

UNIT-II

SENSORS

Sensor is an analytical device or module composed of an active catalyst as sensing material with a signal transducer which transforms physical or chemical information into an analytically useful electrical signal. Physical parameters that are commonly monitored with sensors are temperature, pressure, force, magnetic field, etc., while chemical parameters of interest most often are the concentrations of chemical substances. The sensors are broadly classified into the physical sensor and chemical sensor based on the properties of analytes being measured.

1. ELECTROCHEMICAL SENSORS:

Principle: Electrochemical reactions take place at electrode-electrolyte interfaces and provide a switch for electricity to flow between two phases of different conductivity, i.e. the electrode (electrons or holes are the charge carriers) and solid or liquid electrolyte (ions are the main charge carriers). The reactions which occur at the interface of the surface of an electrode between the recognition element, and the target/binding analyte generate an electrical double layer and thus this potential is measured after transforming these chemical reactions into this measurable electrochemical signal by a recognition element, and a transducer of the sensor.

Construction and Working:

The fundamental concept in the detection of analytes by electrochemical sensors involves the measurement of electric current generated by chemical reactions in the electrochemical system.

Electrochemical sensors are made up of three essential components: a receptor that binds the sample, the sample or analyte, and a transducer to convert the reaction into a measurable electrical signal. In the case of electrochemical sensors, the electrode acts as the transducer. Electrochemical sensing always requires a closed circuit. Current must flow to make a measurement. In most electrochemical sensors. An electrode surface is used as the site of the reaction. The electrode will either oxidize or reduce the analyte of interest. The current that is produced from the reaction is monitored and used to calculate important data such as concentrations from the sample

Electrochemical sensor's working mechanism involves the interaction of the target analyte material with the electrode surface and bringing the desired change as a consequence to a redox reaction, which generates an electrical signal that can be transformed to explore the nature of the analyte species.

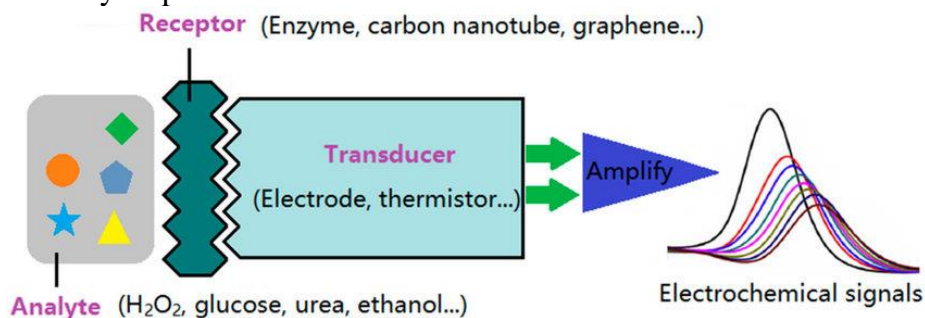


Fig. 1. Electrochemical Sensor

Applications of Electrochemical sensors-

- Detection of important molecules or biomarkers that are used for the diagnosis of diseases and disorders.
- They are used for the monitoring toxic levels of different substances in food quality and environmental control.
- The biosensor application areas of these sensors extend to medical and biomedical applications, process control, bioreactors, quality control, agriculture, bacterial and viral diagnosis, industrial wastewater control.

2. OPTICAL SENSORS:

Optical sensors are electronic components designed to detect and convert incident light rays into electrical signals. Eg: Colorimetric Sensors. Optical sensors are divided into several subclasses such as resonance, dispersion, reflection, refraction, phosphorescence, infrared absorption, Raman scattering, fluorescence, and chemiluminescence.

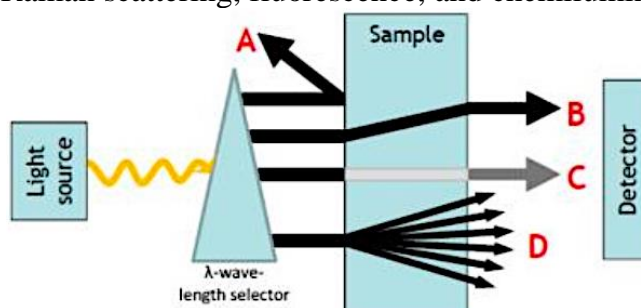


Fig.2. Optical sensor

Principle and working-

- When a sample solution is interacted with a light of suitable wavelength, certain quantity of light is absorbed by the analyte solution and it is observed by a sensor. The transducer converts intensity of absorbed light into electrical signal. The change in intensity at certain wavelength within visible (400–800nm) range can be determined using special instrumentation.
- The relationship between the incident light intensity and the transmitted radiation is given by the Beer-Lambert law:

$$A(\lambda) = \log \frac{I_0}{I} = \varepsilon(\lambda) \cdot d \cdot c$$

where $A(\lambda) = \log \frac{I_0}{I}$ is the absorbance at a given wavelength λ , (I_0 and I are the incident and transmitted light intensities); ε is the molar absorptivity; d is the optical path through the absorbing sample and c is the molar concentration of absorbing analyte.

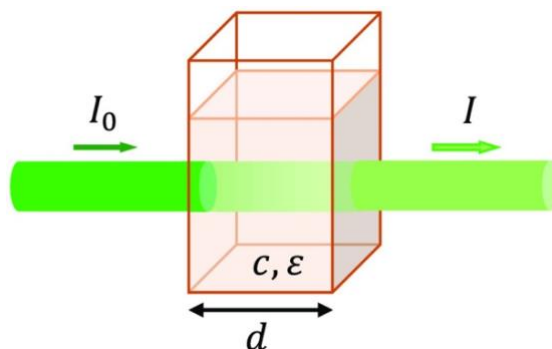


Fig. 3. Beer-lamberts law

- What the detector monitors varies by technique (e.g., refractive index, scattering, diffraction, absorbance, reflectance, photoluminescence, chemiluminescence, etc.), can cover different regions of the electromagnetic spectrum, and can allow measurement of multiple properties.

Eg: Colorimetry: a quantitative measurement of absorbance or reflectance spectra, is one of the oldest of analytical techniques. Optical sensors depends on the colour of the analyte with in the visible range (400-800nm). Its basic components include a light source, a wavelength selector, a photodetector and a read-out device. A block diagram of a typical instrumentation system employed colorimetry. A monochromatic light is made to pass through analyte solution where certain quantity of light is absorbed and it is a function of concentration of analyte. The change in the intensity of light is detected by photodetector (sensing). The light source generates an intense and stable radiation signal needed to probe an optical property of the molecular recognition element in the sensor. The amount of absorbance is governed by Beer- lamberts law.

Applications of Optical Sensors

- Computers
- motion detectors.
- copy machines (xerox machines)
- light fixtures that turn on automatically in the dark.
- alarm systems
- synchro for photographic flashes
- systems that can detect the presence of objects.

SENSORS FOR THE MEASUREMENT OF DISSOLVED OXYGEN (DO)

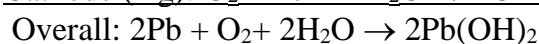
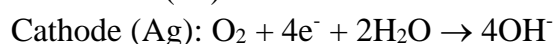
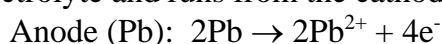
The two methods for estimation of DO are optical method and electrochemical method.

(a) Electrochemical method: Electrochemical DO sensors, also known as amperometric or Clark-type sensors, measures dissolved oxygen concentration in water based on electrical current produced. Galvanic Sensor is a Electrochemical sensor, which is used to measure DO The following are the components:

- Cathode: Working electrode-Ag
- Anode: Zn, Pb or any other active metal
- Electrolyte: KOH, NaOH or any other inert electrolyte
- Membrane: Teflon

Working principle

The difference in potential between the anode and the cathode should be at least 0.5V. DO sensor is immersed in water sample. Oxygen molecule diffuses across the oxygen-permeable membrane (Teflon) and the rate of diffusion is proportional to the pressure of oxygen in the water. Molecular Oxygen reduces to OH^- at cathode. This reaction produces an electrical current that is directly related to the oxygen concentration. This current is carried by the ions in the electrolyte and runs from the cathode to the anode.



(b) Optical method: Optical DO sensors are made of two parts, a sensor spot and a fibre optic reader. The sensor spot is attached to the interior of a cell culture vessel and contains a fluorescent dye suspended in a hydrogel. The sensor spot is the only part of the system that comes in contact with cells or media. The external reader is connected to a computer or data hub and is responsible for sending and receiving optical signals to the sensor spot. Optical DO sensors measure the DO concentration of liquid media or air based on the quenching of luminescence in the presence of oxygen. Since oxygen affects both the intensity and the lifetime of the luminescence, either may be used to measure DO. Optical DO sensor technology was developed from the principle that DO quenches the luminescence associated with chemical dyes in the sensor. The fluorescent dye exhibits an excitation maximum around 455nm, and an emission wavelength of approximately 613nm.

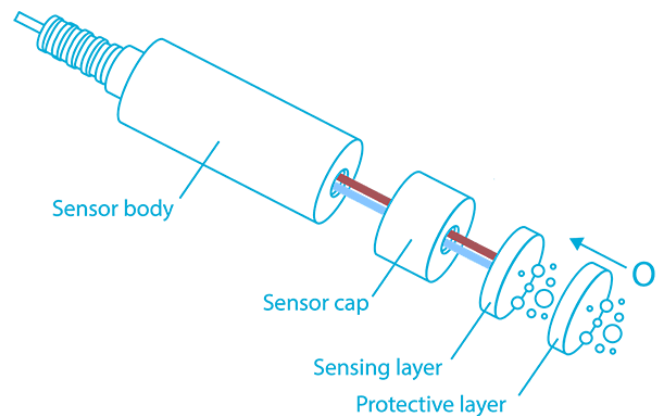


Figure 4. DO sensor

ELECTROCHEMICAL GAS SENSORS:

(a) Detection of SO_x

Sulphur dioxide is one of the main substances that pollute the air. Sulfur oxides, SO₂ released from thermal power stations and other industrial plants, are gases harmful to the environment. It is very important to detect and control the concentrations of SO_x in industrial processes. The attempt to detect sulphur dioxide in the air is a regular task of air inspection.

Gas sensors detect chemicals in the gas phase. The gas sensors operate by reacting with the gas of interest and producing an electrical signal proportional to the gas concentration. A typical electrochemical sensor consists of: a sensing electrode (or working electrode), counter electrode separated by a thin layer of electrolyte and a reference electrode. Gases diffuse through a membrane to be reduced or oxidized at an electrode. Initially the gas passes through a small capillary-type opening and then diffuses through a hydrophobic barrier, and eventually reaches the electrode surface. SO_x sensors utilizing a solid electrolyte such as K₂SO₄, Na₂SO₄, Li₂SO₄, Ag₂SO₄, Nasicon, Na-Al₂O₃ and Ag-Al₂O₃ have been widely studied, because this type of sensor has its own advantages like continuous quantitative measurement; high selectivity and sensitivity; easy operation and fast response; simple construction and low price.

Anode reaction: $2\text{Ag} \rightarrow 2\text{Ag}^+ + 2\text{e}^-$

Cathode reaction: $2\text{Ag}^+ + \text{SO}_3 + \frac{1}{2}\text{O}_2 + 2\text{e}^- \rightarrow \text{Ag}_2\text{SO}_4$

Overall reaction: $2\text{Ag} + \text{SO}_3 + \frac{1}{2}\text{O}_2 \rightarrow \text{Ag}_2\text{SO}_4$.

SO_3 was produced by the reaction can be checked by sensor.

Applications:

1. It is used in thermal power plant.
2. It is used chemical industries to detect sulphur dioxide emission level

(b) Detection of NO_x :

Nitrogen oxide is the general term for a gas mixture composed of various oxides of nitrogen, often referred as NO_x . The normal air is nitric oxide and nitrogen dioxide. In environmental analysis, nitrogen oxide generally refers to NO and NO_2 . NO is an important vasodilator, and monitoring its levels becomes crucial in the diagnostics of cardiovascular complications.

Electrochemical sensors are made up of three essential components: a receptor that binds the sample, the sample or analyte, and a transducer to convert the reaction into a measurable electrical signal. In the case of electrochemical sensors, the electrode acts as the transducer.

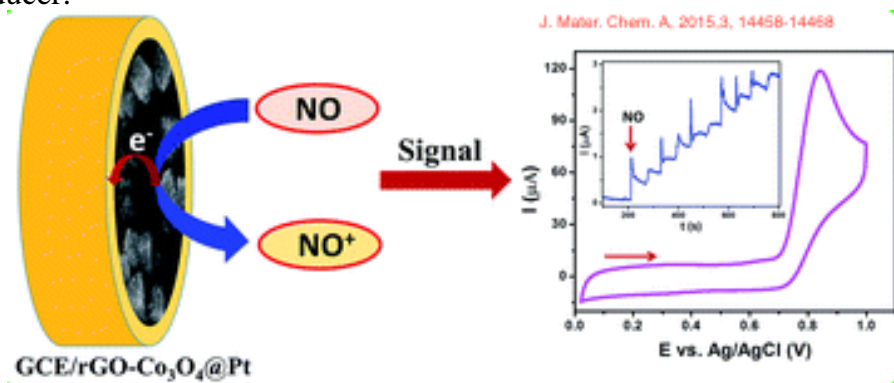
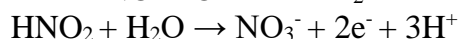


Figure 5. NO_x sensor

The electrode surface is used as the site of the reaction. The electrode will either oxidize or reduce the analyte of interest. The current that is produced from the reaction is monitored and used to calculate important data such as concentrations from the sample. The NO_x sensor monitors the oxidation of NO as it occurs on the electrode surface. In many instances of electrochemical sensors, the electrode surface can be modified with catalysts, membranes, or other metals to make the electrode more sensitive and/or more selective toward the analyte (in the instance below, the Glassy Carbon (GC) electrode is modified with Cobalt (IV) Oxide and Platinum). The direct electro oxidation of NO in solutions follows the following 3 step reaction.

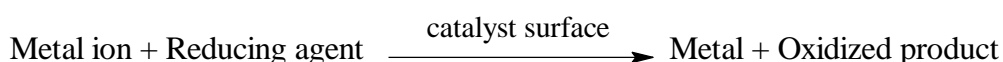


The ΔE for the overall process is +0.5V vs. a Ag/AgCl reference electrode. The reaction for the Ag/AgCl reference electrode is the following: $\text{AgCl} + \text{e}^- \leftrightarrow \text{Ag} + \text{Cl}^-$; $E^0 = +0.222\text{V}$.

ELECTROLESS PLATING:

Definition: Electroless plating is the controlled deposition of a continuous film of a metal from its salt solution on to a catalytically active surface by a suitable reducing agent without using electrical energy.

The reducing agent brings about the reduction of the metallic ions to the metal which gets plated over a catalytic surface. The driving force in electroless plating is an autocatalytic redox reaction on a pretreated active surface.



An important aspect of electroless plating is the preparation of the surface of the object so that an active surface is obtained. This is achieved by one of the following techniques.

- (a) Acid treatment (etching);
- (b) Electroplating a thin layer of the metal. (same as that to be plated or another suitable metal) followed by heat treatment;
- (c) For nonconducting surfaces such as plastics or printed circuit boards, the surface is treated with stannous chloride and palladium chloride solution alternately.

Advantages of electroless plating:

- (i) Use of electrical power and electrical contacts are eliminated.
- (ii) Semiconductors and insulators like plastics can also be plated.
- (iii) Electroless baths have better throwing power. Intricate parts with irregular shapes, inside parts of tubes, recesses can be uniformly coated.
- (iv) Hydrogen gas liberated is not trapped in blind holes.
- (v) Electroless coating are harder than that produced by conventional electroplating.
- (vi) No levelers are required.
- (vii) Deposits have unique chemical, mechanical and magnetic properties.

Electroless plating of Copper (on PCB):

Pretreatment and activation of the surface: The PCB is degreased and etched in acid. It is activated by dipping in stannous chloride solution containing HCl at 25°C followed by dipping in palladium chloride. The surface is dried to get a layer of palladium.

Plating bath solution:

A solution of copper sulphate (12 g/dm³);

Reducing agent- Formaldehyde (8 g/dm³);

Buffer - Sodium hydroxide (15 g/dm³) + rochelle salt (14 g/dm³);

Complexing agent and exaltant – EDTA (20 g/dm³);

pH – 11 ; Temperature – 25°C.

Reactions: Cathode: $\text{Cu}^{2+} + 2\text{e}^- \rightarrow \text{Cu}$

Anode: $2\text{HCHO} + 4\text{OH}^- \rightarrow 2\text{HCOO}^- + 2\text{H}_2\text{O} + \text{H}_2 + 2\text{e}^-$

Overall reaction: $\text{Cu}^{2+} + 2\text{HCHO} + 4\text{OH}^- \xrightarrow{\text{catalyst surface}} \text{Cu} + 2\text{HCOO}^- + 2\text{H}_2\text{O} + \text{H}_2$

Rate of plating: 1 to 5 $\mu\text{m h}^{-1}$.

Applications: An important application of electroless copper plating is printed circuit boards (PCB). In double side and multilayer boards where plating-through-holes is required, electroless technique is the best since the holes cannot be electroplated. The technique used to manufacture printed circuit boards is the subtractive method (Fig.5). The base object in PCB is a plastic material such as glass fibre reinforced plastic (GRP), epoxy or phenolic polymer over which a layer (5 to 100 μm) of copper is electroplated. Selected areas are then protected by a photo-resist or electroplated image and the rest of the copper is etched away to produce the circuit pattern or the track. Usually, double sided tracks are made in order to pack more number components in a small space. Finally, the connection between the two sides of PCB is made by drilling holes, followed by electroless copper through holes.

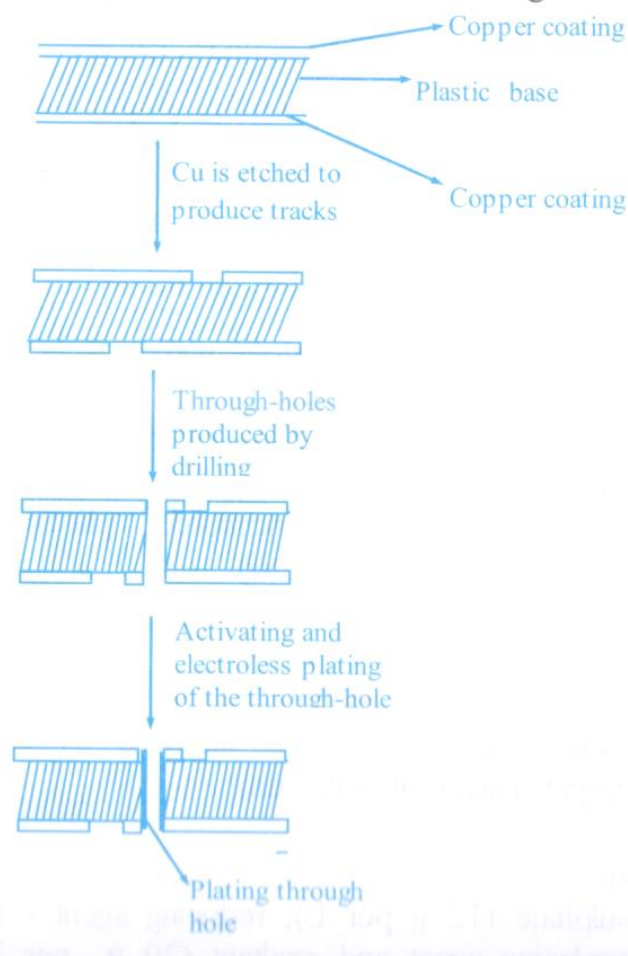


Fig.5. Steps in subtractive technique of plating-through in the manufacture of double sided PCB. Copper clad tracks on each side of the plastic board are connected through-hole.

NANOMATERIALS

Nanomaterials are materials which have at least one of their dimensions in the nanometer ($1\text{ nm} = 10^{-9}\text{ m}$) range (1-100nm). It is concerned with the unique properties associated with assemblies of atoms or molecules on a scale between that of the individual building blocks and the bulk material (1 to 1000 nm). Nanostructures include quantum dots, clusters, nanocrystals, nanowires, nanotubes and so on. The nanoscience field has matured so rapidly that it is probably hard to find a segment of any technical subject where the implications of nanomaterials have not been explored at least to a preliminary extent.

Nanomaterials have the structural features in between of those of atoms and the bulk materials. While most micro structured materials have similar properties to the corresponding bulk materials, the properties of materials with nanometer dimensions are significantly different from those of atoms and bulks materials. This is mainly due to the nanometer size of the materials which render them: (i) large fraction of surface atoms; (ii) high surface energy; (iii) spatial confinement; (iv) reduced imperfections, which do not exist in the corresponding bulk materials. Suitable control of the properties and response of nanostructures can lead to new devices and technologies.

CLASSIFICATION:

The classification is based on the number of dimensions which are not confined to the nanoscale range ($< 100\text{ nm}$).

- (i) **Zero dimensional:** Materials wherein all the dimensions are within the nanoscale range are called as 0-D nanomaterials. The most common representation of 0-D nanomaterials are nanoparticles.
- (ii) **One dimensional:** Here two dimensions are at nanoscale range, another dimension is not. This leads to needle like-shaped nanomaterials. Eg. Nanotubes, nanorods, nanowires.
- (iii) **Two dimensional:** One dimension is at nanoscale range, other two dimensions are not. They exhibit plate-like shapes. Eg. Nanocoatings, nanofilms.
- (iv) **Three dimensional:** These materials are not confined to the nanoscale in any dimension. Thus, these materials are characterized by having three arbitrarily dimensions above 100nm. They are also called as bulk nanomaterials. Bulk nanomaterials can form a nanocrystalline structure by multiple arrangements of nanosize crystals, most typically in different orientations. 3-D nanomaterials can contain dispersions of nanoparticles, bundles of nanowires/nanotubes as well as multilayers.

PREPARATION METHODS:

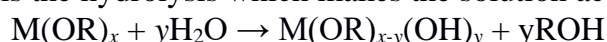
Nanochemistry deals with the synthesis, characterization, reactions and application of nanoparticles and their compounds. Nanomaterials can be synthesized by two different approaches, namely “Bottom-up” approach and “Top-down” approach. These two approaches can be explained in a simplified manner by taking an example of powder production. The synthesis of powder using chemicals represents the “bottom-up” approach whereas crushing of chunks represents the “top-down” approach. Thus in “bottom-up” approach atoms or molecules are used as building blocks to produce nanomaterials whereas in the other approach, large pieces of materials are broken down into nanosize by mechanical or chemical methods.

(i) Sol-gel method:

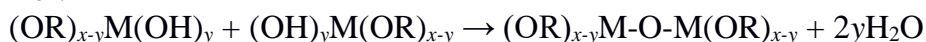
Sol-gel approach is most widely used for nanocomposite fabrication due to its simple processing steps, the flexibility of solution chemistry, the low temperature treatments and small investment in equipment.

A sol is a stable suspension of colloidal solid particles in a liquid. A gel is a porous, three-dimensional, continuous solid network surrounding a liquid phase. The sol-gel process usually consists of following steps:

(a) Preparation of a precursor solution: The desired colloidal particles are dispersed in a liquid to form a sol. The precursors generally used for the formation of sol are metal alkoxides (say silica, alumina and others). This is mainly because alkoxides readily react with water. A catalyst may be used to start the reaction as well as to control the pH. The first reaction to occur is the hydrolysis which makes the solution active.



(b) Formation of gel: The particles in the sol are polymerized through the removal of the stabilizing components. This can be done by either heating the sol at a low temperature or allowing it to stand for certain duration. This results in the formation 1, 2, or 3-dimensional continuous network [M-O-M] bonds (Gel) by condensation polymerization accompanied by the liberation of water molecules. These reactions increase the molecular weight of the oxide polymer.



(c) Aging of gel (syneresis): The reaction mixture is allowed to continue polycondensation reactions until the gel transforms into a solid mass, accompanied by contraction of the gel network and expulsion of solvent from gel pores. Ostwald ripening (is the phenomenon by which smaller particles are consumed by larger particles during the growth process) and phase transformations may occur concurrently with syneresis.

(d) Drying of the gel: Water and other volatile liquids are removed from the gel network. If isolated by thermal evaporation, the resulting nanomaterial is called **xerogel**. If the solvent is extracted under supercritical or near supercritical conditions, the product is an **aerogel**.

(e) Dehydration: During dehydration, surface bound M-OH groups are removed, thereby stabilizing the gel against dehydration. This is normally achieved by calcining at temperatures up to 800°C.

(f) Densification and decomposition of gels at high temperatures ($T > 800^\circ\text{C}$). The pores of the gel network are collapsed, and remaining organic contaminants are volatilized.

The typical steps that are involved in sol-gel processing are shown in the Fig.

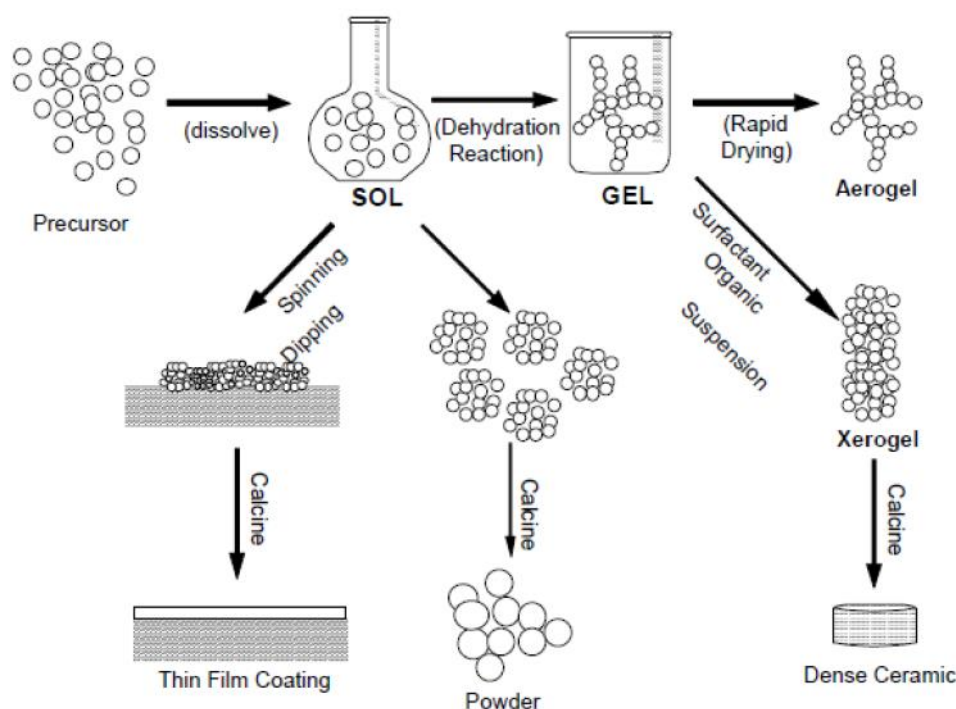


Fig.1. Sol-gel process.

(ii) Co-precipitation method:

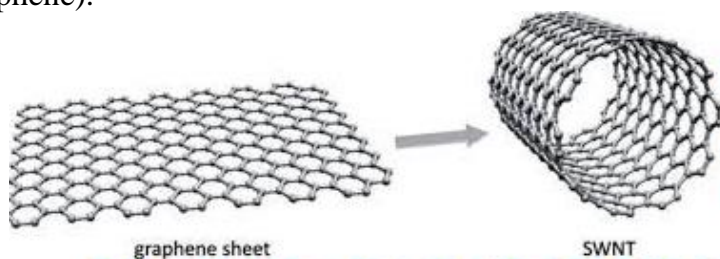
In this technique, an inorganic metal salt such as chloride, nitrate, sulphate etc., is dissolved in aqueous medium. Metal cations exist in the form of metal hydrate species such as $[\text{Al}(\text{H}_2\text{O})_6]^{3+}$ and $[\text{Fe}(\text{H}_2\text{O})_6]^{3+}$. When a precipitating agent such as NaOH or NH_4OH is added, these species get hydrolysed with the increase in pH, condensation of hydrolysed species takes place. This concentration of the solution is termed as supersaturation. At this concentration only, formation of nucleation initiates. The particles get **precipitated** into metal hydroxide. The above precipitate is filtered, washed with water and calcined at higher temperature to remove the counter anions of the metal salt used such as acetate or nitrate then finally grinding to get a fine powder.

Advantages: (i) The process is relatively economical (ii) Wide range of single and multi-components of oxide nanopowders can be synthesized.

Disadvantages: (i) Inability to control the size of the particles. (ii) Chances of aggregation of nano particles.

CARBON NANOTUBES (CNTS):

A **carbon nanotube** is a tubular structure made of carbon atoms, having diameter of nanometer order but length in micrometers. CNTs are related to fullerenes and is regarded as another allotrope of carbon. Fullerenes are spherical and CNTs are cylindrical. One can consider nanotube of carbon as folding of a single layer of graphite sheet (also referred to as graphene).



(a) (b)
Fig.2. Folding of graphite sheet to single wall carbon nano tube

One can fold the graphite sheet into a cylinder like paper. If a single graphite sheet [Fig 2 (a)] is folded, we get Single Wall Carbon Nanotube (SWCNT) [Fig 2 (b)]. There can be Multi Wall Carbon Nanotube (MWCNT) also wherein on CNT is within another as shown in Fig. 3

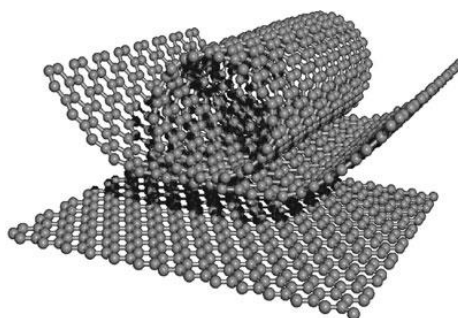


Fig.3. Multi wall carbon nano tube

SWCNTs have diameters ranging from 1 to 2 nm and MWCNTs have outer diameter ranging from 2 to 25 nm. The CNTs we have considered so far have their ends open. It is also possible to get CNT whose ends are closed; the ends being closed by semi-circular fullerene which act as caps.

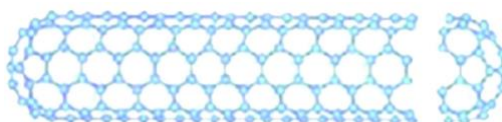


Fig. 4. SWCNT with end caps. Semicircular fullerene acts as a cap.

Nanotubes are regarded as single dimensional (1D) tubes. CNTs have sp^2 hybridized C atoms with C-C bond length 1.4\AA .

Synthesis of carbon nano tubes by Chemical vapour deposition (CVD) method:

In 1993, Chemical vapor deposition (CVD) technique was first reported to produce MWNTs (Multi walled nano tubes) by Endo and his research group. Schematic diagram of the chemical vapor deposition apparatus is shown in Fig. 5.

In this method, CNTs are synthesized by thermal CVD method by using hydrocarbon gas as carbon source. A quartz tube is placed inside a furnace maintained at high temperature ($500\text{--}900^\circ\text{C}$) heated by resistivity heated coil or plasma. A crucible containing the substrate coated with catalyst nanoparticles such as Fe, Co or Ni is placed inside quartz tube filled with inert gas such as argon gas. The hydrocarbon gas (carbon source) is pumped into the quartz tube which undergoes pyrolysis reaction and forms vapor carbon atoms. These carbon atoms bind to the substrate and join to each other by Vanderwaal force of attraction and grow as multi-walled carbon nanotubes (MWCNTs) on the substrate. To synthesize single-walled carbon nanotubes catalyst nanoparticles of Fe, Co, Ni are used. The obtained CNTs are further purified to get the pure form of CNTs.

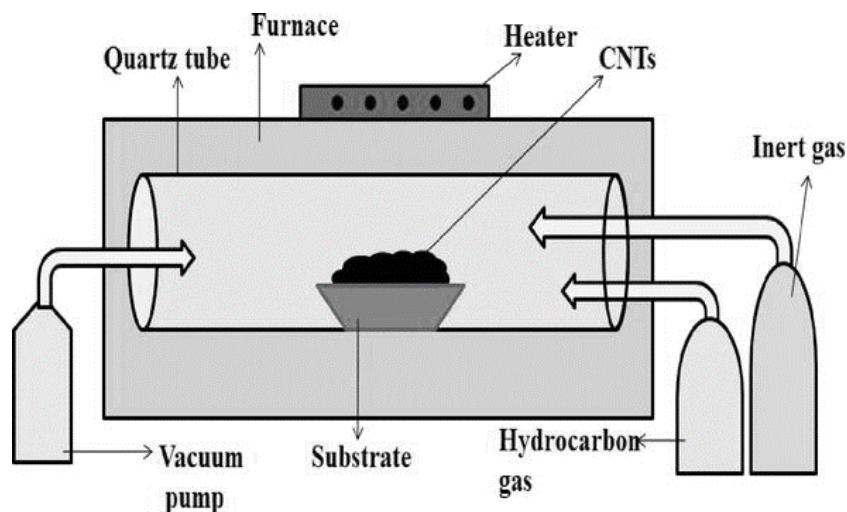


Fig. 5. Schematic diagram of the chemical vapor deposition apparatus

Properties:

- (i) **Electrical conductivity:** Carbon nanotubes (CNTs) are electrically and thermally conductive and have a high mechanical strength. Parallel arrays of multi-walled carbon nanotubes can be drawn into electrically conductive continuous length webs.
- (ii) **Strength and elasticity:** In terms of tensile strength and elastic modulus, carbon nanotubes are the strongest and stiffest materials yet found.
- (iii) **Thermal conductivity and expansion:** The carbon bond's rigidity aids in the transmission of vibrations throughout the nanotube, resulting in excellent heat conductivity. Because each carbon atom is connected to three other carbon atoms by strong covalent bonds, carbon nanotubes have an extremely high melting point. This also leaves a spare electron on each carbon atom, resulting in a sea of delocalized electrons within the tube, allowing nanotubes to conduct electricity.

Applications:

CNTs are extensively employed as carbon nanomaterials in numerous applications due to their exceptional optical, electrical, and mechanical characteristics. They are utilized in photocatalysts, catalysts, adsorbents, membranes, sensors, conductive coatings, batteries, supercapacitors, hydrogen storage devices, solar cells, and fuel cells. Likewise, they are applied in biomedicine as extremely sensitive biosensors (for sensing glucose, and hydrogen peroxide) and drug delivery systems (particularly in cancer treatments).

MEMORY DEVICES:

A memory device is a piece of hardware used to store data.

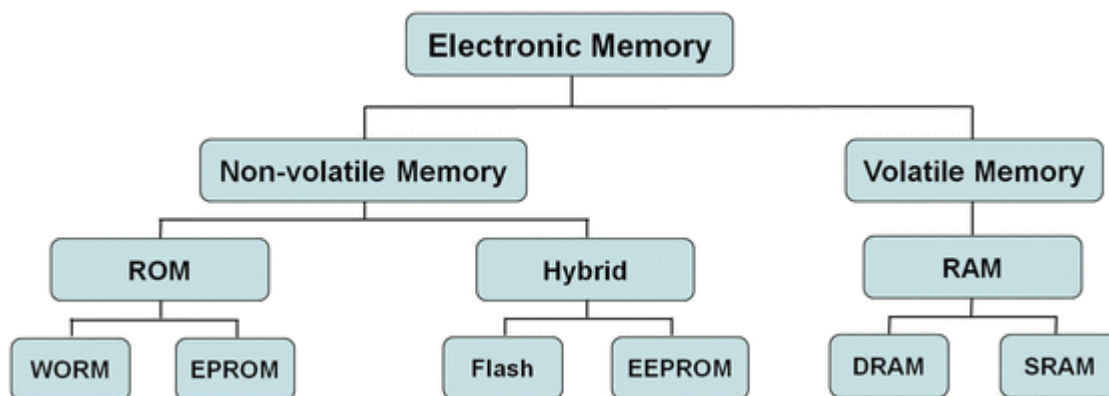
Basic Concepts of Electronic Memory: The requirements of a material to act as memory material are:

- The individual memory cell must possess at least two stable states to exhibit two charge states which are coded as 0 (ON) and 1 (OFF)
- These states must be stable for a period appropriate for data storage.
- They can be switched between two states by an external stimulus. This is called as the writing process.
- The states can be distinguished by applying a further external signal. This is called as the reading process.

The organic/polymeric materials can be used as materials for memory because of the following reasons:

- The organic/polymeric materials exhibit two electrical stable states known as electrical bistability.
- They shift from one state (ON state) to other state (OFF state) when an external electric field is applied.
- These materials store information in the form of change in their properties under applied electric field.
- The information can be retrieved by encoding these two states.

Classification of memory based on volatility:



- 1) **Volatile Memory:** Volatile memory eventually loses the stored information unless it is provided with a constant power supply or refreshed periodically with a pulse.
- 2) **ROM (Read-only memory):** It is a type of computer storage containing non-volatile, permanent data that, normally, can only be read, not written to.
- 3) **WORM (Write once – read many times) :** It can record data once and then the data becomes permanent on the disc.
Eg: CD-R (Compact Disc-Recordable).
- 4) **EPROM (Erasable programmable read only memory):** Here the content can be erased by exposing it to UV light. It allows users to write new data on it after erasing.
Eg: basic input/output system chips (BIOS chips)

- 5) **Hybrid memory:** Hybrid memory allows data to be read and re-written at any time.
- 6) **EEPROM (Electrically erasable programmable read only memory):** The content on EEPROM can be programmed and erased electrically. It is byte-wise erasable.
Eg: Products such as real-time clocks, digital potentiometers, digital temperature sensors, among others, may have small amounts of EEPROM to store calibration information or other data that needs to be available in the event of power loss.
- 7) **Flash:** Flash memory is a distinct type of EEPROM, which is programmed and erased in large blocks.
Eg: Solid state drive (SSD), USB Flash drive, Secure digital card (SD Card)
- 8) **Non Volatile Memory:** Nonvolatile memory does not loses the stored information even in the event of power failure.
- 9) **RAM (Random-access memory):** It is a read/write memory used to store data of currently running programs.
- 10) **DRAM (Dynamic random-access memory):** It stores information with the help of transistors and capacitors. Due to the discharge of capacitors, they need to be periodically refreshed with electricity otherwise there will be data loss. They are used as main memory in computer systems.
- 11) **SRAM (Static random-access memory):** It stores information with the help of transistors. It does not need to be periodically refreshed. They are used as cache memory in computer and other computing devices.

CLASSIFICATION OF ELECTRONIC MEMORY DEVICES:

According to the device structure, electronic memory devices can be divided into four primary categories: transistor-type, capacitor-type, resistor-type and charge transfer- type.

1. TRANSISTOR-TYPE

- It uses transistors to store information.
- A transistor type semiconducting electronic memory device contains a electronic circuit, including a complementary metal oxide semiconductor(CMOS)transistor and capacitor (C).
- In a transistor-type memory device, each transistor represents one bit of information.
- In the electronic circuit, "0" or "ON" and "1" or "OFF" corresponds to the "discharged" and "charged" respectively.
- An organic transistor memory device stores data based on two conductivity states. In the organic transistor memory device, the organic material itself is the memory element.
- But a semiconducting memory device generally consists of a minute and complicated electric circuit.
- Therefore, organic transistor memory device structure can be simplified and the device can be fabricated in simple steps.

- One popular type of transistor-type memory is called Dynamic Random Access Memory or DRAM.

2. CAPACITOR- TYPE

- It uses capacitors to store information.
- Capacitors have two parallel plate electrodes and charges are stored in these electrodes under an applied electric field.
- Each capacitor represents one bit of information, which is a 0 or a 1.
- When a capacitor is charged, it represents a 1, and when it's discharged, it represents a 0.
- One popular type of capacitor-type memory is Ferroelectric Random Access Memory or FeRAM which is used in some specialized applications.

3. RESISTOR-TYPE

- It uses resistors to store information.
- Resistors are electronic components that resist the flow of electrical current.
- It is based on the change of the electrical resistivity of materials in response to an applied voltage (electric field).
- Each resistor represents one bit of information, which is a 0 or a 1.
- The resistors are arranged in a particular pattern to store the information.
- One popular type of resistor-type memory is Programmable Read-Only Memory or PROM.

4. CHARGE TRANSFER TYPE

- It is based on the Charge Transfer effects of a charge transfer complex.
- A charge transfer (CT) complex consists of two parts, one electron donor and other an electron acceptor. It is also called as a donor-acceptor (D-A) complex.
- The conductivity of a CT complex is dependent on the ionic binding between the D-A components. In CT complex, a partial transfer of charges occurs from donor part to the acceptor part. This results in difference in conductivity.
- CT complexes exhibit bistable states due to difference in conductivity. This behaviour is used to design molecular electronic devices.
- Many organic CT systems, including organometallic complexes, carbon allotrope (fullerene, carbon nanotubes and graphene)-based polymer complexes, gold nanoparticle-polymer complexes, and single polymers with intra-molecular D-A structures are used for memory applications.

TYPES OF ORGANIC MEMORY MATERIALS:

There are three classes of materials which can exhibit bistable states and are used in organic memory devices. They are:

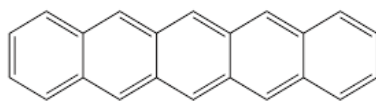
- I) Organic molecules,
- II) Polymeric materials,
- III) Organic- inorganic hybrid materials.

I) ORGANIC MOLECULES

These organic molecules show bistable or multi stable states when external field is applied. When a threshold voltage is applied, they undergo a transition from the OFF state to the ON state, or from the ON state to the OFF state.

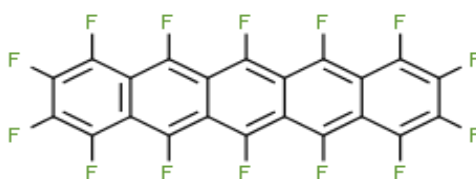
Acene derivatives:

- 1) Acenes are the polycyclic aromatic compounds consisting of linearly fused benzene rings.
- 2) They have high charge carrier mobility.
Examples: naphthalene , anthracene, , tetracene , Pentacene, Perfluoropentacene etc.
- 3) The most important member of the acene family is pentacene.
- 4) It is a linearly fused aromatic compound with five benzene rings.
- 5) It can be obtained in crystal and thin film form. Both forms exhibit a very good hole mobility and hence it behave as a p-type semiconductor.



Pentacene

- 6) When all the hydrogen atoms of pentacene are replaced by fluorine atoms the resulting molecule is perfluoropentacene.
- 7) Strong electron withdrawing nature of fluorine atoms converts this molecule into very good electron mobility and acts as n-type semiconductor.

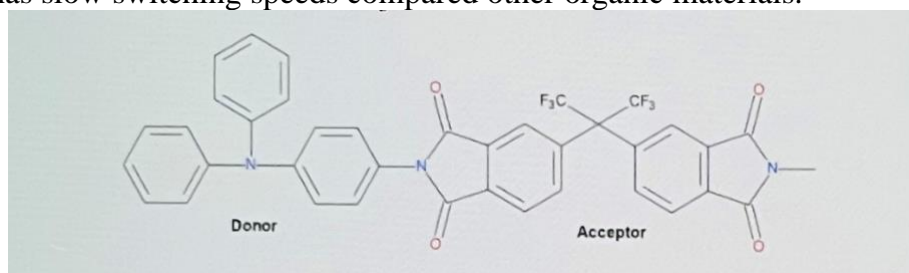


- 8) Pentacene and Perfluoropentacene have similar structure and similar crystal packing but pentacene behaves as p-type and perfluoropentacene behaves as an n-type semiconductor. Therefore, these molecules together exhibit charge transfer processes that are useful for memory applications.
- 9) Organic molecules exhibit fast switching speeds hence have high data transfer rates.
- 10) They are less stable than other memory materials, not suitable for long-term storage as they may get decomposed.

II. POLYMER MOLECULES

- 1) There are five classes of polymers which exhibit memory effect and are used in electronic memory devices.

- 2) Polymer molecules are increasingly being used in memory devices due to their ability to exhibit bistable (2 distinct stable forms) states and also unique properties, such as flexibility, low cost, and compatibility.
- 3) Functional polyimides are a type of polymer that are commonly used in organic electrical memory applications.
- 4) These polyimides are incorporated with organic molecules such as phthalimide and triphenylamine which are incorporated into the polymer backbone of the polyimide.
- 5) It is then sandwiched between two electrodes typically made of metals like gold and aluminum.
- 6) In a functional polyimide, the phthalimide unit acts as the electron acceptor, meaning that it is able to attract electrons. Meanwhile, the triphenylamine unit acts as the electron donor, and is able to donate them to the acceptor unit. When a voltage is applied to the device electrons are transferred from the donor to the acceptor forming donor-acceptor complex
- 7) This creates a dipole moment within the material and changes its electronic structure, that is there is transition from a low-conducting state to a high-conducting state, thus leading to storage of information.
- 8) These are used in different types of memory device, such as volatile DRAM AND SRAM devices and non- volatile ROM and Flash devices.
- 9) Polymeric materials can be easily processed into various shapes and sizes they can store data for long periods without losing information.
- 10) It has slow switching speeds compared other organic materials.



III. ORGANIC-INORGANIC HYBRID MATERIALS

Organic-inorganic hybrid materials are composed of organic layers containing inorganic materials. Inorganic materials used are allotropes of carbon like fullerenes, carbon nanotubes, graphene and metal nanoparticles, semiconductor nanoparticles and inorganic quantum dots (QDs).

a) Organic-Carbon allotrope hybrid materials

- 1) These are composed of organic layers combined with fullerenes.
- 2) These are made up of Polymers containing electron donors such as thiophene, fluorine, carbazole and aniline derivatives. Hence polymers act as electron donor.
- 3) The fullerenes have high electron-withdrawing ability hence acts as electron acceptor.
- 4) Thus these hybrid materials have donor-acceptor ability and electrical bistable states.
- 5) When a voltage is applied to the device electrons are transferred from the donor to the acceptor.
- 6) This creates a dipole moment within the material leading to transition from a low-conducting state to a high-conducting state, thus leading to storage of information.

- 7) They are used in ROM memory effect devices.

b) Organic -Inorganic Nanocomposite hybrid material:

- 1) Organic-Inorganic Nanocomposites are materials made by combining organic molecules or polymers with inorganic nano particles such as metal nanoparticles, inorganic quantum dots and metal oxide nanoparticles.
- 2) These hybrid materials have unique properties, such as high strength or electrical conductivity.
Example: A composite made up of polymer 8-hydroxyquinoline with gold nanoparticle
- 3) The material is composed of a thin film of the 8-hydroxyquinoline-based polymer containing gold nanoparticle, which is sandwiched between two metal electrodes made up of gold and aluminium.
- 4) Bistable states are observed when an electric field is applied due to charge transfer between the Au nanoparticles and 8-hydroxyquinoline. This leads to changes in its optical and electrical properties.
- 5) Organic-inorganic hybrid materials have combined property of organic and inorganic materials.

DISPLAY SYSTEMS

Display System: It is a system through which information is conveyed to people through visual means.

Photoactive materials: These are materials that interact with the light electromagnetic field and modify either their own properties or those of the field.

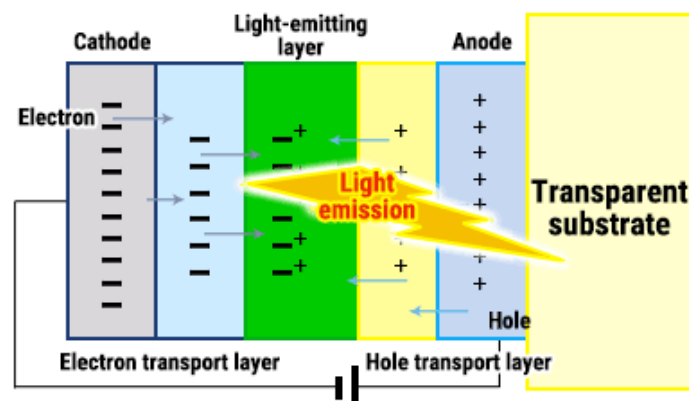
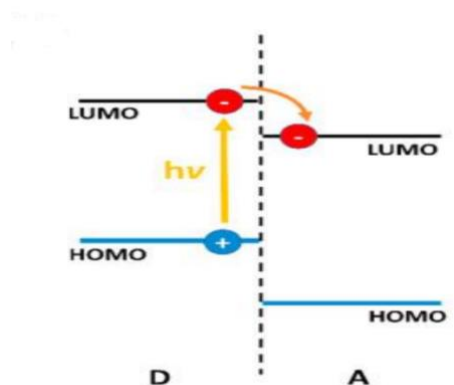
Eg: Photochromic materials, which change colour upon exposure to light.

Electroactive materials: These are materials that interact with an electric field and modify either their own properties or those of the field.

Eg: When an electric field is applied to a piezoelectric material, leads to a deformation or change in shape of the material.

PRINCIPLE OF PHOTOACTIVE AND ELECTROACTIVE MATERIALS:

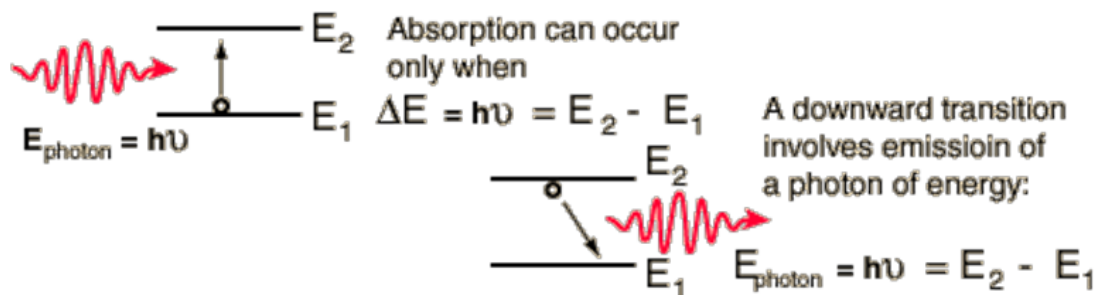
Display system (OLED) consisting of photoactive and electroactive material absorb light and allows an electron to jump from HOMO of a Donor to LUMO of an Acceptor. This phenomenon generate and transport charge carriers.



In an OLED device, the light-emitting layer is excited by the recombination energy of electrons from the cathode and holes from the anode, and then the light-emitting layer emits light when returning to the ground state. One of the electrodes consists of transparent material in order to extract light from the light emitting layer.

OPTOELECTRONIC DEVICES: These are the devices that functions as an electrical-to-optical or optical-to-electrical transducer.

WORKING PRINCIPLE:



If the photon has an energy larger than the energy gap, the photon will be absorbed by the semiconductor, exciting an electron from the valence band into the conduction band, where it is free to move. A free hole is left behind in the valence band. When the excited electron is returning to valence band, extra photon energy is emitted in the form of a light. This principle is used in Optoelectronic devices.

NANOMATERIALS (SILICON NANOCRYSTALS) USED IN OPTOELECTRONIC DEVICE:

Any substance in which at least one dimension is less than 100nm is called nanomaterials. The properties of nanomaterials are different from bulk materials due to:

1. Quantum Confinement effect
2. Increased surface area to volume ratio

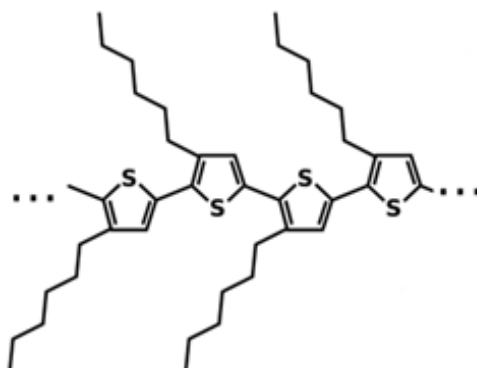
The improved electronic properties yielded for nanostructured silicon in comparison to its bulk, which led the use of Silicon Nanocrystals in electronics and optoelectronics fields.

Special properties of Silicon Nanocrystals for optoelectronics

1. Silicon Nano crystal has wider bandgap energy due to quantum confinement.
2. Si NCs shows higher light emission property (Photoluminescence)
3. Si NCs exhibit quantum yield of more than 60%.
4. Si-NCs exhibit tunable electronic structure.
5. Larger surface area-volume ratio.

ORGANIC MATERIALS USED IN OPTOELECTRONIC DEVICES:

A) Light absorbing materials: eg: polythiophenes (p3ht)

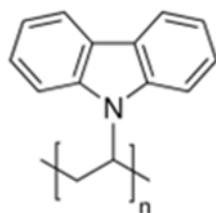


Properties:

- (i) Polythiophenes are an important class of conjugated polymers, environmentally and thermally stable material.

- (ii) Chemical structure of P3HT Poly(3-hexylthiophene) is a polymer with chemical formula $(C_{10}H_{14}S)_n$.
- (iii) It is a polythiophene with a short alkyl group on each repeat unit.
- (iv) P3HT is a semiconducting polymer with high stability and exhibits conductivity due to holes therefore considered as p-type semiconductor.
- (v) Poly-3-hexylthiophene (P3HT) have great capability as light-absorbing materials in organic electronic devices.
- (vi) P3HT has a crystalline structure and good charge-transport properties required for Optoelectronics.
- (vii) P3HT has a direct-allowed optical transition with a fundamental energy gap of 2.14 eV.
- (viii) Fundamental bandgap of P3HT is 490nm visible region, corresponding to $\pi \rightarrow \pi^*$ transition, giving electron-hole pair.
- (ix) P3HT indicate that an increase in the conductivity is associated with an increase in the degree of Crystallinity.

B) Light emitting materials: Poly[9-vinylcarbazole] (pvk)

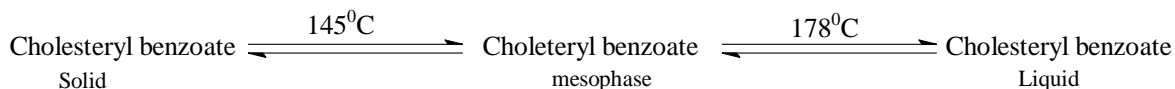


Properties:

- 1) Polyvinylcarbazole (PVK) is produced by radical polymerization from the monomer N-vinylcarbazole.
- 2) Poly (N-vinyl carbazole) (PVK) is one of the highly processable polymers.
- 3) It is a hole conducting material.
- 4) It is used as an efficient hole transport material to prepare highly efficient and stable planar heterojunction perovskite solar cells.
- 5) It is a photoconductive polymer and thus used in organic light-emitting diodes.
- 6) It has been widely used as an electronic and optical material.
- 7) The polymer is extremely brittle, but the brittleness can be reduced by copolymerization with a little isoprene.
- 8) PVK-Perovskite junction is used in Light-Emitting Diodes with Enhanced Efficiency and Stability.

LIQUID CRYSTALS

The study of liquid crystals began with an observation made by Austrian botanist, Freindrich Reinitzer in 1888. He observed that solid cholesteryl benzoate on heating becomes a turbid liquid at 145°C which on further heating turns into a clear, transparent liquid at 178°C. The above changes are reversed on cooling. The changes are generally represented as



Cholesteryl benzoate is said to exit a liquid crystal between 145°C and 178°C. The first temperature at which solid changes into turbid liquid is known as **transition point** and second temperature at which turbid liquid changes into clear liquid is known as **melting point**. Thus, liquid crystal is a distinct phase observed between crystalline solid state and isotropic liquid state.

Definition: Liquid crystals may be described as a distinct state of matter in which the degrees of molecular ordering lie intermediate between the ordered crystalline state and the completely disordered isotropic liquid state.

The liquid crystal state is also referred to as **mesophase**. The compounds which exhibit mesophase are also called **mesogens**. Liquid crystals exhibit optical anisotropy, i.e., they possess different optical properties when light is incident in different directions. Liquids, however, exhibit optical isotropy i.e., they exhibit same optical property irrespective of the direction of incident light.

CLASSIFICATION OF LIQUID CRYSTALS:

Liquid crystals are classified into two main categories, namely,

1. Thermotropic liquid crystals
2. Lyotropic liquid crystals.

1. Thermotropic liquid crystals: The class of compounds that exhibit liquid crystalline behaviour on variation of temperature alone are referred to as thermotropic liquid crystals. The temperature range at which some liquid crystal are stable are given below:

	Solid		Liquid crystal		Liquid
Cholesteryl Benzoate		145 ⁰		178 ⁰	
p-Azoxyphenetole		137 ⁰		167 ⁰	
p-Azoxyanisole		116 ⁰		135 ⁰	

2. Lyotropic liquid crystals: Some compounds transform to a liquid crystal phase when mixed with a solvent. They have a lyophilic and a lyophobic end that is they are amphiphilic compounds. They are usually obtained by mixing the compound in a solvent and increasing the concentration of compound till liquid crystal phase is observed. Such liquid crystals are called lyotropic liquid crystals. The formation of lyotropic mesophases is dependent on the concentration of either the component or the solvent. Variation of temperature also affects the formation of these mesogens.

Examples: (i) soap (soap-water mixture) molecules

Thermotropic liquid crystals have been classified into the following types:

- 1) Nematic liquid crystals; 2) Cholesteric liquid crystals
- 3) Smectic liquid crystals; and 4) Columnar or discotic liquid crystals:

(1) Nematic phase: Nematic (Greek; nematos = thread like) liquid crystals are formed by compounds that are optically inactive. The molecules have elongated shape and are approximately parallel to one another (Fig.1). Nematic phase is characterized by the total loss of positional order and a near normal flow behaviour similar to its liquid phase.

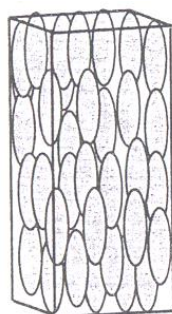


Fig.1 Nematic liquid crystal

Examples: (i) p-Azoxy anisole ($116-135^{\circ}\text{C}$); (ii) p-Azoxy phenetole ($137-167^{\circ}\text{C}$); (iii) p-Anisaldehyde ($165-180^{\circ}\text{C}$).

(2) Chiral (Twisted) Nematic Phase (Fig.2): Chiral nematic liquid crystals also referred to as cholesteric liquid crystals or twisted nematic liquid crystals (TNLC), formed from optically active compounds having chiral centres. Unlike in a nematic phase where all the molecules are approximately parallel to one another, in chiral nematic phase, the molecules arrange themselves in such a way that they *form a helical structure*. In this mesophase, the director is therefore not fixed in space as in a nematic phase, but rotates through the sample forming a helical pattern as it changes its direction just like the motion of a nut on a screw. The distance traveled by the director as it completes one full turn is called the pitch of the liquid crystal. In other words, the pitch length is the distance traveled by the director when it gets turned by 360° . The twisted pattern repeats itself through the liquid crystal phase. The most striking feature of cholesteric mesophase is its strong optical activity and selective light reflection, which are attributed to the twisted structure. The twist present in chiral nematic liquid crystal imparts spectacular optical properties which are made use of as thermochromic materials. The pitch is also temperature dependent and hence cholesterics are used in thermography.

Examples: (i) Cholesteryl benzoate; (ii) Cholesteryl myristate and (iii) Cholesteryl formate etc.

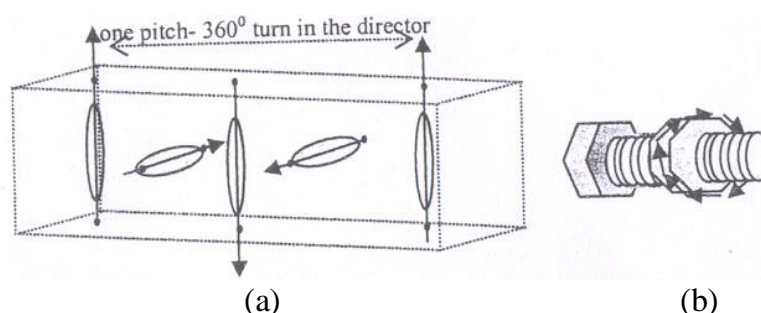


Fig. 2(a) Illustration of the twisted structure in a chiral nematic phase of a liquid crystal as shown by the change in the direction of the director. Arrows show the orientation of the molecules. (b) A nut moves a certain distance when it makes a full turn (one pitch) and comes back to its original direction as shown by the arrows.

(3) Smectic mesophase: Substances that form smectic phases are soap-like (in Greek, smectos means soap). In fact, the soft substance that is left at the bottom of a soap dish is a kind of smectic liquid crystal phase. In smectic mesophase, there is a small amount of

orientational order and also a small amount of positional order. The molecules tend to point along the director and arrange themselves in layers. A snapshot would reveal that more number of molecules position in regularly spaced planes and a few molecules lie between the planes (Fig.5). That is, any one molecule would spend more time in these planes than between the planes. Based on the orientation of the director there are many types of smectic phases. If the director is perpendicular to the planes it is called smectic A (Fig. 3a) and smectic C if the director makes an angle other than 90° (Fig.3b). In smectic B phase, the director is perpendicular to the plane with the molecules arranging themselves into a network of hexagons within the layer.

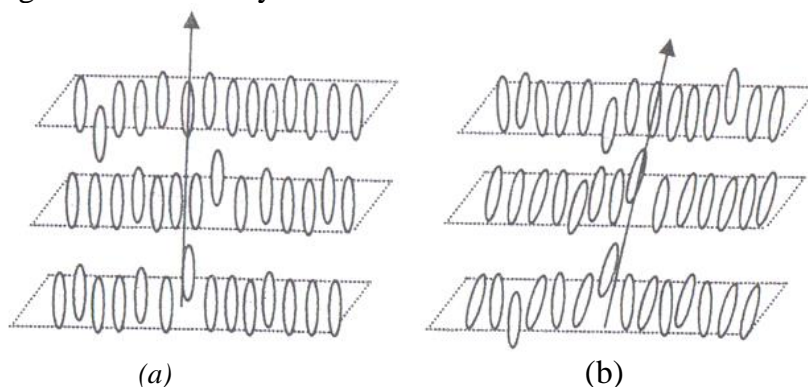


Fig.3 Schematic representation of smectic mesophase where molecules lie on regularly spaced planes (in the form of layers). (a) Smectic A where molecules are perpendicular to the layer planes. (b) Smectic C where the molecules are tilted with respect to the layer planes.

Examples: (i) 4-n-Butyloxybenzylidene aminopropiophenone (smectic-A); (ii) 4,4'-di-n-Heptyloxyazobenzene (smectic-C); (iii) Terephthalidene-bis-4-n-butylaniline (smectic-B).

(4) Discotic or Columnar Liquid crystalline Phase: Liquid crystals formed by molecules which have disk-like or plate-like structure are referred to as discotic or columnar liquid crystals.

The simplest discotic phase is also called discotic nematic phase because there is orientational order but no positional order (Fig.4a). There is random motion of the molecules, but on an average, the axis perpendicular to the plane of each molecule tends to orient along the director.

In the discotic or columnar phase, in addition to the orientational order present in the nematic discotic phase, most of the molecules tend to position themselves in columns (Fig.4b). The columns are arranged in a hexagonal lattice resembling a set of coins stacked as shown below (note: the coins in a stack have a great deal of positional order i.e., the coins are equidistant whereas the molecules in a columnar phase are stacked in random fashion).

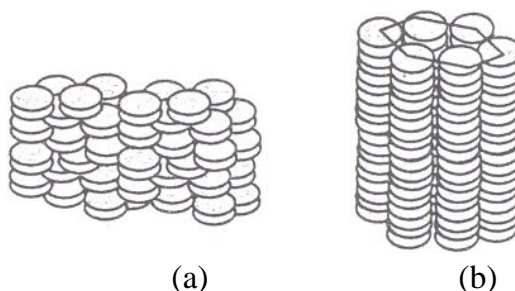


Fig.4. Schematic representation of disc like molecules arranged in (a) Discotic nematic (b) discotic columnar liquid crystal phases

Example: Benzene-hexa-n-alkanoate

PROPERTIES OF LIQUID CRYSTALS:

1. They exhibit optical anisotropy which is defined as the difference between refractive index parallel to the director and refractive index perpendicular to the director. These two properties are important for the electro-optic effects in liquid crystals.
2. The intermolecular forces are rather weak and can be perturbed by an applied electric field.
3. Because the molecules are polar, they interact with an electric field, which causes them to change their orientation slightly.
4. Liquid Crystal can flow like a liquid, due to loss of positional order.
5. Liquid crystal is optically birefringent, due to its orientation order.
6. Liquid crystals, like all other kinds of matter, exhibits thermal expansion.

ELECTRO-OPTIC EFFECT OF LIQUID CRYSTALS:

Nematic liquid crystals have rod like molecular structure and align themselves spontaneously along the director. Nematic materials have two dielectric constants- one in the direction parallel to the director and the other perpendicular to the director. Dielectric anisotropy ($\Delta\epsilon$) is defined as the difference between the dielectric constants parallel and perpendicular to the director. Similarly, the **optical anisotropy** (Δn) is defined as the refractive index parallel to the director minus the refractive index perpendicular to the director. These two properties are important for the electro-optic effects in liquid crystals.

Effect of electric field: The director in a liquid crystal is free to point in any direction. But when a film of liquid crystal is placed between two plates of certain materials, director is forced to point along a particular direction when an electric field is applied. For example, when a film of liquid is placed between two specially treated glass sheets (such as rubbing with a velvet cloth, or applying a thin coat of a polyamide followed by unidirectional rubbing with a roller), the molecules close to the glass surfaces are forced to orient themselves parallel to the surfaces of the glass sheets.

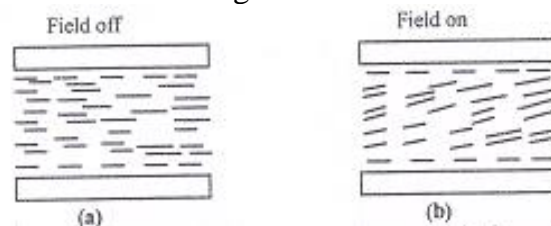


Fig.5 Liquid crystal film kept between two treated glass plates (a) in the field off state all molecules and the director orient parallel to the surface (b) in the field on state the molecules near the surface orient parallel to the surface whereas in others it is deformed

In the absence of an electric field, (below a threshold value) the molecules at other layers are also aligned parallel to the surfaces giving a homogeneous arrangement. But when an electric field is applied perpendicular to the glass surface, molecules near the surface are aligned parallel to the surface (perpendicular to the applied field). The molecules near the centre of the liquid crystal layer (away from the surface) are free to orient themselves along the applied field. The crystal undergoes deformity (Fig. 8). This transition (deformity) is important in the operation of liquid crystal displays (LCD) because the transition brings about a significant change in the optical characteristics of the liquid crystal.

Effect of light: When light is incident on two crossed polarizers, no light emerges because the light emerging from the first polarizer is completely absorbed by the second polarizer and hence appears dark. When a film of a liquid crystal is placed between two polarizers, only a part of the light from first polarizer is absorbed by the second polarizer some light emerges giving bright appearance. A cell is assembled such that the direction of alignment at the top surface is perpendicular to that at the lower surface of the cell. Then it filled with a twisted nematic liquid crystal (TNLC) having a positive dielectric anisotropy (dielectric constant parallel to the director is higher). Twisted structure acts like a wave-guide and gradually rotates the plane of polarization of light by 90° . Hence a linearly polarized light incident on the cell emerges linearly polarized but in an orthogonal direction resulting in a bright appearance (Fig. 6).

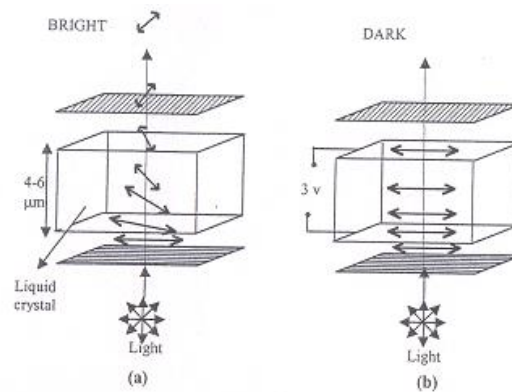


Fig.6 Bright and dark appearance when light is passed through twisted nematic liquid crystal placed between two crossed polarizers (a) appearance is bright in the absence of electric field (b) appearance is dark in the presence of electric field.

The 90° twist in the cell is lost when a sufficiently strong electric field (2-5V) is applied to the cell. Hence the cell appears dark between two crossed polarizers (Fig. 6b). The following conditions, however should be met to see the electro-optic effect.

- (i) The plane of polarization of incident light should be parallel or perpendicular at the surface of the cell.
- (ii) The product of optical anisotropy, Δn , (the difference in refractive indices parallel and perpendicular to the director) and pitch P should be greater the wavelength of the incident light. $\Delta n \times P > \lambda$.

APPLICATIONS IN LIQUID CRYSTAL DISPLAYS (LCD'S):

A liquid crystal display (LCD) is a flat panel display technology that uses liquid crystals to produce images. The light is passed or blocked by changing the polarization.

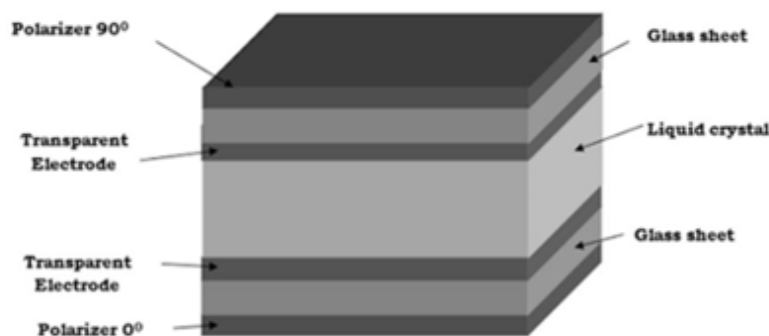


Fig.7. Constitution of liquid crystal display

1. The working principle of an LCD is based on the optical properties of liquid crystals.

2. An LCD consists of a layer of liquid crystal material sandwiched between two transparent electrodes.
3. The molecules adjacent to the glass will align to the polarizer, resulting in a helical structure between the two glass plates.
4. As light strikes the first plate, it gets polarized.
5. The molecules in each layer then guide the light through the display, changing the angle of polarization.
6. When light reaches the final layer of the crystal material its plane of polarization will have rotated 90 degrees, and now matches the plane of the top polarizing film hence comes out through it appearing bright.
7. When electric field is applied across the plates, the liquid crystal molecules untwist and lose their property of rotating the light.
8. Hence the plane of the light no longer matches the angle of the top polarizable plate. Consequently, no light can pass through that area of the LCD, which makes that area look dark.

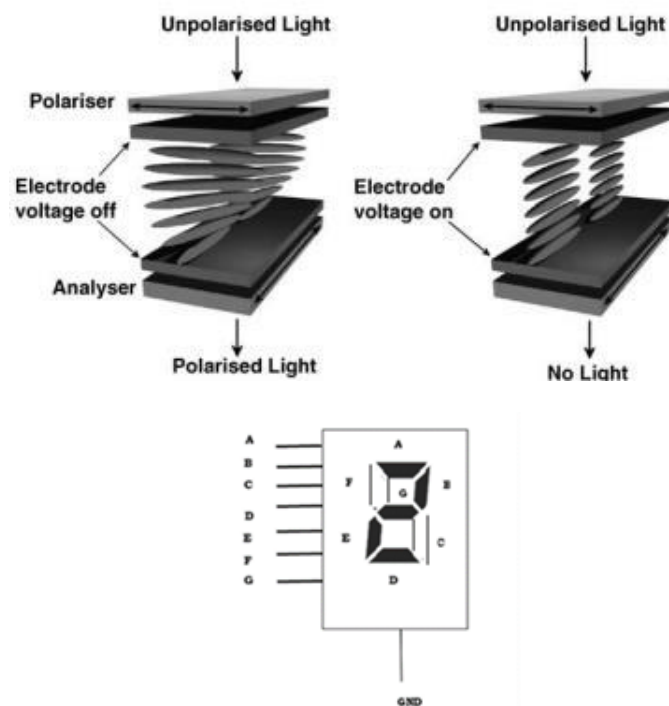


Fig. 8. Liquid crystal arrangement in display number. 2

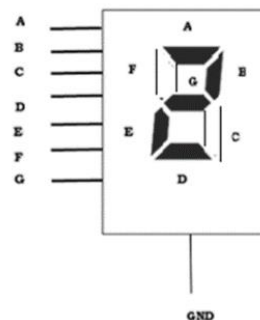


Fig: 2.22 Liquid Crystal Arrangement to display number 2

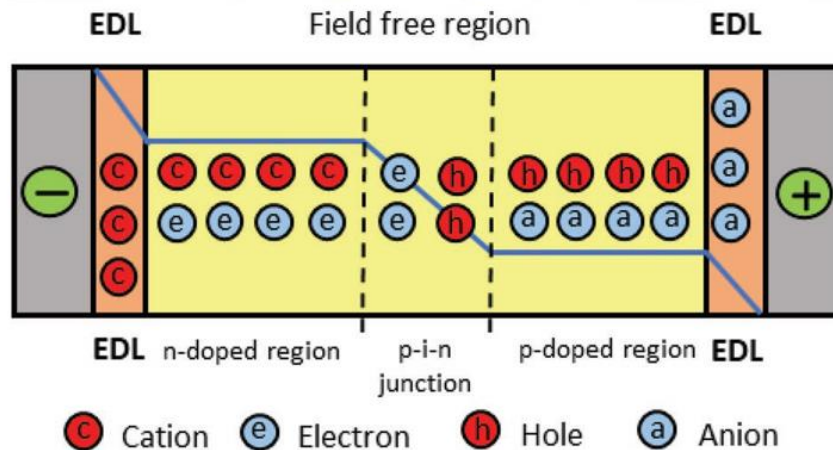
In the segment arrangement, the conducting segment looks dark and the other segment looks clear. To display number 2, the segments A, B, G, E, D are energized.

LIGHT-EMITTING ELECTROCHEMICAL CELLS (LECS):

These are solid-state lighting devices that convert electric current to light within electroluminescent organic semiconductors.

Working:

- 1) The active layer of LECs comprises of electroactive compounds and mobile ions that are sandwiched between cathode and anode.
- 2) When dc current is passed, mobile ions in the active layer drift toward the respective electrodes, and an injection of electrons and holes takes place at the electrode interface.
- 3) Injected charge carriers attract mobile ions through electrostatic force of attraction.
- 4) The charges on injected charge carriers are compensated by charges on mobile ions.
- 5) It results in the formation of n- and p-type doped regions at the respective electrodes.
- 6) These regions extend towards each other and meet at the p-n junction.
- 7) At the p-n junction, the electrons and holes recombine to form excitons.
- 8) The excitons subsequently decay to emit photons, resulting in electroluminescence emission.



Advantages:

LECs are best known for their simple architecture and easy, low-cost fabrication. Active layer of LECs contains ionic species that can be processed using solution techniques like spin coating, inkjet printing and slot-die coating, rendering the fabrication process cost-effective.

LEC devices can be operated at low voltages with high efficiencies. LECs do not rely on the work function of electrodes owing to the presence of mobile ions that enable the use of air stable cathodes and avoid the rigorous encapsulation of air sensitive injection layers. Therefore, these devices can be operated at low voltages.
