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Efficiency of bulk-heterojunction organic solar cells

M.C. Scharber, N.S. Sariciftci*

Linz Institute of Organic Solar Cells (LIOS), Physical Chemistry, Johannes Kepler University Linz, Altenbergerstrasse 69, 4040 Linz, Austria

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ABSTRACT

During the last years the performance of bulk heterojunction solar cells has been improved significantly. For a large-scale application of this technology further improvements are required. This article reviews the basic working principles and the state of the art device design of bulk heterojunction solar cells. The importance of high power conversion efficiencies for the commercial exploitation is outlined and different efficiency models for bulk heterojunction solar cells are discussed. Assuming state of the art materials and device architectures several models predict power conversion efficiencies in the range of 10–15%. A more general approach assuming device operation close to the Shockley–Queisser-limit leads to even higher efficiencies. Bulk heterojunction devices exhibiting only radiative recombination of charge carriers could be as efficient as ideal inorganic photovoltaic devices.

Contents

1. Introduction

Thin film photovoltaic cells based on solution processable organic semiconductors have attracted remarkable interest as a possible alternative to conventional, inorganic photovoltaic technologies. The following key advantages of organic photovoltaic (OPV) devices have been identified:

1. Low weight and flexibility of the PV modules.
2. Semitransparency.
3. Easy integration into other products.
4. New market opportunities, e.g. wearable PV.
5. Significantly lower manufacturing costs compared to conventional inorganic technologies.
6. Manufacturing of OPV in a continuous process using state of the art printing tools.
7. Short energy payback times and low environmental impact during manufacturing and operations.

Most of the advantages listed above do also apply to solar cells based on vapor-deposited small molecule absorbers. This suggests that OPV does have the potential

* Corresponding author. Tel.: +43 732 2468 8753; fax: +43 732 2468 8770.
E-mail addresses: Markus_Clark.Scharber@jku.at (M.C. Scharber), Serdar.Sariciftci@jku.at (N.S. Sariciftci).

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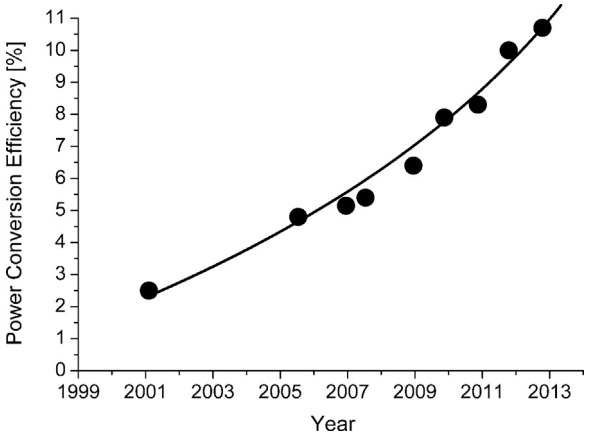

Fig. 1. Certified record power conversion efficiencies of single junction organic solar cells published in Progress in Photovoltaics. The first point in the graph (year 2001) is not listed in any efficiency table.

to be a disruptive technology within the PV market. The bright outlook has initiated a lot of research and development activities and substantial progress has been made in increasing the power conversion efficiency (PCE) of solution processed OPV during the last years. In 2001 Shaheen et al. [1] reported a record efficiency of 2.5%. About 10 years later, Mitsubishi Chemical demonstrated a PCE > 10% for lab devices with an active area of ~1 cm^2 [2]. In Fig. 1 the development of the power conversion efficiency of bulk heterojunction solar cells is summarized. Device data were taken from the solar cell efficiency tables published in Progress in Photovoltaics: Research and Applications [3–9]. In addition, several different printing and coating processes have been developed and classical roll-to-roll processing of organic solar cells has been demonstrated. Today fully printed prototypes are manufactured and first products are available [10]. Commercially available modules do show power conversion efficiencies in the range of 1.5–2.5%.

Remarkable improvement in durability of bulk-heterojunction solar cells remarkable progress has been achieved during the last ten years. While the first devices had to be stored in an inert atmosphere, and degraded quickly on exposure to sunlight, today small organic PV modules on flexible substrates with operational lifetimes of a few years are available [11]. Jorgensen et al. summarized the status of the current understanding of organic photovoltaic stability in a recently published review article [12]. The initiative "International Summits on Organic Photovoltaic Stability" (ISOS) has supported efforts to investigate and improve OPV stability by establishing standard testing protocols and initiating focused research efforts on organic solar cell degradation. Although several studies indicate that a clever design of photoactive materials will improve the photochemical stability of organic absorber layers, rigorous encapsulation appears to be mandatory to ensure long term stability. Manceau et al. [13] investigated the photochemical stability of semiconducting organic polymers under simulated sunlight and ambient atmosphere. They found that the molecular structure including the attached side chains have a strong impact on the photochemical stability. Based on their results they suggest guidelines for the design of polymers with an improved photochemical stability in the presence of ambient air. Tromholt et al. [14] and Hoke et al. [15] studied the photochemical stability of organic semiconducting donor acceptor blends under illumination and ambient conditions. They found that the electron affinity of the acceptor determines the degradation rate of the semiconductor layer.

Besides the detailed understanding of photochemical processes in organic absorber layers, the development of alternative device designs has resulted in a significant improvement of the device stability. In early devices low work function metals like calcium, barium or aluminum were applied as cathodes. Exposure to oxygen or water caused an almost immediate oxidation of these electrodes resulting in a fast degradation of the power conversion efficiency. By introducing the so-called inverted design [16] this fast electrode degradation could be overcome [17]. The low work function metals has been replaced by transparent oxides like zinc oxide [17] or titanium dioxide [16] or the work function of stable electrode materials has been modified using a thin interfacial layer [18] to form the cathode of the solar cell. As anode materials sliver gold or standard hole-injection layers like PEDOT:PSS has been applied. An additional advantage of the inverted device design is that all layers can be deposited from solution and no vacuum process is required [17].

Overall there has been remarkable progress in the field of organic solar cells. Within less than 20 years double digit efficiencies and reasonable lifetimes were achieved. However, before large scale commercialization and entering a direct competition with state of the art inorganic PV technologies, further improvements especially in the power conversion efficiency are required. The review is organized as follows: after the introduction the device architecture and the working principle of bulk heterojunction solar cells are summarized. In the third section we discuss the importance of the power conversion efficiency (PCE) of photovoltaic cells for large area electricity production. In Section 4 we describe a general efficiency limit of photovoltaic cell followed by models for the efficiency of bulk-heterojunction solar cells and a short summary.

2. Bulk heterojunction solar cell basics

The absorber layer of an efficient state of the art bulk heterojunction solar cell is made of so-called donor and acceptor molecules. As donors usually conjugated polymers, oligomers or conjugated pigments, as acceptors frequently fullerene derivatives are applied (Fig. 2). Often these materials are classified as organic semiconductors [19]. They are known for their outstanding optical properties and their ability to transport charges [19].

A schematic diagram of the energy levels of a typical donor acceptor system is shown in Fig. 3. HOMO denotes the highest occupied molecular orbital and LUMO the lowest unoccupied molecular orbital of the organic molecules. It is generally accepted that in state of the art organic semiconductors a bound electron–hole pair (exciton) is generated upon photon absorption [23]. Due to the low dielectric constant of organic materials, there is a strong

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