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Mechanism for Flexible Solar Cells

Ghaida Salman Muhammed

Abstract

Flexible photovoltaics are covering the way to low-cost electricity. The build-up of organic, inorganic and organic–inorganic solar cells on flexible substrates by printing technologies is to provide lightweight and economic solar modules that can be incorporated in various surfaces. Progress of flexible and lightweight solar cell is interesting for many terrestrial and space applications that require a very high specific power. Thin-film solar cells on polymer films can produce more than 2KW/Kg specific power. Flexible solar cells are proposed to open up a numerous of possibilities for enabling new applications in consumer electronics and space satellites. Recent research in thin-film electronics has been concentrated on the replacement of the traditional rigid glass plate substrate with plastic or metallic foils. Organic materials bear the potential to develop a long-term technology that is economically viable for large-scale power generation based on environmentally safe materials with unlimited availability. Organic and organic-inorganic photovoltaics (PVs) (third generation solar cells) continue to attract great attention from the PV community, due to their promising features such as low organic–inorganic cost, flexibility and light weight. In this chapter, many of the possible materials for manufacturing of flexible solar cells are discussed.

Keywords: photovoltaics, organic–inorganic, fabrication, properties, flexible solar cell

1. Introduction

Flexible photovoltaics are including the way to cheap electricity. The preparation of organic, inorganic and organic–inorganic solar cells over flexible substrates by often roll-to-roll printing technologies is to provide lightweight and economic solar modules that can be incorporated in various surfaces. Under standard conditions the current conversion efficiencies are in the 3–15% range for potentially flexible, thin film devices. Meanwhile heavy, stiff, and fragile inorganic materials can exceed 30% efficiency [1, 2], but in real applications the overall productivity is high. In 2012, Luke F. Lester et al. [1] discussed the preliminary studies on the integration of GaAs-based InAs/InGaAs quantum dots-in-a-well (DWELL) solar cells onto flexible surfaces such as Kapton and nanopaper including weight considerations for all the integrated materials. The 2 billion people who lack access to the grid as well as to energy-eager companies and families in the industrialized world facing the increasing costs of electricity generated using fossil fuel resources can get cheap and clean electricity by these new photovoltaic technologies [2].

Progress of flexible and lightweight solar cell is fascinating for many terrestrial and space applications that require a very high specific power. More than 2 kW/kg specific power can be produced by thin-film solar cells on polymer films. They are

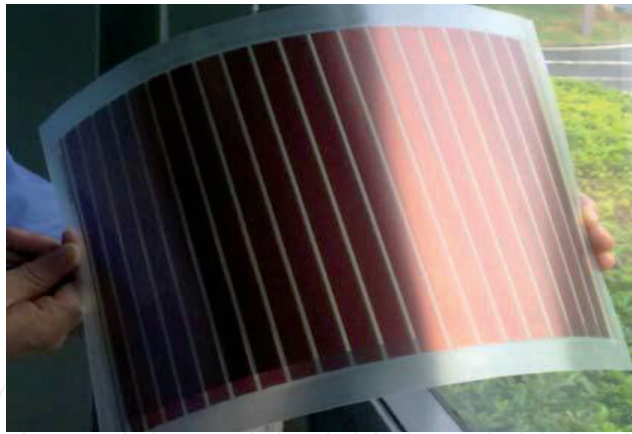


Figure 1.
Picture of a solar cell fabricated on a flexible substrate [4].

important for the development of novel products, such as lightweight and portable sources of power for emergencies and recreational use, photovoltaics incorporated buildings (roof and facades), consumer electronics (smart cards, data and telecommunication products), and solar boats and cars, etc. [3]. **Figure 1** shows a solar cell fabricated on a flexible substrate [4].

Flexible solar cells are proposed to accelerate a numerous of possibilities for providing new applications in consumer electronics and space satellites. Organic and amorphous semiconductors are very important materials to achieve flexible and light-weight solar cells, essentially due to their strong light absorption properties, process temperature compatibility with flexible substrates and potentially cheap processing cost. Due to the highly disordered and defective crystalline structure in these materials, the poor minority carrier lifetime prevent their use for making high efficiency and reliable solar cells [5].

The replacement of the traditional rigid glass plate substrate with plastic or metallic foils has been concentrated by the recent research in thin-film electronics. Metallic materials, stainless steel and molybdenum foils have been used as substrates in the fabrication of thin-film transistors. A number of plastic materials (organic polymers) also have been verified successfully in a variety of thin-film applications [6]. The glass substrate may contribute to more than 90% of the total weight of the solar cells. The glass substrate should be substituted with a lightweight and flexible thin substrate, such as metal or polymer foils to maximize the high specific power. This gives flexibility to the solar panels to change to any kind of shape for incorporation in buildings, and for application in a variety of products. Flexible solar modules can help low cost and easily deployable power generators in space. Solar cells with AM1.5 efficiency of 11.4% on foils (highest efficiency recorded for flexible CdTe cell) have been developed. A comparison of the cells prepared on different polyimides is presented by A. Romeo et al. [7]. Plastic substrates solar cells can also well used in the solar car because of those characteristic [4]. Inexpensive solar cells would help game reserve the environment. Coating existing roofing materials with its plastic photovoltaic cells which are inexpensive enough to cover a home's entire roof with solar cells, then enough energy could be captured to power almost the entire house. Then, the dependence on the electric grid (fossil fuels) would decrease and help to reduce pollution [8].

2. Organic semiconductors

The toleration of the ability to develop a long-term technology that is economically active for large-scale power generation based on environmentally safe

materials with unlimited availability is caused by the organic materials. The organic semiconductors are less expensive materials than the inorganic semiconductors like Si; they have high optical absorption coefficients which offer the opportunity for the production of very thin solar cells. Also, thin flexible devices can be fabricated using high throughput and low temperature approaches that employ well established printing techniques in a roll-to-roll process. The electronic structure of all organic semiconductors is based on conjugated π -alternation between single and double carbon-carbon bonds. Single bonds are known as σ -bonds and are associated with localized electrons, and double bonds contain a σ -bond and a π -bond. The π -electrons are much more mobile than the σ -electrons; they can jump from site to site between carbon atoms thanks to the mutual overlap of π orbital's along the conjugation path, which causes the wave functions to delocalize over the conjugated backbone. The π -bands are either empty (called the Lowest Unoccupied Molecular Orbital (LUMO)) or filled with electrons (called the Highest Occupied Molecular Orbital (HOMO)). The band gap of these materials ranges from 1 to 4 eV. This π -electron system has all the essential electronic features of organic materials: light absorption and emission, charge generation and transport [9]. Also, molecular orbitals which form σ and π bonds represent the energy levels for organic semiconductor materials [10].

The denoted bonding molecular orbitals (σ and π) form the highest molecular orbital (highest energy levels) where the denoted anti-bonding molecular orbitals (σ^* and π^*) form the lowest molecular orbitals (lowest energy levels). These molecular orbitals are similar to energy bands levels in inorganic materials. **Figure 2** shows the method of creating energy gap levels in organic semiconductor [11].

The anti-bonding π^* molecular orbitals (conduction band) joined the π bonding molecular orbitals (valance band) to create the Lowest Unoccupied Molecular Orbital (LUMO) and Highest Occupied Molecular Orbital (HOMO). The gap between the (LUMO) and (HOMO) is the energy gap where the conductivity in organic semiconductor depends on. Thus, from **Figure 2** it is clear that σ bonds are extremely filled with electrons where π bonds are empty. On the other hand, if the energy band gap becomes as small as possible the tolerance of electrons to move from the (HOMO) to (LUMO) increases. Some organic semiconductors have a very small band gap of <2 eV, which mean that it is good materials compared to some inorganic semiconductors, which have a large energy band gap [10].

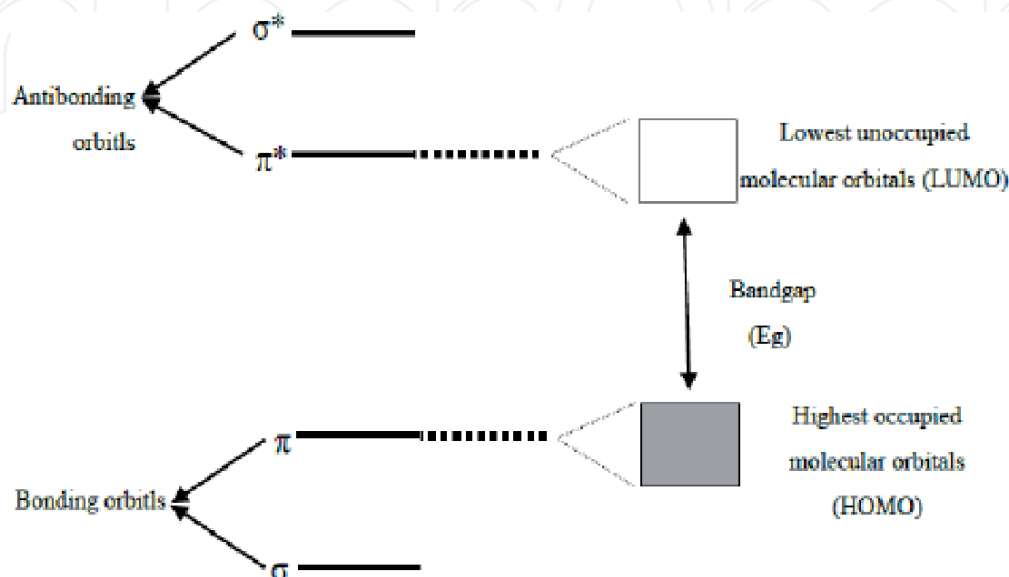


Figure 2.
 The energy levels in organic semiconductors [11].

In organics the small radius excitons generated as a result of photon absorption is the source of photocarriers. Excitons in organics have a binding energy in the range 200–400 meV, which is significantly higher than the binding exciton energy for semiconductor materials $\sim 2\text{--}40$ meV. The exciton dissociation should occur at the interface between the donor and acceptor materials with suitable (HOMO) and (LUMO) energy levels because that thermal energy at room temperature is not sufficient (~ 25 meV) for exciton dissociation to hole and electron in the bulk medium. The mechanism of exciton dissociation is not completely known, however, the charge transfer process between the donor and acceptor components is the major factor controlling the charge separation at the interface. After charge separation, holes and electrons move to the opposite electrodes because of drift and diffusion [12].

The working principle of a polymer bulk heterojunction (BHJ) solar cell as shown in **Figure 3** is summarized by the creation of an exciton in the active layer, due to light absorption, and then this exciton will separate into two charge carriers at the interfaces between the species that constitute the active layer (typically, a binary blend of a polymer and a fullerene or two polymers, which act as the donor phase and the acceptor phase), with subsequent collection by the electrodes. To get efficient steps, all of these steps must follow very strict limitations. At first, the generated excitons must hop between the molecules reaching an interface between the two phases before recombining (radiatively or non-radiatively). This means that the two phases should be mixed in an optimal structure, with phase domains usually in the order of (10–30) nm (the average exciton diffusion length in polymers). Then, the position of the energy levels at the interface must be favorable for a fast exciton dissociation followed by charge separation (*i.e.*, the electron in the acceptor phase and the hole in the donor phase without successive recombination). After that, the charges must travel inside the respective phases, reaching the collecting electrodes again without a charge recombination: at this point, the energetic level structure at the electrode interfaces plays an essential role, ideally the interface being an ohmic contact [13].

The conjugated polymer-PCBM bulk heterojunction is currently the best conjugated polymer-based PV cell. One significant improvement to this device structure was made recently by many researchers, who found that the morphology of the blend could be optimized by casting the polymer and PCBM from a solvent that prevents long-range phase separation and enhances the polymer chain packing. This

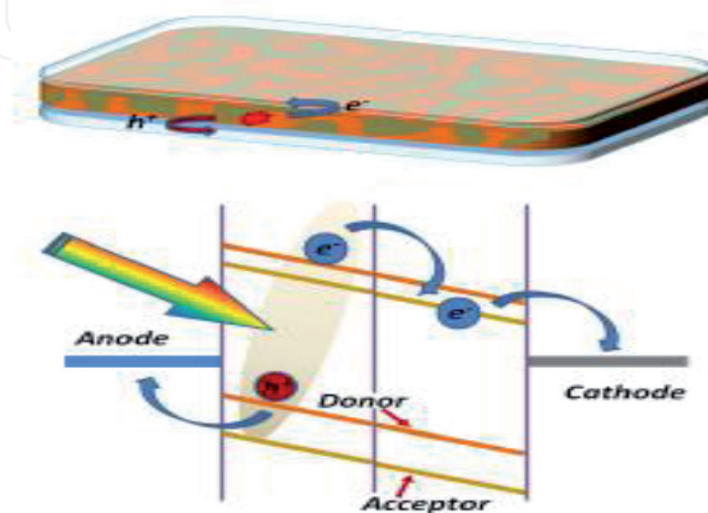


Figure 3.

A schematic diagram for the working principle of a polymeric bulk heterojunction solar cell [13].

avoids the formation of isolated regions of polymer and PCBM in the film and gives the polymer increased hole mobility. This fabricates a device with more than double the EQE of the previous best device and with 2.5% power efficiency under AM1.5G conditions [14].

For organic solar cells, the magnitude of J_{SC} , V_{OC} , and FF depends on parameters such as: light intensity, temperature, composition of the components, thickness of the active layer, the choice of electrodes used, and the solid state morphology of the film. A clear understanding of the device operation and photocurrent J_{ph} generation and its limitations in these devices are required for their optimization and maximization. In order to allow for further design of new materials that can improve the efficiency of this type of solar cells, the relation between the experimental J_{ph} and material parameters (charge-carrier mobility, band gap, molecular energy levels, or relative dielectric constant) needs to be understood and controlled [9].

Two intrinsic issues can be resolved by the bulk heterojunction (BHJ) structure, charge separation and charge transport, in organic layers. These are representative structures; though, they have a fundamental limitation in terms of open circuit voltage (V_{OC}) that is basically determined by the offset energy between the highest occupied molecular orbital (HOMO) of p-type organic semiconductors and the lowest unoccupied molecular orbital (LUMO) of n-type organic semiconductors, even though the work functions of electrodes often affect V_{OC} . A tandem structure can be applied to maximize the power conversion efficiency in organic solar cells by increasing V_{OC} , because the overall voltage becomes the sum of individual V_{OC} values in each sub cell (front and back cells). In addition, the selecting complementary BHJ layers enhances the overall short circuit current density (J_{SC}) of tandem cells, because these layers have different absorption ranges for maximizing solar light harvesting. An adverse effect is also present owing to marginally increased electrical resistances by the presence of additional interfaces and active layers in series connection. As illustrated previously, both normal- type and inverted-type structures are possible by placing suitable electrodes with appropriate work functions on each side. To date, the most popular bulk heterojunction structure is made with the composites of conjugated polymers (p-type) and fullerene derivatives (n-type), leading to polymer:fullerene solar cells. Hence, P3HT polymers have been introduced because they can absorb visible light up to 650 nm and their glass transition temperature approaches $\sim 110^{\circ}\text{C}$. The external quantum efficiency (EQE) of

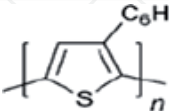
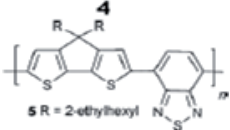
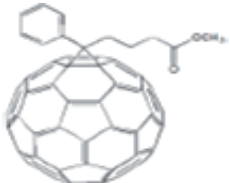
Material	Molecular structure	HOMO (eV)	LUMO (eV)	Carrier mobility (cm^2/Vs) [*]
P3HT		5.2	3.2	$\mu_h = 2 \times 10^{-4}$
PCPDTBT	 R = 2-ethylhexyl	4.9	3.5	$\mu_h = 2 \times 10^{-2}$
PCBM		6	4.2	$\mu_e = 3 \times 10^{-3}$

Table 1.
Organic molecular structure [18].

devices at a maximum wavelength reached more than 70% for P3HT:PC₆₁BM solar cells, compared to ~50% for MDMOPPV: PC₆₁BM solar cells [15]. Because of the semicrystalline nature of P3HT spin-cast films, it has among the highest reported field-effect transistor mobilities for a conjugated polymer. The morphology and the mobility of pure rr-P3HT and blended rr-P3HT: PCBM films are highly dependent on casting conditions [16, 17].

The flexible side chain of the P3HT molecule introduces a good solubility in organic solvents in spite of its kind as stiff polymers. The long and narrow fibrils which are produced by P3HT crystalizes are from a network that is able to create a good percolation paths for the charge carriers' transportation. This leads to high carrier mobility. Differing from the P3HT, PCBM is a derivative of fullerene; it has a high electron affinity which makes it a qualified electron acceptor material in the organic thin film solar cells as shown in **Table 1** [18].

3. Organic-inorganic photovoltaic solar cells (hybrid)

Organic and organic-inorganic photovoltaics (PVs) (third generation solar cells) follows the second generation (thin film inorganics such as amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS)) and first generation (semiconducting, crystalline) PVs. Third generation solar cells continues to attract great attention from the PV community, due to their promising features such as low fabrication cost, flexibility and light weight. The organic PVs include devices with flat and bulk heterojunction between the various types of conjugated polymers, small molecules, fullerene derivatives, and carbon nanotubes. Organic PVs are still unable to overcome the high 6–7% barrier of conversion efficiency, despite considerable progress in solar cell architecture, design and rational choice of the donor-acceptor materials, [19].

The heterojunction in organic-inorganic hybrid solar cells is formed between inorganic semiconductors and organic compounds (small molecules, oligomers, polymers, carbon nanotubes). The hybrid PVs has higher carrier mobility of the semiconductor and the light absorption at longer wavelengths than for organic compounds. Whereas, the organic component allows hybrid solar cells to be superior over conventional semiconducting PVs in terms of cost efficiency, scalable wet processing, the variety of organic materials (mismatch between inorganic components can be minimized or prevented), light weight, and flexibility. The progress in advanced semiconducting nanostructures in combination with organic nanomaterials (fullerenes and carbon nanotubes) opens the way to overcome the 10% barrier of conversion efficiency for hybrid solar cells. Although the band engineering of the hybrid solar cell is not as facile as for semiconducting PVs, but it is a useful instrument in the design of the hybrid solar cell architecture. For example, the chemical functionalizing of the organic component effects on the band gap energy and position of the Fermi level for conducting polymers and small molecules. **Figure 4** illustrates the types of hybrid PVs depending on the nature of organic and inorganic component and the morphology of the devices [20].

One potential alternative to crystalline silicon PV cells is cells made from thin films (<1 µm) of conjugated (semiconducting) polymers, which can easily be cast onto flexible substrates over a large area using wet-processing techniques. Polymer or hybrid solar cells often utilize a nanostructured interpenetrating network of electron-donor and electron-acceptor materials. The hybrid polymer solar cells using blends of the conjugated polymer and inorganic materials to convert sunlight into electricity. These devices will combine the advantages of two materials, high electron mobility and photosensitivity of inorganic semiconductors, and high hole

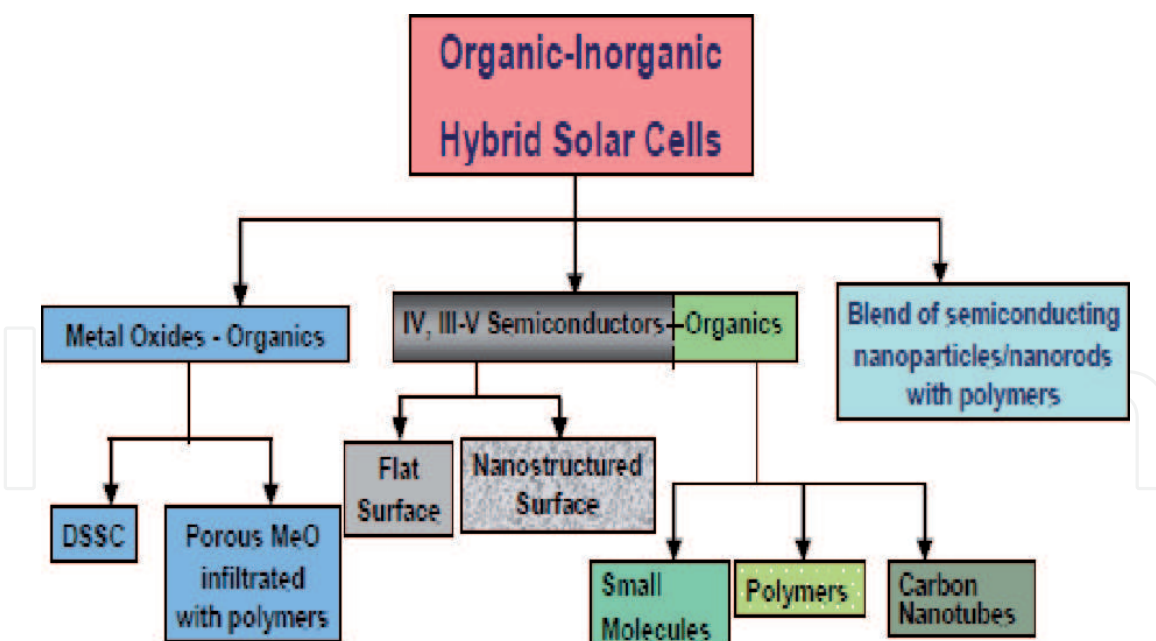


Figure 4.
 Classification of hybrid solar cells [20].

mobility of conjugated polymers. Due to the poor interfacial junction between the organic and inorganic materials, the power conversion efficiency of the hybrid photovoltaic devices is still very low. Improving the heterojunction between two materials is concentrated by many researchers. Therefore, an important method is to use two materials having complementary operation of the p-type and n-type electronic properties for the hybrid polymer solar cell [21].

In bulk heterojunction, electron accepting nanoparticles are mixed with the electron donating polymer and the exciton created in the polymer material diffuse to the donor-accepter interface for charge separation. Bulk heterojunction solar cell are preferred than multilayer or heterojunction polymer solar cells, because of the binding energy of the polymeric excitons, which is in the range of 0.2 eV-0.4 eV and that is considerably higher than the binding energy for inorganic semiconductor materials. Also, the life time of the exciton in the conjugated polymer is about sub-nanoseconds and the small diffusion range which is about (5–10) nm. After absorption of light and for efficient charge generation, each exciton has to find a donor – acceptor interface within femtoseconds within few nano-meter, otherwise it will be lost without charge generation. Because of these properties, a poor efficiency results by the heterojunction or multilayer organic photovoltaic devices. To solve this problem the semiconducting nanoparticles are incorporated into the polymer matrices since polymer materials phase separate on a nanometer dimension. The Junctions throughout the bulk of the material are created due to the mixing of the p and n type materials that ensure quantitative dissociation of photo generated excitons irrespective of the thickness. In such hybrid materials, organic polymer acts as electron donor and the inorganic nanoparticles as an electron acceptor. So that the positive charges move by hole hopping, and the negative charges by electron hopping via charge transfer between molecules. It is obvious from this mechanism; that both the organic and inorganic materials contribute to the photocurrent in hybrid bulk heterojunction cells [22].

Organic-inorganic hybrid solar cells are typically thin film devices consisting out of photoactive layer(s) between two electrodes of different work functions. The anode which is often with high work function is a conductive and transparent indium tin oxide (ITO) on a flexible plastic or glass substrate. The photoactive light absorbing thin film consists out of a conjugated polymer as organic part and

an inorganic part out of e.g. semiconducting nanocrystals [23]. A large number of various semiconductors have been investigated for organic–inorganic hybrid solar cells. For example, titanium dioxide (TiO_2) nanoparticles have been extensively employed due to their high power conversion efficiency. Also, Zinc sulfide (ZnS) is another promising semiconductor, but it has been less studied. A top metal electrode (e.g. Al, LiF/Al, Ca/Al) is vacuum deposited onto the photoactive layer finally. **Figure 5** is a schematic illustration of a typical device structure. For photoactive layers there are two different structure types, the bilayer structure and the bulk heterojunction structure. The bulk heterojunction structure is usually realized by just blending the donor and acceptor materials and depositing the blend on a substrate [24].

The charge separation process at the donor- acceptor interface in a hybrid solar cell is shown in **Figure 6**. The major photovoltaic steps include: photo-excitation

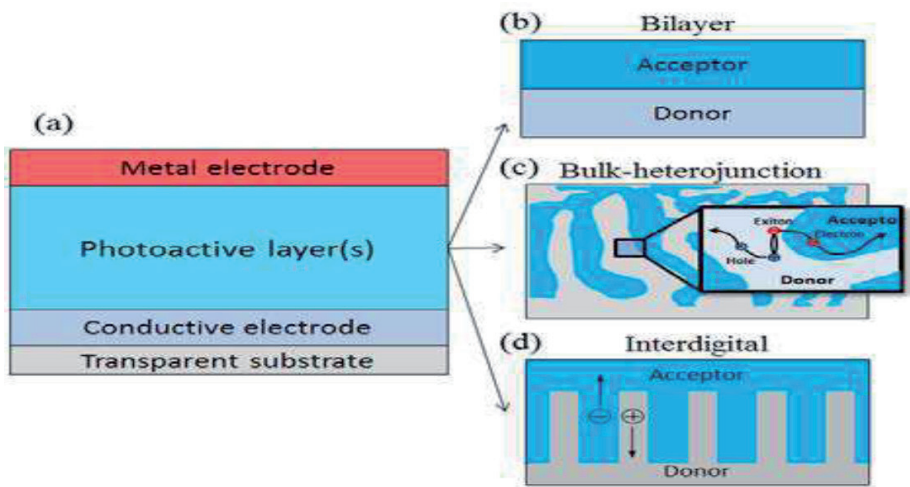


Figure 5.
A schematic illustration of typical device structures for hybrid solar cells [24].

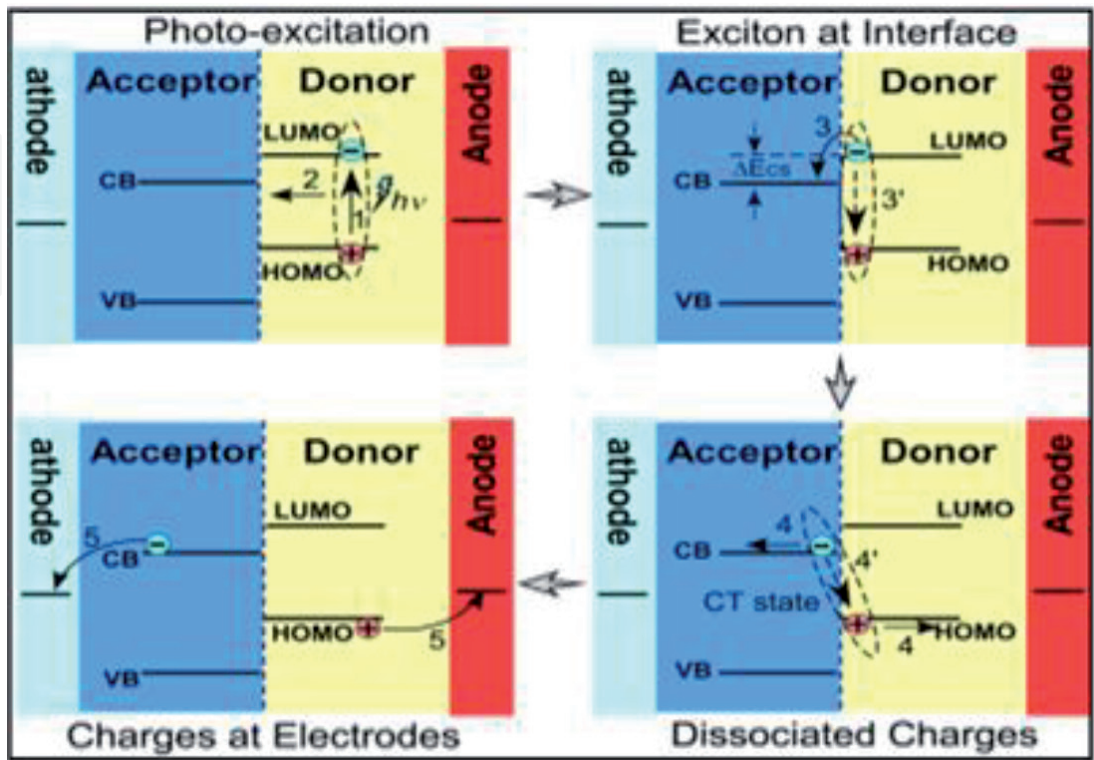


Figure 6.
A schematic diagram of the charge separation process at the donor-acceptor interface in a hybrid solar cell [25].

into excitons (1), excitons migration to interfaces (2), charge transfer from the donor to the acceptor at the interface (3), charge migration to electrodes (4) and charge injections into electrodes. The recombination of the excitons in the donor and separated charges at the interfaces are the processes which resulting in the reduction of the photovoltaic conversion efficiency [25].

4. Conclusions

Nano-science is defined as the study of small dimensions materials that exhibit remarkable properties, functionality and phenomena.

Nanotechnology controls current progress in chemistry, physics, material science, biotechnology and electronics to create novel materials that have unique properties because their structures are determined on the nanometer scale [26]. The world needs to curb CO₂ emissions soon and reduce our dependence on expensive hydrocarbons; thus, a renewable materials and solar energy on a massive scale are required. Therefore, flexible photovoltaic modules will be among the main tools used to get rid of this dependency.

This chapter has highlighted the advancements that have been made for the fabrication of flexible solar cell and the progress in this field, aimed at facilitating diffusion of these technologies [2].

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