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Module 6: Advanced materials

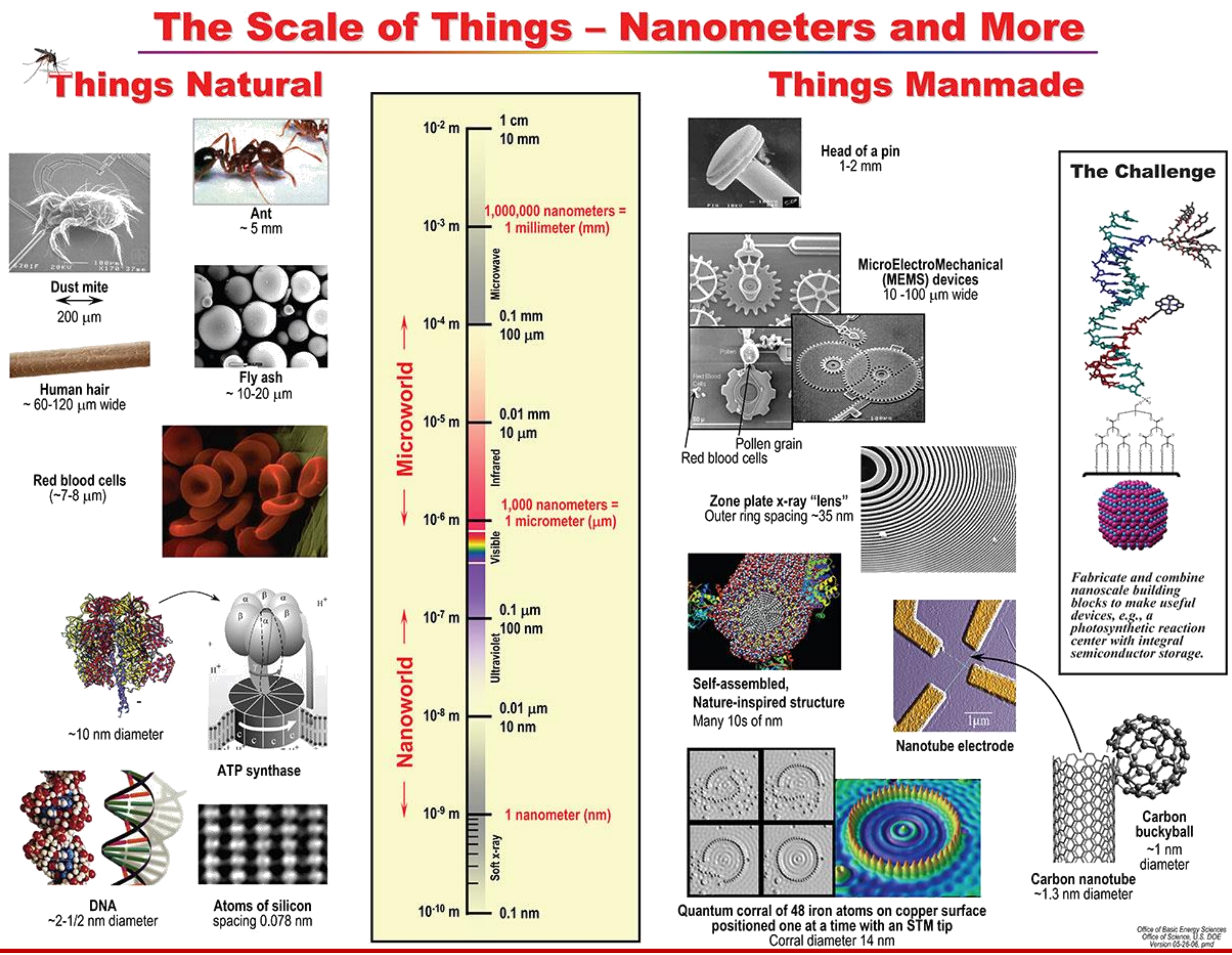
Nanomaterials, Conducting Polymers, Meta materials, Fluorescent Materials. Principles of mesoscopic physics-size effect, Quantum confinement, and Coulomb blockade, Optical effects, Surface plasmon effects. Characterization techniques for nano size-SEM, AFM, TEM.

Advanced materials

- The materials that are utilized in high-technology (or high-tech) applications are sometimes called **advanced materials.**
- Example: electronic equipment (VCRs, CD players, etc.), computers, fiber optic systems, spacecraft, aircraft, high-energy density batteries, energy-conversion systems, and military rocketry .
- Advanced materials are typically either traditional materials whose properties have been enhanced or newly developed high performance materials.
- Advanced materials may be of all material types (e.g., metals, ceramics, polymers) and are normally relatively expensive.

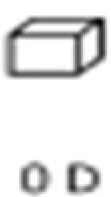
Nanomaterials

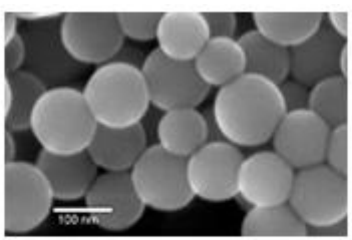
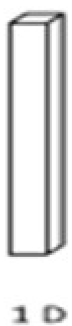
Materials with any one of the dimension (length, width, thickness) in the range of 100 nm to 0.1 nm call it as nano material. **Nanometer= 10^{-9} meter**

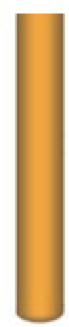
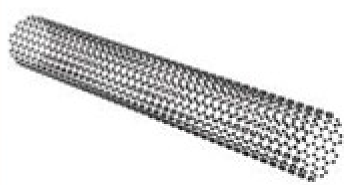
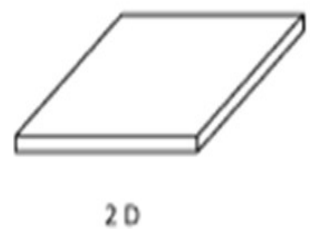


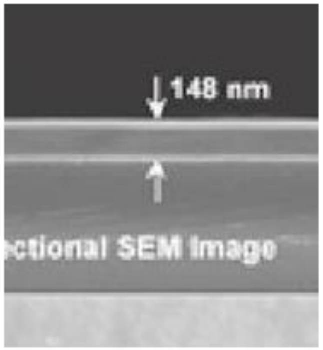
Classification of nano materials

(Quantum dot) **Zero dimensional nano materials**	(Quantum wire) **One dimensional nano materilas**	(Quantum well) **Two dimensional nano materials**
All three dimensions in nano size	Only two dimensions in nano size	Only one dimensions in nano size
Electrons are not free to move any direction	Electrons are free to move only in one direction	Electrons are free to move any direction
Confinement (or)limitations in all three directions	Confinement (or) limitations in two directions	Confinement (or) limitations in one direction
Applications: Drug delivery, Antibacterial, antifungal, anti-viral and anti-inflammatory medicine	Applications: Nanowire Transistors, Nano electronics	Applications: Solar cells, Batteries, Super hydrophobic coatings
Eg: Nano particles	Eg: Nano wires/tubes	Eg: Nano thin films





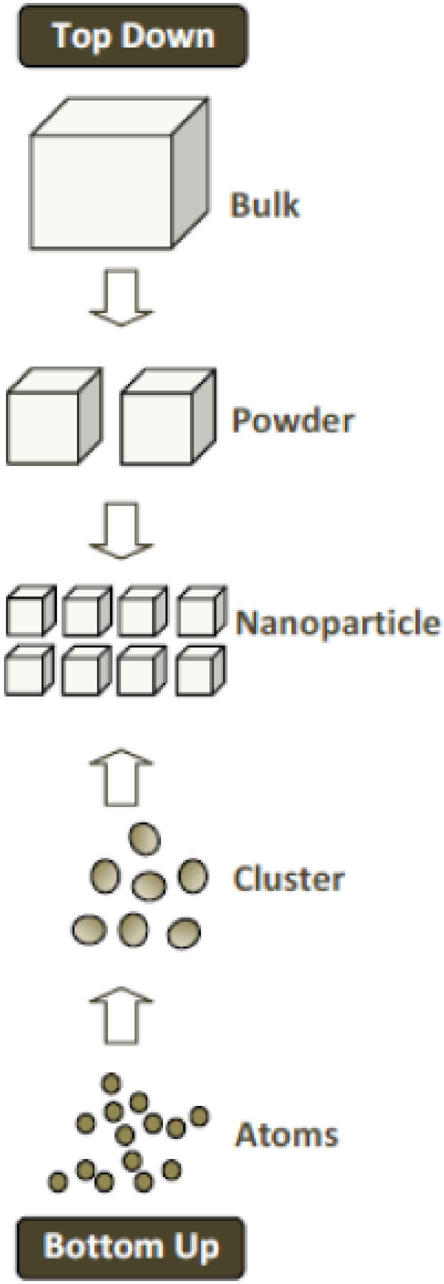
Preparation of nano materials

Top down approach refers to slicing or successive cutting of a bulk material to get nano sized particle.

1. Nanomaterial synthesis, ball-milling is an important top-down approach, where Macrocrystalline structures are broken down to nanocrystalline structures, but original integrity of the material is retained.
2. The crystallites are allowed to react with each other by the supply of kinetic energy during milling process to form the required nanostructured oxide.
3. Attrition or Milling is a typical top down method in making nano particles
4. This approach leads to the bulk production of nano material.
5. Introduces internal stress, in addition to surface defects and contamination
6. Lithography process

Bottom up approach refers to the buildup of a material from the bottom: atom by atom, molecule by molecule or cluster by cluster.

1. The colloidal dispersion is a good example of bottom up
2. Bottom up approach also promises a better chance to obtain nano structures with less defects, more homogeneous chemical composition.
3. Assembling materials from the atoms/molecules up, and, therefore very important for nano-fabrication
4. Though the bottom up approach oftenly referred in nanotechnology, it is not a newer concept.
5. Examples of bottom-up technique are self-assembly of nanomaterials, sol-gel technology, electrodeposition, physical and chemical vapour deposition (PVD, CVD), epitaxial growth, laser ablation
6. Non lithography process



Size effects in nano materials

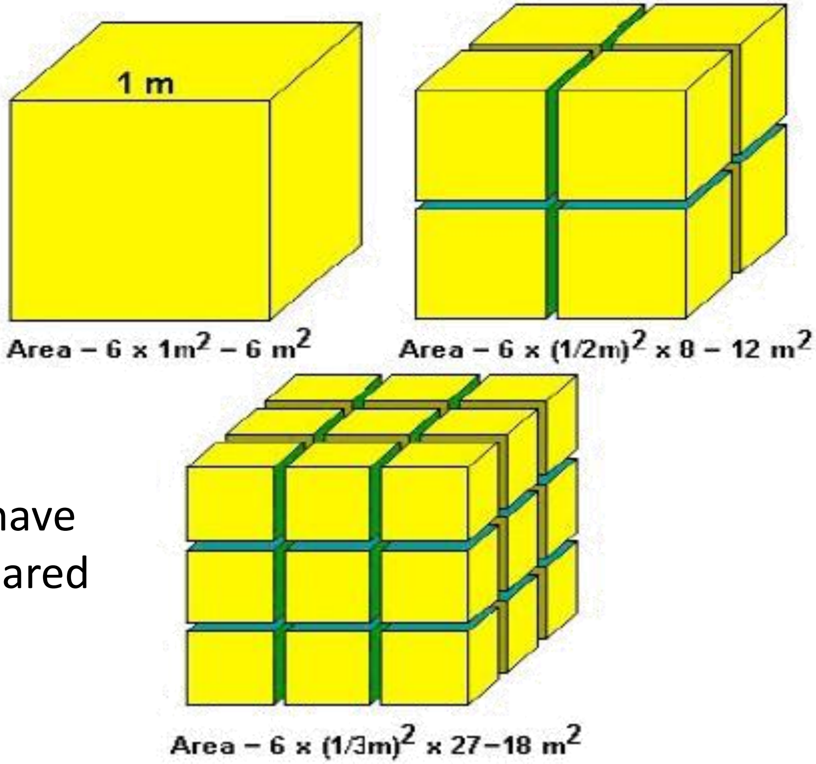
There are mainly two size effects in nanomaterials

1. Large surface area compared to bulk

2. Quantum confinement

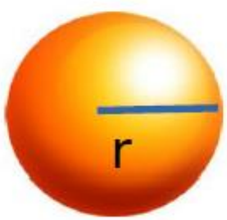
1. (a) Large surface area compared to bulk

Nanomaterials have a relatively greater surface area when compared to the same volume or mass of the same material in bulk form



1. (b) Large surface to Volume ratio: Nanomaterials have a relatively Large surface to Volume ratio when compared to the same volume of the material in bulk form.

For example consider a sphere of radius “r”



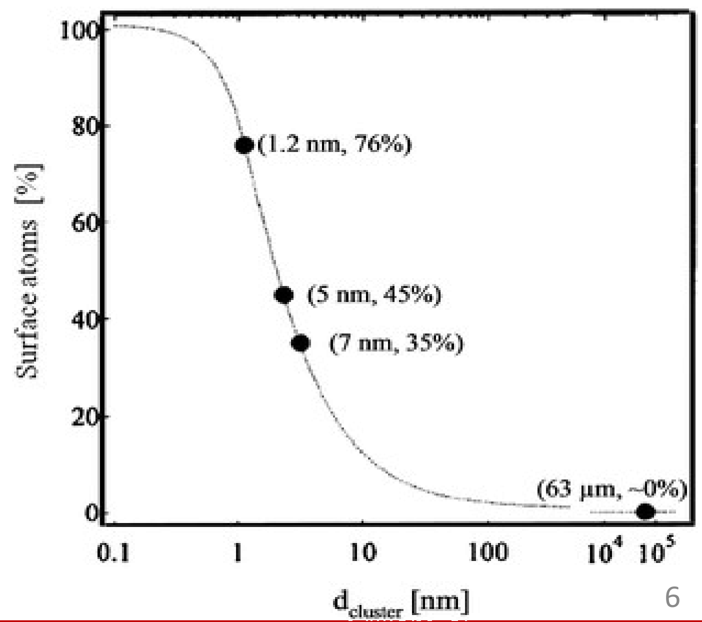
Surface area = $4\pi r^2$

Volume=$4\pi r^3/3$

$$\frac{\text{Surface}}{\text{Volume}} = 4/r$$

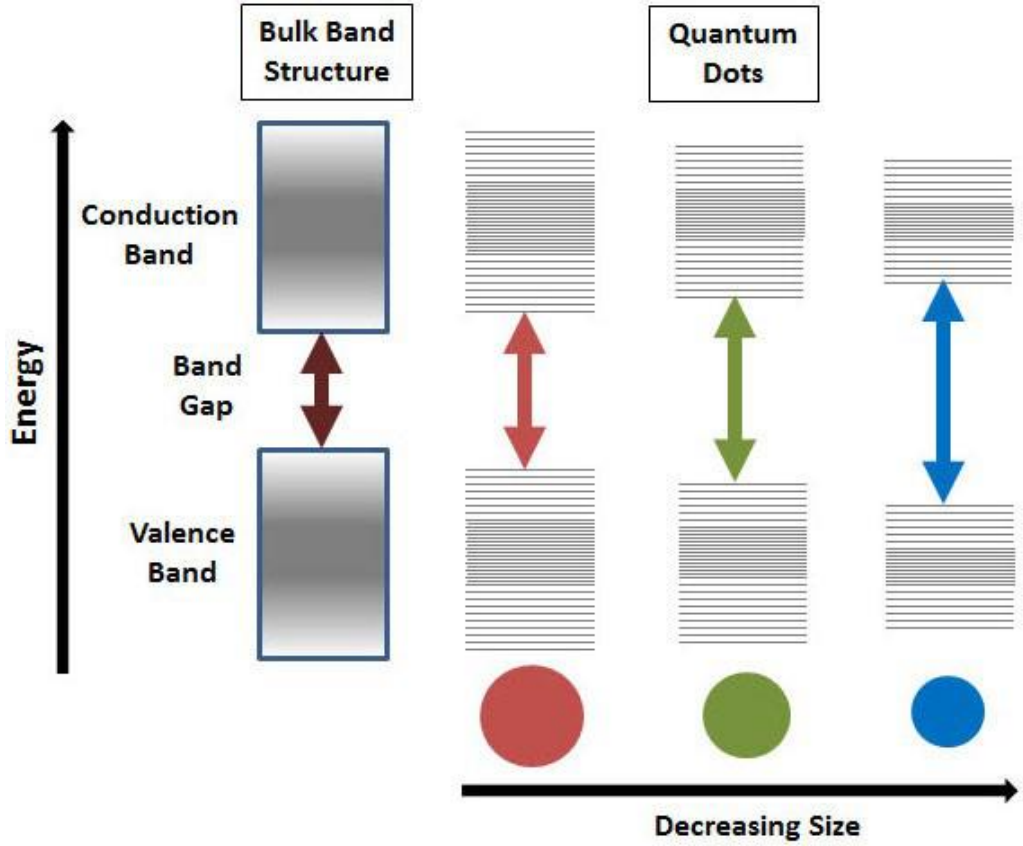
As “r” decreases Surface/Volume ratio increases

1. (c) Large number of surface atoms: Nanomaterials have a relatively greater number of surface atoms when compared to the same volume of the material in bulk form



2. Quantum confinement :

- The quantum confinement effect is observed when the size of the material is too small (<100 nm).
- As the size of the material changes from bulk to nano material, continuous energy levels changes to discrete energy levels (finite density of states) because of the confinement of the electron motion.
- Quantum confinement also responsible for the increase in the band gap of the nano material compared to bulk.

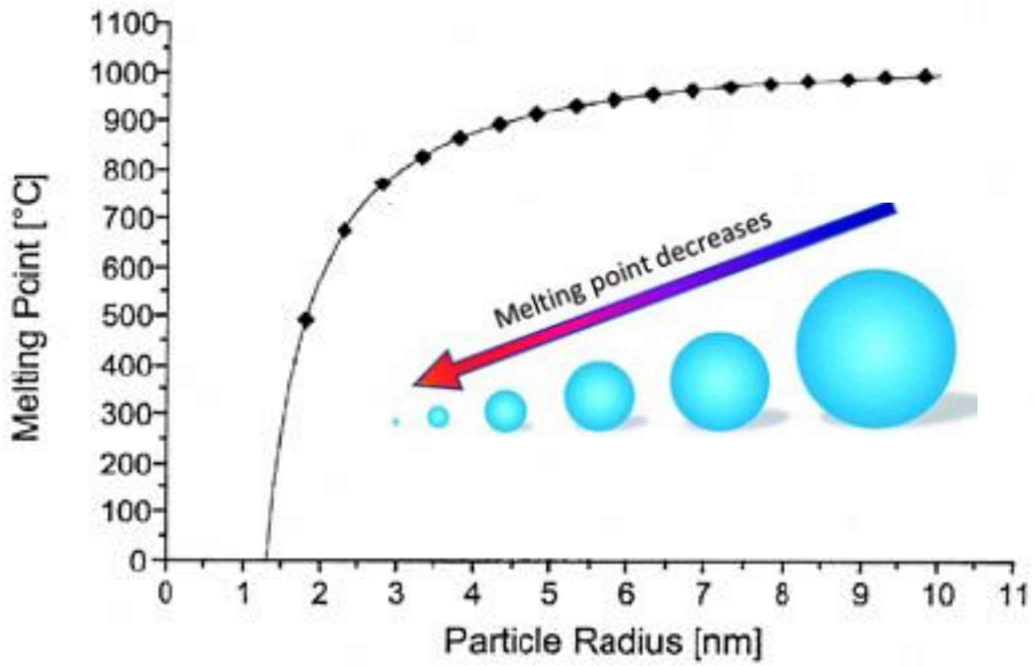


Size dependent properties of nanomaterials

1. Thermal properties

Reduce in the Melting Point: Melting point of the material is reduced as we reduce the size of the material to a nanoscale.

The reduction in the melting point is mainly due to the large increase in the surface energy and large number of surface atoms at the nanoscale.



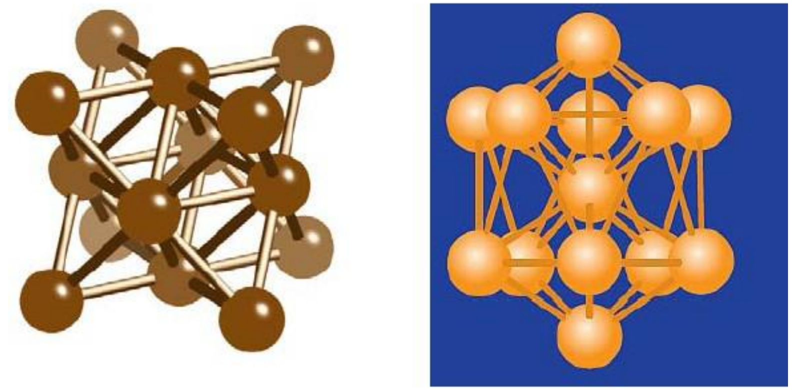
2. Optical properties

Increase in the Band gap: The band gap is increases with reducing the size of the material due to the **quantum confinement**.

$$\lambda = hc/ E_g$$

3. Structural properties

Change in the crystal structure: Crystal structure of nanomaterials may not same as its bulk one.
Eg, gold and aluminium nanoparticles of size with few nanometers are icosahedral rather than face centered cubic.



Crystal structure of (a) bulk (FCC) (b) nano (Icosahedral) Gold

Change in the lattice parameter: The inter atomic spacing (lattice parameter) in nanomaterials decreases compared to bulk.
E.g, Decrease in aluminum separation to 2.81Å from 2.86Å.

4. Magnetic properties:

- Nanomaterials shows different magnetic properties compared to bulk due to large proportion of surface atoms which have a different local environment leads different magnetic coupling with neighbouring atoms.

E.g. Gold and Platinum are non-magnetic at bulk and behaves like magnetic material at nanoscale.

5. Electrical Properties :

- The electronic properties (electrical conductivity/electrical resistance) changes in the nanoscale material are related to the qunatum confinement and scattering.
- Electrical conductivity may increase or decrease at nanoscale depending on the size of the material

6. Chemical properties:

- Nanoscale materials have very high surface area, which leads to higher chemical reactivity and more absorption.
- The ionisation energy is generally higher for small atomic cluster than for the corresponding bulk one.

7. Mechanical properties:

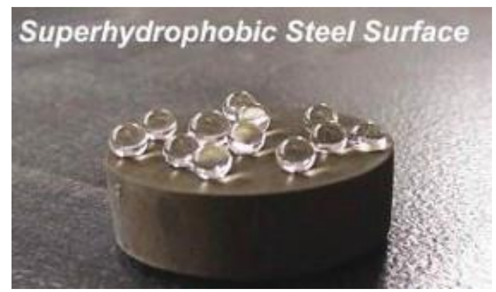
- Mechanical properties such as strength, toughness, hardness are increased at nanoscale compared to bulk.

Applications of nanomaterials

Super hydrophobicity:

- Nanomaterial coating on any surface act as a super hydrophobic surface like as a lotus leaf. This behavior is due the air trapped between the nano materials,which pushes the water drop up.
- We can coat water repellent (super hydrophobic) coating on any surface such as clothes, metals, shoes, car windshield, window glasses and tissue papers etc.
- Example : Silicon nanowires





Nanomaterials in Automobile industry : The Auto mobile parts prepared from Nano materials are flexible, light weight and exhibiting high strength compared to the bulk. We can use these nanomaterials in cars, aero planes etc.
Example nanomaterials: Carbon nanosheets, Graphene sheets.

Nanomaterials in Electronics: Many electronic products such as computers, mobile phones, photographic cameras and memory cards/hard disk drives etc., were already reduced in their size and also improvement in their performance. This is mainly due to the transistor size reduction by Nanotechnology/nanomaterials.
Example nanomaterials: Carbon nanotubes, semiconductor nanowires, nanorods.

Nanomaterials in Energy :

- Solar cells prepared from Nanomaterials are able to produce much power/efficiency compared to the bulk due to the large surface area and light trapping capability of the nano material.
- We are also able to produce high storage Li-ion batteries using nanomaterials. These Li-ion batteries are very useful in cell phones, automobiles etc.

Example nanomaterials: Silicon nanowires, Zinc oxide, Titanium oxide nanowires.

Nanomaterials in water purification: Due to large surface area of Nanomaterials, water purification by these nanomaterials are efficient, clean and also cost effective (cheap) compared to bulk.

Example nanomaterials: Nano TiO_2, Carbon nanotubes,

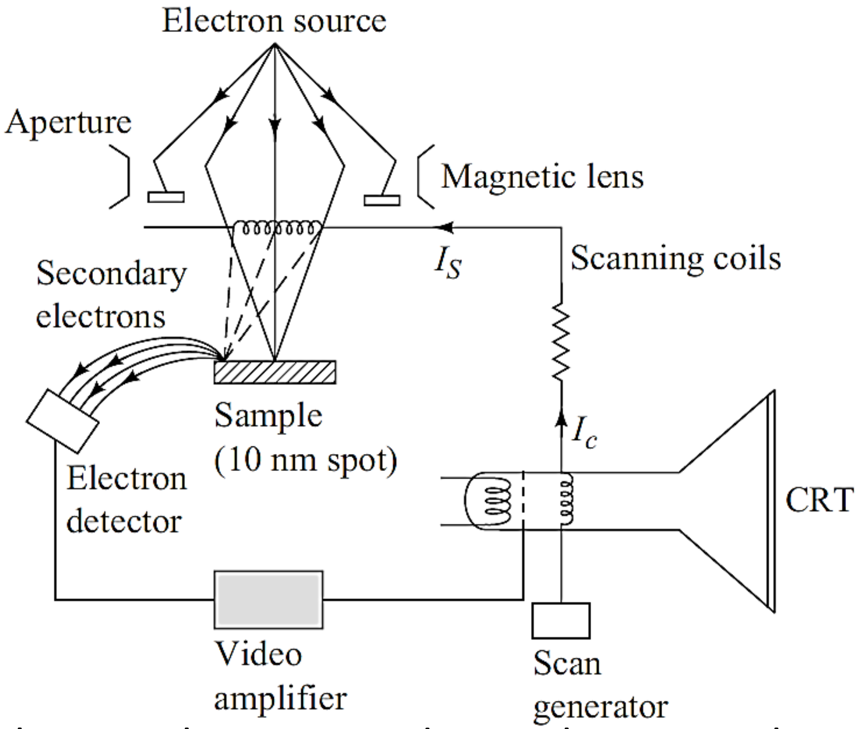
Nanomaterials in medicine:

- Nanomaterials are very helpful in the drug delivery with precise control over the delivery location.
- Nanomaterials are reacting only with the infected cells without damaging the healthy cells in the human body.

Example nanomaterials: Au, Ag nanoparticles.

SCANNING ELECTRON MICROSCOPE (SEM)

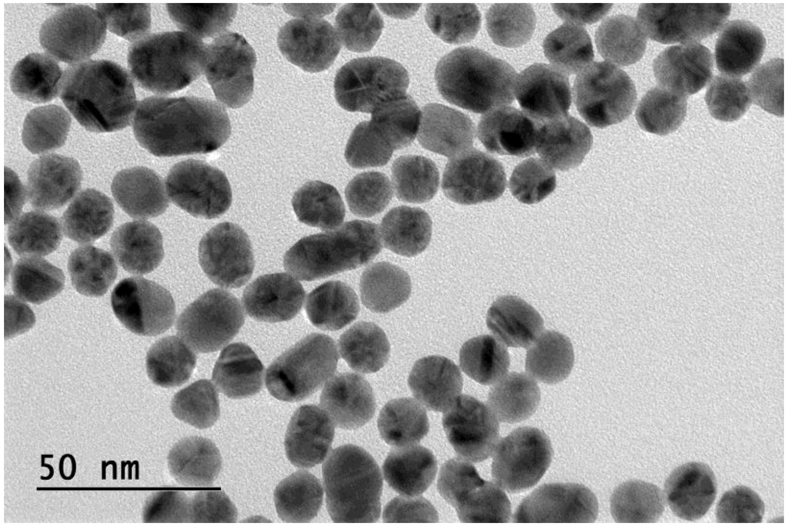
- SEM is used to produce a three-dimensional image of a specimen of any size and thickness.
- The electrons produced by the hot filament are accelerated by electric and magnetic fields.
- The emerging electrons with a spot size of nearly 10 nm is made to be incident on a conducting sample under study.
- If the sample is nonconducting, a thin layer of 5–50 nm thick gold or any other metal coating is made and then the sample is used for study.



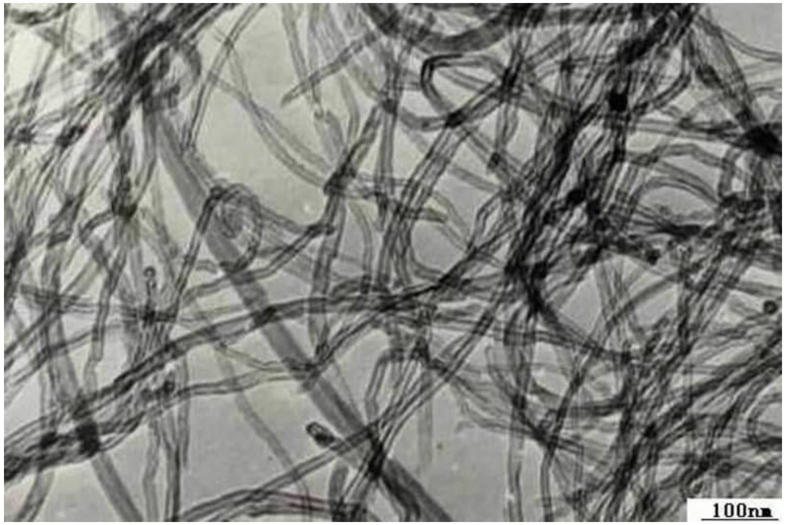
A scanning coil deflects the electron beam, so that the sample is scanned point by point. The electrons striking on the sample produce secondary electrons. The number of secondary electrons produced depends upon the geometry and other properties of the samples. The secondary electrons are collected by a positively charged electron detector, which accelerates the electrons to very high energy in the order of 10 keV. Then, the electrons are made to strike a scintillator. The scintillator produces a large number of photons. These photons are made to fall on a photomultiplier tube. The photomultiplier tube converts the electrons into a highly amplified electric signal. This amplified electric signal is passed into a cathode ray tube, through which the image of the scanned surface is seen. The resolution of the image is about 10–20 nm. The magnification of the microscope can be continuously varied from 15 to 10^5 times. The magnification depends upon the ratio of the variable current I_s in the scanning coil to the current I_c in the deflection coil of the cathode ray tube.

TRANSMISSION ELECTRON MICROSCOPE (TEM)

- Transmission Electron Microscope (TEM) is one of the modern characterisation tools used to obtain structural images of the materials.
- One can explore the surface nature, structure and the properties of the materials using TEM.
- It finds wide applications in almost all areas like chemistry, materials science, geology and biology.
- The basic composition of the materials can be explored with the help of detectors through the energy loss spectrum of the transmitted electrons. On the other hand, the modern TEMs are used to produce the images in the scanning range of 0.1 nm with a magnification of 50 million times.



Gold nano particles



Carbon nano tube

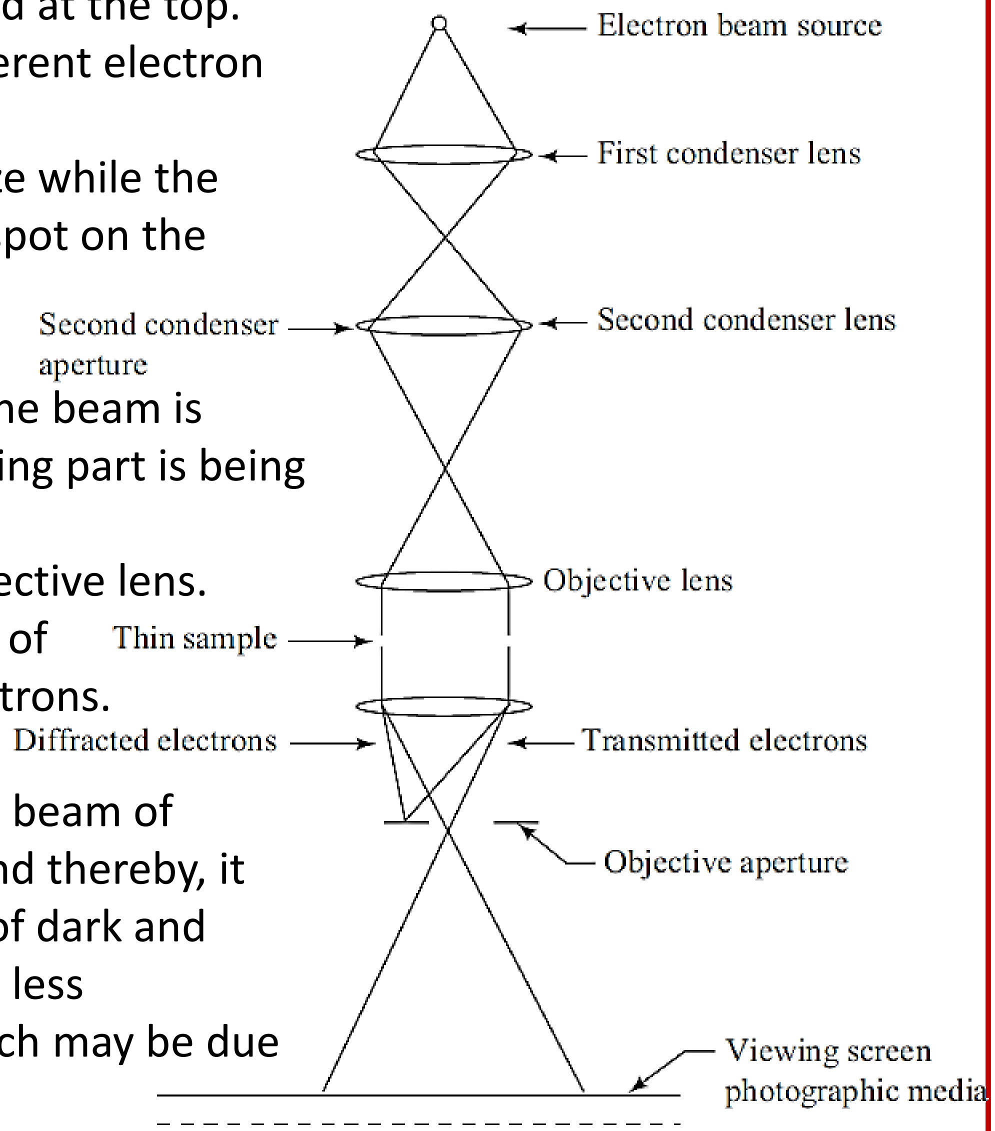
A stream of monochromatic electron beam is produced by the electron gun namely, virtual source located at the top. Two condenser lenses are used to obtain coherent electron beam.

The first lens is used to determine the spot size while the second lens is used to change the size of the spot on the sample.

The electron beam is made incident on the selected points on the sample. A part of the beam is transmitted into the sample while the remaining part is being scattered.

The transmitted portion is focused by the objective lens. The objective aperture enhances the contrast of the image by preventing larger diffracted electrons. Thus, the image is formed after passing through the projector lenses. The transmitted beam of electron strikes the phosphor image screen and thereby, it generates light. The obtained image consists of dark and bright patterns. The dark pattern refers to the less transmission of electron from the sample which may be due to denser or thicker nature of the sample.

Similarly, the bright pattern reveals the high transmission of electron beam through the sample.



A high intensity electron beam is made to be incident on the sample. The interaction of electron beam in crystalline material is based on the diffraction principle. The intensity of the diffraction pattern depends on the orientation of atomic planes in the crystal. The intensity of the transmitted beam may be altered by the volume and density of the materials through which it passes.

A high contrast image is obtained by TEM only by allowing the transmitted electrons through the sample along the optic axis. The scattered electrons are deflected from the optical axis and hence, prevented from reaching the phosphor screen using the objective apertures. The scattered electrons are not taken into account during the formation of an image.

Applications

The applications of the TEM are given below.

a. One can obtain the imaging of individual molecules (or) macromolecular assemblies.

b. It is used heavily in materials, metallurgy and biological sciences.

c. Computer modelling of the images is an added advantage in TEM characterisation.

Limitations

Following are the limitations of TEM.

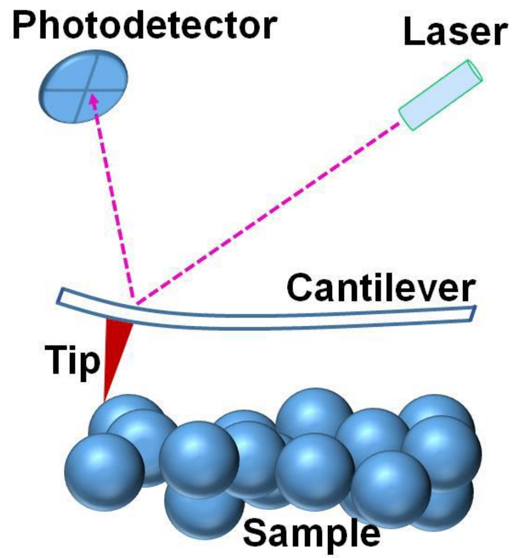
a. The sample must be thin enough to characterise using TEM and hence, it requires extensive sample preparation (electron transparent).

b. The structure may be changed during the process of sample preparation.

c. In biological materials, the electron beam may damage the samples.

Atomic force microscopy (AFM)

- AFM is a type of scanning probe microscopy (SPM), which measures atomic interaction between a sample surface and a tip.
- AFM (multimode) is a high-resolution imaging tool for the complete surface characterization of properties like topography, elasticity, friction, adhesion, and electrical/magnetic fields.
- AFM operates in **contact**, **intermediate (tapping)**, and **non-contact modes**.
- **In contact mode operation**, the AFM tip touches the sample surface, and the tip-sample repulsive force deflects the tip-cantilever. The cantilever deflection is monitored and used as a feedback signal.
- In **intermediate** and **non-contact modes**, the cantilever is externally oscillated at, or close to, it's resonance frequency.



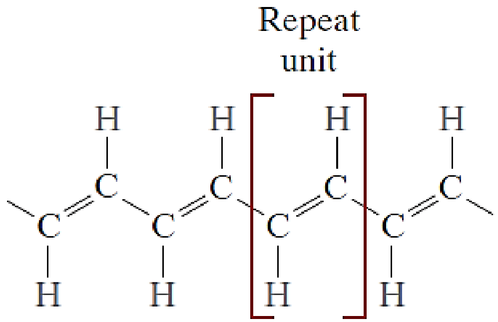
Schematic of the working principle of AFM.

- The tip-sample interaction is changed as the tip-sample distance changes, leading to a **change in oscillation amplitude** (intermediate mode) and **resonance frequency** (non-contact mode).
- These amplitude and frequency changes, with respect to the reference amplitude and frequency, are used as feedback signals to obtain the topography of the sample surface.
- Therefore, **intermediate mode** and **non-contact modes** are referred as **amplitude modulation** (AM) and **frequency modulation** (FM) operation, respectively.
- In **intermediate and non-contact mode** AFM, the tip-sample interaction is disconcerted by attractive and repulsive forces, causing amplitude or frequency changes in the oscillation of the AFM tip.
- In AM mode AFM, changes in the **oscillation amplitude** provide the **feedback signal** for **imaging**.

Conductive Polymers

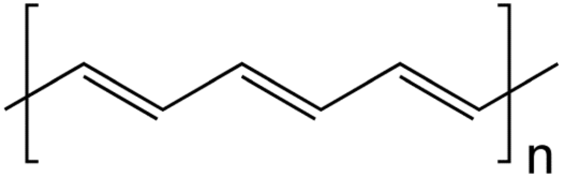
The chemistry Nobel prize in 2000 was awarded for the discovery and study of conducting polymers. **Alan J. Heeger, Alan G MacDiarmid, Hideki Shirakawa**

- Typically conventional polymers such as plastics, rubbers, etc., offer significant resistance to electrical conduction and are either dielectrics or insulators
- **Polymers** are organic macromolecules, a long carbonic chain, composed by structural repeat entities, called ***mer***. These smallest unit (***mer***), for instance, are bonded by covalent bonds, repeating successively along a chain. A monomer, molecule composed by one *mer*, is the raw material to produce a **polymer**.
- Polymers are typicallyutilized in electrical and electronic applications as insulators where advantage is taken of their very high resistivities.
- Typical properties of polymeric materials: Strength, flexibility, elasticity, stability, mouldability, ease of handling, etc
- **Conducting polymers (CPs)** are a special class of poly-meric materials (can be used in the dry or wet state) with electronic and ionic conductivity.

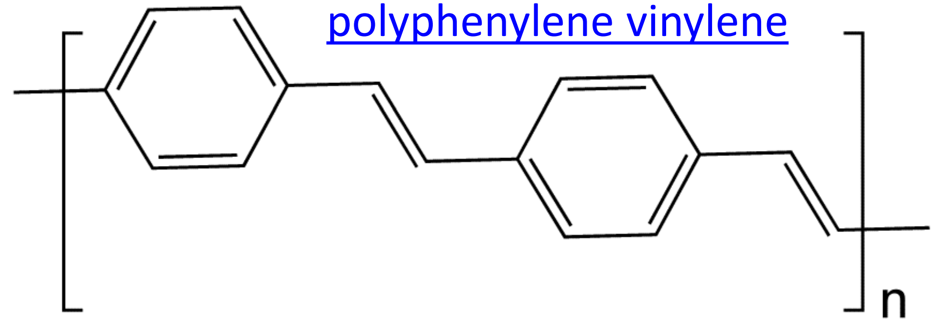


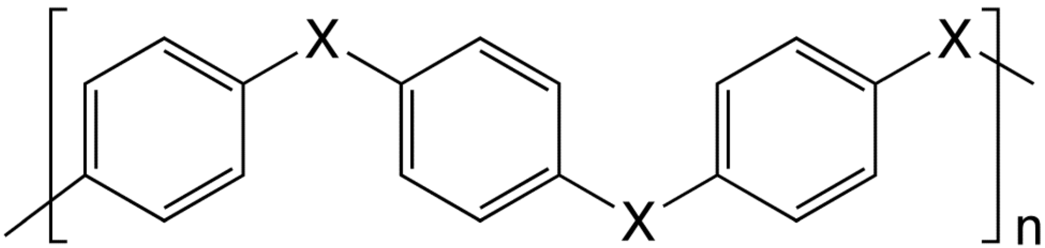
The chain structure of polyacetylene

polyacetylene



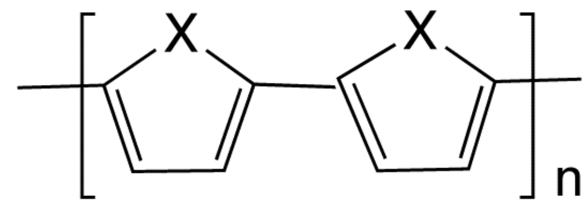
polyphenylene vinylene





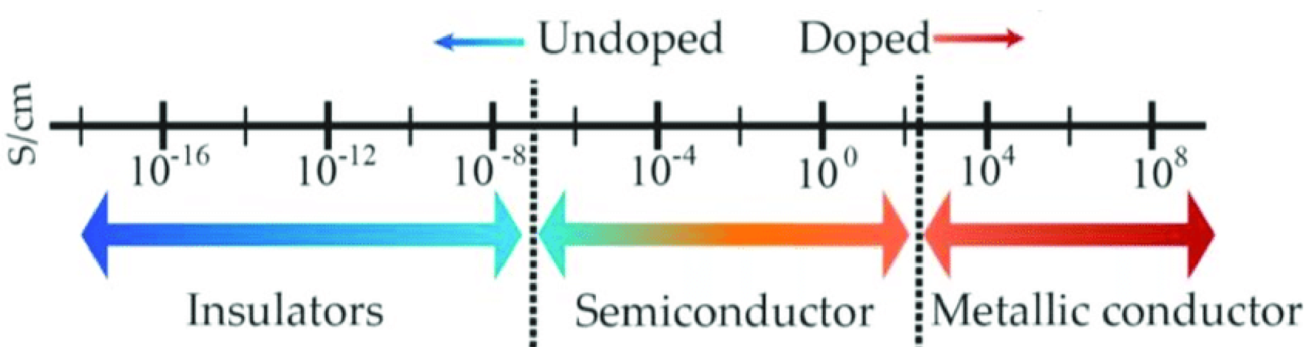
(X = NH/N, S)

polypyrrole (X = NH) and
polythiophene (X = S)



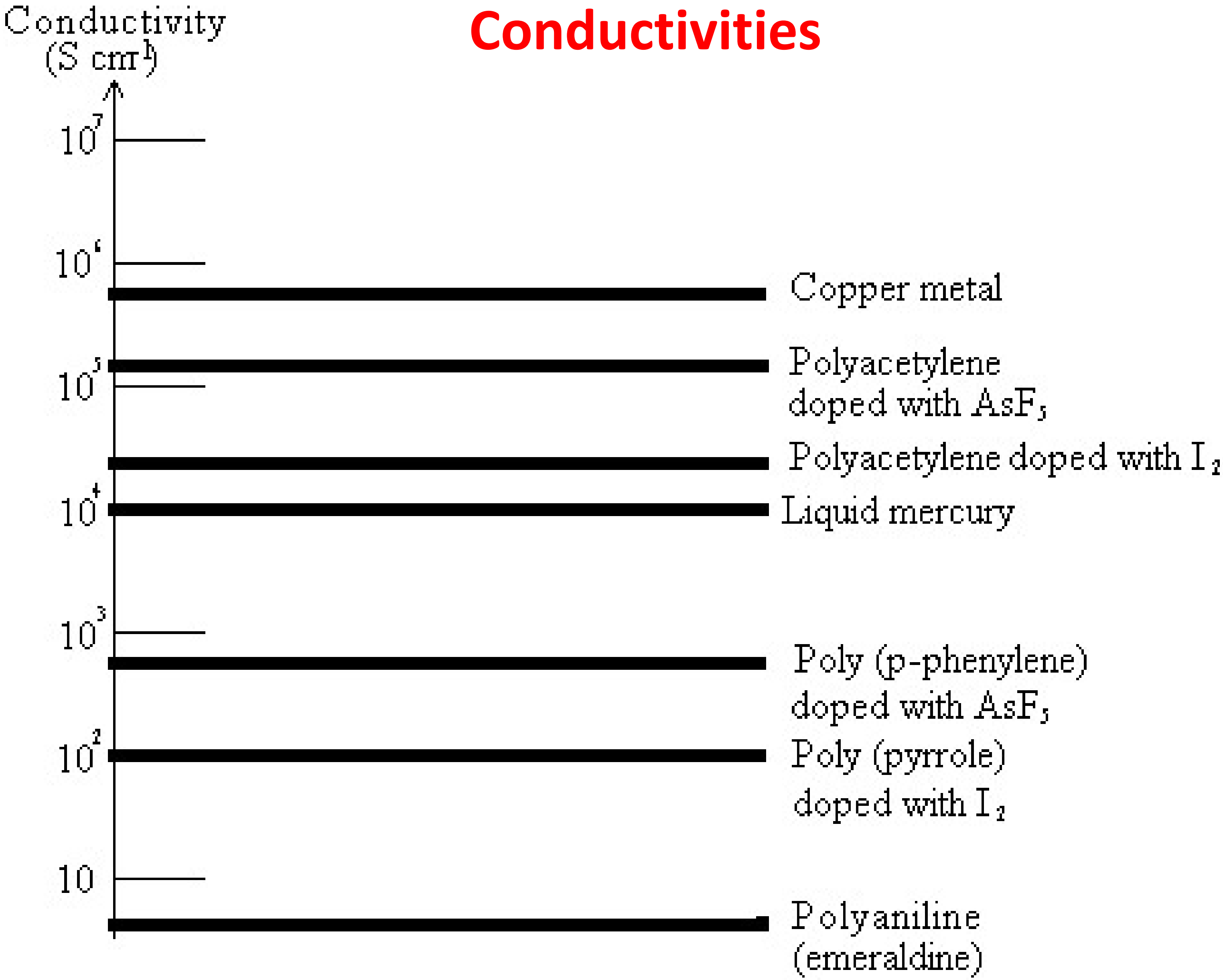
(X = NH, S)

polyaniline (X = NH) and
polyphenylene sulfide (X = S).



The general conductivity range of conducting polymers (CPs)

Conductivities



Logarithmic conductivity ladder locating some metals and conducting polymers

Applications of Conducting Polymers

- Conductive polymers show promise in antistatic materials and they have been incorporated into commercial displays and batteries.
- They used in organic solar cells, printed electronic circuits, organic light-emitting diodes, actuators, electrochromism, supercapacitors, chemical sensors, chemical sensor arrays, and biosensors, flexible transparent displays, electromagnetic shielding and possibly replacement for the popular transparent conductor indium tin oxide.
- Another use is for microwave-absorbent coatings, particularly radar-absorptive coatings on stealth aircraft.
- Can provide electromagnetic shieldingof electronic circuits
- Can be used as antistatic coating material to prevent electrical discharge exposure on photographic emulsions
- Can be used as hole injecting electrodes for OLEDS
- Usage in electroluminescent displays(mobile telephones)
- In use as emissive layer in full-color video matrix displays
- Some are promising for field-effect transistors(Usage in supermarket checkouts)

Metamaterials

- A metamaterial is a material that gains its properties from its structure rather than directly from its composition. It is engineered (at the atomic level) material that has unique properties not found in nature due to the arrangement and design of its constituents. They are typically manmade materials.
- **Metamaterials** can be **defined** as artificially structured materials used to control and mold the flow of electromagnetic waves or possibly any other type of physical waves.
- These materials have diverse potential applications from optical filters to high gain antennas and even to shielding buildings from earthquakes .

PROPERTIES OF META MATERIALS

Metamaterials have unique properties that are not found in natural materials. One such property is negative refractive index. The refractive index can be seen as the factor by which the wavelength and the speed of the radiation are reduced with respect to their vacuum values. The refractive index of a material is conventionally taken to be a measure of the optical density and is defined as

$$n = c/v$$

where c is the speed of light in vacuum and v is the speed of an electromagnetic plane wave in the medium.

From Maxwell's equations the refractive index is given by,

$$n^2 = \varepsilon\mu$$

where ε is the **relative dielectric permittivity** and μ is the **relative magnetic permeability** of the medium. This electrical permittivity (or dielectric constant) is a kind of measure to assess how easily or difficult the electrons can move in the material in response to the incident light.

- Most dielectrics materials have positive permittivities , $\varepsilon > 0$.
- Metals will exhibit negative permittivity, $\varepsilon < 0$ at optical frequencies, and plasmas exhibit negative permittivity values in certain frequency bands.
- However, in each of these cases permeability of the materials remains always positive. A natural material that can achieve negative values for permittivity and permeability simultaneously has not been found, or discovered.
- In these new artificially fabricated metamaterials the electrical permittivity and the magnetic permeability are the main determinants of a material's response to electromagnetic waves.
- In metamaterials, both these material parameters($\varepsilon < 0$, $\mu < 0$) are negative. Correspondingly, the refractive index of the metamaterials is also negative. Therefore, due to negative μ and negative ε the refractive index of the medium is calculated to be negative.

- The key concept to metamaterials is based more on the arrangement of the constituents rather than their individual properties.
- The property that is designed is a macroscopic property that is seeming when the metamaterial is viewed as a uniform object. The central goal in designing metamaterials is wave manipulation unlike that of a natural material. When a wave, like a light or sound wave, moves from one medium to another, it undergoes refraction according to Snell's Law.
- Metamaterials have a negative index of refraction and use this property to redirect waves around. For a metamaterial to be effective, it must be taken as a uniform material rather than an array of particles. This means the units that make up the metamaterial must be relatively small compared to the wavelength that is to be manipulated and redirected.

The two major subcategories of metamaterials are **electromagnetic** and **acoustic**

- Electromagnetic metamaterials bend and manipulate electromagnetic waves like visible light waves, microwaves, and infrared waves. These are transverse waves. The main mechanism of electromagnetic metamaterials utilization of negative electric permittivity and negative magnetic permeability to control wave propagation.
- Whereas, acoustic metamaterials manipulate longitudinal waves associated with vibrations.

Applications

- **Antennas** Metamaterial antennas are a class of antennas that use metamaterials to improve performance. Demonstrations showed that metamaterials could enhance an antenna's radiated power. Materials that can attain negative permeability allow for properties such as small antenna size, high directivity and tunable frequency.
- **Absorber** A metamaterial absorber manipulates the loss components of metamaterials' permittivity and magnetic permeability, to absorb large amounts of electromagnetic radiation. This is a useful feature for **photodetection** and **solar photovoltaic applications.**
- **Superlens** A superlens is a two or three-dimensional device that uses metamaterials, usually with negative refraction properties, to achieve resolution beyond the diffraction limit (ideally, infinite resolution).
- **Invisible submarines** An 'acoustic cloak' could be used in the future to mask submarines from enemy sonars.
- **Photonics OR opto-electronics**
- **Perfect absorber of light**
- **Metamaterials for solar cells**

Fluorescent Materials.

Fluorescence is a function of light energy

Fluorescent molecules by definition absorb light at one color (wavelength) and emit it at another. The difference in colors is called the Stokes shift.

- In most cases, the emitted light has a longer wavelength, and therefore lower energy, than the absorbed radiation.
- The most striking example of fluorescence occurs when the absorbed radiation is in the **ultraviolet region** of the spectrum, and thus invisible to the human eye, while the emitted light is in the **visible region**, which gives the fluorescent substance a distinct color that can be seen only when exposed to UV light.
- Fluorescent materials cease to glow nearly immediately when the radiation source stops, unlike phosphorescent materials, which continue to emit light for some time after.

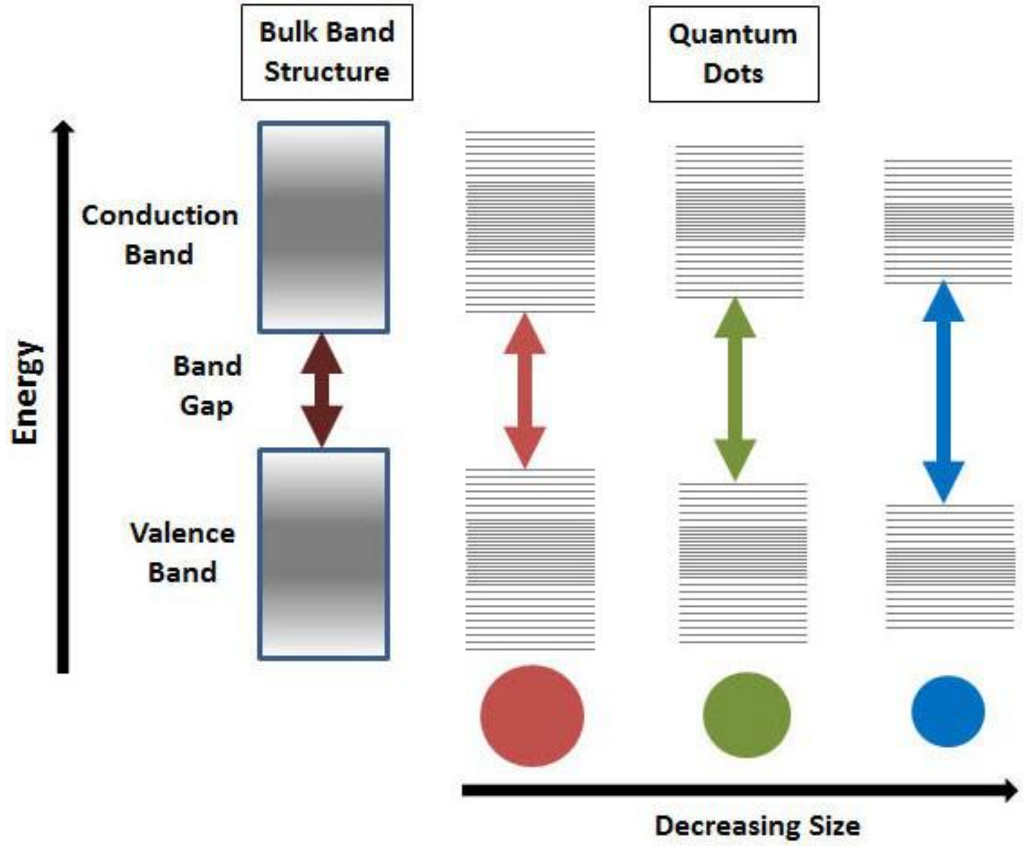
Applications: Mineralogy, gemology, medicine, chemical sensors (fluorescence spectroscopy), fluorescent labelling, dyes, biological detectors, cosmic-ray detection, vacuum fluorescent displays, and cathode-ray tubes. Its most common everyday application is in energy-saving fluorescent lamps and LED lamps, where fluorescent coatings are used to convert short-wavelength UV light or blue light into longer-wavelength yellow light, thereby mimicking the warm light of energy-inefficient incandescent lamps.

Principles of mesoscopic physics-size effect

- **Mesoscopic physics** is a subdiscipline of condensed matter physics that deals with materials of an intermediate size.
- The systems studied are normally in the range of 100 nm (the size of a typical virus) to 1000 nm (the size of a typical bacterium): 100 nanometers is the approximate upper limit for a nanoparticle.
- These materials range in size between the nanoscale for a quantity of atoms (such as a molecule) and of materials measuring micrometres.
- The lower limit can also be defined as being the size of individual atoms. At the micrometre level are bulk materials.
- Mesoscopic physics has a close connection to the fields of nanofabrication and nanotechnology.
- Both mesoscopic and macroscopic objects contain many atoms. Whereas average properties derived from its constituent materials describe macroscopic objects, as they usually obey the laws of classical mechanics, a mesoscopic object, by contrast, is affected by thermal fluctuations around the average, and its electronic behavior may require modeling at the level of quantum mechanics.
- The mechanical, chemical, and electronic properties of materials change as their size approaches the nanoscale, where the percentage of atoms at the surface of the material becomes significant. For bulk materials larger than one micrometre, the percentage of atoms at the surface is insignificant in relation to the number of atoms in the entire material.
- Devices used in nanotechnology are examples of mesoscopic systems.
- Three categories of new electronic phenomena in such systems are interference effects, quantum confinement effects and charging effects

Quantum confinement :

- The quantum confinement effect is observed when the size of the material is too small (<100 nm).
- As the size of the material changes from bulk to nano material, continuous energy levels changes to discrete energy levels (finite density of states) because of the confinement of the electron motion.
- Quantum confinement also responsible for the increase in the band gap of the nano material compared to bulk.



Optical effects

Increase in the Band gap: The band gap is increases with reducing the size of the material due to the **quantum confinement**.

$$\lambda = hc/ E_g$$

Coulomb blockade effect

In mesoscopic physics, a Coulomb blockade (CB), is the **decrease in electrical conductance** at **small bias voltages** of a small electronic device comprising at least one low-capacitance tunnel junction.

Because of the CB, the conductance of a device may not be constant at low bias voltages, but disappear for biases under a certain threshold, i.e. no current flows.

Coulomb blockade can be observed by making a device very small, like a quantum dot.

In a tunnel junction

The tunnel junction is, in its simplest form, a thin insulating barrier between two conducting electrodes. According to the laws of classical electrodynamics, no current can flow through an insulating barrier. According to the laws of quantum mechanics, however, there is a nonvanishing (larger than zero) probability for an electron on one side of the barrier to reach the other side. When a bias voltage is applied, this means that there will be a current, and, neglecting additional effects, the tunnelling current will be proportional to the bias voltage. In electrical terms, the tunnel junction behaves as a resistor with a constant resistance, also known as an ohmic resistor. The resistance depends exponentially on the barrier thickness. Typically, the barrier thickness is on the order of one to several nanometers.

An arrangement of two conductors with an insulating layer in between not only has a resistance, but also a finite capacitance. The insulator is also called dielectric in this context, the tunnel junction behaves as a capacitor.

Due to the discreteness of electrical charge, current through a tunnel junction is a series of events in which exactly one electron passes (tunnels) through the tunnel barrier. The tunnel junction capacitor is charged with one elementary charge by the tunnelling electron, causing a voltage build up **$U = e / C$,** where C the capacitance of the junction. If the capacitance is very small, the voltage build up can be large enough to prevent another electron from tunnelling.

The electric current is suppressed at low bias voltages and the resistance of the device is no longer constant. The increase of the differential resistance around zero bias is called the **Coulomb blockade**.

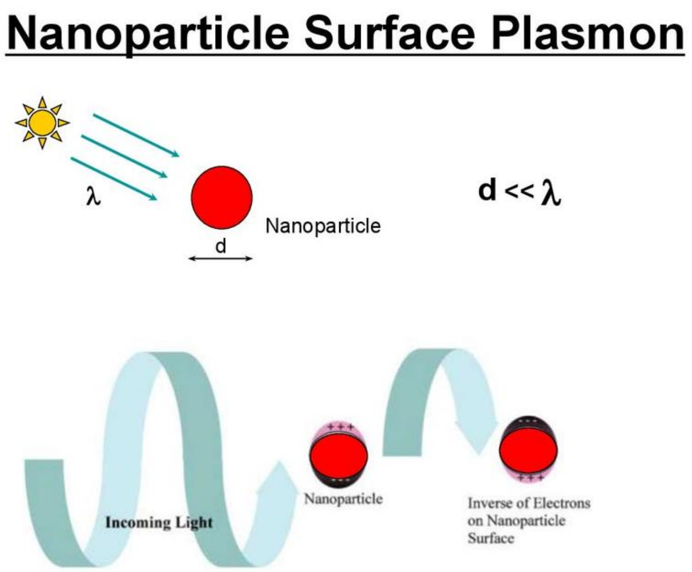
Surface plasmon effect

Surface plasmons (SPs) are coherent delocalized electron oscillations that exist at the interface between any two materials where the real part of the dielectric function changes sign across the interface (e.g. a metal-dielectric interface, such as a **metal sheet in air**). SPs have lower energy than bulk (or volume) plasmons which quantise the longitudinal electron oscillations about positive ion cores within the bulk of an electron gas (or plasma).

The charge motion in a surface plasmon always creates electromagnetic fields outside (as well as inside) the metal. The total excitation, including both the charge motion and associated electromagnetic field, is called either a surface plasmon polariton at a planar interface, or a localized surface plasmon for the closed surface of a small particle.

Surface plasmon resonance (SPR) is the manifestation of a **resonance effect** due to the interaction of conduction electrons of metal nanoparticles with incident photons. The interaction relies on the size and shape of the metal nanoparticles and on the nature and composition of the dispersion medium.

This technique can be used to observe nanometer changes in thickness, density fluctuations, or molecular absorption. Recent works have also shown that SPR can be used to measure the optical indexes of multi-layered systems.



Light resonance with the surface plasmon oscillation causes the free electrons in the metal to oscillate.

Thank you.