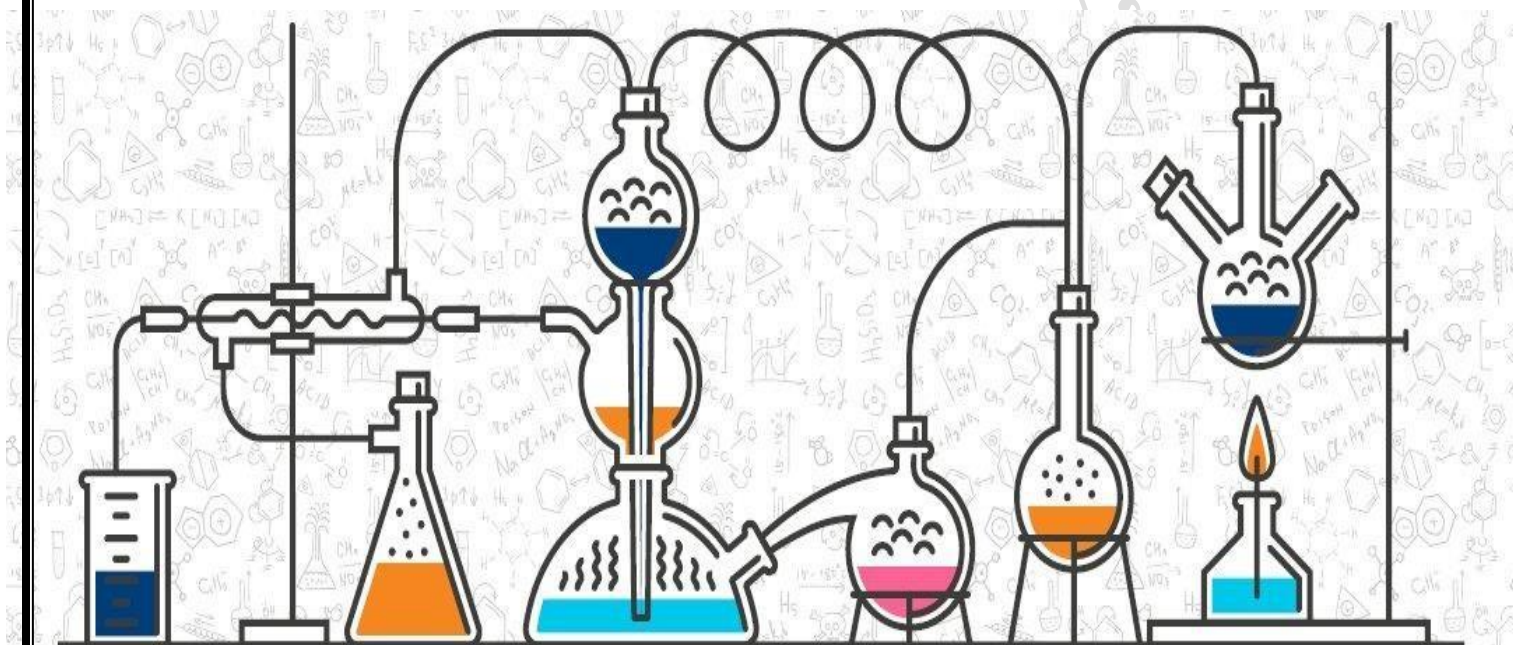




## APPLIED CHEMISTRY- CS Stream

### I / II SEMESTER (22CHES12/22) Module 2: Polymers and Green energy



**DAYANANDA SAGAR COLLEGE OF ENGINEERING**

Accredited by National Assessment & Accreditation Council (NAAC) with 'A' Grade  
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ISO 9001:2015 Certified)

**DEPARTMENT OF CHEMISTRY**

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BENGALURU-560111**

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## Module 2:

### Polymers and Green energy

#### Polymers

A polymer is a large molecule, or macromolecule, composed of many repeated subunits. The term "polymer" derived from the ancient Greek word *polus*, meaning "many, much" and *meros*, meaning "parts, and refers to a molecule whose structure is composed of multiple repeating units, from which originates a characteristic of high relative molecular mass and attendant properties. The term was coined in 1833 by Jöns Jacob Berzelius. Because of their broad range of properties, both synthetic and natural polymers play an essential and ubiquitous role in everyday life. Polymers range from familiar synthetic plastics such as polystyrene to natural biopolymers such as DNA and proteins that are fundamental to biological structure and function. Polymers, both natural and synthetic, are created via polymerization of many small molecules, known as monomers. Their consequently large molecular mass relative to small molecule compounds produces unique physical properties, including toughness, viscoelasticity, and a tendency to form glasses and semicrystalline structures rather than crystals.

**Definition of polymers:** A polymer is a large molecule of high molecular weight obtained by the chemical interaction of many small molecules of low molecular weight of one or more type. The process of manufacture of a polymer is called the polymerization.

**Monomers:** Small molecules of low molecular weight, which combine to give a polymer, are called monomers.

**Degree of polymerization:** The number of monomers used in the process is called degree of polymerization.

**Functionality:** The total number of functional groups or bonding sites present in a monomer molecule is called the functionality of the monomer.

**Polymerization:** Is the process of conversion of low molecular weight substances into high molecular weight substances with or without the elimination of by products such as HCl, H<sub>2</sub>O, NH<sub>3</sub> etc.

#### Number Average and Weight Average:

**Number Average:** The number average molecular weight is defined as the total weight of polymer divided by the total number of molecules.

$$M_n = \frac{\sum n_i M_i}{\sum n_i}$$

(Where  $n_1, n_2$  etc are number of particles having mass  $M_1, M_2$  etc.)

That means

$$M_n = \frac{n_1 M_1 + n_2 M_2 + \dots}{n_1 + n_2 + \dots}$$

**Weight average molecular weight ( $M_w$ ):** Molecular weight of each particle is multiplied by total weight of this species. These factors are added for all the size species and divided by the sum of weights of all individual sizes.

$$M_w = \frac{\sum n_i M_i^2}{\sum n_i M_i}$$

That means

$$M_w^- = \frac{n_1 M_1^2 + n_2 M_2^2 + \dots}{n_1 M_1 + n_2 M_2 + \dots}$$

### NUMERICAL PROBLEMS ON POLYMER

1. A polymer sample contains 2, 3 and 4 molecules having molecular weights  $2 \times 10^3$ ,  $3 \times 10^3$  and  $4 \times 10^3$  respectively. Solve for the number average and weight average molecular weights of the polymer.

$$\text{Answer: } M_n^- = \frac{n_1 M_1 + n_2 M_2 + n_3 M_3}{n_1 + n_2 + n_3}$$

$$= \frac{2(2 \times 10^3) + 3(3 \times 10^3) + 4(4 \times 10^3)}{2 + 3 + 4} = 3.22 \times 10^3$$

$$M_w^- = \frac{n_1 M_1^2 + n_2 M_2^2 + n_3 M_3^2}{n_1 M_1 + n_2 M_2 + n_3 M_3}$$

$$= \frac{2(2 \times 10^3)^2 + 3(3 \times 10^3)^2 + 4(4 \times 10^3)^2}{2(2 \times 10^3) + 3(3 \times 10^3) + 4(4 \times 10^3)} = 3.41 \times 10^3$$

2. A polymer sample has population as follows: 5 molecules of molecular mass each = 2000; 4 molecules of molecular mass each = 3000; 3 molecules of molecular mass each = 4000. Solve for its number average and weight average molecular weights.

$$\text{Answer: } M_n^- = \frac{n_1 M_1 + n_2 M_2 + n_3 M_3}{n_1 + n_2 + n_3}$$

$$= \frac{5(2 \times 10^3) + 4(3 \times 10^3) + 3(4 \times 10^3)}{5 + 4 + 3} = 2833.3$$

$$M_w^- = \frac{5(2 \times 10^3)^2 + 4(3 \times 10^3)^2 + 3(4 \times 10^3)^2}{5(2 \times 10^3) + 4(3 \times 10^3) + 3(4 \times 10^3)} = 3058.82$$

3. Solve for  $M_n$  and  $M_w$  of a polymer which consists of 35% molecules having molecular mass 25000, 35% molecules having molecular mass 20000 and the remaining molecules having molecular mass 10000.

$$\text{Answer: } M_n^- = \frac{n_1 M_1 + n_2 M_2 + n_3 M_3}{n_1 + n_2 + n_3}$$

$$= \frac{35 \times 25000 + 35 \times 20000 + 30 \times 10000}{100} = 18750$$

$$M_w^- = \frac{n_1 M_1^2 + n_2 M_2^2 + n_3 M_3^2}{n_1 M_1 + n_2 M_2 + n_3 M_3}$$

$$= \frac{35 \times (25000)^2 + 35 \times (20000)^2 + 30 \times (10000)^2}{35 \times 25000 + 35 \times 20000 + 30 \times 10000} = 20733$$

4. Solve for number average and weight average molecular weights of a polymer consisting of 150 molecules with molecular mass  $10^2$  g/mol, 200 molecules with molecular mass  $10^3$  g/mol and 350 molecules with molecular mass  $10^5$  g/mol.

$$\text{Answer: } M_n = \frac{n_1 M_1 + n_2 M_2 + \dots}{n_1 + n_2 + \dots}$$

$$= \frac{150 \times 10^2 + 200 \times 10^3 + 350 \times 10^5}{150 + 200 + 350}$$

$$= 50307$$

$$M_w = \frac{n_1 M_1^2 + n_2 M_2^2 + n_3 M_3^2}{n_1 M_1 + n_2 M_2 + n_3 M_3}$$

$$= \frac{150(10^2)^2 + 200(10^3)^2 + 350(10^5)^2}{150 \times 10^2 + 200 \times 10^3 + 350 \times 10^5} = 99395.18$$

## CONDUCTING POLYMERS

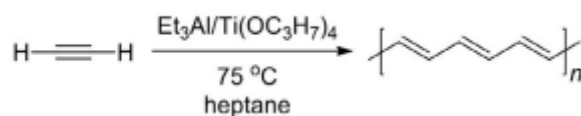
Conducting polymers or, more precisely, intrinsically conducting polymers (ICPs) are organic polymers that conduct electricity. Such compounds may have metallic conductivity or can be semiconductors. The biggest advantage of conductive polymers is their processability, mainly by dispersion. But, like insulating polymers, they are organic materials. They can offer high electrical conductivity but do not show similar mechanical properties to other commercially available polymers. The electrical properties can be fine-tuned using the methods of organic synthesis and by advanced dispersion techniques. Organic polymers with a highly delocalized pi electron system having electrical conductance of the order of a conductor is called conducting polymers.

Requirements for the polymer to be conducting:

1. Presence of delocalized pi electron (conjugation) in the main chain
2. Linearity/Planarity of the molecule
3. Presence of atoms having lone pair of electrons

## Synthesis of Polyacetylene

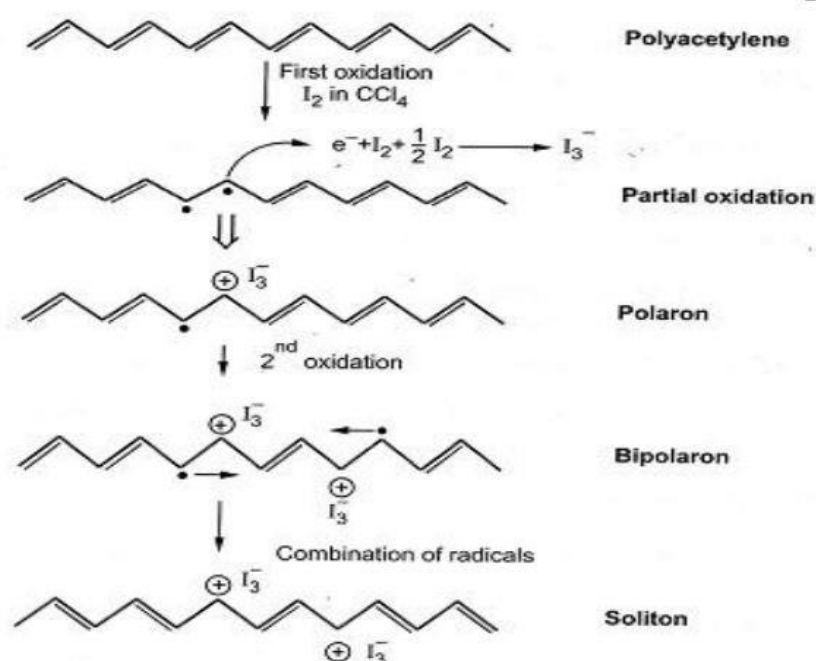
Polyacetylene is the simplest linear synthetic polymer. Fundamental unit consists from one carbon and one hydrogen atoms, as has been called simply (CH). Each carbon is  $sp^2$  hybrid orbital to one hydrogen and two adjacent carbon atoms to form a planar chain molecule. Polyacetylene is synthesized by catalytic polymerization of acetylene using Ziegler-Natta catalyst  $(Et)_3Al$  and titanium(IV) propoxide at  $75^\circ C$ , with a catalyst molar ratio (Al/Ti) of 2.5.



## Synthesis of polyacetylene.

## Conducting Mechanism in polyacetylene

Conductivity of pure polyacetylene is  $4.4 \times 10^{-5} \text{ S/cm}$  upon doping with oxidizing agents like iodine conductivity increases to about  $400 \text{ S/cm}$ . When the dopant iodine is added, it takes away an electron from the  $\pi$ -backbone of the polyacetylene chain and creates a positive center (hole) on one of the carbon atoms. The other  $\pi$ -electron resides on other carbon atom making it a radical called polaron. Further oxidation leads to the formation of a bipolaron. Then the radicals migrate and combine to establish a backbone double bond. As the two electrons are removed, the chain will have two positive centres (holes). The chain as a whole is neutral, but holes are mobile and when a potential is applied, they migrate from one carbon to another accounting for the conductivity as shown below.



### Conducting Mechanism of Polyacetylene.

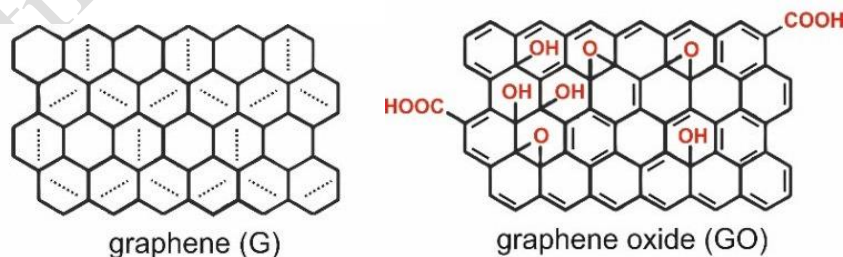
Before doping, there is sufficient energy gap between VB and CB so the electrons remain in VB and the polymer acts as an insulator. Upon doping, polarons and solitons are formed which results in the creation of new localized electronic states that fill the energy gap between VB and CB. When sufficient solitons are formed, a new mid-gap energy band is created which overlaps with conduction bands allowing electrons to flow.

Commercial application:

1. As antistatic coating
2. As sensors

### Graphene Oxide

Graphene oxide (GO), is a compound of carbon, oxygen, and hydrogen in variable ratios, obtained by treating graphite with strong oxidizers. Graphene oxide by analogy to graphene is a single-layer form of graphite having epoxide groups, carbonyl (C=O) and hydroxyl (-OH) functional groups.



### Structure of graphene oxide

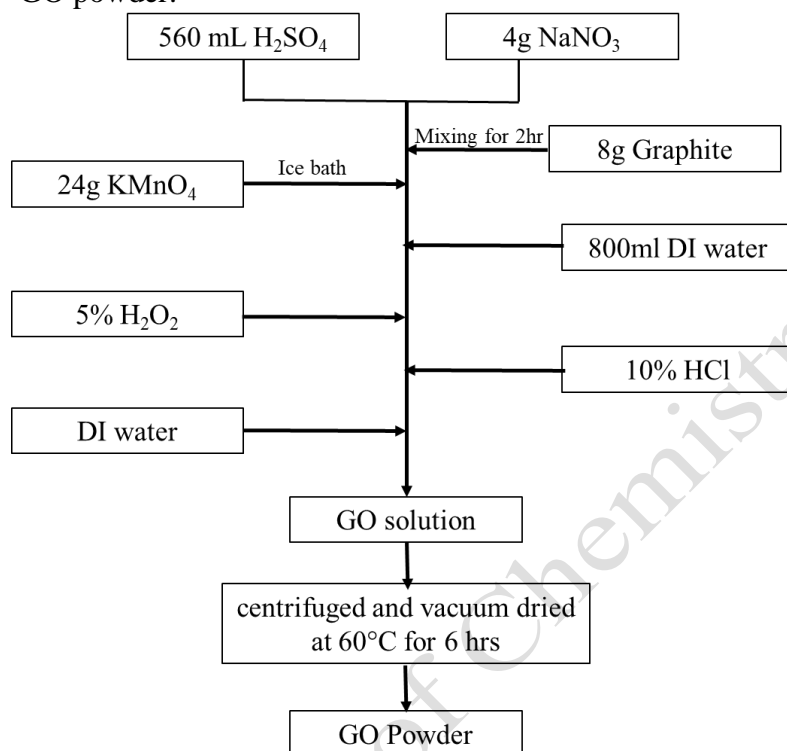
#### Preparation (Modified Hummer's method of synthesis):

Chemicals required: Graphite Flakes (acid treated 99%), Sodium nitrate (98%), Potassium permanganate (99%), Hydrogen peroxide (40% wt.), Sulphuric acid (98%), Hydrochloric acid (35%). Steps of preparation are as follows:

1. 8g graphite powder and 4g  $NaNO_3$  were put into 560 ml concentrated  $H_2SO_4$  solution with stirring for 2 hours.



- Then 24g  $\text{KMnO}_4$  was gradually added into the flask with ice bath for 2 hours.
- The mixture was diluted by 800ml de-ionized water (DI water). After that, 5%  $\text{H}_2\text{O}_2$  was added into the solution until the color of the mixture changed to brown, indicating fully oxidized graphite was obtained.
- The resulting mixture is washed repeatedly by centrifugation with 10%  $\text{HCl}$ . The as-obtained graphite oxide slurry was re-dispersed in DI water. Then, the mixture washed with DI water to remove the residual acid until the pH was reached to  $\sim 7$ .
- The resulting mixture is centrifuged and is vacuum dried at  $60^\circ\text{C}$  for more than 6 hrs to GO powder.



#### Properties:

- In contrast to graphene having high electrical conductivity ( $6500 \text{ Sm}^{-1}$ ) GO is an electrically insulating or semiconducting material having electrical resistivity around  $1.64 \times 10^{-4}$  because of disruption of  $\text{sp}^2$  bonding orbital of graphene due to presence of oxygen functionality
- Low thermal conductivity of  $0.5^{-1} \text{ W m}^{-1} \text{ K}^{-1}$  making it not an ideal option for most applications requiring good thermal properties
- It is hydrophilic and easily dispersed in water and organic solvents.
- Functionalization of graphene oxide can change graphene oxide's properties.
- High surface area

#### Applications:

- Graphene Oxide is used in the production of transparent conductive films after being deposited on any substrate. Such coatings could be used in flexible electronics, liquid crystal devices, chemical sensors, touch screen devices, LEDs
- GO is used as electrode materials in batteries and double-layered capacitors, as well as fuel cells and solar cells due to its extremely high surface area.
- Drug-delivery systems: GO is used as drug delivery systems for anticancer drugs because it does not target healthy cells, only tumors, and has a low toxicity.
- As GO is a fluorescent material it is used for bio sensing applications.
- Although GO shows poor performance in anode materials of Li-ion batteries, they have

- been used in the cathode materials successfully and also in dye-sensitized solar cells.
6. GO shows good sensing abilities due to active surface and high surface area.
  7. Chemically active nature and porous structure of graphene oxide have been utilized for the enhancement of membrane properties and separation performance.
  8. The fluorescent behavior of GO material is used for the optical biosensing applications to detect different biological molecules, such as cancer biomarkers glucose,  $H_2O_2$ , dopamine, food toxins, and metal ions.

### **Green energy: Introduction**

Solar energy is an essential source of renewable energy. Utilization and conversion solar energy utilization can be of two types

1. Direct solar power.
2. Indirect solar power.

**Direct Solar Power:** Direct solar power involves only one step transformation into a usable form. Example 1. Photovoltaic cells: It convert solar energy to electrical energy.

Example 2. Solar Thermal collector. Sunlight hits the dark absorber surfaces of a solar thermal collector and surface warms the heat energy may be carried away by a fluid circuit.

**Indirect solar power:** Indirect solar power involves more than one transformation to reach usable form.

Example, (i) plants convert solar energy to chemical energy when they are burnt.

(ii) Fossils fuels are obtained from plants which produce heat energy that can later be burned as fuel to generate electricity.

(iii) Ocean thermal energy production uses the thermal gradient that is present across ocean depths to generate power. This temperature difference is ultimately due to the energy of the sun.

### **Photovoltaic cells**

Photo-voltaic cells: Photovoltaic cells or solar cells are semiconductor devices that convert sunlight into direct current. As long as light is shining on the solar cell it generates electrical power. When the light stops electricity stops. Solar cells are generally classified into three generations depending on time and categories of materials which are used for their fabrication.

1. The most common solar cells available in the market are the first-generation solar cells which comprise single and polycrystalline silicon.
2. Second-generation solar cells were introduced as a response to high material usage and cost of silicon solar cell. To reduce the material usage the maximum film thickness for this generation was brought down to a few nanometers to tens of micrometers.
3. Third generation solar cell- dye-sensitized solar cells (DSSCs), perovskite, organic solar cells, photo chemical cells, QDs,

The operation of a photovoltaic (PV) cell requires three basic attributes:

- The absorption of light, generating excitons (bound electron-hole pairs), unbound electron-hole pairs (via excitons)
- The separation of charge carriers of opposite types.
- The separate extraction of those carriers to an external circuit.

The Solar cells or Photovoltaic cells are made out of semiconductors which have the capacity to absorb light. When n-type and p-type semiconductor are brought together a semiconductor diode is formed. The semiconductor diode separates and collects the carriers and conducts the generated electrical current preferentially in a specific direction.

## **Solar photovoltaic cell-Silicon**

### **Construction**

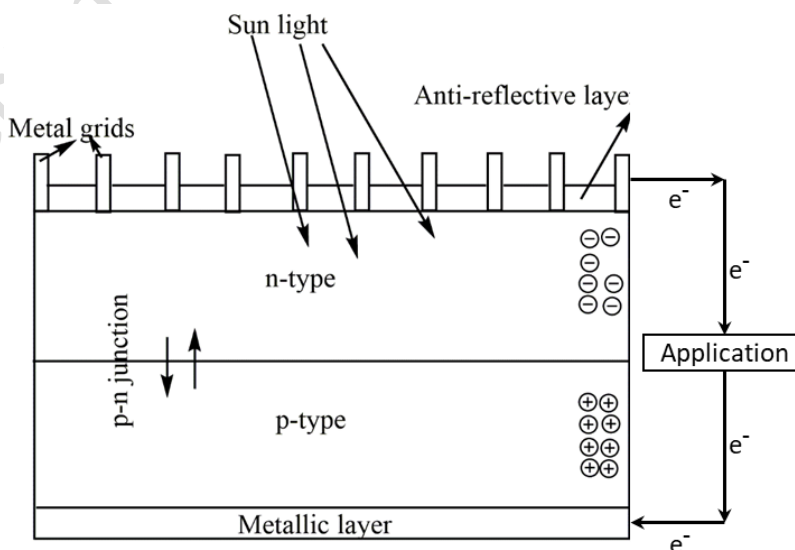
1. A typical silicon photovoltaic cell is composed of a thin wafer consisting of an ultra-thin layer of Phosphorous doped (n-type) silicon on the top and boron doped (p-type) silicon at the bottom. Hence a p-n junction is formed between the two.
2. A metallic grid above the diode forms one of the electrical contacts and allows the light to fall on the semiconductor.
3. The anti-reflexive layer (Silicon nitride or  $\text{TiO}_2$ ) present in between the metallic grid increases the transformation of sunlight to a semiconductor. The other metallic layer at the back of the semiconductor forms another electrical contact.

### **Working**

The solar cell works on the principle of photoelectric effect which is a phenomenon in which electrically charged particles are released from or within a material when it absorbs electromagnetic radiation. The effect is often defined as the ejection of electrons from a metal plate when light falls on it.

Electromagnetic radiation consists of photons. The photon carries a certain amount of energy. It is given by the Planck Constant equation  $E = hc/\lambda$ , where  $h$  is called Planck constant,  $c$  is the velocity of light and  $\lambda$  is wavelength of the radiation.

When light radiation falls on the p-n junction diode, electron – hole pairs are generated by the absorption of the radiation. The electrons are drifted to and collected at the n-type end and the holes are drifted to p-type end. When these two ends are electrically connected through a conductor, there is a flow of current between the two ends through the external circuit. Thus photoelectric current is produced.



**Fig: Si Solar cell**



### Advantages of photovoltaic systems

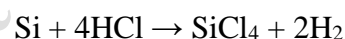
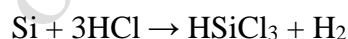
1. High reliability: Photovoltaic systems are still highly reliable even under harsh conditions. Photovoltaic arrays ensure continuous, uninterrupted operation of critical power supplies.
2. Strong persistence: Most modules in a PV system have a warranty period of up to 25 years and remain operational even after many years.
3. Low maintenance costs: Photovoltaic systems require only regular inspections and occasional repairs, which are extremely low cost compared to conventional fuel systems.
4. Zero fuel consumption: Photovoltaic systems do not require fuel and can eliminate associated procurement, storage and transportation costs.
5. Noise pollution is small: The photovoltaic system can operate quietly with minimal mechanical movement.

### Disadvantages of photovoltaic systems

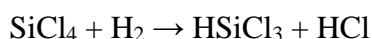
1. High startup cost: Each PV installation should be economically evaluated and compared to existing alternatives. At present, the construction cost of photovoltaic systems is relatively high, but with the reduction of photovoltaic system construction costs and the rise of traditional energy prices, photovoltaic systems will have strong economic competitiveness.
2. Available solar radiation instability: For any solar system, weather changes will greatly affect the amount of electrical energy output. Therefore, the system design needs to be adjusted according to changes in climate and location.
3. Have energy storage requirements: Some photovoltaic systems use batteries as energy storage devices. This increases the footprint, cost and complexity of the system.
4. Efficiency needs to be improved: In order for PV systems to reflect cost-effectiveness, we need to use an efficient method to distribute the energy generated during use. However, they are now often used to power alternative inefficient appliances.

### Production of Solar grade silicon (Union carbide method)

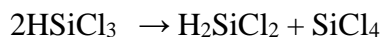
The metallurgical grade silicon is treated with dry HCl gas at 300<sup>0</sup> C to form trichlorosilane & a small amount of tetrachlorosilane. The mixture is distilled to get pure trichlorosilane.



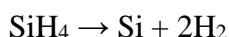
The tetrachloro silane (SiCl<sub>4</sub>) is reduced with hydrogen at 1000<sup>0</sup>C in a reactor to get tri chloro silane (HSiCl<sub>3</sub>).



The tri chloro silane is then passed through fixed bed columns containing quaternary ammonium ion exchange resins catalysts. The products obtained in the above process are separated by distillation.



Tetrachlorosilane & trichlorosilane are again recycled to the hydrogenation reactor & the exchange resin respectively.



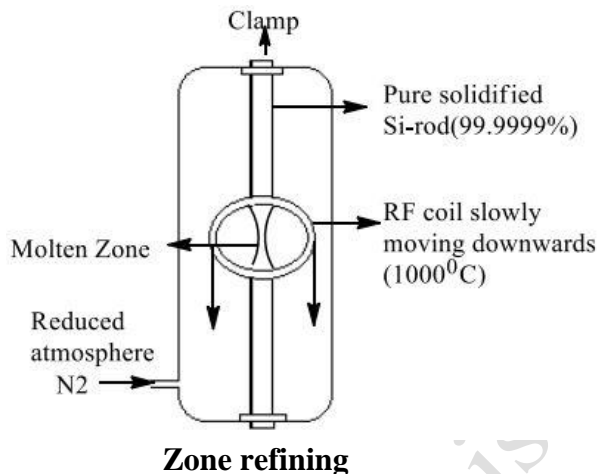
Silicon hydride or silane is further purified by distillation & passed into a reactor containing heated silicon seed rods. Silane gets pyrolysed to form polysilicon (semiconductor grade silicon)

### Purification of Silicon (Zone refining)

The silicon so obtained is melted and made into bricks. It is still not pure. It is purified by

zonerefining technique. Zone refining technique is based on the principle that impurities get concentrated in the molten zone than in solid phase.

A rod of silicon is clamped vertically and heated by a RF coil (Radio frequency coil) in a reduced atmosphere. As the molten zone moves down, the impurities also are swept down with the molten material. When the process is repeated the impurities concentrate at the bottom portion of the rod. It is cut and removed. The purified silicon rod is polycrystalline in nature. It is cut into thin wafers, doped suitably to get P-N junction.



Photovoltaic's deal with the conversion of sunlight into electrical energy. Classic photovoltaic solar cells based on inorganic semiconductors i.e., silicon and today silicon is still the leading technology on the world market of photovoltaic solar cells, with power conversion efficiencies approaching 15 – 20% for mono-crystalline devices. An approach for lowering the manufacturing costs of solar cells is to use organic materials that can be processed under less demanding conditions. Their solution processability makes them a promising technology for delivering cheap solar power. They are very strong light absorbers, with a 100 nm or so thick film capable of absorbing most of the incident light.

**Definition:** An OSC is a type of photovoltaic that uses conductive organic polymers or small organic molecules, for light absorption and charge transport to produce electricity from sunlight by the photovoltaic effect. Most organic photovoltaic cells are polymer solar cells.

### Construction and working of OSC

**Construction:** These cells are made by sandwiching a layer of organic electronic materials between two conductive layer of indium tin oxide (ITO) coated glass and a layer of low work function metal such as Aluminum, Magnesium or Calcium.

1. A flexible or a glass substrate is coated with ITO (transparent photoanode)
2. Hole transporting layer, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) is applied over the ITO.
3. Active layer consisting of bulk-heterojunction layer of donor, P3HT (poly-3-hexyl thiophene) polymer and the acceptor, phenyl-C-butyric acid methyl ester (PCBM) materials is applied using solution processing method
4. A final layer of Al (cathode) is created to establish contact.

### Working:

1. Incident light creates an exciton in the donor material (P3HT) of the active layer.
2. The exciton diffuses between the donor (P3HT) and the acceptor (PCBM) material as hole and electron, respectively.
3. Hole diffuses from the polymer towards PEDOT:PSS and then to ITO.
4. Electron diffuses from the acceptor material (PCBM) towards the Al electrode.
5. Finally, electron from Al travels in the external circuit towards ITO generating electricity.

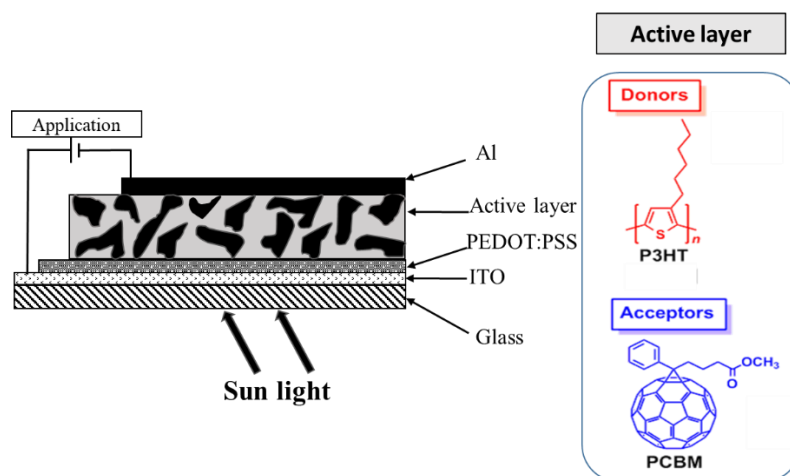


Fig: Organic solar cell

### Quantum dots sensitized solar cells (QDSSC's)

A **quantum dot solar cell** is mainly the type of cell design which makes use of quantum dots as the key **absorbing photovoltaic material**. These solar cells are designed so that they can increase the maximum thermodynamic **conversion efficiency** which can be attained by as much as **66%**.

- Quantum dots are a special class of semiconductors, which are nanocrystals, composed of materials from II-VI, III-V, or IV-VI groups
- The energy band gap increases with a decrease in size of the quantum dot
- The adjustable bandgap of quantum dots allow the construction of nanostructured solar cell that is able to harvest more of the solar spectrum
- The structure and operation principle of QD sensitized photovoltaic cell is almost identical to dye sensitized cells

### Construction and Working of Quantum dots sensitized solar cells (QDSSC's)

**Construction:** These cells are made by sandwiching a layer of photosensitive materials between two conductive layer of Fluorine-doped Tin Oxide (FTO) coated glass/ flexible transparent substrate. The subsequent layers are as follows

1. FTO is applied with QD sensitized TiO<sub>2</sub> as photoanode
2. Electrolyte
3. Pt or graphite coated FTO- counter electrode (CE) or cathode

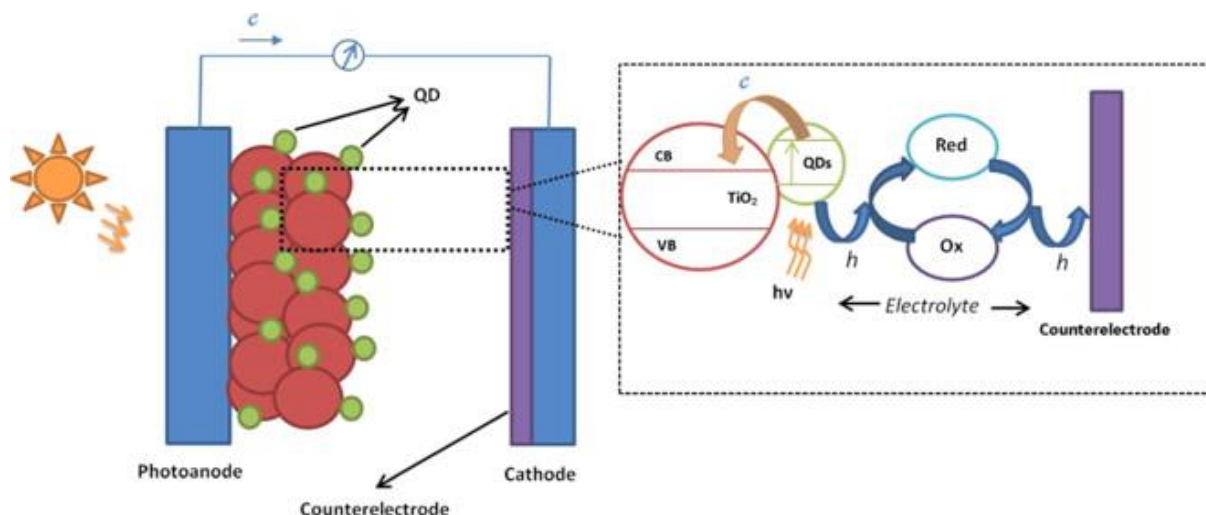
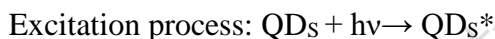


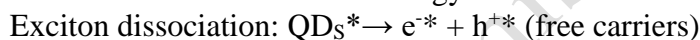
Fig: (a) Quantum Dots Solar Cells, (b) Energy band diagram.

### Working Principle

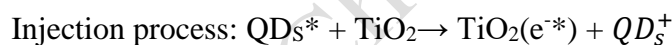
Upon absorption of a photon, a quantum dot is excited from the ground state ( $QDs$ ) to a higher energy state ( $QDs^*$ ).



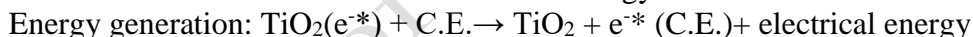
The absorption process results in the creation of electron-hole pair in the form of exciton. Dissociation of the exciton occurs if the thermal energy exceeds its binding energy



The excited electron is then injected in the conduction band of the wide bandgap semiconductor nanostructured  $TiO_2$  thin film. This process will cause the oxidation of the photosensitizer (The  $QDs$ ).



The injected electron is transported between the  $TiO_2$  nanoparticles, and then gets extracted to a load where the work done is delivered as electrical energy



**Properties:** Quantum dots sensitized solar cells have

1. Thermal and moisture stability.
2. Facile tunable absorption range.
3. High absorption coefficient
4. Good photostability.

### Applications

Compared to conventional solar cells QDSSC development have shown that higher-power conversion efficiency and hence can be used for solar to electrical energy conversion.

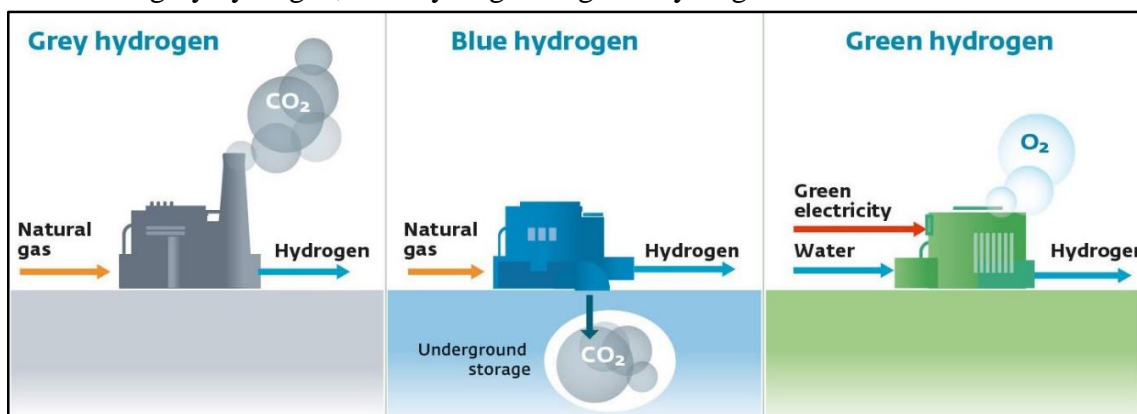
### Hydrogen energy

Hydrogen is considered an alternative fuel under the Energy Policy Act of 1992. The interest in hydrogen as an alternative transportation fuel stems from its ability to power fuel cells in zero-emission vehicles, its potential for domestic production, and the fuel cell's fast filling time and high efficiency. Hydrogen fuel is a zero carbon fuel burned with oxygen; provided it is created in a zero carbon way. It can be used in fuel cells or internal combustion engines.

Regarding hydrogen vehicles, hydrogen has begun to be used in commercial fuel cell vehicles, such as passenger cars, and has been used in fuel cell buses for many years. It is also used as a fuel for spacecraft propulsion. In the early 2020s, most hydrogen is produced by steam methane

reforming of fossil gas. Only a small quantity is made by alternative routes such as biomass gasification or electrolysis of water or solar thermochemistry.

**Types of hydrogen fuel:** It takes energy to produce molecular hydrogen. The source of energy and the production method used to make molecular hydrogen determines whether it's classified as grey hydrogen, blue hydrogen or green hydrogen.



### **Grey hydrogen**

Grey hydrogen is hydrogen produced using fossil fuels such as natural gas or coal. Grey hydrogen accounts for roughly 95% of the hydrogen produced in the world today. The two main production methods are steam methane reforming and coal gasification. Both of these processes release CO<sub>2</sub>. If the carbon dioxide is released into the atmosphere, then the hydrogen produced is referred to as grey hydrogen. Grey hydrogen is not considered a low-carbon fuel.

### **Blue hydrogen**

Blue hydrogen is similar to grey hydrogen, except that most of the CO<sub>2</sub> emissions are sequestered (stored in the ground) using carbon capture and storage (CCS). Capturing and storing the carbon dioxide instead of releasing it into the atmosphere allows blue hydrogen to be a low-carbon fuel. The two main production methods are steam methane reforming and coal gasification, both with carbon capture and storage. Blue hydrogen is a cleaner alternative to grey hydrogen, but is expensive since carbon capture technology is used.

### **Green hydrogen**

Green hydrogen is hydrogen produced using electricity from clean energy sources. Green hydrogen is considered low or zero-emission hydrogen because it uses energy sources such as wind and solar which don't release greenhouse gases when generating electricity. Green hydrogen is made when water (H<sub>2</sub>O) is split into hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>). Water splitting is also known as electrolysis, and requires an energy input. The method of supplying electricity to split water is an expensive process, but much more environmentally-friendly compared to the production of grey hydrogen.

**Methods of production of hydrogen:** There are several ways to produce hydrogen:

1. **Natural Gas Reforming/Gasification:** Synthesis is created by reacting natural gas with high-temperature steam. The carbon monoxide is reacted with water to produce additional hydrogen. This method is the cheapest, most efficient, and most common. The process called **gasification** is created by reacting coal or biomass with high-temperature steam and oxygen in a pressurized gasifier.

**2. Electrolysis:** An electric current splits water into hydrogen and oxygen. If the electricity is produced by renewable sources, such as solar or wind, the resulting hydrogen will be considered renewable as well, and has numerous emissions benefits.

**3. Fermentation:** Biomass is converted into sugar-rich feedstocks that can be fermented to produce hydrogen. Several hydrogen production methods are in development stage:

**4. High-Temperature Water Splitting:** High temperatures generated by solar concentrators or nuclear reactors drive chemical reactions that split water to produce hydrogen.

**5. Photobiological Water Splitting:** Microbes, such as green algae, consume water in the presence of sunlight and produce hydrogen as a by-product.

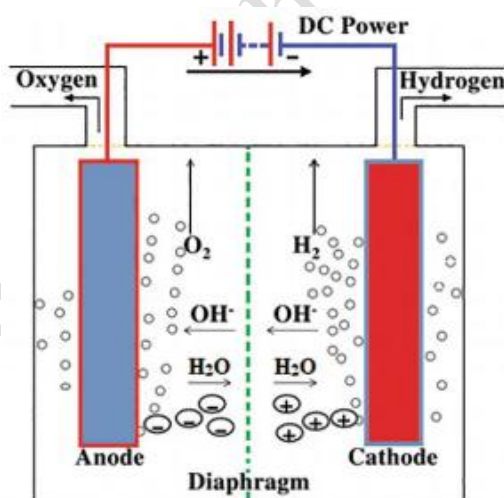
**6. Photoelectrochemical Water Splitting:** Photoelectrochemical systems produce hydrogen from water using special semiconductors and energy from sunlight.

### Generation of energy (green hydrogen) Electrolytic processes

**Electrolysis of water** is the process of using electricity to decompose water into oxygen and hydrogen gas by a process called electrolysis. Hydrogen gas released in this way can be used as hydrogen fuel.

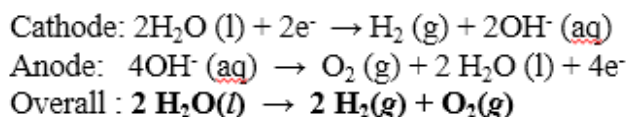
#### **Construction:**

- The electrode materials often used are based on nickel because of its low cost, high activity
- Concentrated solutions of potassium hydroxide are generally used as the electrolytic solution because they have very high conductivities and fewer corrosion problems compared with other alkaline electrolytes.
- protons exchange membrane (PEM)



**Fig: Electrolytic processes**

#### **Working:**



#### **Advantage**

- It can be used in fuel cells to generate electricity.
- It has ZERO carbon footprint.
- Flexible in a variety of applications including energy transmission, generation and storage.



**Disadvantage:**

1. It still has a high production cost when compared with other energy sources, hence it is expensive
2. Storage and transportation of hydrogen is more complex
3. Not yet scalable enough to meet the world's energy demand

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