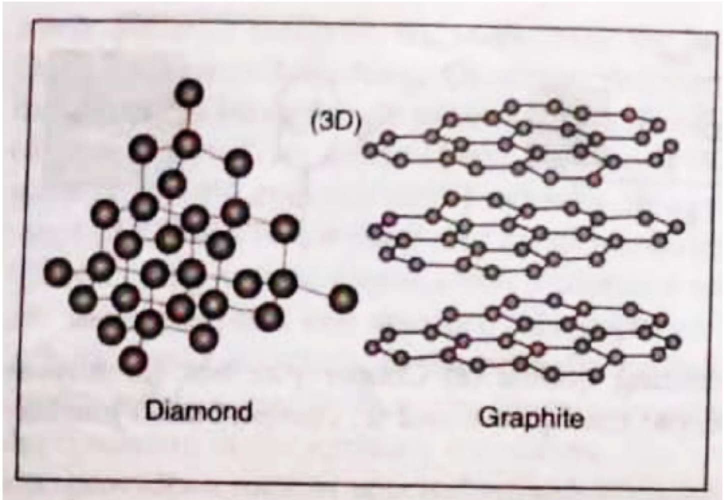
# Fullerenes

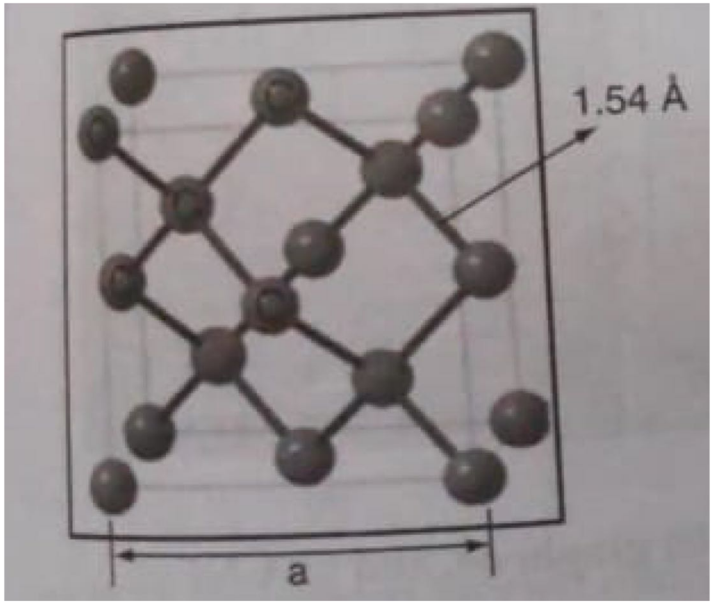
# Allotropes of Carbon

Carbon is a unique element in the periodic table that has an allotrope in all the dimensions.

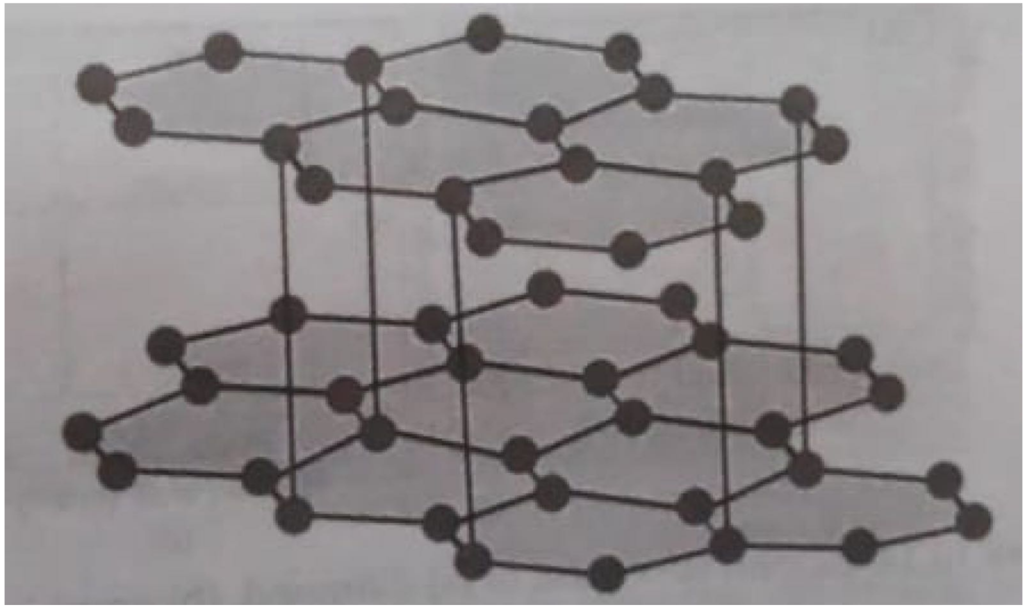
## Classical example of allotropy



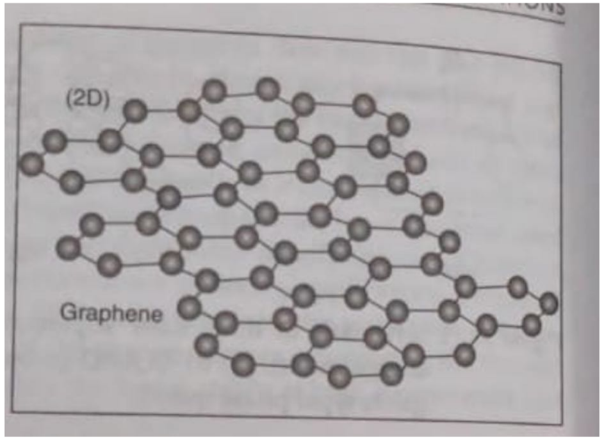

Cubic diamond along with graphite are the 3D bulk forms of carbon allotropes.




**Unit cell of diamond**



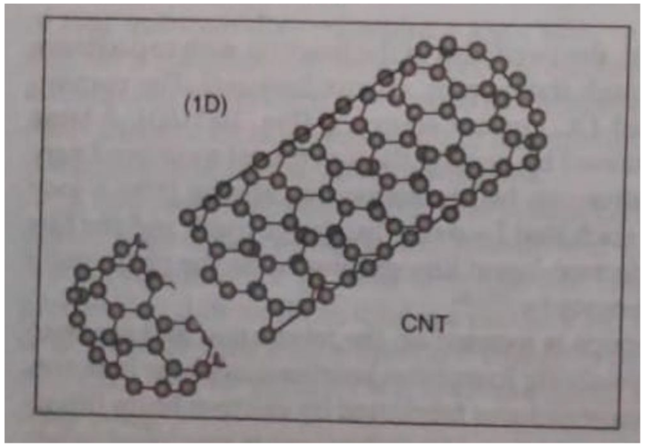
**Layered structure of Graphite**




# Newly added allotropes:

## Graphene : 2D

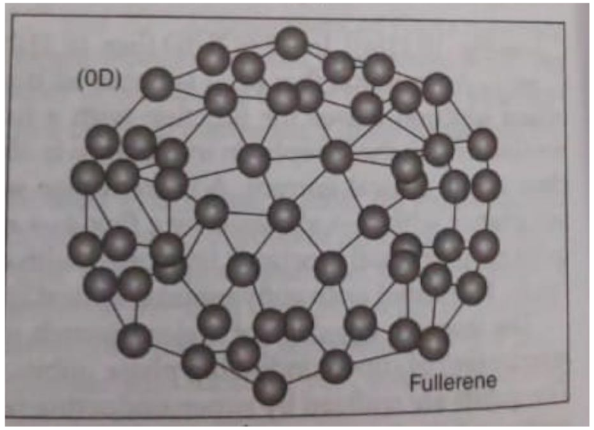
Graphene is formed by removing the single sheets from a graphitic structure




## Carbon Nanotubes: 1D

They are cylindrical fullerenes. Typical diameter of a single-walled carbon nanotube (SWCNT) is 1nm with lengths running into several micrometers. They are also called bucky tubes.

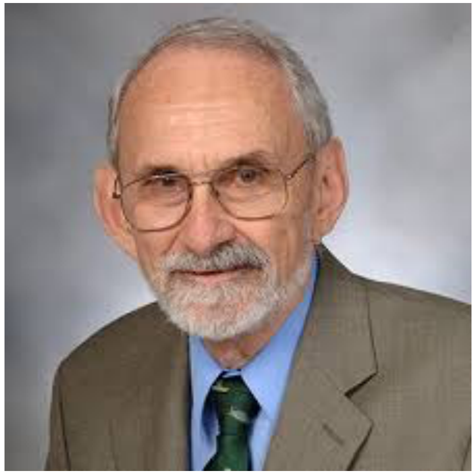
## Newly added allotropes:



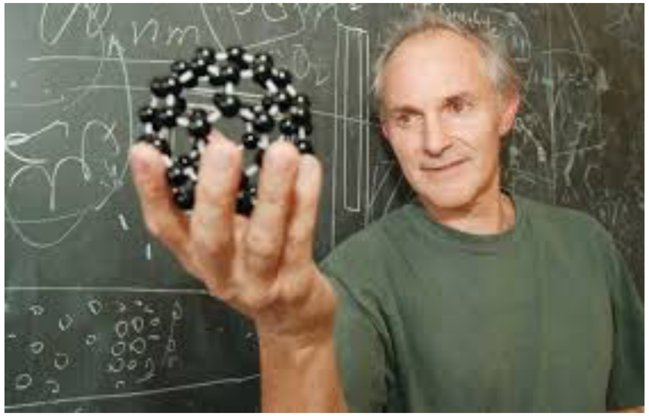

**0D form** of carbon is the **Buckminster fullerene or bucky balls**, which is the smallest fullerene molecule containing pentagonal and hexagonal rings. The structure of $C_{60}$ is a truncated icosahedron.

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

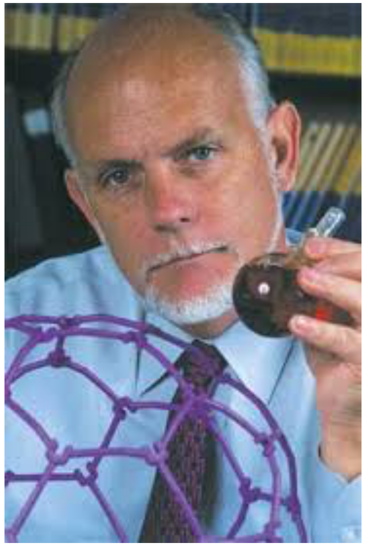
## The Nobel Prize Winners in Chemistry, 1996



**Robert F. Curl**



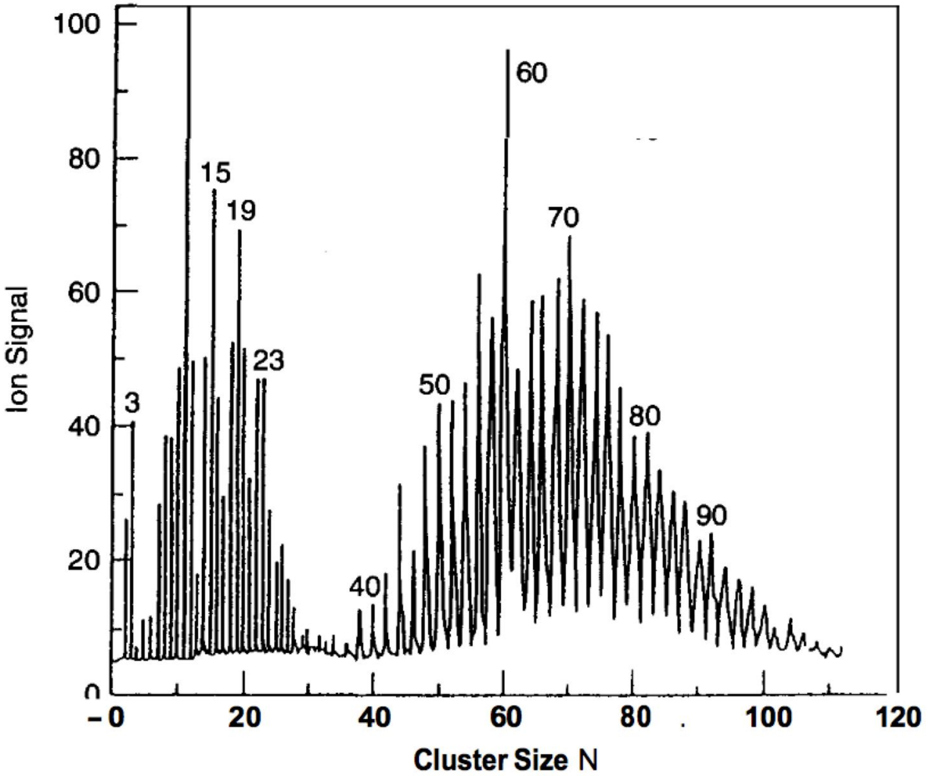
**Sir Harold W. Kroto**



**Richard E. Smalley**

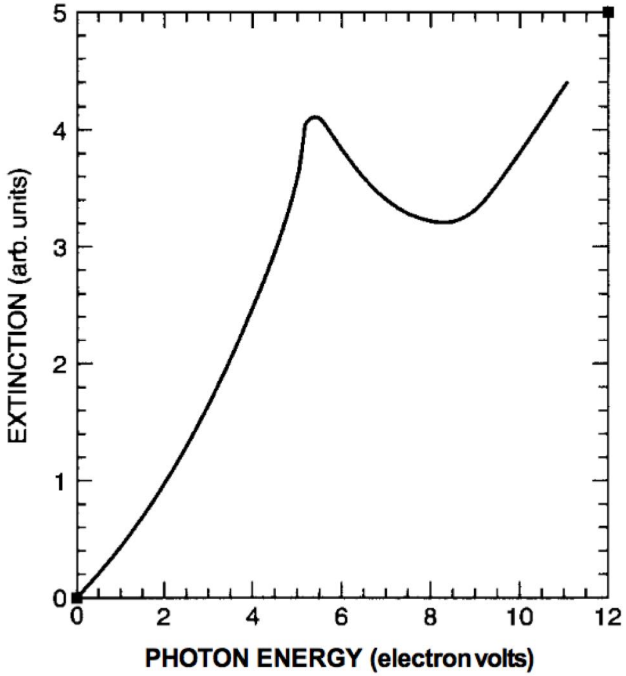
## Nobel Prize for their discovery of Fullerenes

# Discovery of Fullerene ($C_{60}$)



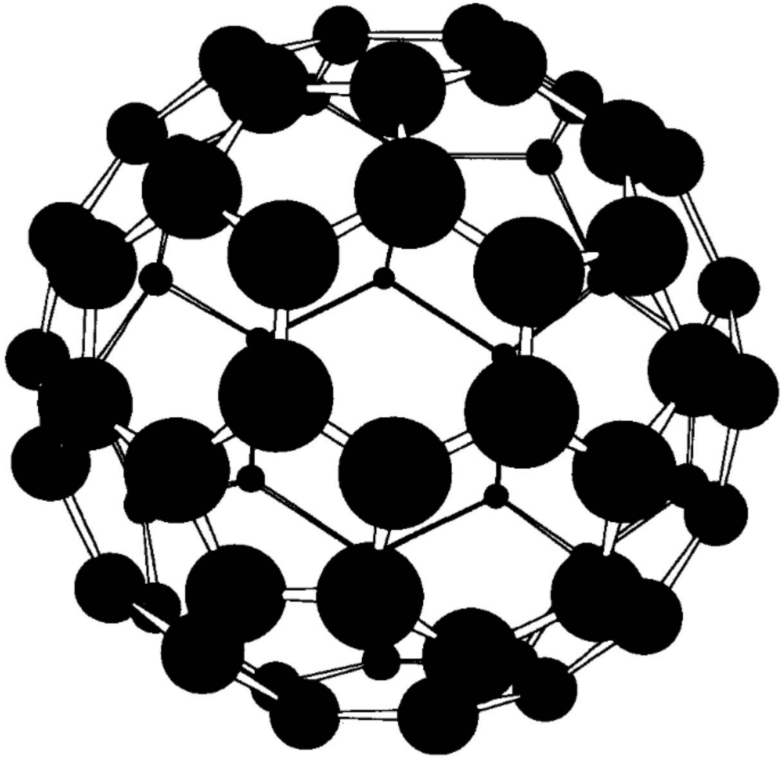

Mass spectrum of carbon clusters
The $C_{60}$ and $C_{70}$ fullerene peaks are evident

# Optical spectrum of light coming from stars




The peak at 5.6 eV 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.
- The diameter of $C_{60}$ fullerene is 0.7 nm.

## Euler's theorem

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

$$V - E + F = 2$$

must be satisfied.

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

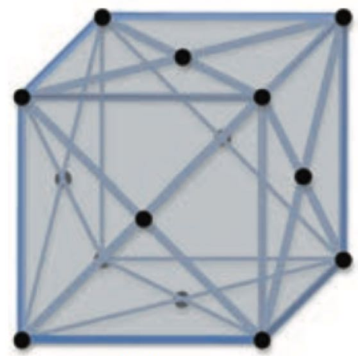
According to this theorem, any closed shell will be produced by 12 pentagons, irrespective of the number of hexagons.

## Structure of the $C_{60}$ fullerene molecule

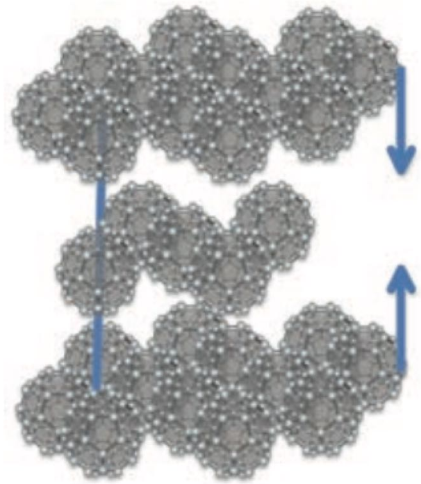

A soccer ball has the same geometric configuration as fullerene

## FCC structure of $C_{60}$ Fullerites

- The assemblies of pure fullerene molecules in the condensed form are known as fullerites.
- The crystal structure of $C_{60}$ is FCC.
- Separation between nearest-neighbour $C_{60}$ is 1 nm.
- They are held together by weak van der Waals forces.
- The FCC crystal of $C_{60}$ is an insulator.



(a)

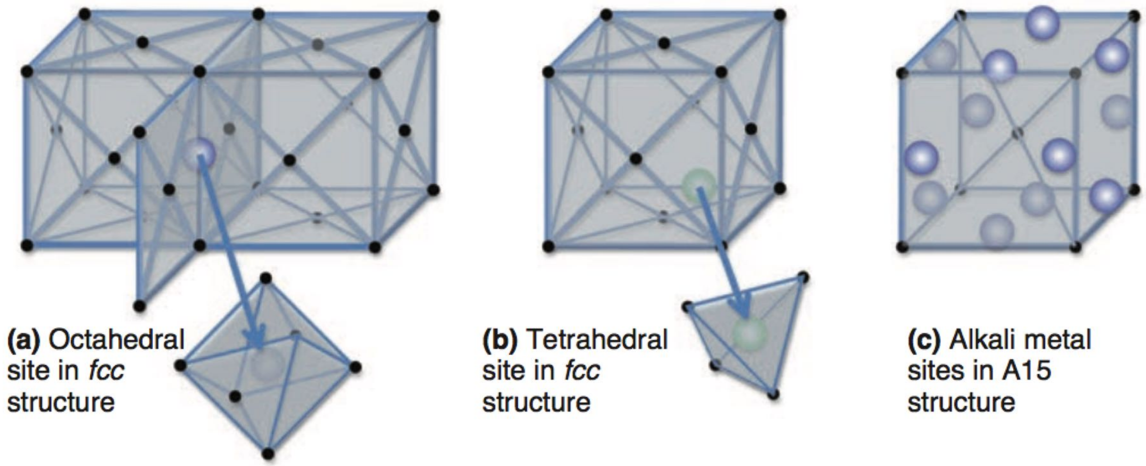


## Application of Fullerites

- When exposed to intense UV light, fullerene molecules in fullerite polymerize. Pure fullerite will dissolve in toluene but becomes insoluble in its polymerized state.

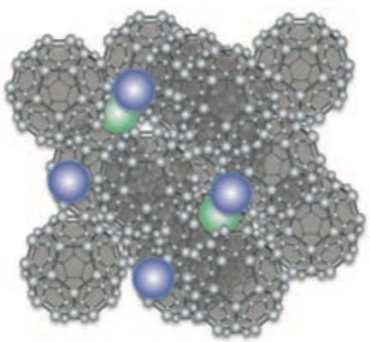
- This photosensitivity makes it useful as a **photoresist** in lithographic processes.

## Fullerides

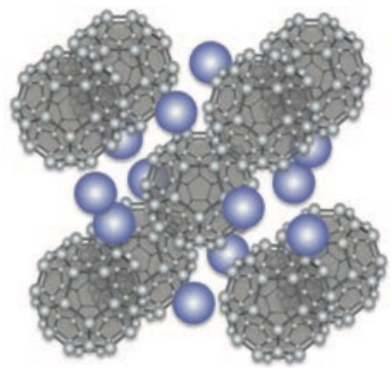



When other atoms are included in the fullerite lattice, a compound known as a fulleride is produced.

## Structure of $C_{60}$-alkali metal Fullerides



**(d)** *fcc*-based $A_3C_{60}$ structure ($Na_3C_{60}$, $K_3C_{60}$, $Rb_3C_{60}$)

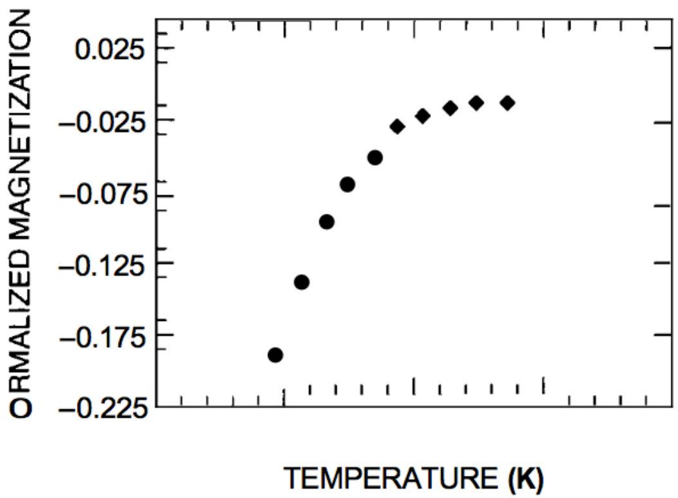


**(e)** *bcc*-based A15 structure ($Cs_3C_{60}$)

**(A: represents Alkali atoms)**

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

## Superconductivity in $C_{60}$

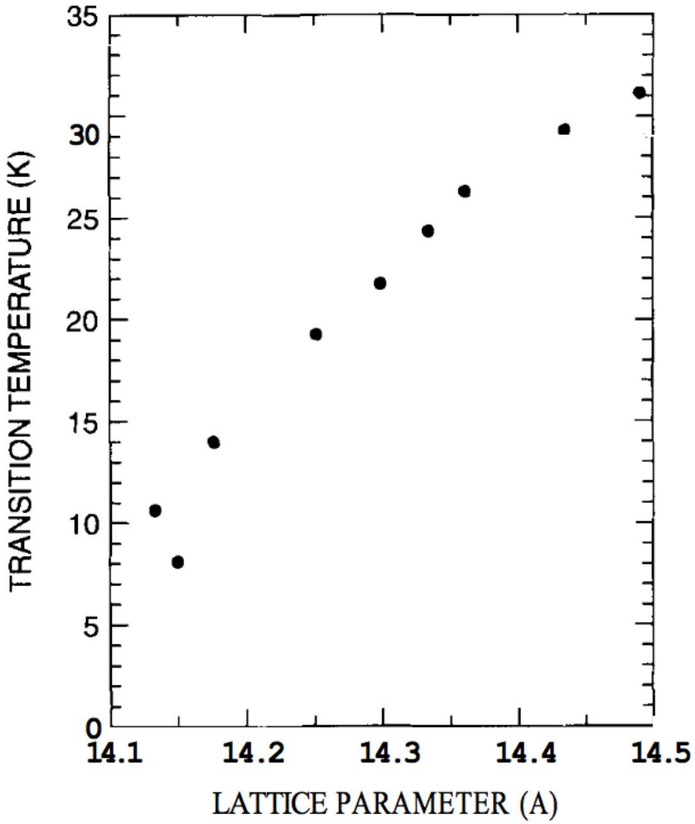



Fullerides have the remarkable property of superconductivity.

Magnetization of $K_3C_{60}$ showing transition to the superconducting state.

The transition temperature is 18K.

Plot of transition temperature of $A_3C_{60}$ , where A is an alkali atom




As the radius of the dopant alkali atom increases, the cubic $\boldsymbol{C_{60}}$ 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 |

## Magic numbers in larger fullerenes

There is a series of stable fullerenes containing n = $\mathbf{60 + (\boldsymbol{k} \times 6)}$ **atoms**

where $k = 0,2,3,4,5\ldots..$

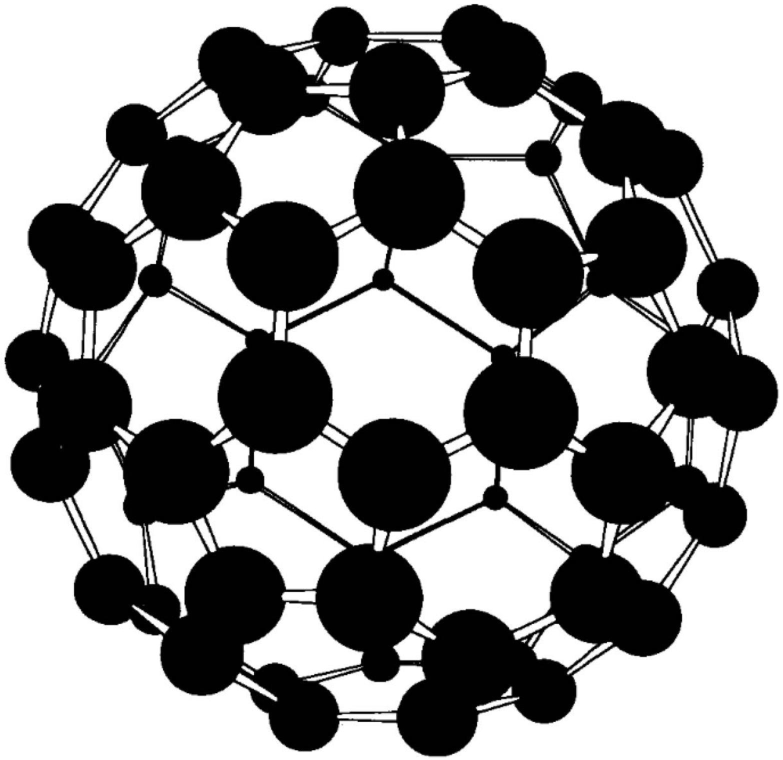
with increasing number of hexagons.

For a stable fullerene with n atoms,

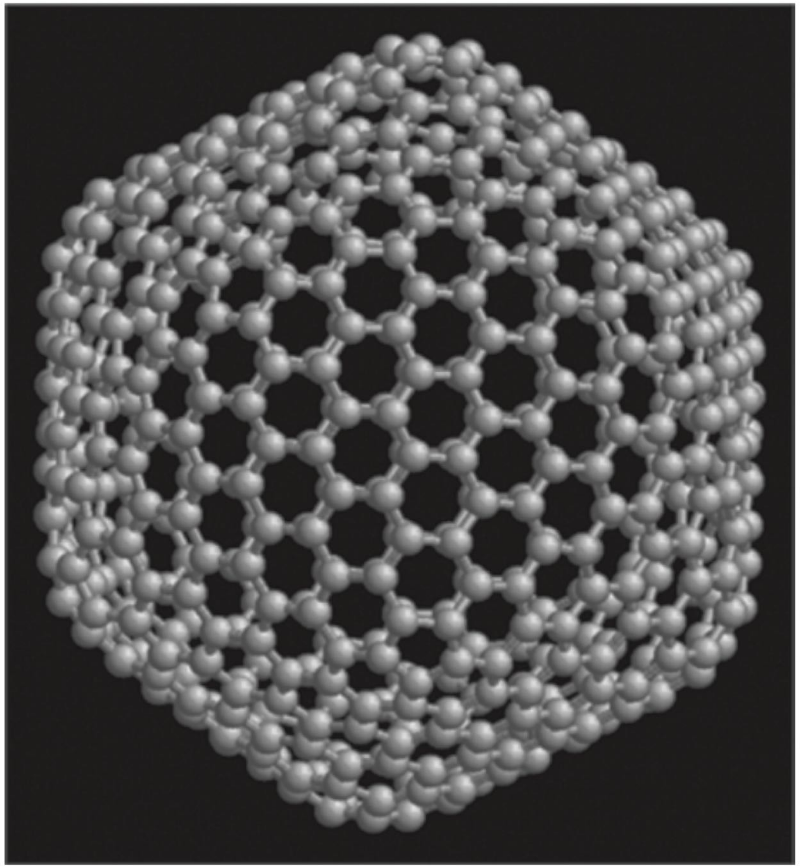
$$\text{Number of hexagons} = \frac{n}{2} - 10$$

They correspond to stable numbers of atoms with a low-energy morphology. They are known as **magic numbers.**

## Examples of large fullerenes

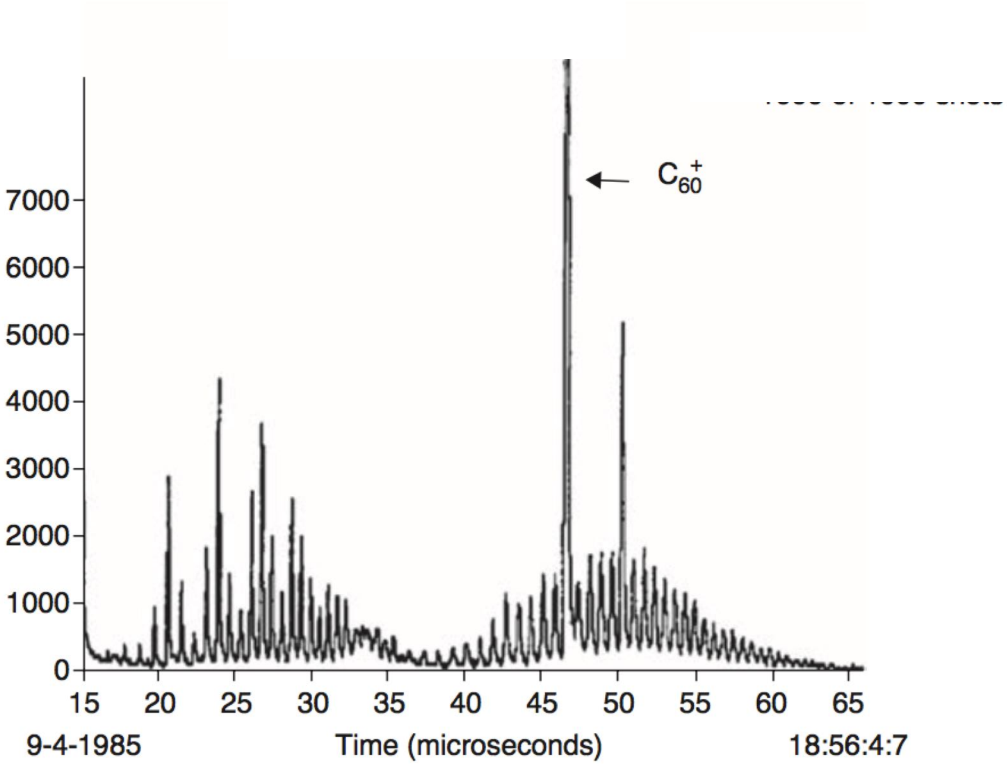


**Icosahedral structure of $C_{60}$**
(magic number $k = 0$)

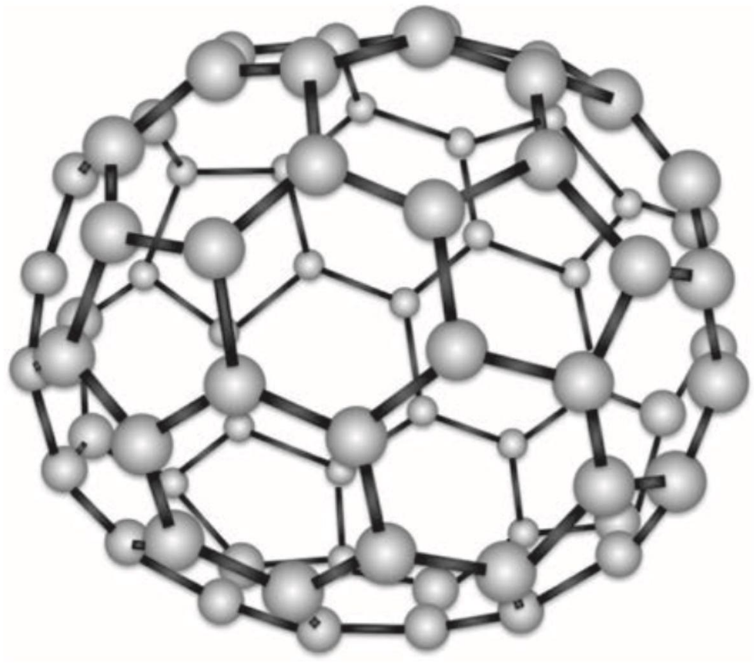


**Icosahedral structure of $C_{540}$**
(magic number $k = 80$)

# 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

Two extra series with stable numbers of atoms, giving rise to elliptical and tubular fullerenes :

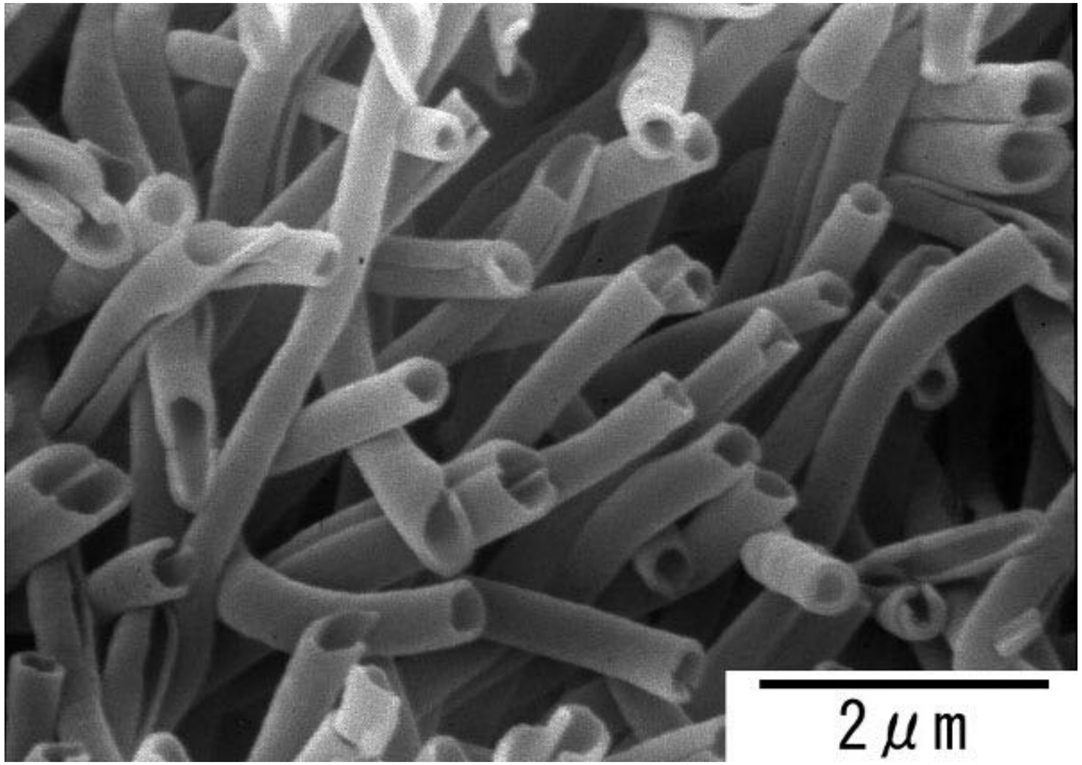
$70 + 30k \quad (\mathrm{k} = 0,1,2,3\ldots\ldots\ldots).$

$\boldsymbol{C_{70}}$: First in this series

$84 + 36k \quad (\mathrm{k} = 0,1,2,3\ldots\ldots\ldots).$

Each next larger member is produced by a tubular extension about the long axis.

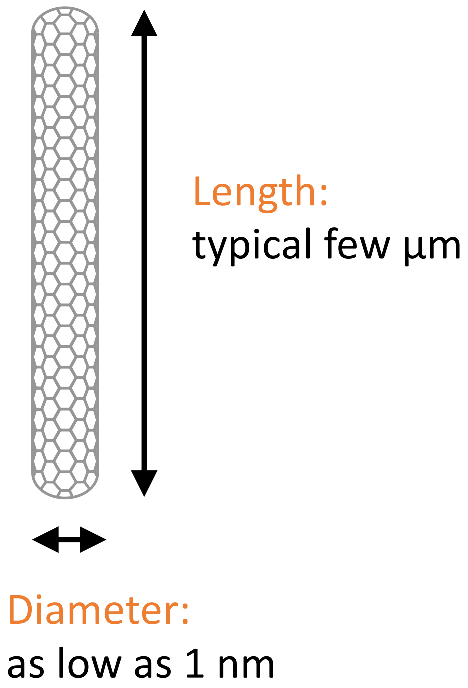
# Carbon Nanotubes




SEM image of Carbon Nanotubes

# 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



# Types of Carbon Nanotubes

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

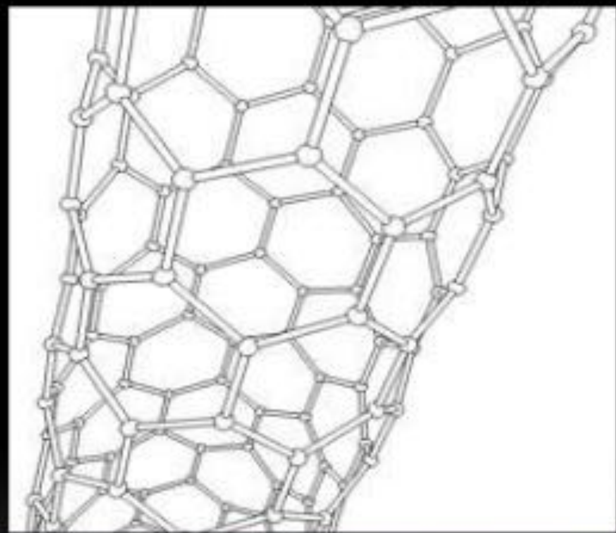
# SINGLE WALLED NANOTUBES

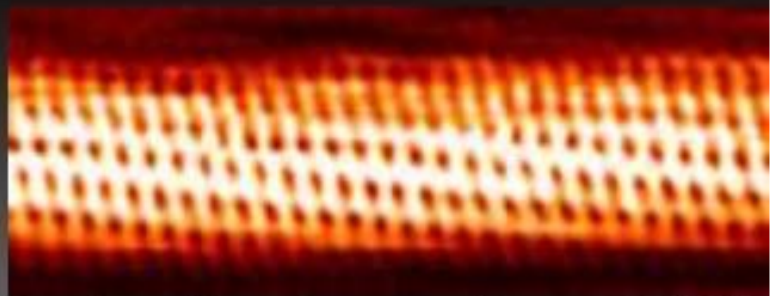
**Diameter :- 1 nanometer**

Band gap :- 0-2ev

A one atom thick layer of graphene into seamless cylinder .

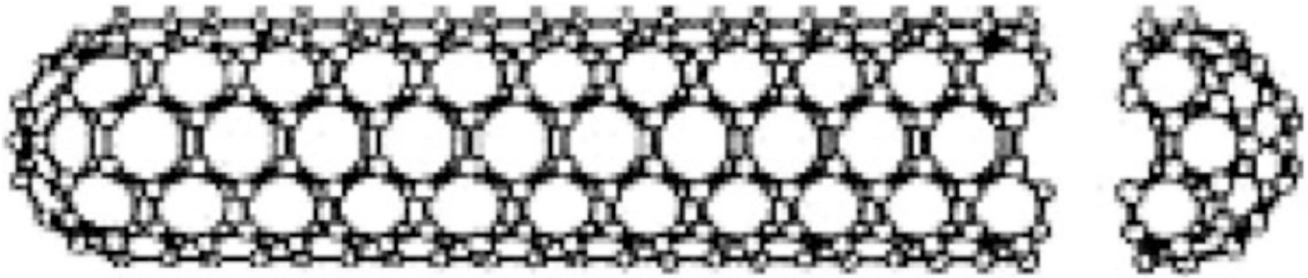
Their electrical conductivity can show metallic or semiconducting behaviour.





**A scanning tunnelling microscopy image of SWNT**

# SWNT



During their formation, nanotubes get capped with hemispheres of fullerenes.

# MULTI WALLED NANOTUBES

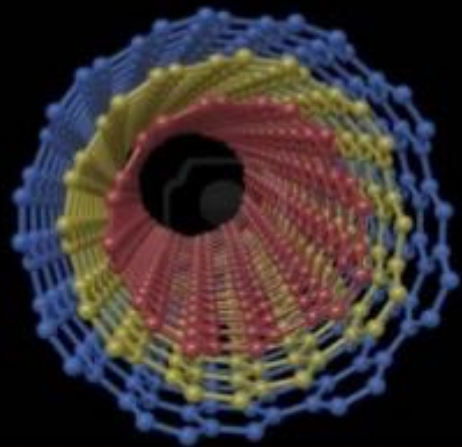
Multi-walled nanotubes (MWNT) consis
of multiple rolled layers (concentric tube
of graphene.

Interlayer distance :- 3.4 Å

To describe structure of MWNT there ar
two models:-

1. Russian doll model

2. Parchment model



## Models of MWCNT

Two models best describe the structure of MWCNT

- In the Russian doll model, graphite sheets are arranged in concentric cylinders—literally tubes inside of larger tubes.

- In the Parchment model, a single sheet of graphite is wrapped around itself, resembling a scroll of parchment or a rolled up newspaper.

The interlayer spacing is close to the distance between the individual graphene layers in graphite ($\sim 3.4\ A^{0}$)

## Fabrication of CNT

Carbon nanotubes can be made by

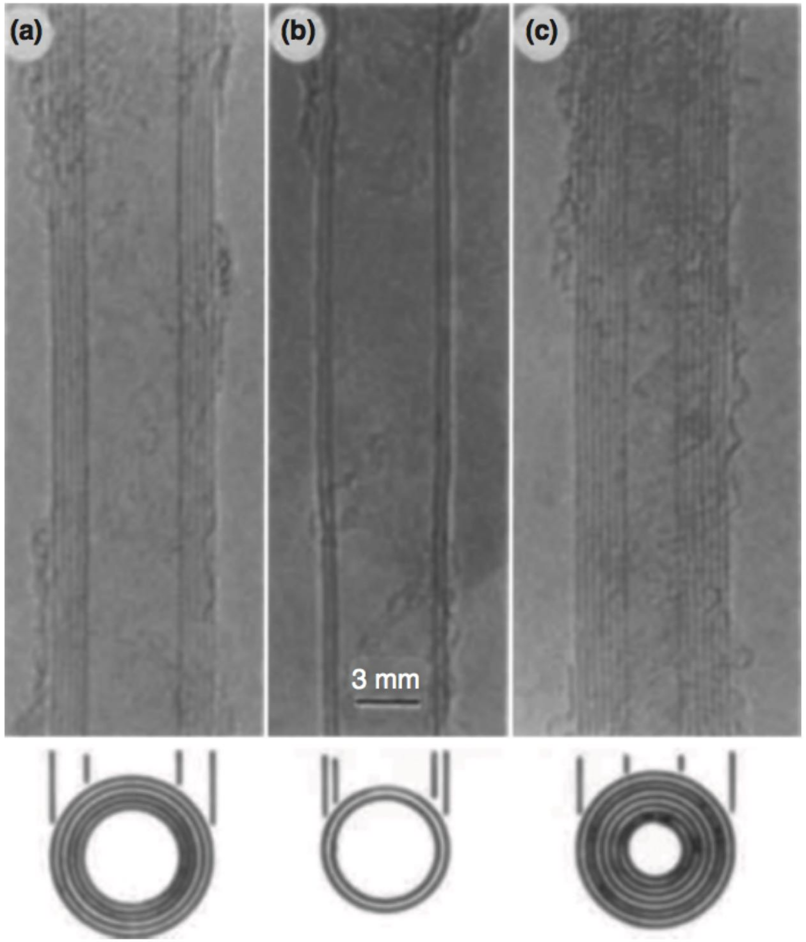
(i) Laser evaporation
(ii) Carbon arc method
(iii) Chemical vapour deposition(CVD)

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.

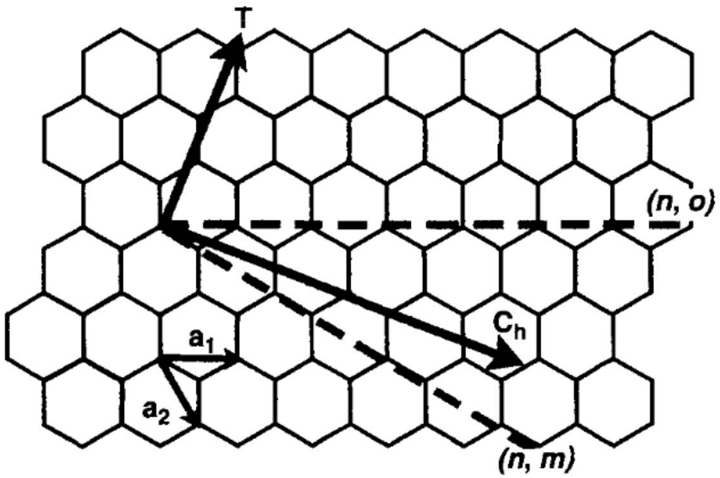
# Discovery of carbon nanotubes (CNT)




First EM images of carbon nanotubes by Sumio Iijima

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

# Structure of SWNTs




Graphitic sheet

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.

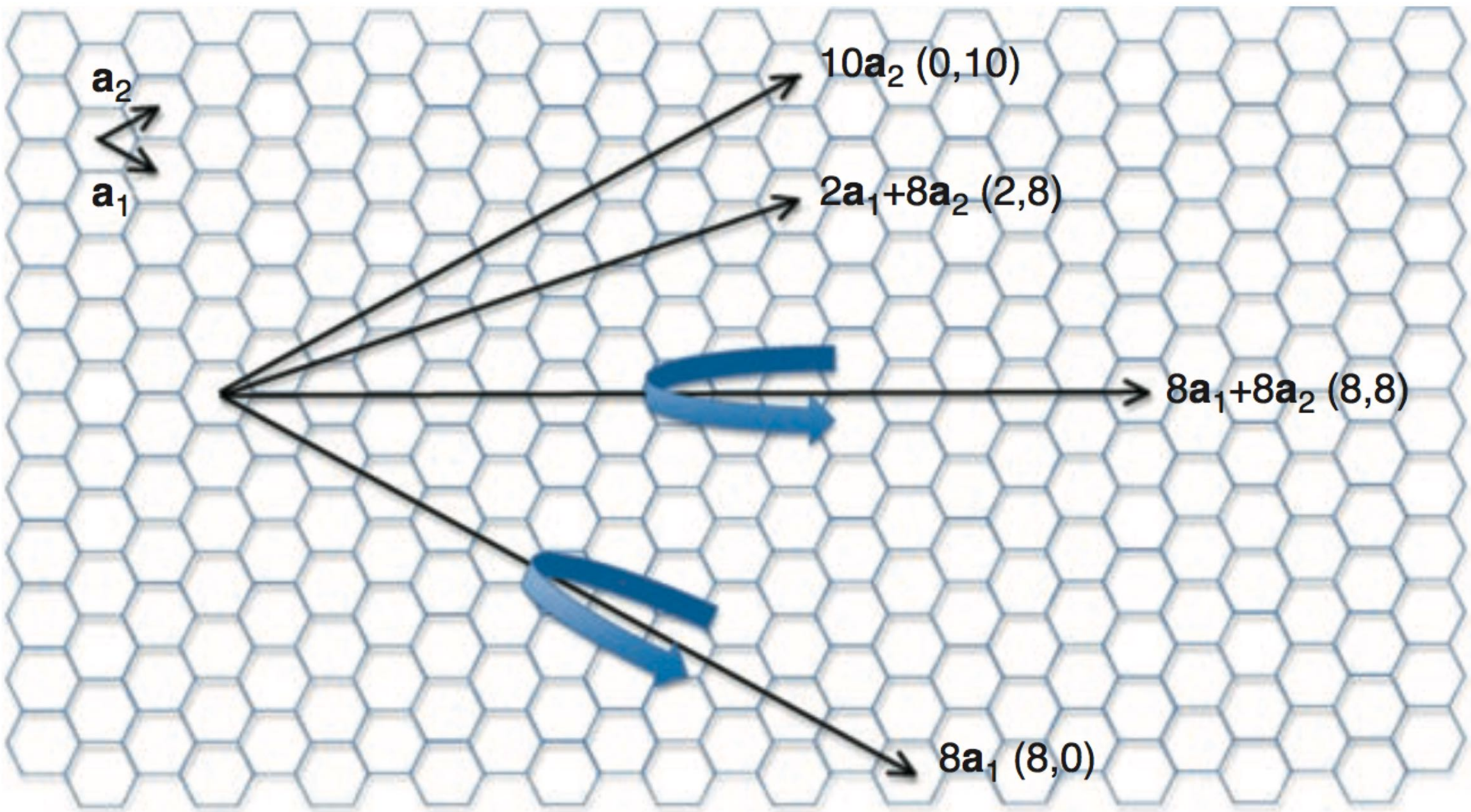
# Chirality

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.

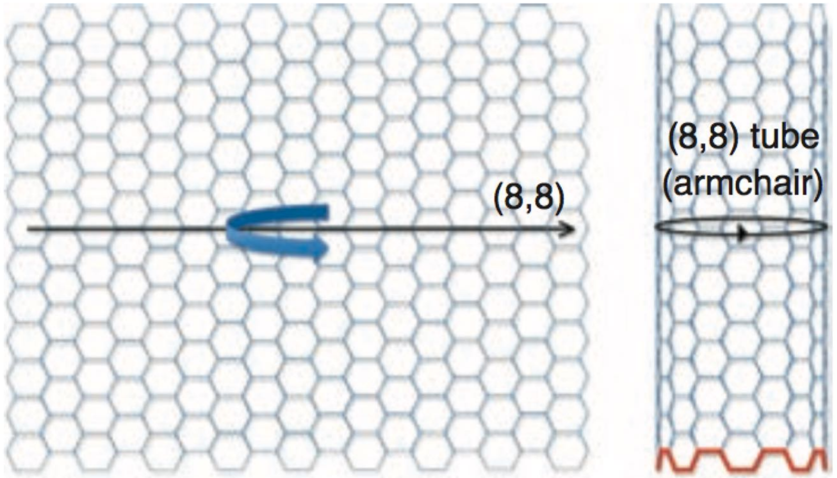
# Nanotube Chiralities




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

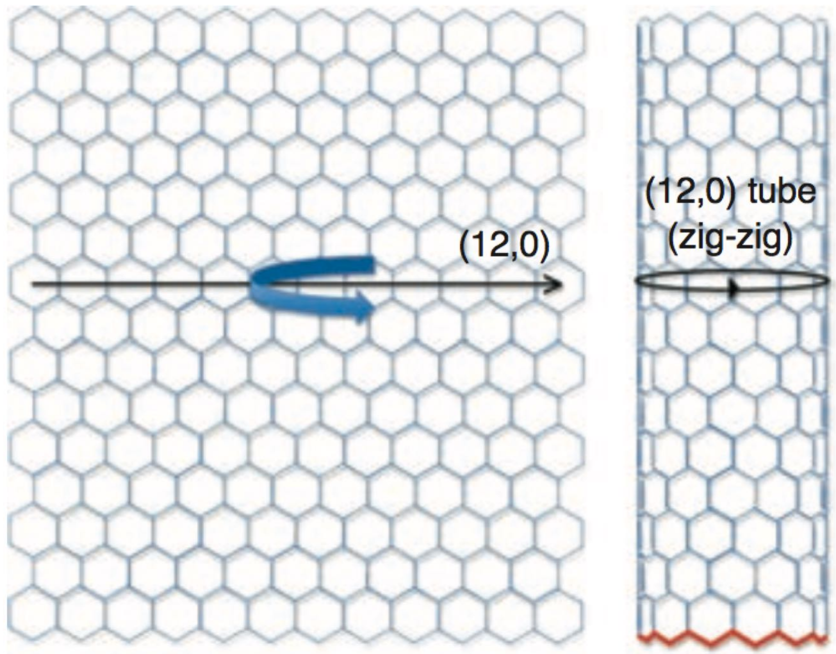
The tube is generated by rolling the graphene lattice so that the vector lies on the circumference.

# Nanotube Chiralities



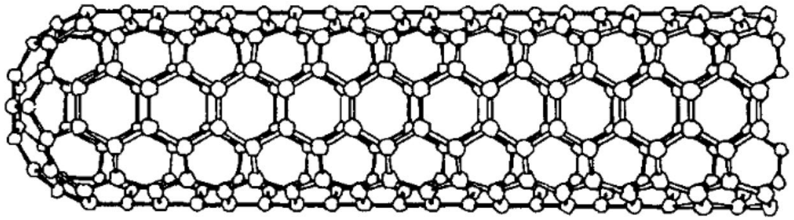

Any (n,n) tube will have an armchair configuration.

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

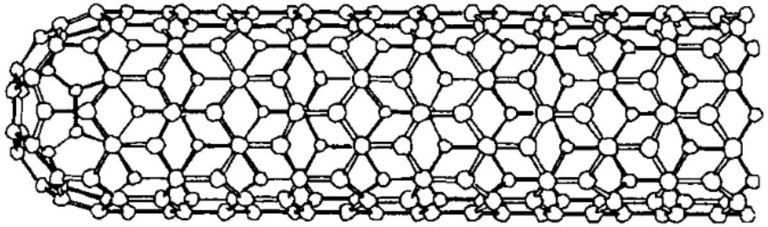



The ends of the tubes are often terminated by a half-fullerene

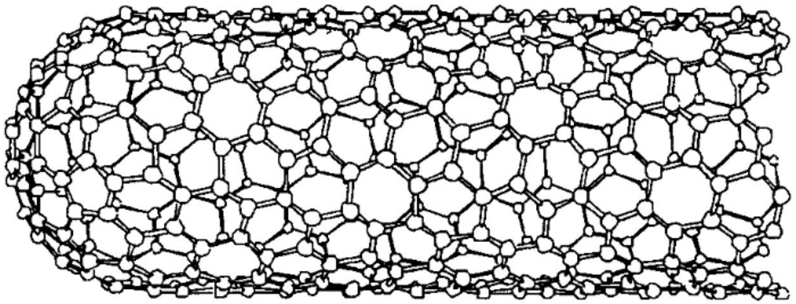
# Classification of carbon nanotubes based on structures



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



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



**Chiral structure (Any $n \neq m$ *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

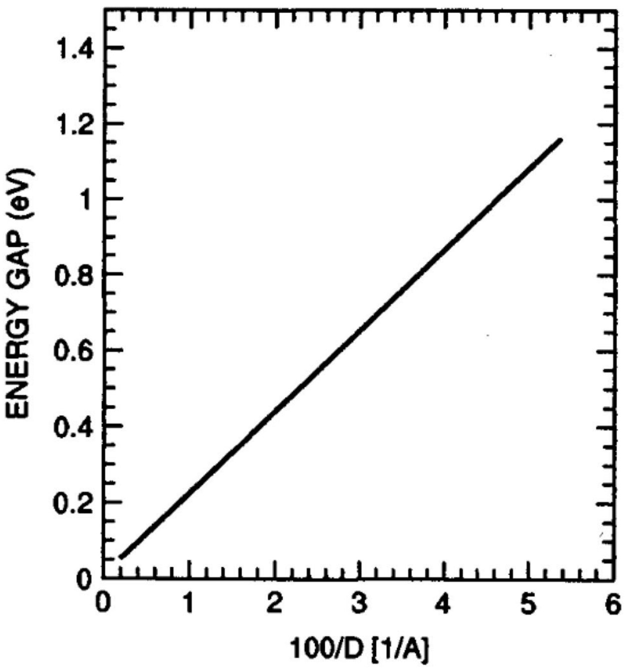
Depending on the diameter & chirality of the tube, carbon nanotubes are metallic or semiconducting.

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.

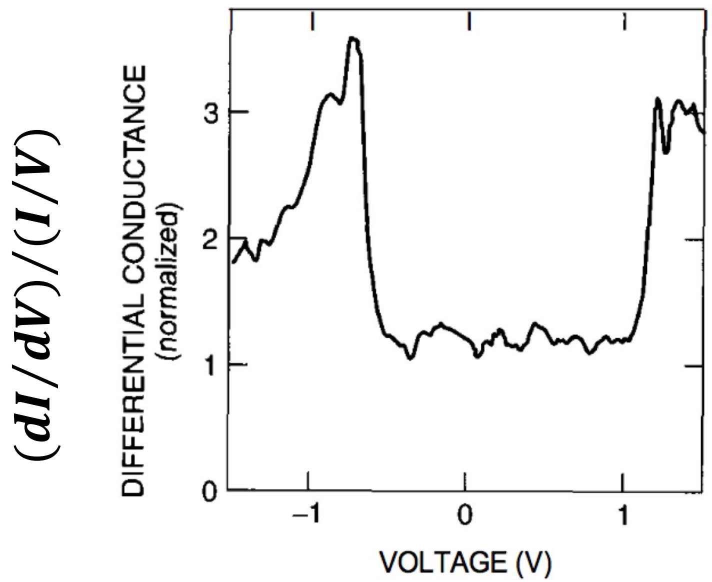
- Any tube for which $n - m \neq 3i$ is semiconducting with a bandgap that is inversely proportional to the tube diameter.

# Electrical properties

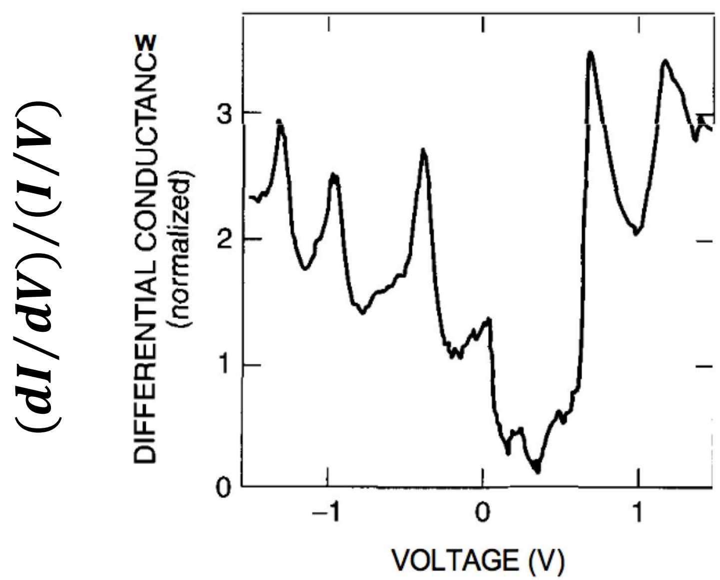



As the diameter of the semiconducting nanotube increases, the bandgap decreases.

# Scanning Tunneling Microscope(STM) measurement of tunneling current




**Metallic nanotubes**




**Semiconducting nanotubes (Energy gap = 0.7 eV)**

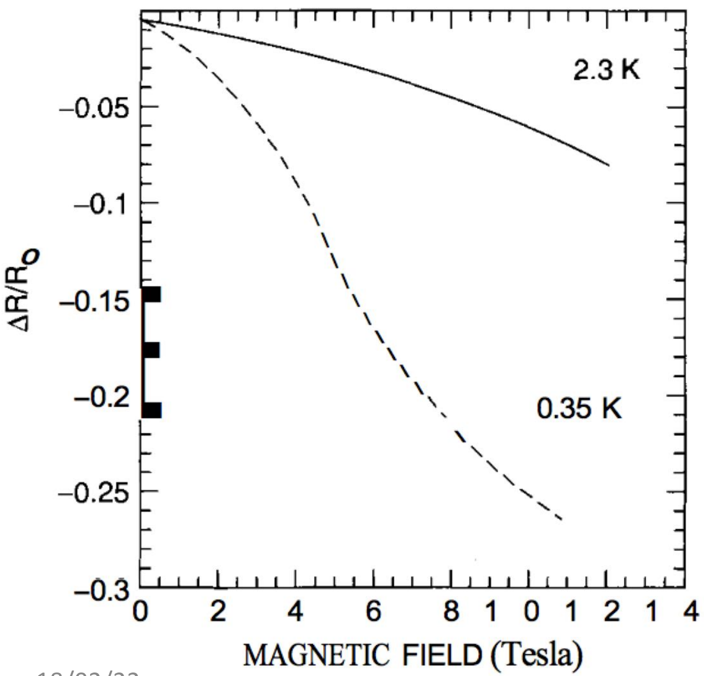
# Electrical properties

**High electrical conductivity:**

Copper wire fails at 1 million $Amp/cm^2$.
But metallic nanotubes can carry 1 billion $Amp/cm^2$

# Magnetoresistance

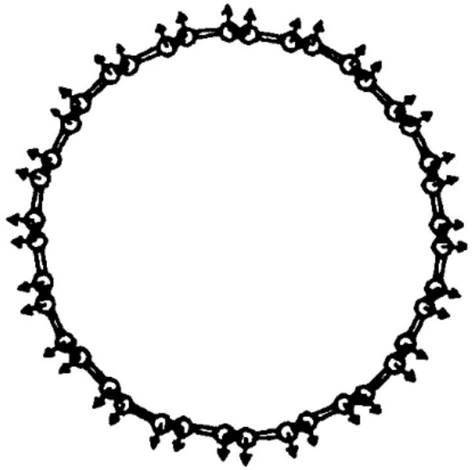
**Magnetoresistance** is a phenomenon whereby the resistance of a material is changed by the application of a DC magnetic field.




CNT shows negative magnetoresistance effect.

Hence conductance $G = I/R$ increases.

# Vibrational properties

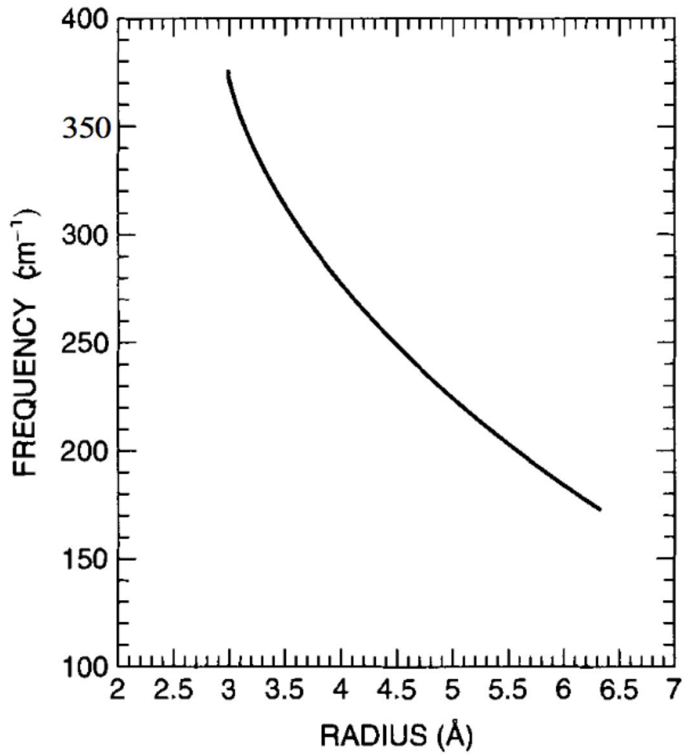




$\boldsymbol{E_{2g}\ mode}$:
Oscillating between
a sphere and an ellipse

$\boldsymbol{A_{1g}\ mode}$: "*in and out*" oscillation
of the diameter of the tube

# Vibrational properties

Frequencies of $\boldsymbol{E_{2g}}$ and $\boldsymbol{A_{1g}}$ modes are Raman active and they depend on the radius of the tube.




**Raman vibrational normal Mode of $\boldsymbol{A_{1g}}$.**

## Mechanical properties

Young's modulus of steel is 0.21 Terrapascal(TPa) (30,000 times that of rubber).

Young's modulus of CNT : 1.28 to 1.8 TPa (10 times that of steel)

When CNTs are bent, they are very resilient – Because, the hexagonal carbon rings in the walls change in structure but do not break.

High-strength steel alloys break at about 2 billion pascals.

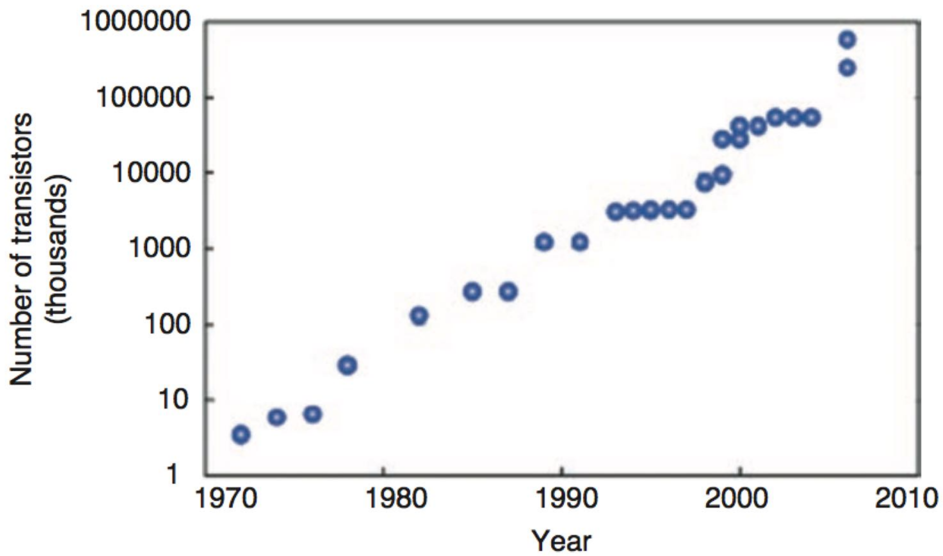
CNTs are about 20 times stronger than steel.

MWNTs are not as good as SWNTs: MWNTs of 200 nm diameter have a tensile strength of 0.007 Tpa and a modulus of 0.6 Tpa.

## Thermal properties

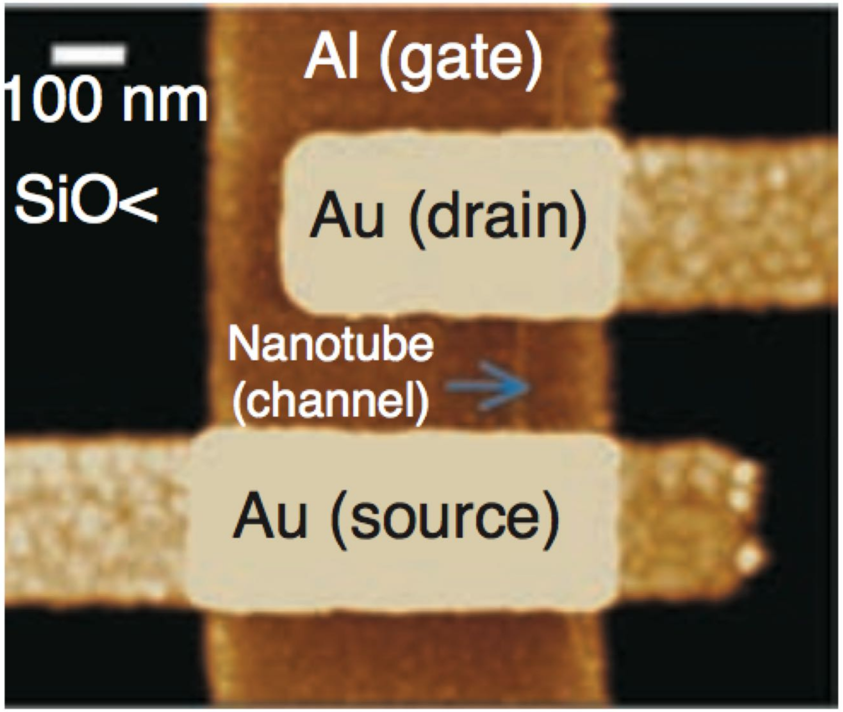
- Carbon nanotubes also display a huge thermal conductivity.
- Thermal conductivity(K) of 6600 $W/mK$ has been predicted for a single (10,10) armchair nanotube.
- Thermal conductivity of over 3000 $W/mK$ has been demonstrated for a single MWNT.
- K value of CNT is almost a factor of 2 more than that of diamond.

# Moore's Law



1000000
100000
10000
1000
100
10
1
Number of transistors (thousands)
1970
1980
1990
2000
2010
Year

# A Carbon Nanotube FET integrated circuit



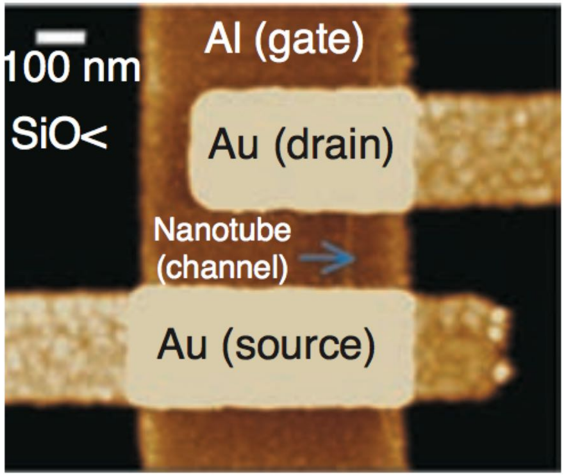

**AFM image of an individual semiconducting CNT Field Effect Transistor (FET)**

3 steps to fabricate a nanotube transistor:

- **Gate electrodes** : EBL was used to deposit Al wires (~ $1\mu m$ width) onto the oxidized Si substrate.

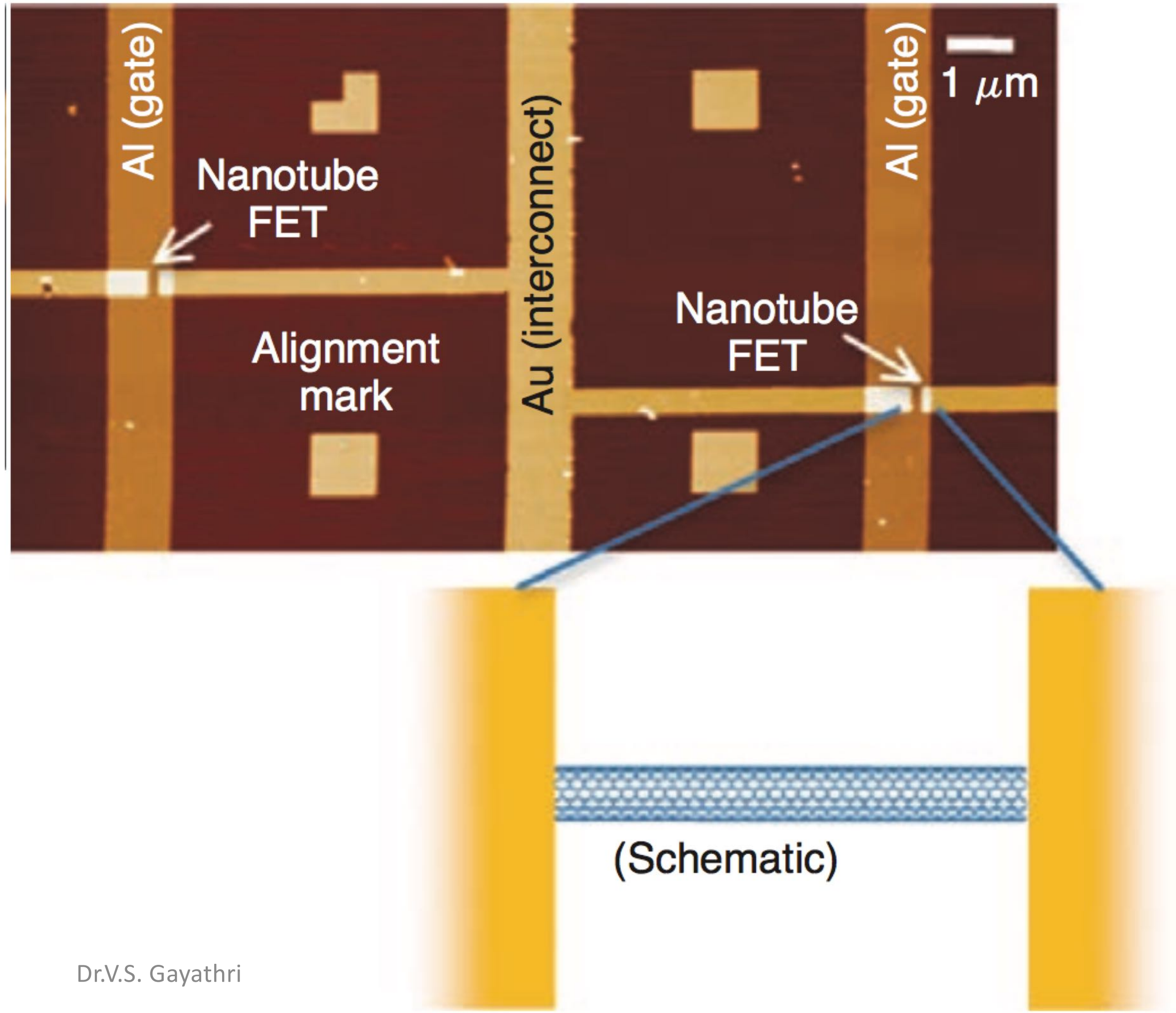
- Insulating barrier between the gate electrode and nanotube: It is the natural oxide formed on the Al wires on exposure to air.

- **Semiconducting nanotubes** were deposited from a liquid suspension & maneuvered onto the gate electrodes using an AFM tip
- **Source & drain electrodes:** A suitable pattern of Au electrodes were deposited using EBL

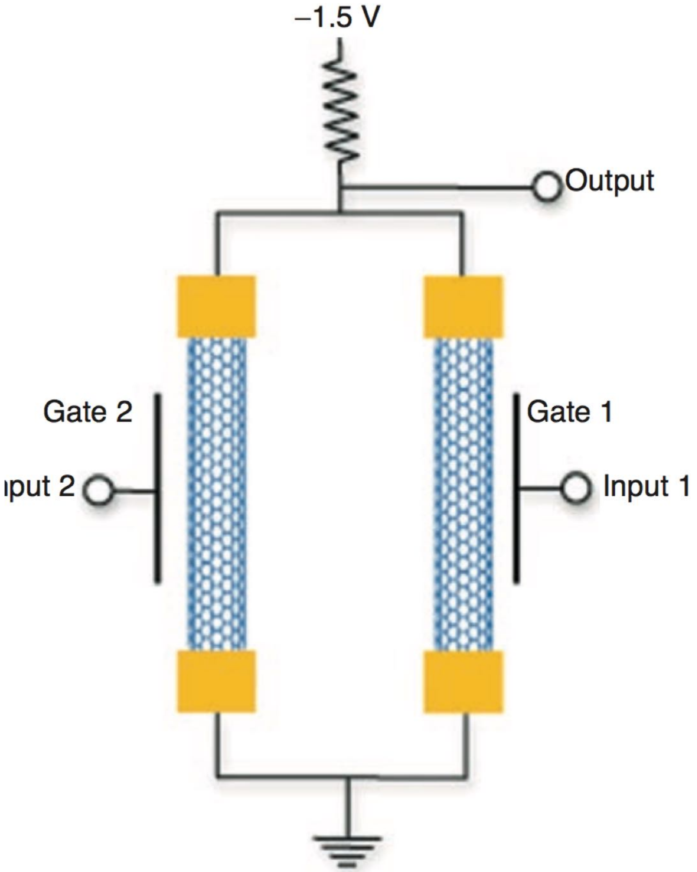


# A Carbon Nanotube FET integrated circuit

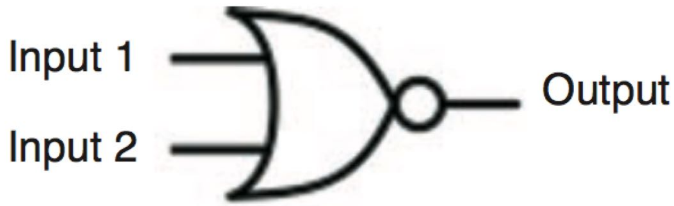
**AFM image of a two nanotube FET integrated circuit after deposition of the Au electrodes and interconnects.**



**Schematic of a nanotube FET Integrated circuit**




**Operates as a Logic NOR gate**

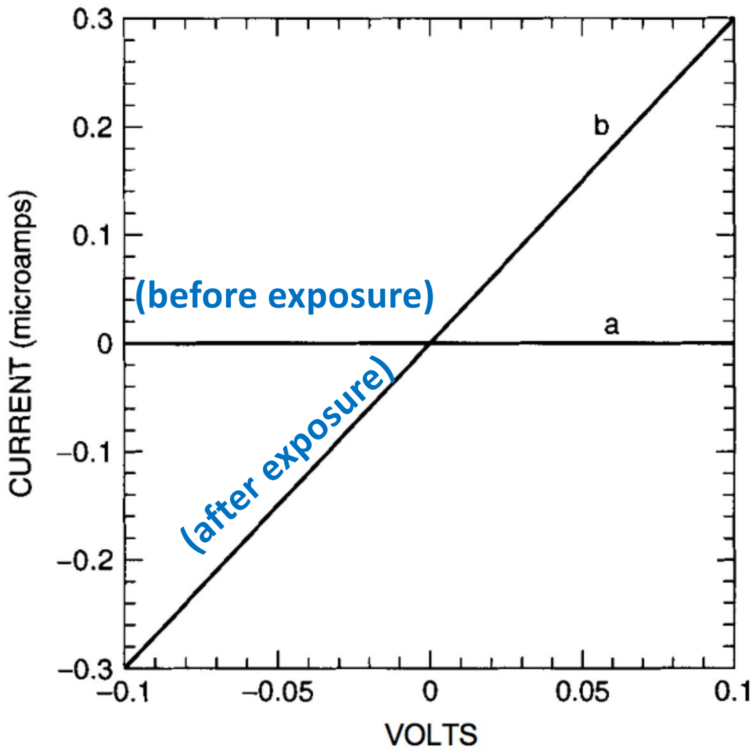



‘0’ = 0 V, ‘1’ = −1.5 V

| Input 1 | Input 2 | Output |
|---|---|---|
| 0 | 0 | 1 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 0 |

**Can be a building block of a microprocessor circuit.**

# Chiral semiconducting nanotube FET as a chemical sensor




❖ Gate voltage = 4V.

❖ Two to 200 parts/million of $NO_2$ flowing at a rate 700 ml/min for 10 mins caused **a three fold increase in conductance of the CNT**.

Nanotube tip has many advantages over conventional
AFM tips:

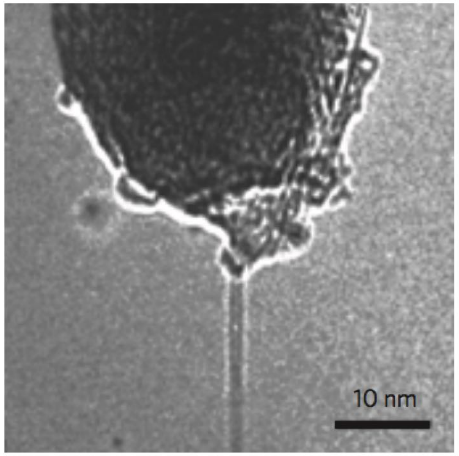
(i) High-resolution topographic imaging.
(ii) Due to reversible buckling & bending characteristics, tip damage of a nanotube tip is significantly reduced (at least a 20 times improvement in the lifetime over conventional silicon probes)
(iii) The exceptional nanotube stiffness allows the use
Of MWNTs (or bundles of SWNTs) with $\mu m$ lengths
And aspect ratios of ~ 100, enabling the probing of structures
Inaccessible to conventional silicon tips.

(iv) Being a high-aspect-ratio probe, nanotube tips are ideal for
Electrostatic force microscopy (EFM).

(iv) Being a high-aspect-ratio probe, nanotube tips are ideal for Electrostatic force microscopy (EFM).

(v) By attaching the end of a MWNT tip with either a magnetic catalyst particle or by filling/coating nanotubes with magnetic material, can be used for high-resolution magnetic force microscopy(MFM).

**TEM image of a 0.9nm diameter SWNT tip**



# Flat screen displays: **Field Emission**

- Television and computer monitors use a controlled electron gun to impinge electrons on the phosphors of the screen, which then emit light of the appropriate colors.

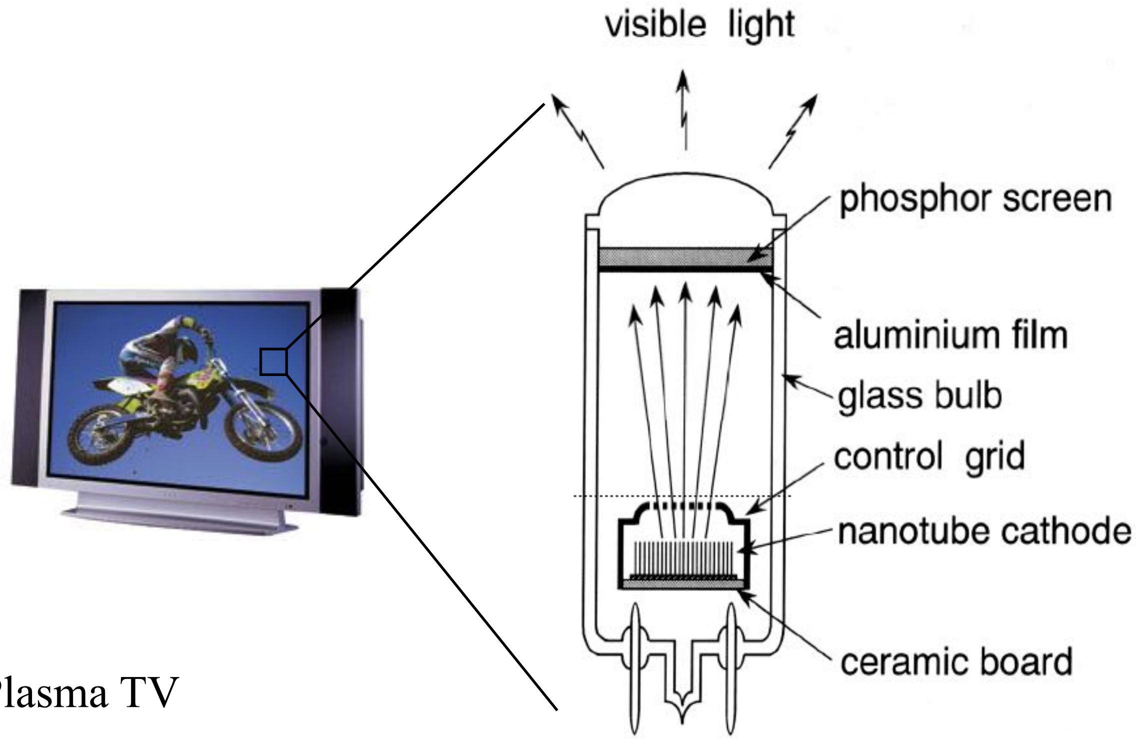
- When a small electric field is applied parallel to the axis of a nanotube, electrons are emitted at a very high rate from the ends of the tube. This is called field emission.

- This effect can easily be observed by applying a small voltage between two parallel metal electrodes, and spreading a composite paste of nanotubes on one electrode.

- **A** sufficient number of tubes will be perpendicular to the electrode so that electron emission can be observed.

- One application of this effect is the development of flat panel displays.

# Field Emission




Plasma TV

# Graphene

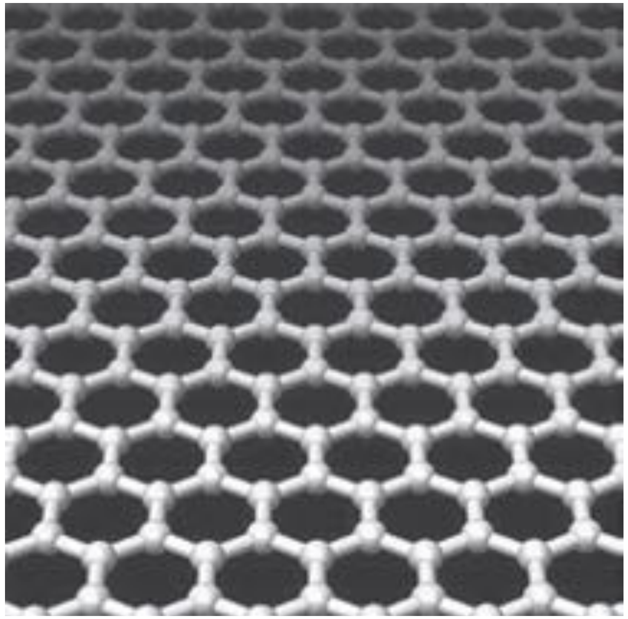
- A single atomic plane of graphite, known as *graphene.*

- *Graphene is a* 2-dimensional, crystalline allotrope of carbon.

- It is a flat hexagonal arrangement of carbon atoms with very strong bonding in-plane.

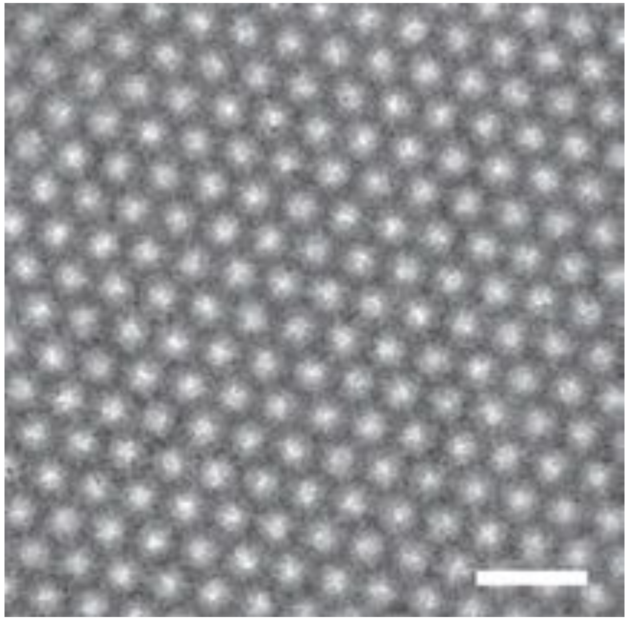
- Because it has become possible to isolate and study these individual atomic planes, graphene has recently become the focus of a significant research effort.

- The flat perfect hexagonal arrangement, however, is hard to isolate and quite unstable.



Honeycomb (hexagonal) lattice arrangement of carbon atom

- The existence of defects such as pentagonal or heptagonal rings will bend and warp the sheets, and they have a tendency to roll up to form tubes or spherical cages. This is the basis of the formation of fullerenes, including bucky balls and nanotubes.



Transmission Electron Microscope (TEM) image of a single graphene layer showing the hexagonal arrangement of carbon atoms.

# History

- Graphene theory first explored by P.R. Wallce (1947)
- Andre Geim & Konstantin Novoselov got Nobel Prize in physics (2010) for their outstanding research on Graphene.
- Geim and Novoselov extracted the graphene from a piece of graphite such as is found in ordinary pencils. Using regular adhesive tape they managed to obtain a flake of carbon with a thickness of just one atom.

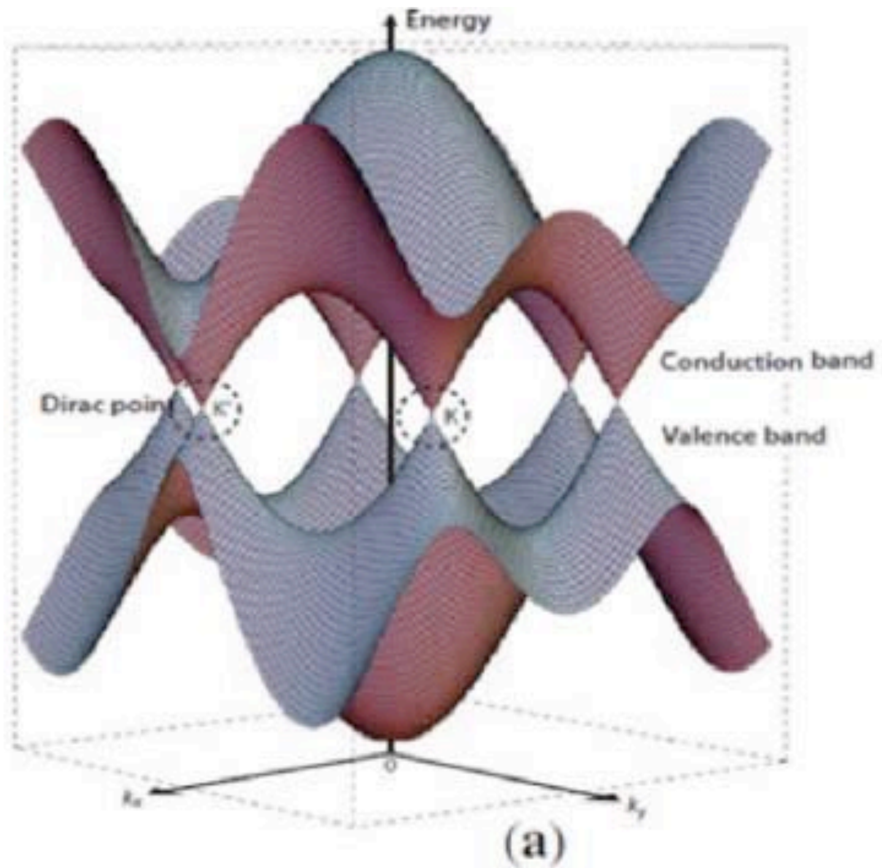
## Electronic Structure of Graphene

- The electronic structure of graphene is rather different from usual 3D materials. Its Fermi surface is characterized by six double cones.

- In intrinsic (undoped) graphene, the Fermi level is situated at the connection points of these cones. Since the density of states of the material is zero at that point, the electrical conductivity of intrinsic graphene is quite low.

- The Fermi level can, however, be changed by an electric field so that the material becomes either n-doped (with electrons) or p-doped (with holes) depending on the polarity of the applied field.

- Graphene can also be doped. The electrical conductivity for doped graphene is quite high and may even be higher than that of copper at even room temperature.




Energy bands near the Fermi level in graphene.

## Electronic properties

- Graphene is a zero-gap semiconductor with unique electronic properties.
- It obeys a linear dispersion relation, similar to massless relativistic particles.
- Graphene has:
    - the fastest electron mobility of ~15,000 $cm^2/(V\ s)$ or $10^6\ \Omega cm$ (lower than Ag),
    - A superhigh mobility of temperature-independent charge carriers of 200,000 $cm^2/(V\ s)$ (200 times higher than Si), and
    - An effective Fermi velocity of $10^6$ m/s at room temperature, similar to the speed of light.

## Mechanical properties

- Single-layer graphene has excellent mechanical properties with a
  - Young’s modulus of 1.0 TPa
  - stiffness of 130 GPa,
  - optical transmittance of ~97.7% (absorbing 2.3% of white light)
  - superior thermal conductivity of 5000 W/(m K) (about 100 times that of Cu).
- It also has a high theoretical specific surface area of 2620 $m^2/g$, extreme electrical conductivity, and good flexibility.

# Unique Properties of Graphene

## Charge carrier mobility:

One of the interesting properties of graphene is its high charge carrier mobility, ranging between 10,000 and 200,000 Vs/cm$^2$, which is independent of temperature. Further, carrier concentration of $n$=2 × 10$^{11}$ have been reported. These numbers translate into ballistic transport in the micrometer range.

## Density of graphene:

The unit hexagonal cell of graphene contains two carbon atoms and has an area of 0.052 nm$^2$. thus the density is 0.77 mg/m$^2$.

## Optical transparency of graphene:

Graphene is almost transparent; it absorbs only 2.3% of the light intensity, independent of the wavelength in the optical domain.

**Strength of graphene:**

Graphene appears to be one of the strongest materials. Graphene has a breaking strength 200 times greater than steel, with a tensile strength of 130 GPa (19,000,000 psi).

Graphene has a breaking strength of 42 N/m. Steel has a breaking strength in the range of 250–1200 MPa=$0.25-1.2 \times 10^9$ N/$m^2$.

**Electrical conductivity of graphene:**

Using the layer thickness, the bulk conductivity of graphene is $0.96 \times 10^6\ \Omega^{-1}\ cm^{-1}$. This is higher than the conductivity of copper, which is $0.60 \times 10^6\ \Omega-1\ cm^{-1}$.

**Thermal conductivity:**

The thermal conductivity of graphene is approximately 5000 W/(m K). Copper at room temperature has a thermal conductivity of 401 W/(m K). Thus, graphene conducts heat 10 times better than copper.

# Applications of Graphene

## Application of Graphene

- Graphene, a one-atom-thick sheet of sp2-hybridized, hexagonally arranged carbon atoms, has triggered tremendous interest due to its high electron mobility, superb mechanical flexibility, and unique optical characteristics.

- Graphene-based applications such as transparent electrodes, solar cells, and ultrafast photodetectors, and phototransistors are also been reported.

- Graphene is an ultimately thin, mechanically very strong, transparent, and flexible conductor. Its conductivity can be modified over a large range either by chemical doping or by an electric field. The mobility of graphene is very high, which makes the material very interesting for electronic high-frequency applications.

- The linear dispersion of graphene and the absence of a band gap, along with its unusual doping properties, make it a material of extraordinary potential for optoelectronic device applications.

- Graphene is a transparent conductor, it can be used in applications such as touch screens, light panels, and solar cells, where it can replace the rather fragile and expensive indium tin oxide (ITO).

- Flexible electronics and gas sensors are other potential applications.

- The quantum Hall effect in graphene could also possibly contribute to an even more accurate resistance standard in metrology.

- Graphene is not only lighter, stronger, harder, and more flexible than steel, it is also a recyclable and sustainably manufacturable product that is ecofriendly and cost-effective in that would allow the development of lighter and stronger cars and planes that use less fuel.

- Large aerospace companies such as Boeing have already started to replace metals with carbon fiber and carbon-based materials, and graphene paper with its incomparable mechanical properties would be the next material for them to explore.

# Touch Screen Devices

**Indium Tin Oxide (ITO) in Touch Screens:**

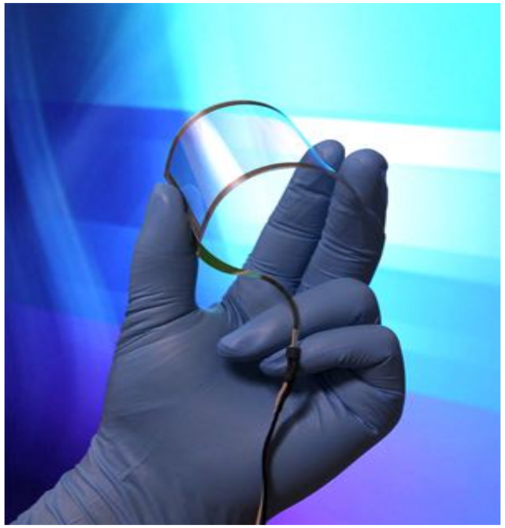
- Indium Tin Oxide (or tin-doped indium oxide) is important to the world's dominant smart phone and tablet manufacturers because of its unique material properties perfect for touch screen applications:
  - high conductivity
  - easily mass produced as thin films
  - optically transparent
- In the majority of the latest smart phones and tablets - ITO forms the conductive layer used to monitor the changes in electrical state as you touch and swipe the screen.
- In its thinnest form, ITO is both transparent and highly conductive which has resulted in ITO being one of the worlds most popular and widely used transparent conducting oxides.
- It is also reasonably easy to handle and deposit ITO as a thin film which makes it perfect for mass production using techniques such as physical vapor deposition, sputtering or evaporation methods.

# Touch Screen Devices

- Currently, the majority of tablets and smartphones are made using indium tin oxide (ITO), which is both expensive and inflexible.

- The second might start to become apparent if the industry starts to produce bendable communications devices, perhaps in the form of smart watches which could clearly benefit from a bit of flexibility.

- Graphene is strong, transparent, highly conductive and cheaper than the materials used in most modern smartphones and is much more supple too.



# Graphene Field Effect Transistors (GFETs)

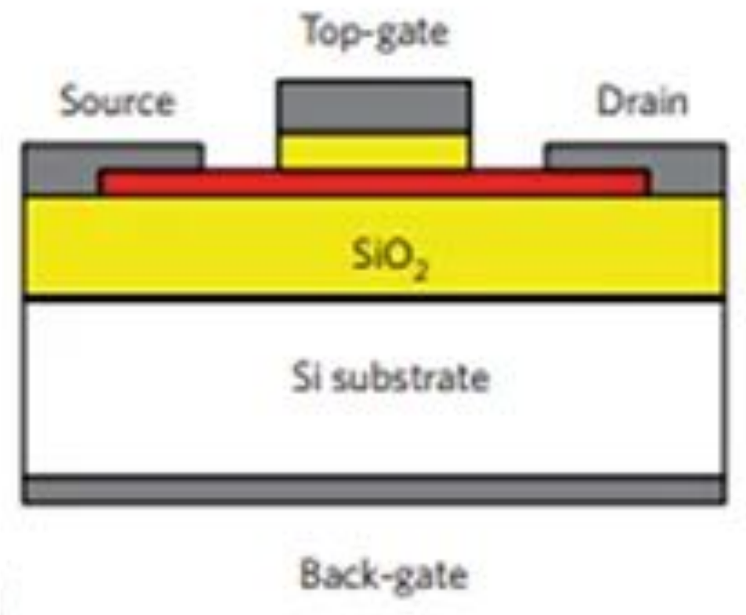
Graphene field-effect transistors (GFETs) is similar as conventional FET device with a graphene channel tens of microns in size between the source and drain. Being graphene, a lattice of carbon atoms that is only one atom thick, the channels in GFETs have  high sensitivity, which can be used on a wide variety of applications such as photosensing, magnetic sensing and bio sensing.

- The basic GFET is a three-terminal device that is similar to the conventional FET.

- It is composed of a source, drain, and a top or back gate or both.

- Unlike a silicon-based transistor, the GFET has a thin graphene channel, usually tens of microns thickness, between the source and drain metal electrodes. The gate controls how electrons respond and hence the channel's behavior.

- There are three main gate configurations for the GFET. Typical transistors can have a top gate, a global back gate, or both gates .

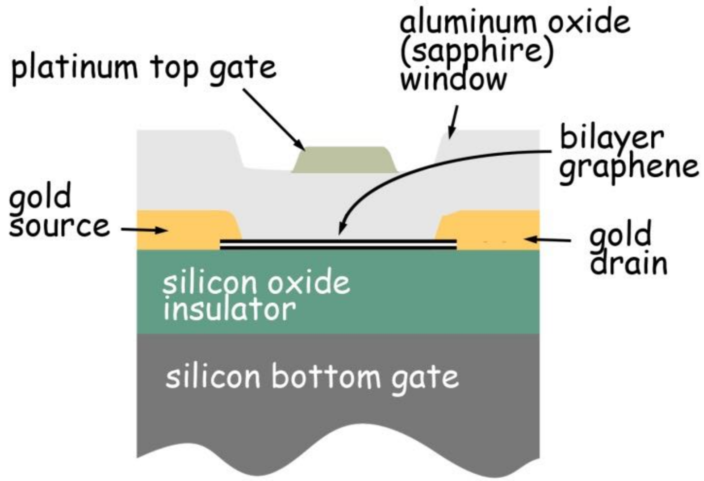



*Gate configurations in dual gate GFET*

- As with traditional silicon FETs, the gate in a GFET controls the flow of electrons or holes across its channel.

- Since the transistor channel is just one atom thick, all the current flows on its surface, hence the high sensitivity of the graphene FETs.

- The current flow in silicon devices is mostly via the electrons or holes. However, the GFET allows equal conduction by both the electrons and holes.



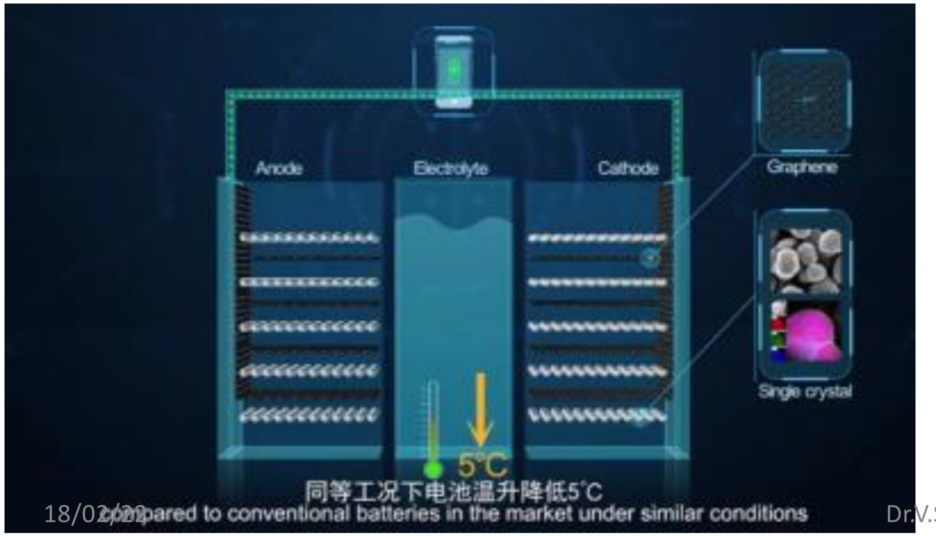

*A typical dual gate GFET*

## Advantages of GFETs

- Graphene's superior electrical and thermal conductivity results in low resistance losses and better heat dissipation than silicon. Consequently, graphene transistors have the potential to provide enhanced performance and efficiency.
- The one-atom-thick structure means that the entire channel is on the surface. For sensor applications, the channel is therefore directly exposed to the material or environment under test.
- Some GFETs are highly sensitive and suitable for a wide range of bio- and chemical-sensing applications..

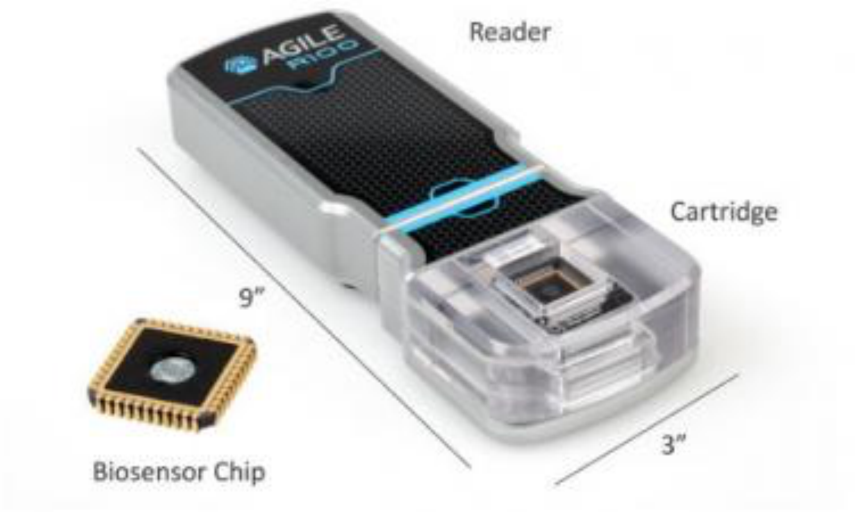
# Graphene Products

**Huawei's phone with graphene film cooling technology**




**Huawei's graphene-enhanced Li-ion batteries**

- ***Life increased***
- ***Operation temperature reduced by 5 degrees***

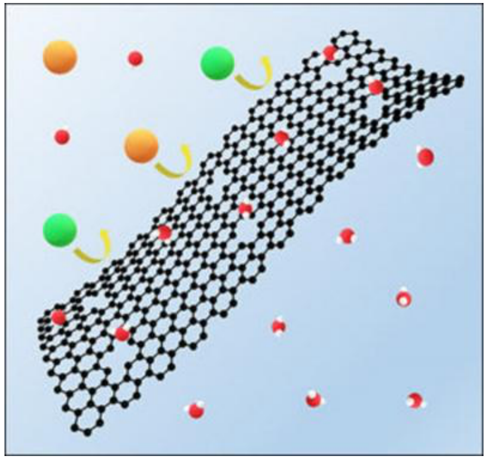



**Graphene-based sensor enables real-time detection of small molecules**

**Tennis racket with graphene coating makes it stronger & lighter**

# Recent advances in Graphene nanotechnology

## Water filters

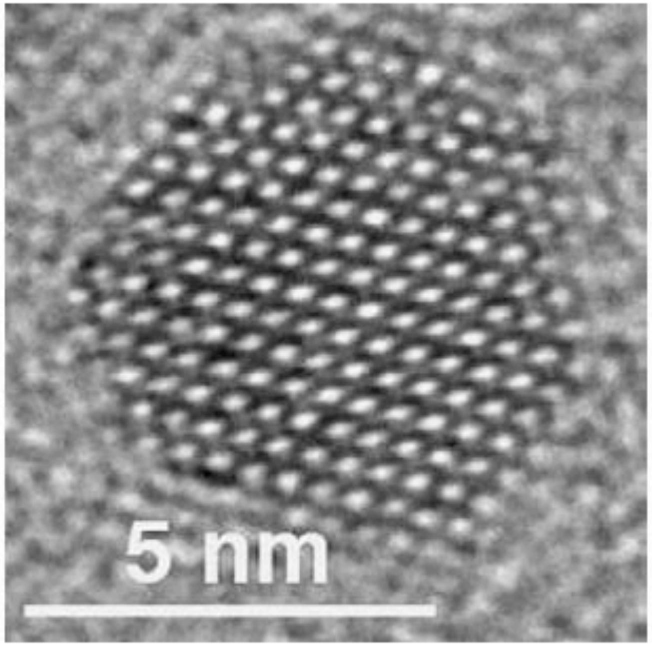


## Solar panels

## Graphene-based backplane for flexible displays

# Quantum dots (QDs)

- Quantum dots are confined, zero-dimensional semiconductor systems created at the nanoscale.
- They're made from a semiconductor such as silicon.
- Although they're crystals, they behave more like individual atoms—artificial atoms.
- 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 .*



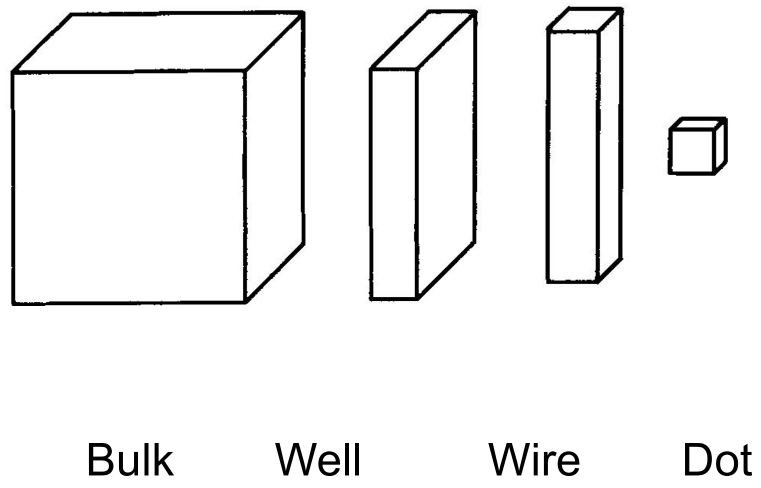

TEM image of one 5nm CdSe quantum dot particle

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.

- If *one dimension* is reduced to the nano range while the other two dimensions remain large, then we obtain a structure known as a ***quantum well.***

- If *two dimensions* are so reduced and one remains large, the resulting structure is referred to as a ***quantum wire.***

- If all *three dimensions* reach the low nanometer range is called a ***quantum dot.***




Progressive generation of rectangular nanostructures.

- The word *quantum* is coined because the changes in properties arise from the quantum-mechanical effect.

- The name is usually reserved to describe nanoparticles of semiconductor materials that, when stimulated, emit light much like a nanoscale light-emitting diode (LED).

- The wavelength of the light they emit depends on their size and shape, allowing control of the color of their fluorescence over a useful range.

- In liquid suspensions they have a number of important applications in biomedical research and diagnostic medicine.

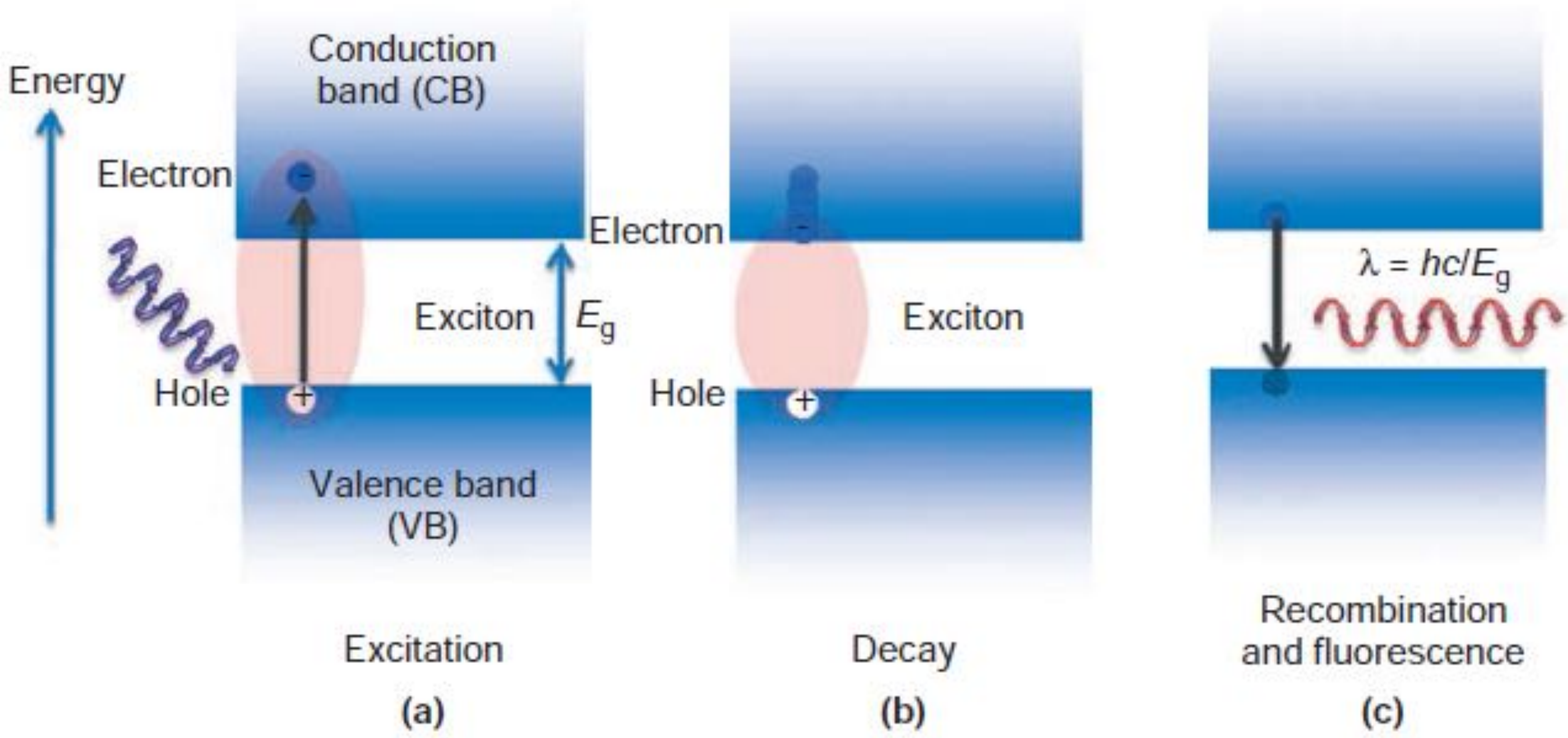
- <u>Before examining the light-emitting properties of semiconductor nanoparticles, let us understand how bulk semiconductors fluoresce</u>.

## Fluorescence from a bulk semiconductor.

(a) An electron is promoted from the valence band to the conduction band by absorbing a sufficiently energetic photon. The electron interacts with the positively charged hole left behind to form a bound particle pair known as an exciton.

(b) The electron energy decays down through the continuum of energy levels in the conduction band till it reaches the gap edge.

(c) The electron recombines with the hole and the energy is released as a fluorescent photon with the gap energy. Thus a wide range of photon energies can be absorbed but mostly a single wavelength is emitted.


Energy
Conduction band (CB)
Electron
Exciton
$E_g$
Hole
Valence band (VB)
Electron
Exciton
Hole
$\lambda = hc/E_g$
Excitation
(a)
Decay
(b)
Recombination and fluorescence
(c)

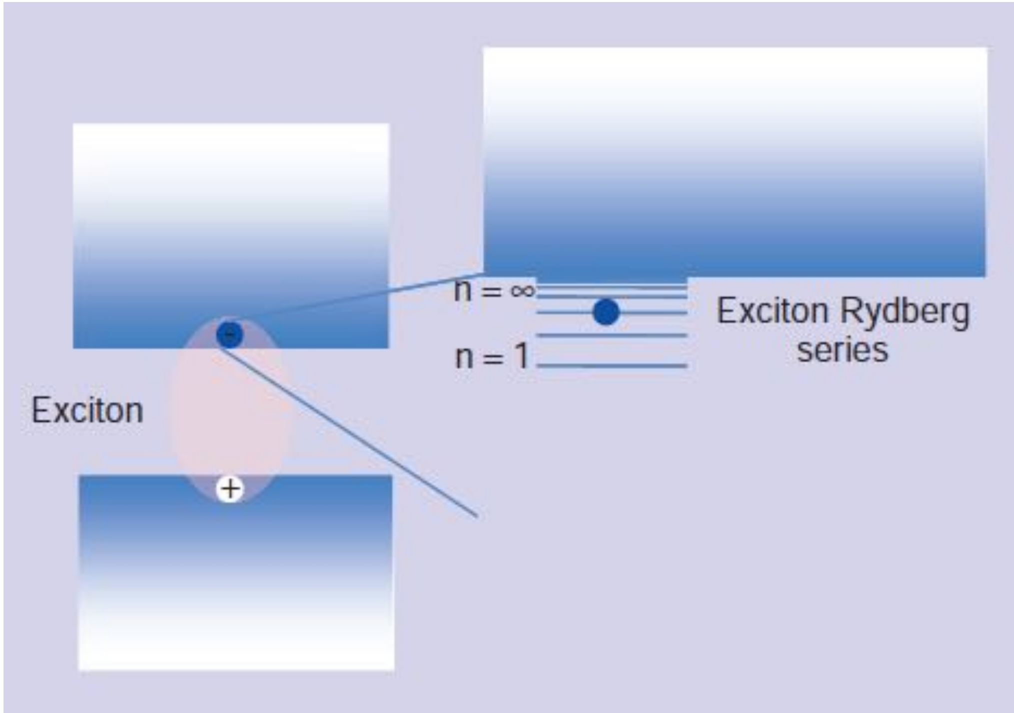
- The bulk semiconductor fluorescence is characterized by the absorption of a wide range of photon energies but emission at a single wavelength given by the gap energy.

- In nanoscale semiconductor particles or quantum dots, the same basic process happens.

- But in order to understand the size-dependence of the optical properties, we need to look in a little more detail at the energy of the recombination.

- While it is in existence the exciton, which is a bound positive and negative charge, behaves like a miniature atom with its own set of energy levels superimposed onto those of the background semiconductor.

- So when the electron decays down through the conduction band states and reaches the gap edge, it then find itself at the top of another staircase of energy levels belonging to the exciton. It decays to the bottom of those before recombining.



- In the bulk, the exciton energies are very small, and the energy released when the exciton collapses is close to the bulk bandgap energy.

- There is a size associated with the exciton known as the exciton Bohr radius, which in the bulk is typically 10 nm. Thus when the spatial extent of the semiconductor is less than this, the exciton is “squeezed” and its energy levels change.

- **For example**, the semiconductor CdSe, an exciton Bohr radius, $r_{ex}$, is 5.3 nm.

- If the physical extent of the semiconductor is of the order of or less than $r_{ex}$, the exciton is “squeezed” and the excitonic energy levels are modified.

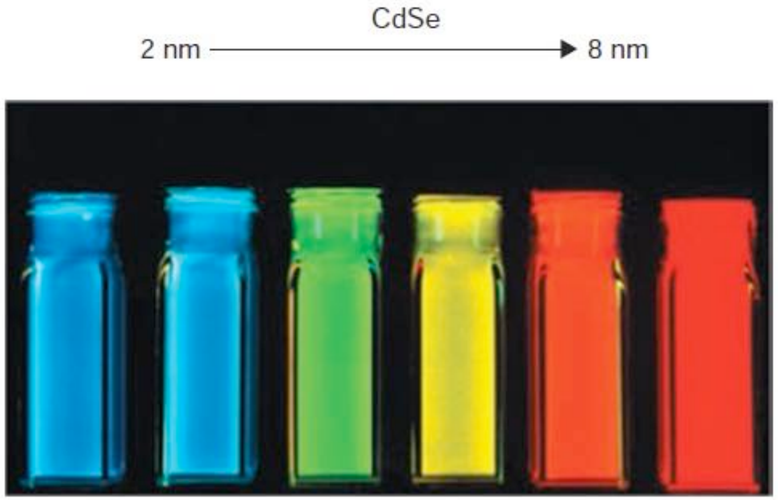
- Below a critical size the exciton enters a new regime where the energy is almost entirely determined by the confinement of the exciton within a box the size of the quantum dot.

The energy between the first two energy levels of this system is given by

$$E = E_g + \frac{\hbar^2 \pi^2}{2\mu r^2}$$

where, as before, *Eg* is the gap energy in the bulk semiconductor.

The primary gap energy and thus the energy of the fluorescent photons is increased by a factor proportional to $1/r^2$ from the bulk baseline as the size of the quantum dot is reduced.

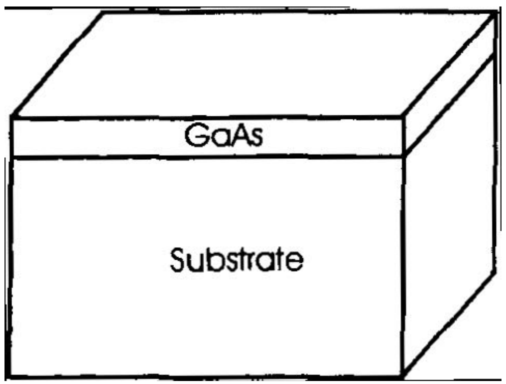


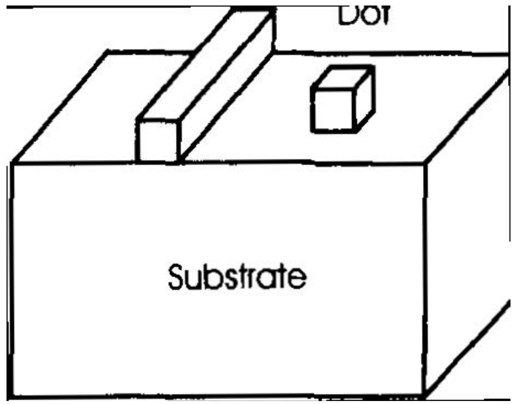

**Fluorescence from CdSe quantum dots of different sizes.**

showing the change in the color of the fluorescence of CdSe quantum dots excited by UV light as a function of their size.

## Preparation of quantum dot

Starting with a square quantum well (e.g., GaAs) located on a substrate, we can fabricate quantum wire or a quantum dot using lithographic process.




(a) Gallium arsenide quantum well on a substrate; (b) quantum wire and quantum dot formed by lithography.

# Application of quantum dots

# Quantum Dot and Computing

- Quantum dot technology has the potential to bring computing devices as we know them to a completely new level.
- Quantum computing exists at the intersection between computer science and quantum mechanics.
- In traditional computing systems, information is conveyed with the use of the mathematical values of either *zero or one* in a computing *bit*, which is the most important aspect of the computing device.

- In the *quantum computing system,* the *quantum bit (*qubit) is the principal element used to convey information.

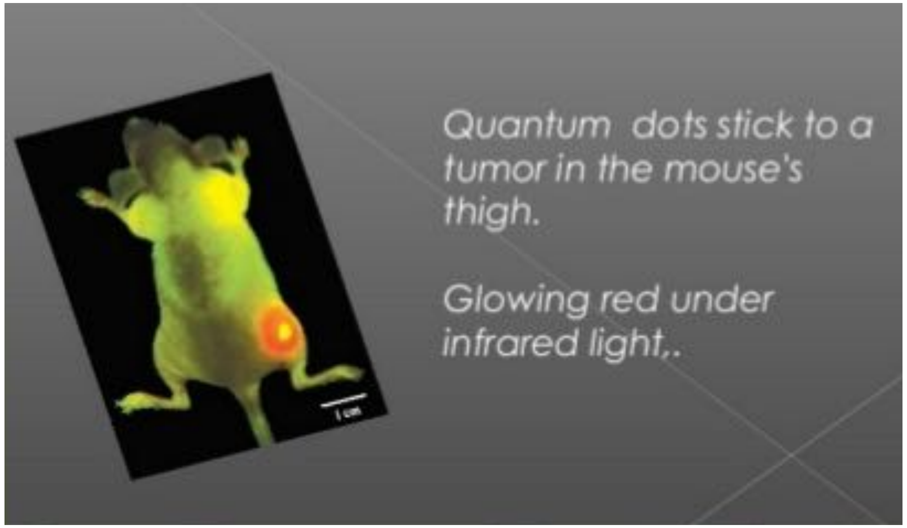
- Qubit can *give information of both states of zero and one simultaneously* and allows the possibility of multiple calculations conducted at one time.

- Simultaneous representation leads to enhance potential of quantum computers to provide more efficient technological system with increased speed.

- In the quantum computing systems, the flow of the electrons through the QD can be controlled by applying small voltages to the leads.

## Quantum dot for diagnostic imaging.

- the electronic energy levels in Quantum dots are spaced appropriately to emit light.
- QDs can emit in a range of colors depending on the dot size, So we can usilize this property of CDs in diagnostic imaging.
- As biological tissues are fairly transparent to certain wavelengths so that targeted quantum dots can be attached to the desired cells and the location and distribution of these cells can be imaged from outside the body.



# Quantum dots in lasing application

Quantum dots can also provide superior performance in lasing application in compare to bulk semiconductors to make laser stable and to provide a narrow spectral emission.

The advantages of quantum dot lasers are :

- reduced threshold current density
- temperature stabilized emission and threshold.
- high differential gain