Course: Engineering Physics
PHY 1701

13-01-2020

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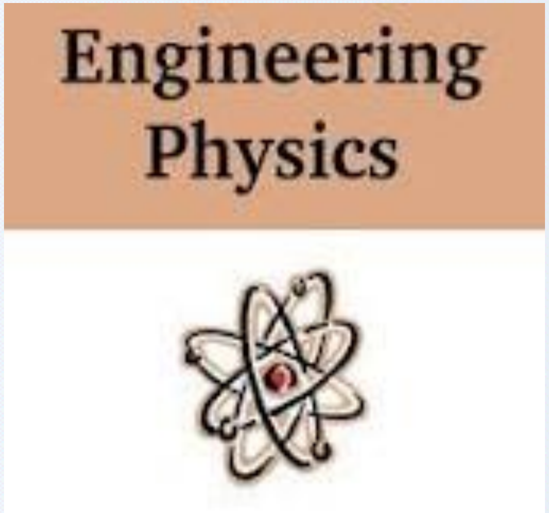
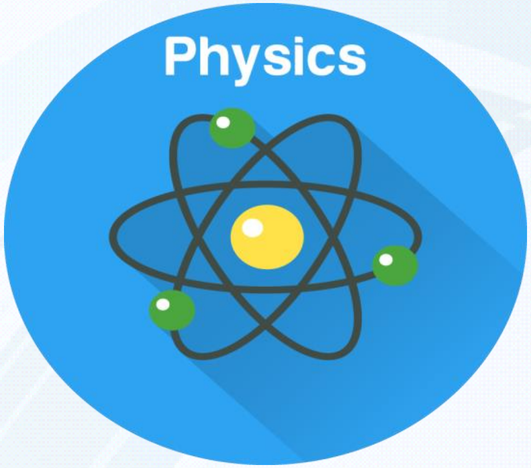
Outline

- Introduction
- Quantum Confinement
- Quantum Well, Wire and Dots
- CNT



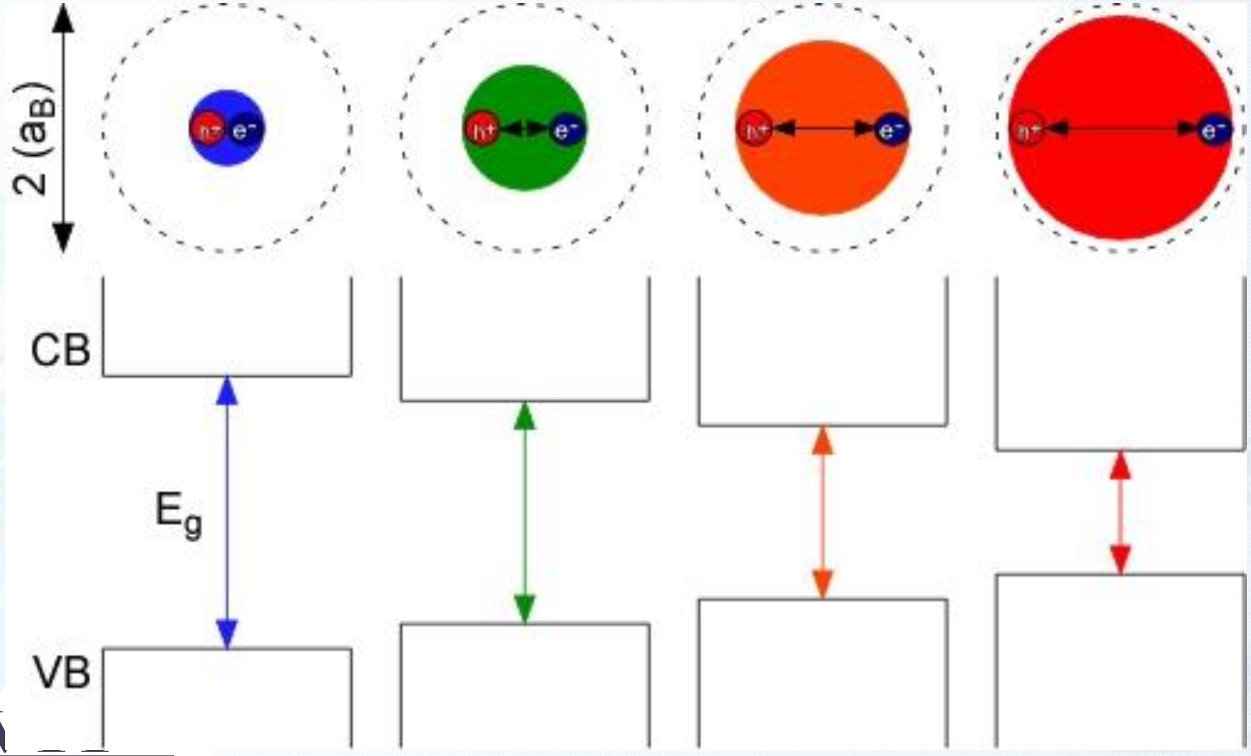


Quantum Confinement

The diameter of the material ⇩

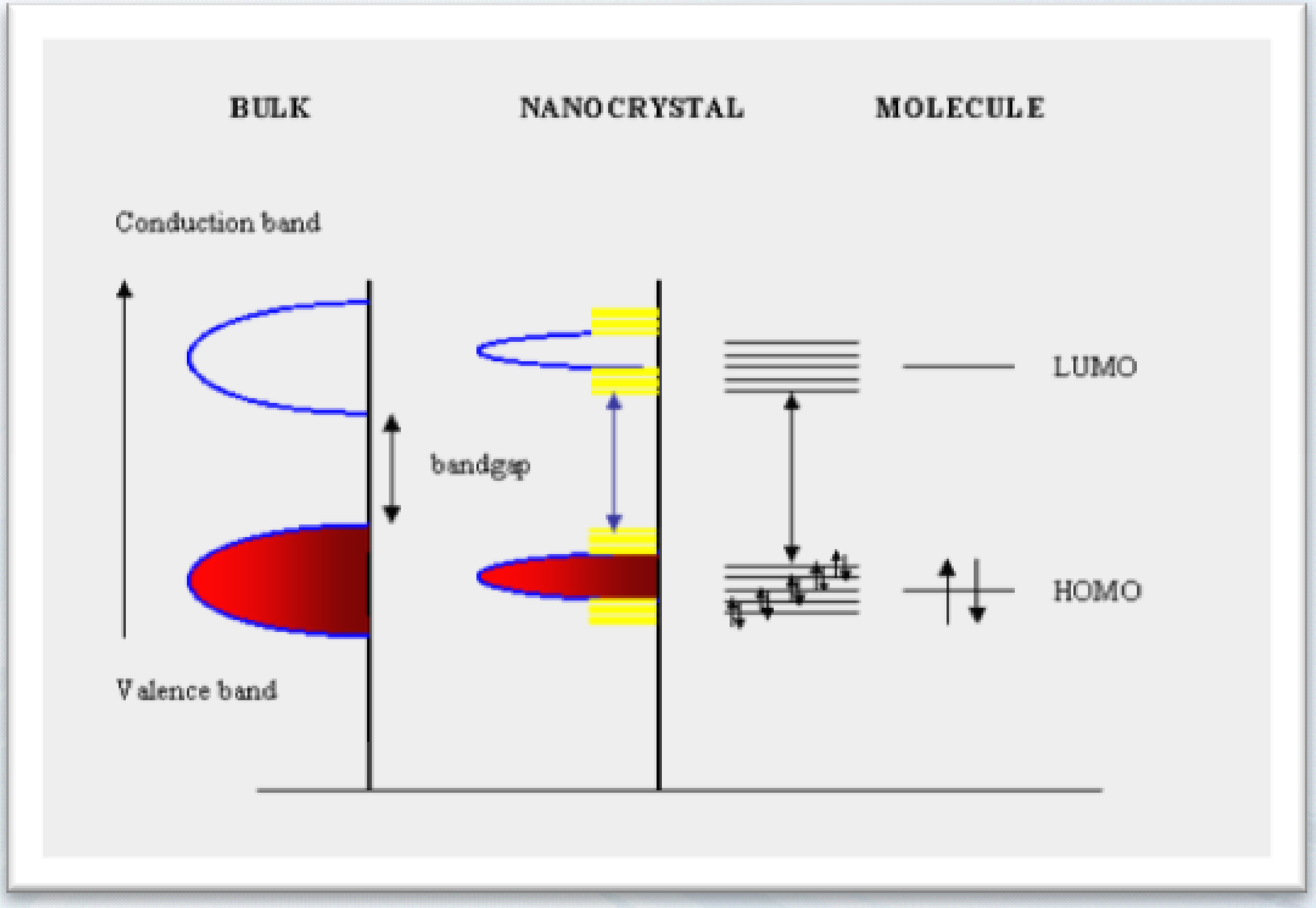
⇨ the electron wave function

their electronic and optical properties deviate substantially from those of bulk materials

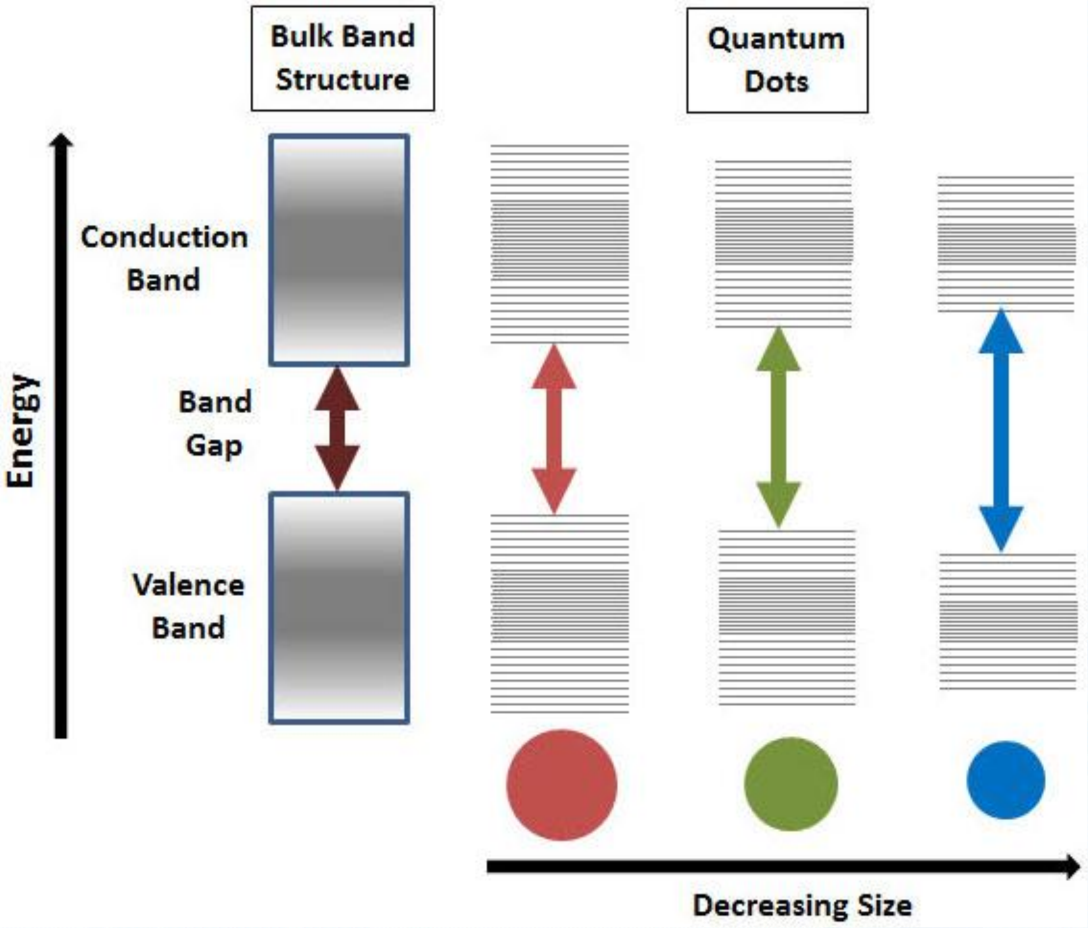


Quantum confinement in semiconductor nanocrystals

Quantum Confinement



Quantum Confinement



The confining dimension is large compared to the wavelength of the particle

→the bandgap remains at its original energy due to a continuous energy state.

However, as the confining dimension decreases and reaches a certain limit, *typically in nanoscale*, the energy spectrum turns to discrete.

As a result, the bandgap becomes size dependent.

This ultimately results in a blue shift in optical illumination as the size of the particles decreases.

Nanostructures

Quantum well

A thin layer of material (typically between 1 and 10 nanometers thick) within which the potential energy of an electron is less than outside the layer, so that the motion of the electron perpendicular to the layer is quantized

Quantum wire

A strip of conducting material about 10 nanometers or less in width and thickness that displays quantum-mechanical effects

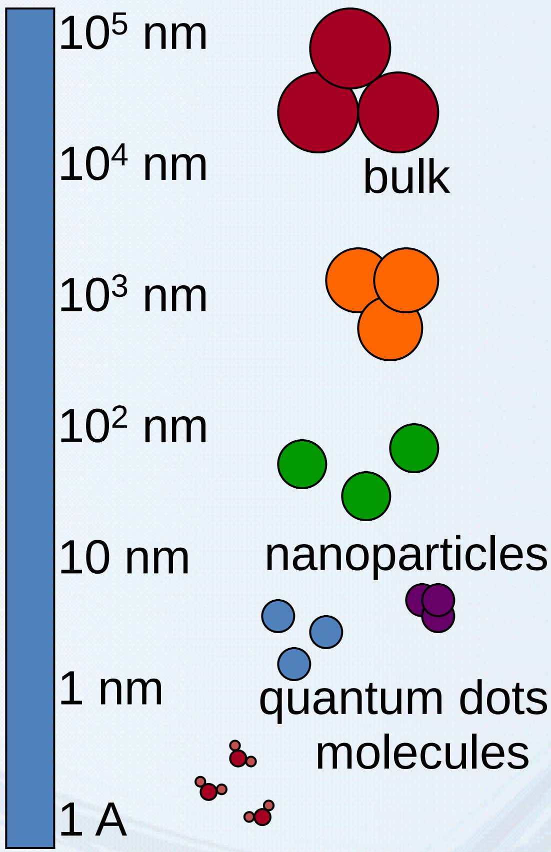
Quantum dot

A quantized electronic structure in which electrons are confined with respect to motion in all three dimensions

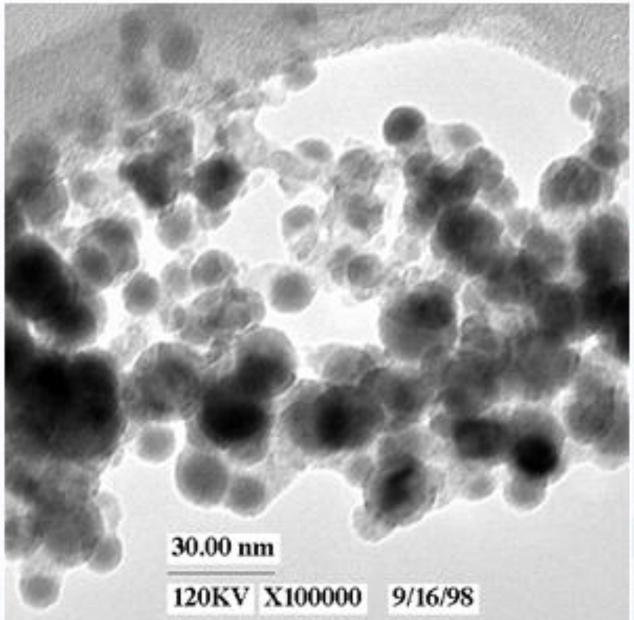
Nanoparticles and Quantum Dots

- "Zero-dimensional" particle
- Surface effects/chemistry important
- Radius < 100 nm
- < 10^6 atoms per nanoparticle
- Size smaller than critical length scales (e.g. mean free path, wavelength)
- Nano/quantum physical phenomena present
- "Large" nanoparticles have same structure as bulk; "small" may be different
- Synthesis: RF plasma, chemical, thermolysis, pulsed laser
- "Old" examples
  - Stained glass – small metal oxide clusters comparable in size to the wavelength of light
  - Photography – small colloidal silver particles for image formation

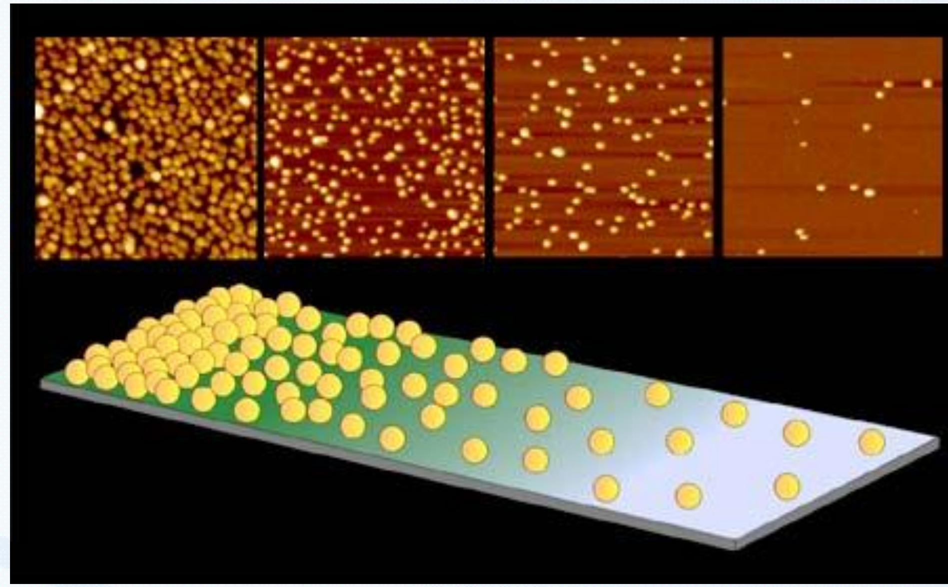
Radius of particle or cluster



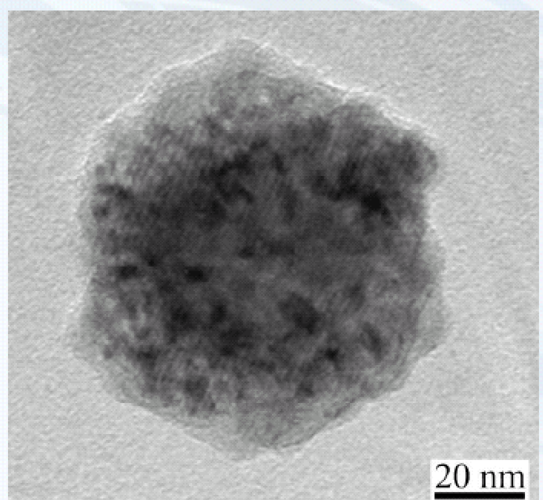
Nanoparticles and Quantum Dots



Metalic nanoparticles

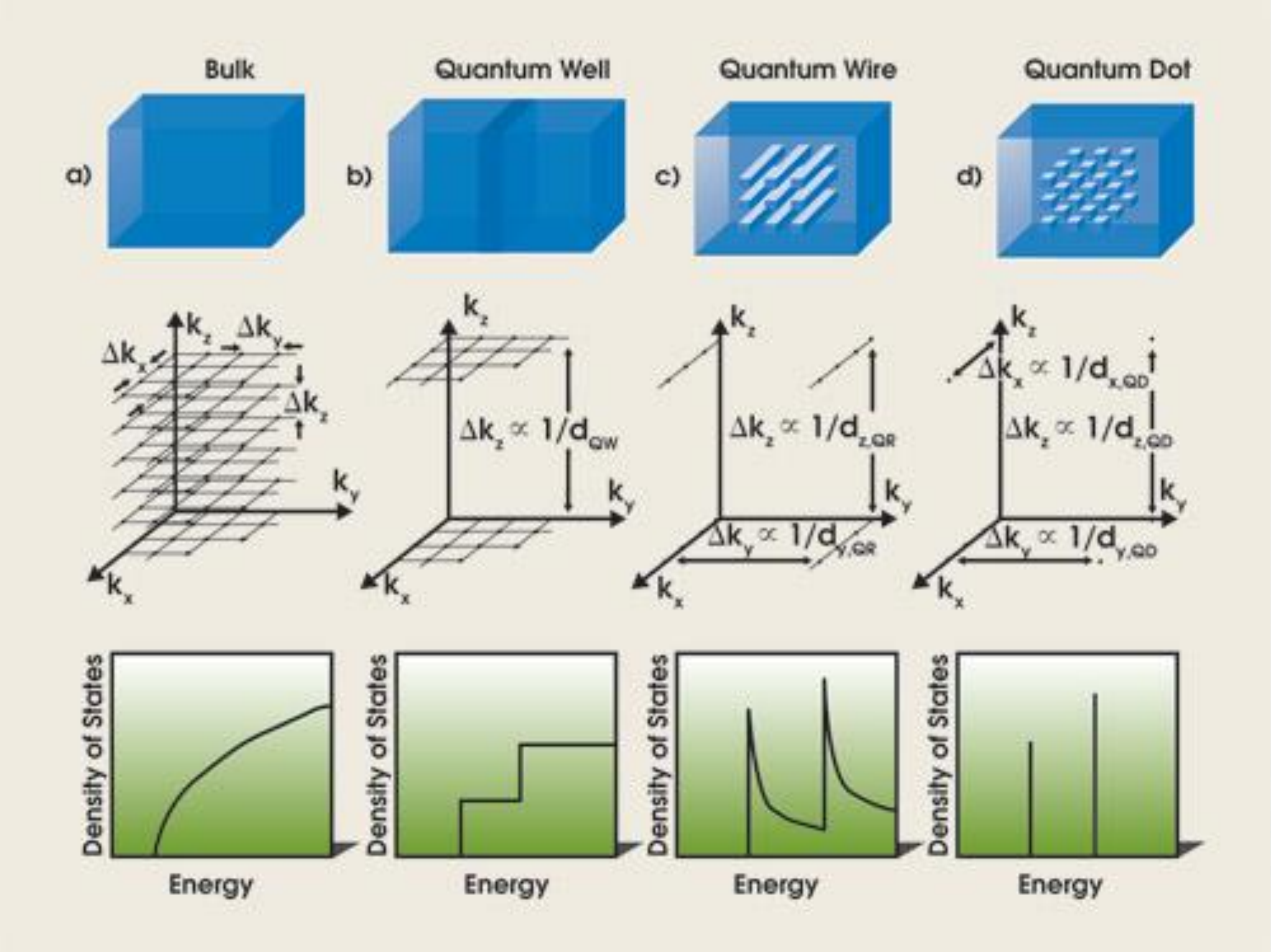


Gradient of gold nanoparticles on a silica surface

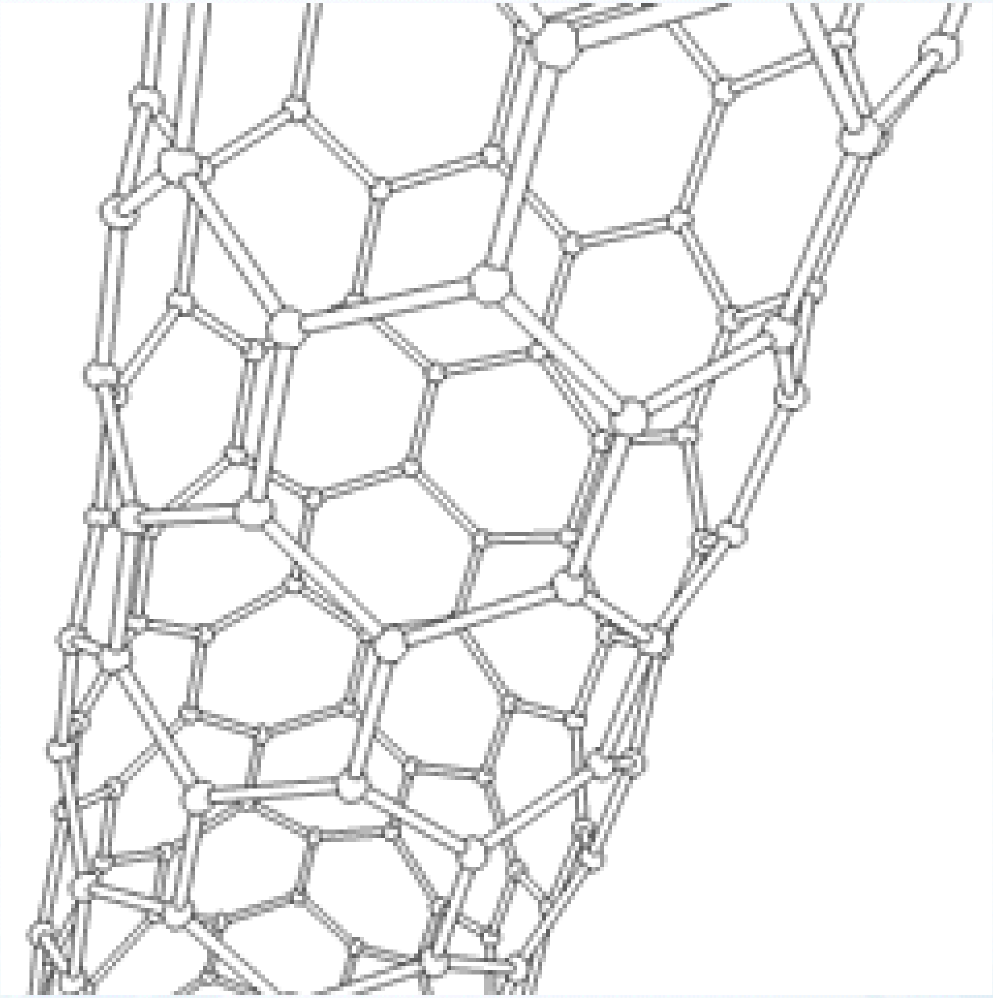


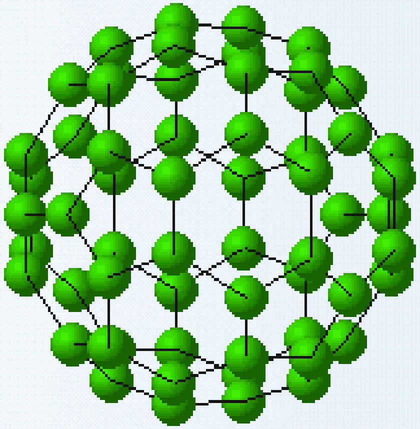
Si nanoparticle; single-crystal; hexagonal shape

Density of States



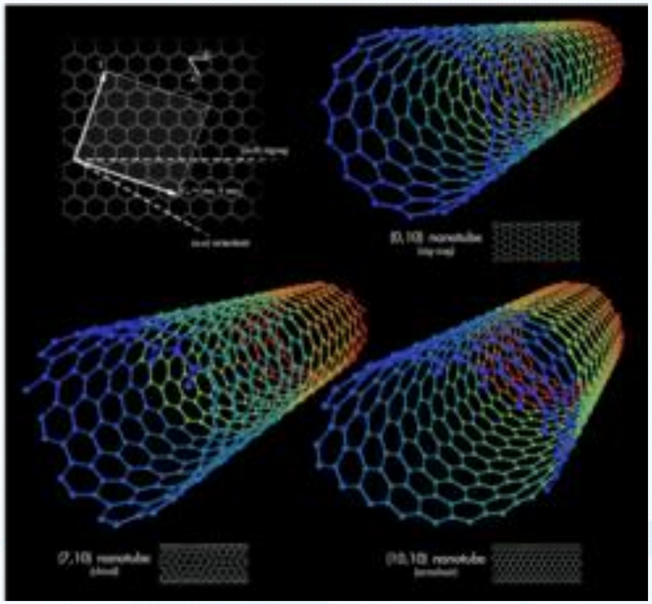
Carbon Nanotube

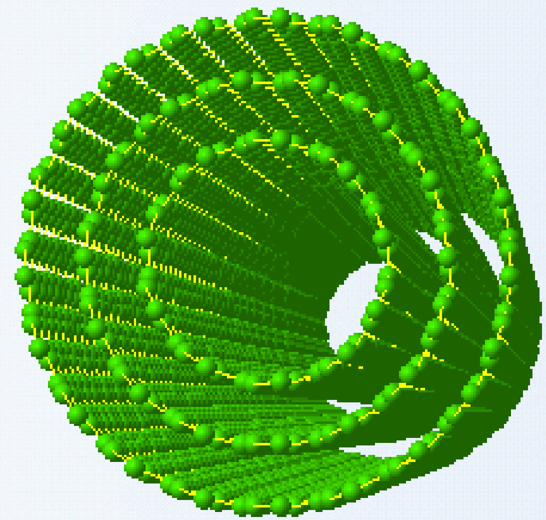




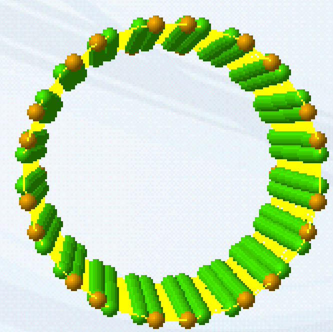
This animation of a rotating Carbon nanotube shows its 3D structure.

Carbon Nanotube





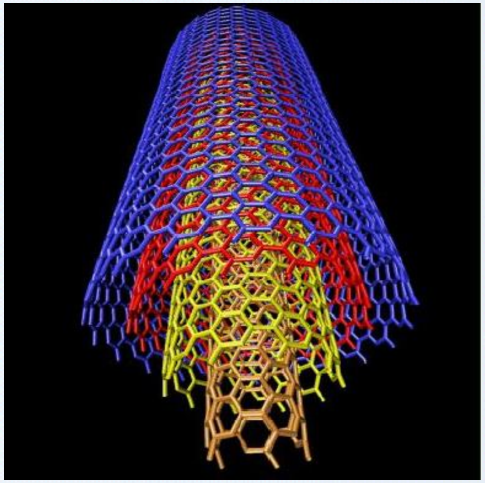
The animation of single and multi wall CNT



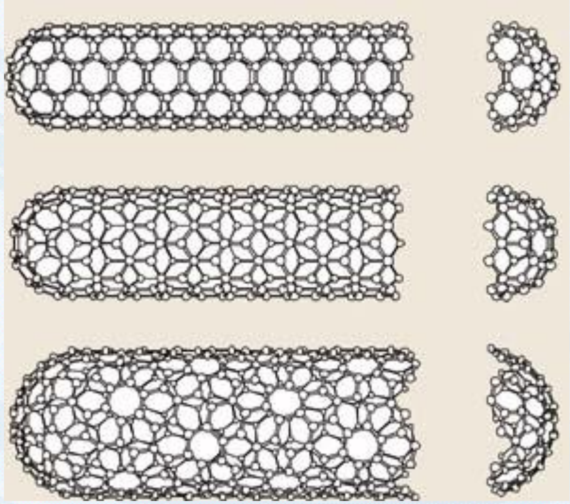
Carbon Nanotube

Carbon nanotube properties:

- One dimensional sheets of hexagonal network of carbon rolled to form tubes
- Approximately 1 nm in diameter
- Can be microns long
- Essentially free of defects
- Ends can be "capped" with half a buckyball
- Varieties include single-wall and multi-wall nanotubes,ropes, bundles, arrays
- Structure (chirality, diameter) influences properties:
  - Semiconducting vs. metallic
  - Thermal, electrical conductance
  - Mechanical strength, elasticity



Multi-wall carbon nanotube



Armchair

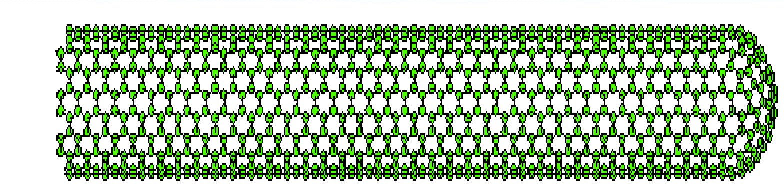
Zigzag

Chiral

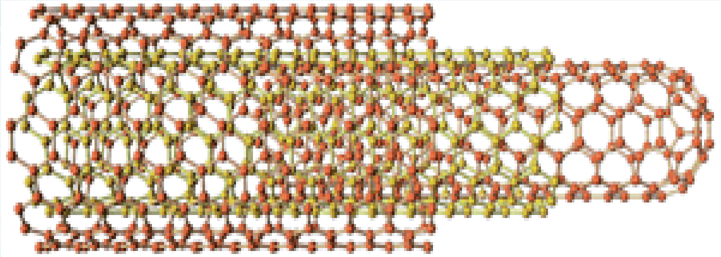
Carbon Nanotube

Carbon nanotube is a new carbon allotrope that was first discovered in 1991 by Dr. Sumio Iijima. It has a nanometer-scale hollow tubular structure and a different atomic arrangement from graphite, diamond and C_{60}. Its unique and promising properties have attracted the attention of researcher around the world and led to active R&D efforts in the commercial industries.

Single-Wall Nanotube (SWNT)



Multi-Wall Nanotube (MWNT)



Carbon Nanotube

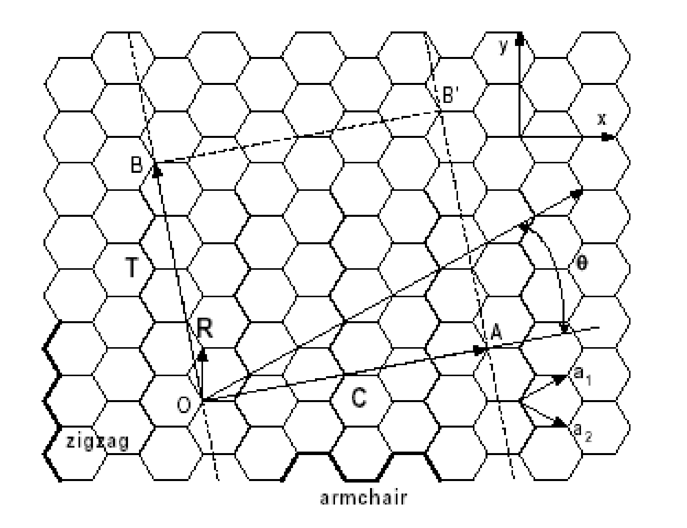
CNT is a tubular form of carbon with diameter as small as 1 nm.

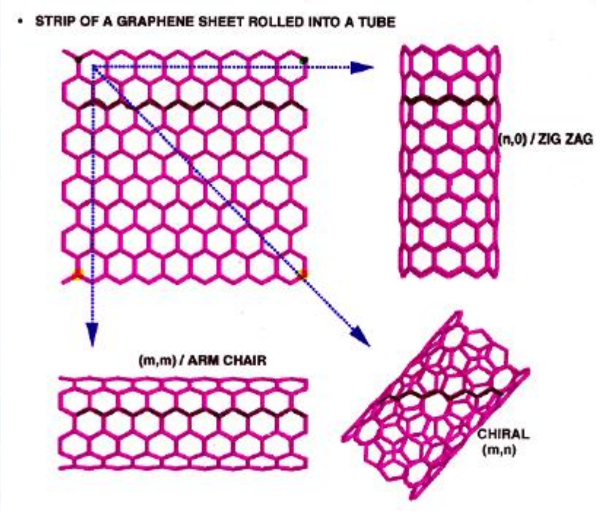
Length: few nm to microns.

CNT is configurationally equivalent to a two dimensional graphene sheet rolled into a tube.

A CNT is characterized by its Chiral Vector: $\mathbf{C}_h = n\,\hat{a}_1 + m\,\hat{a}_2$,

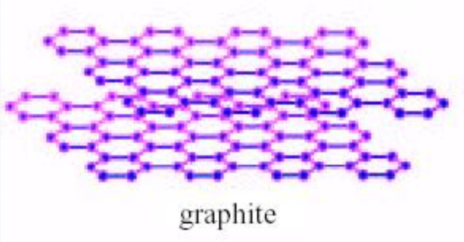
$\theta \rightarrow$ Chiral Angle with respect to the zigzag axis.



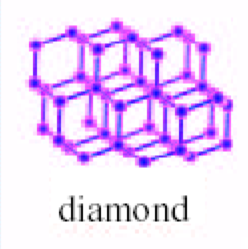


Why do Carbon Nanotube form?

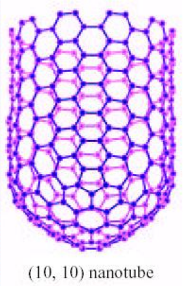
Carbon → Graphite (Ambient conditions)
sp^2 hybridization: planar



Carbon → Diamond (High temperature and pressure)
sp^3 hybridization: cubic



Carbon → Nanotube/Fullerene (certain growth conditions)
sp^2 + sp^3 character: cylindrical



Finite size of graphene layer has dangling bonds. These dangling bonds correspond to high energy states.

Nanotube formation → Eliminates dangling bonds + Increases Strain Energy → Total Energy decreases

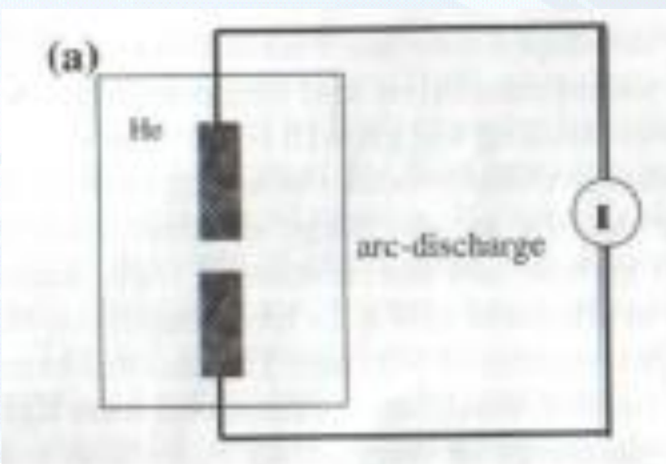
Carbon Nanotube: Growth Method

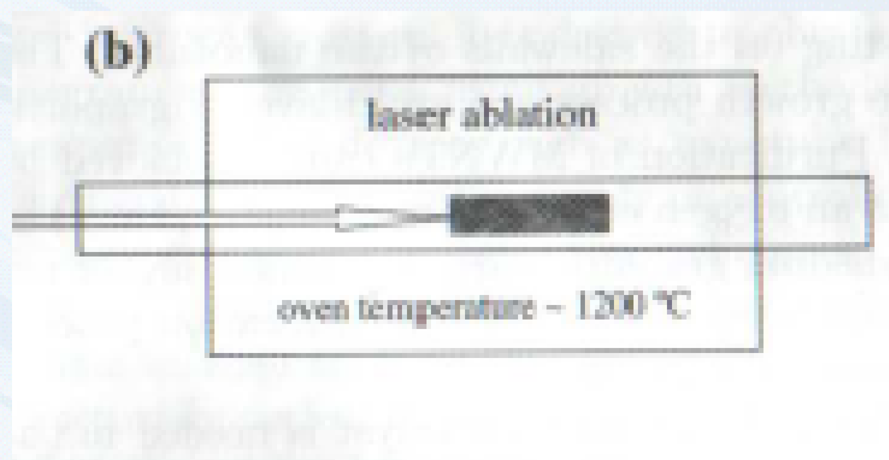
a) Arc Discharge

b) Laser Abalation

- Involve condensation of C-atoms generated from evaporation of solid carbon sources. Temperature ~ 3000-4000 K, close to melting point of graphite.
- Both produce high-quality SWNTs and MWNTs.
- MWNT: 10’s of μm long, very straight & have 5-30 nm diameter.
- SWNT: needs metal catalyst (Ni,Co etc.).

Produced in form of ropes consisting of 10’s of individual nanotubes close packed in hexagonal crystals.





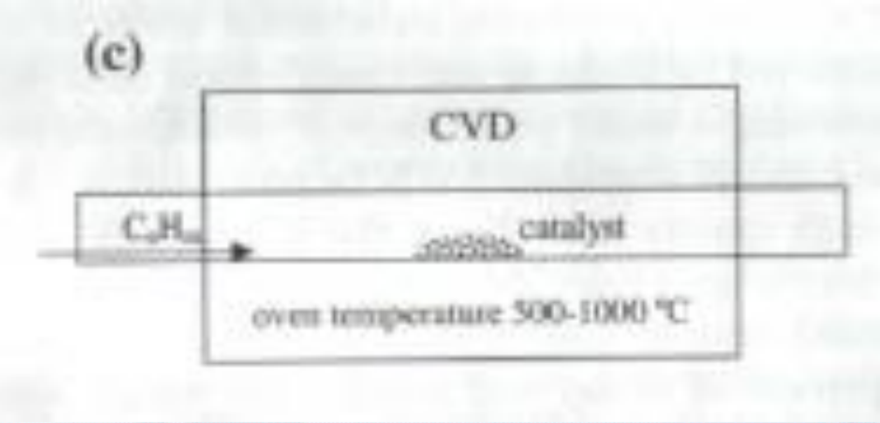
Carbon Nanotube: Growth Method

c) Chemical Vapor Deposition:

$$\text{Hydrocarbon} + \text{Fe/Co/Ni catalyst} \xrightarrow{550\text{-}750^\circ C} \text{CNT}$$

Steps:

- Dissociation of hydrocarbon.
- Dissolution and saturation of C atoms in metal nanoparticle.
- Precipitation of Carbon.



Choice of catalyst material?

Base Growth Mode or Tip Growth Mode?

- Metal support interactions

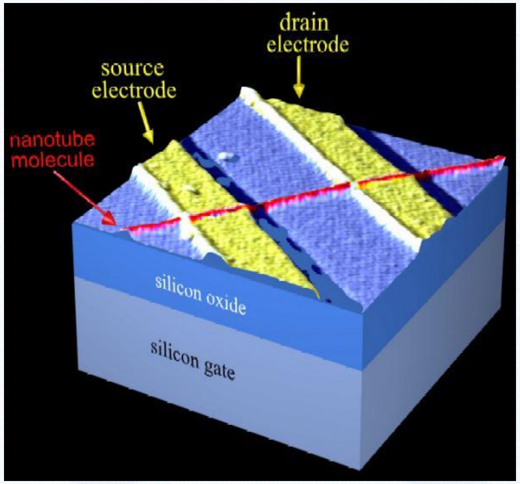
Carbon Nanotube: Properties

- the highest elastic module, and mechanical strength that is approximately 200 times stronger than steel
- novel electronic properties
- high thermal conductivity
- excellent chemical and thermal stability
- promising electron field emission properties
- high chemical (such as lithium) storag capacity

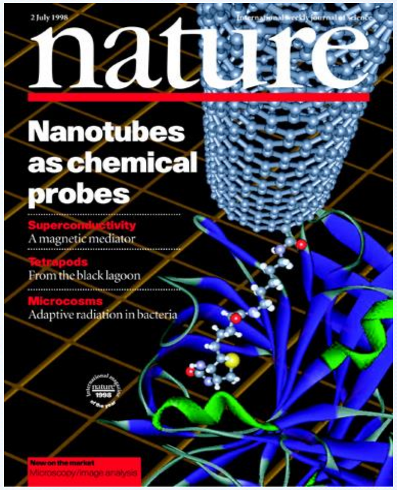
Carbon Nanotube: Applications

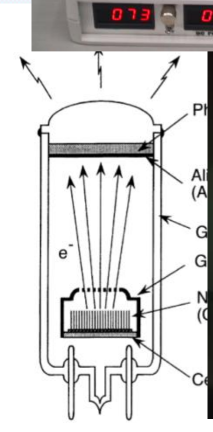
Nanowires

FET

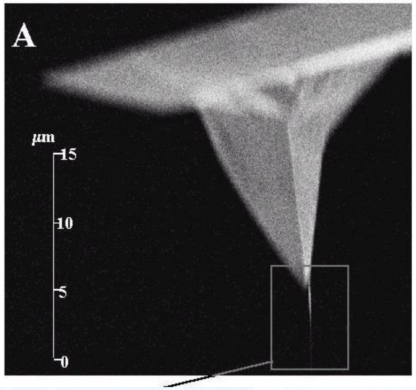


Biosensor

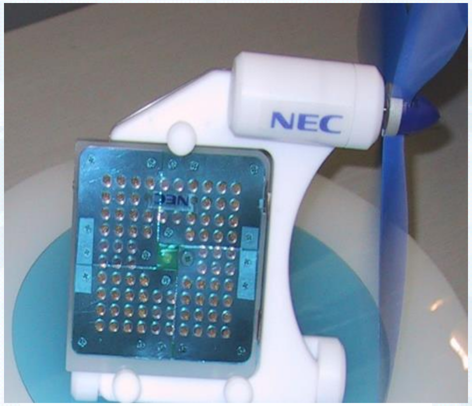




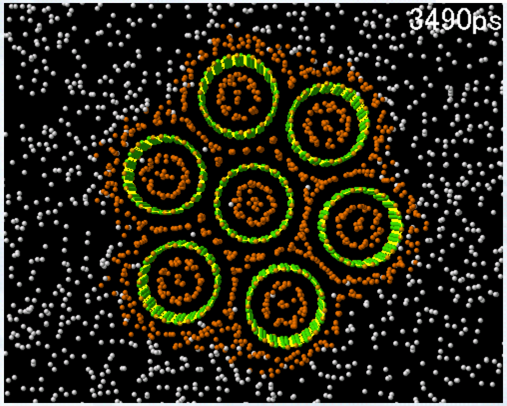
Field Emission



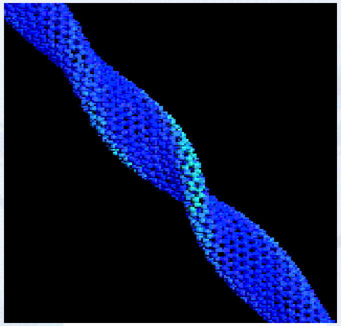
Tips of AFM



Fuel Cell Electrode



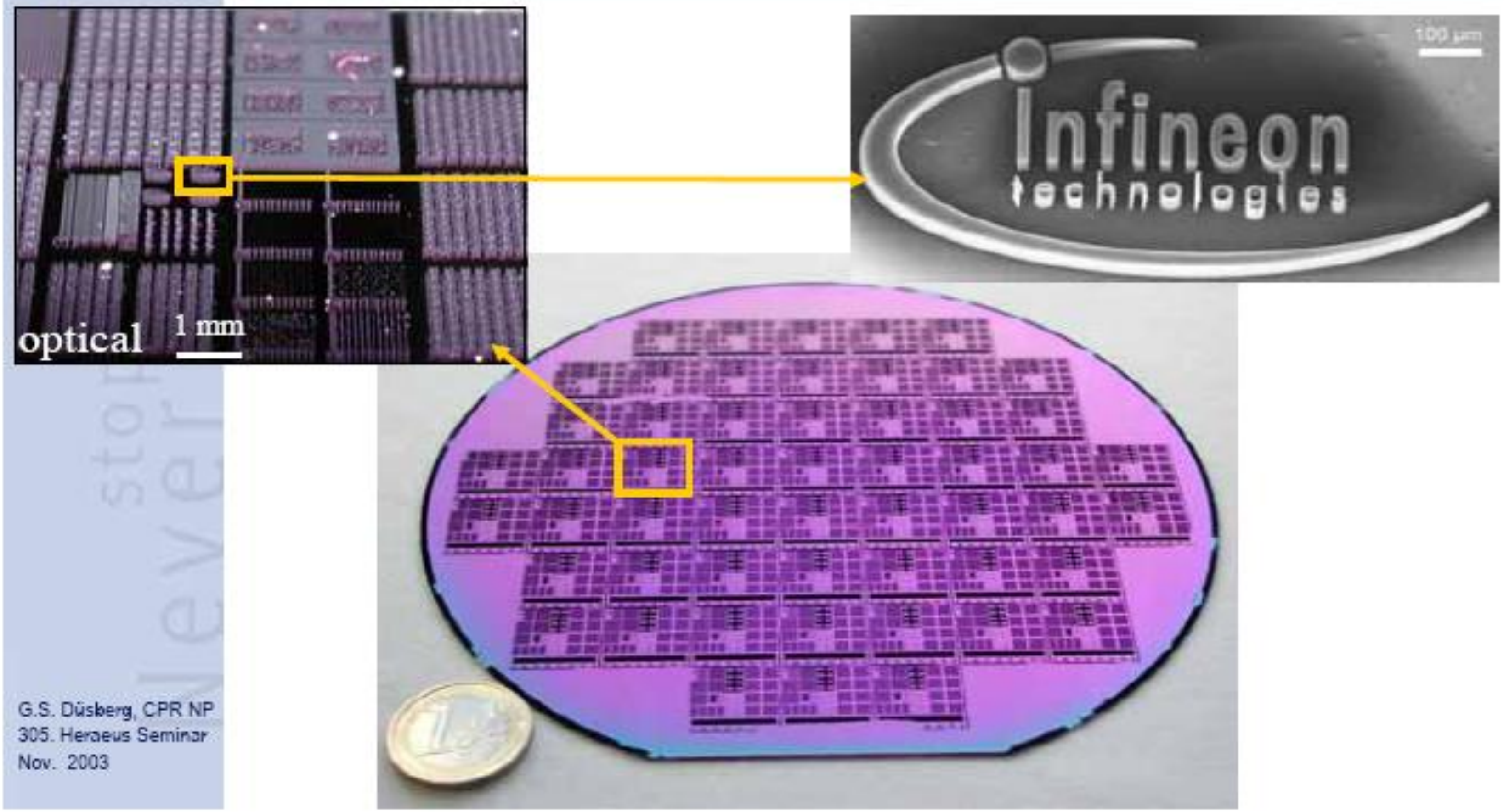
H_2 Storage



Mechanical

Carbon Nanotube: Applications

CNT growth on a patterned 6-inch wafer



G.S. Düsberg, CPR NP
305. Heraeus Seminar
Nov. 2003