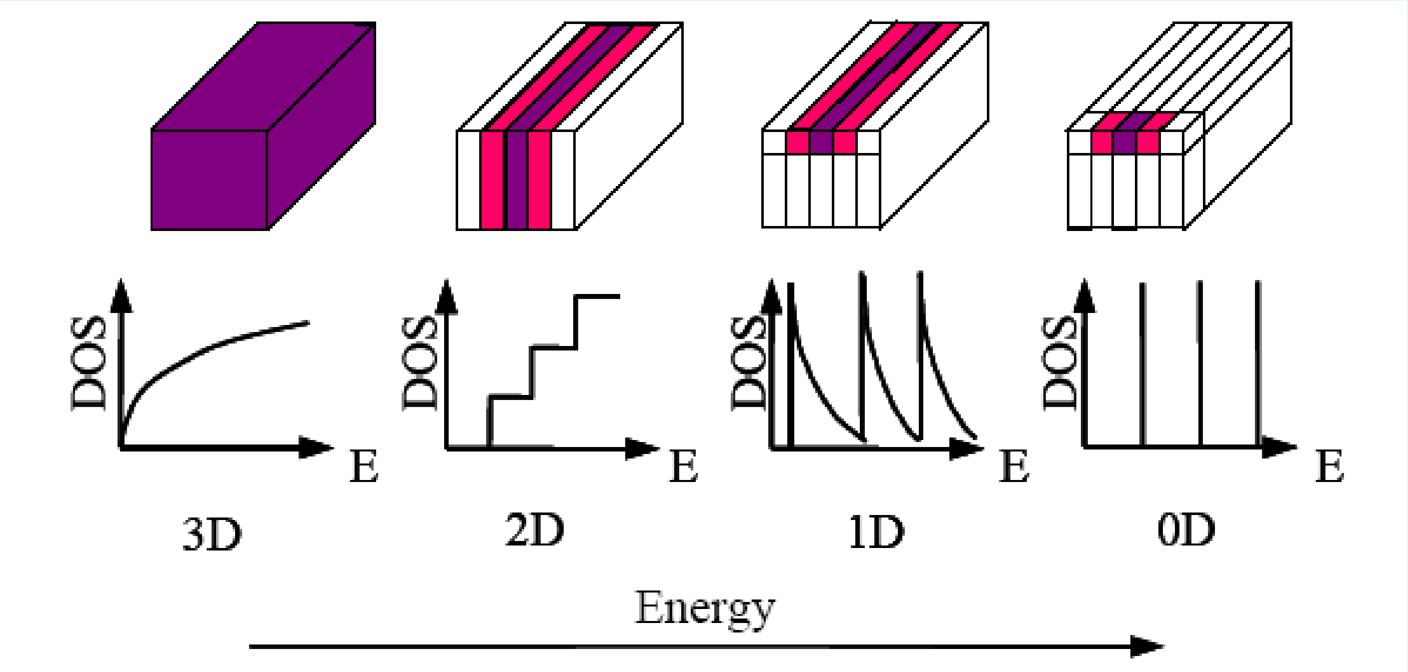



| | | | |
|---|---|---|---|
| **Brilliant, Transparent** | **Metallic lusture Opaque** | **Black, Fibrous** | **Black Shiny Crystals** |
| **Mohs Hardness 10** | **1-2** | **1-1.2** | **-** |
| **20 W/cmK** | **25** | **6000** | **-** |
| **High Melting point** | **Lubricant** | **Unusual Electrical Behaviour** | **Superconductor (10-40 K)** |

# High Axial Ratio Nanostructures



# Role of Dimensionality



# Role of Dimensionality

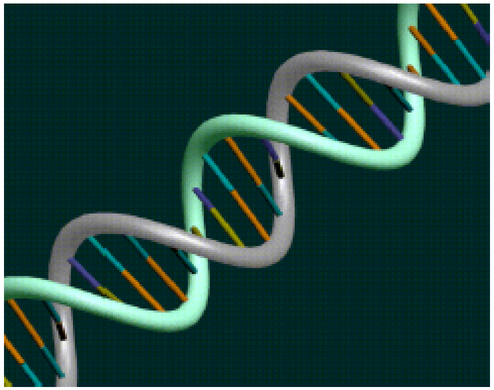
3 D: $E = \frac{\hbar^2}{2m}\left[k_x^2 + k_y^2 + k_z^2\right]$

2 D: $E = \frac{\hbar^2}{2m}\left[k_x^2 + k_y^2 + \left(n_z \frac{\pi}{L}\right)^2\right]$ $n_z = 1,2,3\ldots$

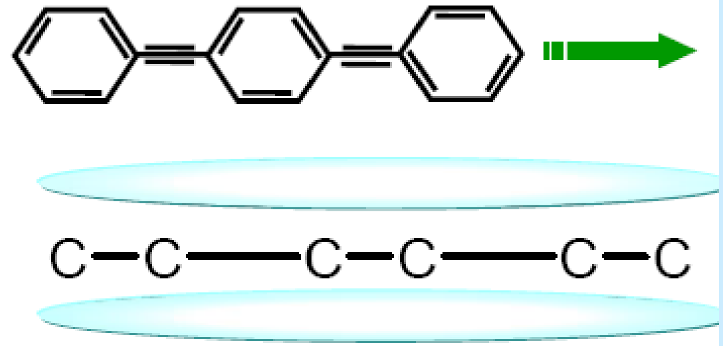
1 D: $E = \frac{\hbar^2}{2m}\left[k_x^2 + \left(n_y \frac{\pi}{L}\right)^2 + \left(n_z \frac{\pi}{L}\right)^2\right]$ $n_y, n_z = 1,2,3\ldots$

0 D: $E = \frac{\hbar^2}{2m}\left[\left(n_x \frac{\pi}{L}\right)^2 + \left(n_y \frac{\pi}{L}\right)^2 + \left(n_z \frac{\pi}{L}\right)^2\right]$ $n_x, n_y, n_z = 1,2,3\ldots$

# 1D Nanostructures

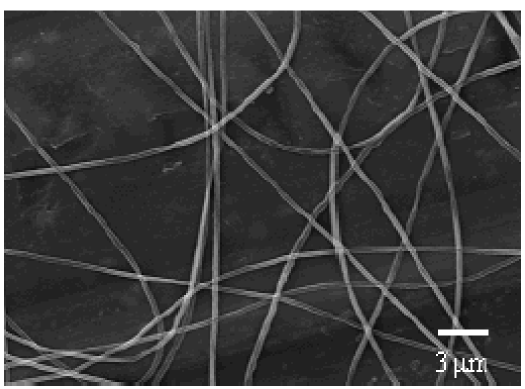


DNA

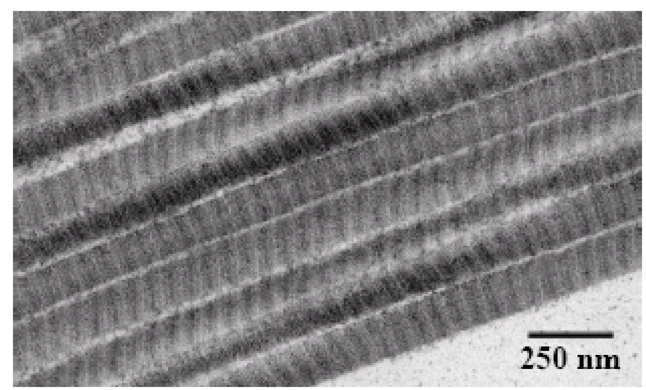



Molecular Wire

The Nano World




Poly (ethylene oxide)




Collagen Fibrils

# Characteristics of 1D Nanostructures

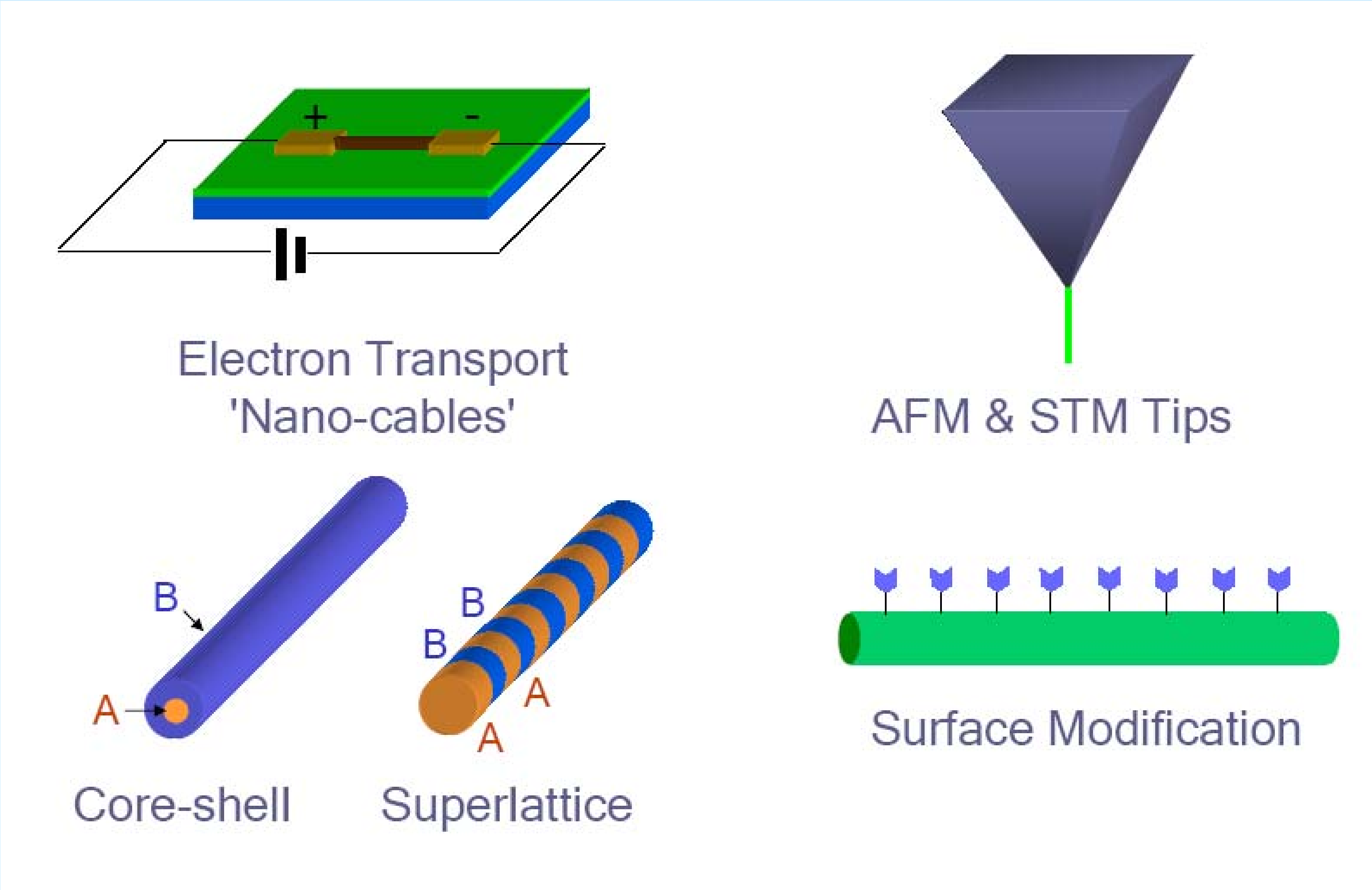
**Properties**

Small
Light weight
Novel 1-D properties
High aspect ratio
High surface area

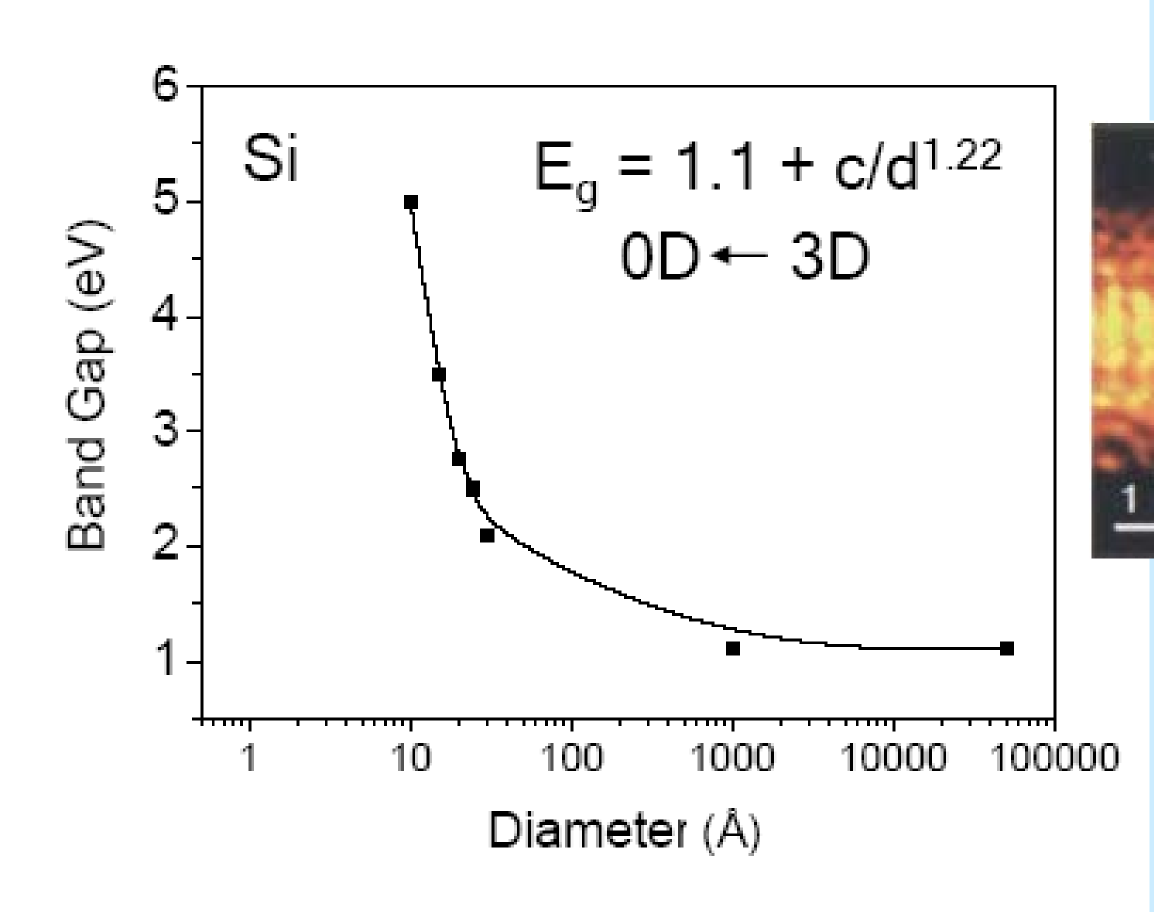
**Potential applications**

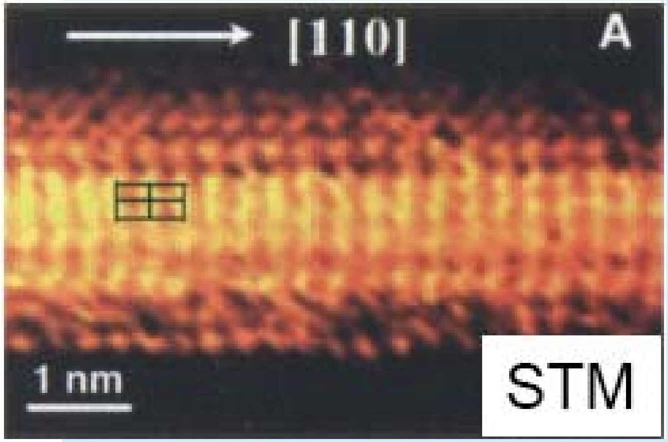
Interconnects
Novel Probes
Multifunctional
Hierarchical alignment
Building blocks for devices

# Potential of Nanowires



# Effect of Confinement

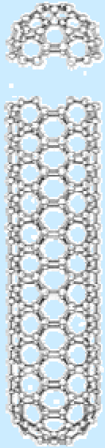



The band gap increases with decreasing diameter (quantum confinement)

# Carbon Nanotubes

- Discovered by Iijima (1991, NEC)
- Rolled up sheet of graphene
- Capped at the ends with half a fullerene



# Carbon Nanotubes

Single Walled Nanotube ( SWNT)
• Single atomic layer wall
• Diameter of 1 – 5 nm
• Length several microns

Multi Walled Nanotube ( MWNT)
• Concentric tubes ca. 50 in number
• Inner diameters : 1.5 – 15 nm
• Outer diameters : 2.5 – 30 nm

# CNTs: Properties and Potential

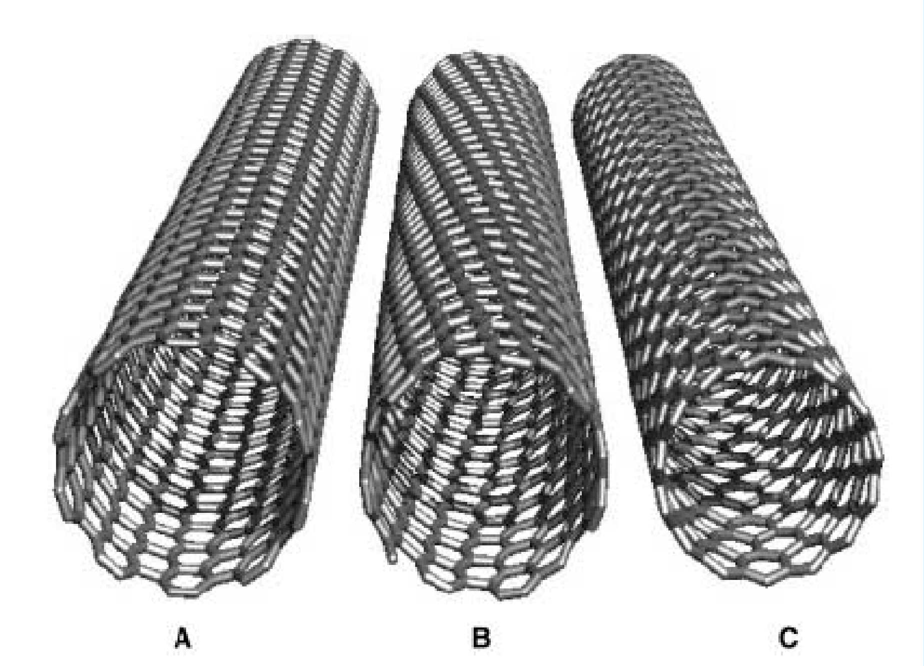
Electronic: Bandgap Eg ~ 1/d

Magnetic: Anisotropic magn. susceptibility $\chi_\perp \gg \chi_{||}$

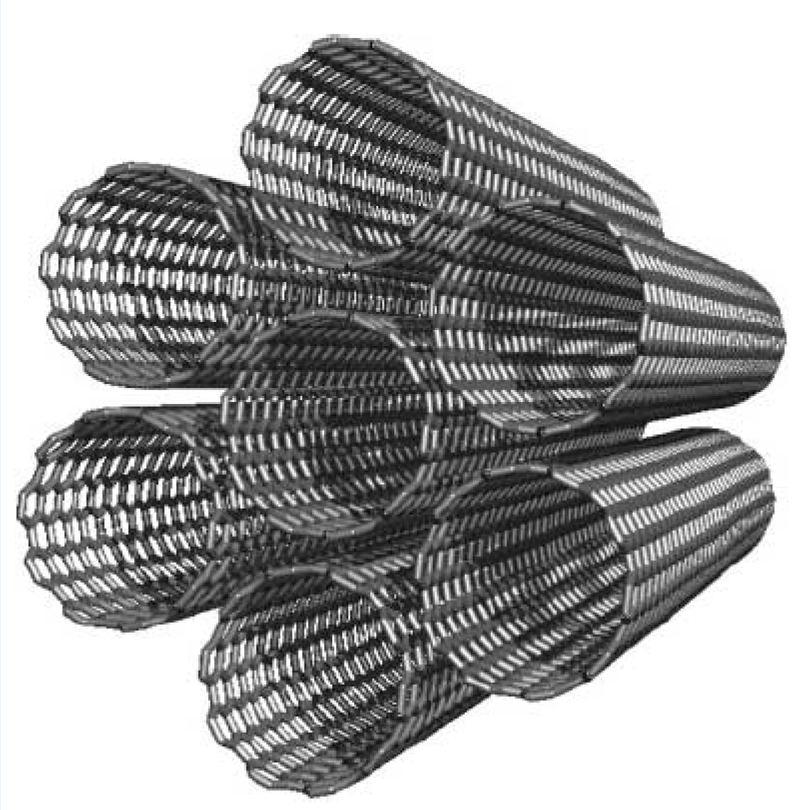
Mechanical: Young's Modulus
~ 1 TPa (SWNT)
1.25 TPa (MWNT)
(Steel: 230 GPa)

Thermal: Conductivity 6000 W/m.K
(Copper 400 W/m.K)

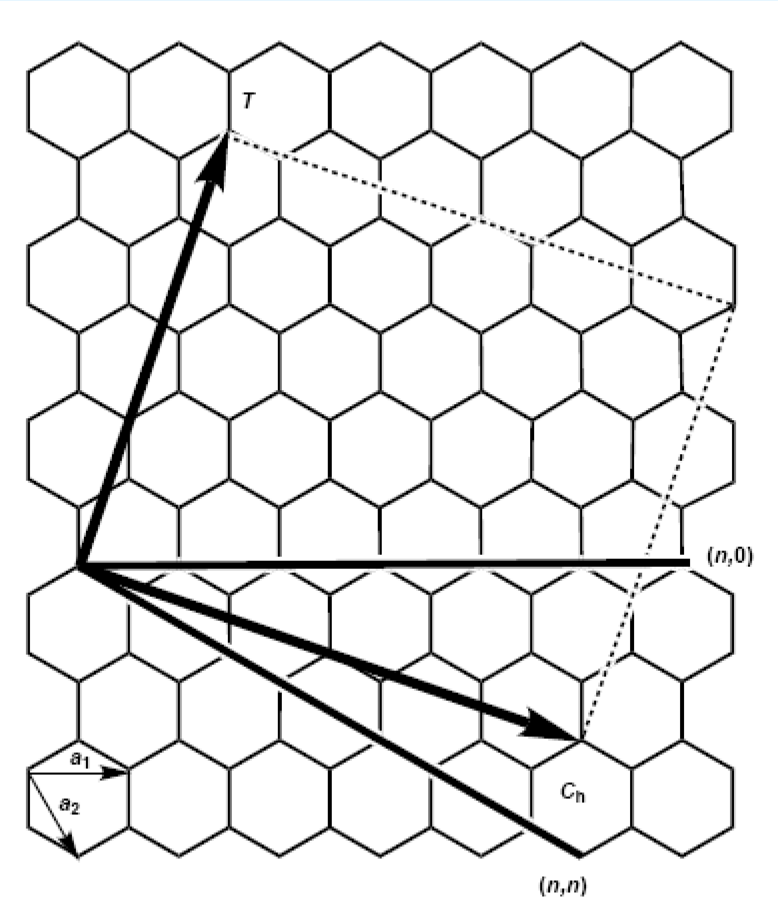
# Defect-free (n,m) SWNTs with open ends




A) A metallic conducting (10,10) tube (armchair)
B) a chiral, semiconducting (12,7) tube,
C) a conducting (15,0) tube (zigzag).
The armchair (A) and zigzag (C) tubes are achiral.
All the (n,n) armchair tubes are metallic, whilst this is only the case with chiral or zigzag tubes if (n-m)/3 is a whole number, otherwise, they are semiconductors

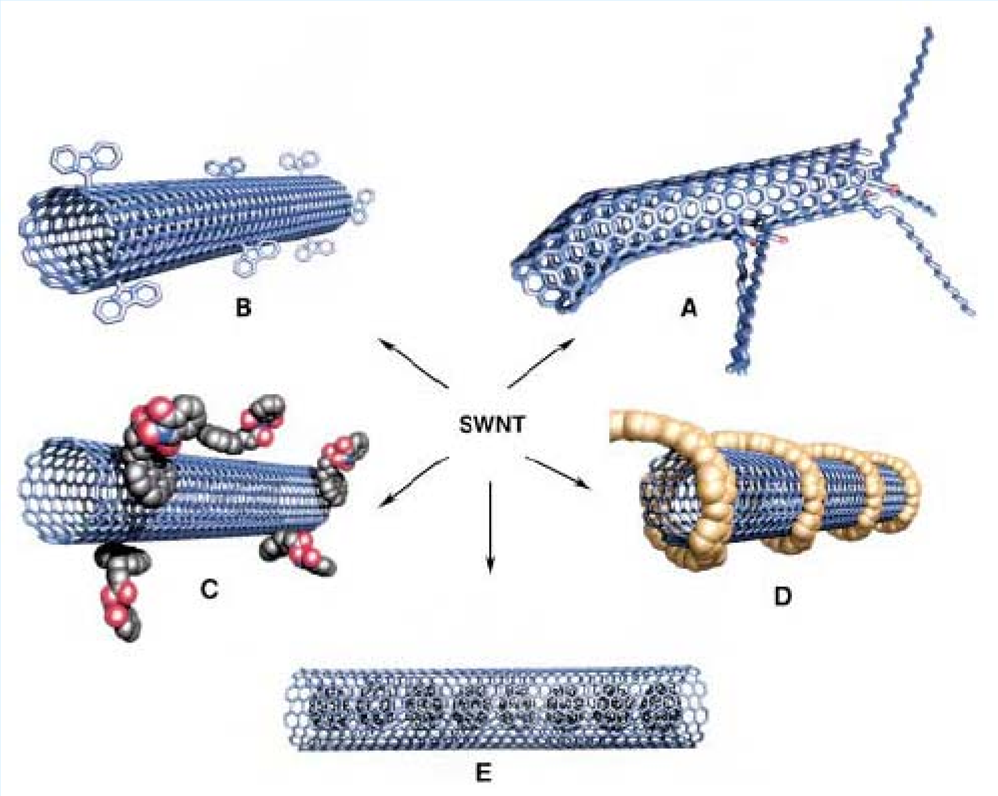


A bundle of (10,10) nanotubes held together with strong π-π-stacking interactions



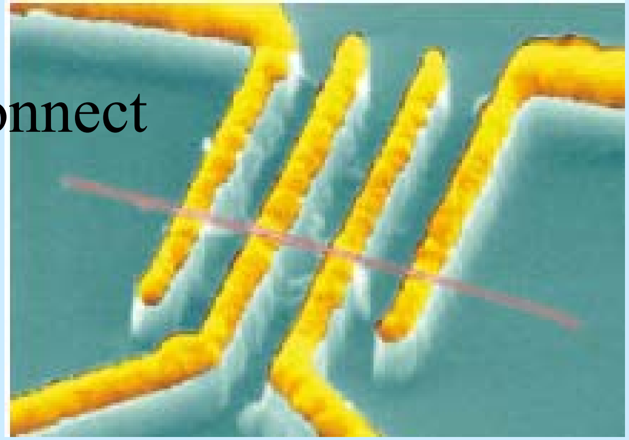

a 2D graphite layer
the lattice vectors $a_1$ and $a_2$
the roll-up vector $C_h = na_1 + ma_2$
Achiral tubes exhibit roll-up vectors derived from (n,0) (zigzag) or (n,n) (armchair).
The translation vector T is parallel to the tube axis and defines the 1D unit cell.
The rectangle represents an unrolled unit cell, defined by T and $C_h$
In this example, (n,m)=(4,2)

# Functionalization possibilities for SWNTs

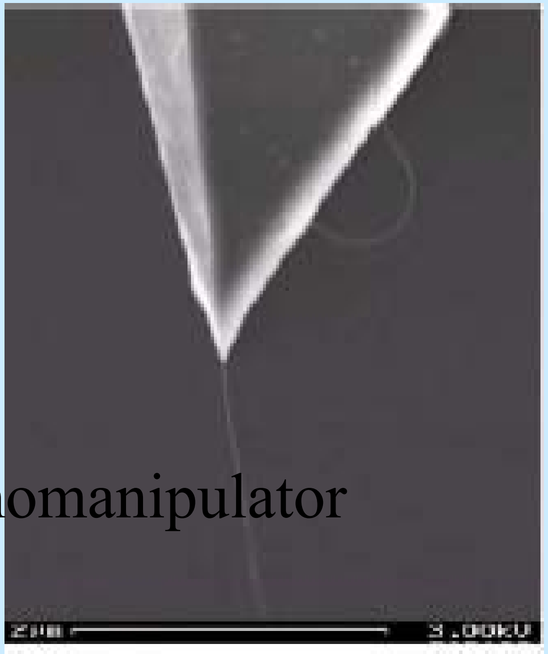



A) defect-group functionalization
B) covalent sidewall functionalization
C) noncovalent exohedral functionalization with Surfactants
D) noncovalent exohedral functionalization with polymers
E) endohedral functionalization with $C_{60}$

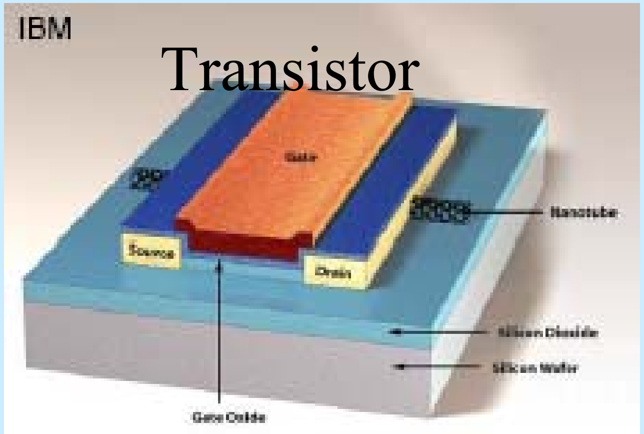
Interconnect

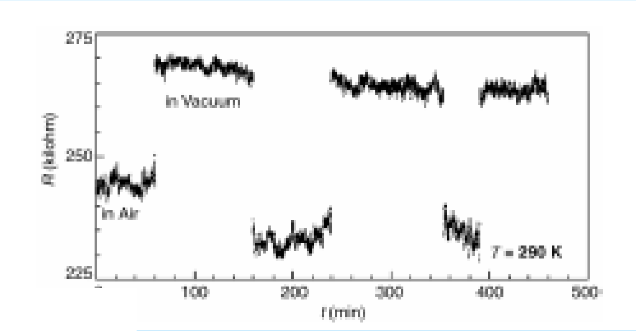


Nanomanipulator

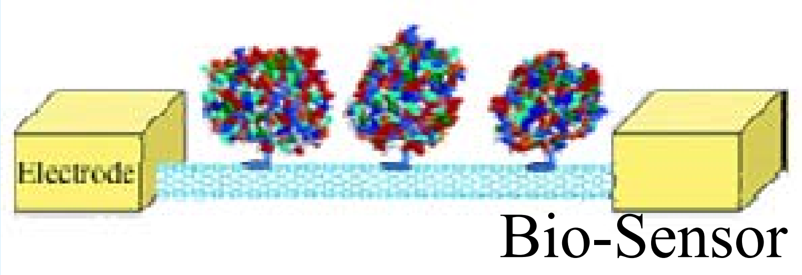


Transistor



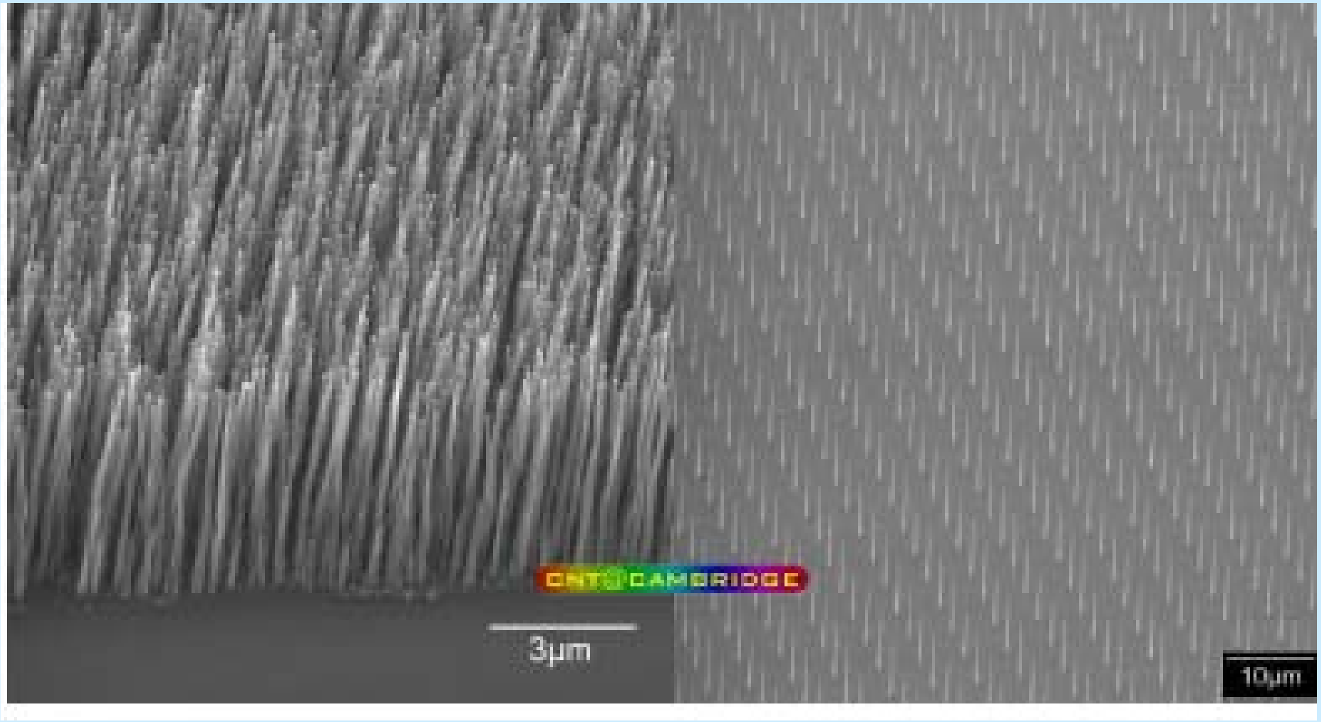




Chemical Sensor




Bio-Sensor

# Assembly of CNTs




CNT applications:
Ultra-hard Composites
Nanopipettes
Field Emission Transistor
Nanomanipulator

# Carbon Nanotubes

Difficult to obtain in pure form (SWNT, MWNT, $C_x$, soot etc.)

As-synthesized CNTs are a mixture of conducting, semiconducting and insulating ones

Not stable under oxidizing conditions

Little manufacturing control over tube diameter

# Nanowires

Good transport properties – Single crystalline nature

Mechanically robust – Defect free

Flexibility in composition

Doping possible to create p- and n-type nanowires

Nanowires-based FETs and basic logic circuits demonstratedin the laboratory.

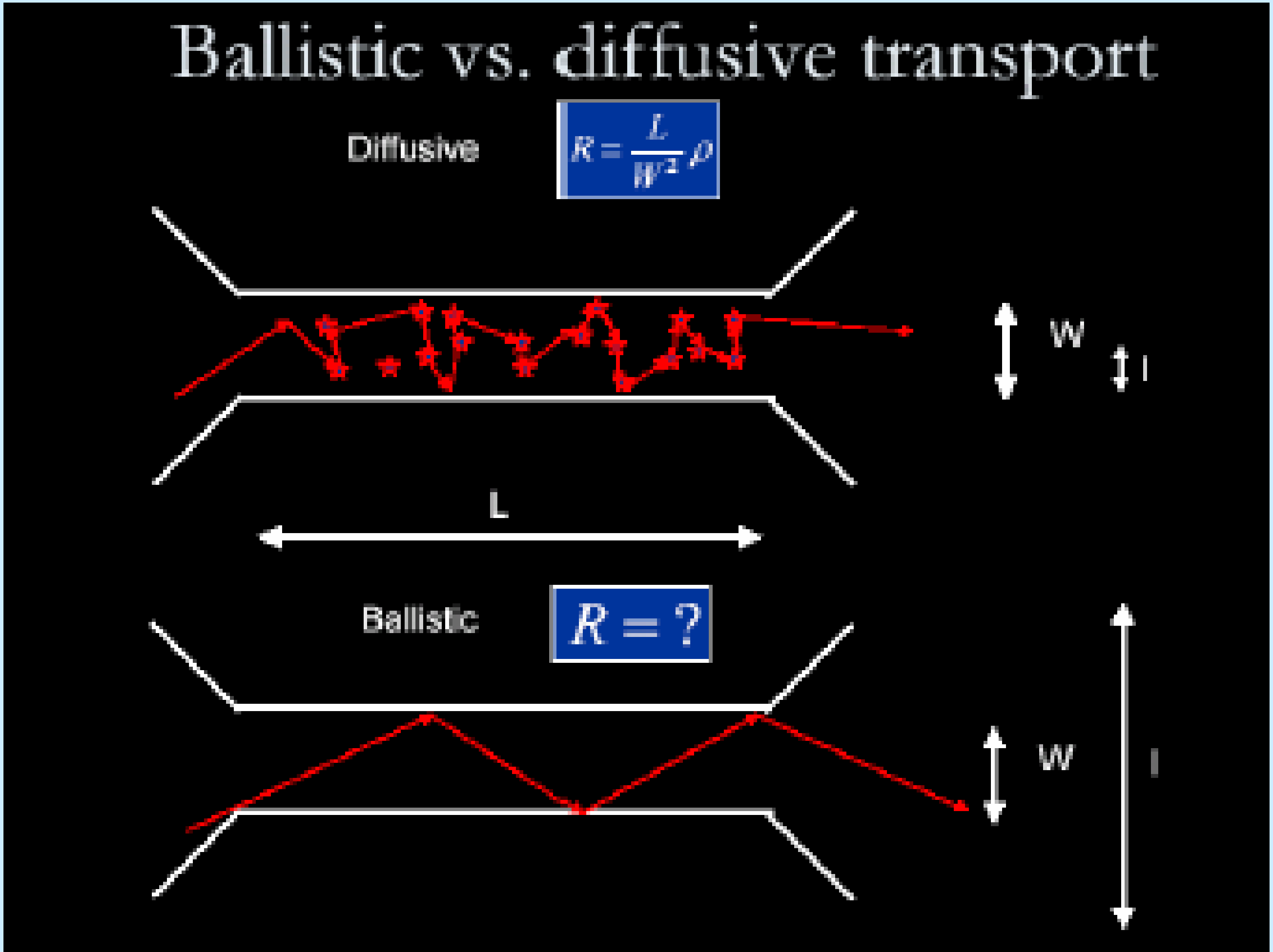
Techniques for mass manufacture

# Transport in Nanowires

Conductance Quantization:
The Landauer equation

$G = (2e^2/h)N$, N = no. of conduction channels

When NW diameter is smaller than the Fermi wavelength, conductance changes in steps of $2e^2/h$


Ballistic vs. diffusive transport
Diffusive
$R = \frac{L}{W^2}\rho$
W
l
L
Ballistic
$R = ?$
W
l

# Synthetic Routes to Nanowires

Epitaxial growth

Catalytic VLS growth

Catalytic base growth

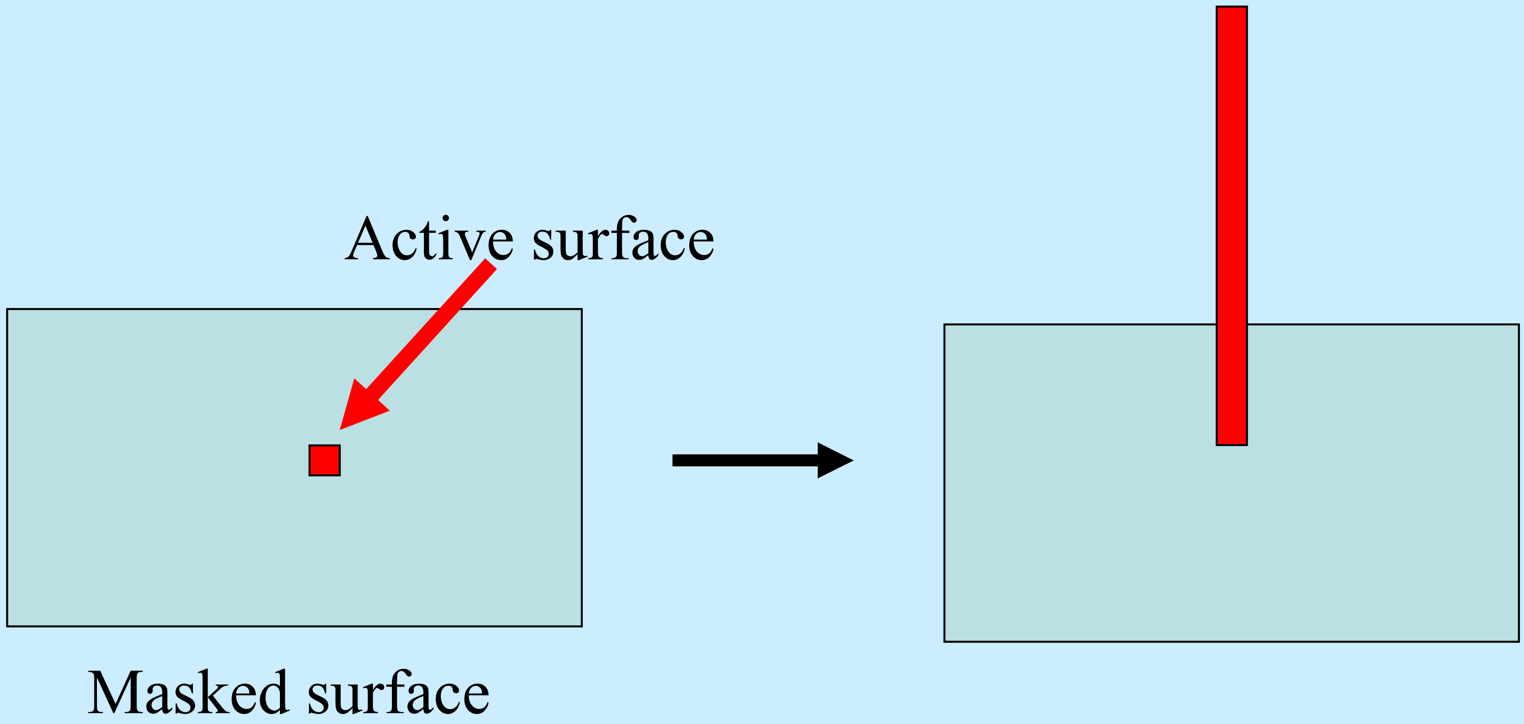
Defect nucleation

Templated growth

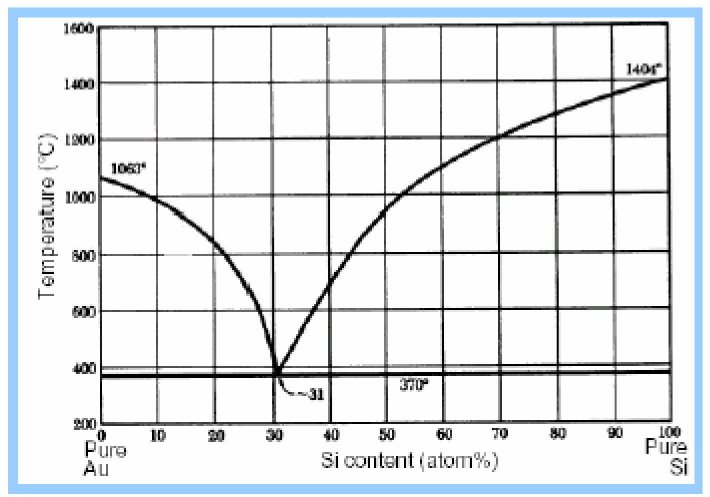
Arrested growth

Assembly of nanoparticles

# Epitaxial growth



# Vapor-Liquid-Solid (VLS) Growth




Start with a metal catalyst

Form a liquid droplet of a metallic eutectic when heated

Gaseous precursor feedstock is absorbed

The droplet becomes supersaturated

Excess material is precipitated out to form solid NWs beneath the droplet

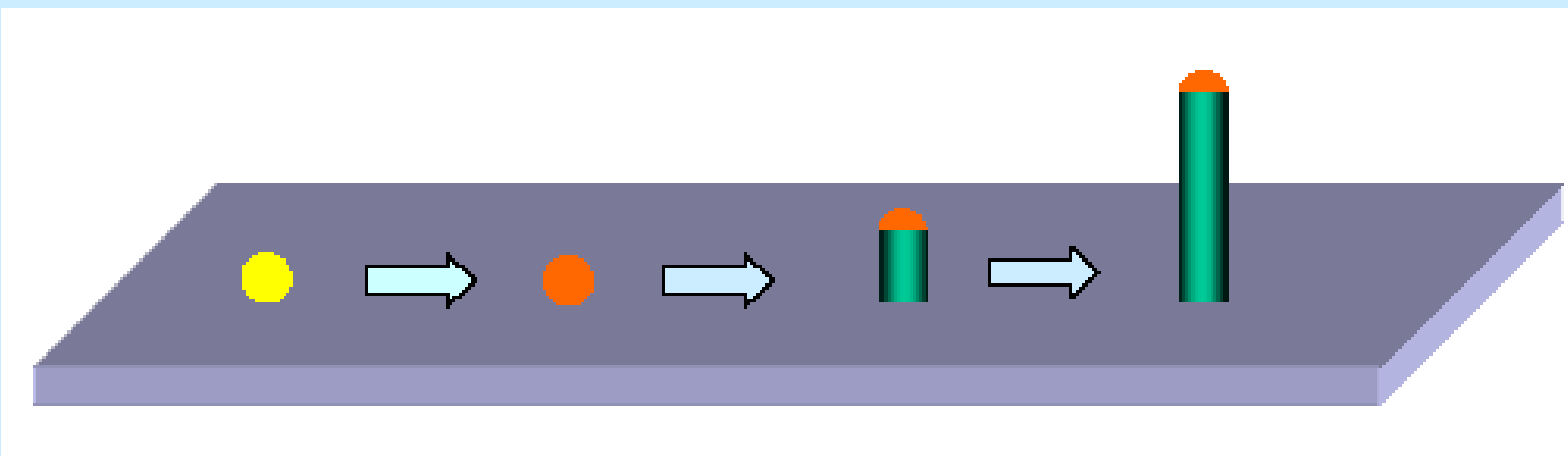
# Vapor-Liquid-Solid (VLS) Growth

Au Particles

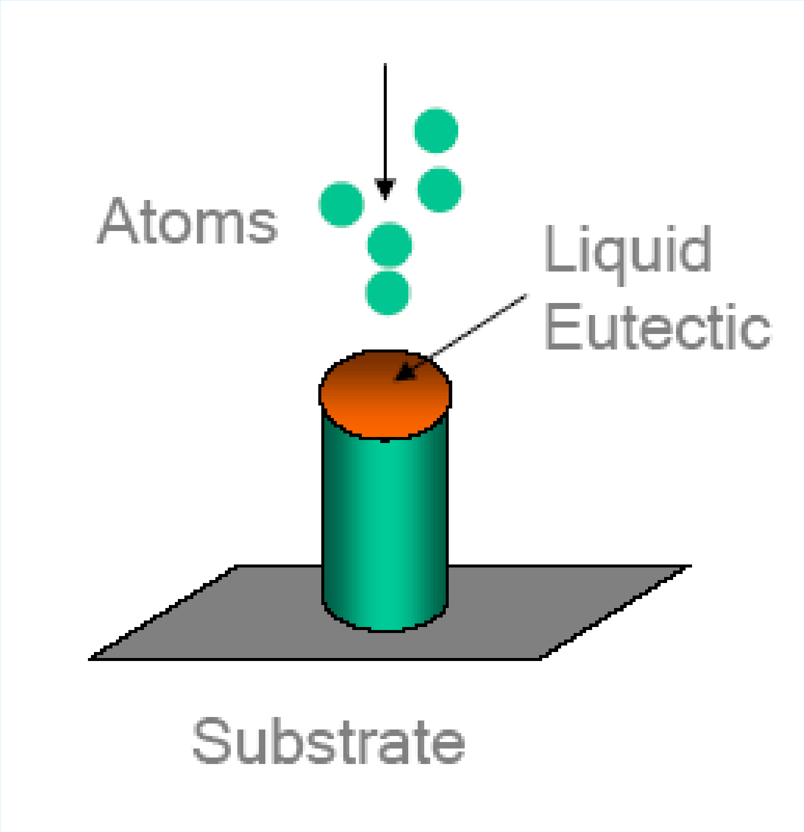
Alloy Liquid

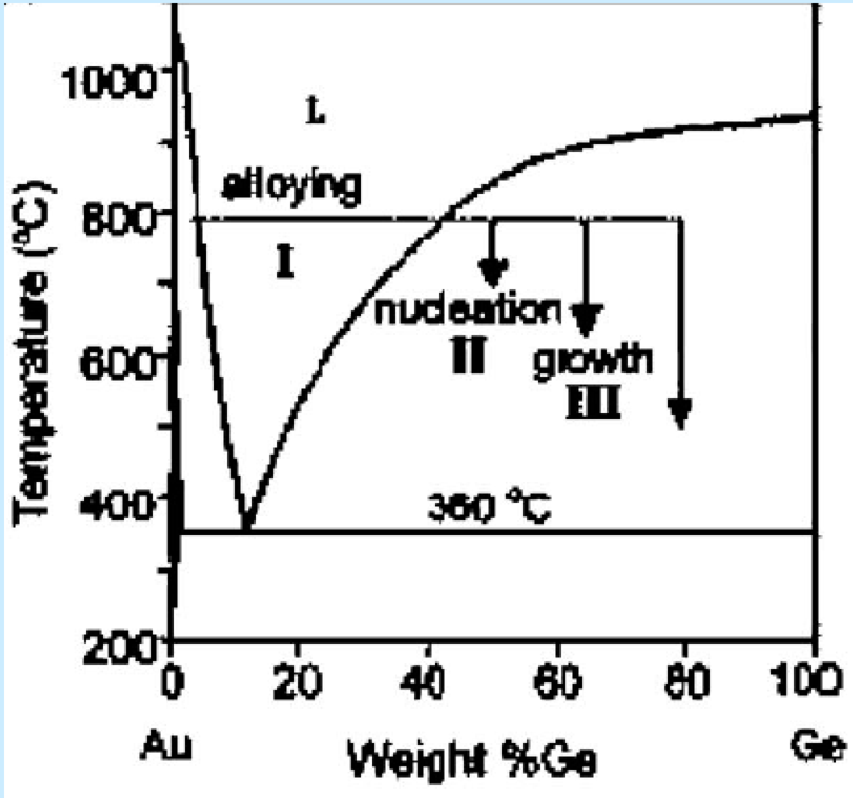
Nucleation of NWs

NW Growth



# Vapor-Liquid-Solid (VLS) Growth

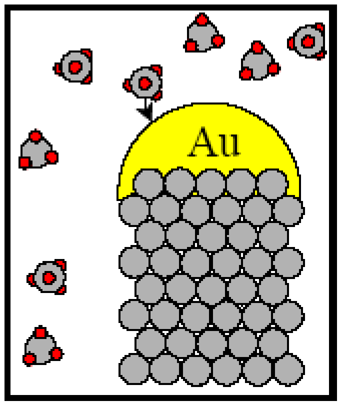


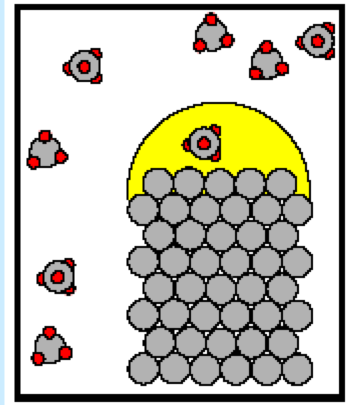
# Si Nanowire Growth

$$SiH_4 \rightarrow Si + 2H_2$$

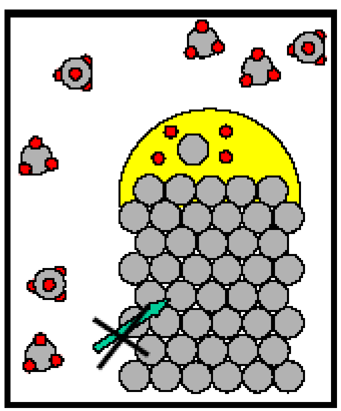
Mass transport in the gas phase



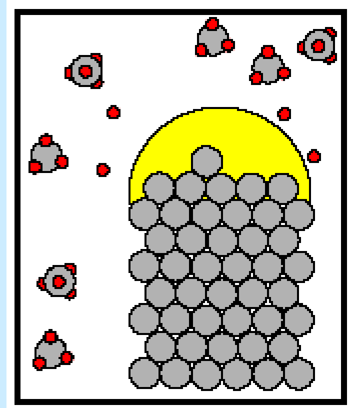

Diffusion in molten catalyst



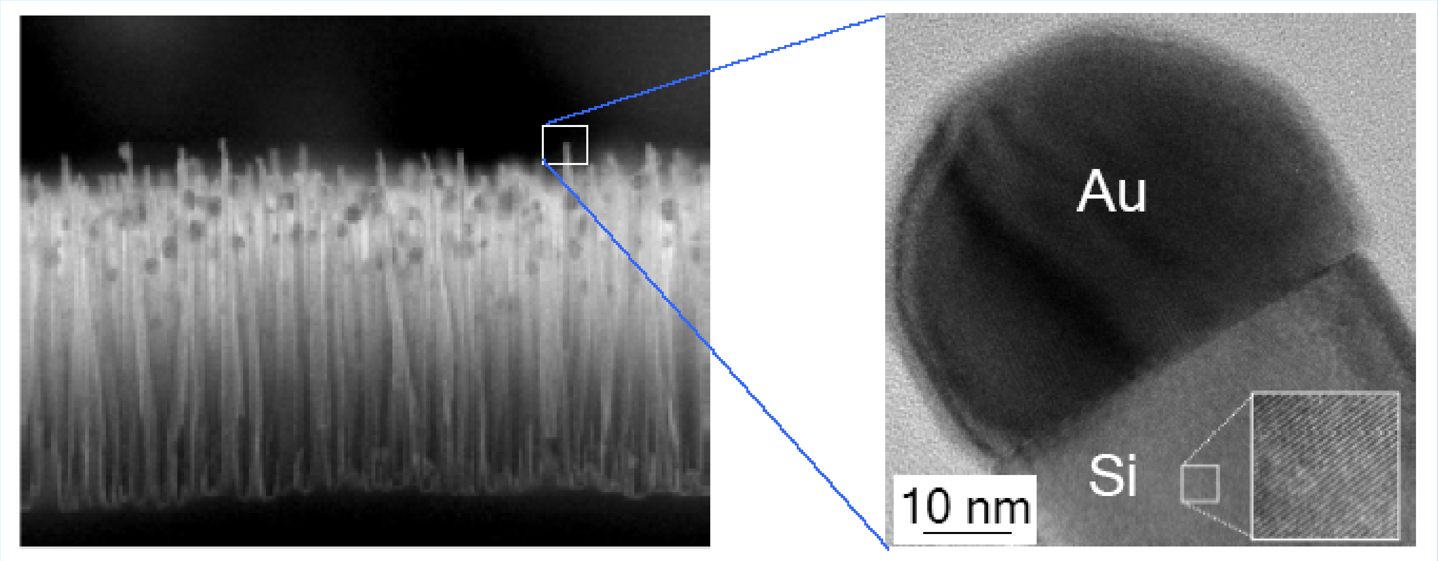
Chemical reaction at the V-L interface



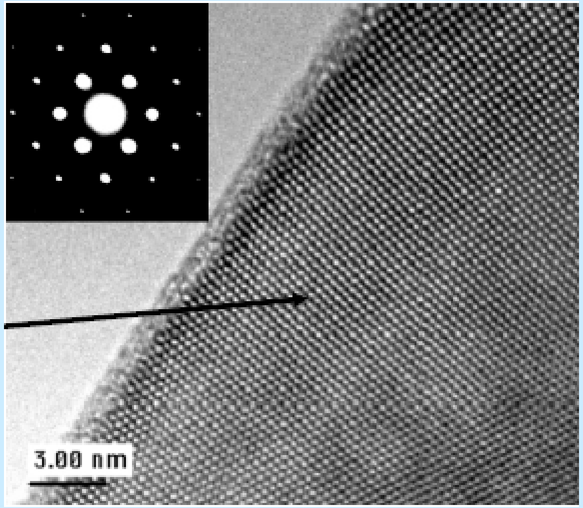
Incorporation of material in the crystal lattice



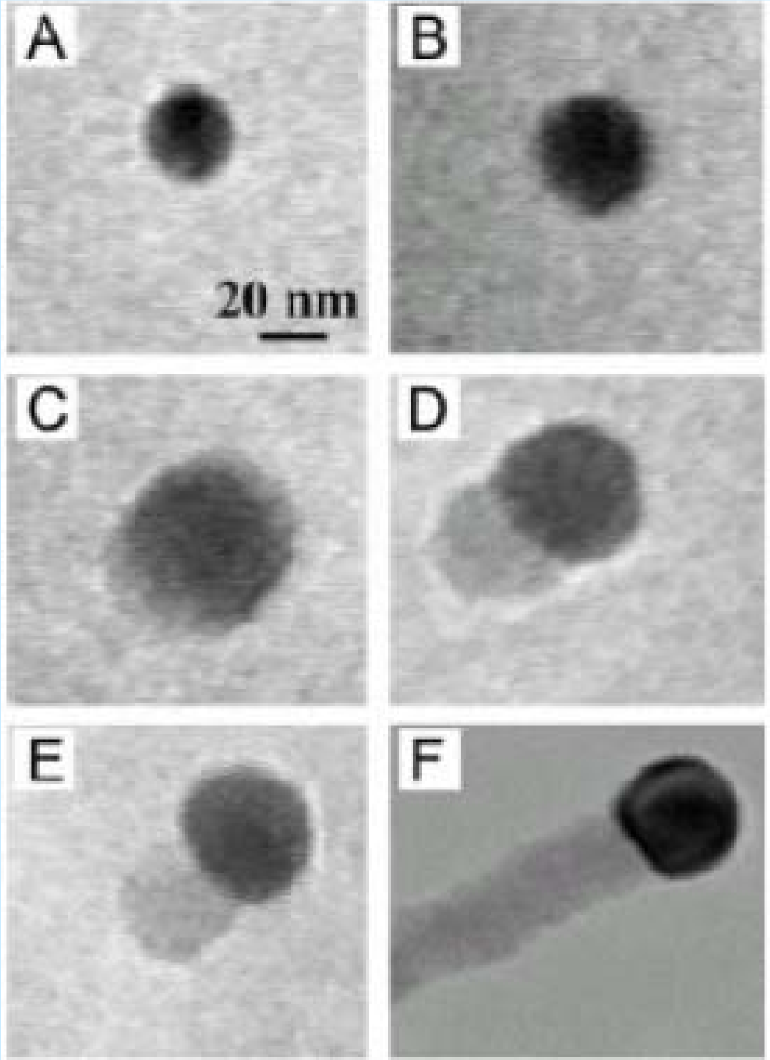
# Si Nanowires




Defect-free Si NW

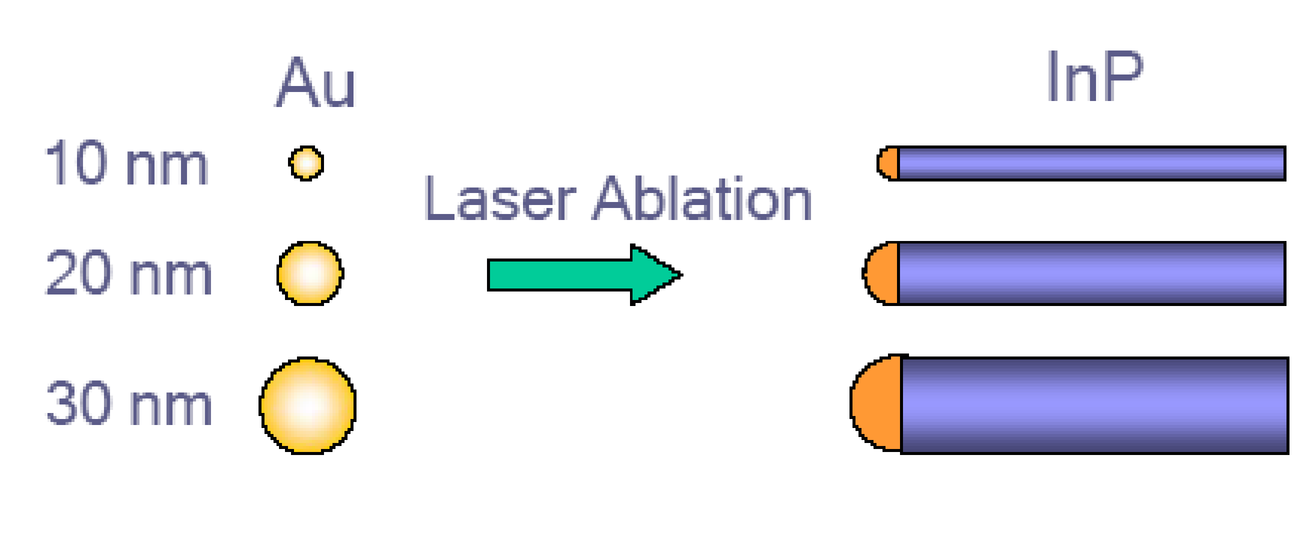


# In situ TEM images recorded during the VLS process

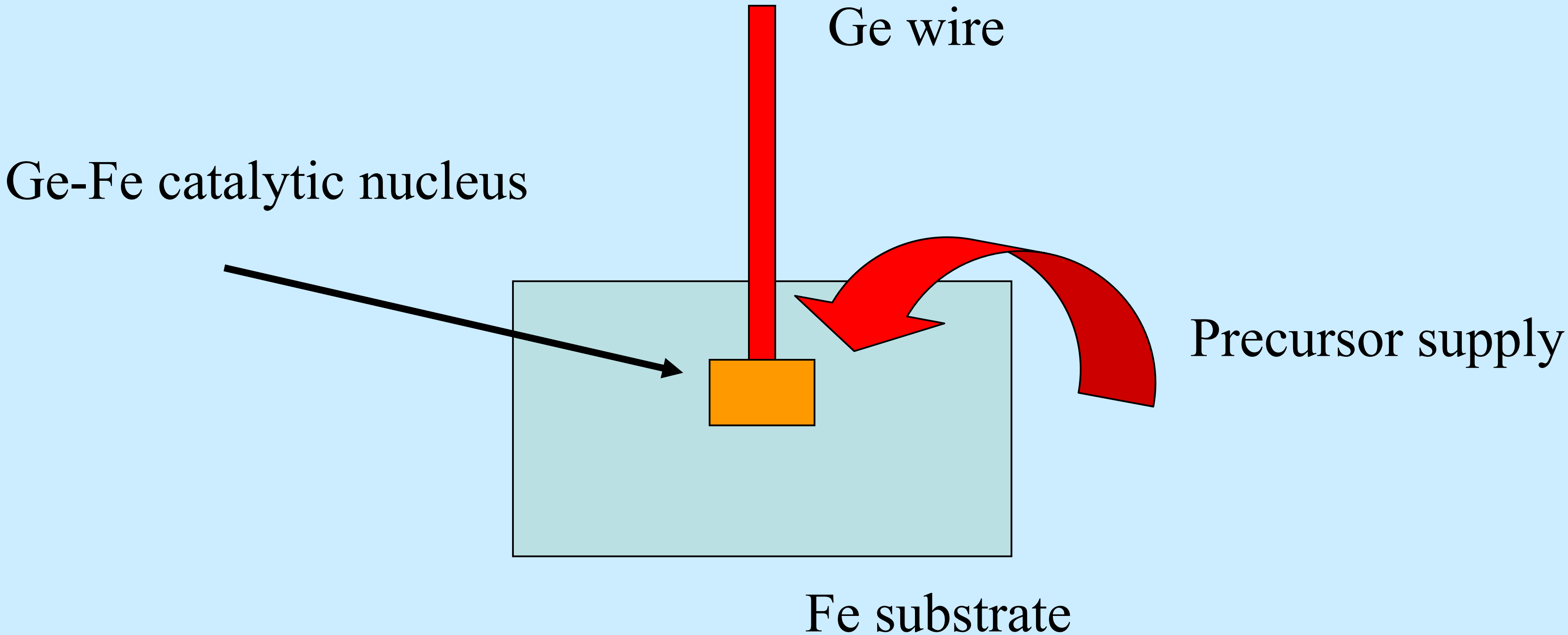


# Size Control

Metal particle acts as a soft template to control the diameter of the nanowire

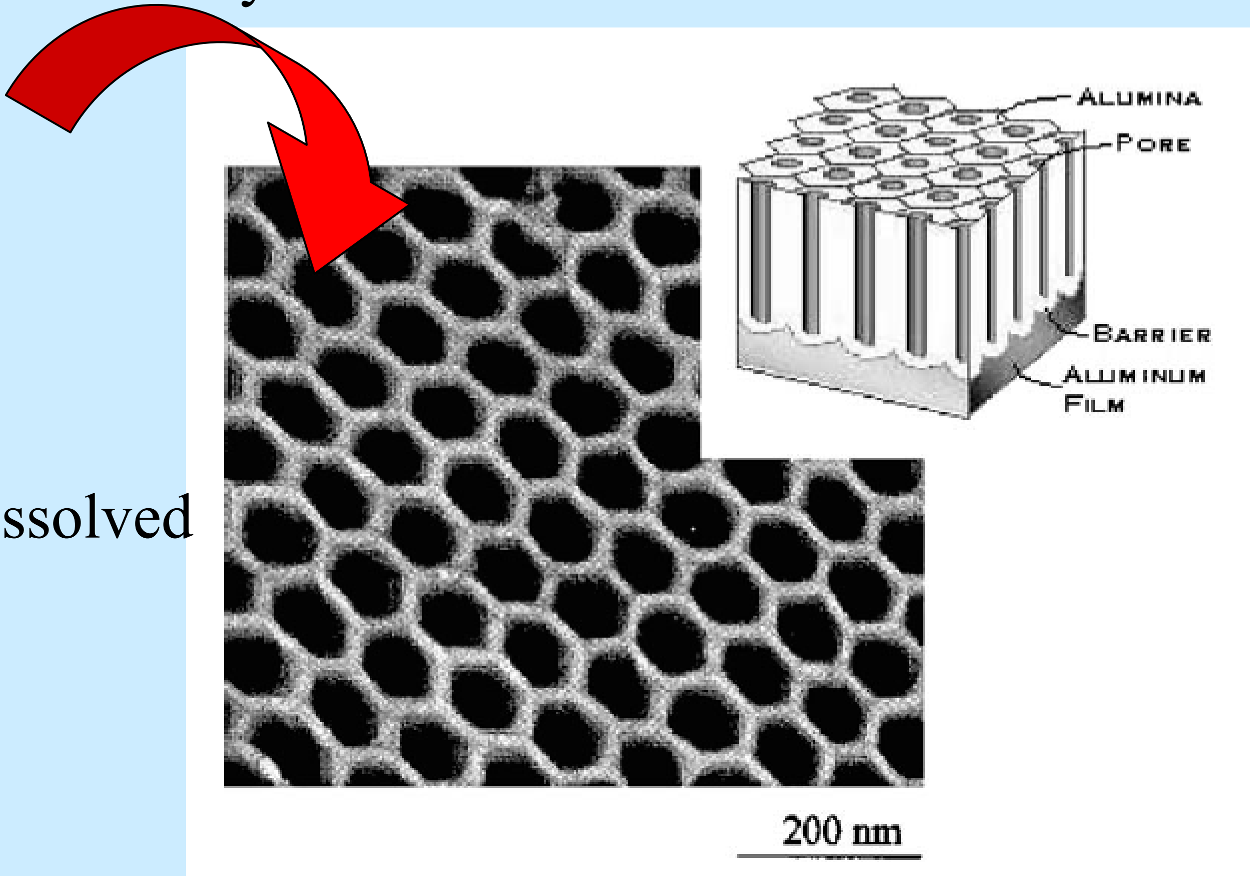


# Catalytic base growth



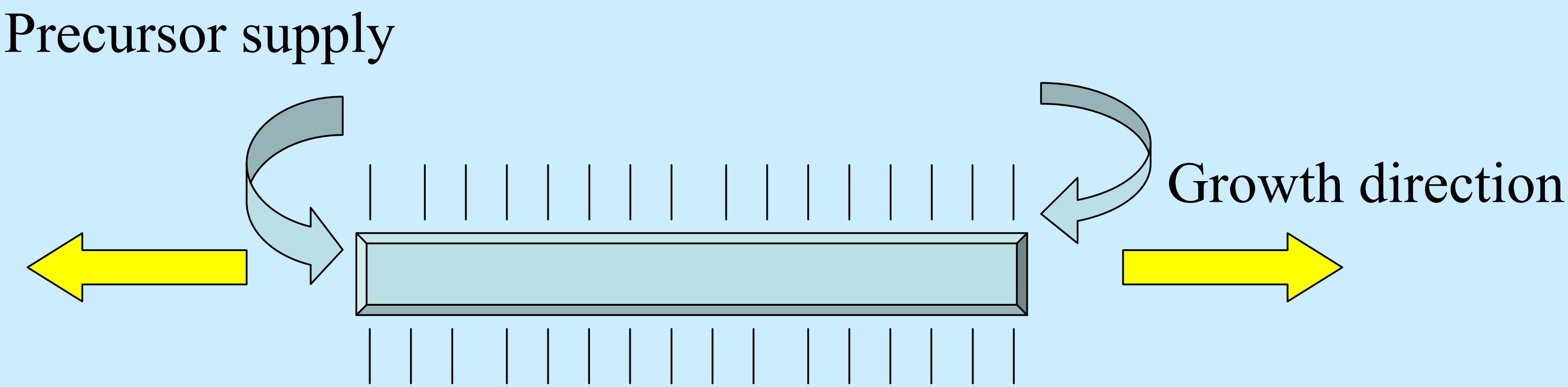
# Templated growth

1. Pores filled with material by CVD




2. Alumina matrix dissolved
3. Wires separated

# Arrested growth

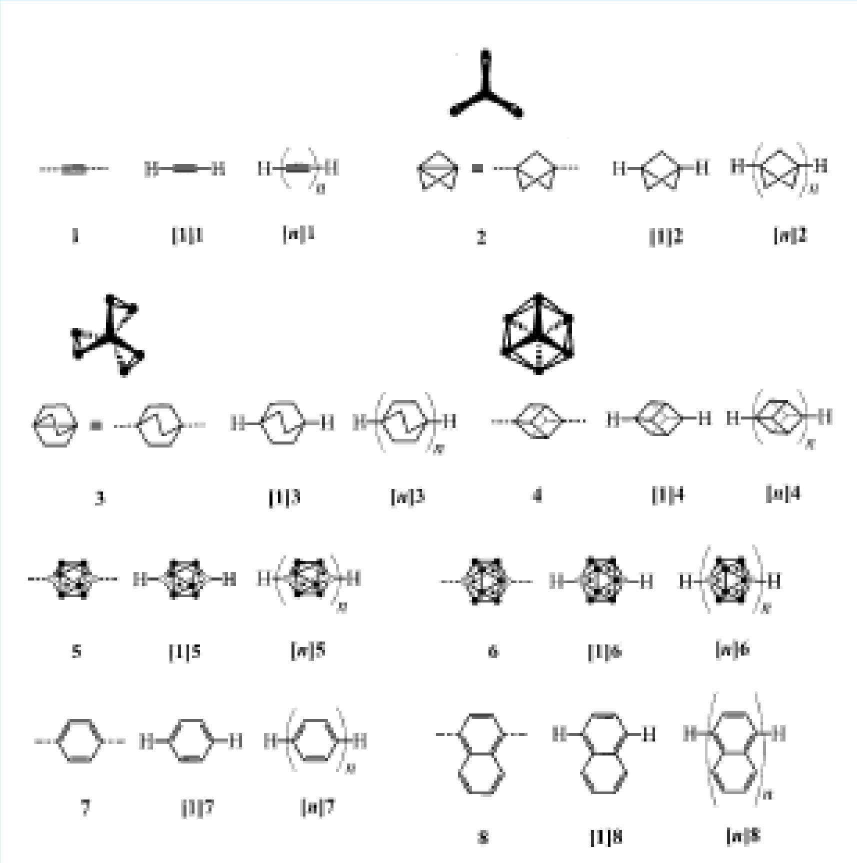


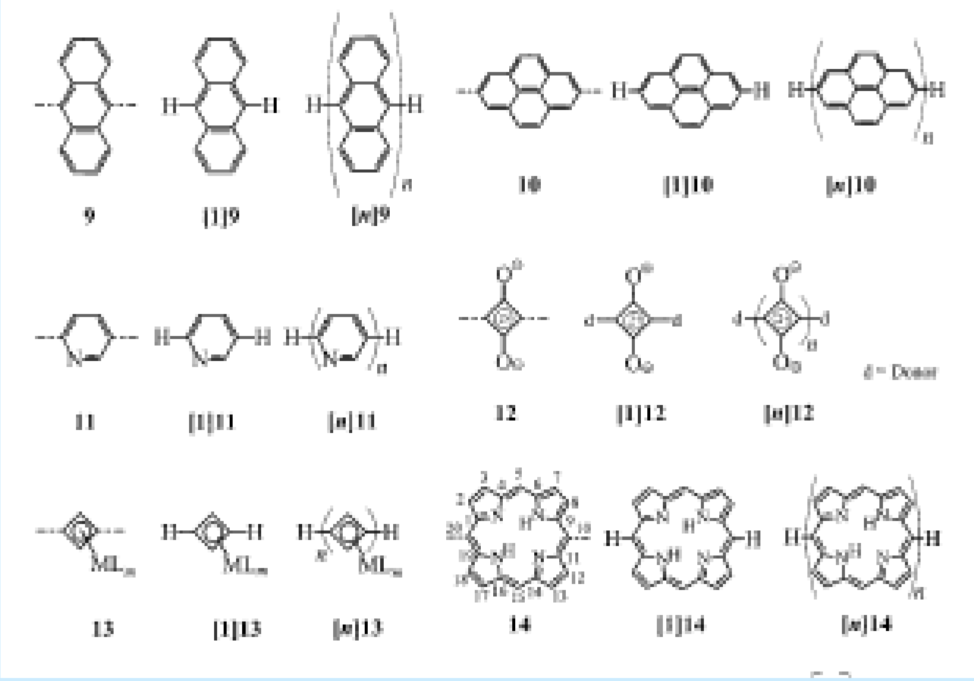

Selective binding of a compound to certain crystal faces

CdTe, TOPO blocks (111)

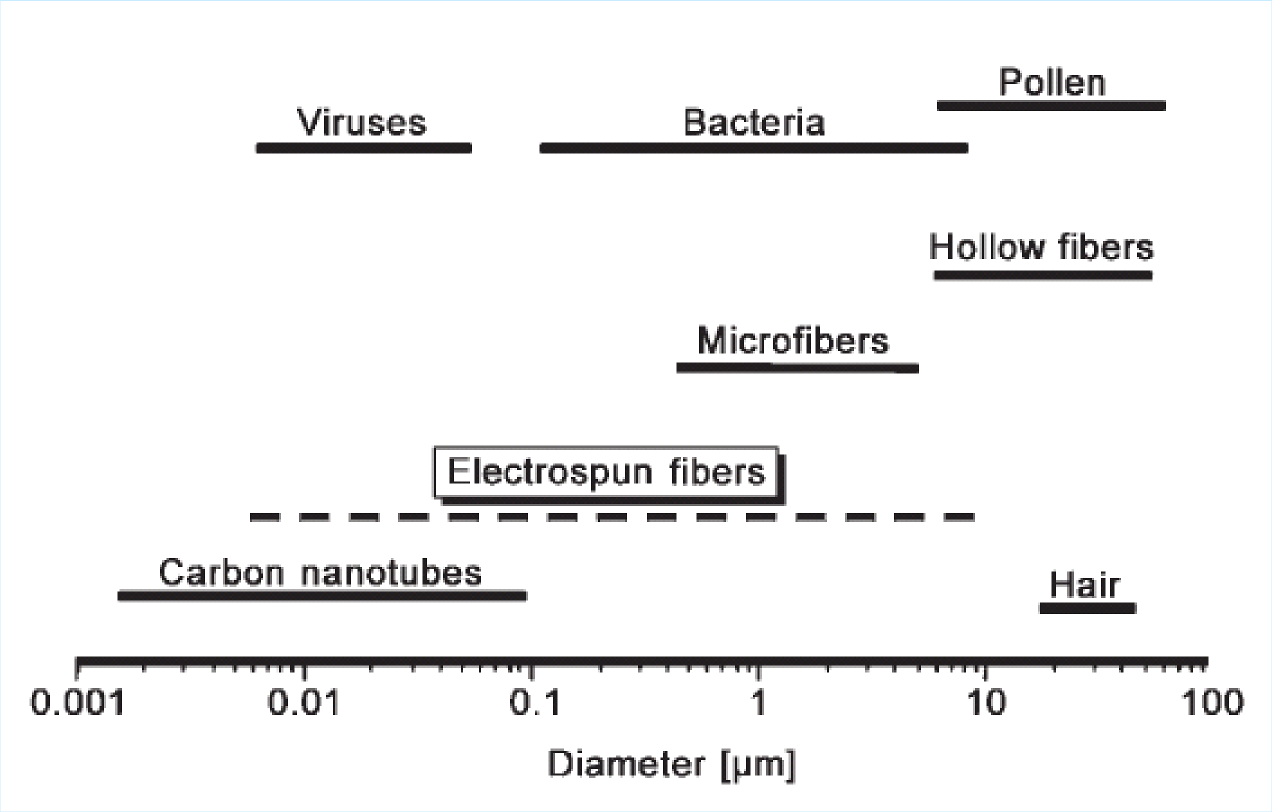
Alivistos

# Molecular rods

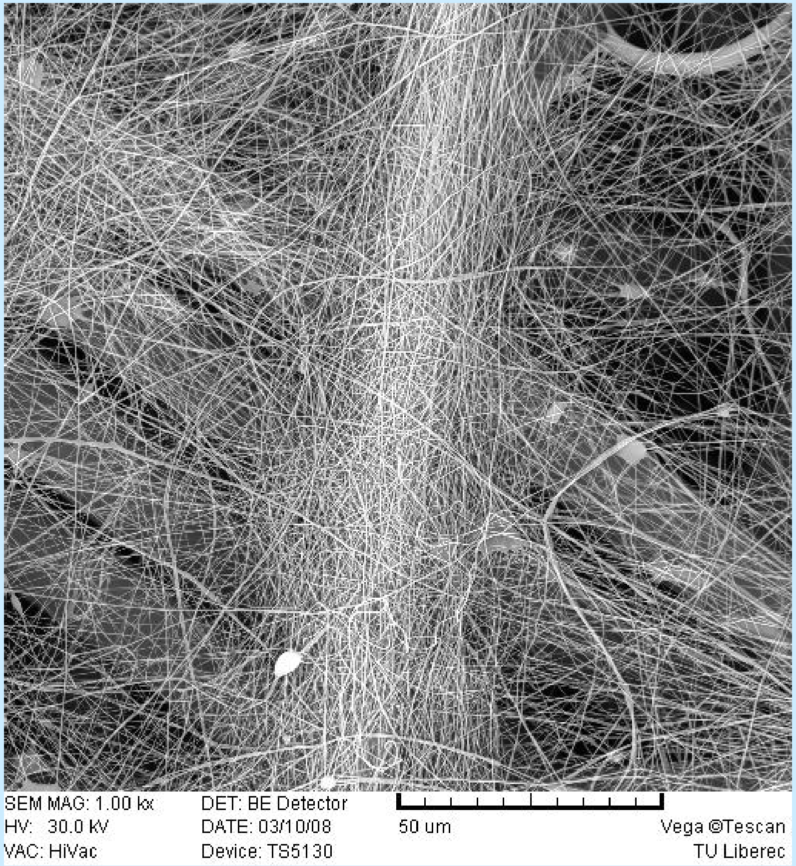


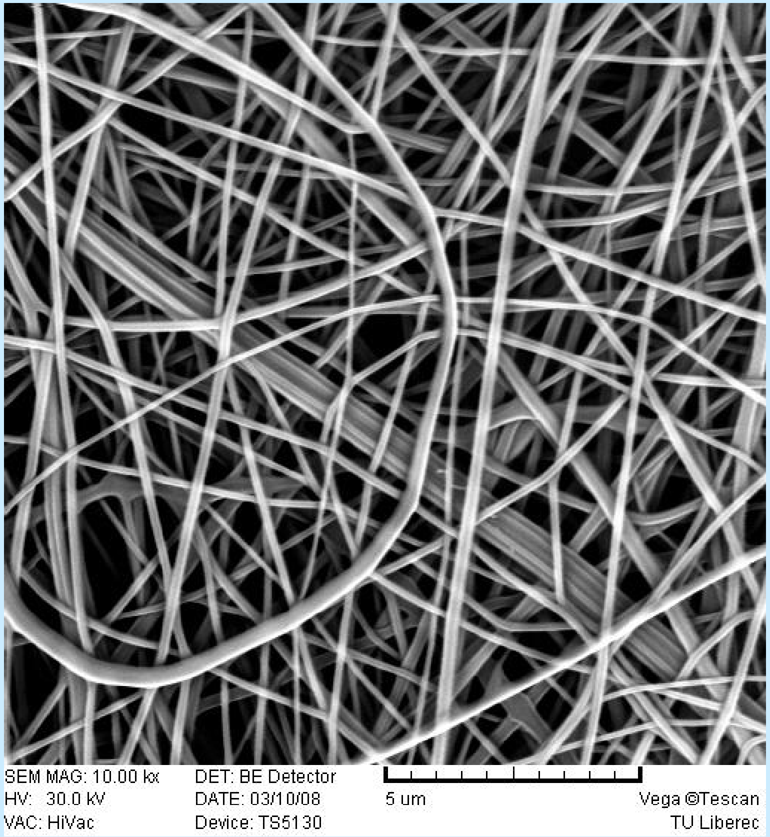



# Fibers

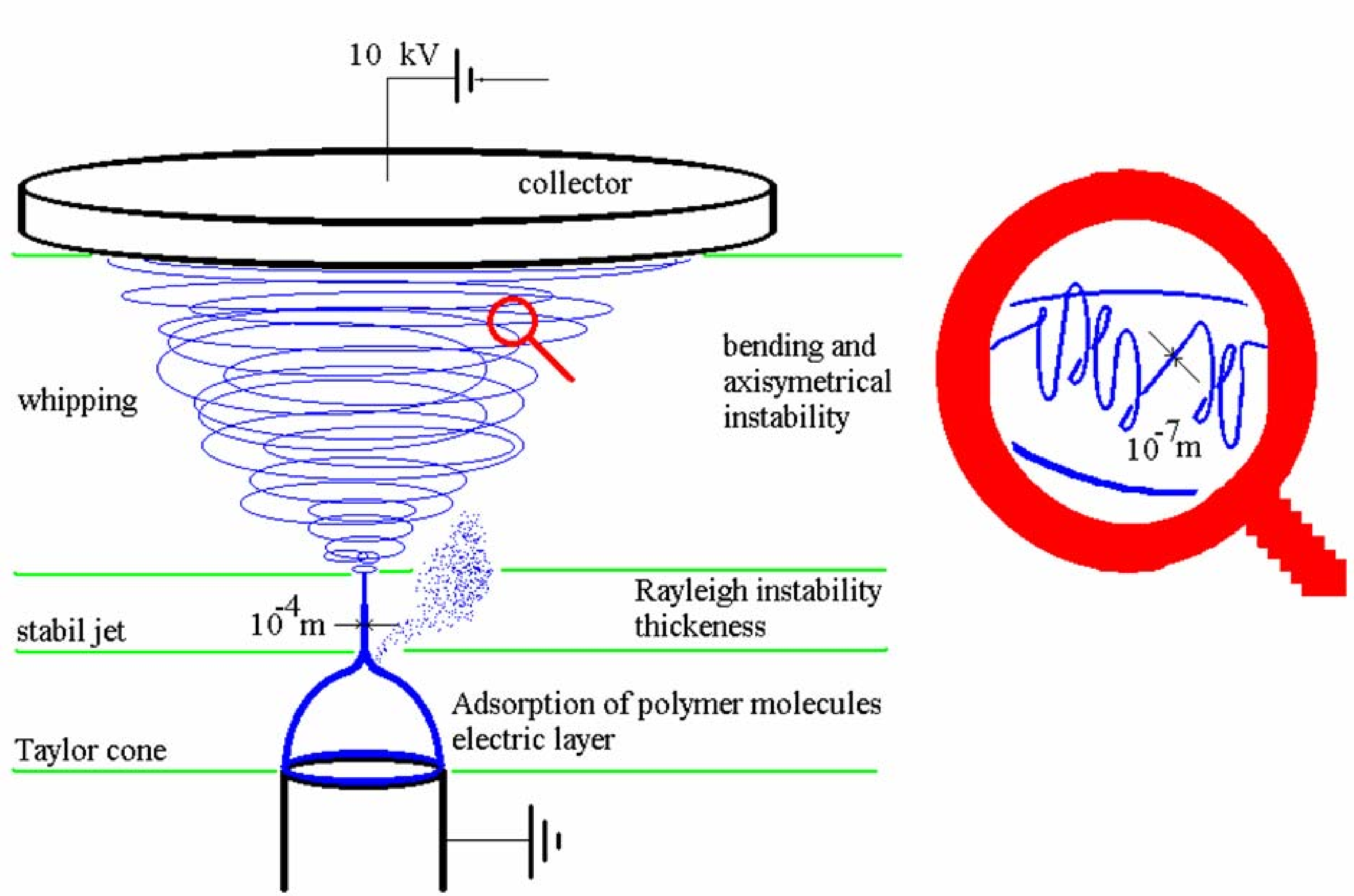

Pollen
Viruses
Bacteria
Hollow fibers
Microfibers
Electrospun fibers
Carbon nanotubes
Hair
0.001
0.01
0.1
1
10
100
Diameter [μm]

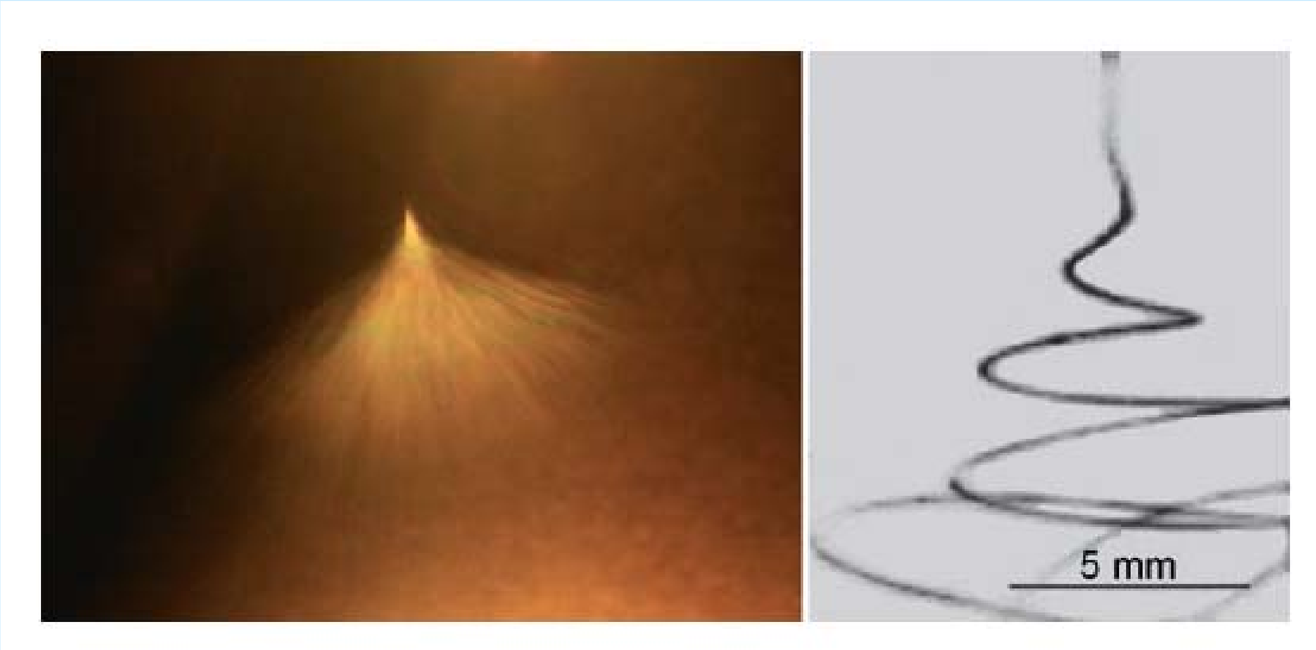
# Electrospinning



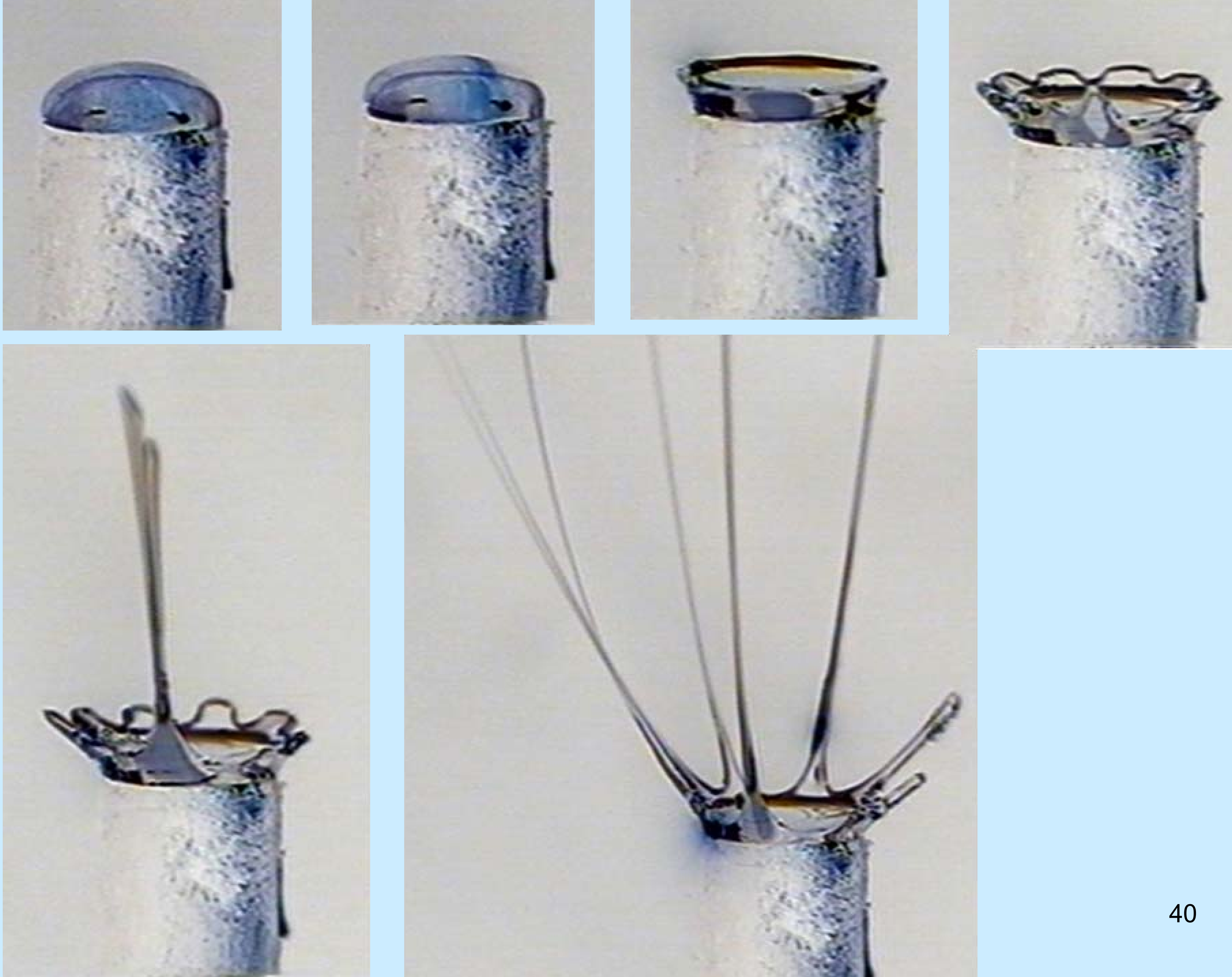



# Electrospinning

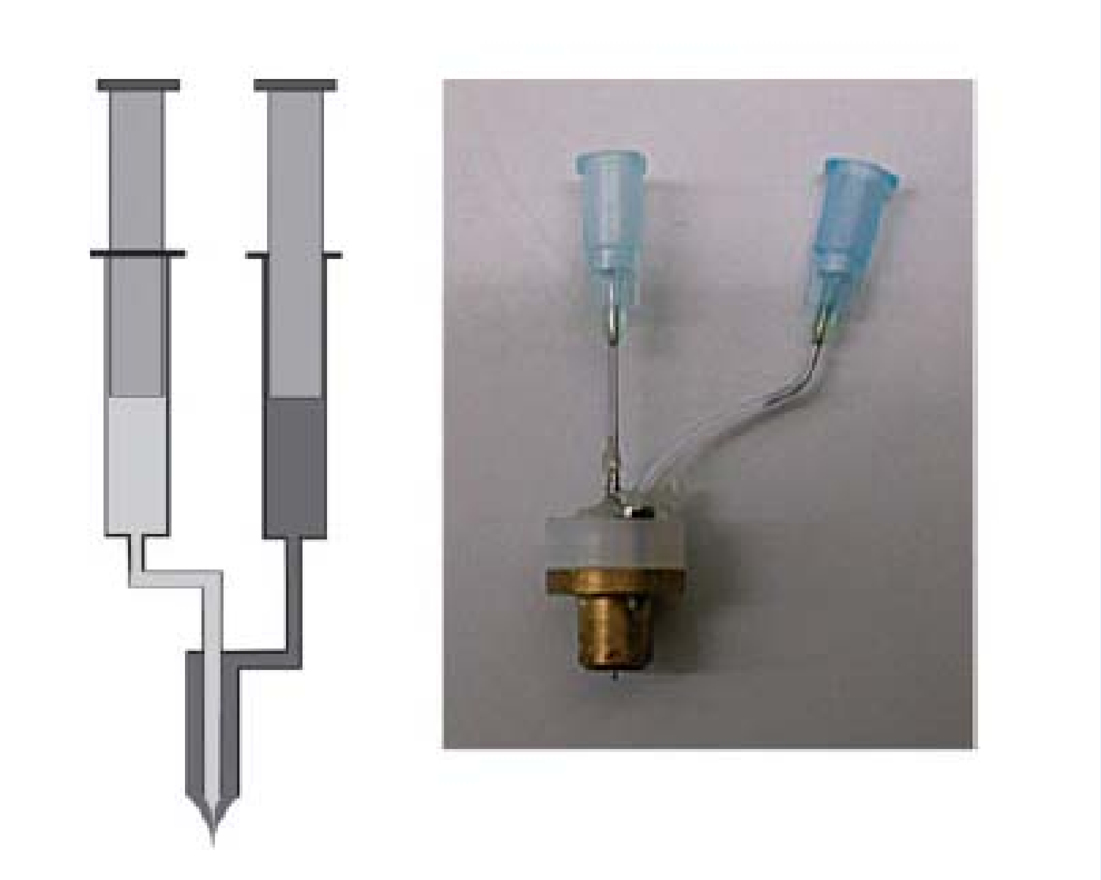





Left: Photograph of a jet of PEO solution during electrospinning.
Right: High-speed photograph of jet instabilities.



# Coaxial electrospinning



# Multijet electrospinning