



UNIT-I

ENERGY STORAGE AND CONVERSION DEVICES

Abstract

This unit mainly focuses on the advanced energy systems used in day-to-day life. In the beginning it starts from basics of battery technology followed by commercial lithium battery used in electronic gadgets along with advanced lithium air battery. Further it explores the innovation in the field of super capacitor and their importance in energy storage. Finally, it covers the green energy systems such as fuel cell and solar energy conversion. Over all this unit helps the learners in exploring the knowledge of energy storage devices for various applications in modern engineering practices.

Blow-up Syllabus

SI No	Topic to be taught	Duration
1	Battery: Introduction, types, characteristics	1 hour
2	Components/materials, construction, working and applications of Lithium cobalt oxide battery along with advantages and limitations	1 hour
3	Construction and working of Metal air batteries along with their advantages and limitations.	1 hour
4	Super-capacitors: Introduction, types (EDLC, pseudo capacitors, hybrid capacitors), with examples.	1 hour
5	Construction and working mechanism of EDLC, pseudo capacitors, hybrid capacitors along with applications.	1 hour
6	Energy conversion devices: Introduction, characteristics, materials, working and applications of H ₂ -O ₂ fuel cells.	1 hour
7	Solar energy: Amorphous Silicon solar cells construction and working	1 hour
8	Construction and working of Quantum dot sensitized solar cells.	1 hour
9	Materials used in solar energy conversion	Self-study

1.1. Battery technology

Introduction to electrochemistry

Electrochemistry deals with chemical reactions that produce electricity and the changes associated with the passage of electrical current through matter. The reactions involve electron transfer, and so they are oxidation-reduction (or redox) reactions. Many metals may be purified or electroplated using electrochemical methods. Devices such as automobiles, smartphones, electronic tablets, watches, pacemakers, and many others use batteries for power. Batteries use chemical reactions that produce electricity spontaneously and that can be converted into useful work. All electrochemical systems involve the transfer of electrons in a reacting system. In many systems, the reactions occur in a region known as the cell, where the transfer of electrons occurs at electrodes.

Introduction to battery:

CELL: A cell designates a single unit. The conversion of chemical energy into electrical energy is a function of cells or batteries.

BATTERY: A Battery is an electrochemical cell or often several electrochemical cells connected in series that can be used as a source of direct electric current at a constant voltage.

Uses: Batteries are used in calculators, watches and pacemakers for heart hearing aids, computers, car engines, standby power supplies, emergency lightning in hospitals, electroplating industrial tractions and military and space applications. Batteries have revolutionized the telecommunication system and are ushering a new era of transportation with the possible replacement of petrol driven automobiles by the electrically powered ones. In modern days portability of electronic equipment's in the form of handsets has been made possible by batteries.

Components of Battery: The cell consists of three major components.

- **Anode:** The anode selected with the following properties in mind; efficiency as a reducing agent, high columbic output (Ah/g) good conductivity, stability, ease of fabrication and low cost.
- **(Cathode:** The cathode must be an efficient oxidizing agent, be stable when in contact with the electrolyte, and have a useful working voltage.
- **Electrolyte:** The electrolyte must have good ionic conductivity but not be electrically conductive. This would cause internal short circuiting. Electrolyte should be non-reactive

with the electrode materials.

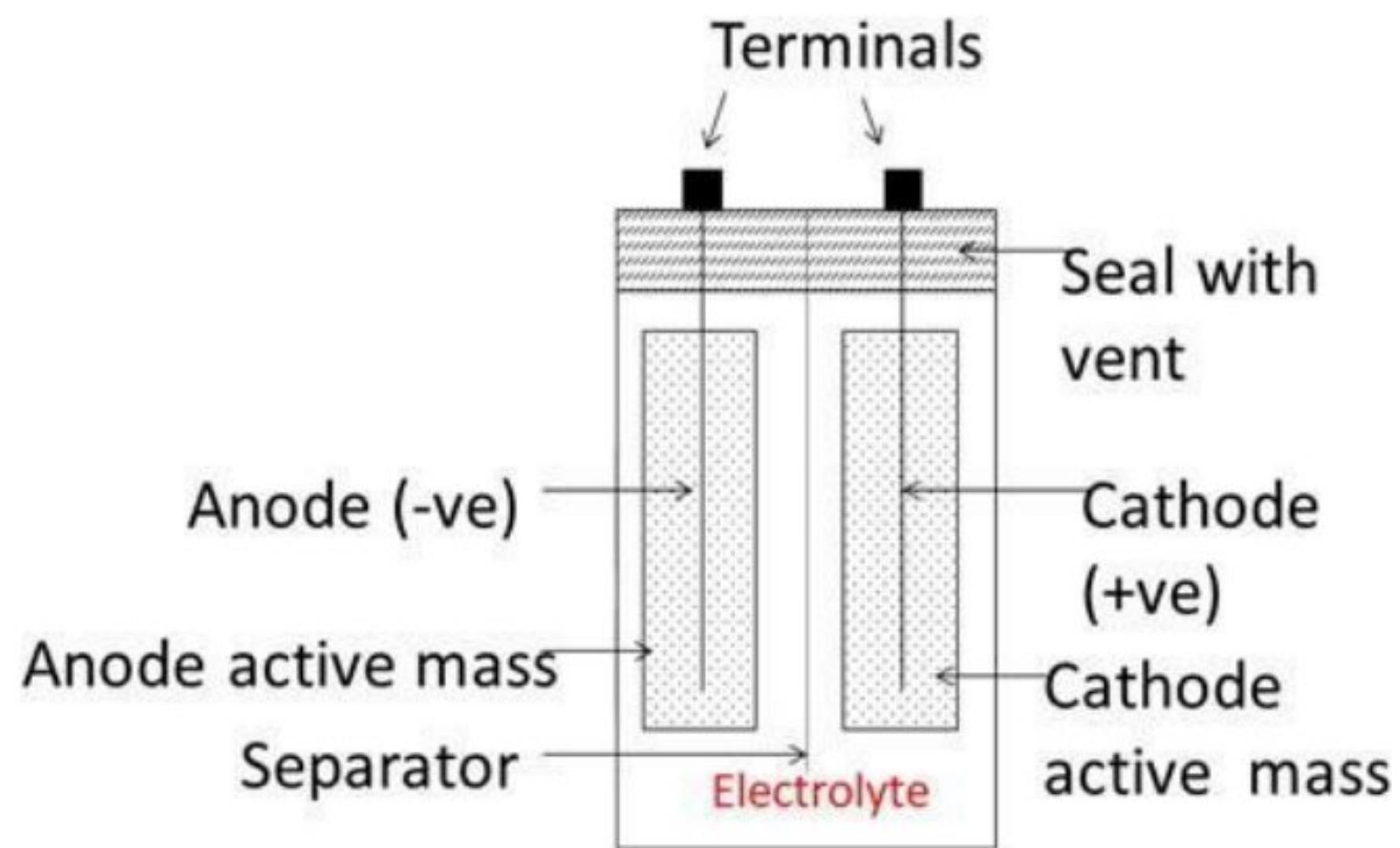


Fig. 1.1: Structure of typical battery

Mechanism of working of battery: During discharging, the Battery acts as voltaic cell i.e. oxidation takes place at the negative electrode (anode) and reduction takes place at the positive electrode (cathode). During charging, The Battery acts as an electrolytic cell. The current flow is reversed and oxidation takes place at the positive electrode (anode) and reduction takes place at the negative electrode (cathode).

Criteria for commercial batteries

An efficient commercial cell should have following basic characteristics

- Portability: cells should be easily transportable without any environmental issues
- Compact: Battery should be more compact and light weight
- Economy: battery should have less price with continuous electric supply.
- Power and energy density: batteries should have high power and energy density
- Recharging; It should be able to charge as well as discharge battery in faster rate with recyclability
- Cycle and shelf life: Batteries should be having high cycle life and shelf life without self-discharge.

Classification of batteries:

Majorly batteries are classified in to three categories

- **Primary battery:** non-rechargeable (cell reactions are irreversible) - Self-discharges whether used or not, lechlanche cells (Zn/C) - Popular low-cost system, Applications: Torch light, portable radios, toys, novelties, etc. Mg/MnO₂ CELLS - High-capacity system: Applications: Military communication equipment, voting machines, etc.
- **Secondary battery:** Rechargeable (cell reactions are reversible), Lead-Acid Battery (Pb/H⁺), Nickel-Cadmium Battery (Ni-Cd), Nickel-Iron Battery (Ni-Fe), Nickel-Metal

hydride Battery (Ni-MH), Lithium battery (Li-LiMxOy), lithium-Ion battery (C-LiMxOy), Lithium-Ion Polymer Battery (C-LiMxOy)

- **Reserve battery:** one of the key cell components, usually the electrolyte, is kept isolated from the rest and is added at the time of need Examples: Mg/Cu₂Cl₂, Mg/AgCl (sea water activated battery), Applications: Torpedoes, Sea beacons (Mainly in Meteorology and Defense fields), Li/FeS₂ (Thermally activated battery). Applications: In Missiles and rockets.

Battery Characteristics

The suitability of any battery for particular application is based on certain characteristic properties. Some of

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- **Voltage (V):** In general, high voltage is desired from any battery. The voltage of any battery depends on the emf of the cells which constitute the battery system. The emf of the cell depends on the free energy in the overall cell reactions as given by Nernst equation.

$$E_{\text{cell}} = E^{\circ}_{\text{cell}} - \frac{2.303RT}{nF} \log \log \frac{\text{Product}}{\text{Reactant}}$$

Where $E_{\text{cell}} = E_{\text{cathode}} - E_{\text{anode}}$

From the above equation, emf of the cell and the voltage available from the battery is dependent on the standard electrode potential difference between the cathode and anode, temperature and the extent of the cell reaction. To get required high voltage, the difference in the standard electrode potential should be more; temperature of the reaction should be low. The conductivity of the electrolyte should be high.

- **Current (A):** Current is a measure of the rate at which the battery is discharging. Higher the rate of spontaneous reaction, higher is the current. Higher the surface area of the electrodes, higher is the rate of reaction. Current is measured in Ampere (A).

$$I = \frac{V}{R}$$

Where I is the current, V is voltage and R is resistance of the battery.

- **Capacity (Ah):** Capacity is a measure of the amount of electricity that may be obtained from the battery. It is expressed in Ah (ampere hours). It is proportional to the amount of

charge in Coulombs that may be transported from anode to cathode through the external circuit. The charge (C) in Coulombs is given by the Faraday's relation:

$$C = \frac{w \times n \times F}{M}$$

Where, C is Capacity of battery (in Ah), W is Weight of the active material (Kg), n is number of electrons involved in discharge reaction, F is Faraday's constant, 96500 C/mol, M is Molar mass of electro active materials.

- **Electricity density (Wh/Kg):** It is the amount of electricity stored in the battery per unit weight of the battery. i.e., it is the capacity per unit weight. It can be expressed in Coulombs/kg or in Ah/kg. The weight includes the weight of all components of the battery (i.e. total weight of active material, electrolyte, terminals etc.). A high storage density depends on a good battery design and also the appropriate selection of electrode reaction.

$$\text{Energy density} = \frac{I(\text{current}) \times t(\text{time}) \times V(\text{Voltage of a battery})}{\text{weight of battery}}$$

- **Power density (W / Kg):** The ratio of the power available from a battery to its weight or its volume (W / V) is called power density. The power density will decrease during discharge and while recharge it will increase.

$$\text{Power density} = \frac{I(\text{current}) \times V(\text{EMF of battery})}{\text{Mass of electroactive material}}$$

- **Energy efficiency:** it is the ratio of energy released during discharge to energy consumed during charging. The energy efficiency of a rechargeable battery is given by

$$\text{Energy Efficiency} = \frac{\text{Energy released during charging}}{\text{Energy supplied during charging}} \times 100$$

- **Cycle life:** The number of recharges per discharge cycles that are possible before the failure of a secondary battery is called cycle life. In secondary battery it is essential for the discharge per recharge cycles to perform the active material in a suitable state for further discharge reaction. The discharge per recharge cycles depends on the correct chemical composition, morphology and proper distribution of active material in the battery.
- **Shelf life:** The duration of storage under specific condition at the end of which battery still retaining the ability to give specific performance is called shelf life. Shelf life for most of the storage must be good. Good shelf life for a battery is possible when there is no self-discharge or corrosion in current collectors.

Lithium-ion batteries:

A Lithium-ion battery is rechargeable battery which stores the energy by reversible reduction of lithium ions. This battery is widely used in the portable electronic gadgets, e vehicles and all medical equipment because of their energy density and compactness. This type of battery is more advanced when compared to other types of battery such as lead acid and nickel cadmium battery. Further these types of batteries are majorly classified as primary and secondary batteries.

Criteria of selection of anode materials for lithium-ion battery

Desired characteristics of anode materials

- Large capability of Lithium adsorption: porous anodes
 - High efficiency of charge/discharge
 - Excellent cyclability: high cycle life
 - Low reactivity against electrolyte: Chemical stability
 - Fast reaction rate
 - Low cost
 - Environmental -friendly, non-toxic
- Commercial anode materials used in lithium batteries: Hard Carbon, Graphite

Criteria of selection of Cathode materials for lithium-ion battery

Desired characteristics of Cathode materials

- High discharge voltage
- High energy capacity
- Long cycle life
- High power density
- Light weight
- Low self-discharge
- Absence of environmentally hazardous elements

Commercial cathode materials for lithium-ion battery: LiCoO₂, LiMn₂O₄, LiNiO₂, LiFePO₄

Electrolytes used in the lithium-ion battery

Electrolyte is one of the important components of battery ecosystem. In general ether-based electrolyte along with lithium salts are used as electrolytes.

The electrolyte should have following Characteristics in order to employ them in battery technology

- Inert: solvent stability
 - High ionic conductivity, low viscosity
 - low melting point & high dielectric constant (ϵ)
 - Appropriate concentration of Lithium salt
 - Chemical/thermal stability, High flash point (T_f), nontoxic,
 - Low cost
 - Environmental -friendly, non-toxic
- Commercial electrolytes: LiPF₆ in Carbonate solvent, propylene carbonate, 1,2 dimethoxy ethane

Role of electrolyte in battery technology

- Ion conductor between cathode and anode
- Generally, Lithium salt dissolved in organic solvent
- Solid electrolyte is also possible if the ion conductivity is high at operating temperature.

Separators: Separator is a membrane placed between a battery electrode. The main function of a separator is to keep the two electrodes apart to prevent electrical short circuits while also allowing the transport of ionic charge carriers that are needed to close the circuit during the passage of current in an electrochemical cell.

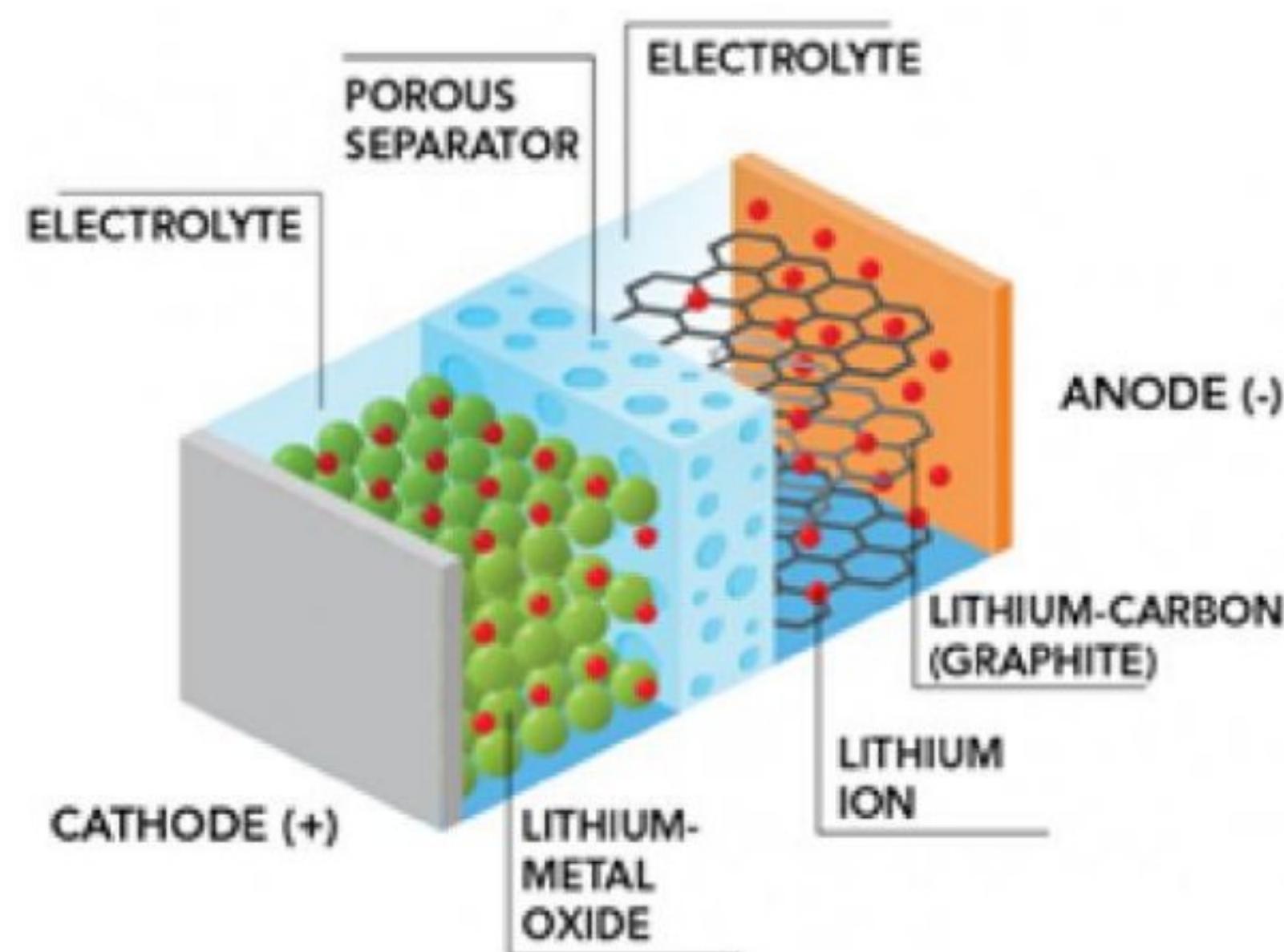


Fig. 1.2: separator in battery technology

Primary lithium batteries: These are batteries in which redox reactions proceed only in the one direction. The reactants in these batteries are consumed after a certain period of time, rendering them dead. A primary battery cannot be used once the chemicals inside it are

exhausted. An example of a primary battery is the dry cell – the household battery that commonly used to power TV remotes, clocks, and other devices. Best example for this battery is lithium-ion battery.

Secondary lithium-ion batteries: These are the rechargeable lithium-ion batteries. Here electroactive materials is converted in to electro inactive materials during discharge and during charging again this electro inactive material can be converted in to electroactive materials with the help of external electricity. Examples: Lithium cobalt oxide battery, Lithium Nickel Cobalt Aluminium Oxide, Lithium iron phosphate etc...

Lithium cobalt oxide battery

Lithium Cobalt is a mature, proven, industry-standard battery technology that provides long cycle life and very high energy density. The polymer design makes the cells inherently safer than "canned" construction cells that can leak acidic electrolyte fluid under abusive conditions. The cell voltage is typically 3.7 Volts[1].

Construction of LiCoO₂ battery

- Positive electrode: Lithiated form of a transition metal oxide (lithium cobalt oxide-LiCoO₂ or lithium manganese oxide LiMn₂O₄)
- Negative electrode: Lithiated Carbon (C) usually graphite (C₆)
- Electrolyte: solid lithium-salt electrolytes (LiPF₆, LiBF₄, or LiClO₄) and organic solvents

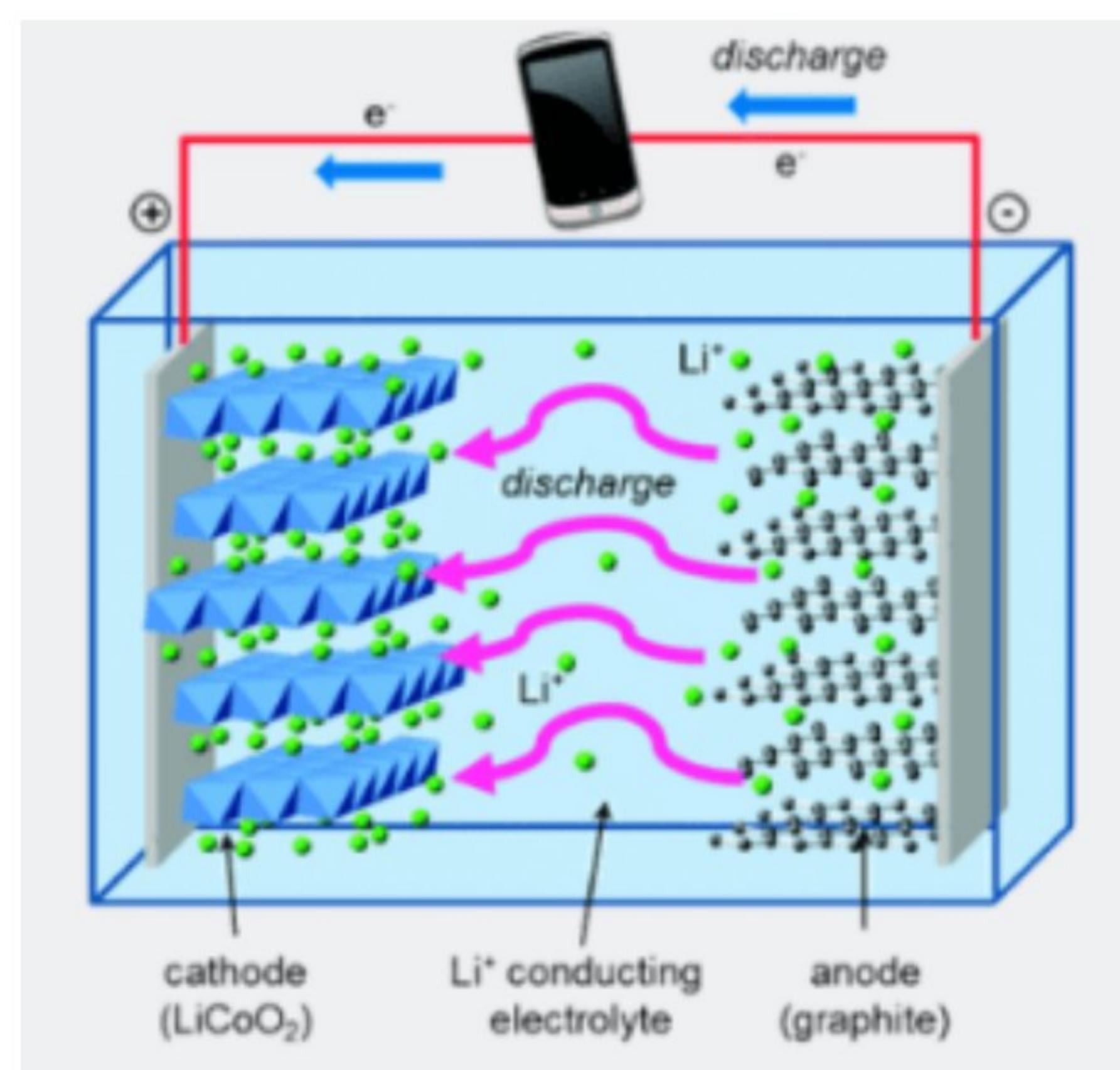


Fig. 1.3: Structure of lithium-ion battery

Solid electrolyte interphase (SEI) layer: A passivation layer called the solid electrolyte interphase (SEI) is formed on electrode surfaces from decomposition products of electrolytes.

The SEI allows Li^+ transport and blocks electrons in order to prevent further electrolyte decomposition and ensure continued electrochemical reactions.

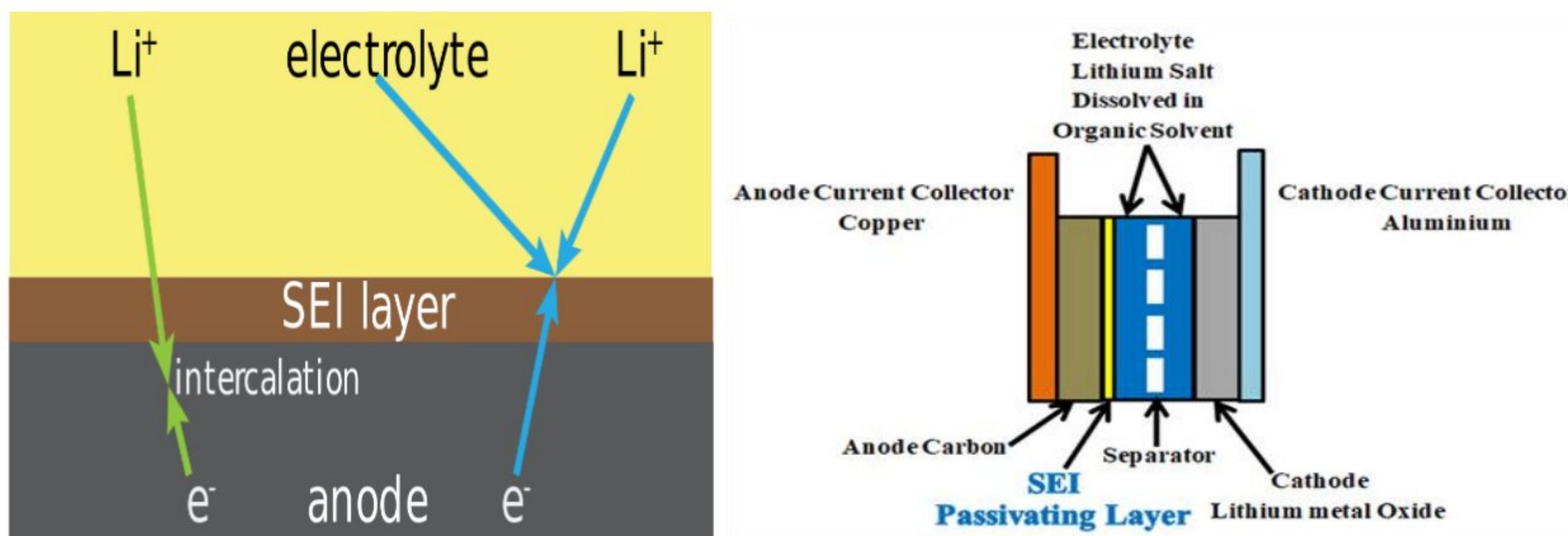
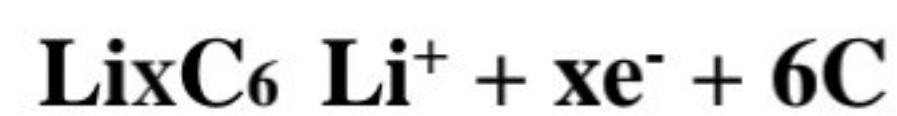


Fig. 1.4: Role of solid electrolyte interphase

Mechanism of working: in lithium cobalt oxide battery, generally lithium salts are used as electrolytes along with 1, 2 dimethoxy ethane and propylene carbonate. The main reason behind the selection of this solvent is its density and high boiling inert nature. During the discharging reaction the lithium metal in the anode compartment converts into lithium ion and it moves through SEI and separator towards cobalt cathode. In the cathode it reacts with Cobalt oxide and the electron to form LiCoO_2 . And this process is reversible during charging. During discharging movement of lithium ion takes place from anode to cathode and it moves from cathode to anode when connected to external power supply.

Charging and discharging reaction

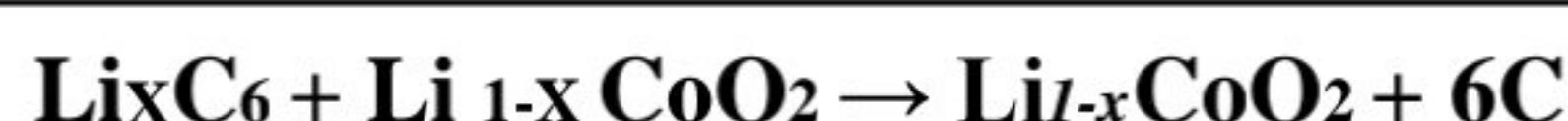
At anode



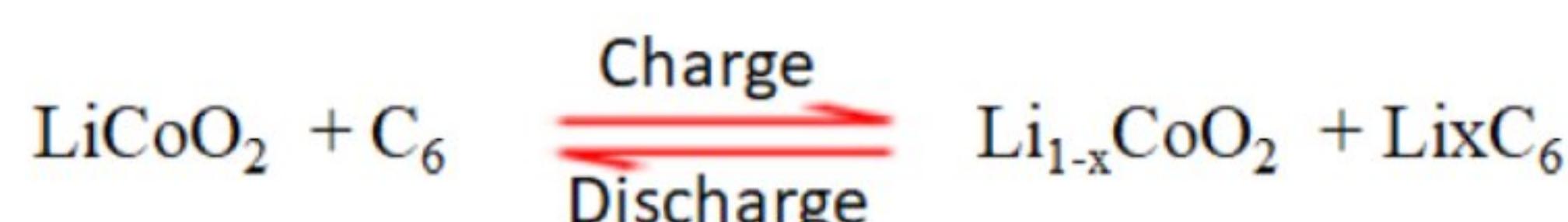
At cathode



Overall reaction



In the above reaction x can be 1 or 0, With discharge the Co is oxidized from Co^{3+} to Co^{4+} . The reverse process occurs when the battery is being charged. The chemical reaction that takes place inside the battery is as follows, during charge and discharge operation:



Advantages and limitations of lithium-ion batteries

When compared to other type of commercial batteries such as lead acid and nickel metal hydride batteries lithium batteries have several advantages. Few of them listed below

Advantages of lithium-ion batteries:

- Light weight compared to other batteries
- Higher theoretical energy density than other types of batteries
- Rate of loss of charge is very less
- Operates at higher voltages than other batteries
- High adoptability to several applications
- As there is no memory effect, no need to completely drain the battery
- Low self-discharge compared to lead acid battery
- Easy maintenance

Limitations of lithium-ion batteries:

- Sourcing of lithium is difficult
- As lithium is not abundant, extraction of it doesn't meet global need
- Expensive than the other commercially available battery
- This battery is temperature sensitive; at higher temperature it may degrade with explosion
- Extra protection is required if want to employ them in large scale application
- Disposal may a problem because of heavy metal cathodes

Metal air batteries

Metal air battery is one of the most advanced batteries in which metal incorporated in carbon matrix acts as anodes and air its self-acts as cathode. Amongst all the studied metal air battery lithium air battery is more attractive because of its high energy density along with light weight. In general lithium ions move between the anode and the cathode across the electrolyte. Under discharge condition, electrons follow from the external circuit to do electric work and the lithium ions migrate to the cathode. During charging the lithium metal in the anode, freeing O₂ at the cathode. In case of non-aqueous lithium air battery Li₂O₂ or LiO₂ are the byproducts.

Similarly in aqueous lithium air battery LiOH is the byproduct. Further aqueous lithium air battery requires a protective layer to protect the lithium metal in the anode[2].

Components and working of lithium air battery

Generally, lithium air batteries consist of lithium anode and porous cathode which will allow air from it. Then air itself acts as cathode. Also, these lithium air batteries can have different electrolyte systems such as aqueous and non-aqueous. The chemical reaction in these types of batteries is given below.

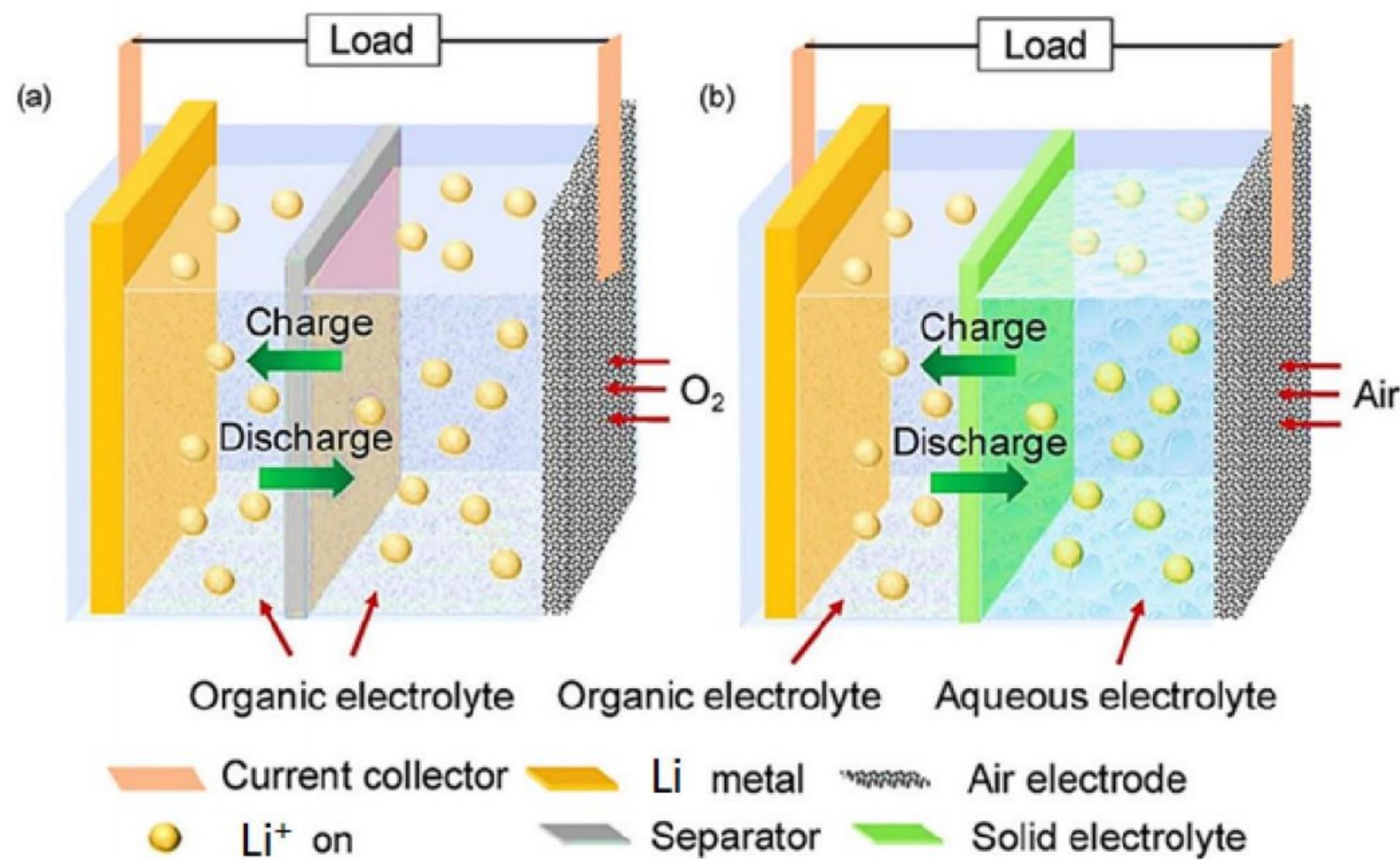


Fig. 1.5: lithium air battery

Non aqueous lithium air battery

Anode: lithium metal

Cathode: Oxygen (air)

Anodic reactions: $\text{Li} \rightarrow \text{Li}^+ + \text{e}^-$

Cathodic reactions: $\text{Li}^+ + \text{e}^- + \text{O}_2 + \rightarrow \text{LiO}_2^*$



Aqueous lithium air battery

Acidic electrolyte



Alkaline aqueous electrolyte



The electrical energy is provided by the chemical reaction between the lithium metal and O₂ from the air. The oxygen electrode has to be porous in order to allow the transport of gasses. The lithium electrode will be protected by a solid electrolyte interphase (SEI), which can be artificially prepared or spontaneously formed by the reaction of lithium with the electrolyte. Lithium–air batteries can also be built in the full solid state by using a solid electrolyte.

The main advantages of lithium air batteries are

- High theoretical specific energy of lithium
- Light weight of lithium
- Use of light weight oxygen
- High theoretical capacity of lithium metal

In the case of non-aqueous lithium air batteries, two main discharge products have been proposed: Li₂O₂ and Li₂O. In the case of aqueous lithium–oxygen batteries, the theoretical specific energies are lower, due to the presence of hydrating water molecules in some of the species involved in the reactions. The main byproduct in the aqueous lithium air battery is LiOH. Limitations of lithium air battery are as follows

- Poor reversibility
- Inferior long term cyclability
- Electrolyte evaporation

1.2. Super capacitor

Introduction to super capacitor

Supercapacitors, also known as electrochemical capacitors, utilize high surface area electrode materials and thin electrolytic dielectrics to achieve capacitances several orders of magnitude larger than conventional capacitors. In doing so, supercapacitors are able to attain greater energy densities while still maintaining the characteristic high-power density of conventional capacitors. A supercapacitor (SC), also called an ultracapacitor, is a high-capacity capacitor with a capacitance value much higher than other capacitors, but with lower voltage limits, that bridges the gap between electrolytic capacitors and rechargeable batteries. It typically stores 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerates many more charge and discharge cycles than rechargeable batteries[3].

Definition: A supercapacitor are double-layer electrolytic capacitor that can store large amounts of energy nearly 10 to 100 times more energy when compared to the electrolytic capacitors. It is widely preferred than batteries because of its faster charging capacity and faster delivery of energy. It has more charging and discharging cycles than rechargeable batteries.

The capacitance of this capacitor is also measured in Farad's (F). The main advantage of this capacitor is its efficiency and high-energy storage capacity.

Principles of Energy storage

The supercapacitor has the self-discharging capacity and unlimited charging-discharging cycles. These types of capacitors can work with low voltages (2-3 volts) and can be connected in series to produce high voltage, which is used in powerful equipment. It can store more energy and releases instantly and more quickly when compared to batteries. When this capacitor is connected to the circuit or DC voltage source, the plates are charged and opposite charges are formed on both sides of the separator, which forms a double-layer electrolytic capacitor. To charge a supercapacitor, connect the positive side of the voltage source to the positive terminal of the supercapacitor and the negative side of the voltage source is connected to the negative terminal of the supercapacitor. If the supercapacitor is connected to 15 volts voltage source, then it charges up to 15 volts. As the voltage is increased beyond the applied voltage source, the supercapacitor may get damaged. So, the resistor is connected in series with the voltage source and capacitor to decrease the amount of current flowing through the capacitor and it doesn't get damaged. The constant current supply and limited voltage supply is suitable for the supercapacitor. When the voltage is increased gradually, the amount of current flowing through the capacitor changes. In the fully charged mode, the current drops by default.

Classification of super capacitor

Supercapacitors majorly classified as follows

- **Electrostatic double-layer capacitors (EDLCs):** EDLCs use carbon-based materials as electrodes with higher electrostatic double-layer capacitance, achieving separation of charge in a Helmholtz double layer at the interface between the surface of a conductive electrode and an electrolyte.
- **Electrochemical pseudo-capacitors:** Use metal oxide or conducting polymer electrodes with a high amount of electrochemical pseudo capacitance additional to the double-layer capacitance. Pseudo capacitance is achieved by Faradaic electron charge-transfer with redox reactions, intercalation or electro sorption.
- **Hybrid capacitors:** Hybrid capacitors are lithium-ion capacitor, use electrodes with differing characteristics. In this type of super capacitors, principles of both battery and super capacitors are involved to increase energy density and power density.

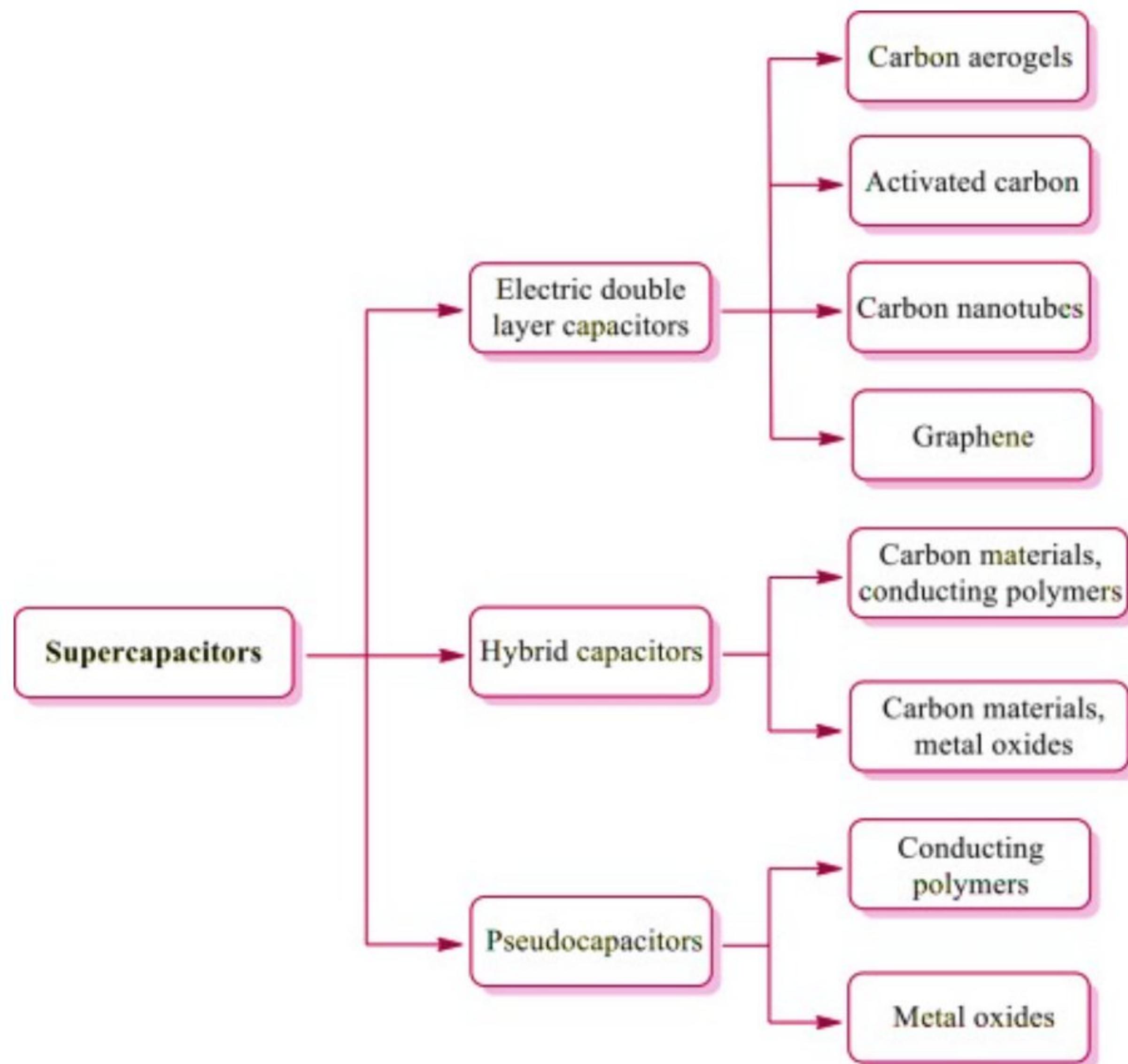


Fig. 1.6: super capacitors classification

Electrostatic double-layer capacitors (EDLCs)

Electrochemical double-layer capacitors (EDLCs) are constructed from two similar carbon-based electrodes, an electrolyte, and a separator. These type of super capacitors store the energy very similar to conventional capacitors. These EDLCs store charge electrostatically, or non-Faradaically, and there is no transfer of charge between electrode and electrolyte. These EDLCs store the charge using an electrochemical double-layer. As voltage is applied, charge accumulates on the surface of both the electrodes. This is followed by the natural attraction of unlike charges, ions in the electrolyte solution diffuse across the separator into the pores of the electrode of opposite charge. In this architecture electrode are designed to avoid recombination of ions. Due to this a double-layer of charge is produced at each electrode. These double-layers, coupled with an increase in surface area and a decrease in the distance between electrodes, allow EDLCs to achieve higher energy densities than conventional capacitors. Due to the non-transferring of charges between electrolyte and electrode, there are no chemical or composition changes associated with non-Faradaic processes. For this reason, charge storage in EDLCs is highly reversible, which allows them to achieve very high cycling stabilities. The performance characteristics of an EDLC can be adjusted by changing the nature of its electrolyte.

An EDLC can utilize either an aqueous or organic electrolyte. Aqueous electrolytes, such as H_2SO_4 and KOH , generally have lower minimum pore size requirements compared to organic electrolytes, such as acetonitrile. In these EDLCs generally carbon-based materials are used because of their higher surface area, lower cost, and more established fabrication techniques than other materials, such as conducting polymers and metal oxides. Different forms of carbon materials that can be used to store charge in EDLC electrodes are activated carbons, carbon aerogels, and carbon nanotubes.

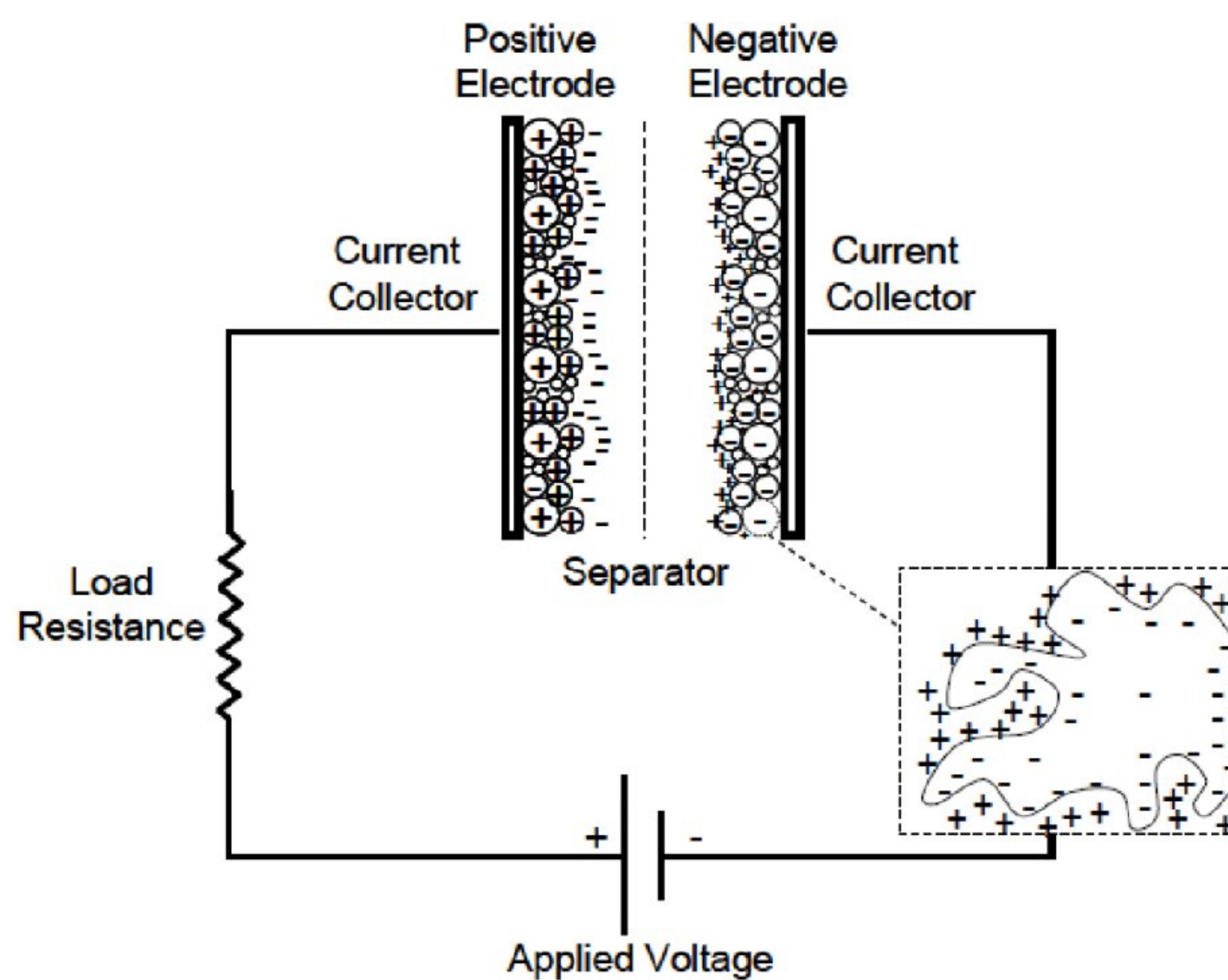


Fig. 1.7: Electrolytic double layer capacitor

Electrochemical Pseudo capacitance:

Applying a voltage at the electrochemical capacitor terminals moves electrolyte ions to the opposite polarized electrode and forms a double-layer in which a single layer of solvent molecules acts as separator. Pseudo capacitance can originate when specifically adsorbed ions out of the electrolyte pervade the double-layer. This pseudo capacitance stores electrical energy by means of reversible redox reactions on the surface of suitable electrodes in an electrochemical capacitor with an electric double-layer. Pseudo capacitance is accompanied with an electron charge-transfer between electrolyte and electrode coming from a de-solvated and adsorbed ion whereby only one electron per charge unit is participating. This faradaic charge transfer originates by a very fast sequence of reversible redox, intercalation or electro sorption processes. The adsorbed ion has no chemical reaction with the atoms of the electrode since only a charge-transfer take place. The electrons involved in the faradaic processes are transferred to or from valence electron states (orbitals) of the redox electrode reagent. They

enter the negative electrode and flow through the external circuit to the positive electrode where a second double-layer with an equal number of anions has formed. The electrons reaching the positive electrode are not transferred to the anions forming the double-layer, instead they remain in the strongly ionized and "electron hungry" transition-metal ions of the electrode's surface. As such, the storage capacity of faradaic pseudo capacitance is limited by the finite quantity of reagent in the available surface[4].

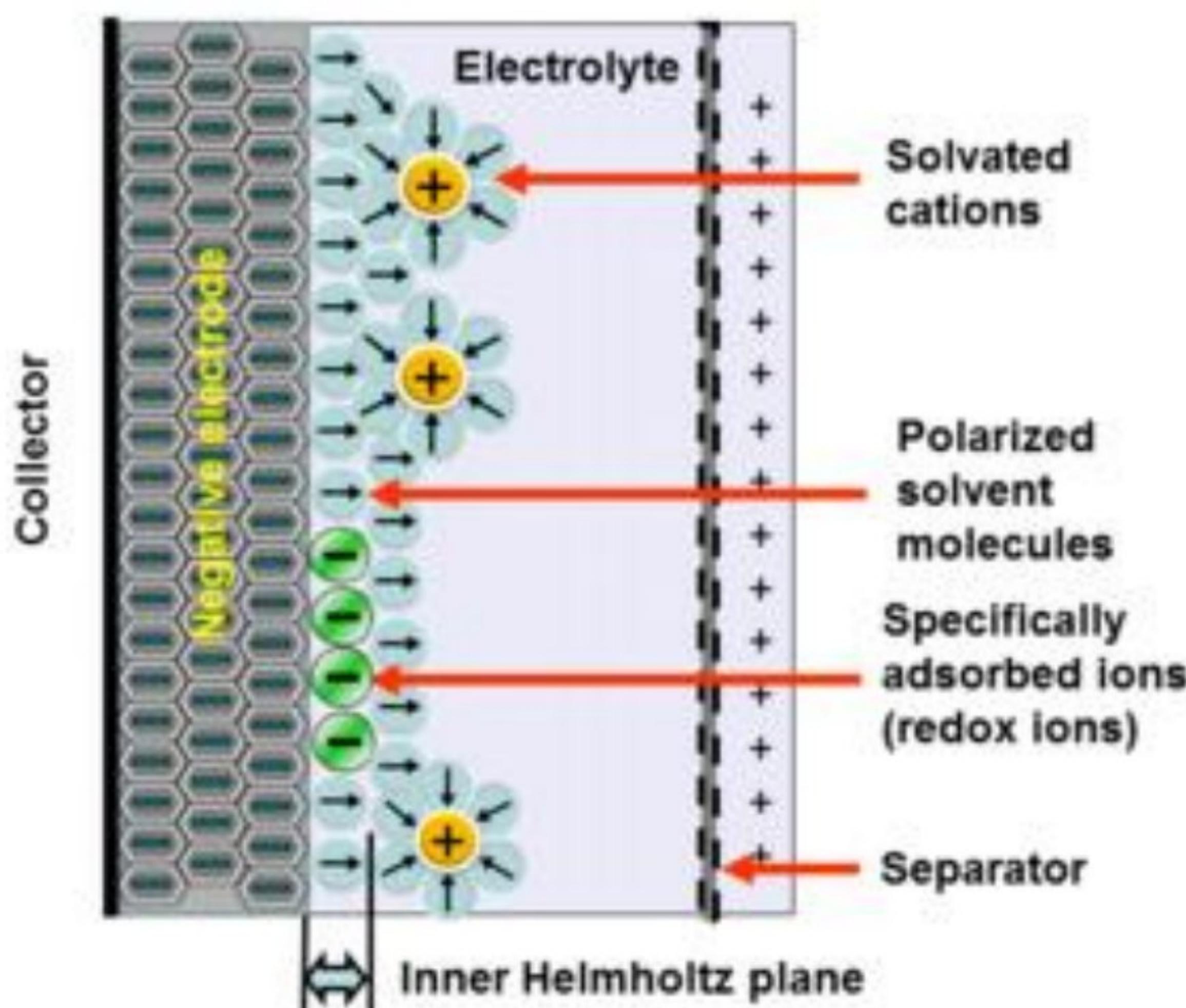


Fig. 1.8: Electrochemical pseudo capacitance

Hybrid Capacitors

Hybrid supercapacitors have higher operating voltage (3.8 V maximum) and much higher capacitance and energy density (up to 10 times) than symmetric supercapacitors. They also have much lower self-discharge and standby current. They can be discharged to zero volts for safety; hybrid supercapacitors cannot be discharged fully. From a construction standpoint, they are very similar, but a hybrid supercapacitor uses an anode made from graphite laced with lithium and a different electrolyte. Utilizing both Faradaic and non-Faradaic processes to store charge, hybrid capacitors have achieved energy and power densities greater than EDLCs without the sacrifices in cycling stability and affordability that have limited the success of pseudo capacitors. The schematic representations of hybrid capacitors are given below.

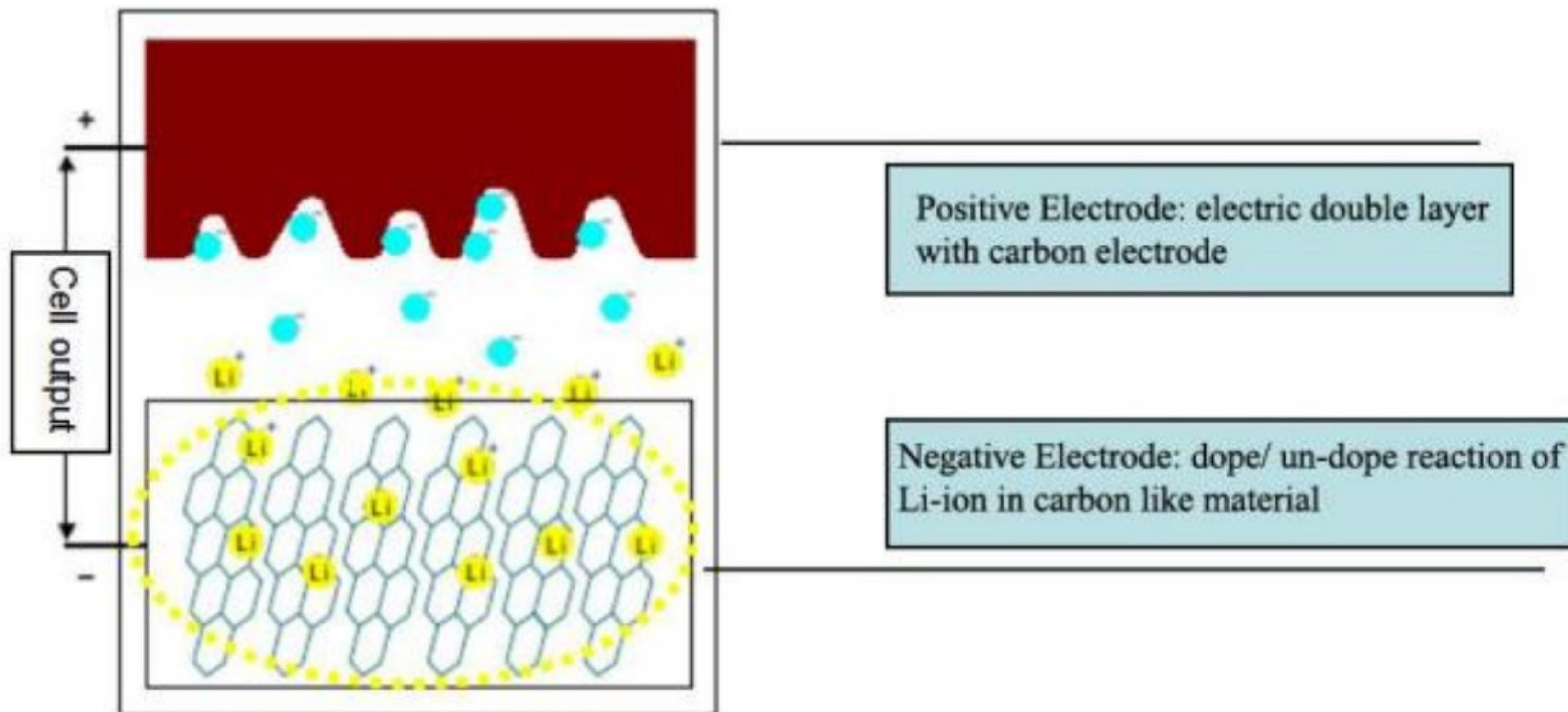


Fig. 1.9: schematics representation of hybrid capacitor

Importance of Electrolytes in super capacitors

Characteristics of electrolyte used in super capacitors

- Wide potential window
- High ionic conductivity
- High chemical and electrochemical stability
- High chemical and electrochemical inertness to ES components
- Wide operating temperature range
- Well-matched with the electrolyte materials
- Low volatility and flammability
- Environmentally friendly
- Low cost

Advantages and limitations of super capacitor

These super capacitors are having advantages as well as limitation some of them highlighted below. Advantages of super capacitor are as follows

- High energy storage.
- Wide operating temperature (-40 °C to 60 °C).
- Eco-friendly.
- Quick charging time.
- Maximum life cycle.
- High cycle efficiency (95%).

- High specific power up to 17 kW/kg.
- Extremely low internal resistance and Safe

Limitations of super capacitors are as follows

- Low energy density; usually holds 1/5 – 1/10 of a battery.
- Cannot use the full energy spectrum for some applications.
- The voltage varies with the energy stored.
- Have high self-discharge rate.
- Individual cells have low voltages, and so serial connections are needed to obtain higher voltages.
- Requires expert electronic control.
- Cannot be used in AC and high frequency circuits.
- High cost.

Applications of super capacitor

- In startup mechanism for Automobiles.
- Used in Diesel engine start up in submarines & tanks.
- In quickly recharged electric bus
- Backup power system in missiles.
- Power source for laptops, flash in cameras.
- Voltage stabilizer.
- To deliver high power and bridge power gaps
- Industrial and electronic applications
- Used in wind turbines, electric and hybrid vehicles
- Regenerative braking to release the power in acceleration
- To start power in start-stop systems
- Regulate voltage in the energy grid
- To capture and assist the power in lower loads and lifted loads
- Back-ups the power in a quick discharging state.

1.3. Energy conversion devices

Fuel cells

Definition

A fuel cell is an electrochemical device, which can continuously convert the chemical

energy of a reducing agent and an oxidant fuel stored externally by a process involving an essentially invariant electrode electrolyte system. A fuel cell consists of two electrodes and an electrolyte. However, the fuel and the oxidizing agents are continuously and separately supplied to the two electrodes of the cell, at which they undergo reactions. These cells are capable of supplying current as long as they are supplied with the reactants. A fuel cell may be represented as: Fuel/electrode/electrolyte/electrode/oxidant At the anode fuel undergoes oxidation and at the cathode oxidant undergoes reduction. Fuel cell is a energy conversion device the main difference between fuel cell and battery are as follows.

Sl No	Battery	Fuel cell
1	These are the energy storage devices	These are energy conversion devices
2	Secondary batteries are rechargeable	Fuel cells are not chargeable.
3	The reactants and products form integral part of the batteries	In fuel cells, there is a continuous supply of fuel, oxidant
4	Products remain in the cell	Products are continuously removed from the cell

Advantages of fuel cells

- Savings in fossil fuels due to the high efficiency of electrochemical energy conversion.
- Low pollution level, no noxious exhaust gases formed.
- Low noise level.
- Low maintenance, exchangeable parts.
- No need of charging.
- Theoretically, the efficiency can be 100%. In practice, the efficiency is 50-80% which is high compared to conventional methods
- Have few moving parts and thus require minimal maintenance, reducing life cycle costs of energy production.
- Modular in design, offering flexibility in size and efficiencies in manufacturing
- Can be utilized for combined heat and power purposes, further increasing the efficiency of energy production

Limitations of fuel cell

- The electrodes used are Pt, Ag or alloys of noble metal which are costly.
- High price of clean hydrogen.

Hydrogen oxygen fuel cell

The hydrogen oxygen fuel cell is categorized under alkaline fuel cells (AFC). The alkaline fuel cell uses an alkaline electrolyte such as 40% aqueous potassium hydroxide. In alkaline fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons.

These fuel cells can use a variety of metals as a catalyst at the anode and cathode and use a solution of potassium hydroxide in water as the electrolyte. Low-temperature AFCs function between 23°C and 70°C, while high-temperature AFCs run between 100° and 250°C. AFCs are high-performance fuel cells because of how quickly chemical processes occur inside the cell. They are also incredibly effective, with space applications achieving efficiency of 60%. This fuel cell type's drawback is that carbon dioxide (CO_2) can poison it readily. It is vital to purify both the hydrogen and oxygen used in the cell because even a small amount of CO_2 in the air can have an impact on how the cell functions. This fuel cell type's drawback is that carbon dioxide (CO_2) can poison it readily. It is vital to purify both the hydrogen and oxygen used in the cell because even a small amount of CO_2 in the air can have an impact on how the cell functions. Potassium carbonate, which is created when CO_2 and KOH mix, will improve resistance. More than 8,000 working hours of AFC stacks have been demonstrated to sustain adequately steady operation[5].

Construction of hydrogen oxygen fuel cells

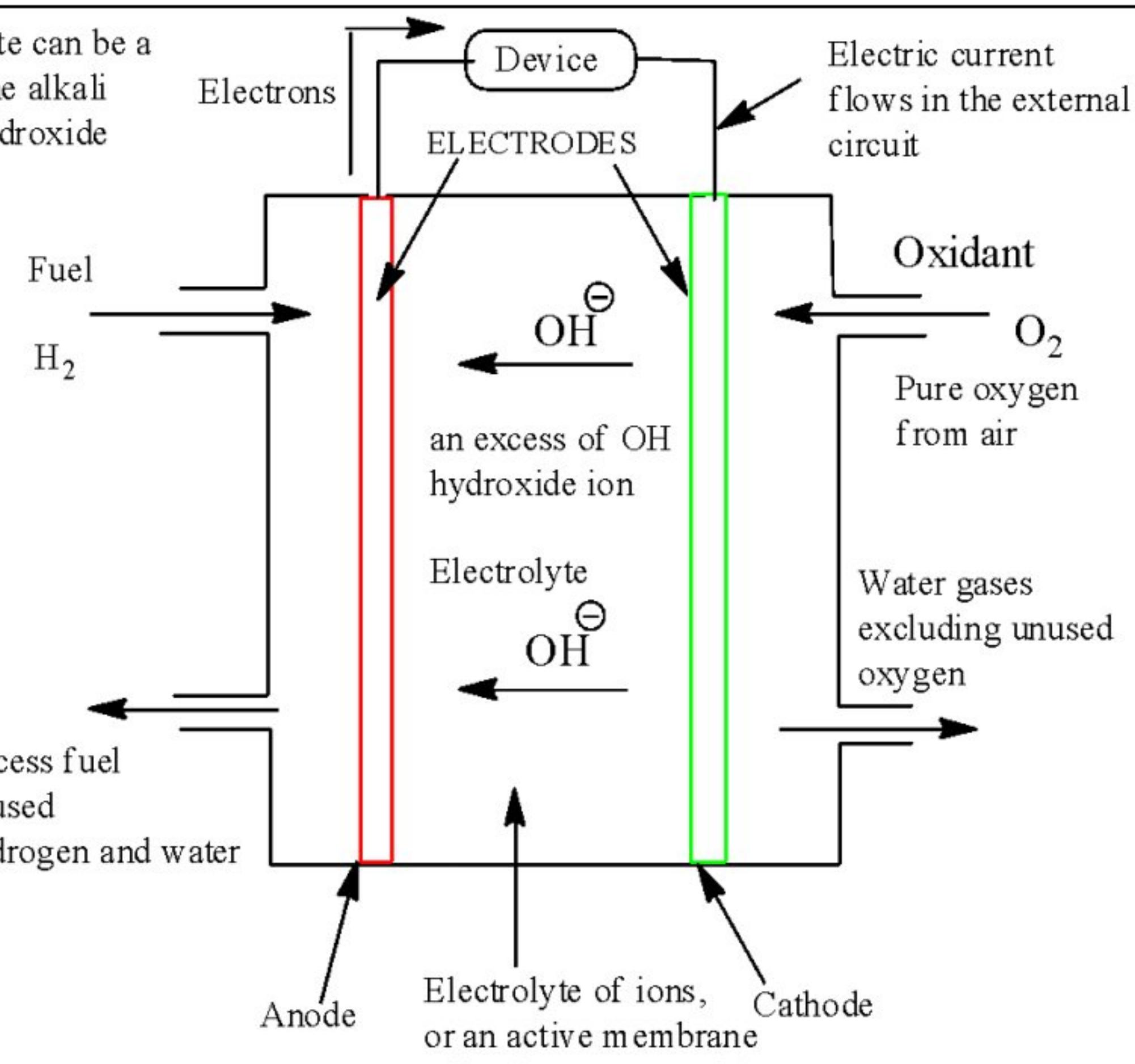
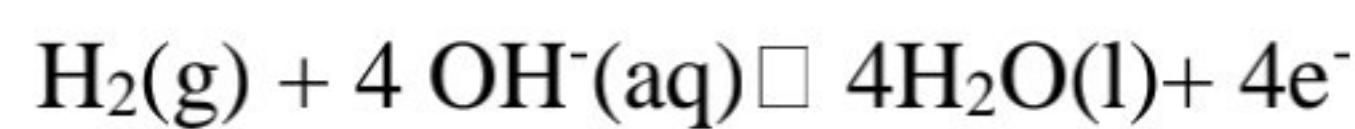
Fuel: Hydrogen	The electrolyte can be a solution of the alkali potassium hydroxide KOH	
Oxidant: Oxygen		
Anode: porous carbon with Pt		
Cathode: porous carbon with Ag		
Electrolyte: KOH		

Fig.: 1.10: Hydrogen oxygen fuel cell

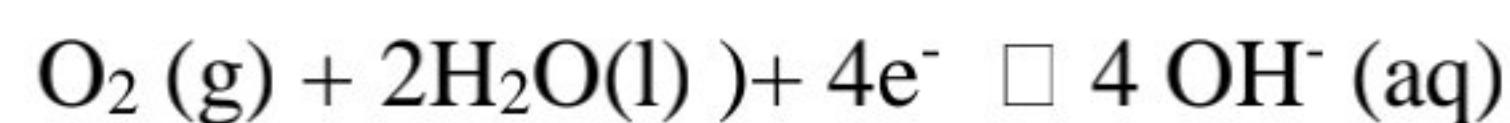
Construction: It is made up of two inert porous carbon plates that serve as the cathode and the anode. 25% solution of NaOH or KOH positioned between the two electrodes serves as the electrolyte. While oxygen gas constantly bubbles at the cathode, hydrogen gas continuously bubbles at the anode. Generally, platinum is used as anode catalyst and silver is used as cathode catalyst.

Working:

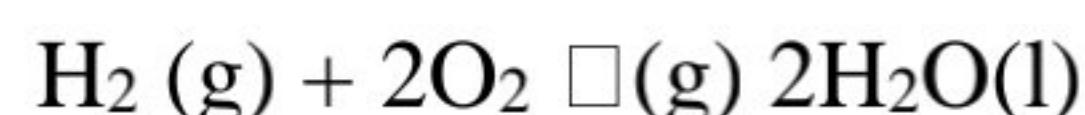
When Hydrogen gas pumped at the anode surface the following oxidation reaction occurs:



The liberated electrons from anode then passes through the external circuit where work is performed, & then finally to the cathode where following chemical reaction takes place



Hence Net reaction:



Advantages:

- Zero emissions: The only byproduct of a fuel cell car is water vapor. As a result, there is no air pollution.
- High efficiency: Without using combustion, fuel cells transform chemical energy directly into electricity. Fuel cells can thus reach significant energy conversion efficiency.
- High power density: Fuel cells can be used in applications where space is limited because of their high-power density
- No Pollution: Fuel cell generators don't produce any thermal, vibrational, or acoustic pollution.
- Replaceable: Because fuel cell systems are modular, it is simple to swap out individual pieces.
- Water is produced by a hydrogen oxygen fuel cell and is of portable quality
- Fuel cell systems: no recharging

Limitations

- It is difficult to manufacture and stores a high pure hydrogen
- It is very expensive as compared to battery
- High cost of pure hydrogen
- Life span of the cells are not accurately known
- Lack of infrastructure for distributing hydrogen.
- Liquification of hydrogen requires 30% of the stored energy

1.4. Photovoltaics

Introduction:

Solar energy is a renewable energy and it is inexhaustible. The earth is receiving approximately 1.8×10^{11} MW of energy which is thousands of times larger than the requirement of energy for present consumption. Thus, solar energy is the only energy that fulfills all our present and future energy needs if we utilize properly. Solar energy can be directly converted into heat energy or electricity. A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect.

Advantages of Solar Cells

- Solar cell is renewable energy which can be continuously drawn from the sun.
- It is economic friendly energy because once it is installed there will be minimum maintenance charges for small usage.
- Solar energy is environment friendly and green energy because it doesn't produce any greenhouse gasses and no pollutants.
- It doesn't involve any combustion reaction or radioactive residue hence no pollution
- Disadvantages of Solar Cells
- Space utilization: Solar cells require large area for installation
- It requires high investment cost for a big power plant
- During the rainy season power production is less hence grid maintenance will be difficult.
- Solar energy is produced only in the day time hence storage will be a big challenge

Classification of solar cells

The solar cells are broadly classified as i) Inorganic solar cells and ii) Organic/polymer solar cells. Amongst them inorganic solar cells are currently in global market. The amorphous

silicon solar cells are classified under inorganic solar cells. There are three types of PV cell technologies that dominate the world market: monocrystalline silicon, polycrystalline silicon, and thin film. Higher efficiency PV technologies, including gallium arsenide and multi-junction cells, are less common due to their high cost, but are ideal for use in concentrated photovoltaic systems and space applications[6]. There is also an assortment of emerging PV cell technologies which include Perovskite cells, organic solar cells, dye-sensitized solar cells and quantum dots solar cells.

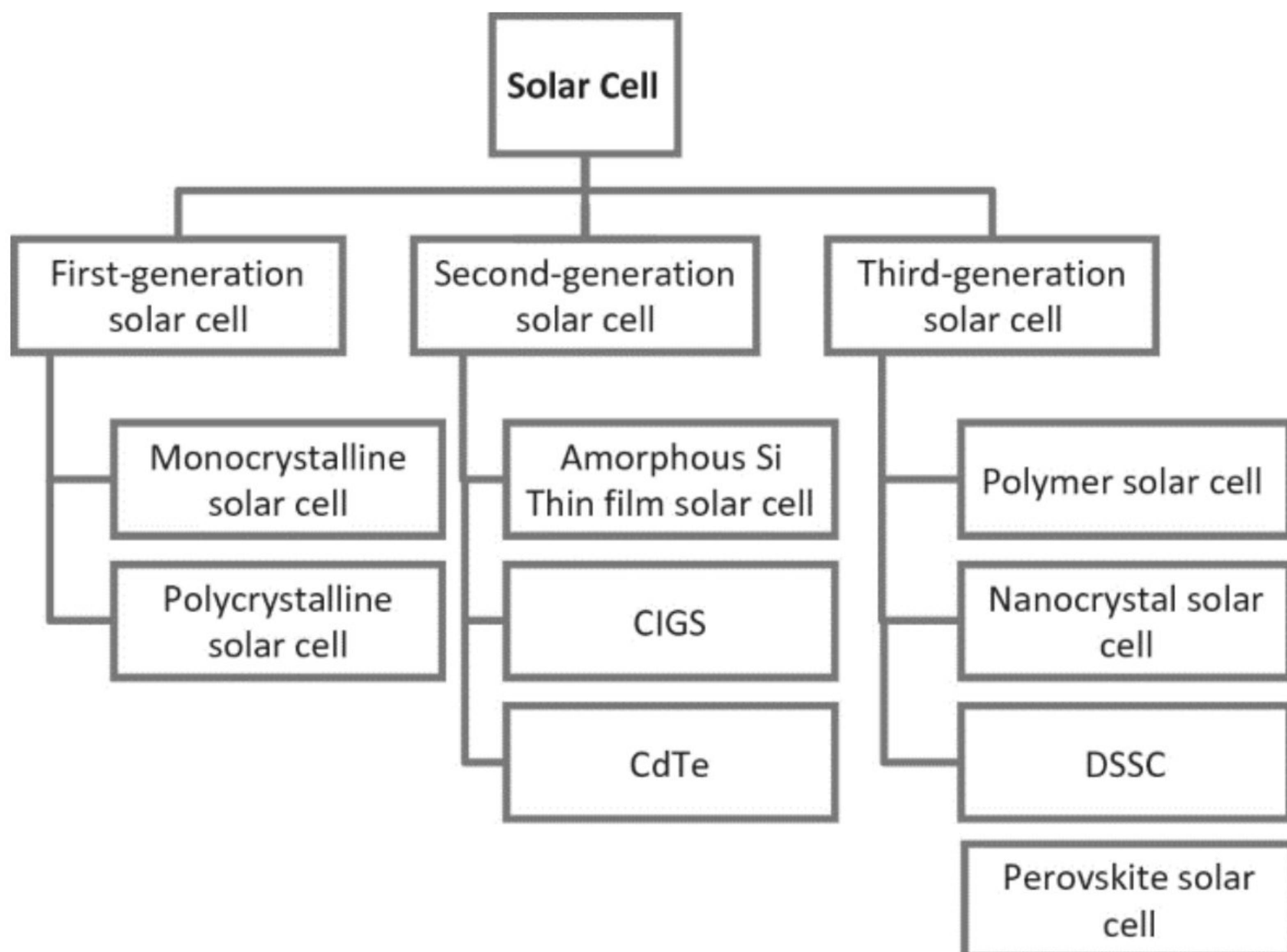


Fig. 1.12: Classification of solar cells

Amorphous silicon solar cells

Construction: A typical silicon solar cell consists of n-type material (Phosphorus doped silicon) and a p-type (Boron doped silicon) material made of silicon. In the fabrication of device these n-type and p-type materials are joined to form a p-n junction. On top of n type connecting front electrodes are placed. The metal back contact is attached to p-type layer. An antireflective coating is filled in between the front electrodes to avoid the reflection of sunlight. Finally p-type and n-type layers are joined externally to the circuit. The complete solar cells are sealed to avoid the environmental contact.

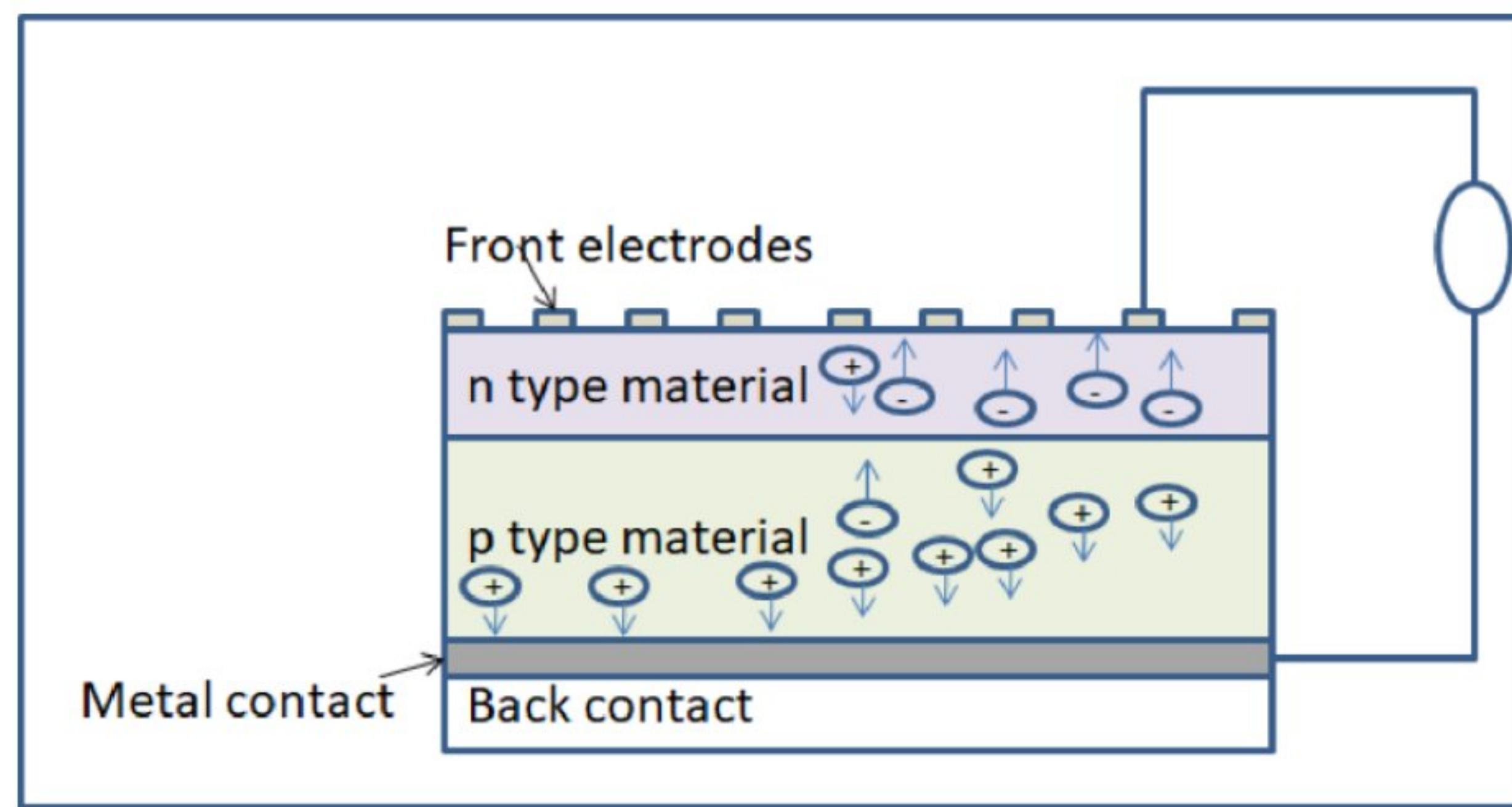


Fig. 1.13: Representation of amorphous silicon solar cells

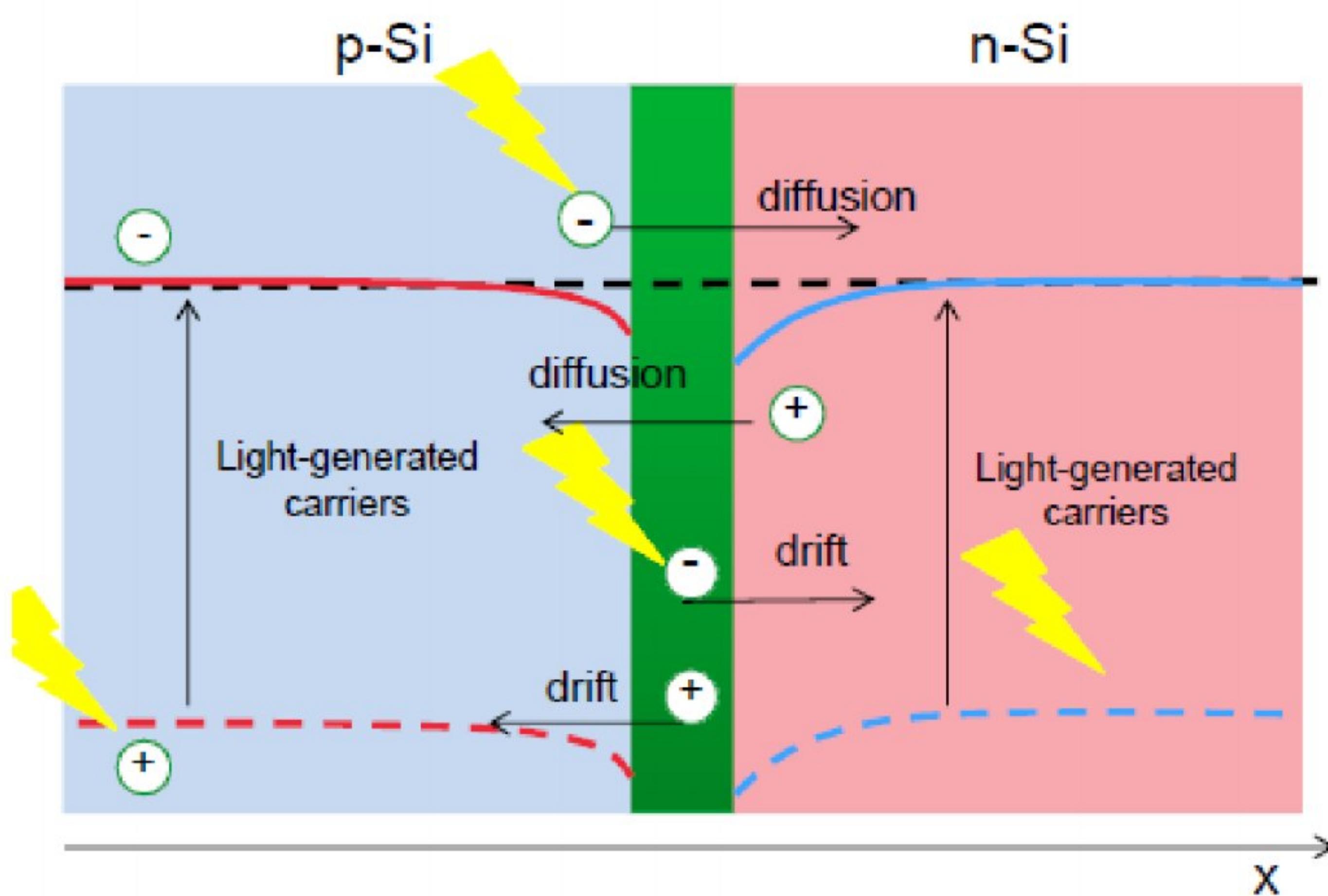


Fig. 1.14: Working mechanism of Silicon solar cells

Working: When sunlight is incident on solar cells photon strikes on p-n junction. Then electron hole pair will be created at the junction by the absorption of photon. This electron hole pair diffuses towards respective layer based on affinity. The electrons diffuse towards n-type later and holes are diffused towards p-type layer. These layers are connected externally through a circuit, hence current will be generated.

Quantum dot sensitized solar cells

Quantum dots (QDs)

Quantum dots are tiny particles or nanocrystals of a semiconducting material with diameters in the range of 2-10 nanometers. When they are illuminated by UV light, an electron in the quantum dot can be excited to a state of higher energy. In the case of a semiconducting

quantum dot, this process corresponds to the transition of an electron from the valence band to the conductance band. The excited electron can drop back into the valence band releasing its energy as light. The color of that light depends on the energy difference between the conductance band and the valence band. Potential applications of these quantum dots include solar cells, LEDs, lasers, quantum computing, cell biology research and medical imaging. Examples for QD sensitizers such as CdS, CdSe, PbS, PbSe, CdTe etc[7].

Construction

It consists of two electrodes cathode and anode generally cathode is made of graphite or platinum. Anode is made of transparent conducting oxide such as Indium tin oxide. Anode is coated with a layer of nano porous materials (TiO_2 or ZnO). Further these nano porous materials are coated with CdSe quantum dots as light absorbing materials. Here the nano porous materials act as semiconductor also it provides road way for electrons. The quantum dots with suitable energy levels helps in electron transfer process. A triiodide electrolyte system is employed in between the electrodes, which helps in electron transfer process.

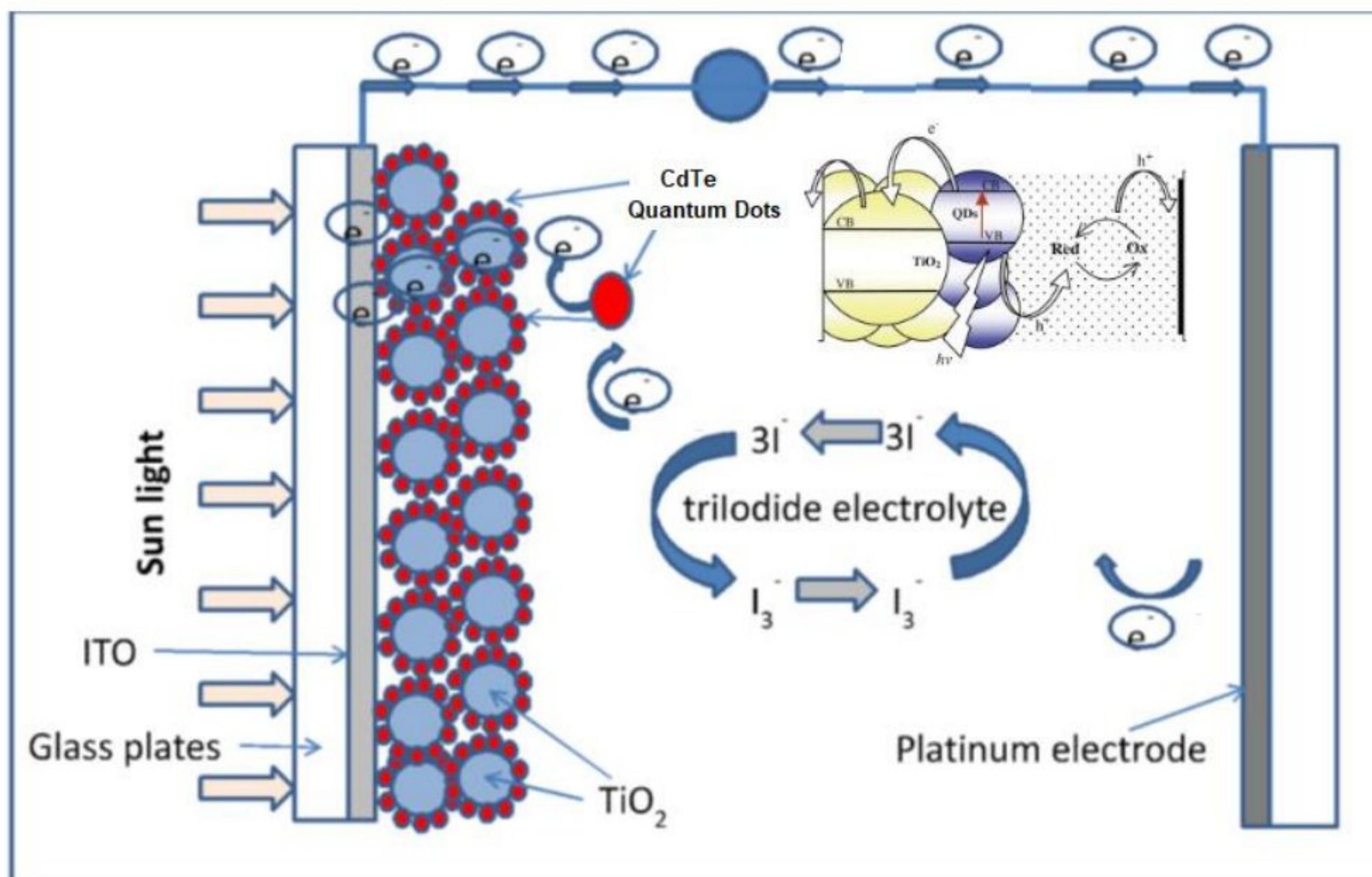


Fig. 1.15. Construction and working of quantum dye sensitized solar cells.

Mechanism of Working

When light photon strikes the solar cell, it passes through ITO layer and it reaches the quantum dots. Once the photon hits the quantum dots, it undergoes excitation with the liberation of electron, which travels through the network TiO_2 nanoparticles (because of matching in energy levels) and finally it reaches to cathode. The cell is completely filled with Triiodide electrolyte. The electron from the cathode directly reduces the triiodide molecule to

three iodide molecules. Further this iodide molecule oxidizes to form triiodide again with the liberation of electrons, which can be easily absorbed by quantum dots. And similar cycle continues whenever sunlight falls on the solar cells.

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Video links

	Topics	Links	QRCode
1	Battery technology	https://drive.google.com/file/d/1rFOYQWvf31TbmRM3Ok_-aVb0PrJqDHQF/view?usp=sharing	
2	Fuel cell technology	https://drive.google.com/file/d/1bTvfVJM3Oacu7Y0Vdmwz6T4pkIF8wE75/view?usp=sharing	

3	Photovoltaics	https://drive.google.com/file/d/1Z8yMvYZVuhWxjmATGR2PGnRn4D3yYdh/view?usp=sharing	
4	Supercapacitor	https://www.youtube.com/watch?v=iFVVv23ZzGE	
5	Introduction to battery technology	https://www.youtube.com/watch?v=nh2xbyOaERw	