Solar Energy Materials and Solar Cells 175 (2018) 29–34

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

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

Enhancing the efficiency of transparent dye-sensitized solar cells using concentrated light

Prabhakaran Selvaraj[a,*], Hasan Baig[a], Tapas K. Mallick[a], Jonathan Siviter[b], Andrea Montecucco[b], Wen Li[b], Manosh Paul[b], Tracy Sweet[c], Min Gao[c], Andrew R. Knox[b], Senthilarasu Sundaram[a,*]

[a] Environment and Sustainability Institute (ESI), University of Exeter, Penryn Campus, TR10 9FE, United Kingdom
[b] School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[c] School of Engineering, Cardiff University, Cardiff CF24 3AA, United Kingdom

ARTICLE INFO

Keywords:
Dye-sensitized solar cell (DSSC)
Low Concentrating Photovoltaics (LCPV)
Temperature effect on DSSC
Scale up of DSSC

ABSTRACT

Transparent dye-sensitized solar cells (DSSCs) can be coupled within a building's architecture to provide daylighting and electrical power simultaneously. In this work, the relationship between the transparency and performance of DSSCs is studied by changing the TiO_2 electrode thickness. The 10 µm thickness device shows a power conversion efficiency of 5.93% and a J_{sc} of 12.75 mA/cm^2 with 37% transparency in the visible range. However, the performance loss in DSSCs during the scale up process is a potential drawback. This can be addressed using an optical concentrator with DSSC to generate more power from small size devices. Here, a compound parabolic concentrator (CPC) is coupled with DSSCs and its performance is compared to a scaled-up device (approx. 4 times). Furthermore, the impact of operating temperature on the performance of the bare and concentrator-coupled devices is discussed in this article. An increase of 67% in power conversion efficiency is observed at 36 °C for the concentrator-coupled device under 1000 W/m^2 illumination. Maximum J_{sc} of 25.55 mA/cm^2 is achieved at 40 °C for the concentrated coupled device compare with the J_{sc} of 13.06 mA/cm^2 for the bare cell at the same temperature.

1. Introduction

Dye-sensitized solar cells (DSSCs) have gained much attention in recent years [1,2] due to their simple manufacturing process, low cost of materials, light weight, flexibility, good photocurrent conversion efficiency, short energy payback time and tunable optical properties [3–5]. Even though DSSCs have achieved PCEs over 14% [3,6] with small active area, the power output decreases with an increase in the cell active area of the photoanode [7]. This is due to some unfavourable issues such as non-homogeneous and non-uniform titania layers because of large area deposition, dye sensitisation and electrolyte filling issues also electrical interconnection of individual cells [8]. However, the performance loss during scale up can be addressed by coupling optical concentrators with small DSSC. Concentrating Photovoltaic (CPV) systems make use of optical components which concentrate the incoming sunlight and focus it on solar cells. The concentrated light reaching the solar cell increases the energy production several times [9–11]. Based on the light illumination intensity it focuses on the solar cell, the concentrators may be classified as low concentration systems, medium concentration systems and high concentrator systems. Low concentration systems are usually simple in their design, manufacture and operation. These systems have a concentration factor of less than 10× [12]. Due to its versatility in applications and geometries, a type of low concentrator – the compound parabolic concentrator (CPC) is used in low and medium temperature ranges [13].

The application of an optical lens-based solar concentrator system mounted on top of DSSCs still poses several challenges in terms of efficiency, cost-effectiveness of optical design, and the provision of uniform and concentrated illumination on a DSSC [14]. Furthermore, various complex phenomena including light scattering, recombination of electron-hole pairs, and dye degradation in the photoactive layers of DSSCs can occur when the intensity of incident light is increased by a solar concentrator [15]. A considerable amount of research has been conducted on increasing the electrical efficiency of DSSCs and their modules [16–18]. Moon et al. [19] employed concentrated illumination using a condenser lens up to 3.72 suns on a DSSC and it was found that an increase in photocurrent and efficiency values. Choi et al. [20] used condenser lens for a vertical stacked- cell configuration DSSC in to increase the efficiency and at 8 mm separation distance between the lens and the cell, the device efficiency increased from 2.5% to 8.3%. Barber

---

[*] Corresponding authors.
E-mail addresses: ps364@exeter.ac.uk (P. Selvaraj), S.Sundaram@exeter.ac.uk (S. Sundaram).

http://dx.doi.org/10.1016/j.solmat.2017.10.006
Received 20 July 2017; Received in revised form 4 September 2017; Accepted 9 October 2017

et al. [21] proposed a concentrator for a hybrid silicon-DSSC system with two different optical filters for visible and IR absorption to achieve about 20% efficiency. More recently, Sacco et al. [22] demonstrated the application of a solar concentrator both in indoor and outdoor working conditions. The outdoor results show a linear behaviour for solar concentration factors up to 1.5. However, the LCPV has not been used on DSSC before. This article focuses on the performance of transparent DSSCs under low concentrated light.

In this work, we report the optical and electrical performance of transparent DSSCs by changing the working electrode thicknesses. A Low concentrator with 3× optical concentration was designed and employed to study the effect of light concentration on DSSCs. Moreover, a systematic study of the temperature dependency on the performance of bare DSSCs and those coupled with LCPV system has been carried out.

2. Experimental methods

2.1. DSSC fabrication

The working electrodes and the corresponding devices were prepared according to the literature procedures [23]. Fluorine doped transparent conducting SnO_2 (FTO) glass substrates (Pilkington 2.2 mm, 13 Ω/sq) were cleaned with distilled water and ethanol. A layer of 20 nm transparent TiO_2 paste (Dyesol 18NR-T) was coated on the conductive glass by screen printing. This was repeated (2–7 layers) to obtain different thicknesses for the working electrode (Labelled as devices L2-L7). The thickness of the TiO_2 electrodes was measured using Dektak 8 Advanced Development Profiler. In order to remove the organic particles, prepared thin films were annealed rapidly at 450 °C for 30 min. After cooling them to 80 °C, the TiO_2 electrodes were immersed into 0.2 mM N719 dye in ethanol at room temperature for 12–15 h. The iodide/tri-iodide electrolyte comprising 0.4 M LiI, 0.4 M tetrabutylammonium iodide (TBAI), and 0.04 M I_2 dissolved in 0.3 M N-methylbenzimidazole (NMB) in acetonitrile (ACN) and 3-methoxypropionitrile (MPN) solvent mixture at a volume ratio of 1:1 was prepared and stirred for 24 h at room temperature [24]. Pt electrode was placed over the dye-adsorbed TiO_2 electrode with a 25 μm hot-melt spacer between two electrodes. Iodide/tri-iodide electrolyte was introduced into the cell through the small hole drilled in the counter electrode. The active area of the TiO_2 electrodes was 0.28 cm^2. The hole in the counter electrode was sealed with a film (Meltonix- Solaronix) and a piece of cover glass. The transparency of the bare devices was measured using a UV–VIS–NIR spectrometer (PerkinElmer, Lambda 1050).

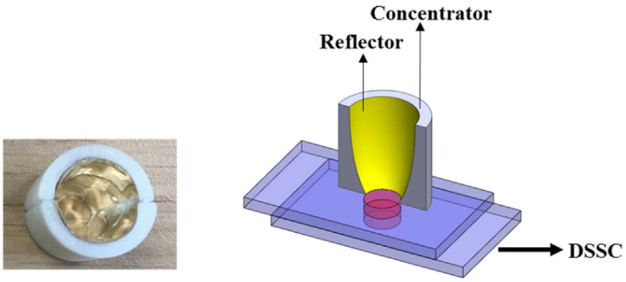
2.2. Low concentrator fabrication

Fig. 1 shows the fabrication of the concentrator with a geometrical concentration factor of C = 4×. The concentrator was printed into two halves (Fig. 1**(a)**), reflective film (94%) was adhered on the CPC surface (Fig. 1**(b)**), and the two halves were assembled together as shown in (Fig. 1**(c)**). The concentrator was placed on top of the solar cell for testing. (Fig. 1**(d)**)

2.3. Device characterization

In an indoor controlled environment, the CPV unit was tested to evaluate the impact of radiation intensity. The setup essentially consists of a solar simulator which is a light source from a xenon lamp emanating collimated light rays and an I-V tracer which is used to characterise the electrical performance of the solar cell. The photovoltaic performances of the assembled devices were measured under 1000 W/m^2 of light from a Wacom AAA continuous solar simulator (model: WXS-210S-20, AM1.5G). The I–V characteristics of the devices was recorded using EKO MP-160i I–V Tracer (similar set up used previously) [25]. The temperature of the devices was recorded using an OMEGA RDXL 12SD temperature recorder. Finally, the concentrator unit was placed on the DSSC to perform DSSC-LCPV measurements.

(a) 3D Printed Half-CPC **(b) Half- CPC with Reflective film**



(c) Assembled CPC **(d) Low concentrator coupled DSSC**

Fig. 1. Fabricated low concentrator. (a) one half of the printed concentrator, (b) adhered reflective film, (c) assembled concentrator used for this work and, (d) low concentrator coupled DSSC.

3. Results and discussion

The advantage of making transparent DSSCs is easily adopt them into building architectures. So, the degree of transparency of DSSCs should be carefully taken into account when evaluating the efficiency of DSSCs [26]. The transparency of DSSCs is heavily depending on the thickness of TiO_2 nanostructured materials. Fig. 2. shows **(a)** the relationship between TiO_2 thickness and DSSC device transparency, and **(b)** current density-voltage (J-V) curves of the corresponding devices. The average transparency of 53% was recorded for the device made with 3.5 μm thick TiO_2 electrode (L2) and the device with 14 μm thick TiO_2 electrode has 19% transparency. When the TiO_2 layer thickness was increased from 3.5 to 10 μm an obvious increase of J_{sc} from 7.36 mA/cm^2 to 12.75 mA/cm^2 was occurred in the corresponding devices, resulting in a corresponding improvement of efficiency from 2.51% to 5.93%. More dye molecules attached to the thick TiO_2 films absorb more light, leading to low transmittance, also thick films physically block/absorb the light [26]. Conversely, the photovoltaic performance decreased after 10 μm thick TiO_2 with further increase in titania layer thickness (12 μm, 14 μm) [27–29]. This is due to increase the length of the electron pathways, and thus decrease FF and V_{oc} [30–32]. The photovoltaic parameters of the devices with different TiO_2 thickness are given in Table 1.

3.1. Scaled up device- comparison with LCPV coupled device

In order to use DSSCs as building integrated photovoltaic (BIPV) element, the devices need to be prepared as transparent as possible especially for window applications. Due to this, scaling up of DSSC has become an important process even though it has associated with different issues. Here, 1.1 cm^2 active area DSSC device with 10 μm titania thickness and 37% transparency was fabricated to study the performance of a scale-up device (Fig. 3). Fig. 4**(a), (b)** shows the current density -voltage and power density – voltage behaviour respectively for device with an active area of 0.28 cm^2 and 1.1 cm^2 (~ 4 times larger area than 0.28 cm^2). The short circuit current of 1.1 cm^2 active area device is higher than the small area device. However, the current density and power density of the scaled up DSSC is much lower than the