Renewable and Sustainable Energy Reviews 79 (2017) 946–959

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Effect of temperature on the photovoltaic performance and stability of solid-state dye-sensitized solar cells: A review

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ARTICLE INFO

Keywords:
Temperature
Stability
Dye-sensitized solar cells
Solid-state
P-type hole transport material
Polymer electrolytes

ABSTRACT

Temperature is probably the most important outdoor variable that affects the photovoltaic performance of the dye sensitized solar cells (DSSCs). Overall stability of DSSCs depends on the properties of charge mediator (electrolyte) between photoanode and counter electrode. The liquid electrolytes show high power efficiency owing to their high dielectric constants to dissolve many ionic salts and additives. However, they may limit the outdoor applications in high temperature region, due to their low boiling points (highly volatile). The objective of this study is to highlight the prospects of solid state dye-sensitized solar cells and its benefit in higher temperature environment. The current review is comprised of four sections. In the first section (introduction), the effect of temperature on the conventional and solid-sate DSSCs is briefly described. In the second section, the mechanism of solid-state DSSCs is explained. Third section we covered recent advances in ss-DSSCs in detail. Finally, the scope of DSSCs in high temperature environment critically analyzed in section four.

1. Introduction

Nearly 13% of world energy demand is coming from different renewable sources such as, biofuel and waste (10%), hydro (2.3%) and others: solar, wind, geothermal, heat, among others 0.9%, while rest of the energy comes from fossil fuels (81%), and 5.7% nuclear power [1,2]. There are several benefits of renewable energy but most important one is that it can reduce the carbon dioxide emission [3]. Therefore, clean energy is getting attention worldwide to minimize the enslavement of mankind on fossil fuels [4]. Solar energy is investigated intensively, it is a clean source of energy and will not deplete as a natural resource, have no CO_2 emission, or generate liquid or solid waste products [5–7]. Environmental protection agency (EPA) has advised many countries to reduce their dependency on fossil fuels and increase the use of alternative source of energy. In the Middle East and particularly in Saudi Arabia, we burn an enormous amount of fossil fuels to meet the energy requirements. Consumption of fossil-based fuel in the world is continuously increasing due to the urbanization and industrialization. However, by taking future into account, many counties, including Saudi Arabia is investing heavily in renewable energy program to generate electricity from sustainable energy sources [8]. Countries located within the equatorial Sunbelt receive abundant solar radiation throughout the year and offers immense potential for solar power generation. This same abundant solar radiation gives another important issue for outdoor solar module deployment, i.e. higher temperature. Most of the commonly used solar panels loosed their power conversion efficiency at higher temperature [9–11].

There are several kinds of solar cell already commercially available and deployed. 1991, Michael Grätzel developed a new photovoltaic cell which became known as dye sensitized solar cell (DSSC) [12]. In recent year DSSCs received global attention due to their several advantages, such as ease of fabrication, can have different color, produce electricity even from stray lights, environmental friendly as compare to other conventional photovoltaic devices [13]. Typically, DSSC consists of a photo-electrode and a catalytic-electrode with an electrolyte between them. Photosensitizer absorbs light and injects electrons to the conduction band of the semiconductor. The electrolyte, which is in contact with the dye, then donates electrons to the dye, reinstating it to the initial state. The electrolyte then diffuses towards the counter electrode where the reduction reaction takes place [14,15]. A catalyst is needed for DSSCs to kinetically accelerate the reduction of the oxidized redox couple. In a solid-sate dye sensitized solar cells DSSCs (ss-DSSC) instead of a liquid electrolyte we use a solid electrolyte, which has a better thermal stability and no sealing issue and in recent year its efficiency also crossed 10% mark [15]. This review is mainly concentrated on the effect of temperature on the conventional and ss-DSSCs,

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http://dx.doi.org/10.1016/j.rser.2017.05.114
Received 24 March 2016; Received in revised form 12 April 2017; Accepted 18 May 2017

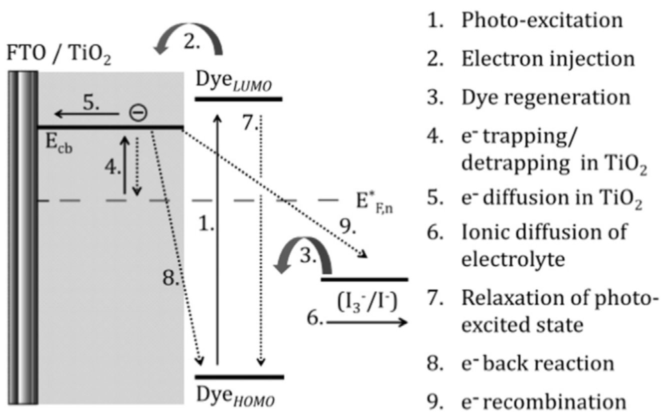

Fig. 1. Schematic view over all electron transfer processes in a DSSC based on a liquid electrolyte [16].

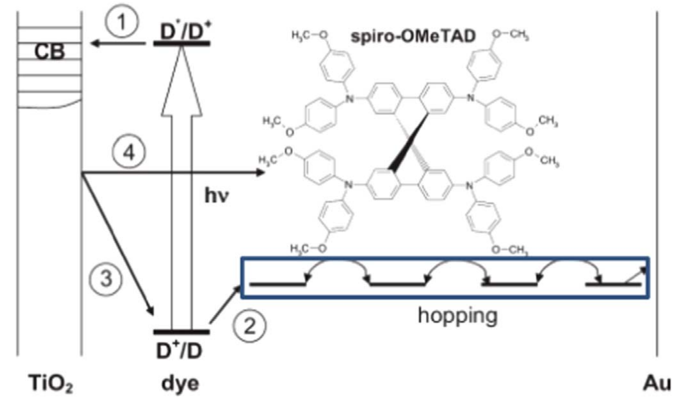

Fig. 2. Energy schematics and kinetic processes in solid-state dye-sensitized solar cell [23].

the mechanism and recent development of solid-state high temperature stable DSSCs in the view of its usefulness in any high temperature region.

1.1. Mechanism of charge transfer in DSSCs

Dye-sensitized solar cell consists of a sensitized semiconductor (photoelectrode) and a catalytic electrode (counter electrode) with an electrolyte sandwiched between them. For liquid electrolyte and solid electrolyte based DSSC, there are few minor differences in the charge transfer mechanism.

1.1.1. Charge transfer mechanism in liquid electrolyte DSSC

Charge transfer mechanism in liquid electrolyte DSSC is shown in Fig. 1. A photon is absorbed by the sensitizing dye, which promotes an electron from a lower energetic state to a higher energetic state. Then the photo-excited electron, which is also the carrier of the absorbed energy, moved into the mesoporous network of TiO_2. The electron vacancy, or the hole, left on the dye molecule is reduced by I^- (iodine ion) from the electrolyte. The driving force for this regenerative electron transfer step is the more negative redox potential of the I^- with respect to oxidized dye molecule. Now the electrons are transported through the mesoporous TiO_2 network by a diffusion process until they reach the FTO substrate where it can be collected by the external circuit. The oxidized I^- molecule on the other hand is going through several intermediate chemical transitions, which finally forms the I_3^- molecule. This species diffuses in the electrolyte phase, until it reaches the platinized counter electrode, where it is reduced back to I^-.

1.1.2. Charge transfer mechanism in solid-state DSSC (ss-DSSC)

Solid-state dye-sensitized solar cell has very similar charge transfer steps as its liquid electrolyte counterpart but occurs through the HOMO level of the solid hole transporting material by a hopping mechanism rather than by ionic diffusion [17–20]. This hopping mechanism is the description of charge carrier transport through a disordered landscape of spatial and energetic states [21]. In this case it is one step process [22], interfacial charge transfer processes and relevant energy levels are shown in Fig. 2.

In these materials charge transport character is either electron or hole transporting or ambipolar (conduct both electrons and holes).

1.2. Effect of temperature on the performance of DSSCs

Challenge of long-term stability has to be addressed before DSSCs can successfully enter into the commercial photovoltaic market. The overall stability and lifetime of DSSCs depend in great extent on the electrolytes. Temperature is stirred as the most important outdoor variable that affects the stability of DSSCs [24,25]. Liquid electrolytes based DSSCs show high power conversion efficiency, however, low boiling point of the liquid electrolytes in one of the major concern for outdoor deployment, mainly in high temperature region. Though there are some good progresses on sealing materials, still the liq-DSSCs face evaporation issues and more generally, permeation of water or oxygen molecules and their reaction with the electrolytes some time worsen this situation.

Moreover, conduction band shift of the TiO_2 film and recombination and charge transport kinetics in a liq-DSSC depends on temperature [26–28]. Charge recombination corresponds to the undesirable reaction of generated electrons with electrolyte species, ultimately affecting the final performance of DSSCs. This reaction involves either free conduction band electrons or electrons trapped in the lower energy states [29]. Driving force for recombination is related to the energy level, wherein the electrons are located in semiconductor (TiO_2), and temperature, both of which are related to the rate constant, k_r(T), and the electron concentration [30–32]. As V_{OC} changes, the Fermi level (E_F) in TiO_2 moves towards or away from the conduction band edge (E_{CB}); when the Fermi level moves up, the respective electron traps below are filled. Taking this into consideration, it can be expected that the activation energy (Ea) of recombination is proportional to (E_{CB}−E_F) [32,33]. The stability problem with the liquid electrolytes can be addressed by using solid-state electrolytes in some extent. Solid-state electrolytes have low evaporation rate as compared to liquid electrolytes and thus enhance life-time of DSSCs. They also reduce the leakage problems and sealing cost of DSSCs.

Solid-state electrolytes can be divided into two types; (1) p-type hole transport material and (2) polymer based electrolytes. The band gap of the p-type semiconductor must be compatible with the highest occupied orbital (HOMO) level of the photosensitizer and the conduction band of the n-type semiconductor. A polymer electrolyte contains a polymer and a liquid electrolyte. Conductivity of polymer electrolytes depends on the molecular weight and the morphology of the polymer matrix. In this review, we will discuss in detail the recent advances in ss-DSSCs and scope of ss-DSSCs in the high temperature environment.

2. Solid state electrolytes for DSSC

Under long storage or exposure in air, in a liquid electrolyte based DSSC, solvent exudation is unavoidable. In this regard, all-solid-state transport materials possess more advantages over liquid transport materials and quasi-solid-state electrolytes, especially in large-scale actual application for DSSCs. Several materials have been developed to replace liquid electrolytes. Solid electrolytes and quasi-solid-state electrolytes used in ss-DSSCs can be categorized as p-type semiconductors, polymer electrolytes (quasi solid-state electrolytes) and ionic liquid electrolytes.