Renewable and Sustainable Energy Reviews 68 (2017) 234–246

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Review on dye-sensitized solar cells (DSSCs): Advanced techniques and research trends

Jiawei Gong[a,b], K. Sumathy[a,*], Qiquan Qiao[b], Zhengping Zhou[b]

[a] *Department of Mechanical Engineering, North Dakota State University, Fargo, ND 58102, USA*
[b] *Center for Advanced Photovoltaics, Department of Electrical Engineering, South Dakota State University, Brookings, SD 57007, USA*

ARTICLE INFO

Keywords:
Dye-sensitized solar cells
Device modeling
Light harvesting
Surface engineering
Tandem solar cells
Perovskite solar cells

ABSTRACT

Dye-sensitized solar cell (DSSC) offers an efficient and easily implemented technology for future energy supply. Compared to conventional silicon solar cells, it provides comparable power conversion efficiency (PCE) at low material and manufacturing costs. DSSC materials such as titanium oxide (TiO_2) are inexpensive, abundant and innocuous to the environment. Since DSSC materials are less prone to contamination and processable at ambient temperature, a roll-to-roll process could be utilized to print DSSCs on the mass production line. DSSCs perform better under lower light intensities, which makes them an excellent choice for indoor applications. Due to the advancement of molecular engineering, colored and transparent thin films have been introduced to enhance the aesthetic values. Up to now, such benefits have attracted considerable research interests and commercialization effort. Here, this review examines advanced techniques and research trends of this promising technology from the perspective of device modeling, state-of-art techniques, and novel device structures.

1. Introduction

The ever-increasing demand in energy supply has accelerated fossil fuel depletion. It is projected that the reserves of fossil fuels throughout the world could only last 40 years for oil, 60 years for natural gas and 200 years for coal [1]. The imminent depletion has spurred the advancement of renewable energy technologies. For example, the European Union (EU) has agreed on a target that by 2030 renewable energy should account for at least 27% of EU's final energy consumption [2]. In accordance, United State has invested more than $90 billion in clean energy development through the Recovery Act [3]. Among all renewable energy technologies, photovoltaic technology is particularly attractive for direct conversion of sunlight into high-quality electricity energy. However, the existing silicon-based solar cells are restricted to the terrestrial PV market due to their high production and environmental costs.

In comparison with high-cost conventional silicon solar cells, dye sensitized solar cells are well known as a cost-effective photovoltaic device because of inexpensive materials and simple fabrication process. Dye-sensitized solar cells are composed of titanium oxide (TiO_2) semiconductor which is commonly used as a paint base in pigment industry, and the dye sensitizer that can be extracted from a variety of natural resources with minimum costs. In addition, carbonaceous materials could be used to replace platinum catalyst which can further reduce the material cost. As such, DSSCs are easy to fabricate since they are insensitive to environment contaminants and processable at ambient temperature. These unique features are favored in roll-to-roll process which is a continuous, low-cost manufacturing method to print dye-sensitized solar cells on flexible substrates. Furthermore, DSSCs work better even during darker conditions, such as in the dawn and dusk or in cloudy weather. Such capability of effectively utilizing diffused light makes DSSCs an excellent choice for indoor applications like windows and sunroof.

The advantages of dye-sensitized solar cells paved the way for intensive research interest, which had reflected a tremendous increase in the number of publications in the past decade (Fig. 1). Though the seminal work on dye-sensitized solar cells (DSSCs) was initiated in 1991 by O'Regan and Grätzel [4], the research has advanced at a rapid pace and a considerable amount of work has been made to improve the device efficiency from 7.1% in 1991 to 13% in 2014, a level deemed as necessary for commercial use [5]. In this work, the current state-of-art on DSSCs including modeling, and critical technologies are reviewed. The interested readers could also refer to our previous review on fundamental concepts and novel materials used in DSSCs including panchromatic dyes, semiconductor photoanode, counter electrode, and electrolyte development for a complete understanding of the processes and parameters controlling their photovoltaic operation [6]. Besides, recent reviews [7,8] detailing material development on all key compo-

* Corresponding author.
E-mail address: sumathy.krishnan@ndsu.edu (K. Sumathy).

http://dx.doi.org/10.1016/j.rser.2016.09.097
Received 23 December 2015; Received in revised form 20 July 2016; Accepted 23 September 2016
1364-0321/

Nomenclature

APCE	absorbed photon to current efficiency
CB	conduction band
DSSCs	dye-sensitized solar cells
FTO	fluorine doped tin oxide
HTPV	hybrid tandem photovoltaic
HTM	hole transport material
ITO	indium tin oxide
IPCE	incident photon to current efficiency
MSSCs	meso-superstructured solar cells
MPP	maximum power point
PEC	power conversion efficiency
TCO	transparent conducting oxides
VB	valence band

Subscripts

oc	open circuit
sc	short circuit

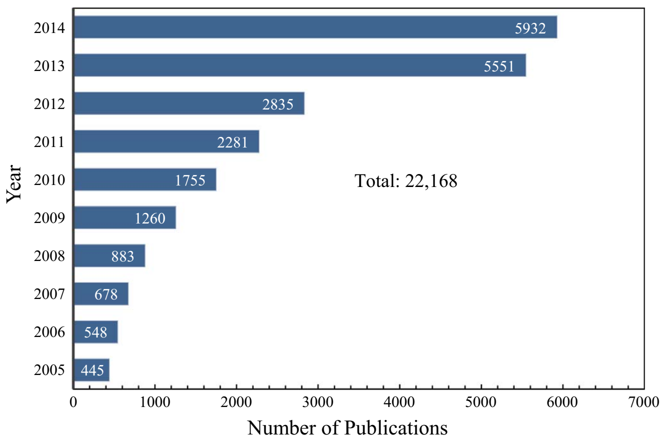

Fig. 1. Number of publications published per year from literature search using the keywords "dye sensitized" and "solar" (data source ISI Web of Knowledge).

nents in DSSC have provided important pathways towards better device performance.

2. The structure and operation principle

A schematic representation of DSSCs is illustrated in Fig. 2 [6]. The system is composed of four main components:

(i) a photoanode made up of a mesoporous oxide layer (typically, TiO_2) deposited on a transparent conductive glass substrate;
(ii) a monolayer of dye sensitizer covalently bonded to the surface of the TiO_2 layer to harvest light and generate photon-excited electrons;
(iii) an electrolyte containing redox couple (typically, I^-/I_3^-) in an organic solvent to collect electrons at the counter electrode and effecting dye-regenerating; and
(iv) a counter electrode made of a platinum coated conductive glass substrate.

.

When the sunlight strikes the solar cell, dye sensitizers on the surface of TiO_2 film get excited and the electrons in turn get injected into the conduction band of TiO_2. Within the TiO_2 film, the injected electrons diffuse all the way through the mesoporous film to the anode and are utilized to do useful work at the external load. Finally, to complete the cycle, these electrons are collected by the electrolyte at counter electrode which in turn are absorbed to regenerate the dye sensitizer. The overall performance of the DSSC can be evaluated based on sunlight-to-electric power conversion efficiency (η).

$$\eta = \frac{V_{oc} J_{sc} FF}{P_{in}} \times 100\% \quad (1)$$

Where V_{oc} is the open-circuit voltage (V), J_{sc} the short-circuit current density (mA cm^{-2}), FF the fill factor, and P_{in} the power of the incident

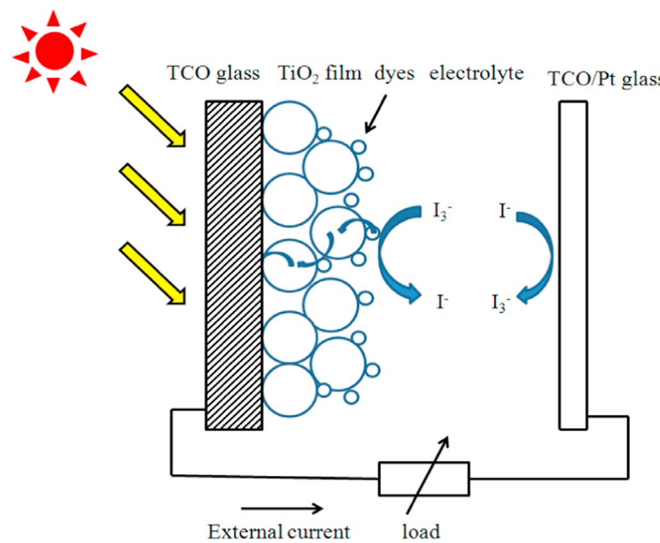

Fig. 2. Schematic diagram of a dye-sensitized solar cell [6].

light. The photovoltage (V_{oc}) is determined by the potential difference between Fermi-level of electrons in the TiO_2 film and redox potential of electrolyte. Similarly, the photocurrent (J_{sc}) is determined based on the incident light harvest efficiency (LHE), charge injection and collection efficiencies. The fill factor (FF) represents the ratio of the actual maximum obtainable power to the product of the open circuit voltage (V_{oc}) and short circuit current (J_{sc}). In general, the overall conversion efficiency of dye-sensitized solar cells is tested under standard irradiation conditions (100 mW/cm^2, AM 1.5).

Under standard test conditions, the device efficiency can be maximized through optimizing each of these three parameters (V_{oc}, J_{sc}, and FF). For instance, high open-circuit potential can be obtained by using Co(II/III) redox couple which has more positive redox potential and therefore increases the potential difference. Likewise, the short-circuit current can be enhanced by using panchromatic dye sensitizers which can absorb broad sunlight covering visible to the near-infrared range in solar spectrum. The fill factor is yet another important parameter that reflects the quality of solar cells. Increasing the shunt resistance and decreasing the series resistance as well as reducing the overvoltage for diffusion and electron transfer will lead to a higher FF value, thus resulting in greater efficiency and pushing the output power of the solar cell closer towards its theoretical maximum. In fact, these parameters are highly dependent on material properties and physical processes within the device. Therefore, theoretical models that can capture the characteristics of physical process and materials properties are critical to optimize various operation parameters and cell configurations.

3. Device modeling

Dye-sensitized solar cells comprise a variety of elementary compo-