

Semiconductor: Devices for Energy Storage and Energy Conversion

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ABSTRACT

Semiconductor devices play a crucial role in modern energy systems by enabling efficient energy conversion and storage. With increasing global energy demand and environmental concerns, semiconductor-based technologies such as solar cells, batteries, fuel cells, and supercapacitors are becoming essential. This research paper presents a detailed overview of semiconductor principles, energy band theory, and electrochemical processes that govern energy storage and conversion. It also discusses recent advancements in nanotechnology and integrated systems, highlighting the future potential of semiconductor devices in sustainable energy solutions. It highlights the indispensable role of energy storage in modern society, particularly in facilitating the transition towards renewable energy sources. Additionally, it explores cutting-edge developments in energy storage technologies and ongoing research initiatives aimed at addressing global energy challenges and promoting sustainability within the energy sector.

Keywords: Energy Storage, Energy Conversion, Solar Cell, Supercapacitors, Fuel Cell, Battery

INTRODUCTION

Energy is a fundamental requirement for human civilization, and its efficient generation, conversion, and storage are key challenges of the 21st century. Traditional energy sources such as fossil fuels are depleting and contribute significantly to environmental pollution. Therefore, renewable energy technologies have gained importance.

Semiconductors are at the heart of modern energy devices due to their unique electrical properties. They can control the flow of electrons and holes, making them suitable for converting solar energy into electricity, storing energy in chemical form, and enabling efficient electrochemical reactions.

Recent research shows that semiconductor-based electrochemical

Fundamentals of Semiconductors

Semiconductors are materials whose electrical conductivity lies between conductors and insulators. Common semiconductor materials include silicon (Si), germanium (Ge), and compound semiconductors such as gallium arsenide (GaAs).

Types of Semiconductors:

- **Intrinsic Semiconductors:** Pure materials with equal electron and hole concentration
- **Extrinsic Semiconductors:** Doped materials
 - n-type (electron-rich)
 - p-type (hole-rich)

Key Properties:

- Conductivity depends on temperature

- Presence of charge carriers (electrons and holes)
- Tunable electrical properties via doping

These characteristics allow semiconductors to be used in devices such as diodes, transistors, and photovoltaic cells.

Energy Band Theory

Energy band theory explains the behavior of electrons in solids and is crucial for understanding semiconductor devices.

- **Valence Band (VB):** Occupied by electrons
- **Conduction Band (CB):** Free electrons move here
- **Band Gap (Eg):** Energy difference between VB and CB

When energy (light or heat) is applied:

- Electrons jump from VB to CB
- This creates electron-hole pairs

Proper alignment of energy bands in semiconductor heterojunctions improves efficiency by reducing recombination losses and enhancing charge separation.

Semiconductor–Electrolyte Interface

The semiconductor–electrolyte interface is essential in electrochemical devices such as batteries, fuel cells, and photoelectrochemical cells.

Key Concepts:

- Band bending at the interface
- Charge transfer between semiconductor and electrolyte
- Formation of electric double layer

This interface controls:

- Reaction kinetics
- Efficiency of energy conversion
- Ion transport

Semiconductors can enhance ionic conductivity and improve electrochemical performance compared to traditional electrolytes.

Semiconductor Devices for Energy Conversion

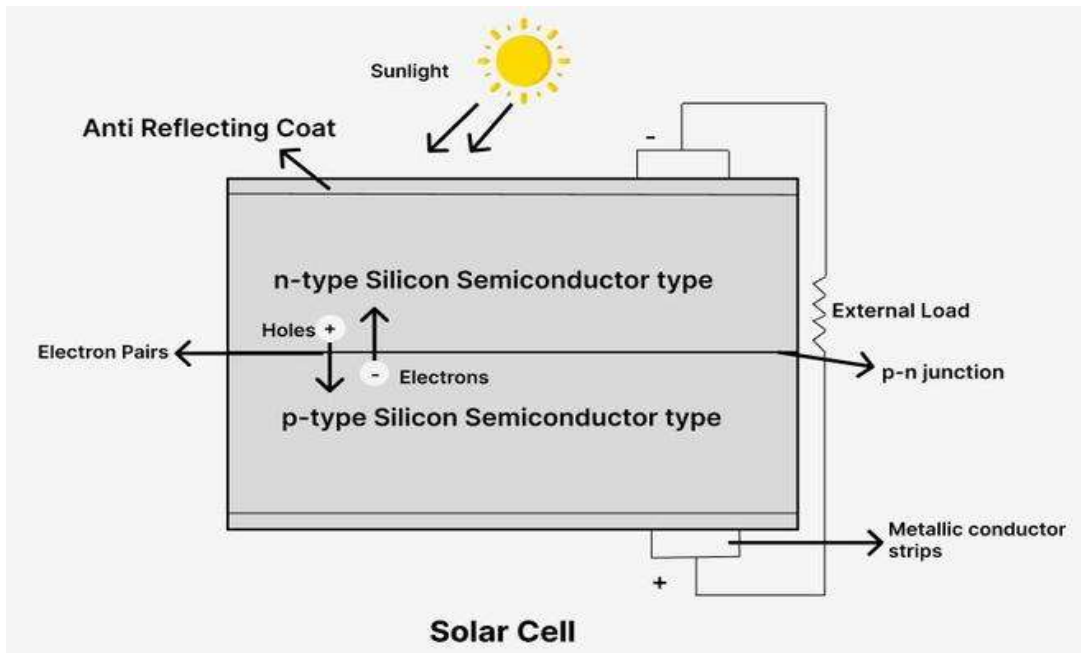
Solar Cell

A Solar Cell is a device that converts light energy into electrical energy using the photovoltaic effect. A solar cell is also known as a photovoltaic cell (PV cell). A solar cell is made up of two types of semiconductors, one is called the p-type silicon layer and the n-type silicon layer. So Solar cell is a p-n junction diode.

The solar energy from the sun in the form of photons creates loose electrons on the n-type semiconductor and holes on the p-type semiconductor. These loose electrons are collected on the aluminum layer and start flowing thus resulting in an electric current.

A solar cell is a device that converts light energy into electrical energy using the photovoltaic effect. It is also known as a Photovoltaic cell.

- A solar cell is made up of two types of silicon semiconductors type, one is n-type silicon semiconductor type and another p-type silicon semiconductor type.
- There is a reflecting coat covered above the solar cell to prevent any external shocks. The solar
- cell's middle layer is known as the p-n junction diode.
- When the sunlight falls on the solar cell, the solar energy from the sun in the form of photons creates loose electrons on the n-type semiconductor holes on the p-type semiconductor.
- These created loose electrons are collected on the aluminum layer and start flowing, thus resulting in generating the electric current.



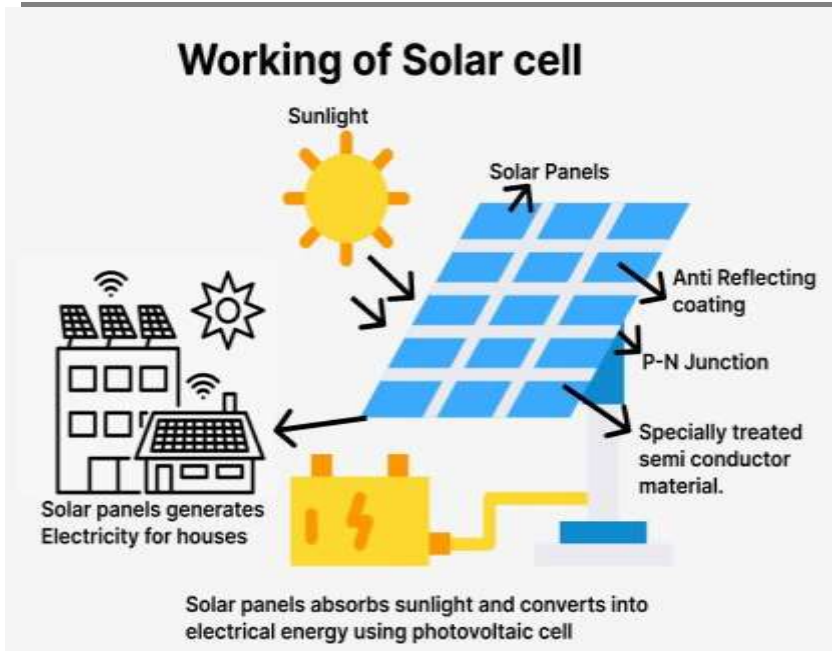
Properties of Solar Cell

- Solar Cell is able to convert light energy into electricity.
- Solar Cell higher efficiency and it can convert using Photovoltaic Effect.
- Solar Cell has more durability and resistance to environmental conditions.
- Solar Cells provide long-term performance and has higher life span.
- Solar Cells has no maintenance cost.

Working of Solar Cell

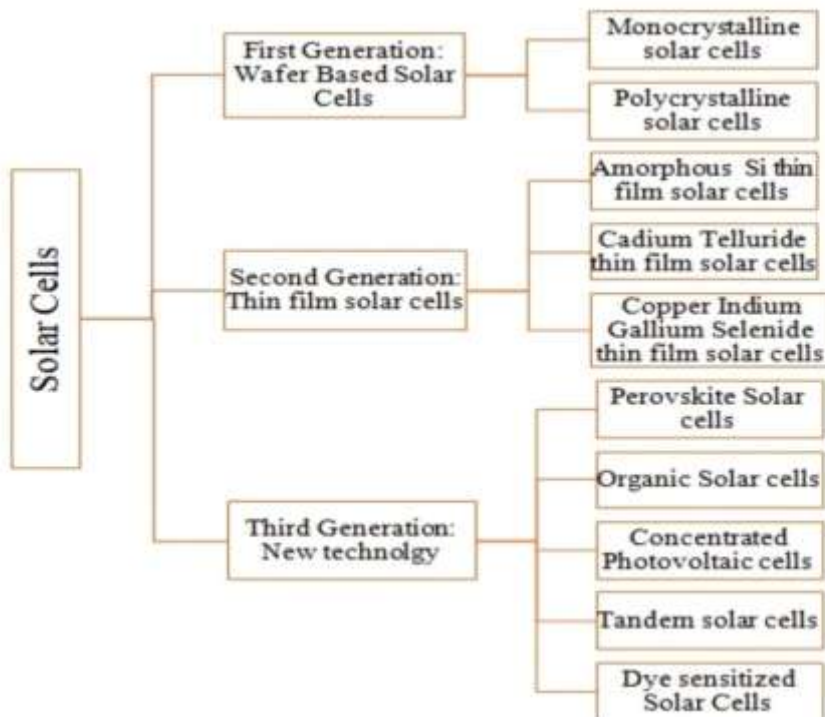
When the light energy falls on a solar panel, then the solar panel absorbs the light energy. Each solar cell in solar panel has a semiconductor which has the properties like insulator and metal. When the energy of sun falls on the panel then a semiconductor material on the panel absorbs, the energy of photons transfers to electrons and allows the flow of electrons through the material like an electric current.

When the sunlight reaches the p-n junction, between the p and n-type semiconductors, photons easily enter through a thin p-type layer. The photons provide energy to the p-n junction, creating electron-hole pairs. This light disrupts the thermal equilibrium condition of the junction, then the free electrons to move to the n-type side of the junction. The holes move to the junction's p-type side in a similar pattern. As a result, free electrons on the n-type side fail to move past the junction due to a potential barrier. The same barrier potential of the junction blocks the newly created holes, which causes an increased concentration of electrons on one side (at the n-type junction) and holes on the other side. This is the process involved in working of a solar cell



Types Of Solar Cells

Alexandre-Edmond Becquerel made the initial observation of a photovoltaic cell in 1839. In the past, sunlight was turned into power using solar cells composed of thin silicon wafers. The first silicon-based solar cell was created by Russell Ohl in 1946. Modern solar cells operate on the basis of the creation of electrons and holes in a semiconductor material, which has two distinct layers, p-type and n-type. When photons collide with a semiconductor material junction, the electrons gain energy and jump into the conduction band, leaving a hole in the process. Electrical power is produced in such a process through the generation of holes and electrons. (Askari et al. 2015). On the basis of materials used in such a photovoltaic cells, solar cells are classified in different classes as discussed in the following sections.



First generation Solar Cells: Wafer Based

Monocrystalline Solar Cells: These cells are constructed from a single crystal. The manufacturing process employs the Czochralski method. A large ingot is cut into Si crystals in this specific kind of technique. The

finished bars will be entirely natural. These solar cells are highly expensive as a result of their purity. These cells' efficiency ranges from 17% to 18%. Due to the hexagonal or spherical shape of these solar cells, when solar panels are built using them, some empty space is left. Such solar cells have a 50-year lifespan.

Polycrystalline (Multicrystalline) Solar Cells: The silicon used in these solar cells is composed of many crystals. Melting rods made of various silicon crystals is followed by the pouring of the molten silicon into square molds. Such a method does not yield identical solar cells every time. Although these solar cells are less expensive than monocrystalline solar cells, they are less efficient. The efficiency of this type of solar cell is between 12% and 14%. Due to the square design of these solar cells, there is less vacant space between the cells.

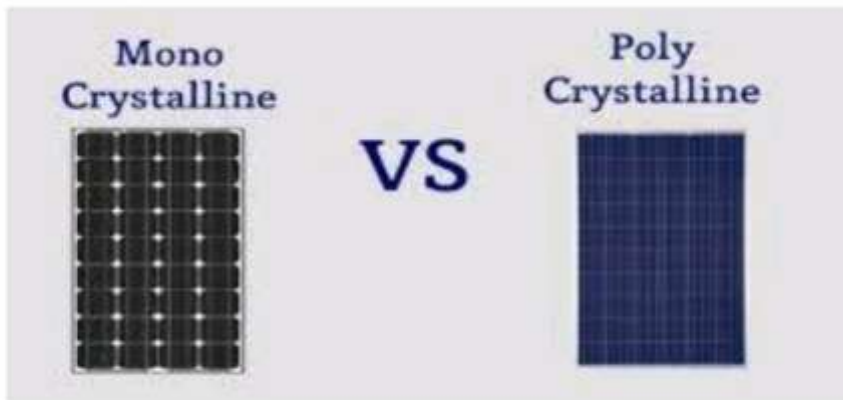


Figure 2: Monocrystalline and Polycrystalline solar panels

Second Generation Solar Cells:

Thin-film Solar Cells: By depositing thin layers of specific photovoltaic materials onto a substrate, thin-film solar cells are created. Glass, metal, or plastic are all acceptable substrates. Its benefits include lightweight and flexibility. However, compared to crystalline silicon cells, its efficiency is low. These solar cells feature absorbing layers that are 1 micron thick, whereas silicon wafers have absorbing layers that are 350 microns thick. Second generation solar cells can be further classified into three types:

Amorphous Silicon (a-Si) Thin-Film: Low temperatures can be used to create this type of solar cell. Therefore, substrates with lower energy requirements can be employed. It can be incorporated into flexible or curved surfaces. These solar cells are created by taking a substrate and coating the back of it with silicon material that has been doped. The silicon material employed in this process has an ambiguous atom structure. Additionally, this type of solar cell is affordable and widely accessible. These solar cells have a conducting side that is silver in color and a dark brown reflecting side. It has a 4%–8% efficiency range as far as productivity is concerned. However, these can be utilized in locations where the sun only shines briefly.

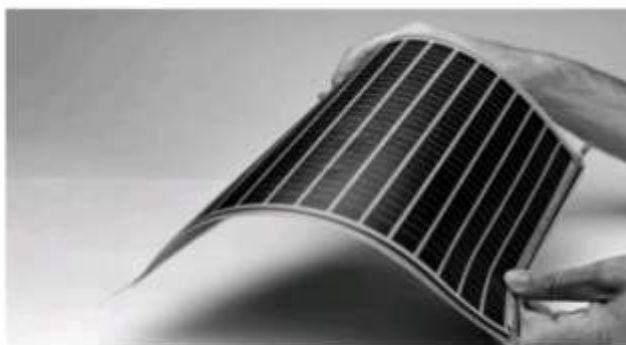


Figure 3: Amorphous Silicon PV modules

Cadmium Telluride (CdTe) Thin-Film: Band gap of CdTe is 1.5 eV. It is direct band gap semiconductor and hence absorption of light is easy. It has high optical absorption coefficient. It is chemically stable. Due to these features, it is one of the most in-demand materials that can be used in designing of such thin-film solar cells. Moreover, CdTe solar cells are more economical as compared to other thin films solar cells. It consists of a p-n heterojunction which contains p-type layer of CdTe layer that matches with window layer made up of n-doped cadmium sulfide. Following are the steps involved in manufacturing process of such a cell:

- A substrate material is chosen such as glass.
- Polycrystalline material is taken from which CdTe solar cells are to be made.
- Deposition method is used in which multiple layers of CdTe are coated on substrate. Its efficiency lies between 9%-11%. The main disadvantage of such kind of cell is the use of Cadmium in it. Cadmium is a toxic agent. It can accumulate in animals, plants and human bodies. Recycling process of such a material is also expensive

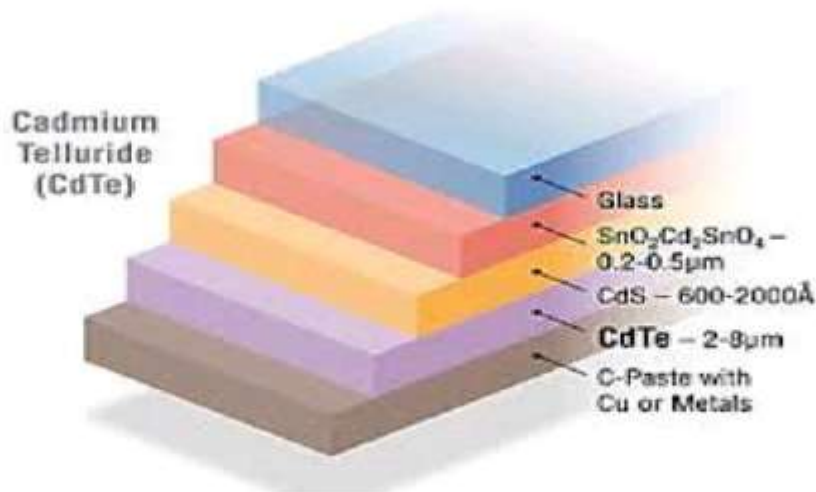


Figure 4: Five layers of CdTe Solar Cell

Copper Indium Gallium Selenide (CIGS) Thin-Film:

These solar cells contain the four elements copper, indium, gallium, and selenide. In order to gather current, the electrodes are constructed on the front and rear surfaces. Due to the high absorption coefficient of this type of solar cell, a significantly thinner coating is needed for them. Sputtering, evaporation, electrochemical coating, and electron beam deposition are the methods used during its production. The semiconductor also has a direct band gap. Its efficiency ranges from 10% to 12%. It has a lengthy lifespan.

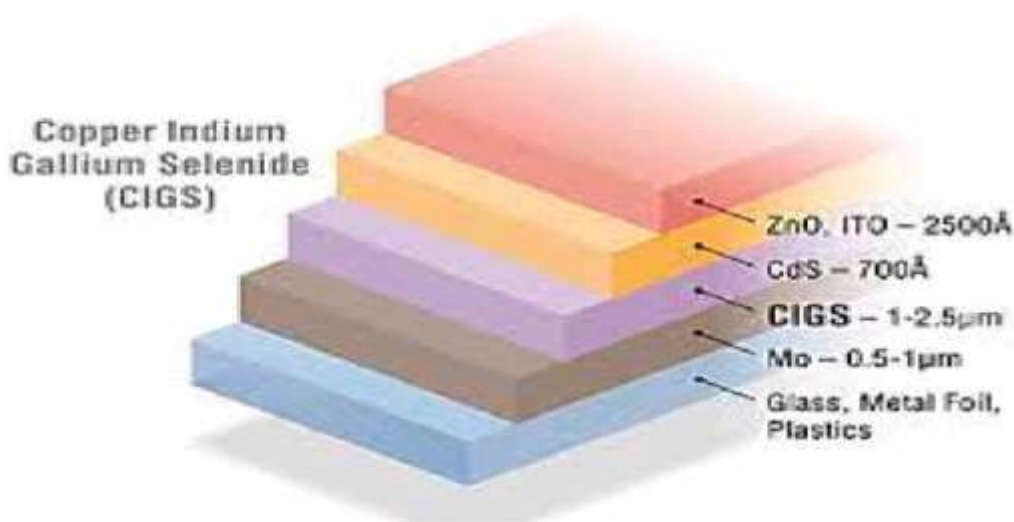


Figure 5: Copper Indium Gallium Selenide Solar cell

Third Generation Solar Cells:

Emerging New Technology:

Third generation solar cells have been introduced so that conversion efficiency could be increased and cost of the material used should be decreased.

Nanocrystal Solar Cells: These cells are known as quantum dot solar cells(QDSC). These types of solar cells can take the place of bulk materials like Si, CdTe, or CIGS. Quantum dots have adjustable bandgaps, which enables them to absorb the most energy possible. These employ absorbing photovoltaic materials from transition metal groups with nanocrystal sizes as their size range. As depicted in the image, quantum dot material is placed between the hole and electron transport channel. A silicon solar cell is known to have an efficiency range of 30%-33%. Efficiency factor rises in direct proportion to the number of layers in a cell

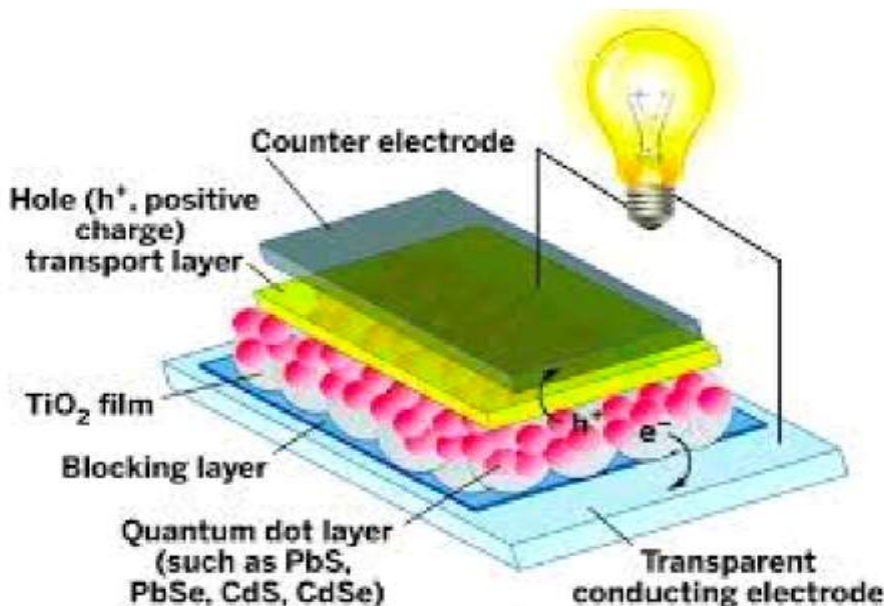


Figure 6: Quantum dot Solar Cell

Principal benefits of quantum dot solar cells include:

We can modify the band gaps by size-based quantum confinement, which enhances optical response. □ Multiple charge carriers can be produced from one photon using quantum dots. Recombination of charge carriers, which is the primary drawback of every solar cell, is the only restriction that happens in such cells.

Concentrated Solar Cells: One of the newest technologies, it is becoming more and more popular in research and development. Here, optics is being used in a way that concentrates a lot of energy on a small area. The placement of mirrors and lenses allows sunlight to be focused on a specific location. The optics underlying this phenomenon is that when radiation strikes certain lenses or mirrors, the light is focused and a significant amount of heat energy is generated. It is a notable solar cell in the solar industry. The amount of energy that is focused on a certain area relies on the type of lens system being employed. These solar cells are more than 40% efficient. These solar cells have advantages such as rapid response times, the absence of moving parts, and the involvement of thermal mass. It can be produced in various sizes.

Dye-sensitized Solar Cells:

DSSCs use a dye-coated semiconductor to absorb light and generate electricity. These are also known as G cells as the first DSSC was made by Michel Gratzel at Swiss Federal Institute of technology. Molecular dyes are used between electrodes. These cells have four different parts: a semiconductor electrode, a dye sensitizer, a redox mediator, and a counter electrode. These solar cells are flexible, translucent, and rather appealing. They are also inexpensive. Its efficiency is higher than 10%. The only problem with these cells is that dye molecules breakdown when they are exposed to ultraviolet or infrared radiation, which reduces their lifetime and stability. However, because of their translucent qualities, they can be used in low-light situations and in some creative applications.

Photocatalysis and Water Splitting

Water splitting to form hydrogen and oxygen using solar energy in the presence of semiconductor photocatalysts has long been studied as a potential means of clean, large-scale fuel production. In general, overall water splitting can be achieved when a photocatalyst is modified with a suitable cocatalyst. It is therefore important to develop both photocatalysts and cocatalysts. In the past five years, there has been significant progress in water splitting photocatalysis, especially in the development of cocatalysts and related physical and materials chemistry.

Process:

- Absorption of photons
- Generation of electron-hole pairs
- Redox reactions:
 - Reduction → Hydrogen production
 - Oxidation → Oxygen production

This technology is promising for hydrogen fuel generation.

Fuel Cells

Fuel cell is a device that generates electricity by a chemical reaction. Every fuel cell has two electrodes called, respectively, the anode and cathode. The reactions that produce electricity take place at the electrodes. Every fuel cell also has an electrolyte, which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds the reactions at the electrodes. Hydrogen is the basic fuel, but fuel cells also require oxygen. One great appeal of fuel cells is that they generate electricity with very little pollution—much of the hydrogen and oxygen used in generating electricity ultimately combine to form a harmless byproduct, namely water cells convert chemical energy directly into electrical energy.

Components:

- Anode
- Cathode
- Electrolyte

Semiconductor-based fuel cells use:

- Built-in electric fields
- Heterostructures

These improve efficiency and reduce operating temperature compared to traditional systems.

Semiconductor Devices For Energy Storage

Energy storage devices are “charged” when they absorb energy, either directly from renewable generation devices or indirectly from the electricity grid. They “discharge” when they deliver the stored energy back into the grid. Charge and discharge normally require power conversion devices, to transform electrical energy (AC or DC) into a different form of chemical, electrochemical, electrical, mechanical, and thermal. Energy storage can store surplus energy from intermittent renewable sources, such as solar PV and wind power, until it is required – allowing therefore for the integration of additional renewable energy into the system.

Batteries (Lithium-ion, Sodium-ion)

There is ample precedent for the history of lithium-ion batteries to be framed as story of innovation and progress

over a period of several decades. The concept of lithium-ion batteries dates back to the 1970s, when John B. Goodenough, as part of his research at Oxford University, first identified lithium cobalt oxide as a promising cathode material in the 1960s. However, Sony Corporation commercialized the first practical Li-ion battery in the 1980s, primarily for use in camcorders and later in portable electronics like laptops and mobile phones. In the 21st century, this discovery ushered in a new era of portable energy storage, revolutionizing consumer electronics and paving the way for electric vehicles and renewable energy storage systems. Batteries store energy in chemical form and release it as electricity.

Working Principles of Lithium-Ion Batteries

The lithium-ion battery operates on the basis of reversible electrochemical reactions that occur between the positive and negative electrodes of a cell. To give you a better understanding of their working principles, here is a simplified overview:

- **Cathode (Positive Electrode):** The cathode typically consists of a lithium metal oxide, such as lithium cobalt oxide (LiCoO₂), lithium manganese oxide (LiMn₂O₄), or lithium iron phosphate (LiFePO₄). During discharge, when the battery is providing power to a device, lithium ions within the cathode material move toward the anode.
- **Anode (Negative Electrode):** The anode is usually made of graphite or other carbon-based materials. When the battery is discharging, the anode absorbs the lithium ions released by the cathode. This movement of lithium ions constitutes the flow of electricity.
- **Electrolyte:** The electrolyte is a lithium salt dissolved in a solvent. It separates the cathode and anode and allows lithium ions to move between them during charging and discharging. The electrolyte also plays a crucial role in the safety of the battery.
- **Separator:** A separator, typically made of a porous material, physically separates the cathode and anode to prevent direct contact while allowing the passage of lithium ions. This prevents short circuits.

During the charging process, a power source (such as a charger) applies a voltage externally to the battery, causing lithium ions to migrate from the anode to the cathode as a result of this voltage. Battery storage is accomplished through this process. In the case of a discharged battery, the lithium ions are transported back to the anode, producing an electrical current that powers the connected device.

Working Principle:



➤ Redox reactions

- Ion movement between electrodes

Example: Lithium-ion Battery

- Anode: Graphite
- Cathode: Lithium metal oxide
- Electrolyte: Lithium salt solution

Semiconductors enhance:

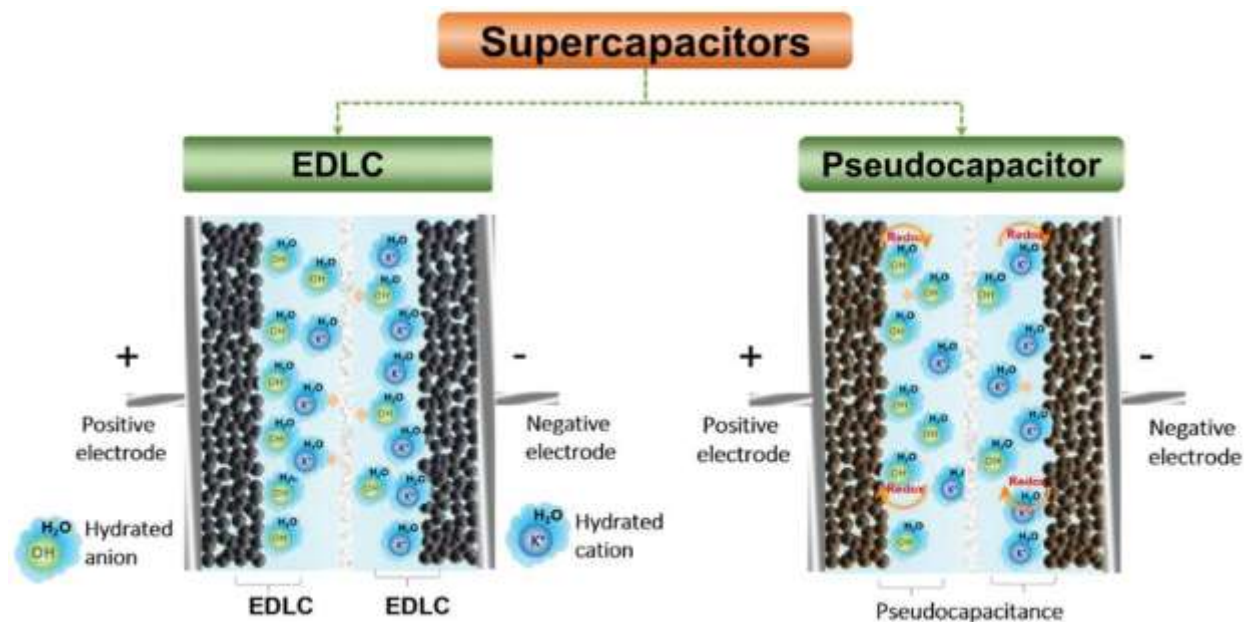
- Charge transfer
- Reaction kinetics
- Energy density

Energy storage involves conversion of electrical energy into chemical energy and back into electricity

Supercapacitors:

An electrochemical capacitor, also known as a supercapacitor, has a history that dates back to the earliest capacitor technology. In the 18th century, capacitors were first developed as a means of storing electrical energy in an electric field between two conductive plates.

Nevertheless, supercapacitors took shape around the mid-20th century. Researchers explored the use of double layer capacitors in the 1950s and 1960s, which rely on the high surface area of activated carbon electrodes in order to store electrical energy. A breakthrough was made in the 1970s when researchers discovered that the high capacitance of these devices was due to the formation of an electric double layer between electrodes and electrolytes. Ultimately, this discovery led to the development of supercapacitors which have a much higher capacitance than traditional capacitors. The technology of supercapacitors continues to evolve with improvements in electrode materials, electrolytes, and manufacturing methods. In the modern world, supercapacitors can be found in a wide variety of industries, such as automotive and transportation



Working mechanism of supercapacitors

Features:

- Fast charging
- High power density
- Long cycle life

Semiconductor nanomaterials increase surface area and improve performance.

Integrated Energy Conversion and Storage Systems

Modern systems combine energy conversion and storage into a single unit.

Examples:

- Solar cell + battery systems
- Photocatalytic storage devices
- Hybrid supercapacitor systems

Integration improves:

- Efficiency
- Energy management
- Sustainability

Recent studies emphasize the importance of combining photovoltaic and storage technologies for future energy systems.

Energy Storage and Conversion Integrated Devices in Future

The electrode, electrolyte, and packing materials must all be flexible to produce a flexible batteries or Solar cells. Given that the flexible packing materials are marketed. The development of flexible electrodes and electrolytes with superior electrochemical properties is the focus of current research. Slurry-casting is the primary technique used to create the electrodes for conventional Li-ion batteries. Active materials are combined with binders and conductive additives like carbon black and graphite, and the resulting mixture is cast onto a current collector composed of metal foil or mesh. High energy density active materials and a small number of inactive components are needed for high-efficiency LIBs. This makes settling the active elements directly onto a flexible conductive substrate without the use of binders or additives the most widely utilized technique for producing flexible electrodes. The use of solar energy is popular, environmentally benign, and renewable. Solar cells have mostly been created for the purpose of collecting solar energy and transforming it further into electrical energy, allowing us to use solar energy in our daily lives. The energy output of a single solar cell may vary due to variations in sunshine intensity at various times, locations, and weather conditions, making it unsuitable for direct use in electronic equipment. The integrated energy device combines energy storage and conversion into one unit. The conventional configuration is a planar shape, making it simple to combine these two components into a single entity. In the beginning, DSSCs are coupled with Li-ion batteries or solar cells due to their low cost and simple manufacture. Both DSSC and Li-ion batteries, or solar cells components, need different electrolytes. These electrolytes are typically liquid and are cumbersome or even problematic due to leakage and volatilization. For practical applications, it is important to further seal such integrated energy devices. The fabrication of solid-state DSSCs and subsequent integrated energy devices has therefore been suggested using gel electrolytes, albeit mechanical and thermal stability still need to be improved. In order to achieve this, a fully solid-state integrated energy device has been extensively researched using solid-state solar cells and solar cells.

Advanced Materials and Nanotechnology

Nanotechnology has revolutionized semiconductor devices.

Key Materials:

- Nanowires
- Quantum dots
- Graphene
- Perovskites

Advantages:

- High surface area
- Enhanced conductivity
- Improved light absorption

Nanostructured semiconductors enable:

- Faster charge transfer
- Better efficiency
- Miniaturization of devices

Advantages And Limitations

Advantages:

- High efficiency
- Renewable energy utilization
- Low environmental impact
- Scalability

Limitations:

- High initial cost
- Material stability issues
- Efficiency losses due to recombination
- Limited lifetime of some devices

Future Scope and Emerging Trends

Future research focuses on:

- Artificial photosynthesis
- Hydrogen energy systems
- Perovskite solar cells
- Solid-state batteries
- Quantum semiconductor devices

Semiconductor electrochemistry is expected to play a major role in next-generation energy systems by combining physics, chemistry, and materials science.

CONCLUSION

Semiconductor devices are essential for efficient energy conversion and storage. Their ability to control electron flow and participate in electrochemical reactions makes them ideal for modern energy technologies. Advances in nanotechnology and materials science have significantly improved their performance.

Integrated systems combining energy conversion and storage represent the future of sustainable energy. Continued research in semiconductor electrochemistry will lead to more efficient, cost-effective, and environmentally friendly energy solutions.

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