Third Generation Solar Cell Technology: Practical Approach

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Abstract— **This article discusses third-generation solar cells technology. Solar cells of this generation are renowned for their unique characteristics, cost-effectiveness, and efficiency. Dye-sensitized solar cells, perovskite solar cells, and organic solar cells have emerged as renewable energy sources playing a pioneering role among third-generation solar cell technologies. The primary reason for their prominence lies in the ease of their processing, as well as their efficient capability to convert solar energy into electricity on a large scale. Consequently, these solar cell devices have garnered significant attention within the scientific community over the past few years. With new researchers in mind, this article sheds light on the historical background, structure, and working mechanism of these solar cells.**

Keywords— Solar cells, DSSCs, Perovskite, Organic solar cells, Efficiency

I. Introduction

It is noteworthy that, driven by rampant population growth and this population's increasing reliance on material comforts, industrial development has led to a significant surge in global energy demand. It is pertinent to observe here that a commensurate expansion of energy sources is absolutely essential to match this demand; however, the instability of this balance—stemming from the continuously escalating demand for energy—has become a growing source of concern for the world's intellectuals and researchers. Therefore, it would be in the public interest for all nations to take the issue of energy requirements seriously. While the developmental contexts of individual nations vary, energy plays a pivotal role for all of them. In the context of these diverse developmental processes, the indiscriminate misuse of traditional energy resources such as fossil fuels (oil, gas, and coal) is not only hastening their depletion but is also severely polluting the ecosystem through the emission of various gases generated during combustion [1]. The pressure arising from the imperative need for energy is not limited solely to developing nations; indeed, economically backward countries, too, have not remained untouched by it. Even today, there are regions in many countries where people are compelled to live without access to electricity. Despite all this, man-made circumstances also compel human beings to lead a life of destitution. Recently, the horrors of war that erupted in Western nations have unleashed havoc across the entire world; as a result of this conflict, an energy crisis—driven by oil and gas shortages—has emerged in several countries [2]. If an energy shortage occurs in the future, the pace of development will come to a halt, and the human lifestyle will revert to the Stone Age. According to one estimate, approximately 10 TWs of additional energy will be required to meet energy demands by 2050 [3]. As a result, using fossil fuels would harm the Earth's environment in addition to depleting its sources. Thus, increasing the use of alternative energy sources has become crucial from the standpoint of environmental protection. Solar, wind, hydropower, and geothermal energy are the most popular renewable energy sources. Solar energy is the most popular of these sources because it is abundant, totally free, and renewable. The Earth receives about 1.8×10^{14} kW of energy from the Sun [4]. This energy potential is far greater than current energy consumption (1.3×10^{10} KW). According to Gratzel, if a solar cell (with an efficiency of 10%) were to cover merely 0.1% of the Earth's surface, the world's energy supply would be fully met [5]. Although in 2008, solar energy accounted for less than 0.1% of the world's total energy consumption figure1 [6]. Moreover, the target is to keep it at 45% by 2030. The cost of creating solar energy is the main barrier to its widespread use. Moreover, it seems to be a difficult task to fabricate high-efficiency solar cells utilizing cheap materials. Therefore, particular, tangible efforts will be required to build solar cells that are robust, highly efficient, and reasonably priced.

First-generation solar cells, which are based on p-n junctions, fabricated from single-crystal silicon. Currently, a maximum efficiency of 24.7% has been recorded for them in a laboratory environment [7]. Due to their high manufacturing and installation costs, these solar cells have been unable to secure a significant foothold in the market. Second-generation solar cells are based on thin-film technology, such as $CuInGaSe_2$ (CIGS), cadmium telluride (CdTe), and gallium arsenide (GaAs). These materials are used to make commercially available technologies that are utilized in spacecraft. Although these solar cells are relatively inexpensive, their production at an industrial level has been hindered due to their low efficiency. Third-generation solar cells such as dye-sensitized solar cells (DSSCs) ([8],[9]) heterojunction cells [10], and organic cells [11] are now not only cost-effective but also demonstrate variable efficiency, which could make them the cornerstone of the future.

In this article, we will discuss the various forms of solar energy; furthermore, we will delve into a detailed discussion regarding the construction and working principles of various types of third-generation solar cells.

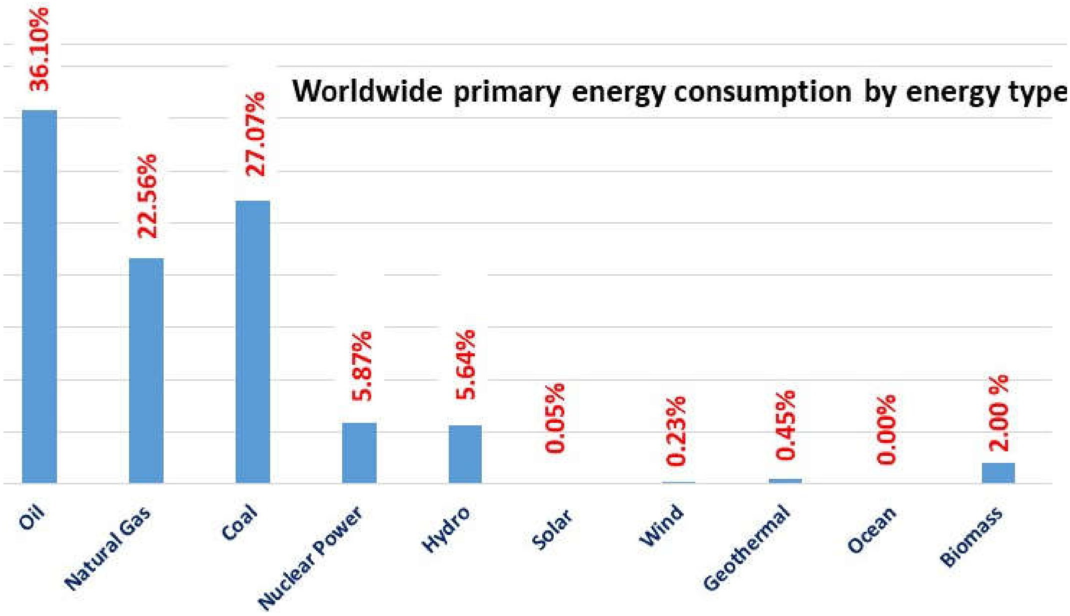

Fig. 1: shows Worldwide primary energy consumption (reproduced; taken data **After reference [6]**)

II. Dye-Sensitized Solar Cells

A DSSC is typically based on the principles of a photoelectrochemical (PEC) solar cell. The fundamental difference lies solely in the fact that its performance depends on the extent of light absorption by the dye as this directly determines the number of excited electrons generated ([12],[13]). Wide-band-gap oxide materials used in DSSCs are insufficient to function as solar cells on their own. Their incapacity to absorb a substantial amount of sunlight is the main cause of this. Their efficiency is low since they can absorb only UV light due to their large band gaps. For this reason, to enhance the efficiency of such solar cells a monolayer of an efficient dye is deposited on wide bandgap semiconductors. These dyes are capable of absorbing the visible light spectrum. A noteworthy point is that the absorption of visible light by the dye is significantly more intense than the absorption of UV light by the wide-band gap semiconductor even if the intensity of the UV light itself exceeds that of the visible light [14]. Thus, from a historical perspective, in 1960, the sensitization of wide-band-gap semiconductors using dyes was initiated by Gerischer and Memming ([15],[16].

Major components of DSSC are – photoanode- a metal oxide semiconductor that act as the electron–acceptor, electrolyte, sensitizer dye which acts like an electron donor, is the photo-active component, and a counter electrode.

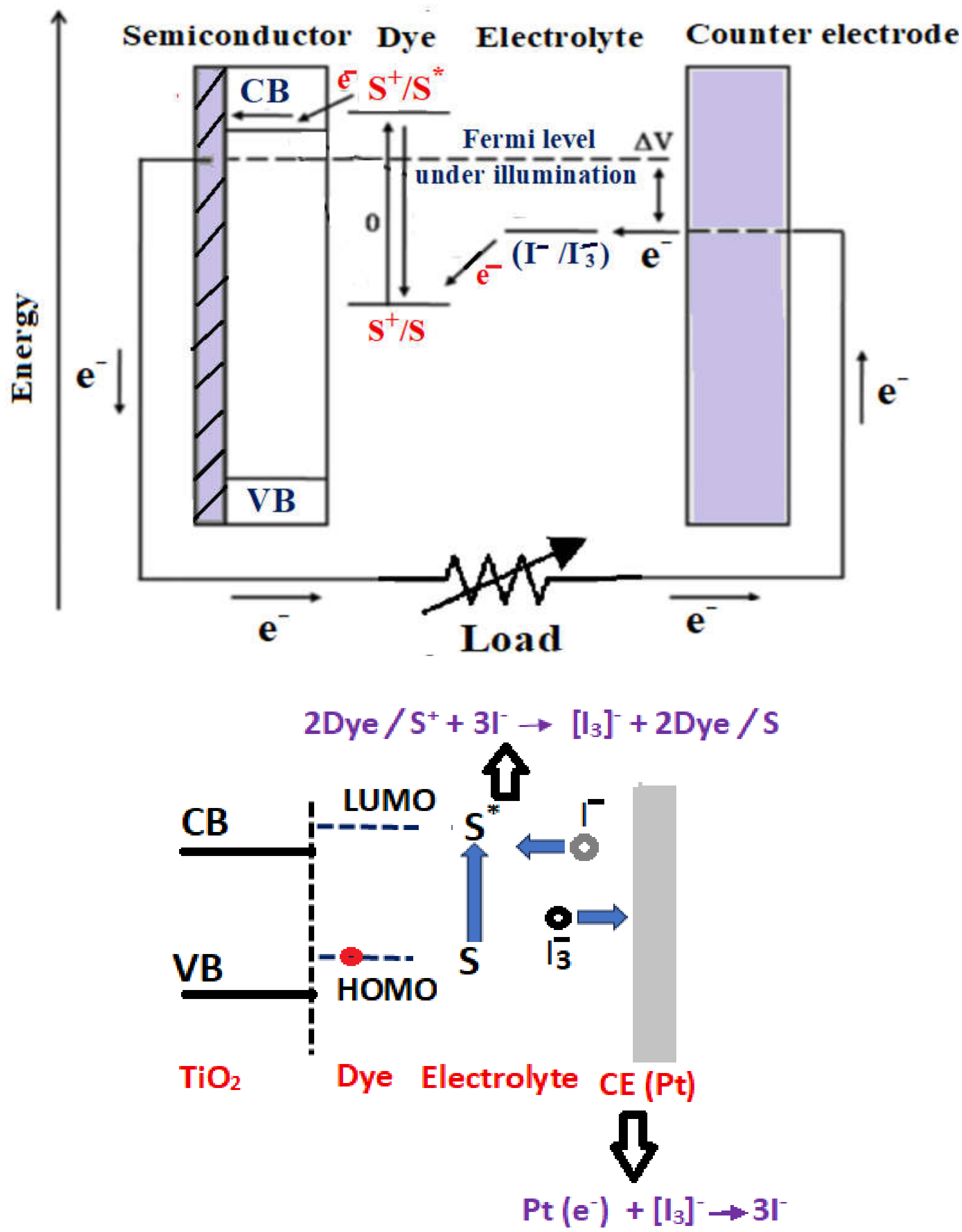

Fig. 1: (a) Above schematic Dye-Sensitized Solar Cell working Principle (b) below the relevant energy levels in its operation.

A. Working principle

The working of DSSC is based on four major steps:

- light absorption,
- electron injection,
- carrier transportation, and
- current collection.

First, the incident light is absorbed by the dye, results in excitation of dye rising from their ground state to the excited state.

Second, in excited state dye injected electrons into the conduction band of the nanoporous TiO_2. Below the dye's excited state, TiO_2 absorbs a small portion of solar photons in the UV region, resulting in the dye's oxidation.

Third, electrons are percolate through TiO_2 particles and diffuse to the back contact of the transparent conductive oxide.

Finally, these electrons then travel through the external circuit and reach at the counter electrode. Then at the counter electrode reduce I_3^- to I^-. consequently, the dye is regenerate when I^- accepts an electron from the redox medicator. The principle of operation of a DSSC is explained by the equation below;

$$TiO_2/\ S + h\nu \leftrightarrow TiO_2\ /S^*_{LUMO} \quad \text{……………..(1)}$$

$$TiO_2/\ S^*_{LUMO} \rightarrow TiO_2\ (e^-_{CB})/\ S^+ \quad \text{……………..(2)}$$

$$TiO_2\ (e^-_{CB})/TCO \rightarrow TiO_2/\ TCO\ (e^-) \quad \text{……………..(3)}$$

$$2Dye\ /\ S^+ + 3I^- \rightarrow [I_3]^- + 2Dye\ /\ S \quad \text{……………..(4)}$$

$$(e^-) + Pt \rightarrow Pt\ (e^-) \quad \text{……………..(5)}$$

$$Pt\ (e^-) + [I_3]^- \rightarrow 3I^- \quad \text{……………..(6)}$$

III. Perovskite solar cells

A. Fundamental of Perovskite Solar cells

Perovskite was first discovered in 1839 by Gustav Rose. Perovskite is a mineral known as 'calcium titanate ($CaTiO_3$)'; it is named after Lev Perovski, a mineralogist. Perovskites are represented by the compound formula ABX_3 in a certain tolerance limit, wherein A and B are cations, whereas X is an anion [17]. The crystal structure of an ideal perovskite is simple cubic. The tolerance is known as the Goldschmidt tolerance factor defined by the following equation [18, 19],

$$t = \frac{r_A + r_0}{\sqrt{2}(r_B + r_0)} \quad \text{------------------------------(7)}$$

where -- r_A is the radius of the A-cation, r_B is the radius of the B-cation, and

r_0 is the radius of the anion.

In equation (7) the factor is based on the ionic radii of the elements that make up the perovskite crystal. An ideal cubic perovskite structure of the unit cell (a) is defined by the following equation [17].

$$a = \sqrt{2}(r_A + r_0) = 2(r_B + r_0) \qquad \text{------------------------------(8)}$$

It has been reported that, to form a stable and cubic phase, the tolerance factor (t) of perovskites must lie within the range of $0.8 \leq t \leq 1$.

Perovskite Solar Cells (PSCs) are cost-effective because they are based on hybrid organic-metal halide perovskites (OMHPs), which are abundant on Earth. They possess a wealth of optical, electrical, and electronic properties—such as high carrier mobility and absorption coefficients, tuneable bandgaps, long charge diffusion lengths, low exciton binding energies, and broad light absorption spectra. Owing to these attributes, they hold immense potential for enabling the development of next-generation solar cells that are chemically inexpensive to manufacture, high-performing, and capable of competing with silicon-based solar cell technologies.

As previously discussed, hybrid OMHP is represented by the general chemical formula ABX_3 where A = monovalent cation, such as FA^+, MA^+, Cs^+;

B = divalent metallic cation, such as Pb^{2+} and Sn^{2+}; and

X = halide anion, such as I^-, Br^-, and Cl^-),

B. Working principle and architecture *of Perovskite Solar cells*

A perovskite solar cell (PSC) typically utilizes a compound with a perovskite structure, which serves as the light-absorbing active layer. This layer is composed of a hybrid organic-inorganic, lead- or tin-based material. Metal oxide thin films—such as TiO_2, ZnO, or ZrO_2—are employed as the electron transport layer. The Hole Transport Layer (HTL) in perovskite solar cells (PSCs) extracts and transports photogenerated holes to the electrode while blocking electrons, crucial for reducing recombination, enhancing stability, and boosting power conversion efficiency. The materials utilized for the purpose includes organic molecules (such as-Spiro-OMeTAD, PEDOT:PSS) and inorganic compounds (like-Cu_2ZnSnS_4), Which not only optimize energy levels but are also crucial for enabling high-performance charge transport [20]. Moreover, pt, Au, Ag etc are used as metal back contact.

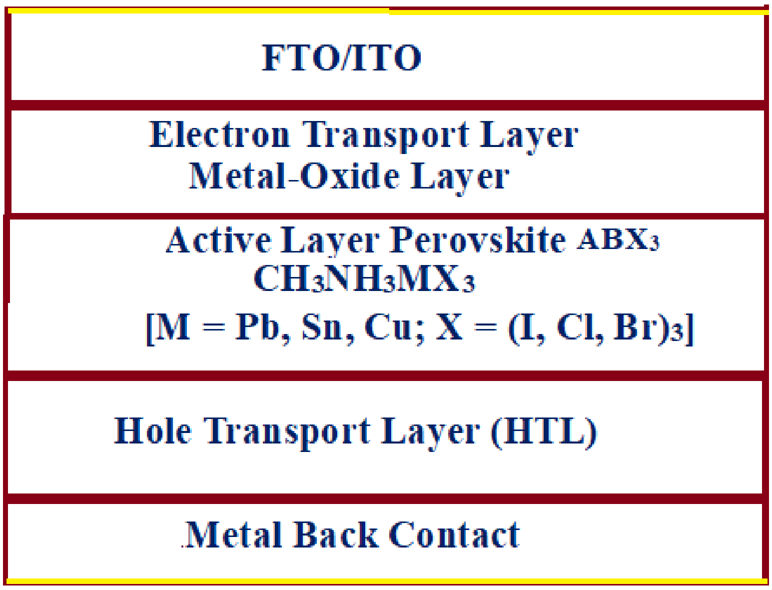

Fig. 2: Schematic general device architecture of a perovskite solar cell.

The overall photovoltaic performance of a Perovskite Solar Cell (PSC) is evaluated based on which transport material (ETM or HTM) is present on the outer surface of the cell where the incident light strikes. Based on this, their architectures can be classified as n-i-p or p-i-n as shown in figure 3. Thus,
1/ n-i-p: where the incident light reaches the perovskite layer through the ETM;
2/ p-i-n: where the incident light reaches the perovskite layer through the HTM.

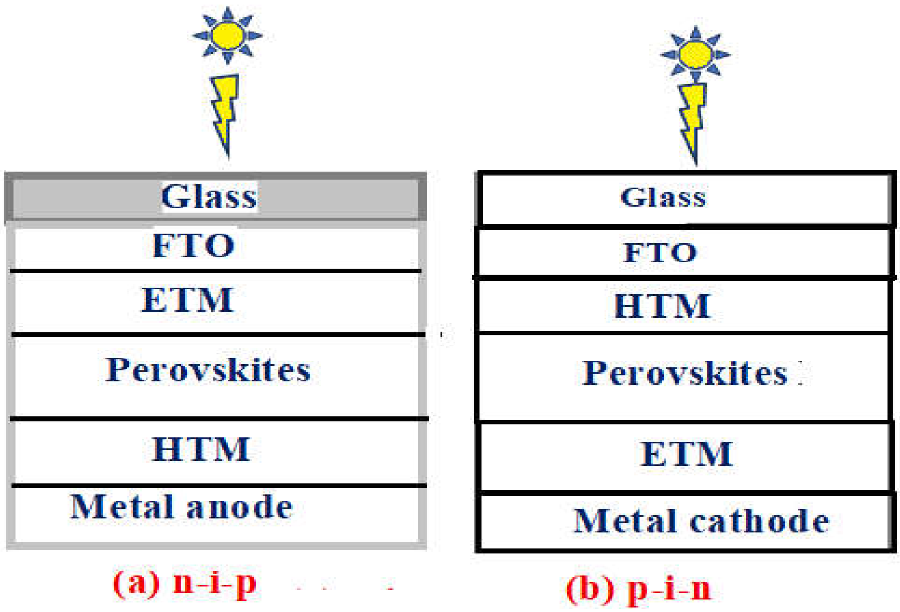

Fig. 3. Architectures of n-i-p and p-i-n type perovskite solar cells.

From the perspective of n-i-p and p-i-n architectures, the operating principles of PSCs largely align with those of solid-state p-n junction solar cells.
The working principles of PSC involve in three steps

1. carrier generation process
2. charge separation and transport process, and
3. charge collection

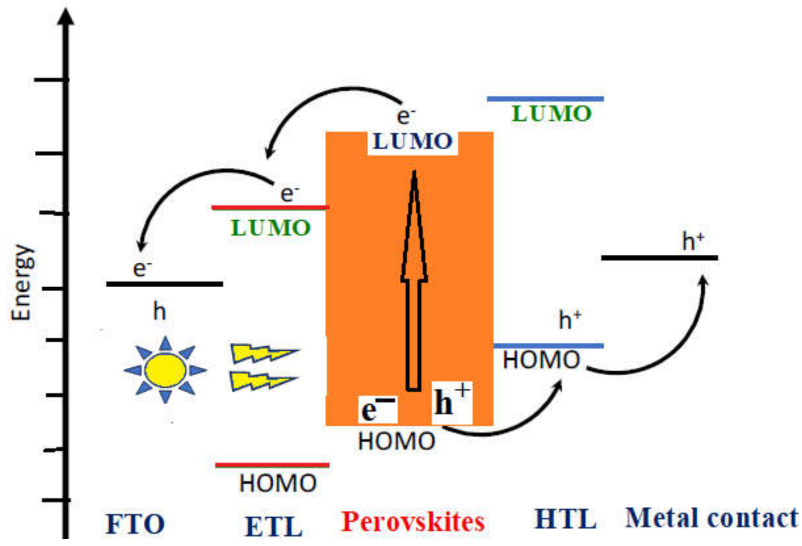

Fig 4. Working principle of a perovskite solar cell with band diagrams.

Hence in first step, the perovskite layer harvest photons to generate electrons and holes. In second step, Electron-hole pairs are separated by the ETL and HTL; specifically, electrons are selectively collected and transported by the ETL layer, while holes are collected and transported by the HTL. In third step, the current is produced by connecting an external circuit to the device. It is noteworthy here that the conduction band (CB) of the n-type ETL and the valence band (VB) of the p-type HTL should be appropriately aligned with the CB and VB of the perovskite layer, respectively. The working operation of a typical perovskite solar cell is explained with band diagrams in figure 4. It is evident from the energy band diagram that if the energy levels are not properly aligned, the efficiency of interfacial charge transport will be severely compromised, resulting in a reduction in PSCs efficiency [21].

IV. Organic solar cells

Organic solar cells are rapidly gaining ground within the category of 'third-generation photovoltaics.' Their key characteristics include flexibility, lightweight nature, transparency, and the potential for high efficiency across a wide range of chemical structures. These cells can be manufactured by printing them onto lightweight substrates, at low costs [22]. Furthermore, OSCs have demonstrated their efficiency not only under direct sunlight but also under indoor artificial lighting [23].

The first organic solar cell was fabricated by Calvin in 1958 [24]. Recently, an efficiency of 21.5% has been reported for tandem Organic Solar Cells [25]. These specific attributes of OSCs have rendered them just as competitive as other third-generation photovoltaic solar cells—namely, perovskite solar cells (PSCs) and dye-sensitized solar cells (DSSCs).

A. Working principle and architecture *of Organic Solar cells*

To fabricate OSCs the most common architecture diagram depicted in figure 5. From the figure it is clear that the OSCs required five components to fabricate device. These are a metal cathode, ITO/FTO as an anode, electron transport layer (ETL), hole transport layer (HTL), photoactive layer donor and acceptor.

Typically, used components are [26]-

Donor component --- p-type conjugated polymer, like poly(3-hexylthiophene-2,5-diyl) (P3HT)

Acceptor layer --- n-type organic semiconductor such as fullerene derivatives [60]PCBM and PC71BM

HTL --- PEDOT:PSS (to maximize the transport of the charge carrier kept between the active layer and the electrodes)

ETL --- ZnO (to maximize the transport of the charge carrier)

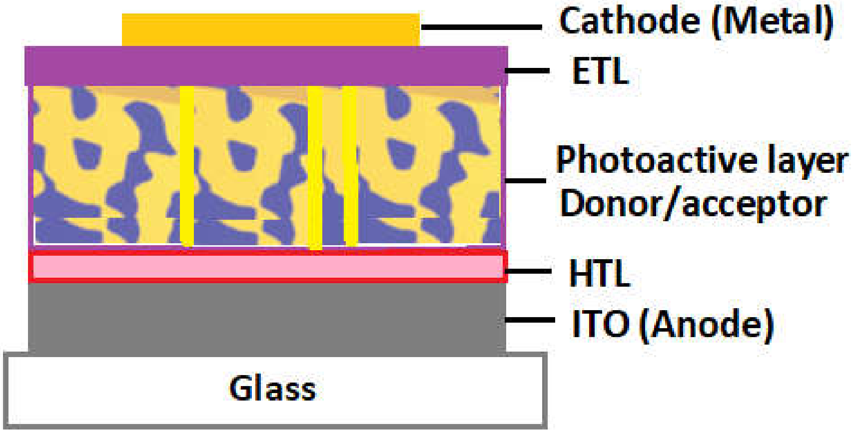

Fig. 5 Schematic general device architecture of an Organic solar cell

When light strikes the device, it is absorbed collectively by both the donor and acceptor semiconductor materials. It is noteworthy that the acceptor conducts electrons in the LUMO (Lowest Unoccupied Molecular Orbital), while the donor transports holes in the HOMO (Highest Occupied Molecular Orbital). Upon the absorption of photons, electrons in the donor materials (or active layer) are excited from the HOMO to the LUMO a bounded electron-hole pair i.e. exciton is generated as shown in figure 6 (process 1). The formation of exciton is mainly attributed to the smaller dielectric permittivity and localized electron and hole wavefunctions [27].

In Process (2), the exciton diffuses towards the donor/acceptor interface due to interfacial electronic interactions at the heterojunction, and its dissociation at the interface results in an electron being left in the LUMO and a hole in the HOMO. Now the charge carriers are the transported through their respective materials i.e. electron across the acceptor material and the hole across the donor material is transported process (3). In (4) process, carriers are transferred toward their respective contacts i.e. electrons to the ETL and holes to the HTL. Finally in fifth process, charge carries are transferred to cathode and anode process (5).

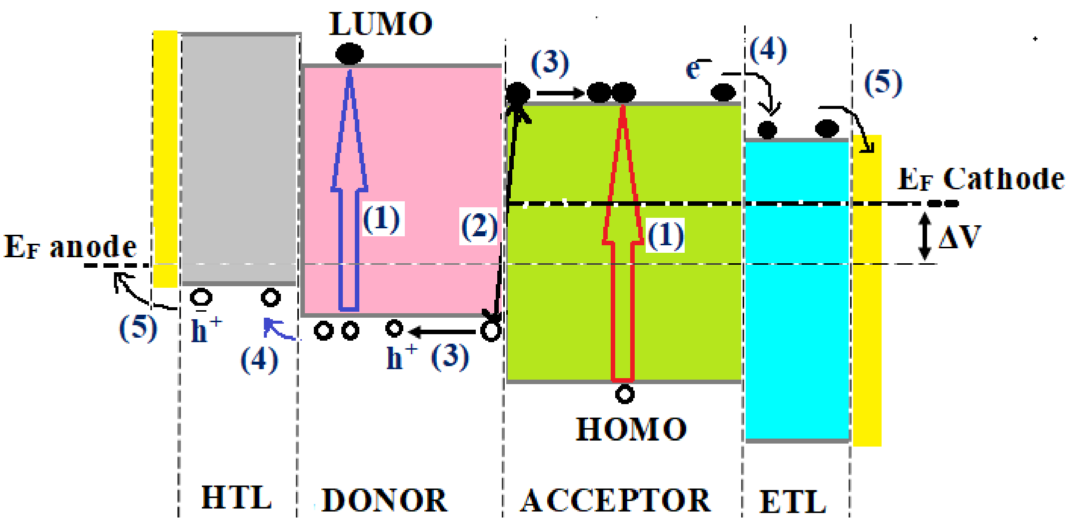

Fig.6 Working principle of a organic solar cell with band diagrams.

V. Application of Solar Energy

Solar energy constitutes a renewable resource; moreover, it is freely available and eco-friendly—meaning it causes minimal harm to the environment. Owing to these distinct attributes, solar energy is being utilized in a multitude of ways [26]:

1/ For heating and cooling buildings;
2/ To provide the heat required for industrial processes;
3/ For food refrigeration, cooking, water heating, drying, etc.;
4/ For electricity generation;
5/ For both heating and lighting in greenhouses;
6/ For desalination purposes;
7/ In space applications etc.

VI. CONCLUSIONS

Due to the continuous depletion of natural energy sources, the prospect of an energy crisis looms large for future generations. Furthermore, their incessant usage has had a profound impact on the environment. Consequently, the development of new energy sources has become absolutely imperative. It is also essential to bear in mind that these energy sources must be environmentally friendly. In this regard, there can be no better alternative than solar energy, as it is not only free but also eco-friendly. This research paper discusses certain specific third-generation solar cells. The structure and operational mechanisms of these specialized solar cells have been discussed in detail.

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