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Solar Cell and its Types- A Review

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Abstract

This paper aims to explore the various evolutionary stages of photovoltaic cells and contemporary research directions that emphasize advancements in their development and manufacturing techniques. The introduction underscores the significance of photovoltaics in the context of environmental preservation and the reduction of reliance on fossil fuels. It subsequently delves into presenting the established generations of photovoltaic cells, primarily focusing on their potential for solar-to-electric conversion efficiencies and the manufacturing technologies associated with them. Specifically, the paper examines the third generation of photovoltaic cells and recent trends within this domain, including multi-junction cells and cells featuring intermediate energy levels within the silicon bandgap. Furthermore, the document highlights the latest breakthroughs in photovoltaic cell manufacturing technology, using fourth-generation graphene-based photovoltaic cells as a prime example. An extensive review of global literature leads to the conclusion that, despite the emergence of newer photovoltaic cell types, silicon-based cells still maintain the largest market share, underscoring the ongoing relevance of research aimed at enhancing their efficiency.

Keywords: photovoltaic solar cells, types, renewable energy, efficiency

1. Introduction

Solar energy refers to the enormous amount of heat and radiation that the sun emits every day. Solar energy is a limitless, cost-free source of energy [1,2]. The primary advantage of solar energy over other traditional power sources is the direct conversion of sunlight into energy through the use of microscopic photovoltaic (PV) solar cells [3,4]. The Sun is the spherical cloud of gaseous atoms composed of hydrogen and helium. This is primarily made of numerous hydrogen nuclei (*H*) that combine together to produce helium (*He*) atoms when energy is released from the nuclear fusion of hydrogen nuclei in the Sun's inner core.

$$^{2}_{1}H + \, ^{2}_{1}H \rightarrow \, ^{3}_{2}He + \, ^{1}_{0}n + 3.27\ MeV$$

$$^{2}_{1}H + \, ^{3}_{1}H \rightarrow \, ^{4}_{2}He + \, ^{1}_{0}n + 17.59\ MeV$$

Four hydrogen atoms fuse together to form one helium atom during this process of fusion, resulting in a mass loss that is radiated as thermal energy [1,4,5]. There are no pollutants, gases, or other reaction

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byproducts present in the radiant energy generated by fusion reactions. As a result, the climate disruption brought on by the release of carbon from fossil fuel reserves, it is the primary driving force behind all renewable energy technology. When compared to the cost of various fossil fuels and oils during the previous decade [1-7]. One of the main advantages of solar energy is that it is free, widely accessible, and available in abundance. Moreover, compared to traditional energy production technology, solar energy requires fewer human costs.

Even though solar energy is freely available everywhere, manufacturing solar cells, panels, and modules requires an initial investment in equipment [8]. These tiny solar cells operate without making any noise. On the other hand, large power pumping apparatuses emit intolerable noise pollution, which makes them exceedingly upsetting to society [6-8]. Due to the depletion of non-renewable energy sources rapidly during the past 10 years, the per Watt cost of solar energy devices has acquired relevance. In the years to come, solar energy devices will undoubtedly become more affordable and advance as a superior technology in terms of both price and applications [9, 10].

A solar cell, also known as a photovoltaic cell, is an electronic device that uses the physical phenomena known as the *photovoltaic effect* to convert light energy directly into electricity. A device whose electrical properties, such as current, voltage, or resistance, change when exposed to light is a type of photoelectric cell. The electrical building blocks of photovoltaic modules, also referred to as solar panels, are frequently individual sun cell devices. The greatest open-circuit voltage produced by a typical silicon single-junction solar cell ranges between 0.5 and 0.6 volts [2]. The vast majority of solar cells are made of silicon (Si), which is available in a variety of forms, from amorphous (non-crystalline) through polycrystalline to crystalline (single crystal), with increasing efficiency and decreasing cost. Solar cells don't use chemical reactions or require fuel to generate electricity, unlike batteries or fuel cells, and they don't have any moving parts as generators do. Arrays, which are big collections of solar cells, are possible. These arrays, made up of thousands of individual cells, can serve as central electric power plants, converting solar energy into electrical energy and distributing it to consumers in the industrial, commercial, and residential sectors. Homeowners have put solar panels on their rooftops to supplement or replace their traditional energy supply with solar cells in much smaller designs, often known as solar cell panels or just solar panels. In many isolated areas of the earth, where installing conventional power sources would be either impossible or excessively expensive, electric power is also provided by solar cell panels. Most space facilities, from communications and weather satellites to space stations, are powered by solar cells since they don't have any moving parts that might need maintenance or fuels that might need to be refilled. However, because radiant energy diffuses with distance from the Sun, solar power is insufficient for space probes deployed to the outer planets of the solar system or into interstellar space. Consumer devices including electrical toys, pocket calculators, and portable radios have all utilised solar cells.

A photovoltaic (PV) cell can either reflect, absorb, or pass through light that strikes it. The PV cell is made of a semiconductor substance; the term “semi” denotes that the material can conduct electricity better than an insulator but not as well as a metal, which is a good conductor. In PV cells, a variety of semiconductor materials are employed. When a semiconductor is exposed to light, the light's energy is absorbed and transferred to the semiconductor's negatively charged electrons. The additional energy enables the electrons to conduct an electrical current through the material. This current can be used to power your home and the rest of the electric grid by extracting it through conductive metal contacts, which are the grid-like lines on solar cells.

A PV cell's efficiency can be calculated as the ratio of the electrical power it produces to the energy from the light shining on it. This ratio shows how well the cell converts energy from one form to another. The qualities of the available light (such as its intensity and wavelengths) and several cell performance factors determine how much energy is generated by PV cells. The bandgap, which describes what wavelengths of light the substance can absorb and convert to electrical energy, is a crucial characteristic of PV semiconductors. The PV cell can effectively use all of the available energy if the semiconductor's bandgap matches the wavelengths of light shining on it.

2. The Photo-Voltaic Effect

In 1839, *Edmond Becquerel* made the initial discovery of the photovoltaic effect (Figure 1). He discovered when working with wet cells that the voltage rose when the cell's silver plates were exposed to sunlight.

Numerous scientists have since tried to create electricity producing methods based on this effect. When the PV effect in selenium was researched in 1870, the findings showed that solid selenium had a power efficiency of only 1%–2%, much below the required level for potential energy converters. High purity crystalline silicon was created in 1950, and in 1954 Bell Labs (its current name is Nokia Bell Labs originally named Bell Telephone Laboratories (1925–1984), a hub of American Nobel laureates) created a silicon photovoltaic cell with a conversion efficiency of 4%. Later, this efficiency was increased to 11%. At this time, a new era of solar energy production was ushered in by the PV effect [11, 12].

In solar cells, the photovoltaic effect takes place. These solar cells are made of a p-n junction, which is formed by joining two different types of semiconductors, a p-type and an n-type. When these two varieties of semiconductors are combined, an electric field is created in the junction area as electrons and holes migrate from the negative n-side to the positive p-side and vice versa respectively. Positively charged particles flow in one direction while negatively charged particles move in the opposite way due to this field. Electrons in semiconducting materials are immobile when not energised because they establish connections with the atoms around them that keep the material together. These electrons can flow freely through the material when they are in an excited state in the conduction band. Photons, which are just tiny bundles of electromagnetic radiation or energy, are the building blocks of light. A photovoltaic cell, which makes up solar panels, can absorb these photons. An atom of the semiconducting material in the p-n junction (Figure 2) receives energy from the photon when light with the right wavelength strikes these cells. The energy is specifically transmitted to the material's electrons (*Einstein's* Photoelectric Effect, 1905). The result is a jump in the electrons' energy to a state known as the conduction band. The valence band where the electron jumped up from has a “hole” left behind as a result. These cells are expected to have a band gap between valence and conduction in between 1.1 and 1.7 eV for improving the efficiency. An electron-hole pair is formed when the electron moves because of the extra energy. Electrons and holes migrate as expected in the opposite direction due to the electric field created by the p-n junction. The liberated electron tends to migrate to the n-side rather than being drawn to the p-side. An electric current is produced in the cell by this movement of the electron. This hole can likewise move, but it does so in the p-side's opposite direction. This mechanism causes a current to flow through the cell.

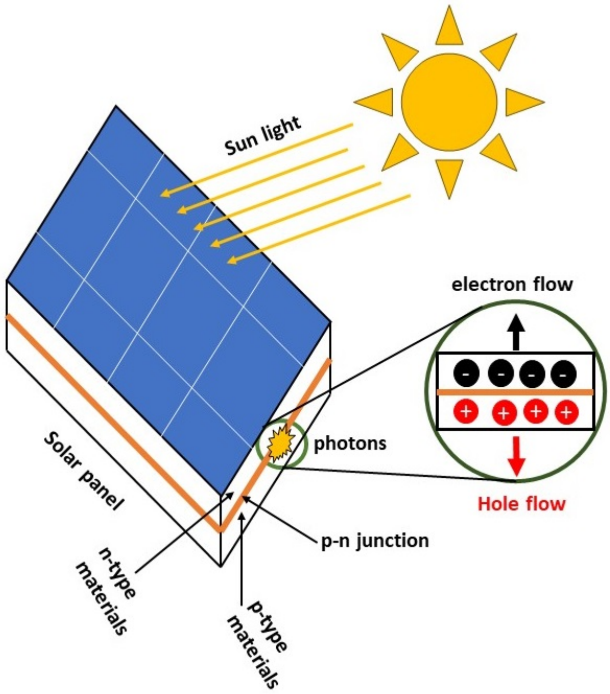

Figure 1: Diagram showing the Photo-Voltaic Effect

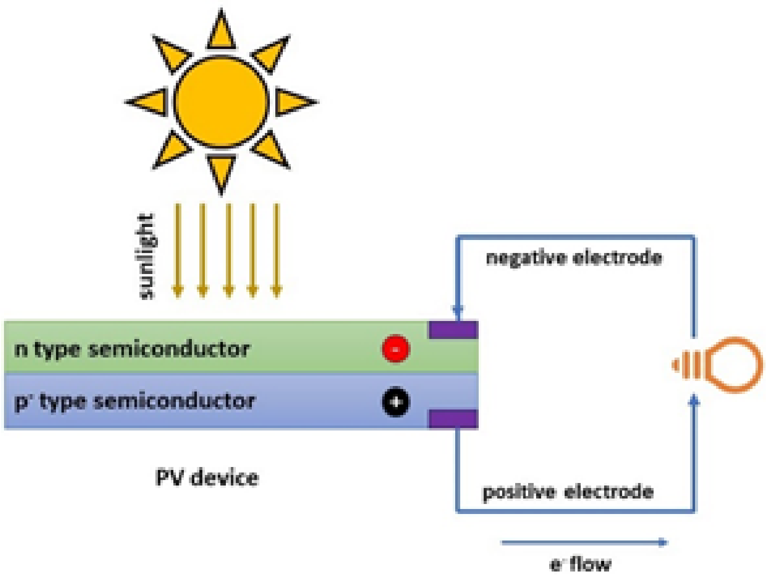

Figure 2: Schematic representation of a solar cell circuit

3. Recent Developments in Solar Cell Technology

Due to its sustainability and lack of environmental impact, society prioritises the development and use of solar energy. One of its most recent uses is to enhance thermal comfort inside buildings as a component of green architecture. A novel glass system that meets building lighting and thermal insulation requirements has surfaced. It comprises of a glazed framework that can capture solar energy.4 Phase change material (PCM) filling in glazed envelopes has recently been put forward as an exciting innovative solution for solar energy storage devices 5-8 because this technique allows for the absorption of part of solar energy in the form of latent heat in the glazing unit during the day and the release of it to the indoor environment during the evening through phase change. This ultimately enables reduction of energy consumption of buildings and the requirement of indoor thermal comfort.

4. Types of Solar Cells:

- **First generation Solar Cells (Wafer Based Silicon Cells)**

Solar cells of the first generation are mainly manufactured on silicon wafers. The initial generation of photovoltaic cells comprises materials constructed from thick crystalline layers primarily composed of silicon (Si). Due to its excellent power efficiency, it is the oldest and most widely used technology. These cells are capable of generation of energy for different wavelengths. This generation relies on monocrystalline (a), polycrystalline/multicrystalline (b) silicon and as well as Gallium Arsenide (GaAs) cells (c).

(a) Single/Mono-Crystalline Silicon Solar Cell (m-Si)

The *Czochralski* technique [13-15] is used to produce silicon single crystals into monocrystalline solar cells, as the name implies. The large-sized ingots are cut into Si crystals during the manufacturing process. Since “recrystallizing” the cell involves more steps and is more expensive, these big single crystal manufacturing require careful processing. Mono-crystalline solar cells made of single-crystalline silicon have an efficiency of 17% to 18%, Band gap: ~1.1 eV; Life span: 25 years.

(b) Polycrystalline Silicon Solar Cell (Poly-Si or Mc-Si)

In a single cell, polycrystalline PV modules often consist of several distinct crystals that are connected to one another. Polycrystalline silicon solar cells, which are made by chilling a graphite mould filled with molten silicon, can be processed more cheaply. Various crystal forms are created as the liquid silicon solidifies. They are less efficient than monocrystalline silicon solar panels. Efficiency is around 12% to 14%; Band gap: ~1.7 eV; Life span: 14 years, but being slightly cheaper to manufacture [16,17].

(c) Solar cells based on GaAs

Gallium arsenide (GaAs) possesses several advantages over silicon: it exhibits a significantly higher electron mobility, enabling faster performance; it features a wider bandgap, which allows power devices to operate at elevated temperatures while reducing thermal noise in low-power devices at room temperature; and its direct bandgap provides more favourable optoelectronic characteristics compared to silicon's indirect bandgap. Efficiency is around 28 - 30%; Band gap: ~1.43 eV; Life span: 18 years [17]. The primary disadvantage is its cost-effectiveness.

■ Second Generation Solar Cells—Thin Film Solar Cells

The majority of second-generation solar cells, including amorphous Silicon (a-Si) and thin film solar cells, are more affordable than first generation silicon wafer solar cells. They are classified as follows: i) a-Si. ii) Cd-Te iii) CIGS (copper indium gallium di-selenide).

i) Amorphous Silicon Thin Film (a-Si) Solar Cell

Primitive solar cells known as amorphous Si (a-Si) based PV modules were the first to be produced industrially. a-Si amorphous solar cells are somewhat more affordable and accessible. When referring to a solar cell, the term "amorphous" denotes that the silicon material that makes up the cell lacks a clear arrangement of atoms in the lattice, is not crystalline, or is not highly organised. These are produced by covering the substrate/glass plate with doped silicon material. These solar cells often have a silvery colour on the conducting side and a dark brown colour on the reflecting side [18]. It has an Efficiency of 5 -12%; Band gap: ~1.7 eV and Life span is around 15 years [17].

ii) Cadmium Telluride (CdTe) Thin Film Solar Cell

Cadmium telluride (CdTe), a type of thin-film solar cell, is a leading option for the creation of more affordable, commercially viable photovoltaic (PV) devices and the first PV technology to be produced at a low cost [8, 19, 20]. CdTe has a chemically stable structure, a high optical absorption coefficient, and a band gap of 1.5 eV. These characteristics make CdTe the most desirable material for thin-film solar cell design. CdTe is a superior direct band gap crystalline compound semiconductor that increases efficiency and facilitates light absorption. The most common CdTe solar cells consist of a p-n heterojunction structure containing a p-doped CdTe layer matched with an n-doped cadmium sulfide (CdS). It shows 15-16% efficiency with a band gap of ~1.45 eV and life span are 20 years.

iii) Copper Indium Gallium Di-Selenide (CIGS) Solar Cells

Copper, Indium, Gallium, and Selenium (CIGS) are the four elements that make up this quaternary compound semiconductor [10, 17, 21]. CIGS are direct band gap semiconductors as well. CIGS thin film solar cells have an efficiency that is 10%–12% greater than CdTe thin film solar cells. One of the most likely thin film technologies is based on CIGS solar cells because of its extraordinarily high efficiency (around 23.4%) and affordability.

The first generation contains solar cells that are relatively expensive to produce, and have a low efficiency. The second generation contains types of solar cells that have an even lower efficiency, but are much cheaper to produce, such that the cost per watt is lower than in first generation cells.

First-generation solar cells are relatively costly to manufacture and have lower efficiency. In contrast, second-generation solar cells are even less efficient but are significantly cheaper to produce, resulting in a lower cost per watt compared to first-generation cells.

■ Third Generation Solar Cells

Third-generation cells are constructed using new technology, but they haven't been well studied on the commercial front. The majority of the developed varieties of third-generation solar cells are [2]:

1. Nano crystal based solar cells
2. Polymer based solar cells

3. Dye sensitized solar cells
4. Concentrated solar cells

1. Nano crystal based solar cells

Quantum dots (QD) (Figure 3) solar cells are another name for nanocrystal-based solar cells. These solar cells are formed of a semiconductor, typically from transition metal groups and are in the nanocrystal size range. The term "QD" simply refers to crystals that are less than a few nanometres in size, such as porous Si or porous TiO_2, which are widely used in QD [22]. These semiconducting nanocrystals are intended to take the place of semiconducting bulk materials like Si, CdTe, or CIGS with the development of nanotechnology. Quantum dots have bandgaps that are adjustable across a wide range of energy levels by changing their size. A theoretical formulation of the QD-based solar cell was employed for the development of a **p-i-n** (PIN Diode) solar cell over the self-organized As/GaAs system [23]. In most cases, the nanocrystals are mixed into a solution before being deposited onto the Si substrate. These crystals rotate incredibly fast and flow away due to the centrifugal force. In ordinary compound semiconductor solar cells, a photon will typically excite one electron, resulting in the formation of one electron-hole pair. However, when a photon contacts a QD constructed comparable semiconductor material, multiple electron-hole pairs can occur, generally two or three, but seven have been reported in a rare case [24].

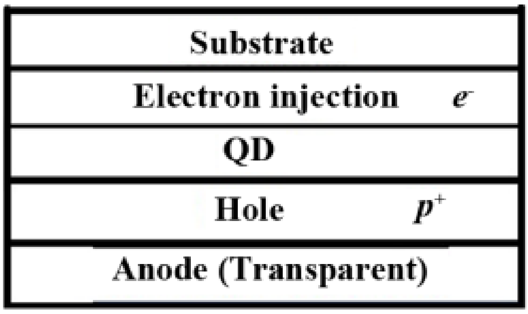

Figure 3: Schematic representation of a Quantum Dot (QD)

2. Polymer based Solar Cells

The polymer substrate of polymer solar cells (PSC, also known as plastic solar cell) makes them typically flexible solar cells. In 1986, at Kodak Research Lab, Tang and his colleagues developed the first Organic Solar Cell (OSC) [23]. A polymer solar cells (PSC) consist of tiny functional layers that are linked in a serial fashion and are coated on polymer foil or ribbon. Typically, a polymer (the donor) and a fullerene (the acceptor) are combined for construction of PSC. Organic materials like conjugate/conducting polymers are among the many different types of materials that may absorb sunlight. Heeger, MacDiarmid, and Shirakawa were awarded the Nobel Prize in Chemistry in 2000 for developing a new class of polymer materials known as conducting polymers. In order to create the first polymer solar cell, Sariciftci *et al.* combined poly [2-methoxy-5-(2'-ethylhexyloxy)-p-phenylene vinylene] (PPV), C60, and its various derivatives [25]. A new era in polymer materials for storing solar energy has emerged as a result of this procedure. Researchers were able to attain an efficiency of over

3.0% for PSCs of the PPV type after extensively optimising the parameters [26, 27]. The development of stretchable solar devices, including textiles and fabrics, has found new usages because to the special features of PSCs [23]. The PSC and other organic solar cells operate on same principle known as the photovoltaic effect, i.e., where the transformation of the energy occurs in the form of electromagnetic radiations into electrical current [13].

The stability, cost, and processing have been highlighted as critical factors in addition to the power conversion efficiency [14]. These particular areas have received relatively little thought. Particularly, organic solar cell's fairly low device stability has received little study. Organic devices need to be significantly studied in order to become technologically attractive in this regard because inorganic silicon-based solar cells have a higher lifespan. By their very nature, organic materials are more prone to chemical deterioration caused by substances like oxygen and water than are inorganic materials. Numerous research has been conducted, and they demonstrate that the stability/degradation problem [4,5] is fairly complex and most definitely not fully understood, despite advances. Work in this area is crucial if polymer solar cells are to become more than a scientific curiosity.

3. Dye Sensitized Solar Cells (DSSC)

Recent studies have concentrated on increasing solar efficiency using molecular engineering and the use of nanotechnology for light energy harvesting. Michel Grätzel of the Swiss Federal Institute of Technology in Lausanne invented the first DSSC solar cell (Figure 4) [3, 10,13-15, 22-24, 26]. In most cases, dye molecules are used between the various electrodes in DSSC-based solar cells. The DSSC device is made up of four parts: a counter electrode (carbon or Pt), a dye sensitizer, a redox mediator, and a semiconductor electrode (n-type TiO_2 and p-type NiO). Because they are very flexible, transparent, and inexpensive, traditional processing techniques like printing make DSSCs desirable [10]. The efficiencies of the DSSC solar cells are increased to better than 10% by photosensitizing the nano grained TiO_2 coatings and combining them with the visible optically active dyes.

A technically sound and economically viable alternative to the current generation of p-n junction photovoltaic devices is offered by dye-sensitized solar cells (DSC). The two tasks are separated here, in contrast to traditional systems where the semiconductor does both light absorption and charge carrier transmission. A sensitizer that is attached to the surface of a wide band semiconductor absorbs light. Through photo-induced electron injection from the dye into the solid's conduction band, charge separation occurs at the interface. The semiconductor's conduction band is where carriers are carried to the charge collector. A considerable portion of sunlight can be captured by combining sensitizers with a wide absorption band with oxide coatings with nanocrystalline shape. Over a broad spectral range spanning from the UV to the near IR area, nearly quantitative conversion of incident photon into electric current is accomplished. Over 10% in terms of overall solar (standard Air Mass 1.5) to current conversion efficiency have been achieved. There are good chances of producing these cells at low cost than typical devices.

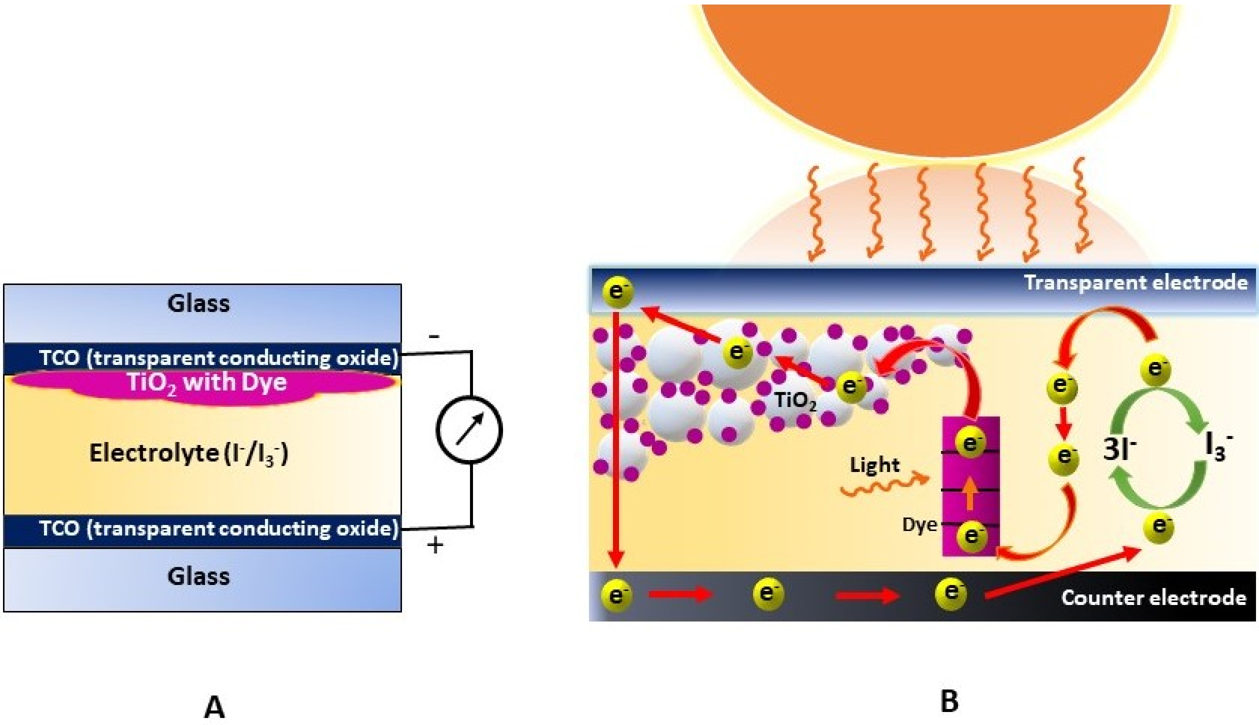

Figure 4: Schematic representation of a Grätzel cell (A) and mode of operation in a Grätzel cell (B)

4. Concentrated Solar Cells

Since the 1970s, concentrating photovoltaic (CPV) technology has existed. It represents the most recent advancement in solar cell research and development. As seen in Figure 5, the fundamental idea behind concentrated cells is to focus a lot of solar energy onto a small area above the PV solar cell. This method works on the basis of optics, concentrating sunlight onto a specific area of the solar cell by means of a system of huge mirrors and lenses [8]. Thus, a significant amount of heat energy is produced by the convergence of sunlight's radiations. An additional heat engine that is functioned by an integrated power generator uses this heat energy. CPVs have demonstrated their promise in the solar industry.

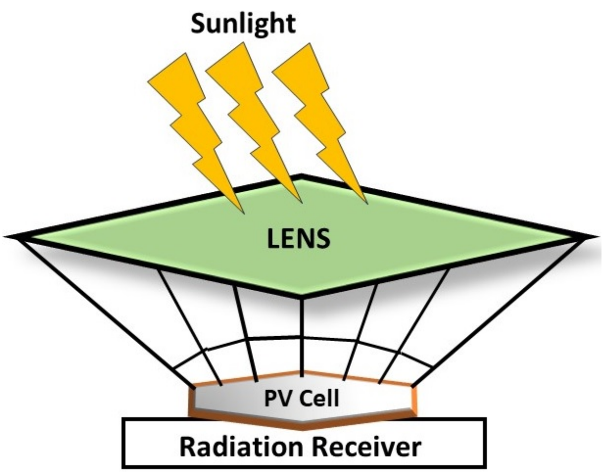

Figure 5: Schematic Representation of a Concentrated Solar Cell

Perovskite Based Solar Cell

Photovoltaics (PV), the process of turning sunlight into electricity, is one of the potential renewable energy strategies. Silicon solar cells, which have profited from recent developments resulting in lower production costs, dominate the photovoltaics market today. However, some fundamental cost obstacles, such as high temperature processing, place restrictions on this developed technology. The cost of processing might be greatly decreased with a fundamental shift in perspective. One such alternate strategy substitutes organic semiconductors in place of crystalline silicon. Organic-inorganic metal halide perovskite semiconductors [28,29] a novel material class, may be able to solve this issue and make really inexpensive solar modules.

A class of substances known as perovskites is denoted by the formula ABX3, where X is a halogen (such as I, Br, or Cl), and A and B are cations of various sizes. In comparison to conventional silicon and thin film based solar cells, perovskite solar cells have just been discovered and have a number of advantages. Conventional Si-based solar cells require high processing temperatures (>1000 °C) and vacuum facilities, which are expensive. The efficiency of perovskites-based solar cells can reach around 31% reported in 2022 [30]. The organic-inorganic metal halide perovskite that is most frequently used in the solar industry is $CH_3NH_3PbI_3$ [31-33]. A large organic cation, methylammonium ($CH_3NH_3^+$), lead (Pb), a smaller organic cation, and iodine, a halogen anion, make up this compound. Perovskites have many advantageous properties that make them suitable as absorber materials in solar devices. Importantly, it is possible to install the perovskite layer using inexpensive coating and printing methods. This suggests that the advancements achieved in polymer solar cells can be transferred to this novel material system. In practice, dependable manufacturing methods for perovskites are readily available [2].

The dye sensitised solar cell (DSSC) technology served as the foundation for the architecture of perovskite solar cells. The traditional design of DSSCs had a porous TiO_2 scaffold that was dye-sensitized and filled with a liquid electrolyte. With varying degrees of effectiveness, $CH_3NH_3PbBr_3$ and $CH_3NH_3PbI_3$ were also examined as potential replacements for the dye material. The inherent instability of devices containing a liquid is a major issue with this technology. The Snaith group made two crucial discoveries that radically altered the way this kind of solar cell was thought of, which dramatically increased PCE (power conversion efficiency) and attracted an unprecedented level of study attention. The first of these innovations was the substitution of an insulator (Al_2O_3) for the TiO_2 scaffold, which is employed to transport electrons [34]. As a result, it was shown for the first time that the perovskite material could transport electrons efficiently without the TiO_2 layer underneath. Following this realization, a planar shape solar cell with a perovskite thin film as the absorber layer was demonstrated [13]. The remarkable efficiency attained with this device structure indicates the perovskite material's ability to transfer both positive and negative charge concurrently, a property known as ambipolar charge transport. This is crucial because the low-cost production techniques developed for polymer solar cells may now be used for this fantastic class of materials.

Perovskite solar cells experience the same environmental stability issues as polymer solar cells (PSC). The perovskite absorber's inherent instability as well as several external issues that weaken the device are to blame for this. Recent studies suggest that one important drawback is the perovskite's disintegration after being exposed to moisture, but there are still numerous factors that need to be considered. Several devices having small surface areas have been produced under perfect laboratory conditions and have attained PCEs above 10% [16, 34-36], but large-scale polymer solar module demonstrations have had poor performance. The solar park demonstration system efficiency was less than 2% [7]. Although these are preliminary studies, considerable development is still needed in this field.

The photovoltaic revolution is anticipated to be led by metal halide perovskite solar cells. Perovskites are sensitive to external stimuli because of their soft and ionic lattice, and this causes the resultant devices to noticeably change under cyclic shocks in practical applications. Effective ways to reduce device fatigue under cyclic illumination are limited due to a lack of a fundamental knowledge of the metastable dynamics of materials deterioration. At the perovskite interface, a starch-polyiodide supermolecule was added as a bifunctional buffer layer that can both prevent ion migration and encourage defect self-healing. The improved stability of the modified perovskite solar cells is demonstrated by the retention of 98% of their initial power conversion efficiency after 42 diurnal cycles (12/12 h light/dark cycle). The devices also produce a powerful electroluminescence with external quantum efficiencies above 12.0% and a power conversion efficiency of 24.3% (certified, 23.9%).

It is now crucial and difficult to comprehend and enhance Perovskite Solar Cell's long-term operational stability in order to guarantee their dependability in outdoor field situations [6, 15, 22, 36, 37-39].

5. Conclusions:

The dye-sensitized nanocrystalline electrochemical photovoltaic system has proven to be a strong and reliable competitor to traditional solid-state devices for converting solar energy into electricity. It serves as a model for many optoelectronic devices that leverage the unique properties of oxide and ceramic semiconductor films, as well as their innovative structures.

Research in polymer solar cells is progressing rapidly, primarily focused on improving their efficiency. Equally important is addressing their relatively limited stability, which has received less attention so far. Perovskite materials hold significant promise for revolutionizing the photovoltaic industry, offering advantages in cost and performance. The rapid advancements in perovskite solar cells, along with their compatibility with low-cost roll-to-roll manufacturing used in organic photovoltaics (OPV), make them particularly attractive [35-40]. Despite current efficiencies being higher than those of polymer solar cells, perovskite cells continue to improve.

One of the most promising technologies is the tandem solar cell combining perovskite and silicon, which aims to surpass the Shockley–Queisser limit of single-junction solar cells at an affordable cost. The efficiency of these tandem cells has surged from 13.7% in 2015 to 34.6% in 2024 [41]. As of 2024, the world record for solar cell efficiency stands at 47.6%, achieved in May 2022 by Fraunhofer ISE using a III-V four-junction concentration photovoltaic (CPV) cell [42]. This surpassed the previous record of 47.1%, set in 2019 by multi-junction concentrator solar cells developed at the National Renewable Energy Laboratory (NREL) [43]. Under real-world conditions, NREL's triple-junction cells have demonstrated an efficiency of 39.5% [44].

The global demand for solar energy is more pressing than ever, and ongoing research in solar cell technology promises a bright future for renewable energy solutions [45-50].

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