Organic Solar Cells: Design, Architecture and Novel Concepts

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Abstract: The rapid development of organic electronics opens up a wide variety of opportunities in the areas of power production and energy consumption. Organic solar cells, solid state lighting (OLEDs), organic display, sensors and thin film transistors includes some of the promising applications of organic electronics. This paper reviews basic fundamentals of organic solar cells, design of organic solar cells focussing on design of materials by donor-acceptor approach, various development of organic solar cell architectures and novel architectural concepts such as optical light trapping devices, dye coated luminescent solar concentrator devices, tandem and organic-inorganic hybrid concepts.

1. INTRODUCTION

According to International Energy Agency (IEA), "the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating climate change, and keep fossil fuel prices lower than otherwise. These advantages are global" [1]. The comment states the importance of developing efficient cost effective solar energy technologies. As a result, over the past decade a wide range of technologies are being studied and researched including organic solar cells, dye sensitized solar cells [2], quantum dot solar cells [3] etc. Among the various upcoming technologies organic solar cells possesses clearly distinctive advantages such as low cost, made of abundant earth materials, easy manufacturing technologies and ability to incorporate various technologies. Although organic solar cells operates at efficiencies 10% [4] and above the widespread commercialization of organic solar cells demands a greater amount of research and developments on various aspects of understanding and development of organic solar cells such as device physics, optimization of device architectures, incorporating various new concepts and technologies etc. This paper reviews basic fundamentals of organic solar cells, design of organic solar cells focusing on design of materials by donor-acceptor approach, various development of organic solar cell architectures and novel architectural concepts such as optical light trapping devices, dye coated luminescent solar concentrator devices, tandem and organic-inorganic hybrid concepts.

2. FUNDAMENTAL PRINCIPLES OF ORGANIC SOLAR CELLS

The fundamental phenomenon of organic solar cells were developed by the discovery of organic semiconductors by H. Shirakawa, Alan G. M. and Alan J. Heeger in 1977 [5]. The interesting optical and electrical properties of organic semiconductors are due to the presence of conjugated π electron system. The most important property related to this conjugation are that the π electrons which are weaker and thus more mobile than σ electrons. This results in the reduction of energy difference between the HOMO-LUMO levels of the organic molecules causing it to act as light absorbers in the case of organic solar cells or light emitters as in organic light emitting diodes.

The basic steps of operation of organic solar cells includes the absorption of light by organic semiconductor molecules generating electrostatically bounded electron hole pair called excitons, in order to split the excitons, organic solar cell generally prefers a heterojunction of two materials with different electron affinities, this causes the major difference in working mechanism of organic solar cells compared to inorganic alternatives. Thus the next important step is the diffusion of excitons from where they are generated to the heterojunction interface, where it under goes splitting into free charges and then they are transported to the corresponding electrodes of different work function [6-9].

3. ORGANIC SOLAR CELL DESIGN- A PERSPECTIVE

The most important aspect in the design of organic solar cell is the bandgap of the light absorbing conjugated molecules. Typically it is desirable to have the bandgap around 1.1 eV as the case of silicon which is capable of absorbing 77% of the solar irradiation. But the organic semiconductor molecules are typically of higher bandgap above 2 eV, which could only absorb a maximum of 30% of solar photons [10]. In organic solar cells, low bandgap materials are typically used as donors and fullerene derivatives such as PC71BM due to their high electron affinity and charge carrier mobility. To obtain the desired performance in organic solar cell, optimization of bandgap by bandgap tuning of the absorbing molecules are employed. There are two fundamental approaches towards this: tune solubility and energy levels, attachment of various

ISBN: 978-81-93024-71-3

chemicals or molecules with the backbone polymer chain transforms the morphology and properties of the active layer. Various class of compounds have been discovered by attachment of different chemicals [11, 12].

Fused heterocyclic forms an important class of compounds that could achieve low bandgap and high carrier mobility. Some successful examples of such derivatives includes PCDTBT, PCPDTBT, PSBTBT, PCPDTPT etc. which are shown in the fig. 1 [13-16].

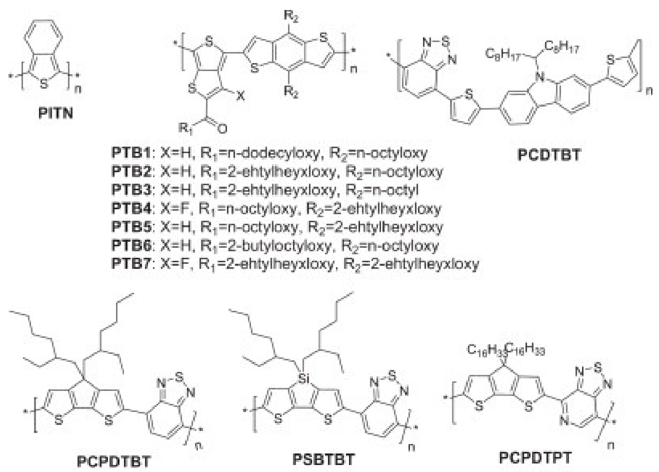

Fig. 1. Examples of fused hetero-cycle based polymers

Another important class of compounds are obtained by fluorination, i.e., typical replacement of the hydrogen atom by the high electro negative fluorine atoms. The tuning of energy level is achieved by the number of fluorine atoms in the repeating structures. Examples includes PBnDT-DTffBT, PBnDT-FTAZ etc which are shown in the fig. 2 [17-19]. Various other techniques are also being studied and researched including substituent effect where various class of substituent compounds are grafted onto the aromatic chain, where various aromatic rings are attached by covalent bondages [20-22].

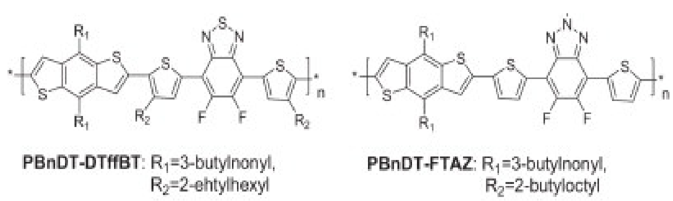

Fig. 2. Fluorinated polymer structures

Design of low bandgap efficient active layer is only the first strategy in developing organic solar cells. To efficiently convert the electromagnetic radiation energy or light energy to electrical energy requires optimization of many intrinsic and extrinsic components and properties that determines the performance of the organic solar cell. As described in the fundamental principles, organic solar cell utilizes heterojunctions formed of donor and acceptor materials to separate the excitons. Thus the selection and design of acceptor materials comprises the next important strategy determining the performance of the cell. Typically fullerene derivatives includes the most successful design, apart, other polymer acceptors includes Rylene diimide based polymer acceptors [23], fluorine and BT- based polymer acceptors [24], CN- constituted polymer acceptors [25] etc.

In study of electrodes, most organic solar cell designs utilizes high work function ITO and low work function metals such as Al, Ca or Mg as the electrodes. The optical and electrical properties of ITO and good stability makes it ideal as anode, apart in case of cathode although Mg and Ca could yield better performance, Al is preferred due to its relative stability in atmosphere. Graphene [26] and carbon nano-tube based electrodes [27] are an important class of promising materials for electrodes.

The next section discusses various types of architectures of organic solar cells.

4. ORGANIC SOLAR CELL ARCHITECTURES

4.1 Single layer organic solar cells

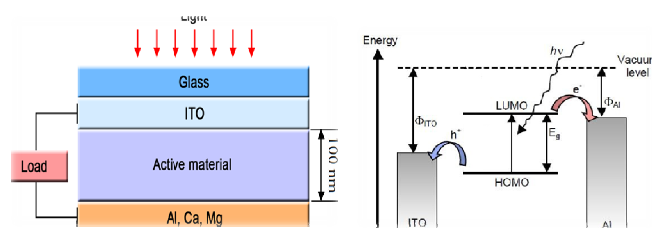

Fig. 3. Single layer organic solar cell structure and energy level diagram.

A single layer semiconductor solar cell consist of an organic semiconductor photoactive material sandwiched between two electrodes of different work function. These cells exhibit low efficiency due to two reasons: the electric field required to break up the excitons are too low and confined to the junctions and the separated charges have to pass through the same medium to reach the electrodes resulting high recombination loses [29].

4.2 Bilayer heterojunction organic solar cells

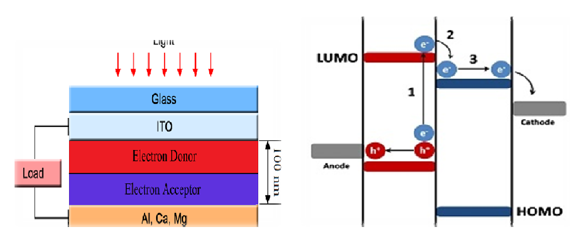

Fig. 4. Bilayer heterojunction organic solar cell structure and energy level diagram.

ISBN: 978-81-93024-71-3

The bilayer heterojunction devices, as the name indicates uses two different materials junctions for charge separation, known as donor and acceptor materials. Although these cells have obtained better performance than single layer devices, inability of a major part of excitons to reach the donor-acceptor junction limits its performance [29, 30].

Bulk heterojunction organic solar cells

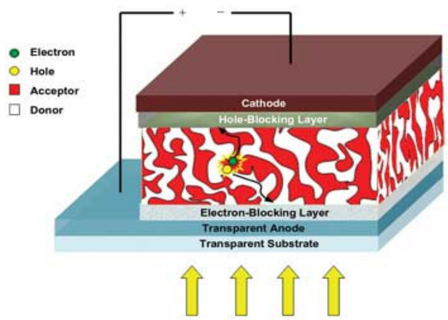

Fig. 5. Bulk heterojunction solar cell architecture.

The bulk heterojunction solar cell uses a blend of acceptor and donor materials such that the effective length scale of the blend is similar to that of the exciton diffusion length. This results in effective extraction of charges and considerably higher performances. Inorder to reduce the leakage current losses as both the donor and acceptor materials would be in contact with both the electrodes, additional layers such as electron blocking or hole blocking layers may be used [32, 41].

4.4 Multiple heterojunction organic solar cells

Apart from bulk heterojunction concept, another idea for optimizing the donor acceptor length scale onto the exciton diffusion length is by forming continuous multilayer structures as the example shown in the fig. 6 [33, 34].

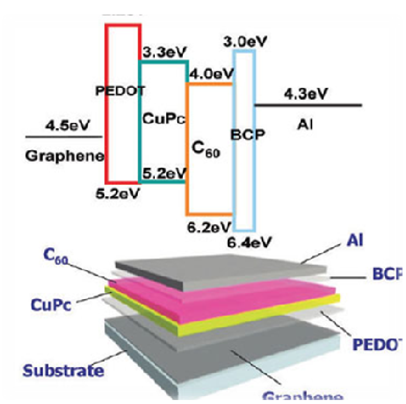

Fig. 6: Multiple heterojunction organic solar cell and energy level diagram.

Novel concepts and recent developments in organic solar cell architectures

The researches is organic solar cell architectures are directed towards optimization of various device parameters such as active layer morphology, interfacial state properties, electrode area etc.

Various techniques are being studied and researched for improving the device performance. Use of optical spacers such as titanium oxide or zinc oxide have been utilized to tailor the distribution of light intensity within the device such that there is local optical maximum at the donor-acceptor interface. Another notable application of this development is their application in tandem designs [35].

Further developments includes the use of solar collectors, micro lens structures, nanostructures including patterned and embossed gratings, diffraction gratings and buried nano electrodes. Light confinement and light trapping are another approaches to enhance the external quantum efficiency. An example device is shown in the fig. 7. It is predicted that these kind of devices could achieve efficiency of 25% [36, 37].

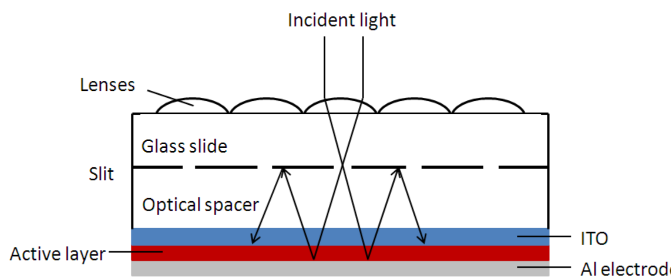

Fig. 7. Schematic of a light trapping device architecture.

Luminescent concentrators are another innovative approach to convert light into more desirable wavelengths [38]. Deposition of short and long wavelength dyes on the glass or plastic substrate such that the dyes absorbs the low wavelength radiations and reemits them at higher wavelengths. This kind of designs also assists in developing efficient multi-colored organic solar cells. Example shown in fig. 8 [39].

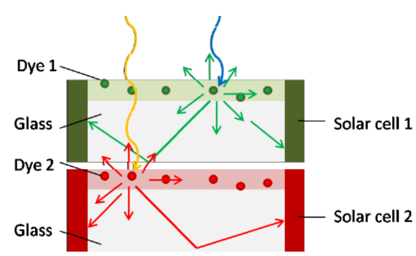

Fig. 8. Schematic of light behavior- the luminescent solar concentrator device utilizing two dye coated substrates.

Tandem cells use multiple junctions, each one tuned to different frequencies of the spectrum. This helps in reducing the limitations of spectrum matching of the active layer. In common designs, a high bandgap solar cell sits on the top,

ISBN: 978-81-93024-71-3

absorbing high energy, low wavelength light and transmitting the rest. Beneath is a low bandgap solar which absorbs the longer wavelength light. Typical designs consists of three or four layers [40].

Application of tandem structure in organic cells began with development of small molecule solar cells fabricated through thermal evaporation. The thermal evaporation technique allows the fabrication of very thin multi layered cells, concepts like incorporation of a metal in between. This kind of cells had reported very high efficiency of 10.6% [4, 41-43]

Another notable improvement is the development of organic-inorganic hybrid solar cells. This design offers wide scope of development due to their inherent advantages such easily tunable bandgap, ease of fabrication, multiple exciton generation, high charge carrier mobility etc. Although the research developments in this field is still in nascent stage and requires tremendous amount of optimization for being capable of providing commercial applications. Various nano architectures that makes uses in different ways are shown in the fig. 9 [37, 44-46].

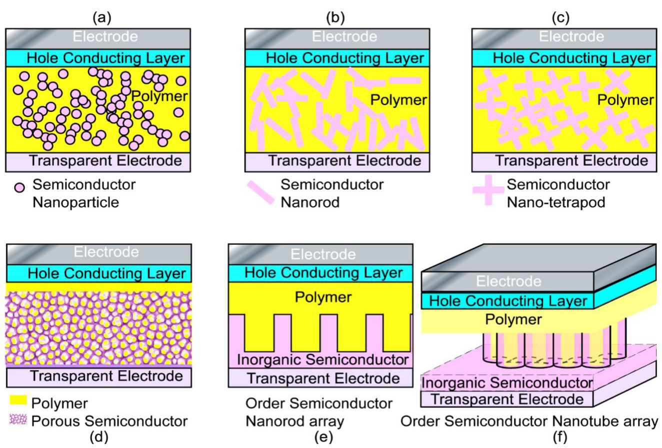

Fig. 9. Various nano-architecture of organic-inorganic hybrid solar cells

5. CONCLUSIONS

Organic solar cells proves to be very promising technology for providing low cost photovoltaics power. Although the current stage of technology requires lots of optimization and research for the effectively utilize the expected advantages. With the current intensity of research in the field, it is expected that organic solar cells could revolutionize the photovoltaic industry in the near future.

Although the technology faces sever technological limitations that is needed to be addressed soon such as the low stability, lower efficiency etc. This paper presented a perspective into the fundamental principles of organic solar cells, a design approach and various architectural designs, their limitations and drawbacks and novel concepts.

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