Renewable and Sustainable Energy Reviews 56 (2016) 347–361

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Progress in emerging solution-processed thin film solar cells – Part I: Polymer solar cells

Qin Wang, Yu Xie, Firuze Soltani-Kordshuli, Morteza Eslamian *

University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai 200240, China

A R T I C L E I N F O

Article history:
Received 9 June 2015
Received in revised form
8 November 2015
Accepted 22 November 2015

Keywords:
Emerging solar cells
Polymer solar cell
Organic solar cells
Organic photovoltaics
Solution-processed solar cells

A B S T R A C T

Polymer solar cell (PSC), also called organic photovoltaic solar cell (OPV), is an emerging solar cell, benefitting from recent advances in nano-structured and functional energy materials and thin films, making it a cutting edge applied science and engineering research field. The driving force behind the development of PSCs is the need for a low-cost, scalable, flexible, light-weight, and easy to manufacture power source, something that does not have the disadvantages of crystalline silicon and inorganic thin film solar cells. The fact that most layers of organic solar cells can be made from materials that can be processed in solution and deposited using low-cost casting methods in ambient conditions is a great advantage of solution-processed (SP) solar cells (SCs). The unique characteristic of this review, compared to other reviews, is its focus on solar cell materials and scalable fabrication techniques that are compatible with the concept of solution-process-ability. Following this perspective, in this paper, an overview of the principle of operation, recent progresses within the past few years, current challenges, and innovations pertinent to each layer of SP-PSCs and the entire device are provided. Detailed discussion on suitable materials for each layer, the effects of solvent treatment on nano-structure of each layer, cell stability and lifetime, and the state-of-the-art scalable methods suitable for large scale manufacturing of SP-PSCs are reviewed. At the end, future research trends in the area are deliberated. In Part II, recent advances in lead halide perovskite solar cells will be reviewed.

Contents

* Corresponding author. Tel.: +86 21 3420 7249; fax: +86 21 3420 6525.
E-mail addresses: Morteza.Eslamian@sjtu.edu.cn, Morteza.Eslamian@gmail.com (M. Eslamian).

http://dx.doi.org/10.1016/j.rser.2015.11.063
1364-0321/

1. Introduction

Harnessing the abundant and clean solar energy is one of the most promising approaches to resolve the ever-increasing energy problems, caused by depletion of non-renewable energy resources [1,2]. The devices converting photons energy directly to electricity, i.e. the photovoltaic (PV) solar cells, have been developed through several generations. The first generation (1G) was based on crystalline silicon with a high efficiency, but also accompanied by a high cost of thick wafers of several hundreds of microns (required for effective photon absorption in silicon), and vacuum processes for the fabrication of defect-free crystalline films. The occurrence of the 2nd generation (2G) based on thin film inorganic semiconductors, such as amorphous silicon, copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) [3], was aimed to address the issue of the high cost of 1G solar cells through the utilization of thin film technology. However, the cost of the electricity produced by 2G SCs is still high, which in turn promoted the exploration of the 3rd generation (3G) or emerging solar cells, with the aim of generating electricity at a lower cost than 2G counterparts. Some 3G or emerging solar cells include dye-sensitized, quantum dot, organic or polymer, and inorganic-organic perovskite solar cells. The emerging solar cells somehow take advantage of the recent advances made in nanotechnology and the development of molecular semiconductors, such as quantum dots, semiconductor nanoparticles, nano thin films and nanostructures.

Most layers of emerging solar cells may be processed in solution and fabricated using vacuum-free and low-cost processes. Therefore, such solution-processed solar cells have attracted tremendous amount of attention not only because of their increasing efficiency and low cost, but also due to potential for scalability, favorable performance-to-weight ratio, easy manufacturing with low environmental impact, as well as short energy payback times [4–6]. Most of the above-mentioned advantages suggest that solution-processed solar cells do have the potential to revolutionize the photovoltaic (PV) industry. This review focuses on solution-processed (SP) polymer solar cells (PSCs). When searching the term "solution processed polymer solar cells" in the ISI Web of Science database, one can find that the number of publications in 2014 was above 700 of a total of approximately 6212 research papers with astonishing 24000 citations (as shown in Fig. 1). The graph shows only about 50 publications in the field 10 years ago. This enormous increase in research activities in this

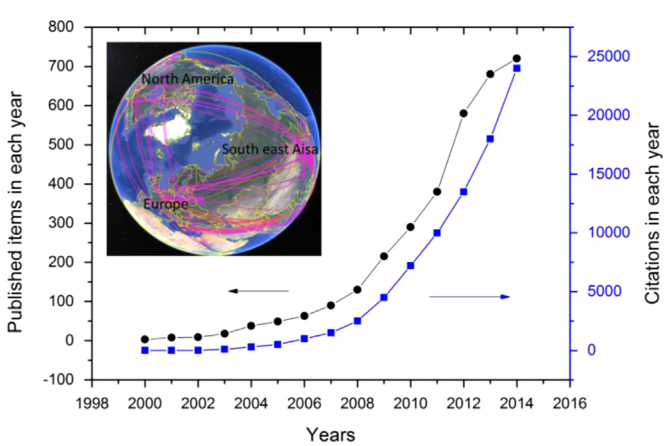

Fig. 1. Published papers and citations in each year for solution-processed PSCs from year 2000 to 2014. The inset picture is the Google Earth map for research institutes (the pink line) in this field by using CiteSpace software analysis from year 2009 to 2014. The parameters for the software are as follows: medium map scale; show links and refresh previously generated files; nodes: aa; links:3a. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

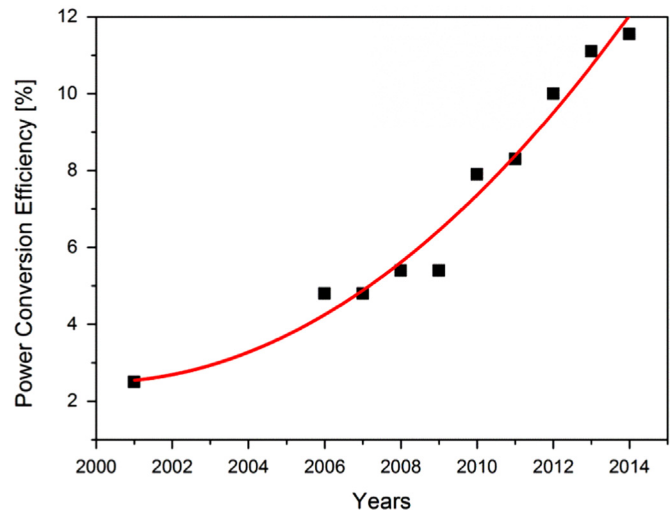

Fig. 2. Trend of change of power conversion effiiciency (PCE) of PSCs from 2001 to 2014.

field has resulted from a tremendous demand for finding efficient and low-cost renewable power sources. By using CiteSpace software [7], a google earth map is generated to visualize the academic institutions in the world that are involved in solution-processed polymer solar cell research (the inset of Fig. 1). It is manifested that most of the research organizations in the SP-PSC field are located in leading research institutions in North America, Europe, and Southeast Asia, which proves that solution-processed PSC is a quite appealing research area.

The power conversion efficiency (PCE), the fraction of the incident photons converted to electricity, is the main factor determining the conversion performance of a solar cell [6]. In 2001, Shaheen et al. [8] successfully prepared a conjugated polymer/methanofullerene blend solar cell, reaching an efficiency of 2.5%, which was a threefold enhancement over previously reported values at the time. In 2014, Chen et al. [9] adopted a creative triple junction structure with a PCE exceeding 11%, which is a more than four times increase within 13 years. Fig. 2 summarizes the rising trend of PCE of PSCs from 2001 to 2014 [8–18]. This notable progress suggests that PSC has the potential to compete with traditional inorganic PV SCs [19], if the device stability, lifetime and large scale fabrication issues are addressed. In order to maintain the current progressive status, and further increase the efficiency [20] and improve the stability, it is crucial to understand the mechanism of operation and identify the factors governing the performance of PSCs.

The basic principle of operation of a PSC is illustrated in Fig. 3. The photons are absorbed either by the donor and/or acceptor, promoting the electrons to the lowest unoccupied molecular orbital (LUMO), leaving behind holes in the highest occupied molecular orbital (HOMO), leading to the formation of excitons (electron-hole pairs) bounded by coulomb attraction forces due to the low dielectric constant of organic materials. The excitons then diffuse to the interface between the donor and acceptor and separate into free charge carriers that can be transported and collected at anode and cathode, generating electricity. The donor/acceptor is a molecular semiconductor, where LUMO and HOMO correspond to the conduction and valance bands in inorganic semiconductors. Excitons have a relatively short lifetime (<1 ns), requiring fast charge dissociation in order to prevent charge recombination [21]. Another precondition for producing effective free charge carriers is that the distance between the generated excitons to the nearest donor/acceptor interface be within their diffusion length, L_D [6]. Mikhnenko et al. [22] found that in several prototype narrow bandgap