Chapter 2

Solar Cells

2.1 Introduction

The need for renewable energy is critical in tackling the challenges posed by climate change and meeting our growing energy demands sustainably. Unlike fossil fuels that release harmful greenhouse gases when burned, renewable energy sources like solar, wind, and hydroelectric power generate electricity without polluting the environment. With finite reserves of fossil fuels and their damaging impact on the planet, shifting to renewable energy is imperative. Embracing renewables not only reduces our carbon footprint but also promotes energy independence, stimulates innovation in clean technologies, creates jobs in the green sector, and paves the way for a more resilient and environmentally conscious future **[1,2].**

Currently, only a tiny bit of energy which comes from solar radiation is consumed about 0.015% for making electricity, 0.3% for heating, and 11% for nature's own way of making things grow, like plants using sunlight. So, finding better ways like solar power to make energy is super important to help keep our planet healthy **[3,4].**

The sun's energy supply to Earth is 3×10^{24} J/year, with only a small fraction now consumed. Covering 0.1% of the earth's surface with solar cells with a conversion efficiency of 10% would suffice to meet our current needs **[5,6].**

Solar Cell

A solar cell, also known as a photovoltaic or photoelectric cell, is a solid-state device designed to convert sunlight into the electric energy through the photovoltaic effect. The term 'photovoltaic' merges the Greek word for 'light' with the name of physicist Alessandro Volta, signifying the direct transformation of sunlight into energy via solar cells. This conversion mechanism leverages the photoelectric effect, it was initially pioneered by Alexander Becquerel in 1839 **[7].** The photoelectric effect explains how the exposure of a solid's surface to light triggers the emission of positive and negative charge carriers, facilitating the generation of electricity.

The photovoltaic effect involves generating a voltage or an electric current in a material when it is exposed to light. While closely related to the photoelectric effect, it's important to differentiate between the two phenomena. Photoelectric effect occurs when electrons are expelled from the surface of a material due to exposure to sufficiently energetic radiation. Conversely, the photovoltaic effect occurs as electrons are moved between different energy levels within the material, specifically from the valence band to the conduction band, leading to the creation of a voltage across two electrodes.

Solar cell works on the photovoltaic effect and hence many times solar cells are termed as Photovoltaic cells. A solar cell is basically p-n Junction diode in which a thin layer of p-type semiconducting material is grown on n-type semiconductor. On exposure to sunlight, the light energy in the form of photon enters the junction and produces electron-hole pair. The generated electrons in the depletion region move towards n-type semiconductor whereas holes move towards p- type semiconductor. The concentration of electron and holes increases at n-type and p-type region respectively and voltage is set up which is known as photo voltage. **[8-10]**

The breakthrough in photovoltaic technology came in 1954 at Bell Laboratories with the creation of an efficient solar cell by Daryl Chapin, Calvin Souther Fuller, and Gerald Pearson. They pioneered the use of a diffused silicon p-n junction, marking the advent of modern solar cells. Initially, these cells found applications in small gadgets and toys, due to their prohibitive cost. The price for a cell generating 1 watt of power in bright sunlight was about $250, starkly contrasting with the $2 to $3 cost for an equivalent amount of electricity produced by a coal power plant.

Solar cells have undergone three generations of evolution from the initial single silicon solar cells to the second-generation solar cells based on semiconductor thin films and now, the third-generation solar cells which includes the dye-sensitized solar cells (DSSC) and organic semiconductor solar cells among others **[11-13].** A maximum of ~11% conversion efficiency has been reported for DSSC **[14].**

2.2 First Generation Solar Cell

First-generation solar cells, also known as traditional, conventional, or wafer-based solar cells, are made from crystalline silicon (c-Si), which is the most common material used for solar cell production to date. This generation is based on mono-, poly- and multi-crystalline silicon, as well as single junctions (GaAs).

Monocrystalline silicon solar cells are manufactured from a single crystal of silicon. They are known for their high efficiency and long lifespan but are generally more expensive to produce due to the complexity of the silicon crystallization process. These cells are characterized by their uniform dark colour and rounded edges.

Polycrystalline silicon solar cells, on the other hand, are made from multiple silicon crystals that are melted together. They are easier and cheaper to produce compared to monocrystalline cells but are slightly less efficient due to grain boundaries in the crystal structure that can impede the flow of electrons. These cells can be identified by their speckled blue colour and square shape.

Single-junction GaAs (Gallium Arsenide) solar cells are a type of high-efficiency photovoltaic device that utilizes the direct band gap semiconductor material Gallium Arsenide. GaAs has several properties that make it an excellent material for solar cell applications, particularly in single-junction configurations. These cells are known for their high efficiency and excellent performance in a variety of conditions, including low light and high temperatures. Due to their high cost, GaAs solar cells are not typically used for standard residential or commercial solar installations. Instead, their applications are found in areas where their high efficiency and performance characteristics outweigh cost considerations, such as space application, portable and wearable electronics.

First-generation solar cells dominate the solar energy market because of their high efficiency, reliability, and durability, with efficiencies typically ranging from about 15% to more than 25% under standard test conditions. However, they are also more material- and energy-intensive to manufacture, which has driven the development of second- and third-generation solar technologies seeking to reduce costs and material usage while maintaining or improving efficiency and sustainability **[15,16].**

Table 1: Comparison of first -generation photovoltaic cells.

Solar Cell Type	Monocrystalline Silicon (m-Si)	Polycrystalline Silicon (P-Si)	Gallium Arsenide (GaAs)
Efficiency Range	15% - 24%	10% - 18%	28% -30%
Bandgap (eV)	~1.1	~1.7	~1.43
Life Span	25 years	14 years	18 Years
Advantages	Stability, High performance, Long service life	Simple manufacturing, Decreases waste of silicon, Higher absorption compared to m-Si	High stability, Lower temperature sensitivity, Better absorption, High efficiency
Restriction	High manufacturing cost, Temperature sensitivity, Absorption problem, Material loss	Lower efficiency, Higher temperature sensitivity	Extremely expensive

2.3 Second Generation Solar cell

Second-generation solar cells, often referred to as thin-film solar cells, represent a technological advancement aimed at reducing the cost of photovoltaic (PV) production by using materials more efficiently and employing manufacturing processes that are potentially less expensive than those used for the first-generation, crystalline silicon (c-Si) solar cells. These cells are characterized by the use of thin films of photovoltaic material deposited on a substrate, significantly reducing the amount of active material used in the cell.

Table 2: Comparison of Second-generation photovoltaic cells.

Solar Cell Type	Amorphous Silicon (a-Si)	Cadmium Telluride/Cadmium Sulfide (CdTe/CdS)	Copper Indium Gallium Selenide (CIGS)
Efficiency Range	5% - 12%	15% - 16%	20%
Bandgap (eV)	~1.7	~1.45	~1.7
Life Span	15 years	20 years	12 Years
Advantages	Less expensive, Available in large quantities, Non-toxic, High absorption coefficient	High absorption rate, Less material required for production	Less material required for production
Restriction	Lower efficiency, Difficulty in selecting dopant materials, Poor minority carrier lifetime	Lower efficiency, Cd toxicity, Limited Te availability, Temperature sensitivity	High price, Instability, Temperature Sensitivity, Unreliability

- **Amorphous Silicon Solar cell:**

These are the non-crystalline form of silicon and can be deposited on substrates like glass, metal, or plastic. Amorphous silicon cells are more flexible and lighter than their crystalline counterparts but generally have lower efficiency.

- **Cadmium Telluride Solar Cells:**

CdTe solar cells offer a good balance between manufacturing cost and efficiency and are among the most commercially successful thin-film technologies. They have one of the fastest energy payback times among all solar technologies.

- **Copper Indium Gallium Selenide (CIGS) solar cells:**

CIGS cells can achieve higher efficiencies in the lab and potentially in production compared to other thin-film technologies. They are made by depositing a thin layer of copper, indium, gallium, and selenium on a substrate. The material's absorption coefficient is so high that very thin films are required to absorb sunlight effectively **[16,17].**

2.4 Third Generation Solar Cell

Third-generation solar cells represent a diverse set of photovoltaic technologies that aim to surpass the limitations of first-generation (based on crystalline silicon) and second-generation (based on thin films) solar cells. These technologies strive to achieve higher efficiencies and lower production costs, potentially enabling more widespread adoption of solar energy. The third generation includes a variety of innovative approaches, each with unique mechanisms and materials.

- **Organic Photovoltaics:**

Organic solar cells use carbon-based materials for light absorption and charge transport. These materials can be processed into thin films at low temperatures, allowing for flexible, lightweight, and potentially less expensive solar cells. However, organic photovoltaics currently suffer from lower efficiencies and shorter lifespans compared to silicon-based cells.

- **Dye Sensitized Solar Cells (DSSC):**

DSSCs mimic photosynthesis using organic dyes to absorb sunlight and convert it into electrical energy. They can be made with low-cost materials and do not require high-temperature processing. DSSCs are known for their good performance in low-light conditions and their ability to be produced in various colors and degrees of transparency, making them suitable for building-integrated photovoltaics (BIPV).

- **Perovskite Solar Cells:**

Perovskite solar cells have emerged as a highly promising technology due to their high conversion efficiencies, which have rapidly increased to rival or even surpass those of traditional silicon solar cells in a relatively short time. They are named after the perovskite structure of the light-absorbing layer, which can be synthesized with various materials. Perovskite cells can be manufactured using solution-based processes, offering the potential for low-cost production and flexible applications. However, challenges related to long-term stability and the use of lead in perovskite materials are areas of active research.

Table 3: Comparison of Third generation photovoltaic cells.

Solar Cell Type	Efficiency Range	Advantages	Restrictions
Organic and Polymeric Photovoltaic Cells	9% - 11%	Low processing cost, Lighter weight, Flexibility, Thermal stability	Low efficiency
Dye-Sensitized Photovoltaic Cells	11% - 17%	Low production cost, Low energy consumption	High toxicity, Degradation
Perovskite	21%	Low-cost, Simplified Structure, Lightweight, Flexibility, High efficiency, Low manufacturing cost	Unstable
Quantum Dots	5% - 20%	Lower production cost, Low energy consumption	High toxicity, degradation, Problems with temperature stability
Multi-Junction Solar Cells	36% and higher	High performance	Complex, Expensive

- ## Quantum Dot Solar Cells:

Quantum dot solar cells utilize nanocrystals with size-tuneable optical and electronic properties, allowing for the absorption of a wide range of the solar spectrum by adjusting the size of the quantum dots. This technology holds the promise for high efficiencies through multiple exciton generation (MEG) - a process where a single photon generates multiple charge carriers. Despite their potential, quantum dot solar cells are still in the early stages of research, with challenges to overcome in terms of efficiency and stability.

- **Multi-junction Solar Cells:**

Multi-junction (or tandem) solar cells stack several layers of materials, each designed to absorb a different segment of the solar spectrum, thereby increasing the overall efficiency of the solar cell beyond the theoretical limit of single-junction cells. While traditionally based on III-V semiconductors and used in space applications due to their high cost, research into more cost-effective materials and fabrication methods aims to make multi-junction cells viable for terrestrial applications **[18]**.

2.5. Dye Sensitized Solar Cell

The dye-sensitized solar cell is a low-cost solar cell. Michael Gratzel and Brian O'Regan devised the Gratzel cell in 1991. The first effort was made in 1970 by employing chlorophyll as a sensitizer, in which TiO_2 crystals was encapsulated by chlorophyll. However, the devices only attained 0.01% efficiency due to a lack of charge carrier separation. In 1988, Gratzel and one of his graduate students employed TiO_2 nanoparticles to generate current of the order of microampere. Further refinement resulted in current in milliamperes. Gratzel's pioneering research work was published in Nature reported 7% efficiency. Now a days, the efficiency of the DSSC has reached 10.4%.

DSSCs are limited by several problems, such as low power conversion efficiency, poor stability, less abundance and high cost of certain materials. Thus, there is a need to address these limitations by doing further improvements to make it commercially viable. Efforts to enhance the efficiency of dye-sensitized solar cells include developing novel dyes, reducing charge recombination, and enhancing nanocrystalline Titania films **[19]**.

2.5.1. Construction of DSSC

The construction of a Dye-Sensitized Solar Cell (DSSC) involves several key components layered together to form a device that can convert light into electrical energy. The primary components include a photoanode (dye-sensitized semiconductor), an electrolyte with a redox mediator, and a counter electrode. Here is a step-by-step overview of the construction of a DSSC:

1) Transparent Conductive substrate:

Dye-sensitized solar cells (DSSCs) are commonly constructed using transparent and conductive substrates to provide a sturdy base for the semiconducting oxide. It's crucial that these substrates are transparent to allow efficient sunlight passage to the dye-sensitized semiconducting oxide layer. Additionally, a high level of electrical conductivity in the substrate is desirable to facilitate efficient charge transfer Typically, fluorine tin oxide (FTO, SnO_2:F) or indium tin oxide (ITO, In_2O_3:Sn) coated soda lime glass plates serve as substrates in DSSCs. ITO glass plates generally boast approximately 80% transmittance with a sheet resistance of 18 Ω/cm^2, while FTO glass plates typically exhibit around 75% transmittance and have a sheet resistance of 8.5Ω/cm^2 **[20].**

2) Semiconducting layer (Photoanode)

TiO_2 is preferred for its. Dye-sensitized solar cells (DSSCs) commonly utilize semiconducting metal oxides with wide band gaps ranging from 3 to 3.8eV, notably including TiO_2, ZnO, SnO_2, and Nb_2O_5. Among these options, TiO_2 nanoparticles stand out as the optimal choice due to their non-toxic nature, affordability, widespread availability, suitable band gap, stability and ability to scatter light. Thanks to their porous structure, TiO_2 nanoparticles offer a large surface area, facilitating strong attachment of dye molecules onto the TiO_2 surface **[21].**

3) Dye Sensitizer

Dyes or sensitizers play a crucial role in harvesting light and thus determining the photoelectric conversion efficiency of solar cells. An ideal sensitizer should possess the ability to absorb a broad spectrum of solar light, tightly adhere to the surface of semiconductor oxides, and effectively inject photoexcited electrons into the semiconductor's conduction band Additionally, it's essential for the dye to have a high redox potential to enable swift regeneration through electron donation from the electrolyte. The dye molecule should demonstrate thermal stability and durability **[22].**

4) Electrolyte with Redox Mediator:

The electrolyte or redox mediator plays a crucial role in supplying electrons to the dye molecules in a Dye-Sensitized Solar Cell (DSSC). As the dye molecule injects electrons into the conduction band of the metal oxide semiconductor, it undergoes oxidation. To return to its normal reduced form, the dye molecule accepts electrons from the redox mediator. Therefore, the stability and efficiency of the electrolyte greatly influence the lifetime of the DSSC. For optimal performance, the electrolyte should exhibit high electrical conductivity and establish good contact with both the dye-sensitized metal oxide semiconductor (anode) and the counter electrode (cathode). Liquid electrolytes containing iodide/tri-iodide (I^-/I_3^-) redox couple have demonstrated significant success. However, recent advancements have sparked interest in alternative electrolytes, such as cobalt-based formulations, quasi-solid-state, and solid-state electrolytes with enhanced stability over extended periods **[22,23]**.

5) Counter Electrode:

A conductive layer, often Platinum or Carbon, is deposited on another TCO substrate. Platinum acts as an excellent catalyst for the reduction of the redox mediator. It collects electrons from the external circuit and catalyses the reduction of the redox mediator in the electrolyte, completing the electrical circuit **[24]**.

2.5.2. Mechanism and Working Principle of DSSC

Dye-sensitized solar cells (DSSCs) are a type of photovoltaic device that mimics photosynthesis in green plants. They convert light energy into electrical energy using a process that involves multiple components including a photo sensitizer (dye), a semiconductor (usually Titanium Dioxide, TiO_2), an electrolyte and a counter electrode. Here is a step-by-step mechanism of how DSSCs work:

1) Light Absorption

The process begins when the dye molecule absorbs sunlight. The dye is usually a complex organic molecule or a metal-organic compound that is designed to efficiently absorb visible light. Upon absorption of light, the electron from dye molecule is excited from its ground state to an excited state.

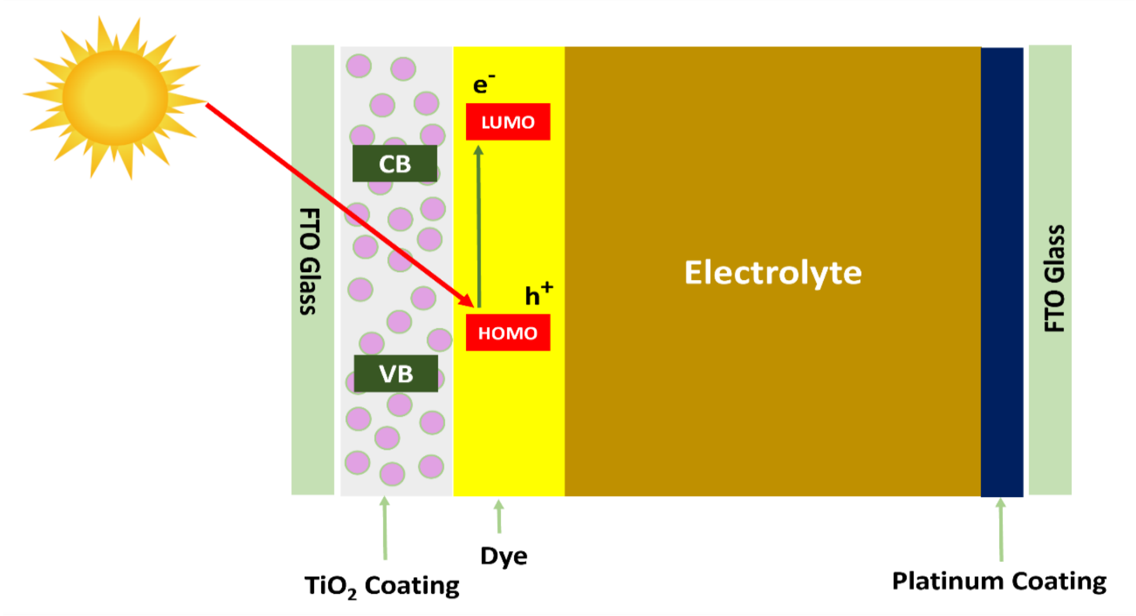

Figure 1. Absorption of light in dye molecules and excitation of electrons.

2) Electron Injection

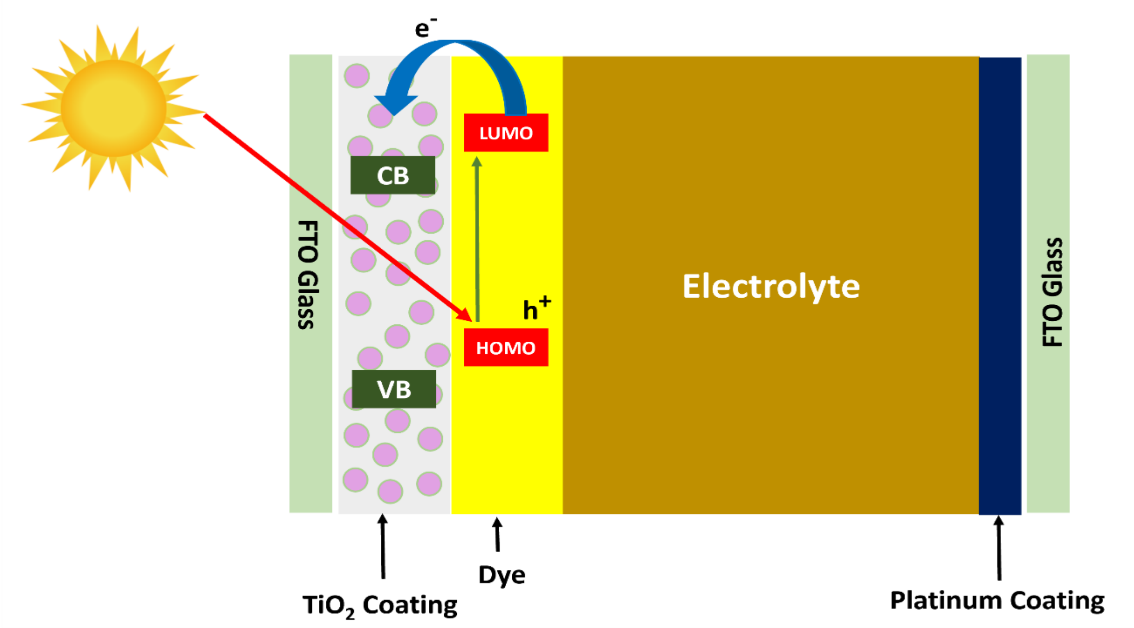

Figure 2. Electron injection form dye TiO_2.

In the excited state, the dye molecule injects an electron into the conduction band of the semiconductor (TiO_2) very quickly (typically within femtoseconds to picoseconds). The semiconductor layer is porous, offering a large surface area for dye molecules to adhere to, which enhances the light absorption and electron injection processes. The injected electron travels through the semiconductor layer towards the front contact, which is usually made of a transparent conducting oxide (like Fluorine doped Tin Oxide, FTO) on glass. This movement creates an electric current that can be harnessed for power.

3) Dye regeneration:

After the electron is injected into the TiO_2, the dye molecule is left in an oxidized state. To return to its ground state and continue the cycle, the dye molecule must be regenerated by accepting an electron from the electrolyte. The electrolyte contains a redox couple (commonly iodide/tri-iodide, I^-/I_3^-), which donates an electron to the oxidized dye.

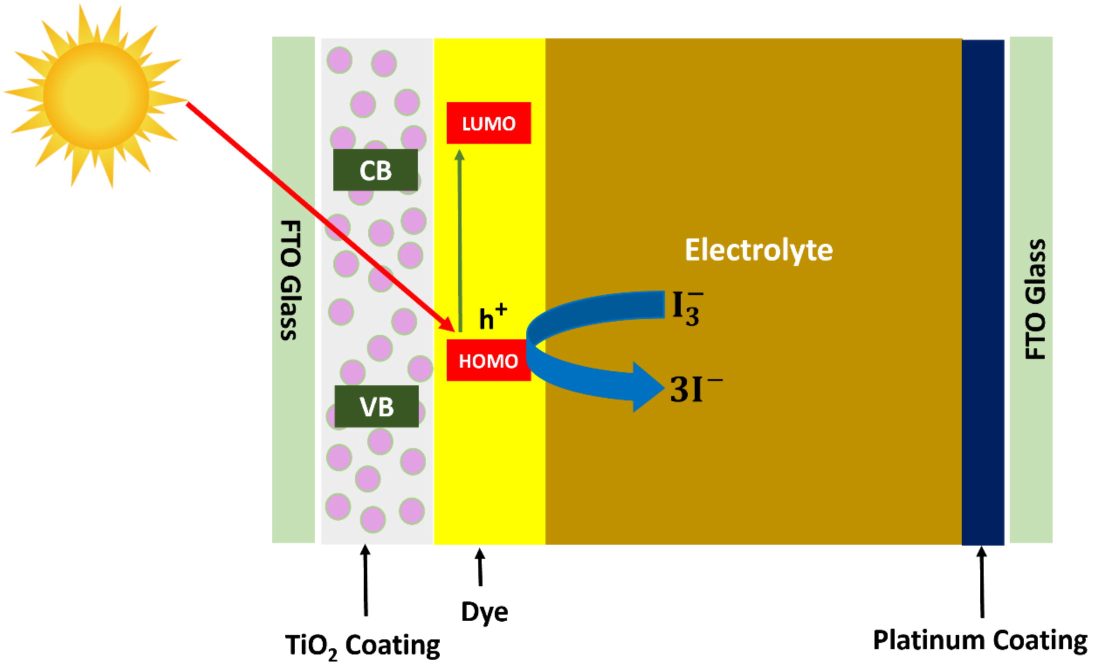

Figure 3. Dye regeneration from electron transfer from electrolyte.

4) Electrolyte regeneration:

The electron that is donated to the dye molecule leaves a positive charge in the electrolyte. This positive charge moves towards the counter electrode (usually platinum or carbon-based materials), completing the electrical circuit. At the counter electrode, the electrolyte is regenerated when the positive charge in the electrolyte (tri-iodide ion, I_3^-) receives an electron from the counter electrode. This step restores the electrolyte to its original state, allowing it to continue the cycle of electron donation to the oxidized dye molecules.

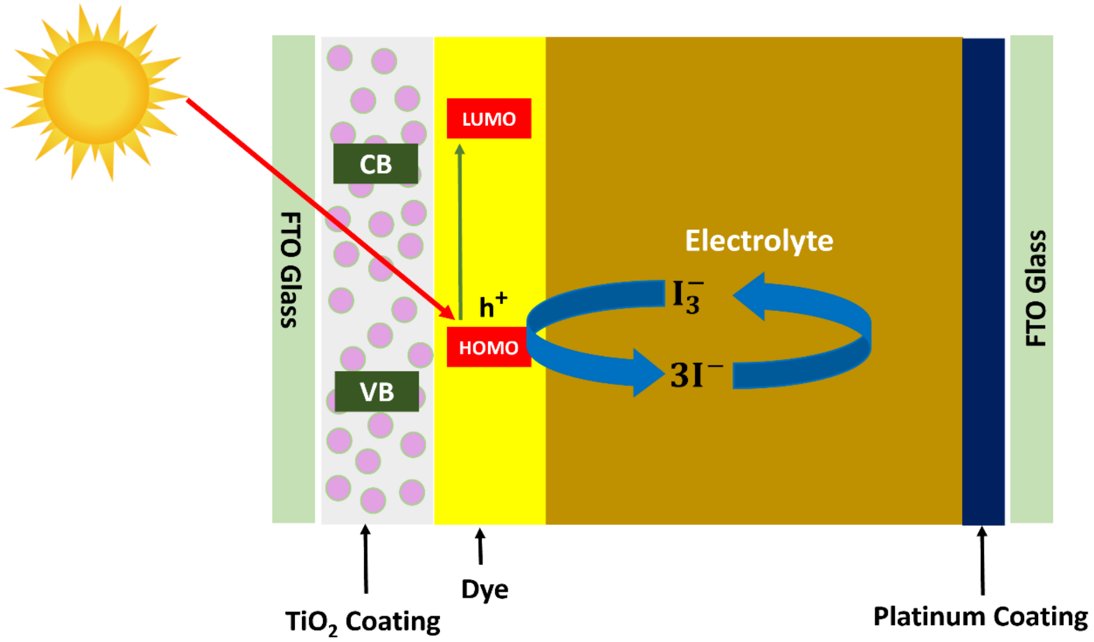

Figure 4. Electrolyte regeneration by movement of positive charge toward counter electrode.

5) Electron Flow in Circuit:

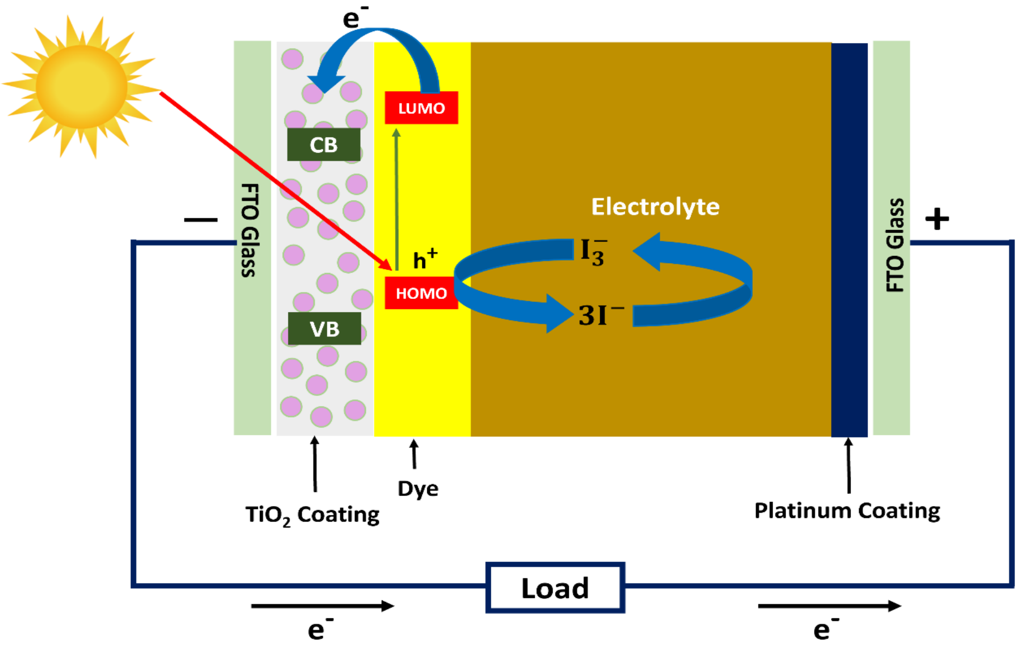

Figure 5. Flow of electrons in the solar cell module circuit.

The flow of electrons through the external circuit from the semiconductor to the counter electrode can be harnessed to do electrical work, such as powering a device or charging a battery.

2.6. Recombination Process in DSSC

In Dye-Sensitized Solar Cells (DSSCs), recombination refers to the process where the electrons that have been injected into the conduction band of the semiconductor (typically Titanium Dioxide, TiO_2) find their way back to the oxidized species (either the dye or the redox mediator in the electrolyte), thereby leading to loss of conduction electrons and reducing the efficiency of the solar cell. Understanding these different recombination mechanisms is crucial for improving DSSC performance.

Semiconductor oxides are materials characterized by the presence of conduction and valence bands. The conduction band accommodates free electrons, while the valence band holds holes **[25]**. The behaviour of these bands is pivotal in understanding the generation and recombination processes occurring within semiconductor oxides **[26]**.

Generation and recombination events unfold as electrons transition between the valence and conduction bands. A hole is essentially a vacancy formed by the absence of an electron within the valence band **[27, 28]**. Carrier recombination arises when a free electron recombines with a hole, effectively neutralizing both entities **[29, 30]**.

A recombination reaction in a semiconductor material is defined as when the electrons in the conduction band fall into holes in the valance band. Then, free electrons and holes disappear or are eliminated **[31-34]**.

These principles also apply to Dye-Sensitized Solar Cells (DSSCs), wherein the efficient operation hinges on minimizing recombination. However, in the context of DSSCs, the recombination of electrons is deemed undesirable. This is because the recombination process diminishes the photocurrent and photovoltage, thereby compromising the device's power conversion efficiency. Efforts in DSSC research focus on mitigating recombination effects to enhance overall performance and efficiency **[35-37]**.

Paths of Recombination:

In a Dye-Sensitized Solar Cell (DSSC), numerous interfaces present for charge recombination to occur. When photons interact with the dye (D/D*), it becomes excited, transitioning from its ground state to an excited state **[38]**. Subsequently, electrons are expected to traverse the semiconductor oxide via the electrolyte. However, prior to the electrons entering the semiconductor oxide, they often revert to the dye's ground state and recombine with a hole **[39, 40]**, as depicted in route 1 **[38]**. This process takes place at the dye/electrolyte/semiconductor oxide interface **[39, 40]**.

Alternatively, in route 2, electrons may successfully traverse the semiconductor oxide and migrate into the Transparent Conductive Oxide (TCO). Nevertheless, due to the substantial thickness of the semiconductor material layer (mesoporous layer), electrons can recombine with the electrolyte solution **[26, 41]**. This recombination process transpires at the interfaces between the semiconductor oxide and the electrolyte. Route 3 happens when the electrons from the semiconductor oxide recombines with the oxidised dye.

Figure below illustrates the charge recombination process and electron movements within the DSSC **[26, 39-41]**. These pathways highlight the complexity of charge transfer mechanisms and the critical role interfaces play in determining the efficiency of DSSC devices.

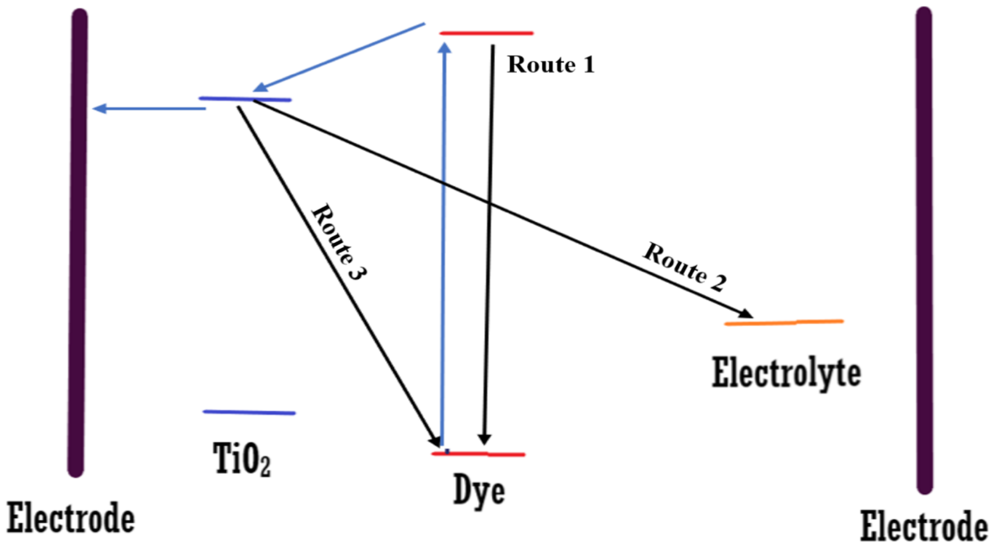

Figure 6. Difference charge recombination processes.

2.6.1. Function of the Recombination Barrier Layer:

In Dye-Sensitized Solar Cells (DSSCs), the recombination of electrons with oxidized species (either in the electrolyte or the dye itself) is a major factor that limits the efficiency of the cell. A recombination barrier layer plays a critical role in mitigating this loss mechanism, thereby enhancing the performance and efficiency of DSSCs. Here's a detailed look at its role:

1) Minimizing electron Recombination:

The primary role of the recombination barrier layer is to minimize the recombination of photo-excited electrons (from the semiconductor's conduction band) with the oxidized dye molecules or the redox species in the electrolyte.

2) Facilitating electron Transport:

While its main function is to act as a barrier to recombination, the layer must also allow for the efficient transport of electrons from the semiconductor to the electrode. This requires careful selection and engineering of materials to ensure they possess the right properties for electron conduction without facilitating recombination.

3) Increased Open Circuit Voltage (V_{OC}):

By reducing recombination, the barrier layer can help maintain a higher potential difference between the photoanode and the cathode, leading to an increased open-circuit voltage.

4) Enhanced Photocurrent (Jsc):

Effective recombination suppression means that more electrons are available to be collected at the anode, increasing the photocurrent.

5) Improved Stability:

By reducing the direct interaction between the semiconductor and the electrolyte, the barrier layer can also help to improve the stability and durability of the DSSC.

2.6.2. Properties of Barrier Layer and challenges.

- **Energy Band Alignment:**

The effectiveness of the barrier layer is significantly influenced by the alignment of its energy bands with those of the semiconductor. The conduction band of the barrier material should be closely aligned with that of the semiconductor (e.g., TiO_2) to ensure seamless electron transfer. Ideally, the barrier layer's conduction band edge should be slightly higher than that of the TiO_2 to facilitate electron flow towards the anode while minimizing the probability of electrons from moving back towards the electrolyte.

- **Electron Conductivity:**

While the primary role of the barrier layer is to prevent recombination, it should still allow for the efficient transport of electrons. Therefore, materials with moderate to high electron mobility are preferred, ensuring that the layer does not become a bottleneck for electron transport from the semiconductor to the electrode.

- **Chemical Stability and Inertness:**

The material should be chemically stable and inert in the DSSC environment. It should not react with the electrolyte and show uniform properties within the operational temperature range. This stability is crucial for the longevity and durability of the solar cell. (justification for chemical stability)

- **Optical transparency:**

Since the barrier layer is situated between the light-absorbing dye and the electrode, it should be optically transparent in the relevant wavelength range to allow the incident light to reach the dye without significant attenuation.

- **Controlled thickness:**

The ability to control the thickness of the layer with precision during deposition is crucial. The layer needs to be thick enough to effectively prevent recombination but thin enough to not hinder electron transport significantly. Typically, a thickness of few nanometers to tens of nanometers has been found to be effective.

- **Strategic placement:**

The recombination barrier layer is typically inserted between the semiconductor layer (e.g., TiO_2) and the electrolyte or between the semiconductor layer and the conductive substrate. Its placement is strategic to ensure it effectively intercepts the pathway of electrons that might otherwise recombine with oxidized species.

2.6.3. Challenges to the incorporation of barrier layer:

Incorporating a recombination barrier layer into Dye-Sensitized Solar Cells (DSSCs) presents several challenges that stem from material properties and fabrication processes. Addressing these challenges is crucial for enhancing the efficiency and stability of DSSCs without significantly increasing their cost or complexity. Here are some of the key challenges associated with incorporating a barrier layer:

- **Layer thickness and Uniformity:**

Achieving the optimal thickness that is thick enough to effectively prevent recombination but thin enough to allow for efficient electron transport is challenging. Non-uniform thickness can lead to areas of increased recombination or hindered electron transport.

Fabricating uniform layers over the rough surfaces of porous semiconductor layers (e.g., TiO_2) can be technically difficult, requiring precise control over deposition techniques.

- **Fabrication and Integration:**

The process for depositing the barrier layer must be compatible with the rest of the DSSC fabrication process, without degrading the performance of other components. The deposition process should be cost-effective and scalable for commercial production. Techniques that require high temperatures, vacuum conditions, or expensive equipment may not be practical.

- **Impact on electron transport:**

While the primary role of the barrier layer is to prevent recombination, it should not significantly impede the mobility or diffusion length of electrons within the semiconductor layer. Finding materials and thicknesses that strike this balance is non-trivial.

- **Optical Properties:**

The barrier layer must be optically transparent to avoid absorbing or scattering light that should reach the dye-sensitized semiconductor layer. Any significant light attenuation can reduce the cell's efficiency.

- **Interface quality:**

The quality of the interface between the barrier layer and both the semiconductor and the electrolyte is critical. Defects, gaps, or poor adhesion can introduce new recombination sites or impede electron transport.

Reference

1. Saleh, H. M. (2024). The challenges of sustainable energy transition: A focus on renewable energy. *Applied Chemical Engineering, 7*(2), 2084.
2. Wilson, G. M., Al-Jassim, M., Metzger, W. K., Glunz, S. W., Verlinden, P., Xiong, G., ... & Sulas-Kern, D. B. (2020). The 2020 photovoltaic technologies roadmap. *Journal of Physics D: Applied Physics, 53*(49), 493001.
3. Lin, R., & Ren, J. (2020). Renewable energy and sustainable development. *Renewable Energy and Sustainable Development, 6*(1), 3.
4. Singh, B. P., Goyal, S. K., & Kumar, P. (2021). Solar PV cell materials and technologies: Analyzing the recent developments. *Materials Today: Proceedings, 43*, 2843-2849.
5. Kabir, E., Kumar, P., Kumar, S., Adelodun, A. A. A., & Kim, K.-H. (2018). Solar energy: Potential and future prospects. *Renewable and Sustainable Energy Reviews, 82*, 894-900.
6. Muhammad, J. Y. U., Waziri, A. B., Shitu, A. M., Ahmad, U. M., Muhammad, M. H., Alhaji, Y., ... & Bala, A. A. (2019). Recent progressive status of materials for solar photovoltaic cell: A comprehensive review. *Science Journal of Energy Engineering, 7*(4), 77-89.
7. Zamostny, D. (2013). Solar history: Alexandre Edmond Becquerel.
8. Desideri, U., & Asdrubali, F. (Eds.). (2018). *Handbook of energy efficiency in buildings: A life cycle approach*. Butterworth-Heinemann.
9. Węgierek, P., & Billewicz, P. (2011). Jump mechanism of electric conduction in n-type silicon implanted with Ne^++ neon ions. *Acta Physica Polonica A, 120*(1), 122-124.
10. Hayat, M. B., Ali, D., Monyake, K. C., Alagha, L., & Ahmed, N. (2019). Solar energy—A look into power generation, challenges, and a solar-powered future. *International Journal of Energy Research, 43*(3), 1049-1067.
11. Tsakalakos, L. (2010). *Nanotechnology for photovoltaics*. CRC Press.
12. Almosni, S., Delamarre, A., Jehl, Z., Suchet, D., Cojocaru, L., Giteau, M., ... & Guillemoles, J. F. (2018). Material challenges for solar cells in the twenty-first century: Directions in emerging technologies. *Science and Technology of Advanced Materials, 19*(1), 336-369.

13. Pastuszak, J., & Węgierek, P. (2022). Photovoltaic cell generations and current research directions for their development. *Materials, 15*(16), 5542.
14. Rajkumar, S., Kumar, M. N., Suguna, K., Muthulakshmi, S., & Kumar, R. A. (2019). Enhanced performance of dye-sensitized solar cells using natural cocktail dye as sensitizer. *Optik, 178*, 224-230.
15. Richter, A., Hermle, M., & Glunz, S. W. (2013). Reassessment of the limiting efficiency for crystalline silicon solar cells. *IEEE Journal of Photovoltaics, 3*(4), 1184-1191.
16. Sharma, P., & Goyal, P. (2020). Evolution of PV technology from conventional to nano-materials. *Materials Today: Proceedings, 28*, 1593-1597.
17. Kuczyńska-Łażewska, A., Klugmann-Radziemska, E., & Witkowska, A. (2021). Recovery of valuable materials and methods for their management when recycling thin-film CdTe photovoltaic modules. *Materials, 14*(24), 7836.
18. Dunlap-Shohl, W. A., Zhou, Y., Padture, N. P., & Mitzi, D. B. (2018). Synthetic approaches for halide perovskite thin films. *Chemical Reviews, 119*(5), 3193-3295.
19. Ngamsinlapasathian, S., Sakulkhaemaruethai, S., Pavasupree, S., Kitiyanan, A., Sreethawong, T., Suzuki, Y., & Yoshikawa, S. (2004). Highly efficient dye-sensitized solar cell using nanocrystalline titania containing nanotube structure. *Journal of Photochemistry and Photobiology A: Chemistry, 164*(1-3), 145-151.
20. Sima, C. (2010). Constantin. Grigoriu, S. Antohe. *Thin Solid Films, 519*, 595.
21. Agrawal, A., Siddiqui, S. A., Soni, A., & Sharma, G. D. (2022). Advancements, frontiers and analysis of metal oxide semiconductor, dye, electrolyte and counter electrode of dye sensitized solar cell. *Solar Energy, 233*, 378-407.
22. Sharma, K., Sharma, V., & Sharma, S. S. (2018). Dye-sensitized solar cells: Fundamentals and current status. *Nanoscale Research Letters, 13*, 1-46.
23. Wu, J., Lan, Z., Lin, J., Huang, M., Huang, Y., Fan, L., & Luo, G. (2015). Electrolytes in dye-sensitized solar cells. *Chemical Reviews, 115*(5), 2136-2173.
24. Hegde, V., Sreekala, C. O., Kulkarni, N. V., Senthurpandi, D., & Mathew, J. (2022). Synthesis and characterization of a series of cobalt complexes: Investigation of their efficacy as sensitizers in dye-sensitized solar cell applications. *Journal of Molecular Structure, 1266*, 133512.
25. Brown, G. F., & Wu, J. (2009). Third generation photovoltaics. *Laser & Photonics Reviews, 3*(4), 394-405.

26. Zaine, S. N. A., Mohamed, N. M., Khatani, M., Samsudin, A. E., & Shahid, M. U. (2020). Trap state and charge recombination in nanocrystalline passivized conductive and photoelectrode interface of dye-sensitized solar cell. *Coatings, 10*(3), 284.
27. Sharma, K., Sharma, V., & Sharma, S. S. (2018). Dye-sensitized solar cells: Fundamentals and current status. *Nanoscale Research Letters, 13*, 1-46.
28. Kumara, N. T. R. N., Lim, A., Lim, C. M., Petra, M. I., & Ekanayake, P. (2017). Recent progress and utilization of natural pigments in dye sensitized solar cells: A review. *Renewable and Sustainable Energy Reviews, 78*, 301-317.
29. Anta, J. A., Guillén, E., & Tena-Zaera, R. (2012). ZnO-based dye-sensitized solar cells. *The Journal of Physical Chemistry C, 116*(21), 11413-11425.
30. Berginc, M. U. O. K., Krašovec, U. O., Jankovec, M., & Topič, M. (2007). The effect of temperature on the performance of dye-sensitized solar cells based on a propyl-methyl-imidazolium iodide electrolyte. *Solar Energy Materials and Solar Cells, 91*(9), 821-828.
31. Dennyson Savariraj, A., & Mangalaraja, R. V. V. (2019). Interfacial engineering and functional materials for dye-sensitized solar cells. *Dye and Solar Cells* (pp. 17-33).
32. Yeoh, M. E., & Chan, K. Y. (2017). Recent advances in photo-anode for dye-sensitized solar cells: A review. *International Journal of Energy Research, 41*(15), 2446-2467.
33. Wu, J., Tang, Z., Huang, Y., Huang, M., Yu, H., & Lin, J. (2014). A dye-sensitized solar cell based on platinum nanotube counter electrode with efficiency of 9.05%. *Journal of Power Sources, 257*, 84-89.
34. Balraju, P., Suresh, P., Kumar, M., Roy, M. S., & Sharma, G. D. (2009). Effect of counter electrode, thickness and sintering temperature of TiO2 electrode and TBP addition in electrolyte on photovoltaic performance of dye sensitized solar cell using pyronine G (PYR) dye. *Journal of Photochemistry and Photobiology A: Chemistry, 206*(1), 53-63.
35. Kumar, D. K., Kříž, J., Bennett, N., Chen, B., Upadhayaya, H., Reddy, K. R., & Sadhu, V. (2020). Functionalized metal oxide nanoparticles for efficient dye-sensitized solar cells (DSSCs): A review. *Materials Science for Energy Technologies, 3*, 472-481.

36. Prabavathy, N., Shalini, S., Balasundaraprabhu, R., Velauthapillai, D., Prasanna, S., & Muthukumarasamy, N. (2017). Enhancement in the photostability of natural dyes for dye-sensitized solar cell (DSSC) applications: A review. *International Journal of Energy Research, 41*(10), 1372-1396.
37. Brown, G. F., & Wu, J. (2009). Third generation photovoltaics. *Laser & Photonics Reviews, 3*(4), 394-405.
38. Minda, I. (2014). Photoinduced charge dynamics in indoline-dye sensitised solar cells (Doctoral dissertation).
39. Sharmoukh, W., Al Kiey, S. A., Ali, B. A., Menon, L., & Allam, N. K. (2020). Recent progress in the development of hole-transport materials to boost the power conversion efficiency of perovskite solar cells. *Sustainable Materials and Technologies, 26*, e00210.
40. Sasidharan, S., Soman, S., Pradhan, S. C., Unni, K. N., Mohamed, A. A. P., Nair, B. N., & Saraswathy, H. U. N. (2017). Fine tuning of compact ZnO blocking layers for enhanced photovoltaic performance in ZnO based DSSCs: A detailed insight using β recombination, EIS, OCVD and IMVS techniques. *New Journal of Chemistry, 41*(3), 1007-1016.
41. Das, A., Wary, R. R., & Nair, R. G. (2020). Cu modified ZnO nanoflakes: An efficient visible light-driven photocatalyst and a promising photoanode for dye sensitized solar cell (DSSC). *Solid State Sciences, 104*, 106290