Renewable and Sustainable Energy Reviews 62 (2016) 1012–1031

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 II: Perovskite solar cells

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ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form
24 January 2016
Accepted 2 May 2016
Available online 19 May 2016

Keywords:
Photovoltaics
Perovskite solar cell
Solar cell stability
Commercialization challenges
Spray coating

ABSTRACT

Perovskite solar cell (SC) is the most attractive and efficient emerging thin film SC, with a power conversion efficiency (PCE) of up to 22%, certified by the United States National Renewable Energy Laboratory (NREL), although the cell is not stable. Most layers of perovskite SCs, including the perovskite light harvesting layer, are solution-processed, and thus can be fabricated by low-cost, scalable and vacuum-free fabrication techniques, such as spray coating. Part I of this work was devoted to polymer or organic SCs, a more mature but less efficient solution-processed SC (Wang et al., Renew Sustain Energy Rev 2016;56:347–61) [1], and Part II reviews the fundamentals and recent advances in perovskite SCs, from an engineering points of view. The review starts off with an introduction to perovskite crystal structure in general, lead halide perovskite crystals as a light harvesting material, and the principle of operation of various architectures of perovskite SCs, such as mesoporous and planar. Then various components, including the light harvesting layer, electron transporting layer (ETL), hole-transporting layer (HTL), and possible materials developed for each layer are discussed. The effects of various processing parameters, such as the annealing time and temperature, solvent effect, reaction time, solution concentration, and the thickness of each layer are discussed, to find the optimum process parameters. Possible methods for the fabrication of perovskite layer and other layers are discussed, including spin–spin and spin–dip sequential methods and scalable methods, such as spray coating. The stability of perovskite SCs is also deliberated and advances made to improve the device lifetime are reviewed. The review concludes with a summary and discussion of research trends and challenges in the field. Other general issues, such as the necessity for the development of flexible substrates, indium-tin-oxide (ITO)-free devices, solution-processed back contact, and comprehensive discussion of all solution-processed techniques have been already considered in Part I of this review.

Contents

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http://dx.doi.org/10.1016/j.rser.2016.05.042
1364-0321/

1. Introduction

Photovoltaic (PV) solar cells (SC) are appealing and promising renewable power sources, and are regarded as a viable future substitute for fossil-fuel-based electricity generation systems. Silicon-based and inorganic thin film PV solar panels have already commercial applications in specialty devices and in rather limited scale in residential and commercial buildings. In order to reduce the cost of the energy delivered by PV SCs, low-cost SC materials and vacuum-free fabrication methods have been sought, leading to the emergence of the new generation of thin film solar cells. The research on emerging SCs, however, is slowing down due to a decrease in the cost of silicon wafers and silicon solar cells, and challenges associated with stability and/or efficiency of such SCs. Most layers of the emerging solar cells may be processed from solution and fabricated using low-cost casting and printing methods on flexible and transparent substrates for existing and emerging applications such as solar windows. Two categories of emerging SCs that very well fit within the definition of the solution-processed SCs include the polymer (organic) and perovskite SCs. Polymer solar cells were discussed in Part I of this review [1] and Part II is devoted to perovskite SCs. Other solution-processed solar cells include but are not limited to quantum-dot SCs, kesterite SCs, chalcopyrite SCs, etc..

Perovskite SC is the most exciting and the frontrunner of the emerging thin film SCs, where most of its layers are solution-processed in mild conditions [2,3]. The main outstanding features of perovskite materials include their direct band-gap property, high absorption coefficient, satisfactory carrier transportation properties, high power conversion efficiency (PCE) and tuneable stability [4]. They are composed of nature abundant materials and can be crystalized from solution at low temperatures. The current challenges associated with perovskite SC are the instability of the lattice at room temperature, and difficulties associated with controlling the semiconductor structure by solution-processed methods, which is hard to tune in molecular scale. The perovskite crystal structure will be discussed in the next section.

Methylammonium lead iodide ($CH_3NH_3PbI_3$) is a light harvesting semiconducting molecule, with a perovskite structure, and is used in perovskite SCs. $CH_3NH_3PbI_3$ possesses a suitable band gap of 1.55 eV corresponding to the onset value of 800 nm wavelength in the sunlight spectrum [3], thus it is an ideal light harvesting molecular semiconductor. Fig. 1 compares the normalized external quantum efficiency (EQE) of different types of PV devices, including $CH_3NH_3PbI_3$, cadmium telluride (CdTe), copper indium gallium selenide (CIGS), dye-sensitized SC (DSSC), and amorphous silicon (a-Si). EQE is defined as the ratio of the number of charge carriers collected by the solar cell to the number of the incident photons. The $CH_3NH_3PbI_3$ active layer in a perovskite SC can absorb a wide range of photons in the light spectrum, near to the infrared wavelengths, surpassing the light harvesting capability of some other counterpart SC materials. Its EQE is not as high as inorganic thin film SCs shown in Fig. 1, however given that perovskite SC is a solution-processed molecule and thus potentially low-cost, its EQE is quite impressive. Aside from their high light absorption coefficient compared to some inorganic semiconductors, as shown in Fig. 2, $CH_3NH_3PbI_3$ has a weak exciton binding energy, [5] whereby electrons and holes are easily generated and conducted in ambient conditions. As another advantage, perovskite SCs can be combined with other types of SCs, making hybrid or tandem SCs.

Owing to its high absorption coefficient, a sub-micron perovskite thin layer may function as efficient as other types of active layers, with much larger thickness [4]. However, low thickness and coverage in perovskite thin films may result in direct contact between buffer layers and a drop in device performance. Accordingly, devising a good combination of electrical charge diffusion and interface contacts entails a careful planning of formulation and architecture [6,7].

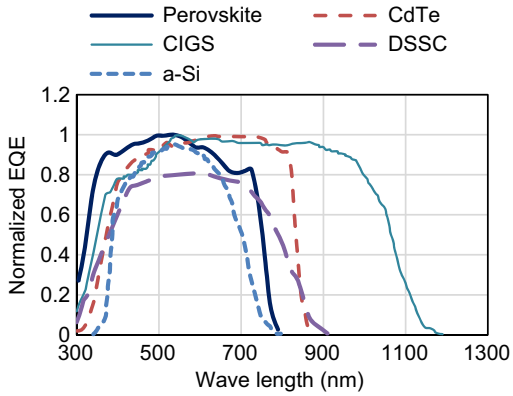

Fig. 1. Normalized external quantum efficiency (EQE) of mixed-halide perovskite SC, compared with some other types of thin film SCs. Data reproduced from different references, e.g. [42,75]. The perovskite here is mixed-halide $CH_3NH_3Pb(I_{0.9}Br_{0.1})_3$.

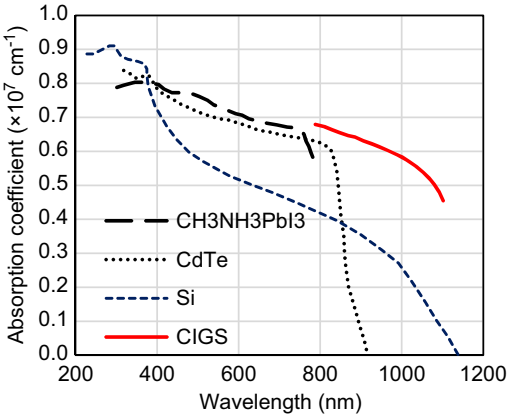

Fig. 2. Absorption coefficient of various light harvesting materials, in comparison with perovskite layer (data taken from Ref. [41]).