Speed up dye-sensitized solar cell fabrication by rapid dye solution droplets bombardment

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ARTICLE INFO

ABSTRACT

The adsorption of the dye molecules onto TiO_2 in a dye solution bath usually takes hours and is the rate-limiting step in rapid dye-sensitized solar cell (DSSC) fabrication. Here, we show that by high-speed dye solution droplet bombardments, TiO_2 dye adsorption time reduces from hours to minutes. While 24-hr dye solution bath gives the cell with the efficiency of 4.62% (9 mm × 9 mm), 9 min dye adsorption time in the 1500 rpm spinning disc system and 8.3 min dye adsorption time in the 2000 rpm spinning disc system give cells with efficiencies of 4.68% and 4.58%, respectively. The proposed method is ideal for rapid DSSC fabrication.

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1. Introduction

Dye-sensitized solar cells (DSSC) have shown themselves as a potential low-cost alternative to silicon-based solar cells due to their relatively high conversion efficiency and simple fabrication processes [1–3]. The working principle of the dye-sensitized solar cells (DSSC) is the photon excited dye molecules transferring the electrons to the dye-molecule-absorbed nanoporous semiconductor (such as TiO_2 nanoparticles and nanowires, ZnO nanoparticles and nanowires, etc.) and then to the transparent-conductive-oxide thin film. The dye molecules are later regenerated from a catalytic counter-electrode through a redox couple in the electrolyte [1–6]. Because of the attractions of the relatively high conversion efficiency and the low-cost fabrication process, several studies have been carried out to improve the performances of DSSC [7–10]. To ensure good light harvest and electron transportation, the nanoporous semiconductor layer is usually immersed in a dye solution bath for several hours (typically 8–24 h) to allow sufficient and good contacts between the organic dye molecules and the nanoporous semiconductor.

Since the technologies for flexible, low manufacturing temperature, rapid annealed and long-term stability tested DSSCs have been developed, the roll-to-roll process can be potentially used for high throughput (say tens meter per minute) DSSC fabrication [11–16]. However, the conventional 8–24 h bathing dye adsorption procedure implies that the DSSC fabrication throughput is significantly retarded. Several approaches have been proposed to accelerate the dye absorption rate. These approaches enhance the dye diffusion flux by the use of higher dye concentrations and temperatures [17], reflux pumping [18,19] and pressurized CO_2 condition [20]. The dye absorption time was reported to decrease to approximately 5–10 min. In this work, we show that the time for dye adsorption anchor onto the nanoporous TiO_2 semiconductor layer can also be reduced to several minutes by using a forced convection spinning dye solution distribution system. The spinning disc (typically several thousand rpm) produces high-speed dye solution droplets moving towards the nanoporous TiO_2 semiconductor layer in a confined space. The droplets can penetrate the nanoporous TiO_2 semiconductor structure easily and complete the dye adsorption procedure within minutes.

2. Experimental

2.1. Dye solution distribution system

The dye solution distribution system is schematically shown in Fig. 1(a). It is similar to the "higee" system used in environmental and reaction engineering [21–23]. It consists of a motor, a spinning disc with packings inside, which is shown in Fig. 1(b), and an

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outside chamber. The dye adsorption process starts with the injection of dye solution to the center of a high-speed spinning disc shown in Fig. 1(a). The disc spinning at 1500 rpm or 2000 rpm contains a chamber packed with stainless sponges. The inner diameter of the disc is 2 cm and the outer diameter of the disc is
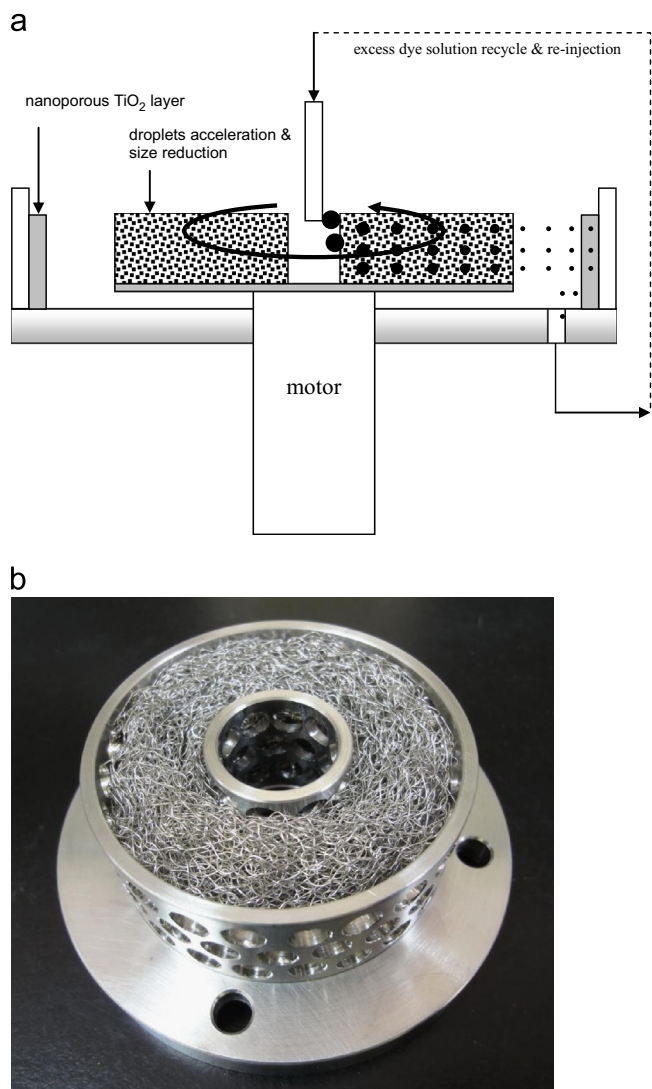

Fig. 1. The spinning dye solution distribution system. (a) The relative position of each part. The droplets formation is schematically shown in the right hand side of the system. (b) The illustration of the spinning disc with the stainless sponge packing.

6.5 cm. The diameter of the hole on the inner and outer walls of the disc is 6 mm. The dye solution flows into the holes on the inner wall of the high-speed spinning disc by gravitational force. When the centrifugal force acts on the dye solution in the disc, the dye solution accelerates through the packing material and is fractured into tiny droplets. The accelerated tiny droplets are expelled from the holes on the outer wall of the spinning disc and bombard the nanoporous TiO_2 layer pre-coated fluorine-doped tin oxide (FTO) covered substrate. Excess dye solutions after bombardments are collected from the bottom of the system, recycled, pumped and re-injected to the center of the spinning disc. In principle, the unabsorbed dye solution can be fully recycled and 100% used. In this work, the entire higee system costs around $2500 USD. The cost of the dye solution distribution system added to the DSSC fabrication process is very little comparing to the dye adsorption time saved (see later).

2.2. DSSC fabrication and performance evaluation

The 15 ± 0.3 μm DSSC working electrode was prepared by screen printing P200 coating paste (Everlight Chemical Industrial Corp., Taiwan) on a pre-cleaned FTO conducting glass surface (10 Ω cm), followed by 2 h 450 °C sintering. The counter electrode was fabricated by spin coating H_2PtCl_6 solution (5 mg:1 ml of isopropanol) on the pre-cleaned FTO conducting glass surface (10 Ω cm), followed by 400 °C heat treatment for 20 min. D719 dye, cis–bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato) ruthenium(II)bis-tetrabutylammonium, (Everlight Chemical Industrial Corp., Taiwan) was dissolved in acetonitrile for the preparation of the 0.3 mM dye solution. Two different methods were used to anchor the dye molecules onto TiO_2 nanocrystalline. One is the conventional 24-hr dye solution bath method and the other is the speed dye solution droplet bombardment method. The dye absorbed working electrode and the counter electrode were sealed using 125 μm Surlyn® film. 0.5 M 4-tert-butyl-pyridine, 0.05 M I_2, 0.5 M LiI and 0.6 M tetrabutylammonium iodide in acetonitrile were used as the electrolyte. The size of the active area was 0.81 cm^2 (9 mm $\times$ 9 mm). The experimental parameters are summarized in Table 1.

The photovoltaic performance of the solar cells were evaluated based on the amount of the absorbed dye on the nanoporous TiO_2 layer, the current density and voltage of the cell under a 180 W Xenon simulated sunlight (AM 1.5, 100 mW cm^{-2}, YSS-50A, Yu-Yi, Taiwan) and the Incident Photon-to-electron Conversion Efficiency (IPCE, Newport® 74000, Oriel Instrument, USA). The amount of the absorbed dye was determined by desorption the adsorbed dye into a 0.1 M NaOH solution in de-ionized water. The absorption spectra of the desorbed-dye solution were then measured to determine the amount of absorbed dye on the nanoporous TiO_2 layer. Each

Table 1
Summary of the experimental parameters.

Disc inner diameter (cm)	2.0
Disc outer diameter (cm)	6.5
Packing materials inside disc	Stainless sponge
Disc rotational speed (rpm)	1500, 2000
Disc hole diameter (mm)	6
Dye adsorption time (s)	20, 40, 60, 80, 100, 120, 140,…, 580, 600
Substrate	FTO (10 Ω cm)
Working electrode thickness (μm)	15 ± 0.3
Working electrode	P200 (Everlight Chemical Industrial Corp., Taiwan)
Dye	D719 (Everlight Chemical Industrial Corp., Taiwan)
Counter electrode	Pt
Electrolyte	0.5 M 4-tert-butyl-pyridine+0.05 M I_2+0.5 M LiI+0.6 M tetrabutylammonium iodide in acetonitrile
Spacer	125 μm Surlyn®
Cell active area	0.81 cm^2 (9 mm $\times$ 9 mm)