

Up Scaling of Highly Transparent Quasi-Solid State, Dye-Sensitized Solar Devices Composed of Nanocomposite Materials

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Abstract—At the present work, highly transparent strip type quasi-solid state dye-sensitized solar cells (DSSCs) were fabricated through inkjet printing using nanocomposite TiO_2 inks as raw materials and tested under outdoor illumination conditions. The cells, which can be considered as the structural units of large area modules, were fully characterized electrically and electrochemically and after the evaluation of the received results a large area DSSC module was manufactured. The module design was a sandwich Z-interconnection where the working electrode is deposited on one conductive glass and the counter electrode on a second glass. Silver current collective fingers were printed on the conductive glasses to make the internal electrical connections and the adjacent cells were connected in series and finally insulated using a UV curing resin to protect them from the corrosive (I^-/I_3^-) redox couple of the electrolyte. Finally, outdoor tests were carried out to the fabricated dye-sensitized solar module and its performance data were collected and assessed.

Keywords—Dye-sensitized solar devices, inkjet printing, quasi-solid state electrolyte, transparency, up scaling.

I. INTRODUCTION

THE gradual depletion, the cost increase and the environmental impact of the fossil fuel has led to an increase in the investigation of renewable energies. Among them, solar energy may successfully meet the ever increasing energy demands and photovoltaics can assist towards this direction. Particularly, third generation solar cells, as dye-sensitized solar cells, have attracted intense interest over the past decades due to their simple and environmentally friendly fabrication procedures, low cost and the fact that it is possible to manufacture transparent cells that can be integrated as photovoltaic windows at building facades operating by front-face light incidence, but also by diffuse light and even by back face light incidence [1], [2].

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The long term goal and the motivation to go from the laboratory scale to large area dye sensitized solar devices, which would also lead to their commercialization and to an industrially mass production, is to reach a satisfactory efficiency and an increased life expectancy. By now their efficiency has reached an almost 13% overall performance for small sized cells and there is even more room for improvement [3]. Over the past years, research groups have attempted manufacturing large area dye-sensitized solar modules, trying to overcome the difficulties that they come across which will lead to the fabrication of an optimized device [4]-[7].

In this work, we started by investigating the effect of the varying length of strip shaped dye-sensitized solar cells, employing a quasi-solid state electrolyte, to their electrical parameters, since strips can be considered as the structural units of large area devices. Electrodes, photoanode and counter electrode were fabricated through inkjet printing ensuring uniformity of the samples. Firstly, the basic individual components of a cell were studied. In particular, the cells' photoanode was structurally characterized and the electrolyte was subjected to thermal treatment. Secondly, the strips were characterized electrically and electrochemically and after evaluating the obtained results we proceeded with the up-scaling, fabricating a sandwich module sized 24.5 cm x 21 cm with an active area of 253 cm^2 consisting of serially connected strips. Silver collecting grid was also printed on the conductive glass for an efficient current collection.

II. MATERIALS AND METHODOLOGY

A. Materials

Commercially available lithium iodide, iodine, 1-methyl-3-propylimidazolium iodide, tert-butyl pyridine, guanidine thiocyanate, chloroplatinic acid hexahydrate (H_2PtCl_6), O, O'-Bis(2-aminopropyl) polypropylene glycol-block-polyethylene glycol-block-polypropylene glycol (Jeffamine® ED-600), 3-isocyanatopropyltriethoxysilane and all solvents were purchased from Sigma-Aldrich and used as received: 3 - *Cis*-diisothiocyanato - bis (2,2'-bipyridyl-4,4'- dicarboxylato) ruthenium(II) bis(tetrabutylammonium), N719 was purchased from Solaronix S.A, Switzerland. SnO_2 : F transparent conductive electrodes (FTO, TECTM A10) 10 Ohm/square were purchased from Pilkington NSG Group. UV cured resin Dymax 429 gel was used to cover silver grids inkjet printed on FTO glasses using Cabot silver ink. Commercial ultra-pure

titanium butoxide (TTBU, 97%, Aldrich), Triton X-100 (polyethylene glycol p-tert-octylphenyl ether) surfactant (99.8%, Fisher Scientific), glacial acetic acid (AcOH, Aldrich) were used to make precursor TiO_2 sols.

B. Preparation of TiO_2 Nanostructured Photoanodes Sensitized With Dye and of Platinum Counter Electrode

TiO_2 transparent thin films were fabricated via the sol-gel method following a previously reported procedure [8]. Briefly, for 5.4 ml solution, 0.72 g of Triton X-100 was mixed with 4 ml of ethanol, followed by addition of 0.4 ml of glacial acetic acid and 0.37 ml of titanium butoxide under vigorous stirring. After a few minutes stirring, the solution was deposited on the FTO glasses with inkjet printing (Dimatix Materials Printer DMP-5000). The films were heated up to 500°C for 30 minutes using $20^\circ\text{C}/\text{min}$ heating ramp rate. This procedure, of sequential printing and sintering steps, was repeated several times until the TiO_2 thickness was approximately $2\ \mu\text{m}$. Finally the TiO_2 films were immersed in an ethanol/acetonitrile (1/1 v/v) solution of N719 (the dye concentration was $4 \times 10^{-4}\ \text{M}$) in order to sensitize the TiO_2 electrode in the visible. Excessive dye molecules that weren't adsorbed on the TiO_2 surface were removed by rinsing with acetonitrile. The platinized FTO glasses were made by inkjet printing of a H_2PtCl_6 solution (5 mg/1 ml of n-propanol) followed by heating at 500°C for 10 minutes.

C. Quasi-Solid Electrolyte Preparation

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 [9], [10]. Briefly, O, O'-Bis(2-aminopropyl) polypropylene glycol-block-polyethylene glycol-block-polypropylene glycol (Jeffamine® ED-600), of molecular weight 600 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: 0.0788 g of the functionalized alkoxide precursor (ED600-ICS) was dissolved in 0.2 g of sulfolane and 0.1 g of methoxypropionitrile under vigorous stirring. Then, 0.046 g AcOH were added followed by 0.015 g 1-methyl-3-propylimidazolium iodide, 0.015 g LiI and 0.0075 g I_2 . Finally, the electrolyte solution was completed by adding 0.0255 g tert-butyl pyridine and 0.00445 g guanidine thiocyanate. After a few minutes of 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 two electrodes tightly stuck together by Si-O-Si bonds developed by the presence of the hybrid material.

D. Fabrication of Strip Shaped Dye-Sensitized Solar Cells and Up-Scaling

Before transitioning to the fabrication of large area modules we fabricated and tested strip shaped dye-sensitized solar cells with constant width of 1 cm and variable length from 1 to 25 cm, as the strips can be considered to be the structural units for big size solar cells and modules. A visual appearance of the proposed cells can be seen in Fig. 1. After evaluating the results of the strip shaped DSSCs, we proceeded with the fabrication of dye-sensitized solar modules using a sandwich Z-interconnection where the working electrode is deposited on one glass and the counter electrode on a second glass. A silver paste was printed on the glasses to make the internal electrical connections and serially connect the adjacent cells. After the deposition of the silver wires the glasses were sintered at 400°C for 10 minutes. A UV curing resin was used to insulate the silver wires to avoid their corrosion from the electrolyte.

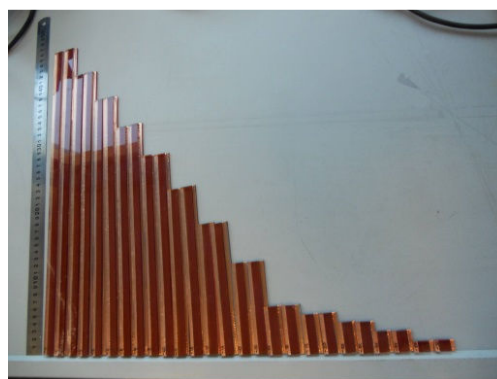


Fig. 1 Strip shaped DSSCs with variable length from 1 to 26 cm and constant 1 cm width

E. Characterization Techniques

The photoanode and the electrolyte were characterized separately before characterizing the complete cell. Firstly, the structural properties of the TiO_2 films were investigated through nitrogen sorption-desorption analysis using Micromeritics Tristar 3000 and the surface area, porosity, and pore size distribution were derived by differentiating them according to BET method. Secondly, the materials responsible for the jellification of the electrolyte, namely the hybrid organic-inorganic material and the acetic acid were diluted in the electrolyte solvents, sulfolane and 3-methoxypropionitrile, under vigorous stirring and the solution was left in an open bottle to speed up its solidification. The formed gel was used to perform thermal gravimetric analysis (TGA) measurements using a Perkin Elmer Simultaneous Thermal Analyzer STA6000 controlled by Pyris Manager Software. The measurements were carried out from a temperature of 15°C to 440°C .

For the J-V curves, the cells were subjected to outdoor solar irradiation. The light intensity was almost constant at $950\ \text{W}/\text{m}^2$ during all experiments and measured with a Newport power meter (Model 843-R). Finally, the J-V plots were recorded by connecting the devices to a Keithley Source Meter

(model 2420) which was controlled by Keithley computer software (LabTracer). The cells' total active area varied from 1 cm x 1 cm to 1 cm x 25 cm. For each case, we made two devices which were tested under the same conditions in order to avoid any misleading estimation of their efficiency. Cell performance parameters, including short-circuit current density (J_{SC}), open circuit voltage (V_{OC}), maximum power (P_{max}), fill factor (FF) and overall cell conversion efficiency, were measured and calculated from each J-V characteristic curve.

Electrochemical impedance spectroscopy measurements (EIS) were also carried out under outdoor illumination at some strip cells with indicative length. EIS measurements were performed with Metrohm Autolab 3.v potentiostat galvanostat (Model PGSTAT 128N) through a frequency range of 100 kHz-0.01 Hz using a perturbation of ± 10 mV over the open circuit potential. Experimental data are presented by scattering symbols while lines represent the fitted plots obtained using Nova 1.10 software.

III. RESULTS AND DISCUSSION

A. Photoanode Characterization

The measurement for the porosity of the TiO_2 film was carried out on powder which resulted by scratching thick films made on glass microscope slides and grinding the obtained flakes to break all agglomerations. The sample was degassed for 2h at $100^\circ C$ before N_2 sorption analysis. The particle surface area and pore structure of the TiO_2 powder are summarized in Table I, while the results are presented in Fig. 2. The hysteresis loop in Fig. 2 appears at low relative pressure ($0.4 < P/P_0 < 0.8$) which is attributed to smaller mesoporosity of the material. The sample's Brunauer, Emmett and Teller (BET) specific surface area was high while the Barrett, Joyner and Halenda (BJH) pore volume was relatively low. Moreover, the TiO_2 sample had a small mean pore diameter. In addition, based on SEM cross section image (Fig. 3 (a)), the film was thin highly homogeneous without cracks and the desirable thickness of $2\ \mu m$ was achieved. Besides, the film is consisted of very small nanoparticles of spherical shape with an average diameter of ~ 10 nm. The particles appear in a dense agglomerated form but any of them was very small.

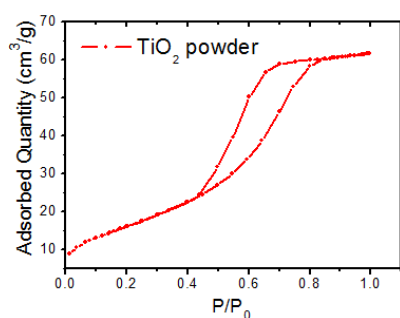


Fig. 2 Sorption-desorption isotherm of TiO_2 powder

B. Electrolyte Characterization

The solution used for the thermal gravimetric analysis was composed by sulfolane, 3-methoxypropionitrile, the hybrid organic-inorganic material and acetic acid for the solvolysis. The bottle containing the solution was left without a cap to expedite the gelation process and the measurements were carried out using the resulting gel.

TABLE I
STRUCTURAL PROPERTIES OF TiO_2 POWDER

Sample	Porosity (%)	S_{BET} (m^2/g)	Pore diameter (nm)	Pore volume (cm^3/g)	Pore width (nm)
TiO_2 powder	26.51	60.46	4.45	0.095	6.31

From the thermal gravimetric analysis curve (Fig. 4) the weight of the gel started to be slightly reduced after $50^\circ C$. The fact that the weight starts to be reduced at a temperature lower than $100^\circ C$ probably is an indication of water presence in the sample [11]. The weight loss increased significantly in the temperature range of $150^\circ C$ - $250^\circ C$ probably because of the evaporation of the gel's solvents.

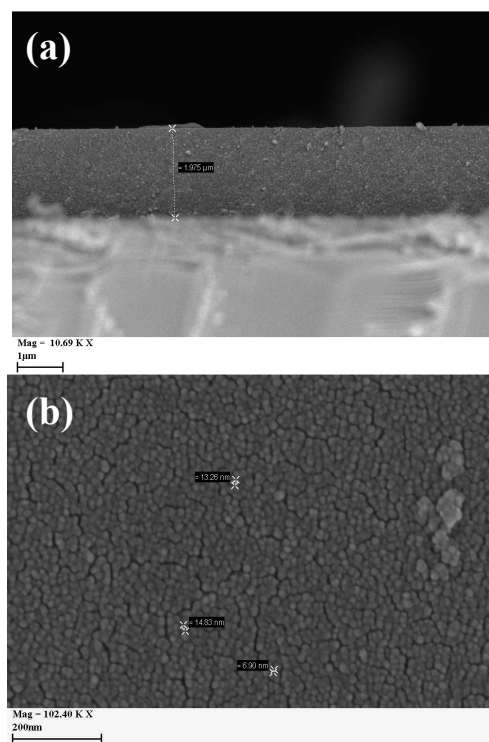


Fig. 3 (a) Cross section of the TiO_2 film with an average thickness of $2\ \mu m$ and (b) image of the surface of the film consisted of nanoparticles with average size $10\ nm$

C. Solar Cells' Performance

Figs. 5 (a) and (b) present the current density-voltage (J-V) characteristic curves of the strips with the varying length. The electrical parameters measured and calculated for all cells are summarized in Table II.

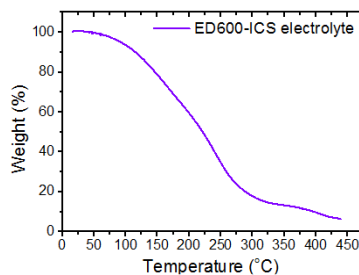


Fig. 4 TGA curves of the formed gel

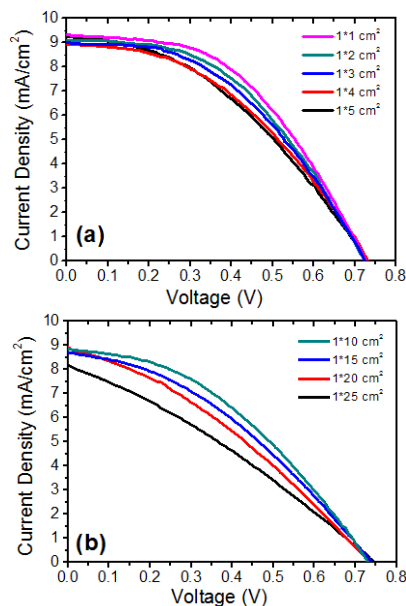


Fig. 5 Photocurrent density-voltage characteristic curves of dye-sensitized solar cells of length from (a) 1 to 5 cm and (b) from 10 to 25 cm

It can be seen that the short circuit current density values measured have small variations as the length increases from 1 to 25 cm. The V_{oc} values recorded for the cells with the different strip length had small variations as expected, since the same anode and electrolyte was used for manufacturing the cells. Variations were mainly noticed at the fill factor values calculated and as a result to the overall efficiency. This decrease is attributed to the fact that the size of the cell affects the FF due to the total internal in series resistance of the cell (R_s). Finally, we considered that a solar module with an almost square form and dimensions between 20 and 25 cm for each side could provide adequately satisfactory results.

D. Electrochemical Impedance Spectroscopy (EIS)

Fig. 6 shows the Nyquist plots obtained for some of the strip shaped cells. The first semicircle, starting from left to right, at the high frequency, corresponds to the charge transfer resistance of the Pt/electrolyte interface, R_{pt} . The resistance element related to the response in the intermediate frequency represents the charge transport at the TiO_2 /dye/electrolyte interface (R_{it}) and shows diode like behavior. The semicircle at the low frequency, which is attributed to the diffusion of

redox species in the electrolyte (R_{dif}), was small and not well distinguished, indicating a fast diffusion. Finally, the intercept of the horizontal axis stands for the resistance of the sheet resistance of the FTO substrate and the contact resistance of the FTO/ TiO_2 (R_h) [12], [13].

TABLE II
ELECTRICAL CHARACTERISTICS OF DSSCS OF VARIABLE LENGTH

Strip size (cm ²)	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	n (%)
1x1	9.33	0.73	0.48	3.3
1x2	9.07	0.72	0.47	3.1
1x3	9.03	0.73	0.45	3.0
1x4	9.05	0.73	0.43	2.9
1x5	9.26	0.73	0.42	2.8
1x10	8.84	0.73	0.39	2.6
1x15	8.70	0.74	0.40	2.6
1x20	8.85	0.73	0.36	2.4
1x25	8.12	0.75	0.33	2.1

The total series resistance of the cell can be calculated using (1):

$$R_s = R_h + R_{pt} + R_{dif} \quad (1)$$

The equivalent circuits, which were used to fit the experimental data, are presented in Fig. 7. For electrodes having a rough surface the capacitance element in Fig. 7 (a) is replaced by a constant phase element (CPE, Q) which depends on the parameters Y_0 and N (Fig. 7 (b)) [14]. According to instrument software's manual Y_0 is the admittance of an ideal capacitance while N is an empirical constant ranging from 0 to 1. It is possible to convert a CPE element, which is in parallel with a resistance, to a pseudo capacitance using (2). As shown in (2) for N=1 the CPE element describes a pure capacitor, while for N=0 an ideal resistor.

$$C_{pseudo} = Y_0^{1/N} \cdot R \left(\frac{1}{N} - 1 \right) \quad (2)$$

Moreover, for N=0.5 the CPE element is equivalent to the Warburg element often used to describe the diffusion in the electrolyte.

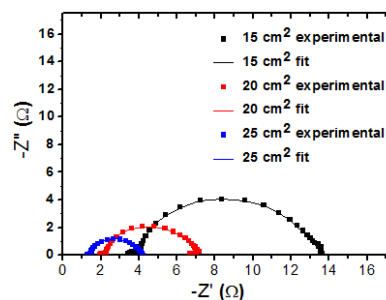


Fig. 6 Impedance spectra of dye-sensitized solar cells with varying length measured at open circuit voltage under outdoor illumination

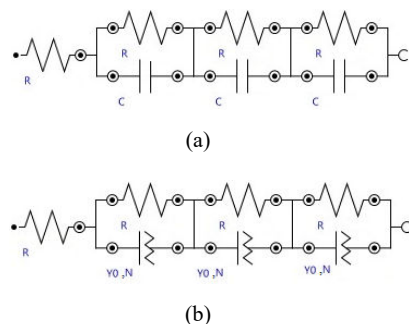


Fig. 7 DSSCs equivalent circuits (a) $R(RC)(RC)(RC)$ and (b) $R(RQ)(RQ)(RQ)$ used to fit the experimental data from the EIS measurements

It is generally thought to arise from the lack of homogeneities in the electrode-material system. The fitted parameters are summarized in Table III. Since the tested cells have different active area, due to their different length, it is not accurate to compare their total series resistance in Ω using (1). Thus, we decided to multiply the obtained values from (1) with the active area of each cell and derive a conclusion from the final values calculated in $\Omega \text{ cm}^2$.

TABLE III
ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY FITTED PARAMETERS FOR STRIP SHAPED DSSCs WITH VARYING LENGTH

Strip size (cm^2)	R_h (Ω)	R_{pt} (Ω)	C_{pt} (F) (10^{-4})	R_{tr} (Ω)	C_{tr} (F) (10^{-3})	R_{dif} (Ω)	C_{dif} (F) (10^{-1})
1x15	3.44	0.54	0.41	7.86	2.61	2.09	0.73
1x20	1.97	0.50	0.80	3.49	5.53	2.27	0.64
1x25	1.41	0.55	1.27	2.15	8.40	1.96	1.95

The values of R_s for the cells with strip length 15 cm, 20 cm and 25 cm were $91.05 \Omega \text{ cm}^2$, $94.8 \Omega \text{ cm}^2$ and $98 \Omega \text{ cm}^2$ respectively. It can be seen from these values that the total series resistance didn't increase significantly as the length increased, which was very encouraging for the transition to large scale.

E. Dye-Sensitized Solar Module

A module employing optimized electrode width of 1 cm was realized on a $24.5 \text{ cm} \times 21 \text{ cm}$ FTO plate consisting of nine independent solar cells serially connected by mechanical scribing of the FTO substrate to test the reliability of serial connection in DSSC scaling up (Fig. 8).

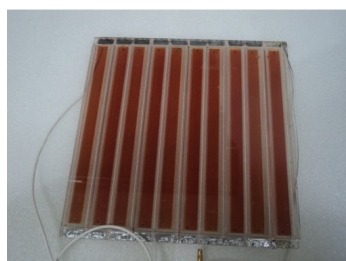


Fig. 8 A highly transparent 253 cm^2 DSSC module with 10 serially connected elements

The use of thin films of TiO_2 as described in the experimental section, low content Pt inkjet printed strips on the counter electrode and the low-surface density of N719 dye allow for a high transparency of the module.

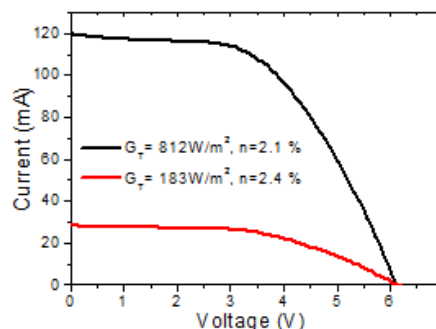


Fig. 9 Photocurrent density-voltage characteristic curves of dye-sensitized solar module of active area 253 cm^2

High transparency and serial connection have demonstrated that the module I-V characteristics were almost independent from the light direction i.e. front or back illumination providing similar performances. The I-V curves of the module measured at two different light intensities (183 and 812 W m^{-2}) are presented in Fig. 9. As it can be seen, there are no serious differences among the efficiencies obtained for $1 \times 20 \text{ cm}^2$ strip type DSSC cell and the 253 cm^2 module.

IV. CONCLUSIONS

At the present work we prepared DSSCs at different sizes varying their length by keeping constant their width at 0.5 cm . The cells were constructed with thin nanocrystalline TiO_2 films made with inkjet process using appropriate sols. We have shown that the serial connection of individual cells with a suitably chosen size to encompass a simple electrode pattern while keeping current losses at minimum values, was demonstrated to be a successful approach. The use of gel electrolytes in such geometry was possible employing low sheet resistance FTO glass, a thin film of TiO_2 and a low dye concentration that allowed dye regeneration not to be limited by slow electrolyte diffusion processes. The gel electrolyte DSSCs realized reached an almost 2.5% efficiency. Stability issues can be addressed by the use of gel electrolytes, which avoids leakage problems and leads to a stable shelf life.

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