

MATERIAL SCIENCE

VTU University Syllabus (2006-07)

Unit-VIII

Material Science

Nano-materials – Molecular Manufacturing. Nano-mechanical bearings. Fabrication technology. Scaling of classical mechanical systems – Basic assumptions. Mechanical scaling. Scaling of electromagnetic systems – Basic assumptions. Corrections. Magnitude and scaling – Steady state systems, Time dependent systems. Carbon nano-tubes

Ultrasonic non-destructive testing of materials. Measurement of velocity in solids and liquids. Determination of elastic constants in solids and liquids.

6 Hours

Fastest growing research in the world is down scaling technology nanoscale technology. Nano science sets new miniaturization standards. Conventional Silicon electronics is likely to be replaced by Nano electronics.

“Nano” derives from the Greek word “nanos”, which means extremely small. A nanometer is a billionth of a meter or 10^{-9} m. Nano particles are small clusters of atoms about 1 to 100 nanometers diameter. Matter in a size range of 1-100 nm is called nano matter.

Comparison of Nano Particles with other small size familiar particles.

- 100000th size of an human hair-1nm
- Width of DNA-Deoxyribonucleic acid-2nm
- Diameter of proteins Varies from 1nm to 10nm
- Diameter of Virus – 100nm
- Bacterium is of the size of 10 μ m
- Ant is 1000 times bigger than bacterium.

The quantification for the physical properties of a material undergoes amazing changes when we reach the limiting size i.e., nano size and downward. The state of mater around this size is referred to as mesoscopic state. The exact size at which mesoscopic state is attained is different for different materials but it will be in the nano-range. Therefore, the physics of nanotechnology is also sometimes called as mesoscopic physics.

The nano particles whose size below 20 nm, the dimensions become comparable to deBroglie wavelength of the electrons in the nanoparticle and quantum effects could be observed impressively. Large size nanoparticles are of interest not for their size effects but for their surface effects, which is important for chemical reaction or catalysis.

The figure in the next page shows the four varieties of nanomatters.

- 2) Large clusters/ Particles (3-D)
- 3) Thin films and layers (2-D)
- 4) Rods and Wires (1-D)
- 5) Small Clusters: Quantum Dots (0-D)

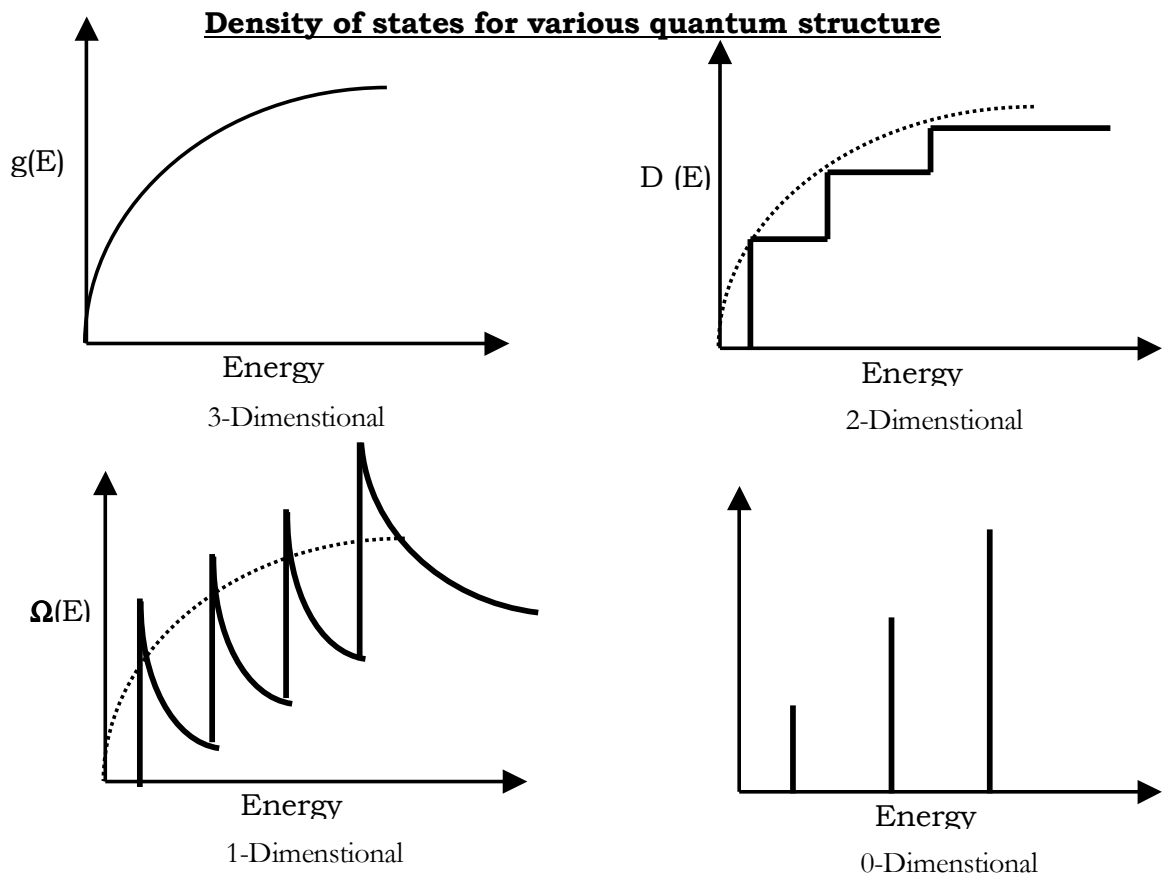
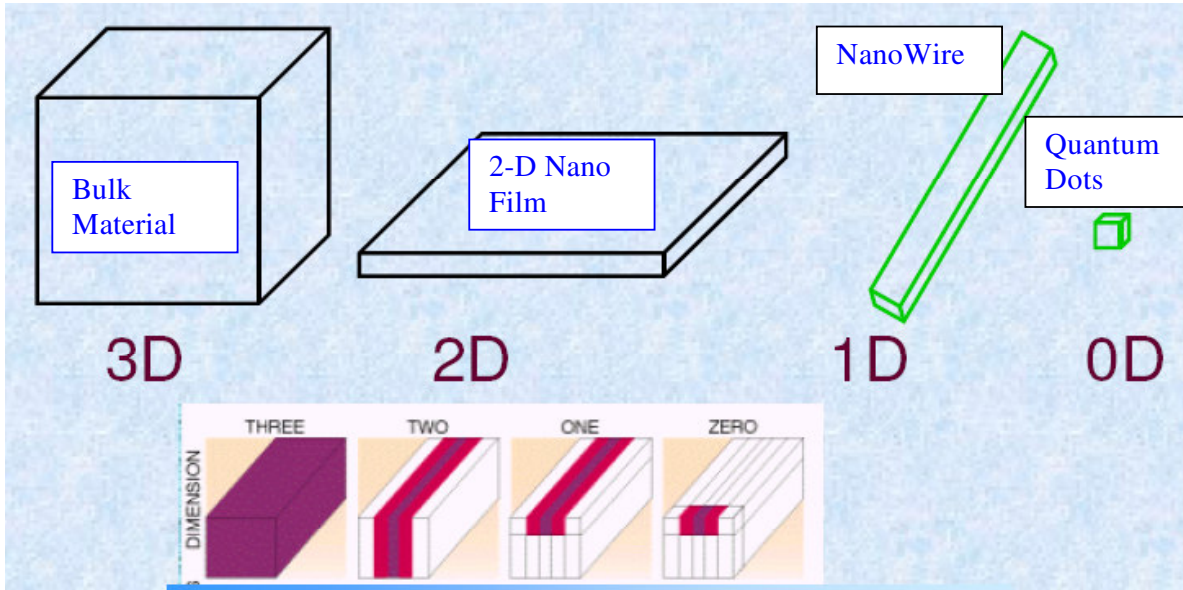


Fig.1: - Shows the Density of states for various quantum structures as a function of energy.

The density of states for the various quantum structures as function of energy is shown in Fig 1. The Density of states (DOS) as $g(E)$ for 3-D materials varies continuously. The density will be typically of the order **of $10^{26}/m^3 \text{ eV}$** . For a 2-D structure, the DOS denoted as $D(E)$ varies as a step-function. That is there would be sudden rises in $D(E)$ at certain energy values such as E_1, E_2, \dots . It happens so because the energy progress of the first sub-band continues even when the second sub-band starts. Therefore, in the second sub-band, in addition to its own energy states, there will be additional contribution from the continuation of energy states of first sub-band. Hence, the DOS rises at once at the beginning of second sub-band. The same trend will continue for further higher bands. Thus, the overall variation takes a stair case shape. If the thickness of the 2-D materials increased, more sub-bands will be created which results in decrease of the step width. If the thickness increase continues, then the material reaches 3-Dimensions, the innumerable steps would be seen merged into an envelope of parabolic variation for DOS. **The density is of the order of $10^{18}/m^2 \text{ eV}$ for 2-D structure.**

The DOS for sub-bands in a 2-D structure is given by

$$D(E) dE = \frac{m^*}{\pi \eta^2} \sum H(E - E_i) dE$$

Where m^* is the effective mass of electron in the structure, and $H(E-E_i)$ is a step function called Heaviside function, its values are zero for $E < E_i$ and, 1 for $E \geq E_i$.

For a 1-D structure, i.e., for a quantum wire, the DOS variation is not smooth as in the case of 3-D structure not even constant over the subband also. The density hits peaks at energy values E_1, E_2, \dots , and decreases rapidly in the range in-between.

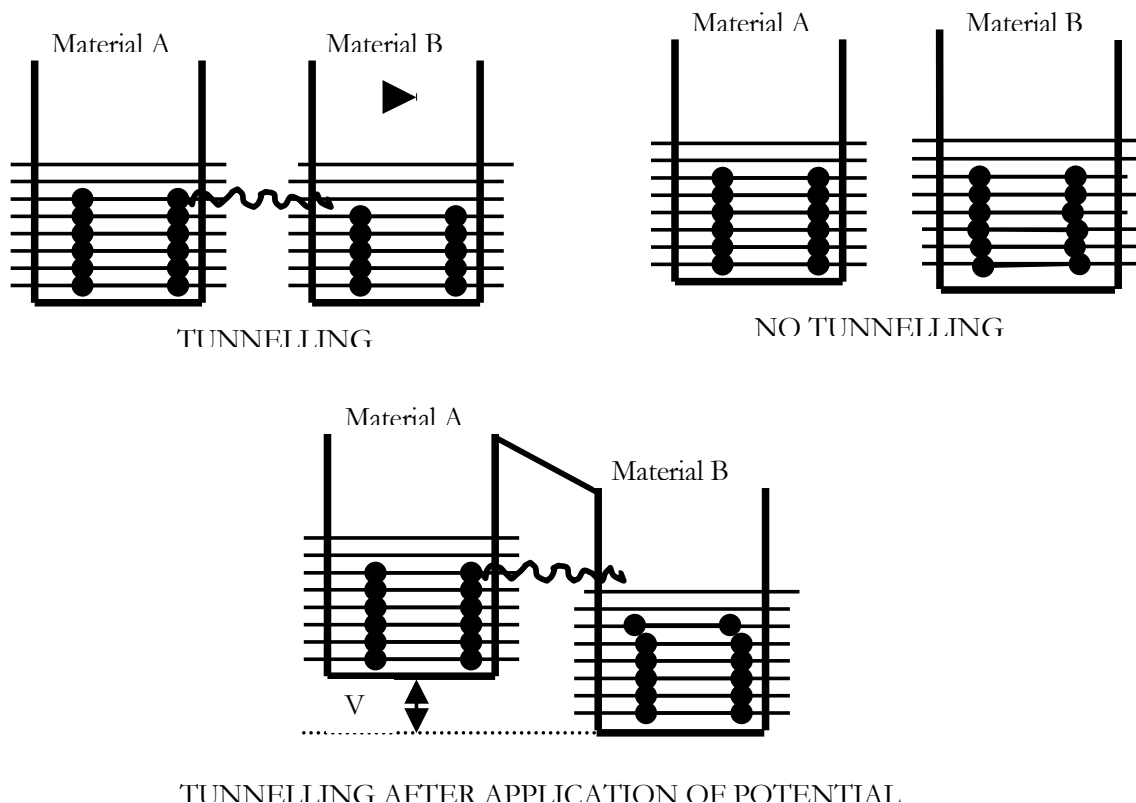
$$\Omega(E) dE = \frac{\sqrt{2m}}{\pi \eta} \sum \left(\frac{n_i H(E - E_i)}{\sqrt{(E - E_i)}} \right) dE$$

Where, $H(E-E_i)$ is the Heaviside function. n_i is degeneracy factor. The density is typical of the order **of $10^9/m \text{ eV}$** .

For a 0-D structure, the permitted energy values are just discrete because of confined condition for electrons. In real quantum dots, however, the size distribution leads to a broadening of the lines.

Quantum Tunneling

An effect in which electrons are able to tunnel through a narrow potential barrier that would constitute a forbidden region if the electrons were treated as classical particles. This effect is called the Quantum tunneling. When there are vacant energy levels between the neighboring quantum wells, there occurs Quantum tunneling as in the first figure. This occurs between the levels which are at the same height as there are filled levels in the adjacent wells. When the energy levels are in the same height and if there is no vacant level then the tunneling occur only when the potential difference is applied between the two quantum wells. This situation can be seen in the second and third figures.



Nanomaterials:-

NANOMATERIALS are of two types. Inorganic and Organic. Inorganic nanomaterials are nanostructures like Fullerenes, carbon nanotubes and nanowires. Fullerene is in the soccer ball shaped structure; therefore, it is called as Bucky ball. Each fullerene molecule comprises of 60 carbon atoms arranged in globular shape. Nanowires are arrangements in one dimension made of silicon, zinc oxide and various metals. They are having diameter in nanometer range but lengths in micrometer range. Nanowires can act like an optical fiber, and their conductance can be tuned by binding it to different molecules. They could be made to emit light.

Organic Nanomaterials. They are the nanostructures made of carbon compounds. Researches have observed that artificially synthesized DNA structures possess the repeatable capability, show promise of self-assembly into geometrical structure. It is also reported, that an 8-sided structure is a good candidate for cloning. When success is achieved by manipulating the DNA of cells, the cells could be induced to produce the type of proteins. Protein-based nanostructures could be then made which even conduct electricity.

Molecular Manufacturing.

Molecular manufacturing is a process in which very tiny objects of complex structures as per requirements are manufactured. It involves chemical reactions controlled by a type of machinery called molecular machinery that is non biological in its functioning.



A complete molecular manufacturing system (like a complete conventional manufacturing system) will be complex. It must have, for example:

- a casing to protect its interior from air, moisture, and dirt
- inlets for liquid feedstocks to supply molecules for processing
- molecular sorting mechanisms to purify inputs
- alignment and binding mechanisms to organize streams of molecules
- mechanosynthetic devices to process inputs into reactive tools
- mechanosynthetic devices to apply tools to workpieces
- mill-style mechanisms to join workpieces into larger blocks
- programmable mechanisms to join blocks into complex products
- a port to deliver finished products while protecting the interior space
- motors to drive moving parts
- computers to control material flows and assembly mechanisms
- stored data and programs to direct the computers
- data communication channels to coordination actions
- electrical systems to distribute power
- a cooling system to dissipate waste heat
- a structural framework to support the casing and internal components

Individual operations must either be subject to testing and correction, or must be extremely reliable. Moving parts must be supported by bearings. Building blocks must be relatively rigid, and must be designed to fit and join when brought together with correct alignment. The analysis of molecular operations must take account of quantum phenomena and thermal vibration. The overall analysis must take account of entropy and thermodynamic issues.

Mechanosynthesis

The act of controlling or guiding a chemical reaction mechanically during a synthesis is called mechanosynthesis. The control over the reaction is exercised at the atomic scale. However, the manner in which it happens has no similarity to any biological reaction such as enzymatic process that gives a similar result. Drexler proposes that this process is going to become a reality, as in 1990; Eigler and Schwiezer have demonstrated how atoms or molecules could be plugged into the required slots in a molecule. However, in order to achieve results according to the requirements, new tools at nano-level are needed to be developed. The study of techniques employed in molecular manufacturing in obtaining products with specific qualities comprises a vast field called molecular nanotechnology.

Nano-mechanical Bearings: -

Nano-mechanical bearing is an example of the future product of molecular nanotechnology.

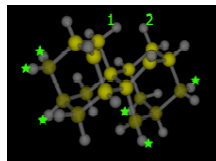
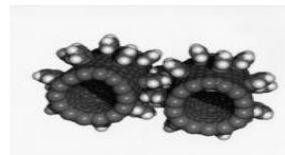
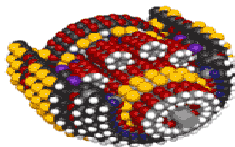
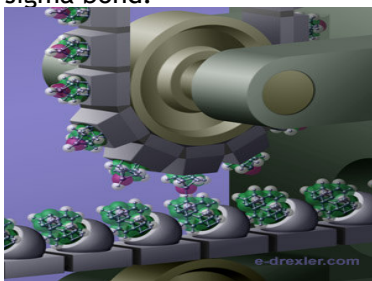
- 1) Its molecules are polycyclic in nature and form a structure that resembles roughly a mechanical bearing used in the bulk sized machines.
- 2) As we know, atoms in a molecule are linked together by means of chemical bounds. At room temperatures, the atoms are subjected to the internal motions such as vibrations, rotations etc., and due to the supply of thermal energy.

The constituent parts/components of a nanomechanical bearing comprises of molecules. It is expected for the bearing that some of its components be so stiff that the internal motions in between atoms/molecules is practically absent and in some others it should be almost of free motion type, depending on the requirement.

Ideally, a nano-mechanical bearing has zero-static friction. As the atoms are granular, they will not provide a smooth surface in the molecular bearing because of which it results in friction. However, low friction bearings can be constructed with proper choice of materials that are stiff. To achieve this, the fact that there is overlapping of the boundaries of the bonded atoms is made use. In such cases where the overlapping portion is more, the irregularity of the bearing's surface becomes lesser. A type of structure named "nested structure" formulated using carbon nanotubes is showing promise for building low-friction rotational bearings.



MECHANOSYNTHETIC REACTIONS Based on quantum chemistry by Walch and Merkle [Nanotechnology, 9, 285 (1998)], to deposit carbon, a device moves a vinylidene carbene along a barrier-free path to bond to a diamond (100) surface dimer, twists 90° to break a pi bond, and then pulls to cleave the remaining sigma bond.



Fabrication Technology

There are five widely known methods to produce nanomaterials, and they are as follows:

1. Sol-gel synthesis,
2. Inert gas condensation,
3. Mechanical alloying or high-energy ball milling,
4. Plasma synthesis, and
5. Electrodeposition.

All these processes synthesize nanomaterials to varying degrees of commercially viable quantities. To date, of all the above process, only sol-gel synthesis can produce materials (both metals and ceramics) at ultra-low temperatures (around 150-600 °F vis-à-vis 2500-6500 °F for conventional techniques),

- Large quantities (to be commercially viable) relatively cheaply,
- Synthesize almost any material,
- Co-synthesize two or more materials simultaneously,
- Coat one or more materials onto other materials (metal or ceramic particulates, and three-dimensional objects),
- Produce extremely homogeneous alloys and composites,
- Synthesize ultra-high purity (99.9999%) materials,
- Tailor the composition very accurately even in the early stages of the process, because the synthesis is actually performed on an atomic level,
- Precisely control the microstructure of the final products, and precisely control the physical, mechanical, and chemical properties of the final products.

The aspects of self-assembly, self-repair and adjusting to the environment is observed in cells or different molecules in biological systems. Here biological systems function as molecular machines. Physicists have observed self-organization occurring in principle in case of inorganic materials as in the case of biological systems.

When Germanium is deposited on Silicon, because of the mismatching of lattice a strain is developed at the interface. A strained state refers to a state with higher energy. However, the lattice overcomes this strained state by the spontaneous formation of islands of Germanium by splitting themselves away from the Germanium film. It is considered special here since some kind of desired order i.e., the formation of islands has taken place. Since it occurs spontaneously, the act of formation is called self-organization or self-assembly. Similar effects were observed in case of InAs, GaAs heterostructure wherein it is possible to obtain arrays of quantum dots. When InAs layer is grown on GaAs, islands of InAs are formed. Above this layer, if GaAs and InAs layers are deposited alternately, the new islands in the respective cases are observed to pile up over the previously existing islands. This procedure points towards growing three dimensional quantum dots super lattices.

With nanotechnology, a large set of materials with distinct properties (optical, electrical, or magnetic) can be fabricated. Nanotechnologically improved products rely on a change in the physical properties when the feature sizes are shrunk. Nanoparticles for example take advantage of their dramatically increased surface area to volume ratio. Their optical properties, e.g. fluorescence, become a function of the particle diameter. When brought into a bulk material, nanoparticles can strongly influence the mechanical properties, such as the stiffness or elasticity. Example,

traditional polymers can be reinforced by nanoparticles resulting in novel materials e.g. as lightweight replacements for metals. Therefore, an increasing societal benefit of such nanoparticles can be expected.

Such nanotechnologically-enhanced materials will enable a weight reduction accompanied by an increase in stability and an improved functionality.

Most of the physical magnitudes characterizing nanoscale systems differ enormously from those familiar in macroscale systems.

The some of the properties that are size dependent are

- 1] Melting point and other phase transition
- 2] Colour (Band Gap)
- 3] Conductivity
- 4] Ionization potential and electron affinity: Chemical Properties
- 5] Kelvin Equation

$$\frac{p_v}{p_w} = \exp\left[-\frac{2\sigma}{r\rho_w R_v T}\right]$$

p_v = vapor pressure of nanoparticles

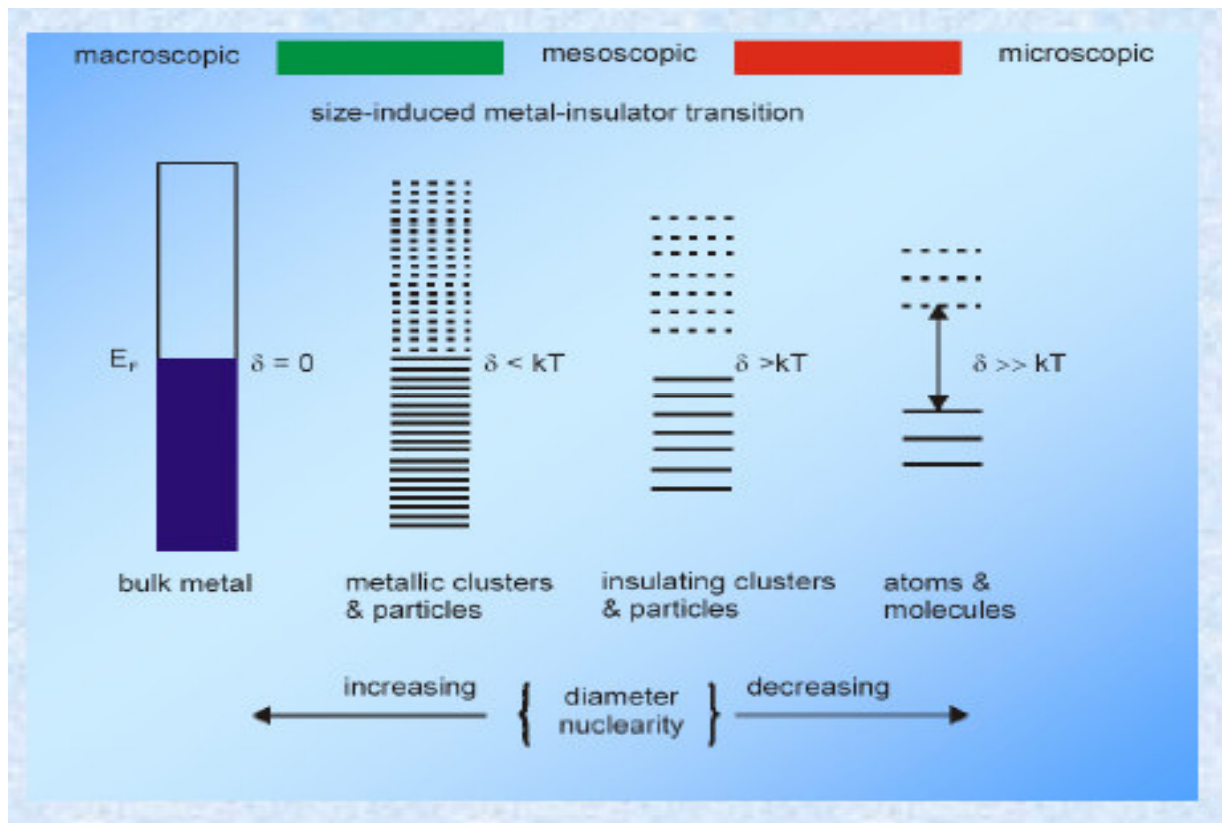
p_w = vapor pressure of bulk

σ = Surface tension

ρ_w = density

R_v = gas constant

T = temperature



Carbon nanotubes

A carbon nanotube is a sheet of carbon atoms joined in a pattern of hexagons and rolled into a cylinder. The nanotube's conducting properties depends upon how the two ends of the sheet meet along. For a particular way of arrangement of atoms along the meeting line, makes the entire tube conducting like a metal and for an other type of arrangement, the tube behaves like a semiconductor. The impressive advantages with nanotubes is that they are 100 times stronger than steel. In addition to it, their weight is about only one sixth that of steel.

The image is a composite of several diagrams and micrographs illustrating carbon-based materials:

- Diamond (3D):** A 3D ball-and-stick model of a diamond crystal structure, showing a tetrahedral arrangement of carbon atoms.
- Graphite:** A 3D ball-and-stick model of graphite, showing layers of carbon atoms arranged in a hexagonal lattice.
- Graphene (2D):** A 2D ball-and-stick model of a single layer of carbon atoms in a hexagonal lattice.
- Fullerene (0D):** A 3D ball-and-stick model of a C₆₀ fullerene molecule, showing a spherical cage of carbon atoms.
- carbon nanotubes (1D):** A 3D ball-and-stick model of a carbon nanotube, showing a cylindrical structure of carbon atoms.
- Linear Carbon Hexagon Conductor:** A diagram showing a linear arrangement of carbon hexagons where the hexagons are connected in a way that results in a conductor.
- Spiraling Carbon Hexagon Semiconductor:** A diagram showing a linear arrangement of carbon hexagons where the hexagons are connected in a way that results in a semiconductor.
- Carbon nanoribbon:** A series of SEM images (A, B, C, D) showing carbon nanoribbons. Image A shows a ribbon with a width of 1.87 μm. Image B shows a ribbon with a width of 10.9 μm. Image C shows a ribbon with a width of 500 nm. Image D shows a ribbon with a width of 10 nm.

Properties of carbon nanotubes

1. Optical Properties

Fundamental gap

Metallic= 0eV

Semiconducting material=0.5eV

2. Electrical Transport

Resistivity= $10^{-4} \Omega\text{-cm}$

Maximum current density= 10^9 A/cm^2

3. Thermal Transport

Thermal Conductivity (Room Temperature) $\sim 2000 \text{ W/m}\cdot\text{K}$

Phonon Mean Free Path $\sim 100 \text{ nm}$

Relaxation Time $\sim 10^{-11} \text{ s}$

4. Elastic Behavior

Young's Modulus (Semiconductor wire Nano Tubes-SWNT) $\sim 1 \text{ TPa}$

Young's Modulus (Metallic wire Nano Tubes-MWNT) $\sim 1.28 \text{ TPa}$

Maximum Tensile Strength $\sim 30 \text{ GPa}$

5. Carbon nanotubes are stable in Argon environment.

6. Carbon nanotubes are very strong against strong acid and high temperature because of their perfect conjugated system. Acid and heat are often applied to purify carbon nanotubes.

7. Good filler matrix (Carbon reinforced composites).

Different methods of Carbon nanotubes synthesis

1. Arc-discharge

2. Chemical Vapour deposition (CVD)

3. Plasma Enhance Chemical Vapour Deposition (PECVD)

4. Plasma Assisted Chemical vapour Deposition (PACVD)

5. Laser Ablation

6. Flame synthesis

7. Pyrolysis

8. Spray pyrolysis

9. High-pressure carbon monoxide (HipCO)

10. Template method

Characterization of carbon nanotubes

1. X-ray diffraction (XRD)

2. Scanning Electron Microscopy (SEM)

3. Transmission Electron Microscopy (TEM)

4. Raman effect

5. Scanning Tunneling Microscopy (STM)

6. Thermogravimetry Analysis (TGA)

Potential applications of Carbon nanotubes

1. Field Effect transistor

2. Electron field emitter

3. Optoelectronics

4. spintronics

6. Gas storage

7. Energy storage

9. Supercapacitor

10. Sensor (Gas & Biological)

Many more to be explored

Scaling of Classical Mechanical Systems

Classical systems are those in which

1. The wave nature of matter is not playing any role.
2. The energy exchange process do not comprise of quantization energy.
3. The measurement of position and momentum could be carried out with accuracies limited by only the precision of instruments. Essentially, they are bulk systems.

The mechanical systems, which have these properties, are called classical mechanical systems.

Scaling Laws

The relationships that characterize the variation of ratios or measures of the related “physical Quantities “ of a system with size are called Scaling law.

With the scaling law

- A mechanical system that manufactures a specific material will have capability of handling a predetermined mass of materials in unit time.
- The power consumed by a system could be related to its volume.
- Machines could be characterized by certain measures and ratios with various factors. The ratios will be numbers that vary with the size of the system and the variation could be predicted.

Basic assumptions in Mechanical scaling: -

Physical magnitudes depend on the size of a system (defined by the length parameter L) if all shape parameters and material properties (e.g., strengths, moduli, densities, coefficients of friction) are held constant.

While investigating the influence of scaling on the functioning of the system,

- The material properties such as the density, elastic moduli, coefficient of friction, mechanical strength etc., remain unchanged with size.
- There might be fields and current in the system, but their role is not expected to change with scaling.

These scaling methods imply constancy of the space-time shapes describing the trajectories of moving parts.

The list for mechanical scaling of some physical quantities are given below:-

Physical Quantity	Scaling relation	Dimensional dependence	Examples
Mass	\propto Volume	L^3	For diamond Cubic nanoblock of density $3.5 \times 10^3 \text{ kg/m}^3$ is $3.5 \times 10^{-24} \text{ kg}$
Force, strength	\propto Area		
Aceleration	\propto Force/mass	L^{-1}	Nanoscale devices exert small forces: (a stress of 10^{10} N/m^2) $= 10^{-8} \text{ N/nm}^2$ $\sim 3 \times 10^{15} \text{ m/s}^2$

Shear stiffness/stretching stiffness	$\propto \text{Area/Length}$	L	Cubic nm block of Youngs Modulus (E)= 10^{12} N/m ² has a stretching stiffness 1000 N/m
Bending Stiffness	Radius ⁴ /Length ³	L	
Period of vibration (T)	$\propto \text{Length}$	L	The acoustic speed in diamond is $\sim 1.75 \cdot 10^4$ m/s And {(1000 N/m) / (3.5 * 10 ⁻²⁴ kg)} ^{0.5} ~ 1.7 * 10 ¹³ rad/s A 10 nN force and a speed of 1.7 * 10 ³ m/s the power is 17 μ W Power density is of 1.7 * 10 ²² W/m ³
Frequency/Vibrational Frequencies in mechanical systems	$\propto 1/\text{period} \propto$ (acoustic speed /length) or (Stiffness/mass) ^{0.5}	L ⁻¹	
Power	$\propto \text{Force} * \text{speed}$	L ²	Power density is of 1.7 * 10 ²² W/m ³
Power density	$\propto \text{Power} / \text{volume}$	L ⁻¹	
Vibrations	-----	L ⁰	For diamond the mean thermal speed of a cubic nanometer object at 300K is ~ 55 m/s.
Speed	$\propto \text{Acceleration} * \text{time}$	L ⁰	
Time	$\propto \text{Displacement} / \text{speed}$	L	L ^{-3/2}
Energy, work	$\propto \text{Force} * \text{distance}$	L ³	
Friction (Frictional Force)	$\propto \text{Area}$	L ²	L ^{-3/2}
Thermal Speed	$\propto (\text{Thermal Energy/mass})^{0.5}$	L ^{-3/2}	

Note some quantities in this table are invariant with length scaling, meaning they do not depend on a simple length scaling parameter at all. Thus, in the table, vibrations and speed do not depend on "L" but paradoxically it appears that a characteristic time does depend linearly on "L". By this statement, it is meant that if something typically will take 1 second to occur in a macroscopic system: it is predicted to take 10⁻⁹ seconds in a nanoscaled system.

According to the table, something that has a lifetime of 1 year at the macroscopic level, might only have ~ 30 milliseconds at the nm scale!

Corrections:-

- Matter is treated as a continuum with bulk values of strength, modulus and soforth.
- The influence of surfaces on mechanical properties is neglected; it gives the crude estimates regarding small components.

- Apart from the molecular structure of matter, major corrections to the results suggested by these scaling laws include uncertainties in position and velocity resulting from statistical and quantum mechanics.

Quantum Mechanics --- Characteristic Quantum Energy ---- $\hbar\omega$

Statistical Mechanics --- Characteristic Thermal energy ----- $K_B T$

Where K_B is Boltzmann constant.

The ratio $(\hbar\omega/K_B T)$ varies directly with the frequency of vibrations, that is, varies as L^{-1} . The associated quantum mechanical effects are smaller than the classical thermal effects, but still significant.

Ex. An object of cubic nanometer size with $\omega=1.7 \times 10^{13}$ rad/s has $(\hbar\omega/K_B T)=0.456$ at $T=300K$.

Scaling of electromagnetic systems

All the scaling of electromagnetic systems implies that we can legitimately scale to the atomic level using continuum laws. These numbers of macroscopically based scaling laws for electromagnetism, again assume particular models of behavior with length scaling that may or may not apply at the nm length scales. This is unlikely to be true given that on this scale given the distribution of electrical charges is discrete and that quantum mechanical laws will probably apply.

Basic assumptions:-In this,

- It is convenient to assume that electrostatic field strengths are independent of scale. With this assumption, the above constant-stress, constant-speed scaling laws for mechanical systems continue to hold for electromechanical systems, so long as magnetic forces are neglected.

Corrections

- Nanometer scale electromechanical systems, require consideration of the electrical conductivity of fine wires and of insulating layers thin enough to make tunneling a significant mechanism of electron transport.
- Electromagnetic systems on a nanometer scale commonly have extremely high frequencies, yielding large values of $(\hbar\omega/K_B T)$. Molecules undergoing electronic transitions typically absorb and emit light in the visible to ultraviolet range.

Property	Scaling law	Reason	Example
Voltage	L	Voltage is related to its electric field, in turn depends on the local distribution of electrical charges	A field strength of $E=10^9$ V/m yields 1 volt over 1nm distance
Electrical resistance	L^{-1}	$R=\sigma l/A$ σ is constant	If a 1 cm^3 resistor has a 1Ω resistance, a 1nm cube of it would have a calculated $10^7 \Omega$.
In reality, a cube of this small would not obey this scaling law due to the discrete nature of the material at this scale.			
Electric Current	L^2	$I=V/R$	
Electric	L^0	$J= I/A$	

current Density			The maximum possible current density through a conductor was about 10^{10}A/m^3 . For a 1nm^2 cross sectional conductor, we can pass up to 10nA . The voltage drop across 1nm cube with $10^7\Omega$ is 0.1 Volts and the field strength is 10^8V/m .
Electric capacitance	$L^3/L^2=L$	\propto Electro static energy/voltage ²	A parallel plate capacitor with 1nm square plates separated by 1nm has an capacitance of about 10^{-20} F, which is very small capacitance, it may be important in modern electronics
Electrostatic power density	L^{-1}	$(1/2) CV^2$ \propto Electrostatic power/volume	At the typical applied 5 volts, a power density of $1.3 \times 10^{-9}\text{W/nm}^3$ is developed if switching rate is continuous.
Magnetic Filed	L	\propto Current/distance	At 1nm from a conductor carrying 10nA , the field strength of $\sim 2 \times 10^{-6}$ tesla
Magnetic force	L^4	\propto Area*(magnetic field) ²	Typical magnitude of 10^{-23}N
Magnetic Energy	L^5	\propto Volume * (magnetic field) ²	
Magnetic energy density	L^2	\propto Magnetic energy/volume	
Inductance	L	Magnetic energy/(current) ²	10^{-15}Henry

The electromagnetic system in which if we consider the no end nor beginning of both the electric and magnetic field strengths is called the steady-state systems.

Magnitudes and scaling: time varying systems

In systems with time-varying currents and fields, skin depth effects increase resistance at high frequencies; these effects complicate scaling relationships and are ignored here. The scaling of Classical AC circuits into nanometer size regime.

For LR circuits

$$\text{Inductive time constant} \propto (\text{inductance/resistance}) \propto L^2$$

$$\text{Capacitive time constant} \propto (\text{resistance} * \text{capacitance}) = \text{constant}$$

$$\text{Oscillation frequency} \propto \{1/(\text{inductance} * \text{capacitance})\}^{0.5} \propto L^{-1}$$

$$\text{Alternatively oscillation frequency} \propto (\text{wave speed/ length}) \propto L^{-1}$$

$$Q \propto (\text{oscillation frequency} * \text{inductance/resistance}) \propto L$$

Since Q is a measure of the damping time relative to the oscillation time, small AC circuits will be heavily damped unless nonclassical effects intervene.

Applications of Nanomaterials (Not in the VTU Syllabus)**Medicine**

The biological and medical research communities have exploited the unique properties of nanomaterials for various applications (e.g., contrast agents for cell imaging and therapeutics for treating cancer). Terms such as biomedical nanotechnology, bionanotechnology, and nanomedicine are used to describe this hybrid field.

Functionalities can be added to nanomaterials by interfacing them with biological molecules or structures. The size of nanomaterials is similar to that of most biological molecules and structures; therefore, nanomaterials can be useful for both in vivo and in vitro biomedical research and applications.

Thus far, the integration of nanomaterials with biology has led to the development of diagnostic devices, contrast agents, analytical tools, physical therapy applications, and drug-delivery vehicles.

Diagnostics

Nanotechnology-on-a-chip is one more dimension of lab-on-a-chip technology. Biological tests measuring the presence or activity of selected substances become quicker, more sensitive and more flexible when certain nanoscale particles are put to work as tags or labels. Magnetic nanoparticles, bound to a suitable antibody, are used to label specific molecules, structures or microorganisms. Gold nanoparticles tagged with short segments of DNA can be used for detection of genetic sequence in a sample. Multicolor optical coding for biological assays has been achieved by embedding different-sized quantum dots into polymeric microbeads. Nanopore technology for analysis of nucleic acids converts strings of nucleotides directly into electronic signatures.

Drug delivery

The overall drug consumption and side-effects can be lowered significantly by depositing the active agent in the morbid region only and in no higher dose than needed. This highly selective approach reduces costs and human suffering. An example can be found in dendrimers and nanoporous materials. They could hold small drug molecules transporting them to the desired location. Another vision is based on small electromechanical systems: NEMS are being investigated for the active release of drugs. Some potentially important applications include cancer treatment with iron nanoparticles or gold shells.

A targeted or personalized medicine reduces the drug consumption and treatment expenses resulting in an overall societal benefit by reducing the costs to the public health system.

Tissue engineering

Nanotechnology can help to reproduce or to repair damaged tissue. This so called "tissue engineering" makes use of artificially stimulated cell proliferation by using suitable nanomaterial-based scaffolds and growth factors. Tissue engineering might replace today's conventional treatments, e.g. transplantation of organs or artificial implants. On the other hand, tissue engineering is closely related to the ethical debate on human stem cells and its ethical implications.

Chemistry and environment

Chemical catalysis and filtration techniques are two prominent examples where nanotechnology already plays a role. The synthesis provides novel materials with tailored features and chemical properties e.g. nanoparticles with a distinct chemical surrounding (ligands) or specific optical properties. In this sense, chemistry is indeed

a basic nanoscience. In a short-term perspective, chemistry will provide novel “nanomaterials” and in the long run, superior processes such as “self-assembly” will enable energy and time preserving strategies.

In a sense, all chemical synthesis can be understood in terms of nanotechnology, because of its ability to manufacture certain molecules. Thus, chemistry forms a base for nanotechnology providing tailor-made molecules, polymers etc. and furthermore clusters and nanoparticles.

Catalysis

Chemical catalysis benefits especially from nanoparticles, due to the extremely large surface to volume ratio. The application potential of nanoparticles in catalysis ranges from fuel cell to catalytic converters and photocatalytic devices. Catalysis is also important for the production of chemicals.

Filtration

A strong influence of nanochemistry on waste-water treatment, air purification and energy storage devices is to be expected. Mechanical or chemical methods can be used for effective filtration techniques. One class of filtration techniques is based on the use of membranes with suitable hole sizes, whereby the liquid is pressed through the membrane. Nanoporous membranes are suitable for a mechanical filtration with extremely small pores smaller than 10 nm (“nanofiltration”). Nanofiltration is mainly used for the removal of ions or the separation of different fluids. On a larger scale, the membrane filtration technique is named ultrafiltration, which works down to between 10 and 100 nm. One important field of application for ultrafiltration is medical purposes as can be found in renal dialysis.

Magnetic nanoparticles offer an effective and reliable method to remove heavy metal contaminants from waste water by making use of magnetic separation techniques. Using nanoscale particles increases the efficiency to absorb the contaminants and is comparatively inexpensive compared to traditional precipitation and filtration methods.

Energy

The most advanced nanotechnology projects related to energy are: storage, conversion, manufacturing improvements by reducing materials and process rates, energy saving e.g. by better thermal insulation, and enhanced renewable energy sources.

Reduction of energy consumption

A reduction of energy consumption can be reached by better insulation systems, by the use of more efficient lighting or combustion systems, and by use of lighter and stronger materials in the transportation sector. Currently used light bulbs only convert approximately 5% of the electrical energy into light. Nanotechnological approaches like light-emitting diodes (LEDs) or quantum caged atoms (QCAs) could lead to a strong reduction of energy consumption for illumination.

Increasing the efficiency of energy production

For more details on this topic, see Nanocrystal solar cell.

Today's best solar cells have layers of two different semiconductors stacked together to absorb light at different energies but they still only manage to use 30 percent of the Sun's energy. Commercially available solar cells have much lower efficiencies (less than 20%). Nanotechnology could help increase the efficiency of light conversion by specifically designed nanostructures. The degree of efficiency of combustion engines is not higher than 15-20% at the moment. Nanotechnology could improve

combustion by designing specific catalysts with maximized surface area. Scientists have recently developed tetrad-shaped nanoparticles that, when applied to a surface, instantly transform it into a solar collector.[citation needed]

The use of more environmentally friendly energy systems

An example for an environmentally friendly form of energy is the use of fuel cells powered by hydrogen, which is ideally produced by renewable energies. Probably the most prominent nanostructured material in fuel cells is the catalyst consisting of carbon supported noble metal particles with diameters of 1- 5 nm. Suitable materials for hydrogen storage contain a large number of small nanosized pores. Therefore many nanostructured materials like nanotubes, zeolites or aluminates are under investigation.

Nanotechnology can contribute to the further reduction of combustion engine pollutants by nanoporous filters, which can clean the exhaust mechanically, by catalytic converters based on nanoscale noble metal particles or by catalytic coatings on cylinder walls and catalytic nanoparticles as additive for fuels.

Recycling of batteries

Because of the relatively low energy density of batteries the operating time is limited and a replacement or recharging is needed. The huge number of spent batteries and accumulators represent a disposal problem. The use of batteries with higher energy content or the use of rechargeable batteries or supercapacitors with higher rate of recharging using nanomaterials could be helpful for the battery disposal problem.

Information and communication

Current high-technology production processes are based on traditional top down strategies, where nanotechnology has already been introduced silently. The critical length scale of integrated circuits is already at the nanoscale (50 nm and below) regarding the gate length of transistors in CPUs or DRAM devices.

Novel semiconductor devices

An example of such novel devices is based on spintronics. The dependence of the resistance of a material (due to the spin of the electrons) on an external field is called magnetoresistance. This effect can be significantly amplified (GMR - Giant Magneto-Resistance) for nanosized objects, for example when two ferromagnetic layers are separated by a nonmagnetic layer, which is several nanometers thick (e.g. Co-Cu-Co). The GMR effect has led to a strong increase in the data storage density of hard disks and made the gigabyte range possible. The so called tunneling magnetoresistance (TMR) is very similar to GMR and based on the spin dependent tunneling of electrons through adjacent ferromagnetic layers. Both GMR and TMR effects can be used to create a non-volatile main memory for computers, such as the so called magnetic random access memory or MRAM.

Novel optoelectronic devices

In the modern communication technology traditional analog electrical devices are increasingly replaced by optical or optoelectronic devices due to their enormous bandwidth and capacity, respectively. Two promising examples are photonic crystals and quantum dots.

Photonic crystals are materials with a periodic variation in the refractive index with a lattice constant that is half the wavelength of the light used. They offer a selectable band gap for the propagation of a certain wavelength, thus they resemble a semiconductor, but for light or photons instead of electrons.

Quantum dots are nanoscaled objects, which can be used, among many other things, for the construction of lasers. The advantage of a quantum dot laser over the traditional semiconductor laser is that their emitted wavelength depends on the diameter of the dot. Quantum dot lasers are cheaper and offer a higher beam quality than conventional laser diodes.

Displays

The production of displays with low energy consumption could be accomplished using carbon nanotubes (CNT). Carbon nanotubes can be electrically conductive and due to their small diameter of several nanometers, they can be used as field emitters with extremely high efficiency for field emission displays (FED). The principle of operation resembles that of the cathode ray tube, but on a much smaller length scale.

Nanologic

Nanoscale devices exhibit dominant nonlinearities that prevent their use as two-state devices in digital computers. The idea behind nanologic is to exploit these nonlinearities (rather than suppress them) to implement functions that correspond to mathematical sets: interval numbers, disjoint intervals, fuzzy numbers, fuzzy sets, etc. Simple nanoelectronic circuits can be designed that can represent sets and set operations, and an array of such devices constitutes a universal mathematical processor, able to solve any problem that can be expressed in set theory. Nanologic will find most value for human-meaningful problems involving uncertainty, ambiguity, error, under-specified and over-specified systems, and for approximate analysis of combinatorially intractable problems, including mathematical theorems.

Quantum computers

Entirely new approaches for computing exploit the laws of quantum mechanics for novel quantum computers, which enable the use of fast quantum algorithms. The Quantum computer will have quantum bit memory space termed qubit for several computations at the same time.

Consumer goods

Nanotechnology is already impacting the field of consumer goods, providing products with novel functions ranging from easy-to-clean to scratch-resistant. Modern textiles are wrinkle-resistant and stain-repellent; in the mid-term clothes will become “smart”, through embedded “wearable electronics”. Already in use are different nanoparticle improved products. Especially in the field of cosmetics such novel products have a promising potential.

Foods

Nanotechnology can be applied in the production, processing, safety and packaging of food. A nanocomposite coating process could improve food packaging by placing anti-microbial agents directly on the surface of the coated film. Nanocomposites could increase or decrease gas permeability of different fillers as is needed for different products. They can also improve the mechanical and heat-resistance properties and lower the oxygen transmission rate. Research is being performed to apply nanotechnology to the detection of chemical and biological substances for sensing biochemical changes in foods.

Household

The most prominent application of nanotechnology in the household is self-cleaning or “easy-to-clean” surfaces.

Optics

The first sunglasses using protective and antireflective ultrathin polymer coatings are on the market. For optics, nanotechnology also offers scratch resistant coatings based on nanocomposites. They can also help in laser surgery, as they can fix the pupil.

Textiles

The use of engineered nanofibers already makes clothes water- and stain-repellent or wrinkle-free. Textiles with a nanotechnological finish can be washed less frequently and at lower temperatures. Nanotechnology has been used to integrate tiny carbon particles membrane and guarantee full-surface protection from electrostatic charges for the wearer.

Cosmetics

One field of application is in sunscreens. The traditional chemical UV protection approach suffers from its poor long-term stability. A sunscreen based on mineral nanoparticles such as titanium dioxide offer several advantages. Titanium dioxide nanoparticles have a comparable UV protection property as the bulk material, but lose the cosmetically undesirable whitening as the particle size is decreased.

As per the VTU syllabus not required-just for view/reference

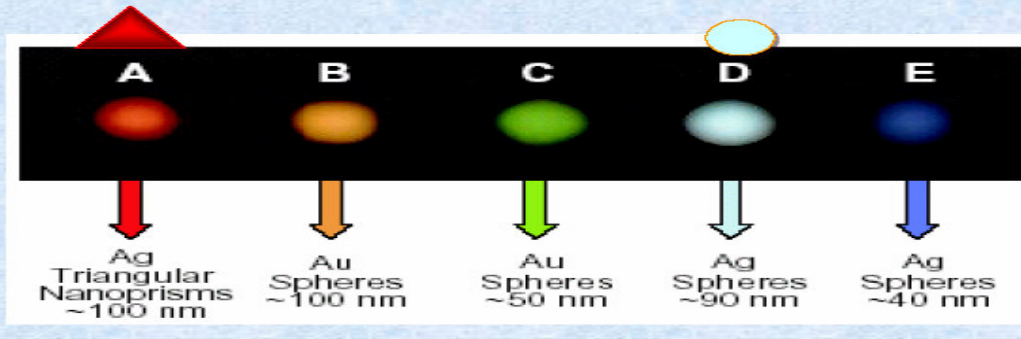
The size dependence of 'colour'



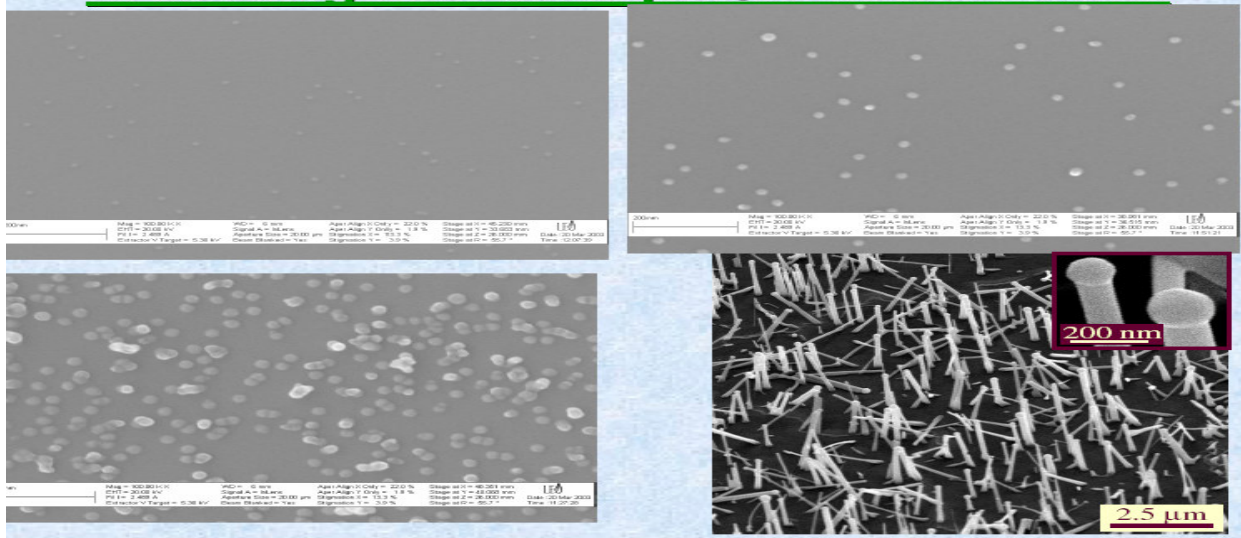
Fluorescence of different size colloidal CdTe nanoparticles

Source: H. Weller, Institute of Physical Chemistry, University of Hamburg

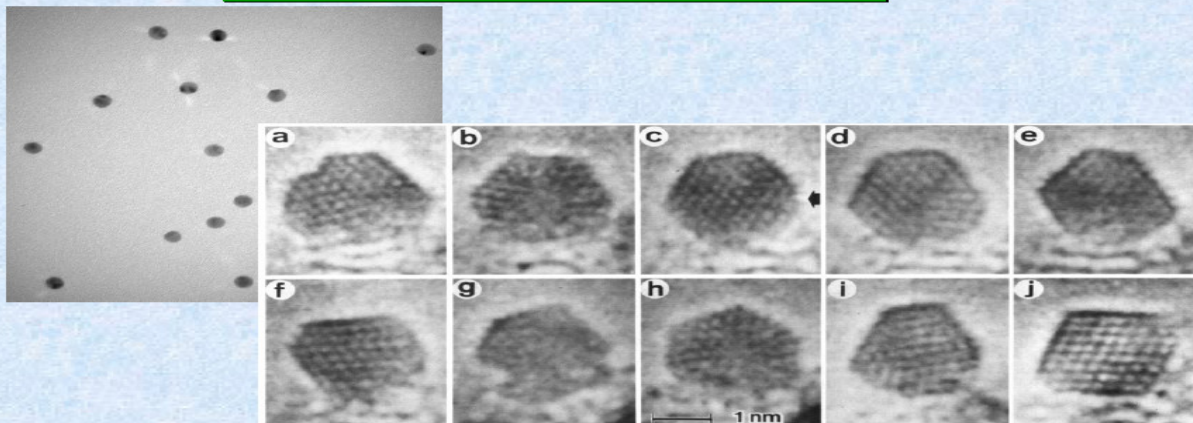
Effect of shape



SEM images of nanoparticles/nanowires

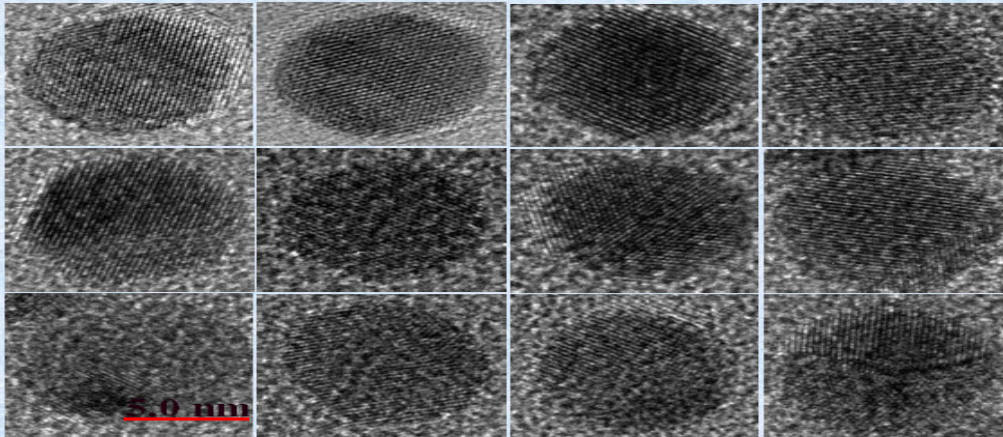


TEM images of gold particles



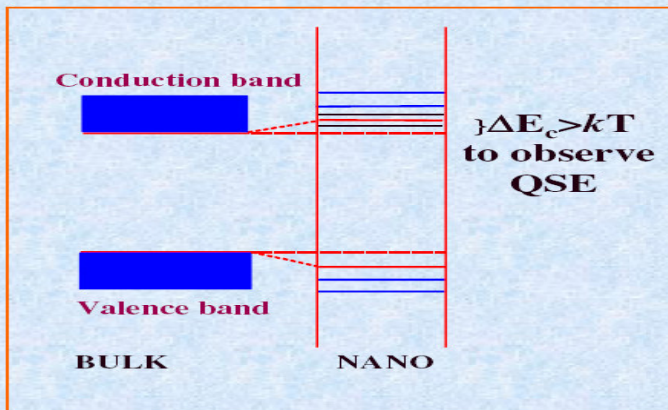
- Determine the size accurately
- Small nanoparticles undergo a shape and a structural transition

HRTEM images of gold particles

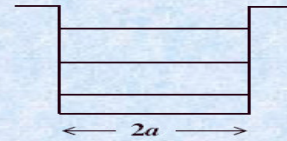


Size effect of nanoparticles-I

Quantum Size Effect – (change in optical, electronic properties)



Energy levels must be sufficiently separated to remain distinguishable under broadening (e.g. thermal)

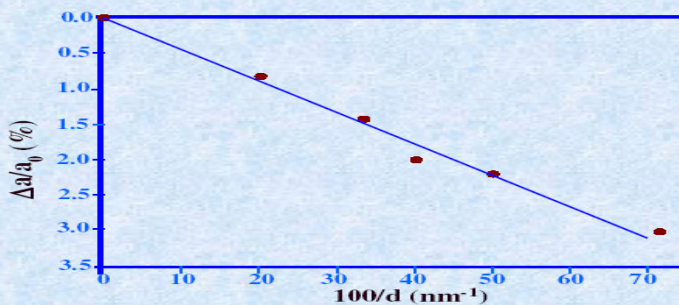


$$\Delta E_c = \frac{\hbar^2 \pi^2}{2a^2} \left[\frac{1}{m_c^*} \right]$$

$$\Delta E_v = \frac{\hbar^2 \pi^2}{2a^2} \left[\frac{1}{m_h^*} \right]$$

$$\Delta E_g = \Delta E_c + \Delta E_v$$

Size effect of nanoparticles-III



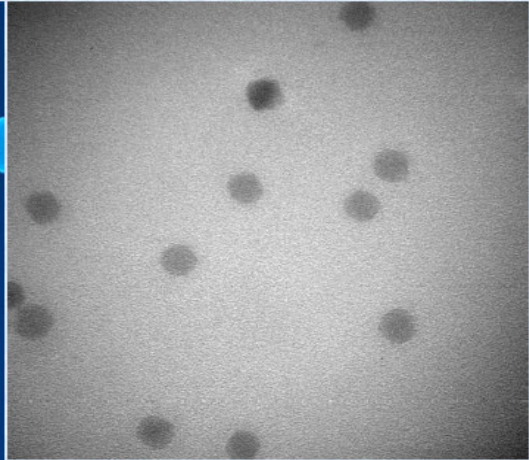
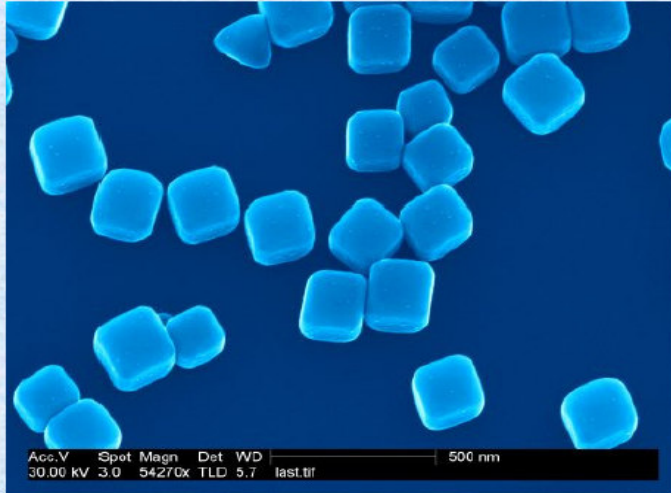
$$\frac{\Delta a}{a_0} = \frac{4\gamma\kappa}{3d}$$

γ : surface tension
 κ : compressibility

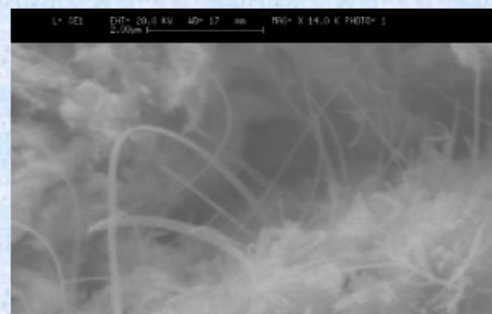
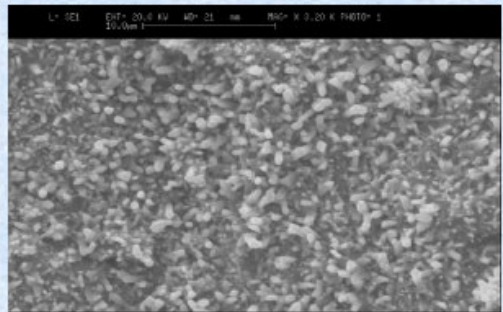
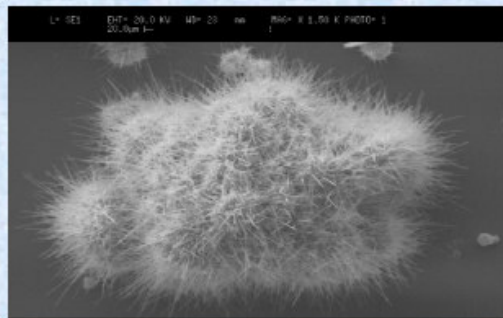
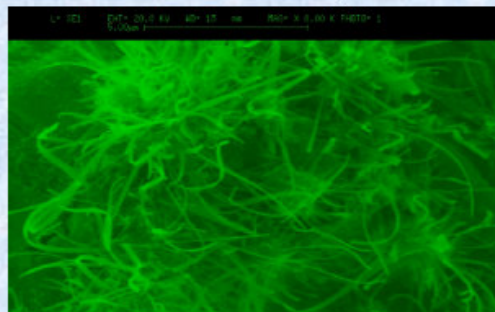
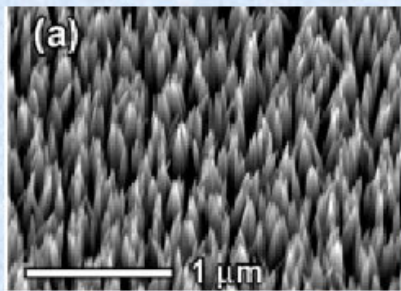
$\gamma = 6.0 \text{ J/m}^2$
(that of bulk is 1.808 J/m^2)

Lattice contraction of Pd nanoparticles in polymer:
Lamber, Wetjen & Jaeger, *Phys. Rev. B* 51, 10968 (1995)

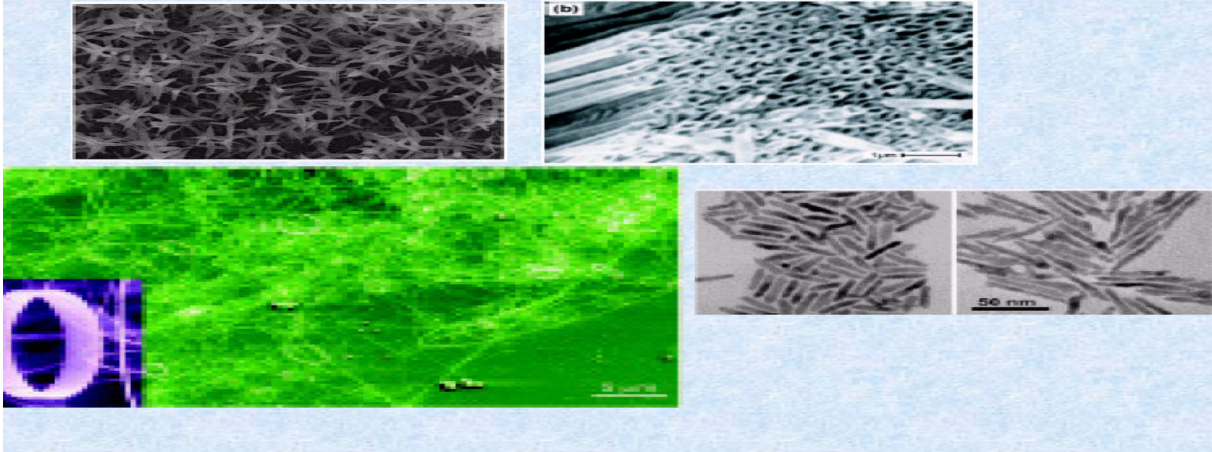
Different shape of nanoparticles



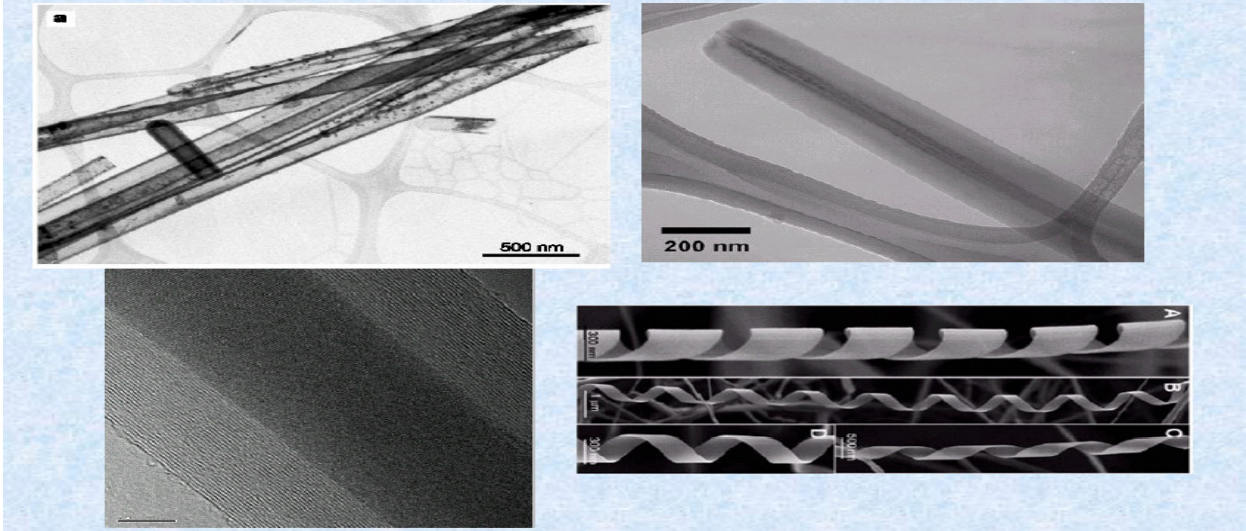
Other nanostructures



Other nanostructures

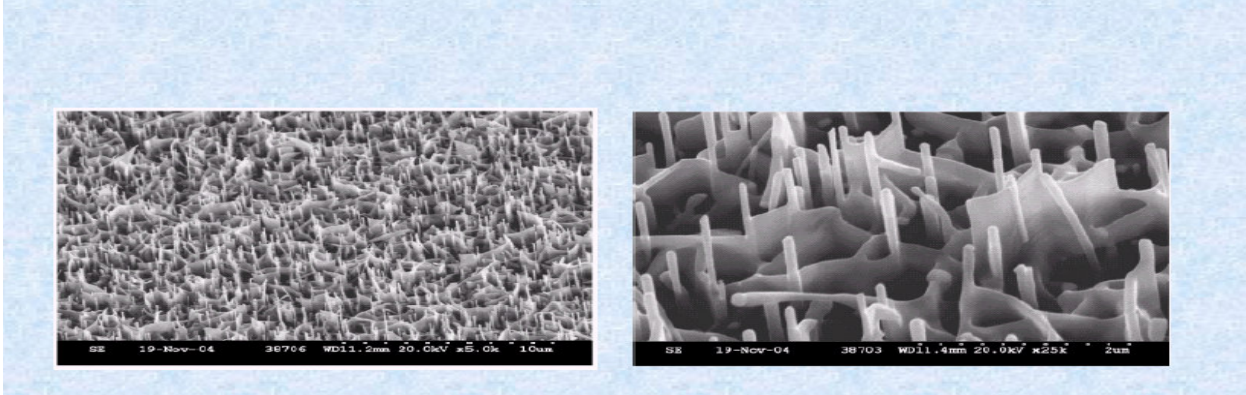


Other nanostructures



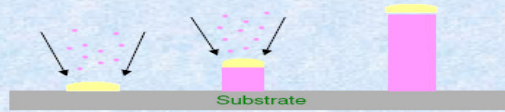
Other nanostructures

nanowalls/nanorods



Synthesis of nanowires

VLS mechanism

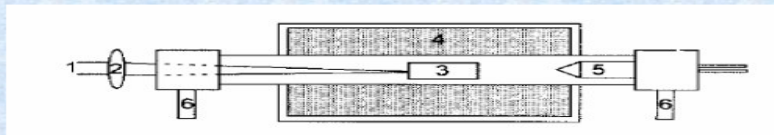


1. Vapors form alloy with the catalyst
2. Continuous supply of vapor leads to supersaturation and precipitates out to initiate the nanowire growth

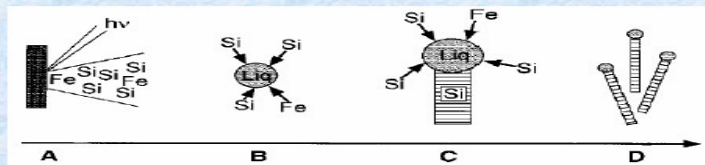
➤ Diameter can be controlled by the size of the catalyst. Diameter is slightly larger than the size of the catalyst.

➤ Length can be controlled by the reaction/deposition time.

Laser ablation



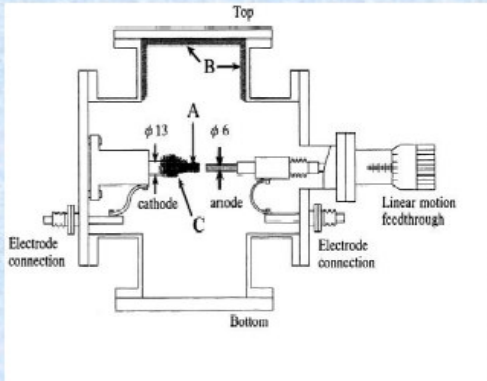
1. Laser
2. Lens
3. Target ($\text{Si}_{0.9}\text{Fe}_{0.1}$)
4. Tube furnace
5. Cold finger
6. Inlet & outlet of gas flow



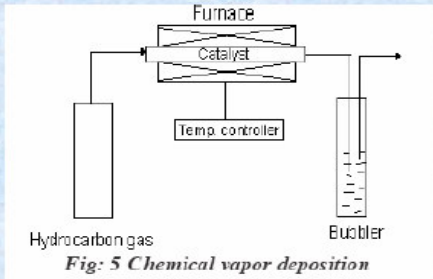
A. M. Morales and C. M. Lieber, Science 279, 208 (1998).

Different methods of Carbon nanotubes synthesis

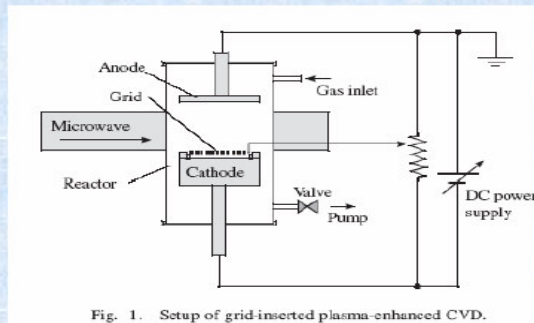
1. Arc-discharge



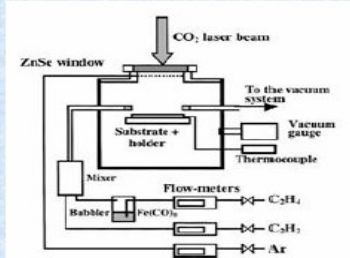
2. Chemical Vapour deposition(CVD)



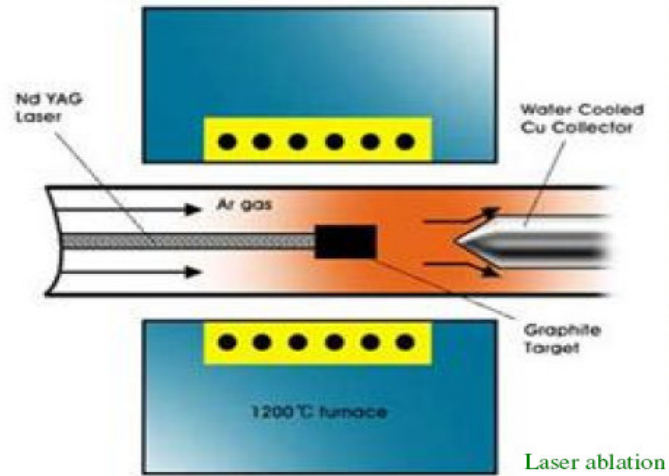
3. Plasma Enhance Chemical Vapour Deposition (PECVD)



4. Plasma Assisted Chemical vapour Deposition (PACVD)



5.Laser Ablation



6.Flame synthesis

7.Pyrolysis

8.Spray pyrolysis

9.High pressure carbon monoxide(HipCO)

10.Template method(usingAAO)

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Reference Books: - Nanosystems by E. Drexler