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Transparent Solar Cells in Large Scale for Energy Harvesting in Buildings.

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Abstract. Dye sensitized solar cells (DSSCs) for almost two decades ago were proposed as low cost alternatives to the conventional amorphous silicon solar cells, owing to the simplicity of their fabrication procedures, practically under ambient conditions with mild chemical processes. At the present work, we will show some recent developments to the fabrication of dye-sensitized solar cells in large scale based on TiO₂ while issues that limited their performance will also be presented. Outdoor data measurements are included to verify our conclusions.

Keywords: Dye sensitized solar cells, transparency, energy saving, organic inorganic materials.

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INTRODUCTION

Renewable energies have been widely investigated due to the continuous increase of the fossil energy cost and their low impact on the environmental problem. Among the sustainable energies, solar energy may successfully meet a significant part of energy demands for future generations. Photovoltaics can assist toward this direction especially if improvements regarding (a) their cost, (b) their applicability and (c) their sustainability are made [1]. Dye sensitized solar cells (DSSCs) are placed in the category of third generation photovoltaics (PV) and they attract intense interest because of their low cost, simple preparation procedures and benign methods of construction compared with the methods applied in other generations' photovoltaics [2]. Third generation solar cells are based on nanostructured (mesoscopic) materials and they are made of purely organic or a mixture of organic and inorganic components, thus allowing a vast and inexhaustible choice of materials [3]. Their mesoscopic nature makes it possible to manufacture transparent cells which can be used as photovoltaic windows [4]. Photovoltaic windows can be integrated in building facades operating by front-face light incidence, but also by diffuse light and even by back face light incidence.

In this work we demonstrate that the cell size doesn't seem to affect the cell efficiency, which is a great advantage for the DSSC commercialization. We study the effect of cell size to the short circuit current density, open circuit voltage; fill factor and overall efficiency of the cells. Our studies are limited to strip like cells which are the structural units for big size solar cells and modules.

MATERIALS SYNTHESIS AND CHARACTERIZATION

Commercially available lithium iodide, iodine, 1-methyl-3-propylimidazolium iodide, hydrogen hexachloroplatinate(IV) hydrate (H₂PtCl₆), poly(propylene glycol)bis(2-aminopropyl) ether, 3-isocyanatopropyltriethoxysilane and all solvents were purchased from Sigma-Aldrich. 3- *Cis*-diisothiocyanato-bis(2,2'-bipyridyl-4,4'-dicarboxylato) ruthenium(II) bis(tetrabutylammonium), N719 was purchased from Solaronix S.A, Switzerland. SnO₂:F transparent conductive electrodes (FTO, TECTM A10) 10 Ohm/square were purchased from Pilkington NSG Group. Commercial ultra pure titanium isopropoxide (TTIP, 97%, Aldrich), Triton X-100 (polyoxyethylene-10- isooctylphenyl ether) surfactant (99.8%, Aldrich), glacial acetic acid (AcOH, Aldrich) were used to make precursor TiO₂ sols. TiO₂ thin films were deposited by following a previously reported procedure [5, 6]. Briefly, for 12.5 ml solution, 1.8 g of Triton X-100 was mixed with 10 ml of ethanol, followed by addition of 0.8 ml of glacial acetic acid and 0.9 ml of titanium isopropoxide under vigorous stirring. After a few minutes stirring, FTO glasses were dipped in the above sol and withdrawn with 2cm/sec. The films were heated up to 500°C for 30 minutes using 20°C/min heating ramp rate. The above procedure for TiO₂ films was repeated several times in order to make films with thickness around 1.5 microns (based on cross-sectional FE-SEM images). The size of TiO₂

electrodes was varied from $1 \times 1 \text{ cm}^2$ to $1 \times 45 \text{ cm}^2$ with always kept the one dimension constant. TiO_2 films were finally immersed in ethanol/acetonitrile (1/1 v/v) solution of N719 (the dye concentration was $5 \times 10^{-4} \text{ M}$) in order to sensitize the TiO_2 electrode in the visible.

In the construction of the solar cells a quasi-solid state electrolyte was used. This was chosen as a promising approach to DSSC technology as it combines the high ionic conductivity of liquids while it reduces the risk of leaks and minimizes sealing problems in the cells. For the gel electrolyte applied to the DSSCs, we used a hybrid organic-inorganic material which was prepared according to a procedure described in previous publications [7-9]. Briefly, poly(propylene glycol)bis(2-aminopropyl ether) of molecular weight 230 and 3-isocyanatopropyltriethoxysilane (ICS; molar ratio ICS/diamine=2) react in a vessel (acylation reaction), producing urea connecting groups between the polymer units and the inorganic part. The gel electrolyte was synthesized by the following procedure: 0.7grams of the functionalized alkoxide precursor were dissolved in 2.4 grams of sulfolane under vigorous stirring. Then, 0.6 ml AcOH were added followed by 0.3M 1-methyl-3-propylimidazolium iodide, 0.1M LiI and 0.05M I_2 in a final molar ratio AcOH:LiI:MPIImI: $\text{I}_2 = 2.5:0.1:0.3:0.05$. After six hours stirring, one drop of the obtained sol was placed on the top of the titania electrode with adsorbed dye molecules and a slightly platinized FTO counter electrode was pushed by hand on the top. The platinized FTO glass was made by exposing it to a H_2PtCl_4 solution (5mg/1ml of ethanol) followed by heating at 450°C for 10 minutes. The two electrodes tightly stuck together by Si-O-Si bonds developed by the presence of the hybrid material.

For the J - V curves, the samples were subjected to outdoor solar irradiation. The light intensity was almost constant at 950 W/m^2 measured with a CMP 3 Kipp & Zonen pyranometer. Finally, the I - V curves were recorded by connecting the cells to a Keithley Source Meter (model 2420) which was controlled by Keithley computer software (LabTracer). For an in depth examination of the factors that may cause a decrease to the efficiency of the DSSC we constructed cells in the shape of a strip with variable size. The cell active area for these measurements was varied from 1 to 45 cm^2 while masks and back reflectors were not used in the measurements. For each cell size, we have made two devices which were tested under the same conditions in order to avoid any misleading estimation of their efficiency. A visual appearance of the proposed cells can be seen on Fig.1a along with a solar module of $20 \times 20 \text{ cm}^2$ on Fig.2b which obviously consists of successive strips of $1 \times 20 \text{ cm}^2$. We decided to keep the one dimension constant in order to limit the factors that affect the efficiency of the cells. Usually, the optimum width of the strips is found to be varied from 0.8 to 1 cm. Cell performance parameters, including short-circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power (P_{max}), fill factor (ff) and overall cell conversion efficiency, were measured and calculated from each I - V characteristic curve.



FIGURE 1. (a) Image of all strip shaped DSSCs used varied from 1×1 to $1 \times 45 \text{ cm}^2$. (b) DSSC module of $20 \times 20 \text{ cm}^2$

Cell performance parameters, including short-circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power (P_{max}), fill factor (ff) and overall cell conversion efficiency, were measured and calculated from each I - V characteristic curve. The results for all cell parameters are presented in Table 1. It can be seen that the solar parameters measured (J_{sc} , V_{oc} , ff and $n \%$) are almost constant as the length increases from 1 to 45 cm. In particular J_{sc} has small variations, while V_{oc} is unaffected from the size of the cells as it depends on the metal oxide and the type of electrolyte used. The ff was slightly affected by the size of the cell mainly due to the internal in series resistance of the cell (R_s). Experimental results on I - V characteristic curves for the aforementioned strip cells are presented on Fig.2.

TABLE 1. Solar cell parameters from I - V curves of DSSC strips with variable length.

Strip size (cm ²)	J_{sc} (mA/cm ²)	V_{oc} (volts)	ff [*]	n (%) ^o
1x1	6.22	0.73	0.48	2.24
1x2	5.72	0.73	0.34	1.50
1x3	6.17	0.73	0.36	1.72
1x4	5.96	0.73	0.42	1.98
1x5	6.17	0.73	0.40	1.93
1x10	5.89	0.73	0.36	1.85
1x15	5.80	0.74	0.40	1.71
1x20	5.90	0.73	0.34	1.56
1x25	5.41	0.75	0.31	1.33
1x30	5.87	0.74	0.41	1.85
1x35	5.03	0.74	0.35	1.38
1x40	5.46	0.74	0.39	1.65
1x45	5.76	0.73	0.341	1.54

* Fill factor: $ff = \frac{(V \cdot J)_{max,p}}{V_{OC} \cdot J_{SC}}$, and ^o overall efficiency calculated from the equation:

$$n = \frac{V_{OC} \cdot I_{SC} \cdot ff}{A \cdot P_{light}} \text{ where } A \text{ is the effective area of the cells. } P_{light} \text{ was kept at around } 950 \text{ W/m}^2.$$

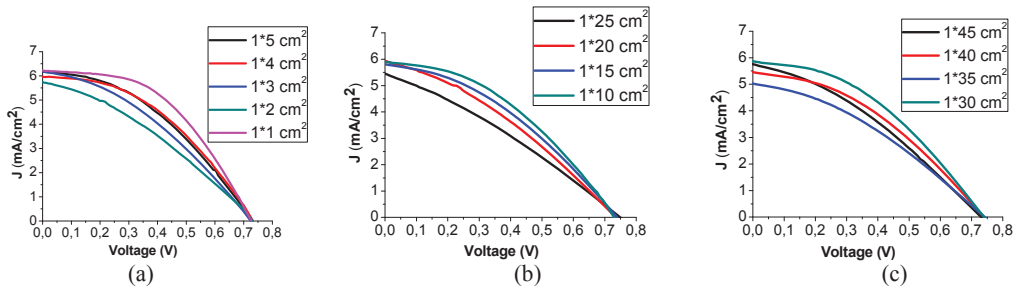


FIGURE 2. I - V curve for DSSC strip sizes (a) 1x1 to 1x5 cm² (b) 1x10 to 1x25 cm² and (c) 1x30 to 1x45 cm².

Similar results were obtained for cells with variable electrolyte thickness. Excessive amounts of electrolyte in the cells affect the overall efficiency, as a higher electrolyte thickness leads to an increased R_s value. The interesting fact to the data is that the overall efficiency is 10% lower when the thickness of the electrolyte is increased from 50 to 80 μ m. In all cases of long cells we used Kemtron's copper conductive foil tape for current collection which has a resistance of 1-1.5 Ω . Therefore, we may consider that the resistance of the conductive tape is another factor for efficiency limitations as they put additional resistance to the cells. The effective current collection is one of the major factors for safe measurements and conclusions. Bad contacts usually add parasitic resistances with a direct effect on the I_{sc} and ff of the cells.

The most interesting results were found for three strips connected in parallel on the same glass substrate. The glass was previously etched in order to separate the one strip from the other so as three isolated conductive strips

were created on the same glass. The final connection of the cells in parallel was made at the three edges using copper tape. The fill factor of the module of the three cells was seriously affected while the total short circuit current of the assembly was lower of that expected. A 35% drop to the ff value among 1x20 cm² strip like cell and isolated strip cell of the same dimensions on the parallel connection was found while a 5% drop to the expected value for the I_{sc} was also monitored. The main reasons for these evidences are (a) the poor external connections of the strip like cells and (b) the difficulty to isolate the strip like cells on the same glass. The existence of electrolyte in each cell requires effective isolation between cells with no electrolyte leakage between them.

Finally, DSSCs, as promising alternatives to the conventional silicon based solar cells, require specific modifications and inspired connections before they reach the production line. The electrolyte thickness, the efficient current collection and effective isolation of the cells to the module are of the main issues to be solved primarily.

CONCLUSIONS

In this work we present the major advantages of using dye sensitized solar cells but also express the main issues arise from their up-scaling. The efficiency for a quasi-solid state DSSC could be further improved as the main factors of limitation were found to be the current collector material and structure, while the internal resistance of the cell depending on the FTO glass substrate and electrolyte do also affect the overall efficiency.

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