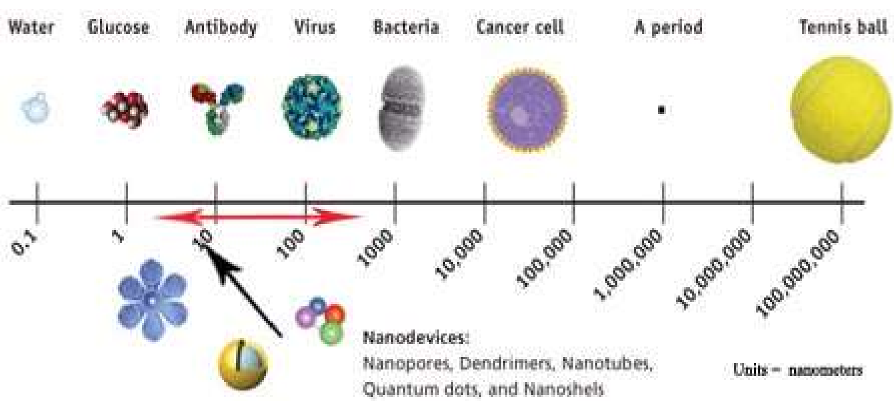
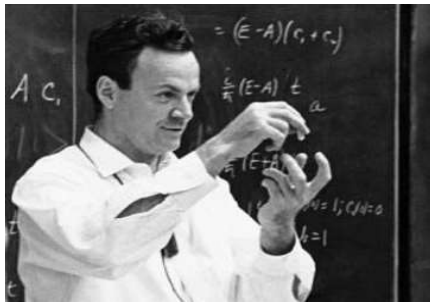
SC 302-Physics II

The nanometre scale



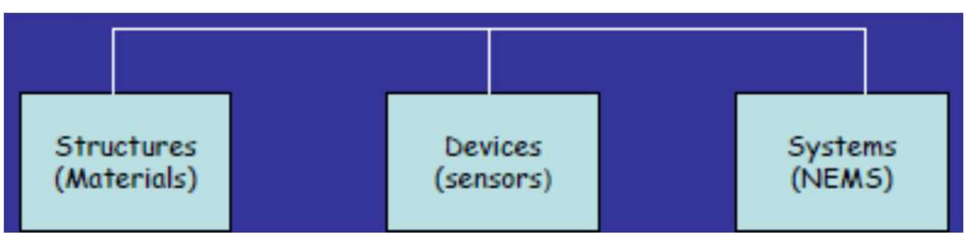
Who gave this term Nano?



The first person to *identify and discuss the 'nanometer-scale world* was Richard Feynman in his talk during a conference of the American Physical Society : "*There's plenty of the room at the bottom*" in 1959.

Development

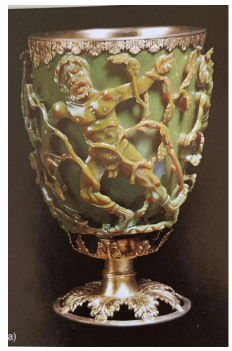
Nanoscience → Nanophysics → Nanotechnology



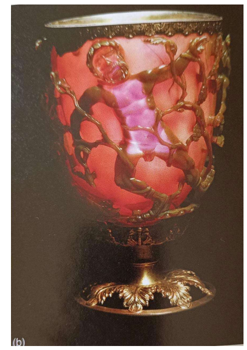
Nanotechnology from the perspective of Medieval Period

Coloured stained glasses

Lycurgus cup



Appears green in reflected light



Appears red in transmitted light

What actually happens when objects turn so small?

- Properties of materials change as their size approaches the nanoscale as there is a vast increase in ratio of surface area to volume.
- Quantum size effect is observed on decrease in size which is caused by confinement of electrons within particles of dimensions smaller than bulk counterpart.

Nanomaterials

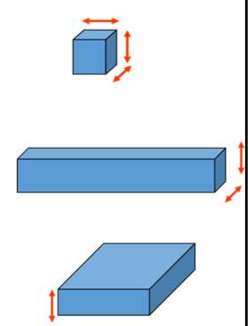
A nanomaterials are the object that have at least one dimension in the nanometre scale (approximately 1 to 100 nm).

Nanomaterials can be of two types:

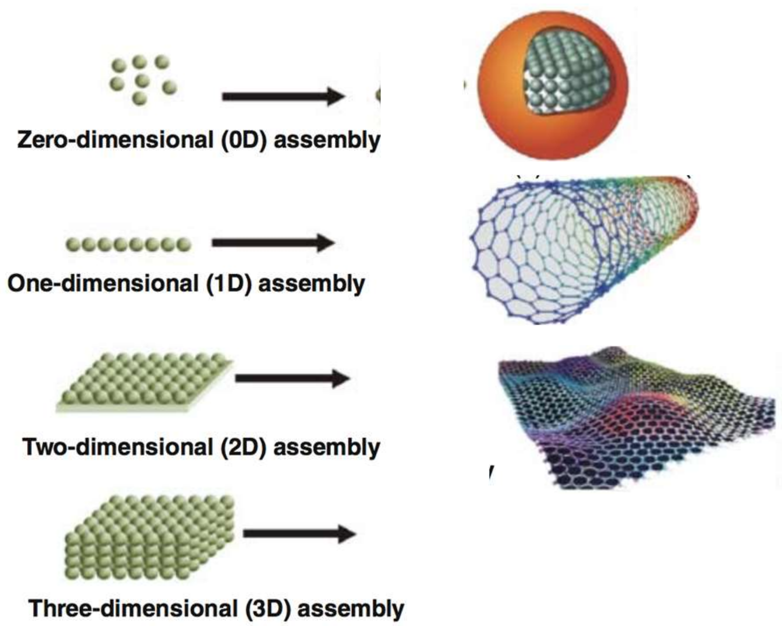
1. Non-intentionally-made nanomaterials
2. Intentionally-made nanomaterials

Nanomaterials are categorised according to their dimensions as follows:

Nanomaterial dimension	Example
All three dimensions < 100 nm	Nanoparticles, quantum dots, nanoshells, nanorings, microcapsules
Two dimensions < 100 nm	Nanotubes, fibres, nanowires
One dimension < 100 nm	Thin films, layers and coatings



Classification of nanostructured materials



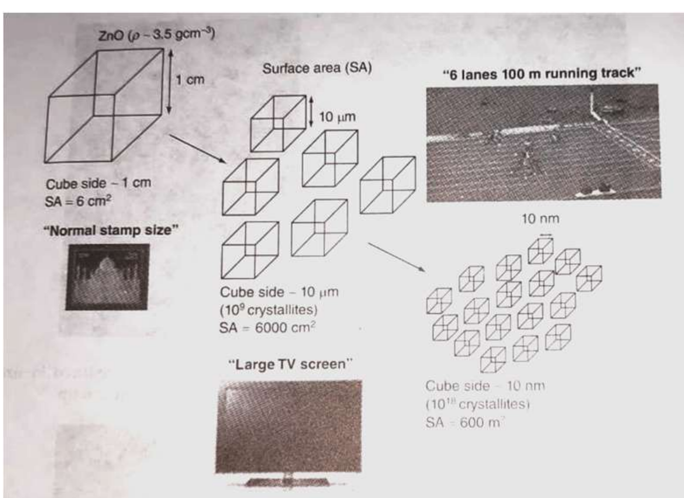
Quantum dot

Nanotube

Nanofilm

Bulk

Changes in surface area in going from bulk to nanocrystals



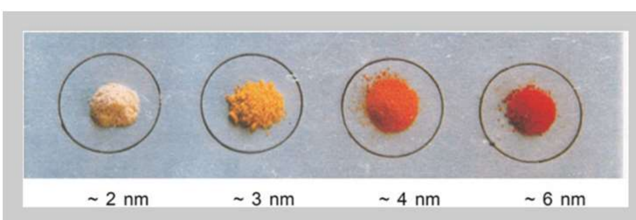
Spherical nanoparticles are expected to have large surface-to-volume ratio given as

$$\frac{Surface}{Volume} = \frac{4\,\pi R^2}{4/3\ \pi\, R^3} \propto \frac{1}{R}$$

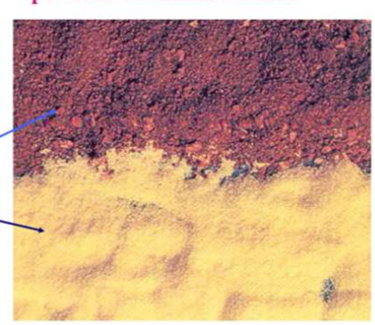
Nano-sizing causes changes in

1. Colour
2. Melting point
3. Magnetism
4. Crystal Shape
5. Conductivity
6. Chemical Reactivity

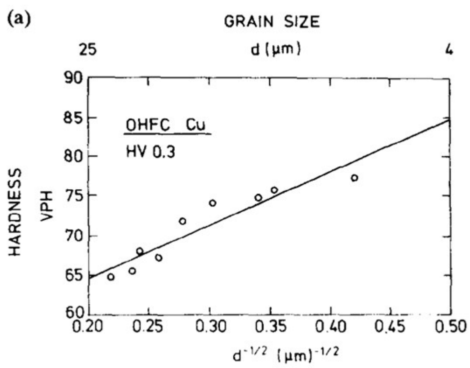
Size dependence of colour and Optical properties of CdS



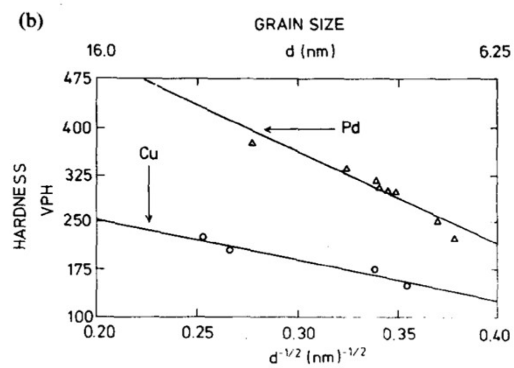
powered cadmium selenide



Hardness variation in Copper polycrystals

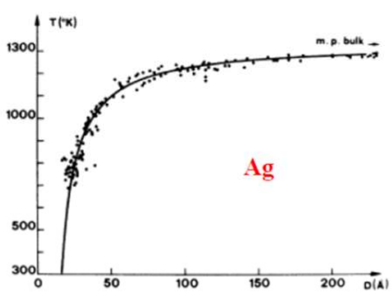


Hardness increases with decreasing grain size

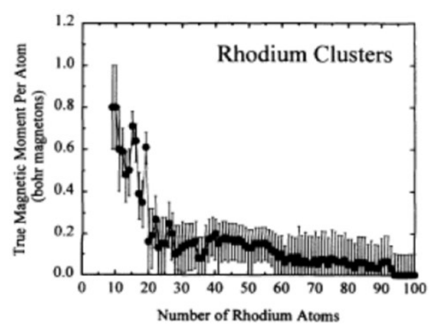


Hardness decreases with decrease in grain size

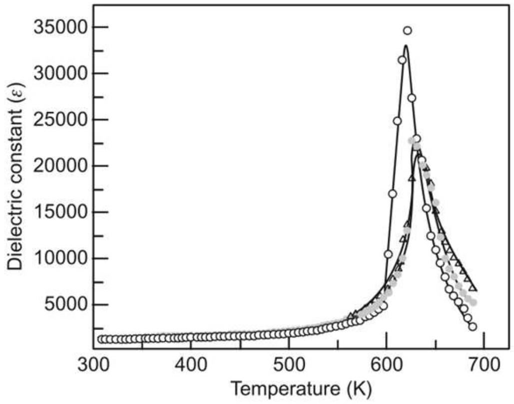
size-dependence of melting temperature



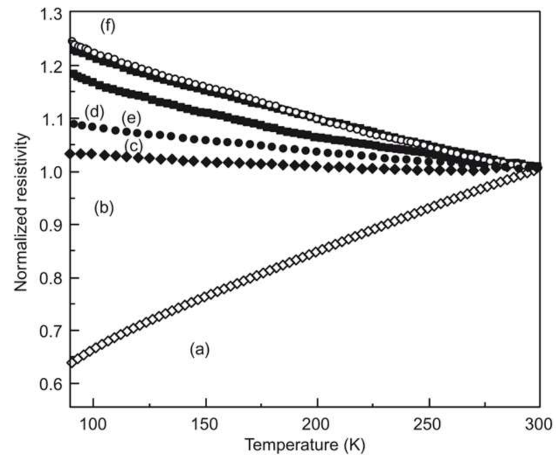
size-dependence of magnetism



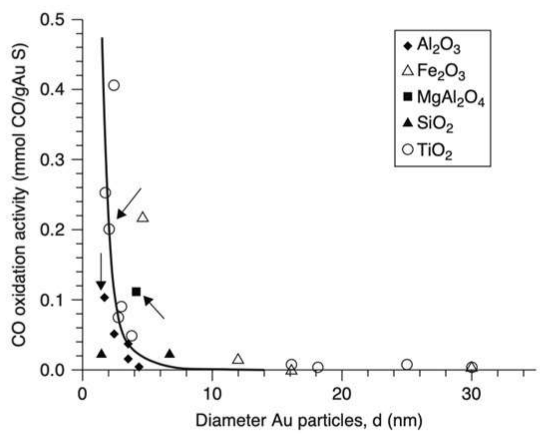
High dielectric constant in nanocrystalline PZT



Change in electrical resistivity



Increase in the Catalytic Activity of Gold Nanoparticles



Making Nanostructures: Nanofabrication

Nanomaterials can be fabricated by two methods:

1. Top-down approach

Examples

- Ion-beam Lithography
- Ball milling
- Etching
- Microfabrication

2. Bottom-up approach

Examples

- Sol-Gel synthesis
- Hydrothermal growth
- Thin film growth:
  - Physical vapor deposition
  - Chemical vapor deposition
  - Pulsed laser deposition

Top- down approach: Lithography

Lithography is a printing method that uses chemical processes to create an image.

Lithographic techniques can be divided into two main groups:

1. **Photolithography** *(Semiconductor Lithography or Mask Lithography)*

2. **Scanning Lithography** (*e-Beam and Focused Ion-Beam Lithography)*

Steps in Lithography:

A typical lithographic process consists of three successive steps:

(i) **Coating a substrate** (Si wafer or glass) with a sensitive polymer layer **(the resists).**
(ii) **Exposing the resist to light**, electrons or ion beams.
(iii) **Developing the resist image** with a suitable chemical (developer), which reveals a positive or a negative image on the substrate depending on the type of resist used (i.e., positive or negative resist).

Resists are of two types based on their solubility after exposure with e-beam:

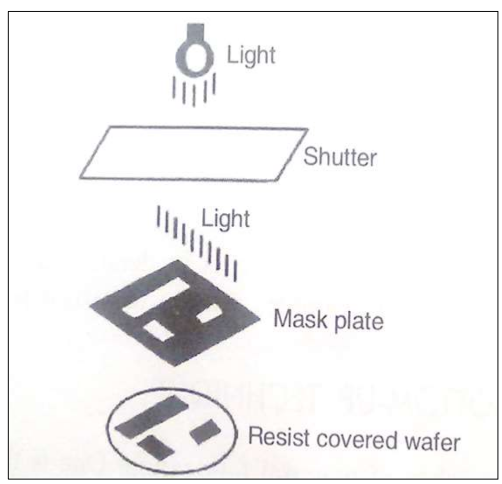
(a) Positive resists : solubility of exposed area increases

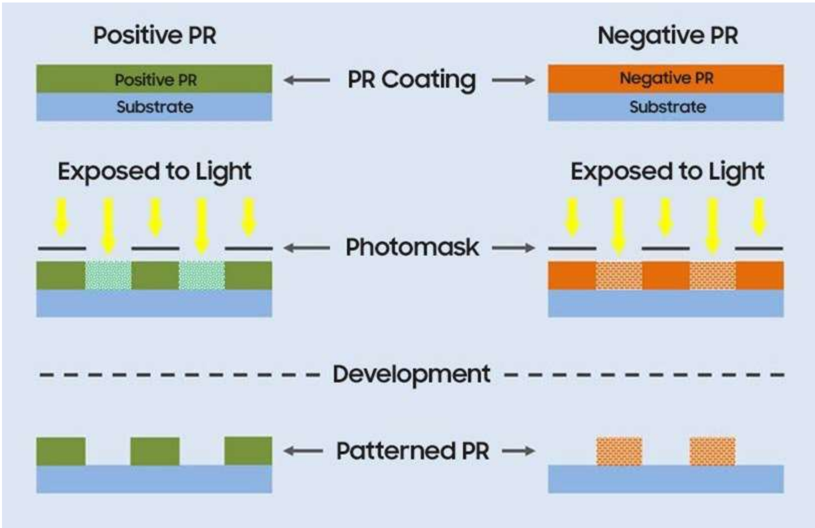
(b) Negative resists: solubility of exposed area decreases

Photolithography

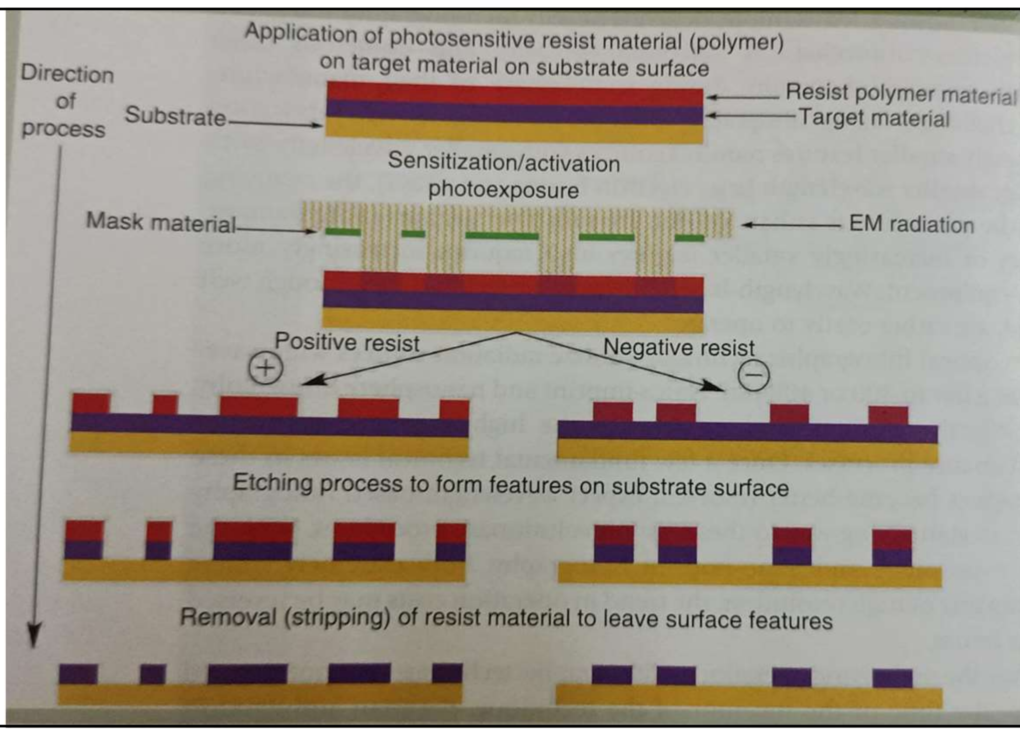
Light source: Photolithography uses UV(360-460 nm), deep UV, extreme UV or X-ray light, laser beam of KrF(248 nm)/ArF(193 nm).

Mask : The mask is a nearly optically flat glass (or quartz) plate that contains the desired pattern, that is, opaque areas (the pattern, made of an absorber metal) on a UV-transparent background.





Positive PR
Negative PR
Positive PR
Substrate
PR Coating
Negative PR
Substrate
Exposed to Light
Exposed to Light
Photomask
Development
Patterned PR



Application of photosensitive resist material (polymer) on target material on substrate surface
Direction of process
Substrate
Resist polymer material
Target material
Sensitization/activation photoexposure
Mask material
EM radiation
Positive resist
Negative resist
Etching process to form features on substrate surface
Removal (stripping) of resist material to leave surface features

Types of Photolithography

The image on the mask can be replicated:

- By placing it in close proximity to the photoresist (**Proximity-mode photolithography)**
- By placing the mask in physical contact with the resist **(contact mode photolithography),**
- By projecting it to the resist layer through an optical system. The image is reduced, usually by a factor of 5 or 10 **(projection-mode photolithography).**

Electron beam lithography(EBL)

- In EBL, a scanning beam of electron irradiates the surface of the resist sequentially, point by point, through a computer-controlled program where the mask pattern is defined.
- This systems have produced linewidths of ~20 nm, but it is not suitable for very small size nanostructures.

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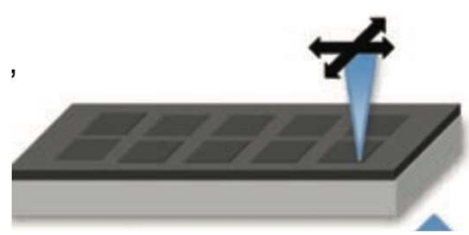
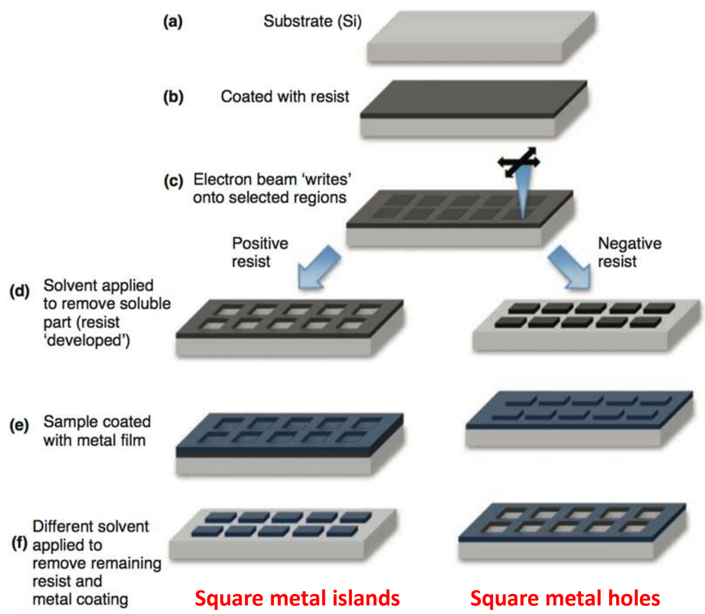
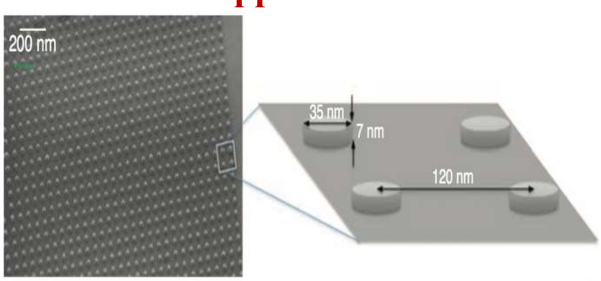


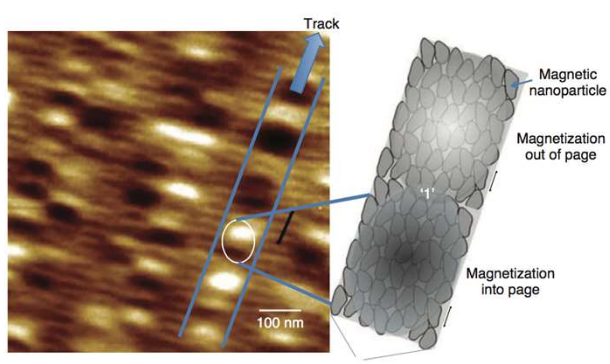
EBL to create metal nanostructures on a surface using positive and negative resists



Application of EBL: data storage on CoPt magnetic dots

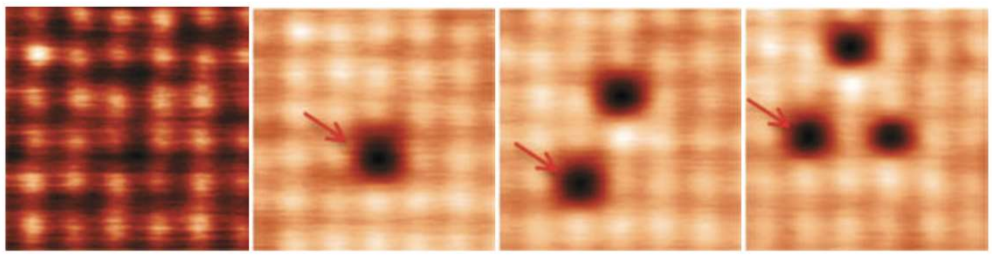


(a)



Magnetic Force Microscopy(MFM) image of a Seagate hard disk

Writing to CoPt nanoparticle using Magnetic Force Microscopy(MFM)

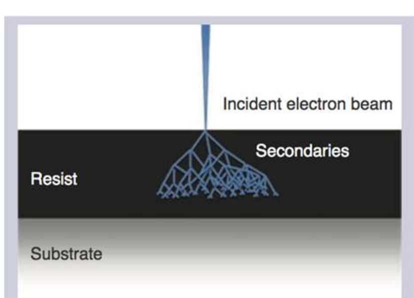


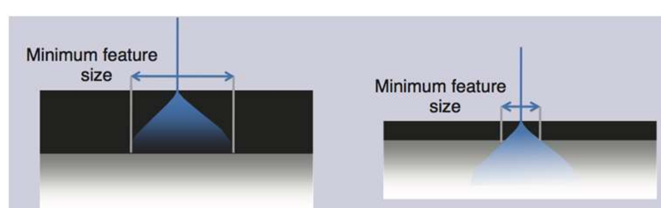
(b) 700 nm x 700 nm MFM scan of array with every nanodisk initially magnetized in the same direction

The first particle reversed is indicated by a red arrow in each frame. The space occupied by Each bit corresponds to a storage density of ~40 Gb/in^2.

Limitations of EBL

- EBL will remain a nanotechnology tool restricted to research labs.
- Beam broadening due to electron scattering within resist.





Difference between Photo lithography and Electron beam lithography

The main difference between mask and scanning lithography is *speed.* Mask lithography is a parallel, fast technique and scanning lithography is a slow, serial technique.

Another important difference is *resolution*, which is higher for scanning methods. More energetic radiation sources are used to achieve higher resolution.

Non-lithographic approaches: Bottom up approach

This technique is divided in two groups:

1. Solution based synthesis- Sol-Gel Method
2. Vacuum based synthesis -PLD

Sol-gel Method

- Sol-gel is a wet –chemical-based self assembly process for nanomaterial formation.
- A sol is a colloidal or molecular suspension of solid particles of ions in a solvent.
- A gel is a semi-rigid mass that forms when the solvent from the sol begins to evaporate and the particles or ions left behind begin to join together in a continuous network.
- This sol–gel process depends on the precursor material, solvent, and catalysts (if necessary).
- Hydrolysis and polycondensation are the two important steps, involved in the sol–gel process, those prefer water as solvent medium.

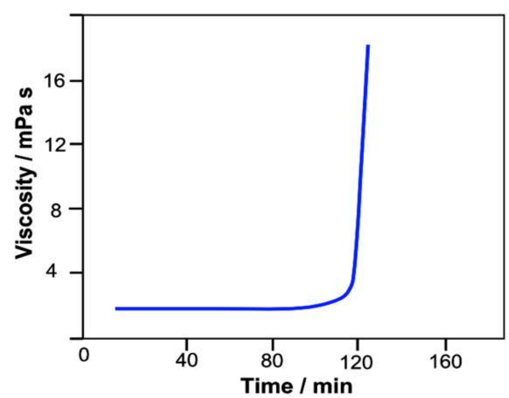
Steps involved:

Step 1: Synthesis of the colloid from precursors (usually ions of a metal)

$$MOR + H_2O \rightarrow MOH + ROH \ \ (hydrolysis)$$

MOR : Metal alkoxides such as aluminates, titanates and borates

Step 2: $MOH + ROM \rightarrow M - O - M + ROH$ (condensation)



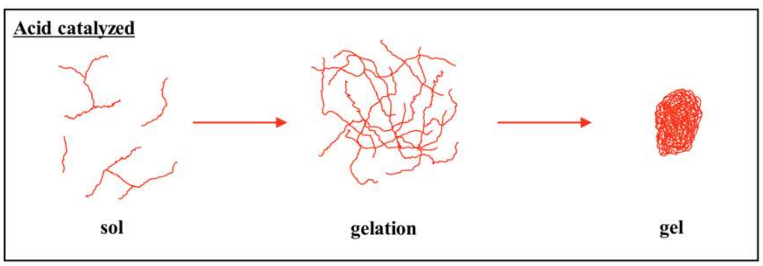
The sharp increase in viscosity during sol-gel transition.

Step 3: Syneresis (aging of the gel)

Accompanied by the contraction of the gel network and expulsion of the solvent from gel pores. The aging process of gels can exceed 7 days and is critical to the prevention of cracks in gels.

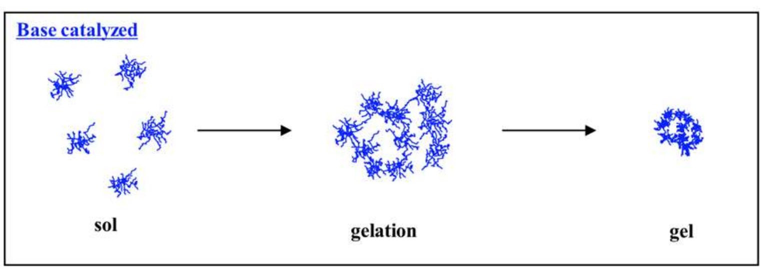
Step 4: Calcining/Drying of the gel at temperatures upto 800 ℃

During this step, water and other volatile liquids are removed from the gel network.
If the solvent is extracted under supercritical conditions, the product is an aerogel.



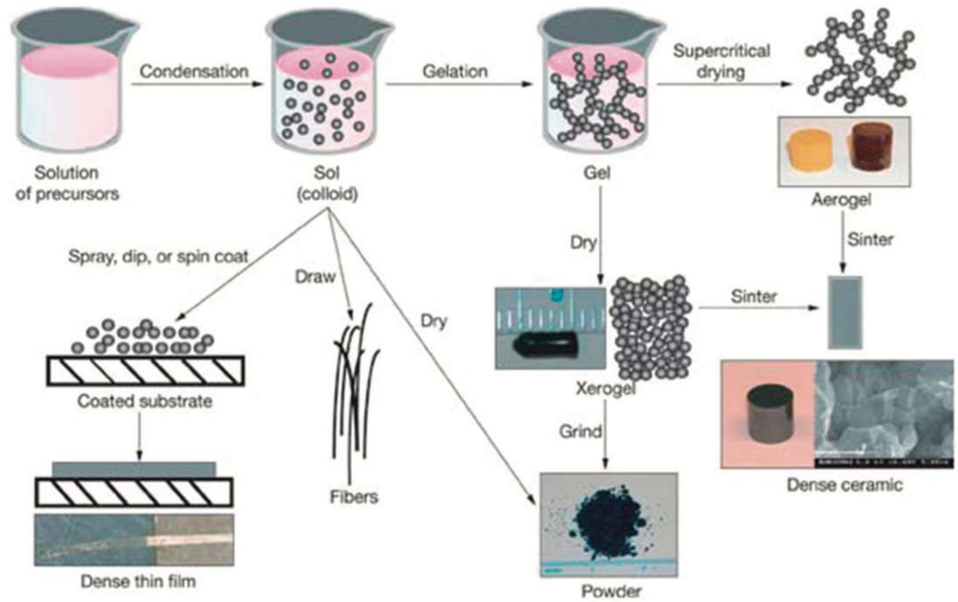
Acid catalyzed hydrolysis

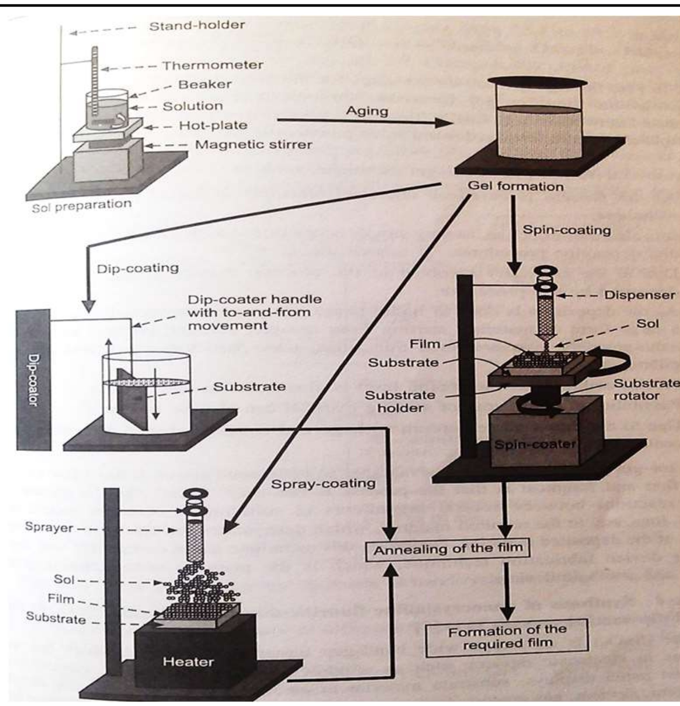
Favours formation of linear or weakly branched silica species. Gelation is via entanglements



Base catalyzed hydrolysis

Gelation occurs via formation of agglomerated clusters which condense to form a 3D network


Condensation
Gelation
Supercritical drying
Solution of precursors
Sol (colloid)
Gel
Aerogel
Sinter
Dry
Spray, dip, or spin coat
Draw
Dry
Sinter
Coated substrate
Xerogel
Grind
Dense ceramic
Fibers
Dense thin film
Powder


Stand-holder
Thermometer
Beaker
Solution
Hot-plate
Magnetic stirrer
Sol preparation
Aging
Gel formation
Spin-coating
Dip-coating
Dip-coater handle with to-and-from movement
Dip-coater
Substrate
Dispenser
Sol
Film
Substrate
Substrate holder
Substrate rotator
Spin-coater
Spray-coating
Sprayer
Sol
Film
Substrate
Heater
Annealing of the film
Formation of the required film

Aerogels

Comparison of densities in g/cm^3

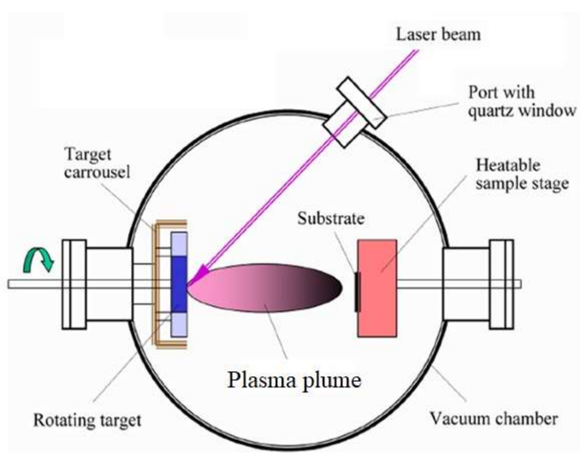
Iron	Diamond	Glass	Graphite	C_{60}	Paper	Charcoal	Aerogel	Air
7.87	3.5	2.4	2.3	1.7	0.7	0.57	0.003–0.8	0.0013

Aerogels –

- are the lightest materials ever synthesized.
- have 2-5 nm size particles
- Have very low value of thermal conductivity (0.003 W/m.K). This makes them the best available thermal insulator.

Pulsed laser deposition method

1. Physical Vapor Deposition Technique for nanostructured thin films.
2. High Powered Laser is focused on target (material to be deposited) in vacuum.
3. Material is vaporized into plasma plume which extends from target.
4. Proceeds to deposit on substrate forming a thin film.
5. Highly advantageous



Nanoscale Characterization techniques

- Scanning Electron Microscope (SEM)
- Transmission Electron Microscope (TEM)
- Atomic Force Microscopy(AFM)
- X-rays Diffraction (XRD)

Electron microscope (EM)

DIFFERENCES BETWEEN OM AND EM

OPTICAL MICROSCOPE	ELECTRON MICROSCOPE
1. The source of light. 2. The specimen. 3. The lenses that makes the specimen seem bigger. 4. The magnified image of the specimen that you see.	1. The light source is replaced by a beam of very fast moving **electrons**. 2. The specimen usually has to be specially prepared and held inside a **vacuum chamber** from which the air has been pumped out (because electrons do not travel very far in air). 3. The lenses are replaced by a series of coil-shaped **electromagnets** through which the electron beam travels. 4. The image is formed as a photograph (called an electron micrograph) or as an image on a **TV screen**.

Advantages of Using EM over OM

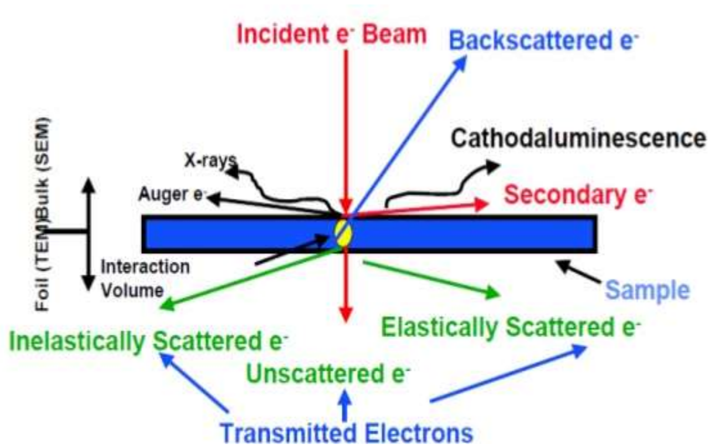
Magnification	Depth of Field	Resolution
OM: 4x – 1400x	0.5mm	$0.2\ \mu m$
SEM: 10x – 500Kx	30mm	1.5nm

- The SEM has a large depth of field, which allows a large amount of the sample to be in focus at one time and produces an image that is a good representation of the three-dimensional sample.

- The combination of higher magnification, larger depth of field, greater resolution, compositional and crystallographic information makes the SEM one of the most heavily used instruments in academic/national lab research areas and industry.

Electron stimulated Signals when it strikes a sample

Electrons are a type of ionizing radiation, capable of removing one of the tightly bound inner-shell electrons from the attractive field of the nucleus and produces many of the secondary signals from the specimen as some of the electrons are transmitted through the sample, get backscattered or emit secondary electrons that are used in electron microscopy



Types of Electron microscopy

1. Transmission electron microscope (TEM)

It forms images using electrons that are transmitted through the specimen.

2. Scanning electron microscope (SEM)

It utilizes electrons that have bounced off the surface of the specimen.

SCANNING ELECTRON MICROSCOPE (SEM)

- It is a type of electron microscope that images a sample by scanning it with a high-energy beam of electrons in a raster scan pattern.
- When a finely focused beam of electrons impinges on the surface of the solid sample and interacts with the atom of sample, several signals in the form of backscattered electrons, secondary electrons, Auger electrons and characteristic X-rays are generated from the surface, which contains information about surface topography and composition of specimen.
- It shows detailed 3D images with a resolution of few nm.

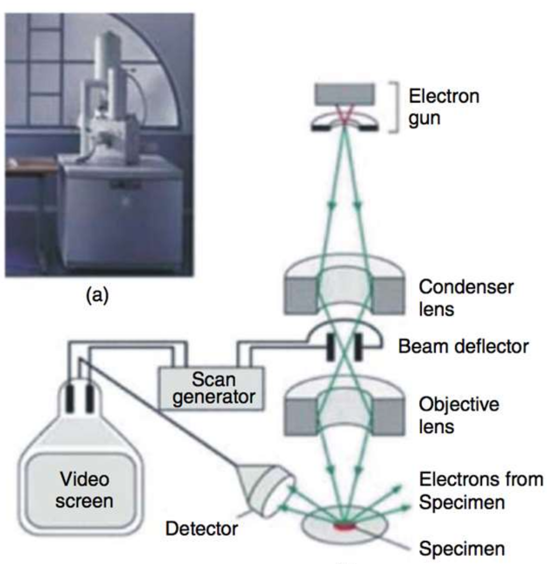
In SEM, different type of signal gives different information:

a. Secondary electrons: surface structure.

b. Backscattered electrons: surface structure and average elemental information. The production of backscattered electrons varies directly with the specimen's atomic number. They may be used to detect the contrast between the areas with different average atomic numbers.

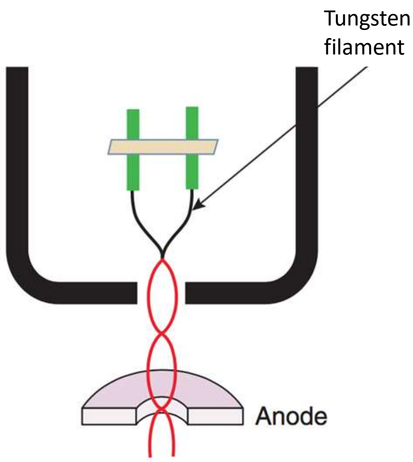
c. X-rays and Auger electrons: elemental composition with different thickness-sensitivity.

Experimental set up of Scanning Electron Microscope(SEM)

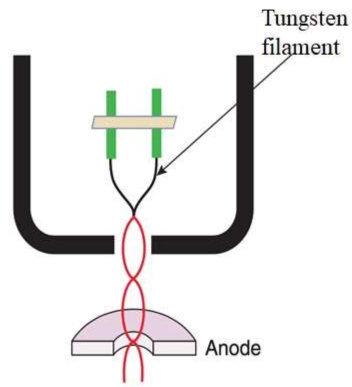


Sources of electrons

Types of electrons guns



Thermionic gun



Field emission gun

Comparative Overview of Characteristics of Different Electrron Guns

Emission	Thermionic		Field Emission
	W	LaB_6	W/C
Size (nm)	1×10^5	2×10^4	0.2
Brightness (A/cm^2 sr)	10^4–10^5	10^5–10^6	10^7–10^9
Energy spread (eV)	1–5	0.5–3.0	0.2–0.3
Operating lifetime (h)	>20	>100	>300
Vacuum (torr)	10^{-4}–10^{-5}	10^{-6}–10^{-7}	10^{-9}–10^{-10}
Crossover diameter	50 μm	10 μm	10 nm

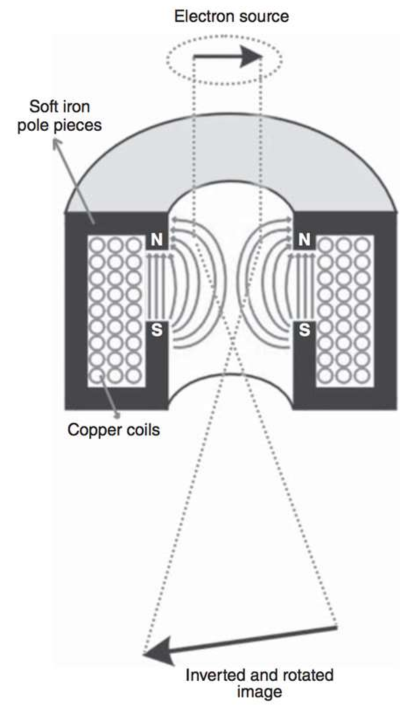
Electromagnetic lenses

In magnetic field, an electron experiences Lorentz force F:

$$\boldsymbol{F} = = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

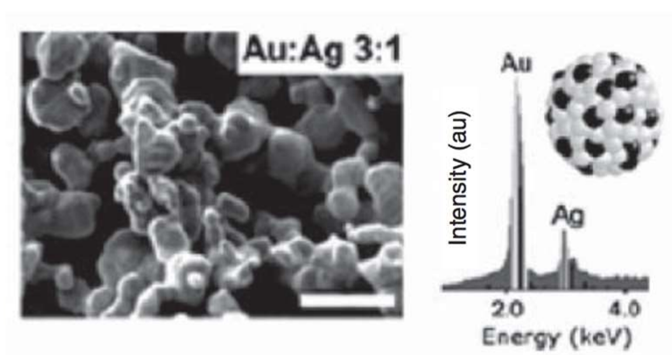
F leads to helical trajectory of the electron and to the magnetic rotation.

The focal length can be changed by alterin the strength of the current.



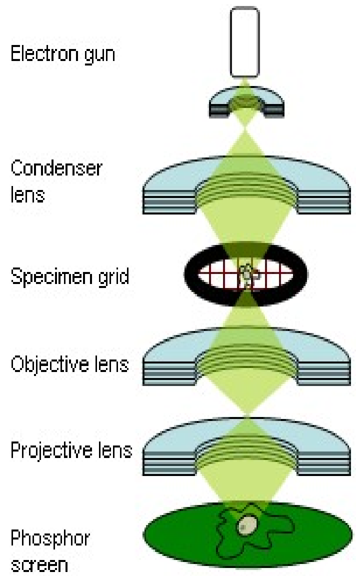
Energy dispersive X-ray analysis (EDX):

Chemical composition can be analysed using EDX analysis when it is attached with SEM.

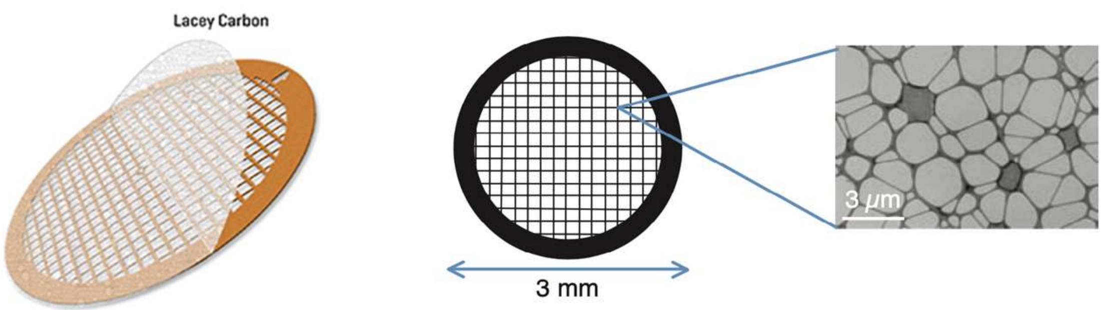


SEM image and EDX spectra

Transmission electron microscope (TEM)

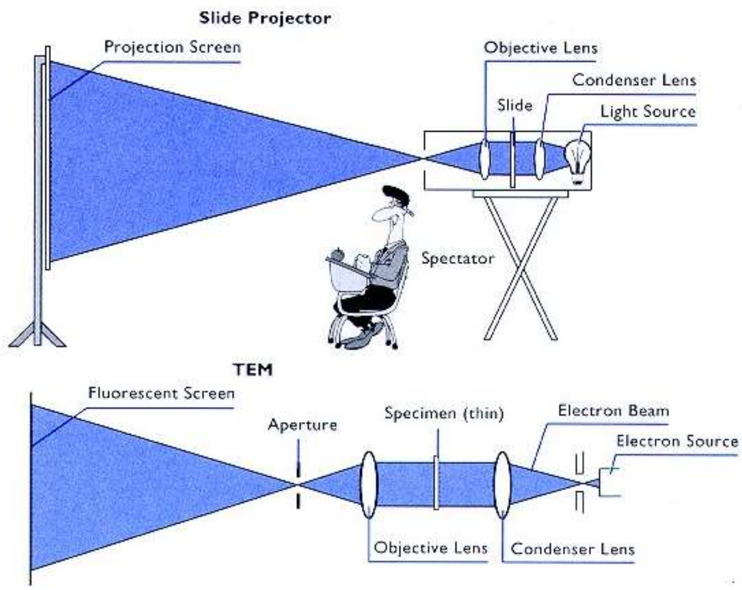


Lacy carbon TEM sample grid



The sample grid must be coated with lacy carbon for high quality imaging

A transmission Electron Microscope is anologous to a slide projector

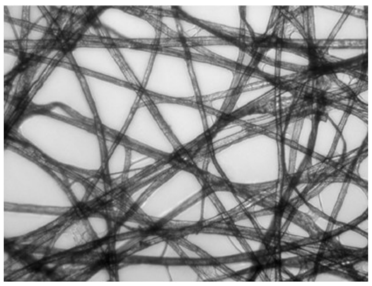


Difference between SEM and TEM

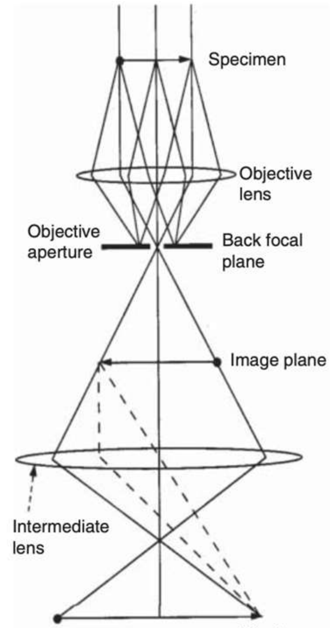
SEM	TEM
1. Based on scattered electrons	1. Based on transmitted electrons.
2. Sample's surface and its composition	2. Internal composition.
3. No such need.	3. The sample has to be cut thinner.
4. Large amount of sample can be analysed at a time.	4. Only small amount of sample can be analysed at a time.
5. For surfaces, powders, polished & etched microstructures, IC chips, chemical segregation.	5. For imaging of dislocations, tiny precipitates, grain boundaries and other defect structures in solids.
6. Pictures are shown on monitor.	6. Pictures are shown on fluorescent screens.
7. Provides 3-dimensional images.	7. Provides 2-dimensional images.
8. Lower resolution than TEM.	8. Higher resolution than SEM.

Modes of TEM

- The image obtained using only transmitted beam is called "**bright field image**".
- It is selected with the aperture which blocks the scattered electrons.
- The areas of the sample with high mass materials will appear dark.

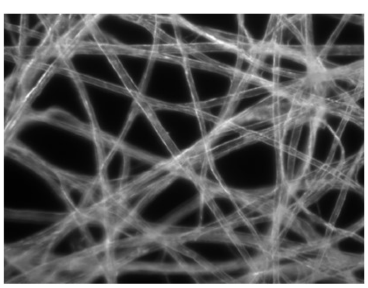


Bright-field mode

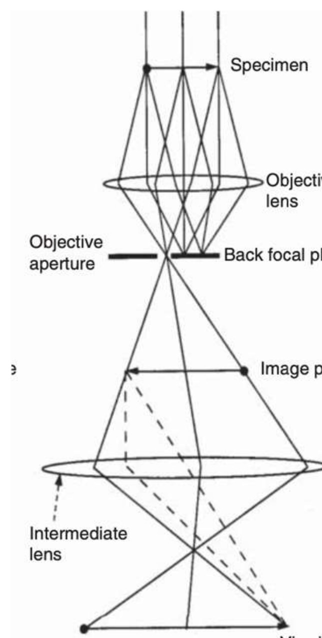


Modes of TEM

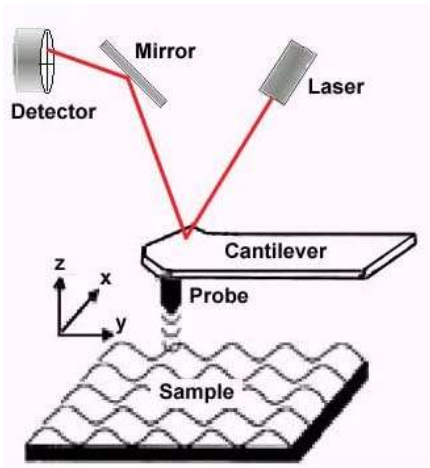
- The image obtained from scattered beam is called as "**dark field image".**
- The areas around the sample will appear dark and the sample will appear bright.
- The unscattered beam is excluded from the aperture.

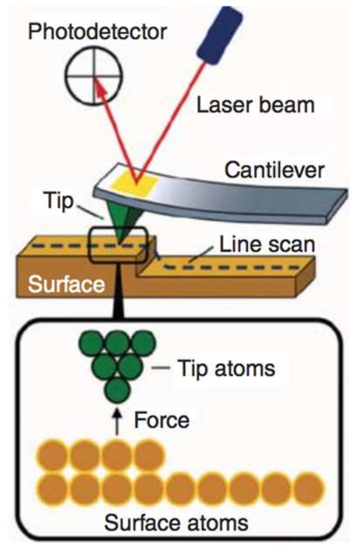


dark-field mode



Basic set-up and working of an AFM

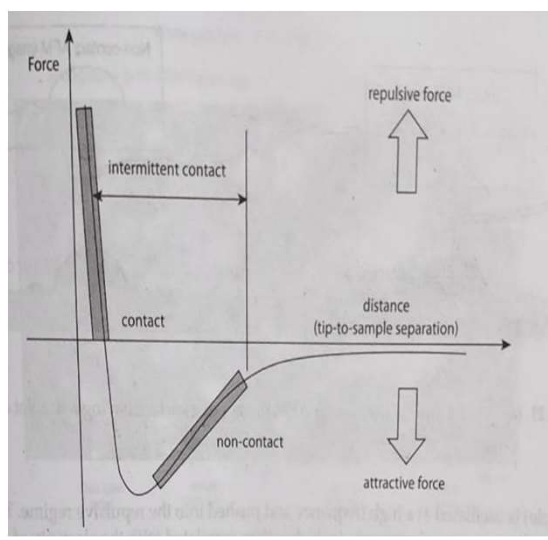




AFM modes

The common modes are :

(i) static mode : Contact mode
(ii) **Dynamic modes:**
Non-contact mode
Tapping/intermittent mode

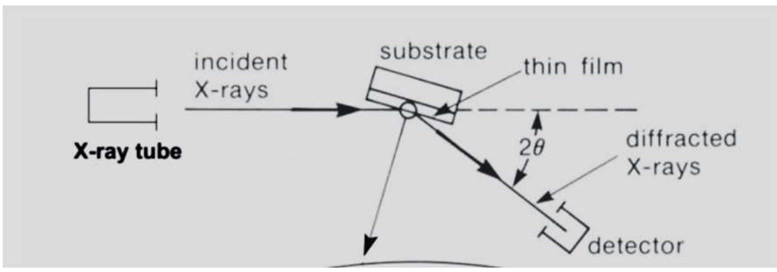


X-ray diffraction(XRD)

Types of X-ray Diffractometers:

- X-ray thin film diffractometers
- X-ray powder diffractometers

X-ray thin film diffractometers:



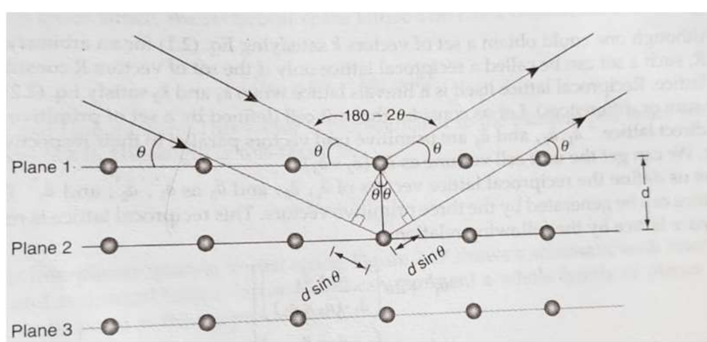
Bragg's Law

For a sharp intense peak of the diffracted X-ray beam (Bragg peak) , there should be constructive interference between the diffracted rays originating from successive planes.

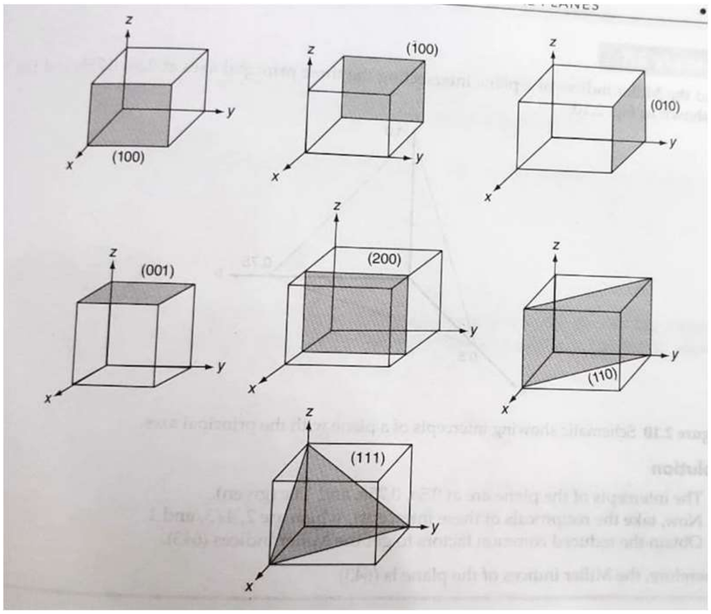
"Bragg's Law"

$$2d\ sin\theta\ = n\lambda$$

θ : angle of incidence.
n :order of reflection(integer)
d :spacing between planes



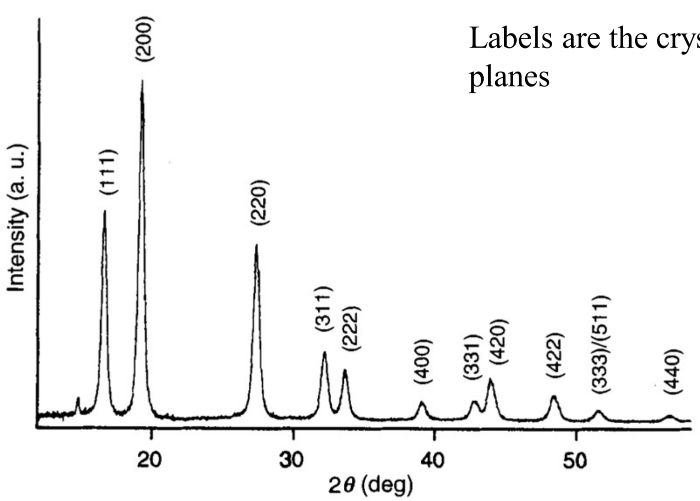
Miller indices of some important planes in a cubic crystal



The distance between parallel crystallographic planes with indices hkl for a simple cubic lattice of lattice constant a has the form:

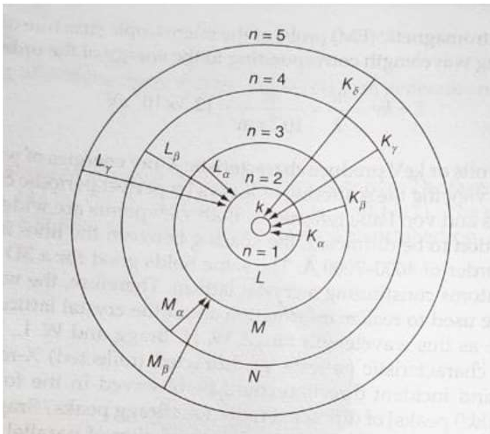
$$d_{hkl} = \frac{a}{(h^2+k^2+l^2)^{1/2}}$$

X-ray diffraction scan of nanocrystalline TiN



Labels are the crystallographic planes

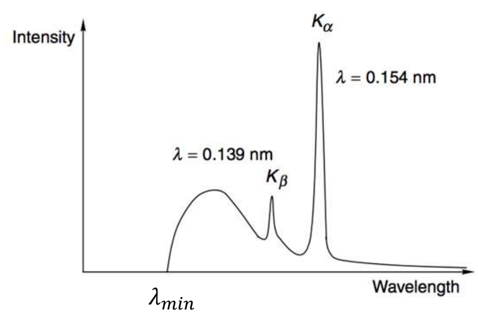
Production of several characteristic X-ray lines ($K_\alpha, K_\beta, L_\alpha$.....)



X rays emitted by certain heavy elements consist of a continuous wavelength range known as Bremsstrahlung or white radiation.

The minimum wavelength (λ_{min}) in the continuous wavelength spectrum is inversely proportional to the applied voltage.

For high voltage, in addition to continuum, a characteristic radiation is also emitted.

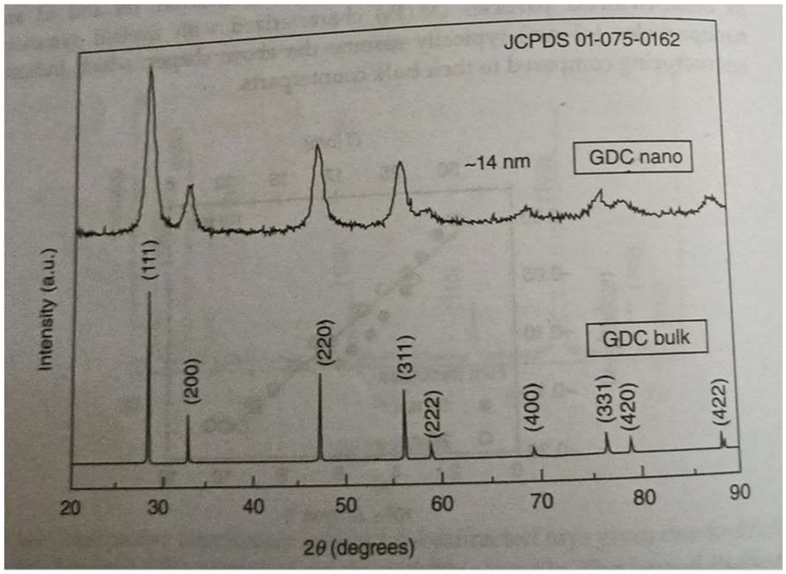


X-ray emission spectrum from copper

Target metals and their characteristic K_α wavelengths

Target Metals	*Mo*	*Cu*	*Co*	*Fe*	*Cr*
K_α wavelength (Å)	0.71	1.54	1.79	1.94	2.29

Diffraction pattern for nanoparticles of Gd-doped ceria

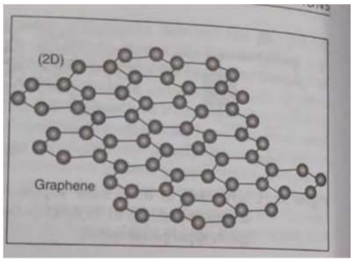


Carbon nanotechnology

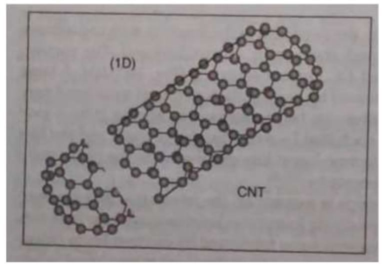
- **Fullerene**
- **Carbon nanotubes**
- **Graphene**

These are the newly added allotropes of carbon

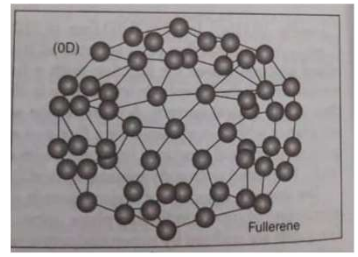
Newly added allotropes:



Graphene : Flat fullerene
Graphene is formed by removing the single sheets from a graphitic structure



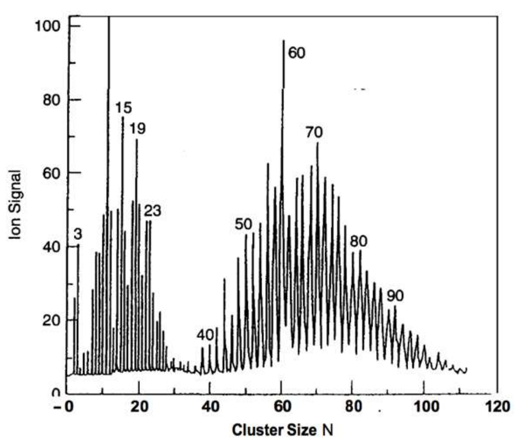
Carbon Nanotubes: bucky tubes.



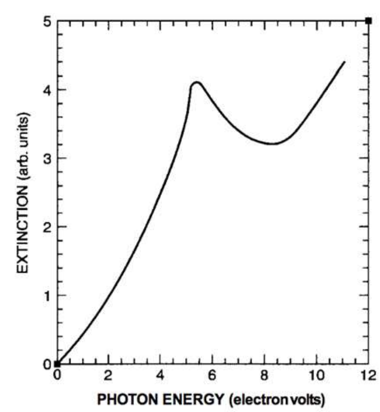
Buckminster fullerene: bucky balls.

The general class of carbon molecules including graphene and all the tube and balloon structures it forms on curling up are known as fullerenes.

Discovery of Fullerene (C_{60})

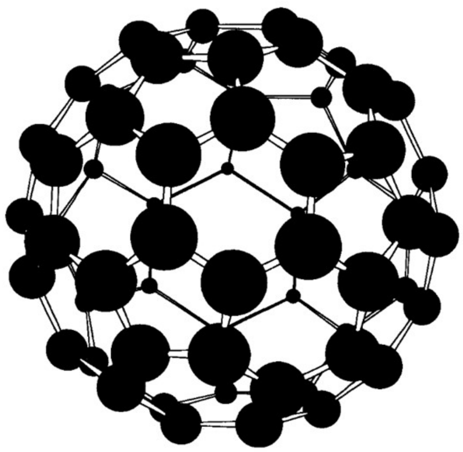


Mass spectrum : Evidence of C_{60} and C_{70}



The peak at **5.6 eV(220 nm)** is due to absorption from C_{60} present in interstellar dust

Structure of the C_{60} fullerene molecule



- The C_{60} molecule has been named fullerene after the architect and inventor Buckminister Fuller, who designed the geodesic dome that resembles the structure of C_{60}.
- The structure has 12 pentagonal (5 sided) and 20 hexagonal (6 sided) faces symmetrically arranged to form a molecular ball.

Euler's theorem

If we construct a perfect closed shape with polygonal tiles, then

$$V - E + F = 2$$

must be satisfied.

V: number of vertices
E: number of edges
F: number of faces/tiles

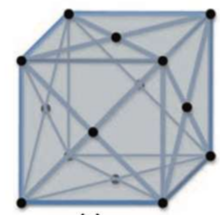
For C_{60}:

F = 32, E=90, V = 60. ∴ Euler's theorem is satisfied.

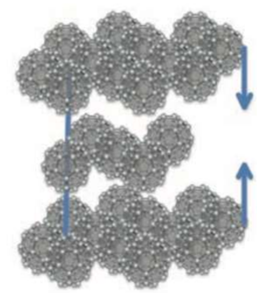
According to this theorem, any closed shell will be produced by 12 pentagons, irrespective of the number of hexagons.

Materials produced by assembling fullerene: Fullerite

- The assemblies of pure fullerene molecules, C_{60} in the condensed form are known as fullerites.
- The crystal structure of C_{60} fullerite is face centered cubic (fcc) and an insulator.
- Separation between nearest-neighbour C_{60} is 1nm.
- They are held together by weak van der Waals forces.



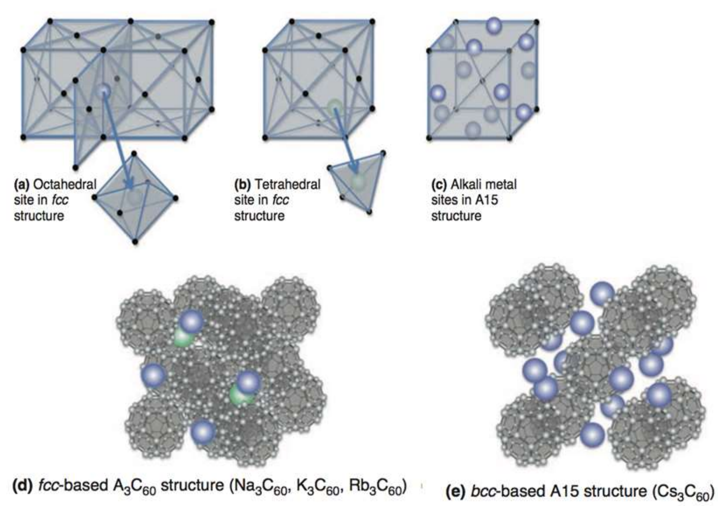
(a)



Fullerides

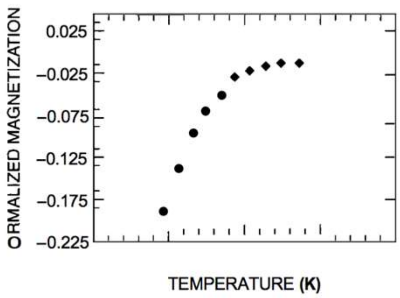
When other atoms are included in the fullerite lattice, a compound known as a fulleride is produced.

Alkali metal atoms (Ex: Na, K, Cs..) fit into the hollows left between the C_{60} cages.

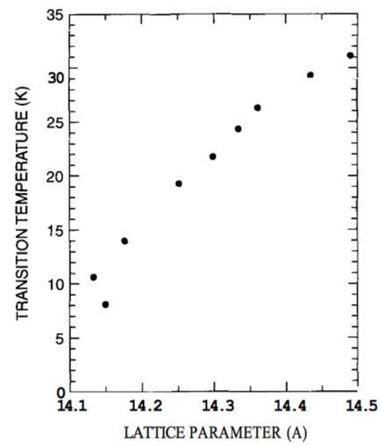


(A: represents Alkali atoms)

Superconductivity in C_{60} fulleride



Magnetization of K_3C_{60} showing transition to the superconducting state (18 K).



As the radius of the dopant alkali atom increases, the cubic C_{60} lattice expands and the superconducting transition temperature goes up.

Superconducting transition temperatures of the Fullerides

Fulleride	Superconducting Transition Temperature (K)	Size of Alkali Atom (nm)
Na_3C_{60}	Not superconducting	0.429
K_3C_{60}	18	0.533
Rb_3C_{60}	29	0.559
$Rb_xCs_{3-x}C_{60}$	33	0.559-0.614
Cs_3C_{60}	38	0.614

The superconducting transition temperature increases with increasing size of the alkali atom.

Magic numbers in larger fullerenes

- There is a series of stable fullerenes containing **$60 + (k \times 6)$ atoms** where $k = 0,2,3,4,5\ldots$..with increasing number of hexagons.

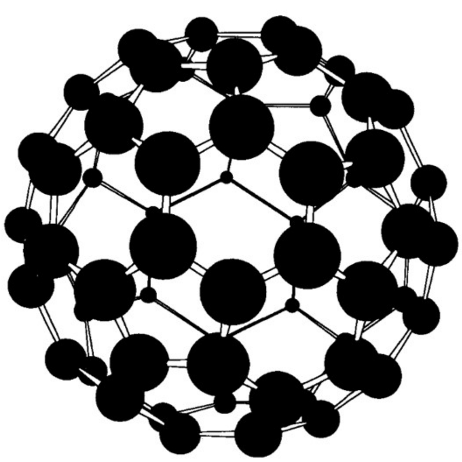
- For a stable fullerene with n atoms,

$$\text{Number of hexagons} = \frac{n}{2} - 10$$

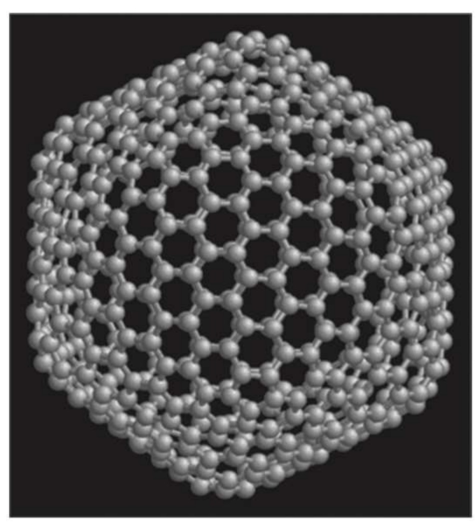
- Within this series, there are especially stable numbers of atoms (special values of *n)* when, the closed shell has a low-energy morphology. They are known as **magic numbers.**

- $k = 0$ (C_{60}) corresponds to the first magic number.

Examples of large fullerenes

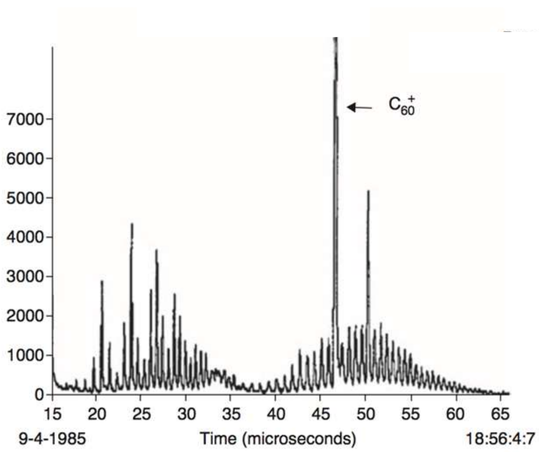


Icosahedral structure of C_{60}
(magic number $\boldsymbol{k = 0}$)

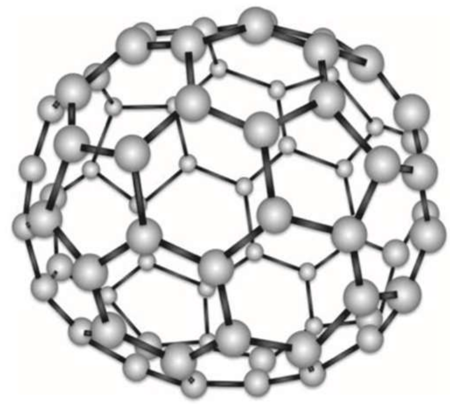


Icosahedral structure of C_{540}
(magic number $\boldsymbol{k = 80}$)

Larger fullerenes: other possible stable series



C_{70} peaks: most prominent peak after C_{60}



C_{70}

structure of C_{70} (has 25 hexagonal & 12 pentagonal faces)

Larger fullerenes: other possible stable series

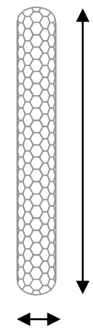
Including elliptical and tubular fullerenes, there are two extra series with stable numbers of atoms given by:

- $70 + 30k$ ($k = 0, 1, 2, 3, \ldots$)
- $84 + 36k$ ($k = 0, 1, 2, 3, \ldots$).

Each next larger member involves a tubular extension about the long axis producing an increasing elongation.

Carbon Nanotubes (CNT)

- CNTs are another stable carbon structure.
- They are a rolled-up shell of graphene sheet one-atom-thick layer.
- The tubular shell is mainly made up of hexagonal rings of carbon atoms.
- The aspect ratio (length-to-diameter) can be greater than 1000



Length:
typical few µm

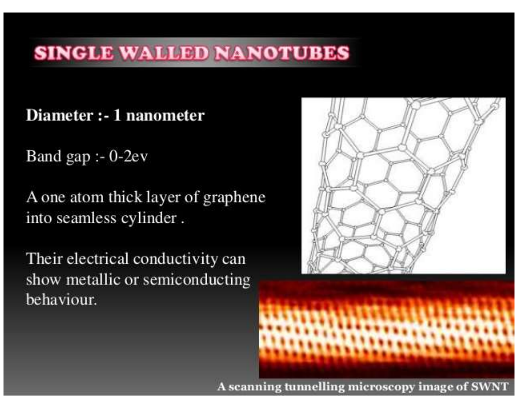
Diameter:
as low as 1 nm

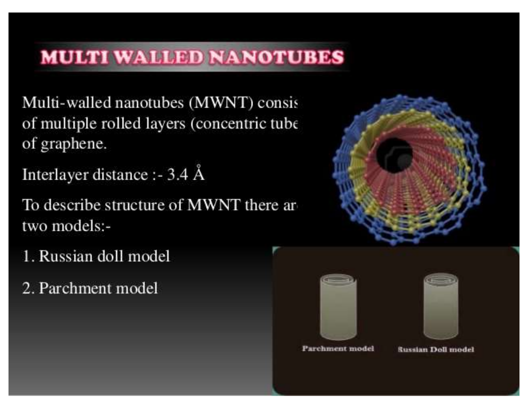
High aspect ratio:

$$\frac{length}{diameter} > 1000$$

Types of Carbon Nanotubes

- Single walled carbon nanotubes (SWCNT)
- Multi-walled carbon nanotubes (MWCNT)



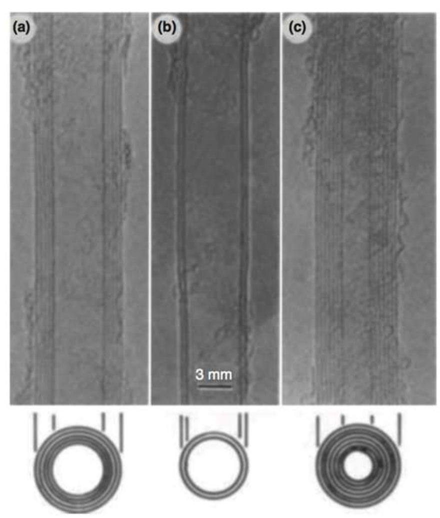


Fabrication of CNT

- To produce SWNT, a small amount of cobalt, nickel or iron is incorporated as a catalyst.
- If no catalysts are used, the tubes are nested or MWNT.
- Generally, when nanotubes are synthesized, the result is a mix of different kinds, some metallic and some semiconducting.

Discovery of carbon nanotubes (CNT)

- These are Multi-walled carbon nanotubes(MWCNT).
- Its diameters range from 4 to 30 nm, up to 1μm in length.
- The number of concentric walls vary from 2 to 7.
- Iijima reported tubes with up to 50 walls.



First EM images of carbon nanotubes by Sumio Iijima

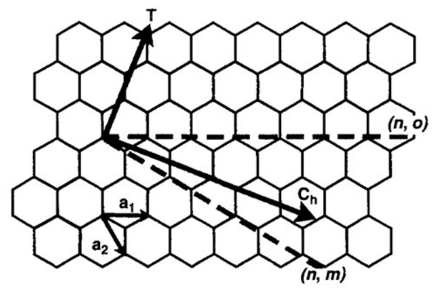
Structure of SWNTs

A nanotube can be formed when a graphite sheet is rolled up about the axis T.

T: axis vector about which the sheet is rolled.

$\boldsymbol{a_1, a_2}$: basis vectors of the 2D unit cell

$\boldsymbol{C_h}$: circumferential vector, at right angles to T.



Graphitic sheet

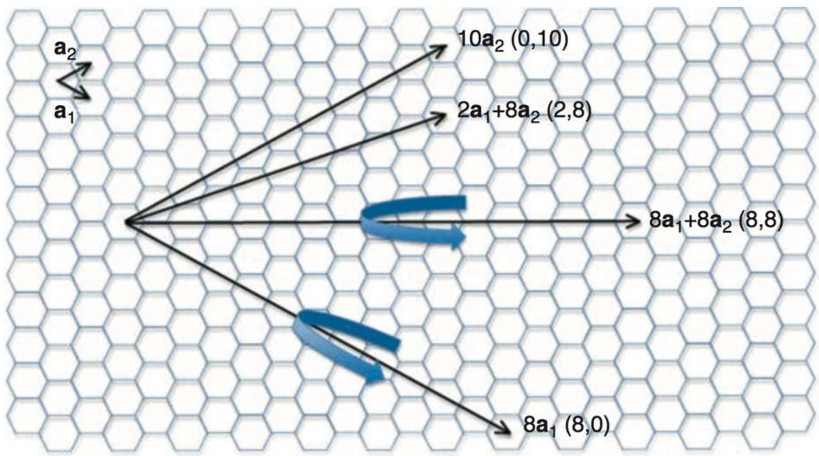
Chirality

Chirality refers to how the tubes are rolled with respect to the direction of the T vector in the graphite plane.

The choice of axis angle (between hexagons & tube axis) produces profound changes in the electronic properties of the tubes.

For each chirality there is an infinite family of tubes with different diameters and lengths, which also affect the tube properties.

Nanotube Chiralities



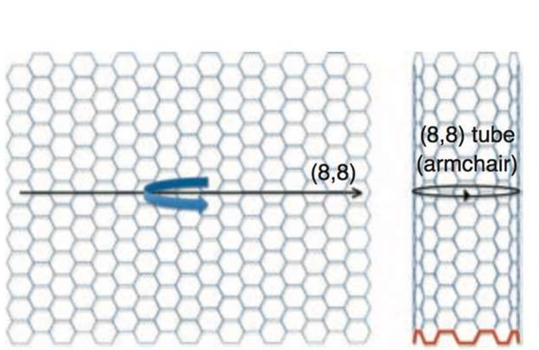
The chirality of nanotube is specified by the circumferential vector $n\boldsymbol{a_1} + m\,\boldsymbol{a_2}$.

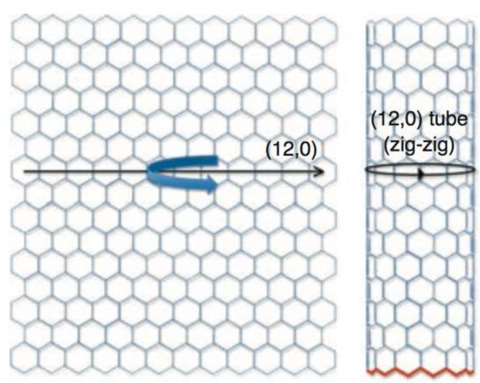
The tube is generated by rolling the graphene lattice so that the vector lies on the circumference.

Nanotube Chiralities

Any (n,0) tube will have a zigzag configuration.

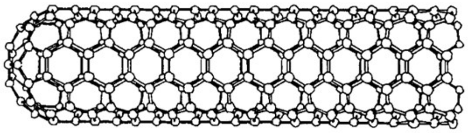
Any (n,n) tube will have an armchair configuration.



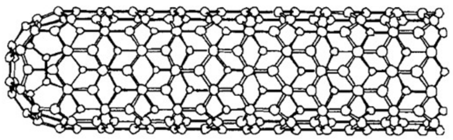


The ends of the tubes are often terminated by a half-fullerene

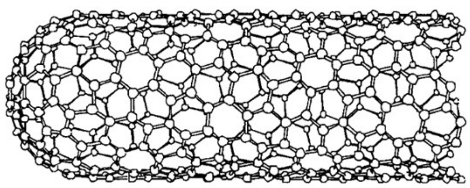
Classification of carbon nanotubes based on structures



Armchair structure:
T is parallel to the C-C bonds



Zigzag structure:
T vector not parallel to C-C bonds



Chiral structure (Any n$\neq$ $\boldsymbol{m}$ *tube*):
T vector not parallel to C-C bonds.
Looking down the tube of the chiral structure, one can see a spiraling row of carbon atoms.

Electrical properties of SWNTs

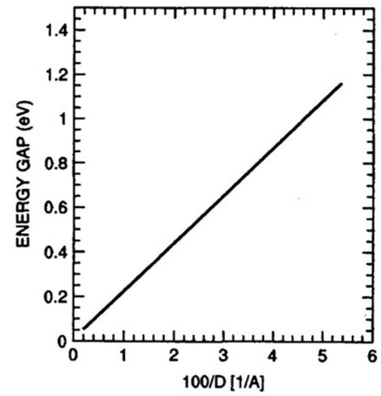
Depending on the diameter & chirality of the tube, carbon nanotubes are metallic or semiconducting.

Synthesis of carbon nanotubes result in a mixture of tubes two-thirds of which are semiconducting and one-third metallic.

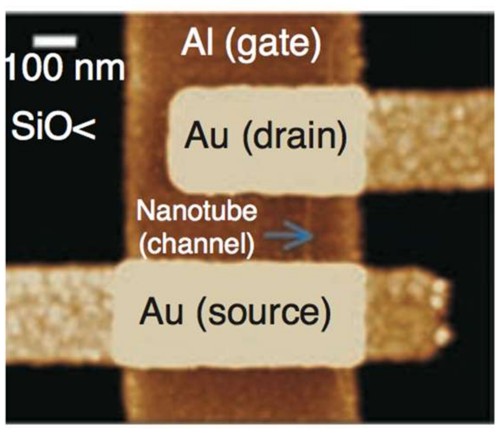
- All armchair tubes (n, n) are conducting.
- (n, m) tubes with $n - m = 3i$ $(i = integer)$ are also almost metallic but have a very small bandgap generated by the curvature of the tube.
- Any tube for which $n - m \neq 3i$ is semiconducting with a bandgap that is inversely proportional to the tube diameter.

Electrical properties

As the diameter of the semiconducting nanotube increases, the bandgap decreases.

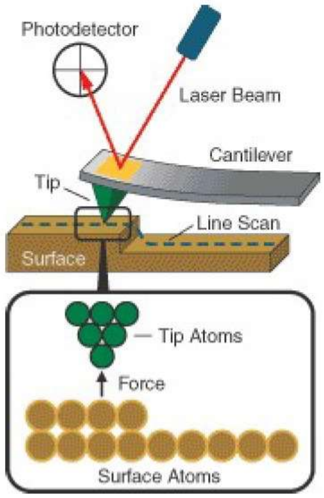


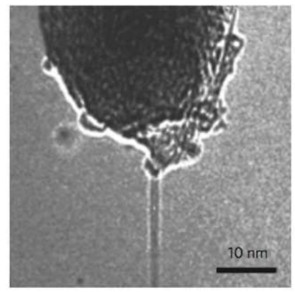
A Carbon Nanotube FET integrated circuit



AFM image of an individual semiconducting CNT Field Effect Transistor (FET)

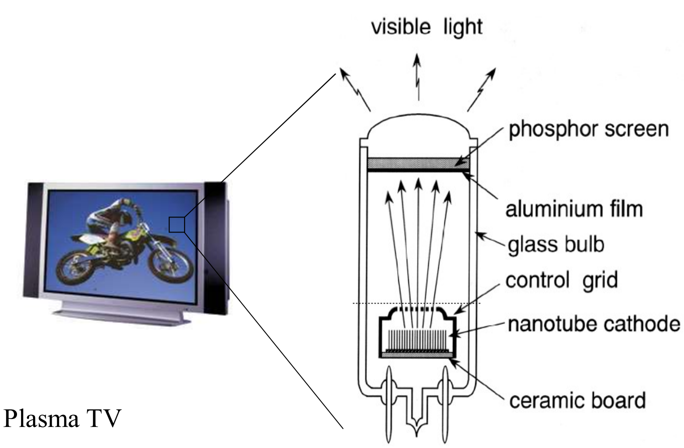
Nanotubes in Atomic Force Microscopy(AFM)





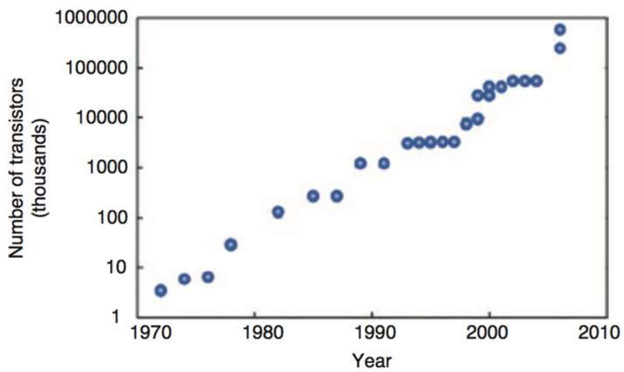
TEM image of a 0.9nm diameter SWNT tip

Flat screen display : Field Emission



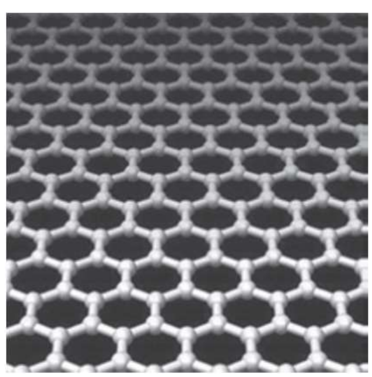
Plasma TV

Moore's Law



Exponential growth(doubling of components every 2 or 3 years) in ICs

Graphene



Single sheet of graphite, 2D honeycomb lattice arrangement of carbon atoms

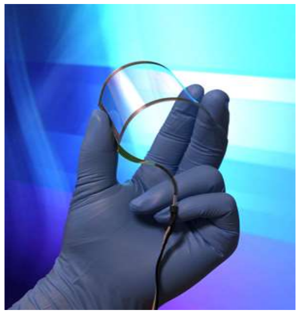
Unique Properties of Graphene

- **High electrical current density :** million times that of copper.
- **High intrinsic mobility :** 100 times that of Si.
- **High thermal conductivity**: higher than CNT, graphite and diamond.
- **Optical transparency:** optical transmittance of ~97.7% (absorbing 2.3% of white light)
- **Strength:** 200 times stronger than steel
- **One of the world's thinnest materials:** only one carbon atom thick (around 0.34 nm)

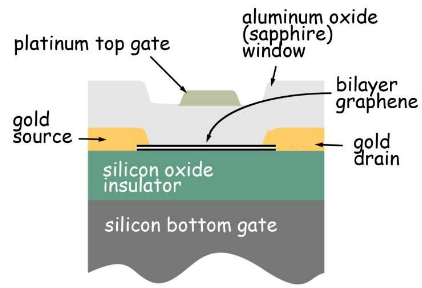
Unique Properties of Graphene

- **Toughest 2D material** : Harder than steel or diamond of same dimension.
- **Highest surface area**
- **Most stretchable crystal :** can be stretched upto 20% of its initial size without breaking.
- **Highly impermeable** : even He atoms cannot go through it.
- **Density of graphene:** light weight, density is 0.77 mg/m^2.

Applications of Graphene



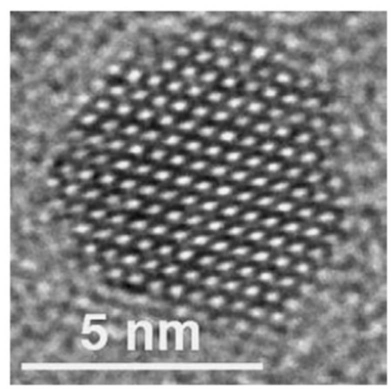
Flexible touch screen devices



GFET

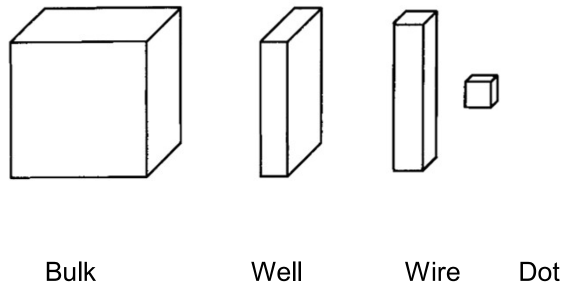
Quantum dots (QDs)

- Quantum dots are confined, zero-dimensional semiconductor systems created at the nanoscale made of silicon.
- In general, quantum dots are any particles that are sufficiently small that the electron energy level spacing becomes larger than thermal energy—*the quantum size effect .*



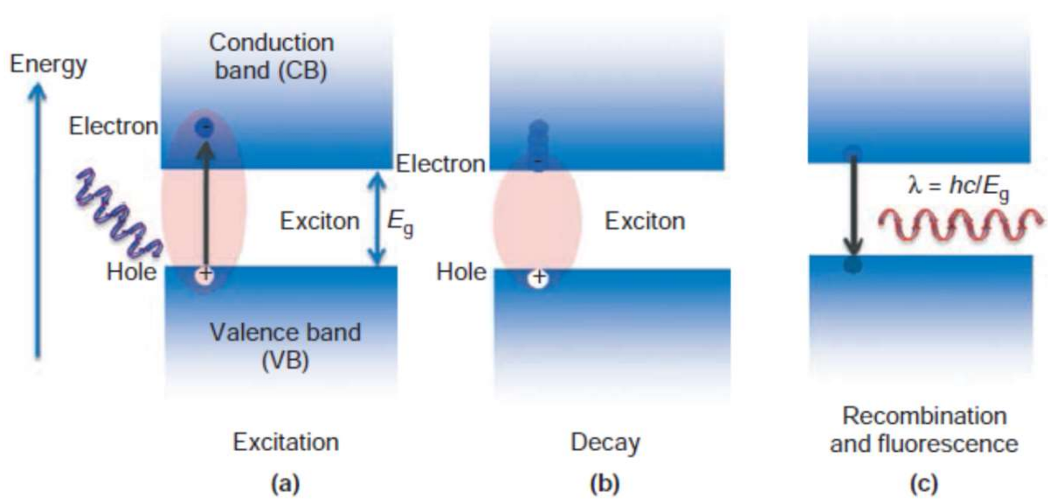
TEM image of one 5nm CdSe quantum dot particle

When the size or dimension of a material is continuously reduced from a large or macroscopic size to a very small size, dramatic changes in properties can occur, as we go below 100 nm.

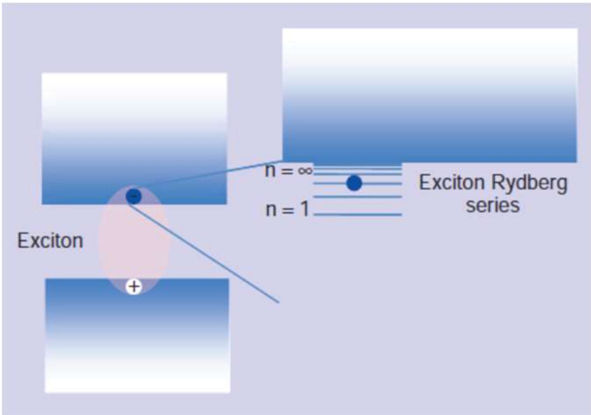


Progressive generation of rectangular nanostructures.

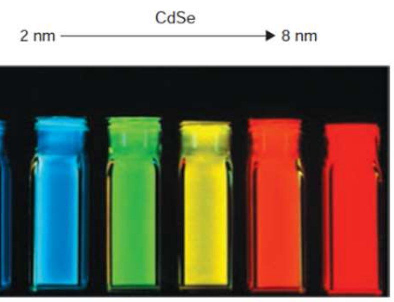
Fluorescence from a bulk semiconductor



Fluorescence from Quantum dot

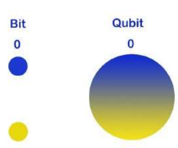


Fluorescence from CdSe quantum dots of different sizes



Application of quantum dots

Quantum Computing



Quantum dot for diagnostic imaging.