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Organic materials for photovoltaic applications: Review and mechanism

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ABSTRACT

Recently Heliatek have reported the 12% certified efficiency of organic photovoltaic (OPVs). This rapid progress suggests that the commercialization of OPVs will be realized soon. In addition to the achievement of such high efficiency in OPVs, yet there is a wide need of improvements e.g. the need of electron-acceptors materials other than fullerene, better understanding of charge-transport mechanism in organic materials, requirement of the material compatible with the flexible substrate, durability of the organic materials based devices etc. The aim of this paper is to review the recent developments in OPVs and the potentials of organic photovoltaic, which has caught the attention of many researchers working in the field of optoelectronics. In this article, the organic solar cell mechanism, the basic design, the recent developments and the efficient organic materials for OPVs are reviewed. The authors have reviewed the recent articles to understand the mechanisms of photocurrent generation and sketched out the search for alternative materials for these devices.

Contents

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1. Introduction

Over the years, the world's industries and research organization have shown their interest in the renewable energy resources due to the limited fossil fuel reserves [1,2]. The efficient use of sunlight to produce the domestic electricity by means of solar cell devices is the perfect way to deal with the limitation of the reserve fossil fuel. The solar cell industry has been growing by over 30%/year, albeit admittedly from a very low base, and thus still represents a tiny fraction of the world energy supply (much below 1%) [3]. The conventional inorganic materials based solar cells, such as silicon solar cells and heterojunction solar cells which currently dominate the photovoltaic (PV) market, are relatively mature technologies, and the power conversion efficiency of these devices is approaching record limits of about 24.7% for crystalline silicon solar cells [4] and greater than 42.3% for certain multijunction solar cells [5] exposed to more than 400 suns (all reported efficiencies are under AM1.5 illumination conditions). Regardless of the efficient silicon based technology, their fabrication processes are complex, which involves a number of steps that make solar panels expensive and the energy they produce uncompetitive compared to traditional energy sources (e.g. coal, natural gas, hydropower, etc.) Moreover, silicon solar cells are rigid and cannot be fabricated industrially in large sizes due to the limitation of the silicon wafer processing technology. These disadvantages of silicon PVs and their relative limited ability to provide cost effective energy are some of the reasons that have led many researchers to explore alternative materials for solar energy generation. Several different materials have investigated as an alternative for high cost silicon PVs and some of them are currently dominating the PV market. Among them the most promising alternative candidates of the high cost silicon PVs are the organic photovoltaic cell (OPV) which expected to have a major impact in terms of reduction of production costs [6–8]. An organic solar cell or organic photovoltaic (OPV) cell is a photovoltaic cell that uses organic electronics – a branch of electronics that deals with thin film of π-conjugated semiconducting organic molecules, oligomers or polymers for light absorption and charge transport. They are fabricated by very simple and cost-efficient techniques, such as spin coating, spray deposition, and printing. Although OPV efficiencies are not yet competitive with more traditional technologies, a very rapid improvement has been observed in recent years and laboratory certified cells now reach 12% [9]. OPVs are commonly fabricated in thin film form of electron-donor (D) and -acceptor (A) materials with suitable energy levels matching, sandwiched between electrodes. Out of the two, one electrode must be transparent which acts as a window to the incident light. Due to the low dielectric constant in organic components (∼3) photoexcitation leads to a strongly bound exciton, which needs to be dissociated into free carriers [10]. This dissociation can take place at the D–A interface. Then, free carriers need to be transported to the corresponding electrodes via drift and diffusion processes, where they are collected, giving rise to an electric current. The main reason behind the improper dissociation and transport of the charge carrier is the small diffusion length (10–20 nm) of the excitones [11,12].

The first report on an organic (excitonic) PV cell came as early as 1959, when Kallmann and Pope studied anthracene single crystal. The resulting cell exhibited an extremely low efficiency [13]. Till now, the resulting efficiency of the OPV cell with single active organic layer remained below 0.1% due to the formation of strongly bound excitons which need to be split to produce an external current. The pioneer work in this field has been done by the Tang when he fabricated the novel photovoltaic cell based on a two-layer structure of organic thin films and he achieved a power conversion efficiency of about 1% under simulated AM2 illumination [14]. He takes two organic semiconductors with offset energy bands (i.e. with different electron affinities: an electron donor and an electron acceptor) and demonstrated that the interface region is primarily responsible for the photogeneration of charges. Although the Tang work was remarkable but the limitation in the Tang's device is due to the low exciton diffusion length in conducting polymers (typically <10 nm), the only light absorbed very close to either side of the interface is effectively active to generate free carriers. Due to this device efficiencies were limited to around 1% for many years.

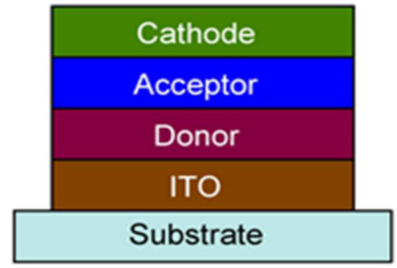

Fig. 1. Bilayer organic solar cell structure.

From the last ten years a large work has been devoted to understanding the basic transport mechanism of organic molecules for the improvement in the efficiency of the cell [15–18]. With the help of these studies and the introduction of new materials a remarkable improvement is observed in the field of OPV. Many simple and useful methods of optimization have been successfully performed in the last decade [19]. The choice of proper solvents [20] as well as the thermal treatment of the solution-processed polymer: fullerene solar cells [21] both lead to a more favorable inner structure in view of the dissociation of bounds electron–hole pairs and the subsequent charge transport. Thus, the power conversion efficiency was increased in the case of annealing from a bare half percent to above 3%. Indeed, optimization by novel routes is an ongoing process, and within the last five years, further steps in improving the power conversion efficiency have been made. Using a concept of planar-mixed heterojunction, coevaporated copper phthalocyanine/fullerene solar cells have reached 5.0% efficiency [22]. The solution-processed polythiophene: fullerene cells achieved between 6% and 8% efficiency by the use of novel materials as well as additives optimizing the phase separation [23–25]. The threshold efficiency for commercial applications of OPV is 10% and the researchers have strived to reach this goal. The remarkable effort to achieving this goal has been done by Zhicai He et al. group. The group demonstrates highly efficient polymer-based organic photovoltaic solar cells with a certified efficiency of 9.2% using an inverted structure [26]. Till now the highest reported efficiency of the OPV cell is 12% which is recently achieved by Heliatek Company [9].

In this article we present an organic solar cell mechanism and review of efficient organic materials. The basic photovoltaic characteristics, OPV device structure, materials for OPV and parameters affecting the efficiency of the solar cell have been described shortly. The different architectures of organic solar cell and their influence on the device performance are also included. We tried to include all the recent work on the OPV cell which have been done by the majority of researchers around the world over the years and request our apology if any contribution has left from this review.

2. Organic solar cell mechanism

To explain the mechanism of organic solar cell, let us take an example of bilayer organic solar cell (Fig. 1). In a bialayer devices two active organic materials namely donor (D) and acceptor (A) are sandwiched between the two electrodes. Out of the two electrodes at least one of the electrodes must be transparent to allow