Dye-sensitized solar cell scale-up: Influence of substrate resistance
R. Escalante, D. Pourjafari, D. Reyes-Coronado, and G. Oskam

Citation: Journal of Renewable and Sustainable Energy 8, 023704 (2016); doi: 10.1063/1.4944969
View online: http://dx.doi.org/10.1063/1.4944969
View Table of Contents: http://scitation.aip.org/content/aip/journal/jrse/8/2?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Design of hybrid nanoheterostructure systems for enhanced quantum and solar conversion efficiencies in dye-sensitized solar cells
J. Appl. Phys. 117, 135704 (2015); 10.1063/1.4916783

Enhancing the optical absorption of anthocyanins for dye-sensitized solar cells
J. Renewable Sustainable Energy 7, 013120 (2015); 10.1063/1.4907599

Investigation of the influence of coadsorbent dye upon the interfacial structure of dye-sensitized solar cells

Charge transport through split photoelectrodes in dye-sensitized solar cells

Laser assisted dye-sensitized solar cell sealing: From small to large cells areas
J. Renewable Sustainable Energy 6, 011208 (2014); 10.1063/1.4865948
Dye-sensitized solar cell scale-up: Influence of substrate resistance

R. Escalante,1,a) D. Pourjafari,1 D. Reyes-Coronado,2 and G. Oskam1,a)
1Departamento de Física Aplicada, CINVESTAV-IPN, Mérida, Yucatán 97310, Mexico
2Unidad Académica Playa del Carmen, Universidad de Quintana Roo, Playa del Carmen, Quintana Roo 77710, Mexico

(Received 9 December 2015; accepted 17 March 2016; published online 31 March 2016)

Dye-sensitized solar cells can be considered as a future candidate to complement current photovoltaic systems; however, scaling-up the dye-sensitized solar cell is a complicated issue. One of the challenges is the module resistance, which includes the resistance of the transparent conducting oxide substrate. By increasing the substrate area, the internal module series resistance increases, resulting in a decrease of the fill factor; hence, charge collectors must be introduced in the module. In this work, silver lines are incorporated in a mini-module design and the dependence of distance between the two silver current collectors, on the working and counter electrode sides, respectively, and the module series resistance is illustrated. A module of 7 cells with 0.60 mm silver lines, and 23.8 cm² of active surface area reached an efficiency of 4.8%. © 2016 AIP Publishing LLC.

[http://dx.doi.org/10.1063/1.4944969]

I. INTRODUCTION

After the introduction of dye-sensitized solar cells (DSSCs) by Grätzel and O'Regan in 1991, they became the center of attention due to their inherent advantages such as low cost, simple fabrication, and the use of abundant and environmentally friendly materials.1,2 Current confirmed efficiencies stand at 11.9% for a 1 cm² solar cell, 10.7% for a mini-module of 26 cm², and 8.8% for a 400 cm² sub-module.3 For cells smaller than 1 cm², several reports have been published with higher efficiencies using a novel cobalt complex-based redox couple, which results in higher values for the open circuit voltage; the Grätzel group reported a 13% solar cell,4 while Kakiage et al. reported an efficiency of 14.3% both under 1 sun (AM 1.5G) illumination;5 however, the cell areas were only 0.28 cm² and 0.10 cm², respectively. From the above, it is clear that the area of the device is a critical parameter determining the efficiency, and the series resistance introduced by the transparent conducting oxide (TCO) substrate is an important factor. Hence, one of the most important challenges in scale-up of the DSSC is the incorporation of current collectors in the module design.

There are many reports on the performance of small laboratory cells; however, investigation on large scale modules is still in progress6,7 and design details and optimization parameters are generally not reported in the literature. Several research groups have tried to overcome the challenges of DSSC industrialization, which include the deposition of uniform TiO₂ films on a large substrate, electrolyte leakage and sealing, long-term stability, ohmic losses associated with the larger area substrates, and efficient module design.7,8 The first report on scale-up of the DSSC was in 1996 by Grätzel’s group, in which they reported a solar mini-module with a total surface area of 21.06 cm² and an efficiency of 5.65% with respect to its active area.9 There are various reports on reproducibility, stability, TiO₂ deposition methods, and configuration of solar modules.8–14 Spáth et al. reported on the reproducibility of a semi-automated
fabrication line, illustrating the repeatable preparation of 100 cm² modules with a 5.9% efficiency (in active area), and they report that upon decreasing the distance between the silver lines in the module design from 12 mm to 8 mm, related to a decrease in the width of the TiO₂ cells of 0.8 cm to 0.5 cm, the fill factor increases from 0.66 to 0.71.8 This example clearly illustrates the importance of the current collector and module design.

In this work, we focus on the relation between solar cell performance and series resistance corresponding to the TCO, and we study this by systematically varying the distance between the Ag collector lines on the working and counter electrode, respectively. We use both DC measurements, such as IV curves and 4-point probe resistivity measurements, and electrochemical impedance spectroscopy to characterize the relationships between the solar cell performance and these parameters. Both small area laboratory-scale solar cells (0.5 cm²) and two mini-modules of different design were fabricated, and their performance has been related to the properties of the silver collector lines.

II. EXPERIMENTAL METHODS

A. Chemicals

Acetic acid (≥99.7%), titanium (IV) isopropoxide (>97%), nitric acid (ACS reagent, 70%), ethyl cellulose (viscosity 100 cP), terpineol (anhydrous), lithium iodide (99.9%), iodine (99.8%), guanidine thiocyanate (GuSCN, ≥97%), acetonitrile (99.93%), valeronitrile (99.5%), and 4-tert-butylpyridine (TBP, 96%) were purchased from Sigma-Aldrich and used as received. The N719 dye and silver screen printing ink (DIAG50) were purchased from Dyesol, and absolute ethyl alcohol (ACS Reagent Grade) was bought from Macron. An electroless platinum deposition solution (Platisol T) and 1,2-dimethyl 3-propylimidazolium iodide (DMPII) were purchased from Solaronix.

B. Instruments and devices

For TiO₂ paste preparation, a rotary evaporator (BUCHI Rotavapor R-210) was used. The thickness of silver collector lines and TiO₂ films was measured by profilometry (KLA-Tencor AlphaStep D-120). To observe the deposited TiO₂ film morphology, a JEOL JSM-7600 F field emission scanning electron microscope was used. The crystallographic phase of TiO₂ was determined with a Siemens D5000 X-ray Powder Diffraction (XRD) set-up. Photovoltaic characterization of small laboratory cells was performed using a set-up consisting of a 450 W ozone-free Xe-lamp (Oriel) with a 10 cm water filter and an AM 1.5G optical filter; the intensity was calibrated using a certified 4 cm² monocrystalline silicon reference cell and employing a KG-5 filter to optimize calibration. The photovoltaic performance of the mini-modules was determined using an Oriel Sol2A Class ABA Solar simulator calibrated using a certified reference cell. To determine the uniformity of Ag collector lines, an optical microscope (Stemi 2000-C) with camera (AxioCam ERc 5s-Zeiss) was used. Electrochemical impedance spectra were collected with an Autolab PGSTAT302N/FRA2 set up, and data analysis was performed using the Nova 1.10 software. The resistance of the Ag lines was measured by a 4-point probe method employing a Keithley 2000 digital multimeter.

C. TiO₂ paste synthesis

The screen printing paste was prepared from TiO₂ nanomaterial synthesized using sol-gel processing similar to methods described in the literature15–18 In summary, 4.04 ml of acetic acid was added to 21.22 ml of titanium (IV) isopropoxide, and the solution was vigorously stirred for 15 min at room temperature. The mixture was added drop-wise to 145 ml of deionized water with stirring. After 40 min of agitation, a quantity of 4.0 ml of nitric acid was added to the mixture, which was subsequently heated to 80 °C within 40 min and the suspension was peptized for 75 min. Aliquots from the resultant mixture were hydrothermally treated at 200 °C for 12 h in a Teflon-lined autoclave (Parr Instruments). After this process, the suspension was centrifuged and washed with ethanol and dried. A paste was prepared by adding 1.0 g TiO₂
powder and 0.30 g ethyl cellulose to 30 ml and 15 ml ethanol, respectively, and the resulting suspensions were sonicated separately for 1 h. After sonication, the two solutions were mixed and 4.1 g terpineol was added to the mixture, followed by 1 h of sonication. The excess ethanol was removed with a rotary evaporator resulting in the TiO$_2$ screen printing paste as final product.\textsuperscript{19}

D. Working electrode: TiO$_2$ film deposition by screen printing

TiO$_2$ was deposited by screen printing on fluorine-doped tin oxide (FTO) on glass as a substrate; FTO with a sheet resistance of 8 $\Omega$ /$\square$ was used for both working and counter electrodes (TEC 8; Xop Glass). Depending on the substrate dimensions, three different solar cells were fabricated: a small cell on $2 \times 2$ cm$^2$ FTO, a distance test cell on $2 \times 6$ cm$^2$ FTO, and solar mini-modules on $6 \times 8$ cm$^2$ FTO substrates. Two solar mini-modules were fabricated with 4 and 7 strips of TiO$_2$ (4S and 7S mini-modules).

For the small and distance test cells, TiO$_2$ was printed on an area of 0.5 cm$^2$ ($1 \times 0.5$ cm$^2$) followed by sintering at 530 $\degree$C. The substrates were immersed at 80 $\degree$C in a N719 dye solution in ethanol for 24 h. For the solar mini-modules, TiO$_2$ was deposited in areas of 13.6 cm$^2$ and 23.8 cm$^2$, denoted 4S and 7S, respectively. In this case, after the TiO$_2$ heat treatment, the silver lines were deposited by screen printing between the strips of TiO$_2$ and were cured at 180 $\degree$C for 45 min; the substrates were then immersed in the N719 dye solution for 24 h. The thickness of TiO$_2$ films was determined by profilometry to be approximately 9–10 $\mu$m for all cells and mini-modules.

E. Counter electrode: Platinum deposition

Two electrolyte filling holes per substrate were drilled in the counter electrodes for the small and distance test cells, and multiple holes for the solar mini-modules. In each case, the counter electrodes were selected to be the same size as the working electrodes. The electroless platinum deposition solution was brushed onto the counter electrodes on the same active area as the TiO$_2$ area on the corresponding working electrodes, followed by heat treatment at 400 $\degree$C for 5 min.

F. Silver current collector deposition

Ag lines were deposited from a silver ink by screen printing on both working and counter electrodes of the distance test cell and solar mini-modules after TiO$_2$ film deposition. In all cases, the Ag lines were cured at 180 $\degree$C for 45 min. For the distance test cells ($2 \times 6$ cm$^2$ FTO), the distance between two first Ag lines (one on the working and the other on the counter electrode) was 14 mm. Subsequent lines were printed on both electrodes at an interval distance of 10 mm. For the solar mini-modules, Ag lines were deposited between the TiO$_2$ strips, and the distance between the lines and the border of active area was 1.5 mm (see Figure 1).

G. Cells and mini-modules design and assembly

The thermoplastic material Surlyn (Dupont, 70 $\mu$m) was used between working and counter electrode as a sealing material. The electrolyte solution consisting of 0.1 M LiI, 0.05 M I$_2$, 0.6 M DMPII, 0.1 M GuSCN, and 0.5 M TBP in a mixture of acetonitrile and valeronitrile (volume ratio 85:15) was injected into the cells and mini-modules via the holes in the counter electrode, which were subsequently sealed using Surlyn and a cover glass.\textsuperscript{19} Figure 1 shows the small cell and one strip of TiO$_2$ in a mini-module with the dimensions, active area, and silver lines.

For small laboratory cells, the silver lines were painted onto the FTO substrate manually, and the distance between the silver collectors on the working and counter electrodes was 16 mm. In the case of the strips in the mini-module, the width was 0.5 cm and the length was 6.8 cm, and the silver current collector lines were deposited by screen printing with a length of 7.2 cm and width of 0.6 mm.
III. RESULTS AND DISCUSSIONS

A. X-ray diffraction

Figure 2 shows the X-ray diffraction pattern for a TiO$_2$ film deposited onto FTO substrate after sintering. The diffraction peaks can be indexed to anatase TiO$_2$, and no other diffraction peaks were found, other than those corresponding to the FTO substrate (not indexed), indicating that the prepared TiO$_2$ films consist of pure anatase. In the inset of Figure 2, an SEM image of the deposited TiO$_2$ films is shown: based on the images, the average TiO$_2$ particle size was determined to be 12 nm, which is in agreement with an analysis of the XRD peak width of the (101) anatase reflection using the Scherrer equation.

B. Small laboratory cell performance

Figure 3 shows the current density versus voltage curve for a typical small cell with a 0.5 cm$^2$ active area under 100 mW cm$^{-2}$ (1 sun) illumination; the inset shows a photo of a solar cell. For this particular laboratory scale solar cell, a short circuit current density of 10.6 mA/cm$^2$, open circuit voltage of 0.70 V, a fill factor of 0.60, and an efficiency of 4.5% were obtained.
Note that 0.5 cm$^2$ area is sufficiently large to assure reproducibility and extrapolation of results to larger area devices.$^{20}$

C. Silver current collector lines: Effect of width

As mentioned before, to overcome the ohmic losses of the large transparent, conductive substrate and to minimize the inactive surface area losses of the device, it is important to use Ag grid lines between the strips of sensitized TiO$_2$.\textsuperscript{8,21} To study the effect of line width, silver lines with a thickness of approximately 11–12 $\mu$m and a width of 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 mm were deposited on a glass substrate from a silver screen printing paste. Figure 4(a) shows the deposited silver lines on the transparent glass substrate, while Figure 4(b) shows an optical microscope image of a silver line incorporated on the working electrode of a mini-module.

![Graph showing X-ray diffraction pattern](image1)

**FIG. 2.** X-ray diffraction pattern of the TiO$_2$ films, illustrating that the material is pure anatase; the peaks without index correspond to the FTO substrate. The inset shows an SEM image of the TiO$_2$ film.

![Graph showing current density vs. voltage](image2)

**FIG. 3.** Current density versus voltage curve for a representative small cell with an active area of 0.5 cm$^2$; the inset shows a photo of the cell.
In Table I, the width of each line and its resistance are listed, showing a good correlation. An important factor in mini-module design is the total active area on the substrate with respect to the mini-module area. By choosing narrow silver lines, the total active area on the substrate can be larger; however, silver lines of a width of 0.2 and 0.4 mm showed a high resistance, which makes them unsuitable as collector lines. Lines of width larger than 0.6 mm showed a low resistance, but choosing these lines would result in a decrease of the total active area on the substrate. In addition, the manipulation and fabrication process of the mini-module becomes more challenging, since the Surlyn sealant has to cover the Ag lines but not the TiO\textsubscript{2} strips. The results in Table I illustrate that Ag collector lines with a width of 0.6 mm are optimal, allowing a balance between low resistivity and larger active area of the mini-module.

D. Silver collector lines: Effect of distance

Figure 5 shows Ag printed lines for a distance test solar cell before cell fabrication, illustrating the design of the test.

The effect of the distance between the silver lines on the working and counter electrodes on the fill factor and efficiency of a solar cell was observed by measuring current density versus voltage curves, which are presented in Figure 6(a). Figure 6(b) indicates that upon increasing the distance between Ag collector lines from 14 mm to 104 mm, the fill factor decreased from 0.59 to 0.38 and the efficiency from 4.6\% to 3.0\%, corresponding to a decrease of approximately 35\% in both parameters. The open circuit voltage and short circuit current were essentially independent of the distance. These results illustrate that the series resistance of the solar cell directly affects the fill factor, indicating that the resistance of the conducting glass substrate is a significant, efficiency-determining parameter.

Electrochemical impedance spectroscopy (EIS) was used to determine the series resistance of the distance test solar cells; the measurements were performed with 1 sun illumination and under open circuit conditions. The complete impedance of DSSCs is usually described using a transmission line model\cite{19,22} and the series resistance related to the FTO, wires, and contacts

![Figure 4](image)

**FIG. 4.** (a) Deposited silver lines on transparent glass substrate of different width and (b) optical microscope image of a line deposited on the working electrode of a mini-module.

<table>
<thead>
<tr>
<th>Width (mm)</th>
<th>Thickness ((\mu m))</th>
<th>Transversal area (mm(^2))</th>
<th>Length (mm)</th>
<th>Resistance ((\Omega))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.40</td>
<td>11.4 ± 0.2</td>
<td>0.016</td>
<td>55</td>
<td>0.19 ± 0.02</td>
</tr>
<tr>
<td>1.20</td>
<td>11.4 ± 0.5</td>
<td>0.014</td>
<td>55</td>
<td>0.23 ± 0.02</td>
</tr>
<tr>
<td>1.00</td>
<td>11.5 ± 0.2</td>
<td>0.012</td>
<td>55</td>
<td>0.29 ± 0.02</td>
</tr>
<tr>
<td>0.80</td>
<td>11.7 ± 0.1</td>
<td>0.009</td>
<td>55</td>
<td>0.40 ± 0.02</td>
</tr>
<tr>
<td>0.60</td>
<td>12.0 ± 0.3</td>
<td>0.007</td>
<td>55</td>
<td>0.54 ± 0.02</td>
</tr>
<tr>
<td>0.40</td>
<td>11.9 ± 0.1</td>
<td>0.005</td>
<td>55</td>
<td>0.82 ± 0.02</td>
</tr>
<tr>
<td>0.20</td>
<td>11.0 ± 0.1</td>
<td>0.002</td>
<td>55</td>
<td>1.5</td>
</tr>
</tbody>
</table>
can be obtained from the intercept on the x-axis in a Nyquist plot at high frequency. Figure 7(a) shows the Nyquist plots, where the imaginary part of the impedance, $Z''$, is plotted versus the real part of the impedance, $Z'$, for the test cell as a function of the distance between the Ag lines.

Figure 7(b) shows that by increasing the distance between silver lines from 14 to 104 mm, the substrate resistance increased from 21.5 to 69.5 $\Omega$ in an essentially linear fashion. These results confirm that the resistance of the FTO limits the cell performance, highlighting the importance of the presence of silver current collector lines in any module design based on transparent conducting oxide substrates.

**E. Solar mini-modules: 4-strip (4S) and 7-strip (7S) TiO$_2$**

As described in Sec. II, two mini-module designs with either 4 or 7 strips of TiO$_2$ were fabricated on $6 \times 8$ cm$^2$ FTO. In both cases, the width of silver current collector lines was 0.6 mm. Each strip was 6.8 cm in length and 5 mm in width. Figures 8(a) and 8(b) show photos of the working electrodes with dye-sensitized TiO$_2$ films and screen printed Ag collector lines between the strips on the left side, and the counter electrode with electrolyte filling holes on the right side. The darker shade on the counter electrode is the deposited platinum catalyst. Figure 8(c) shows the assembled mini-modules.

The performance of the solar mini-modules was studied by measuring current-voltage curves under simulated solar illumination. For the 7S mini-module, the silver lines were

---

FIG. 5. Ag collector lines printed on working and counter electrodes for a distance test cell before cell fabrication.

FIG. 6. (a) Current density-voltage curves for a distance test cell as a function of the distance between Ag lines; (b) Fill factor and efficiency as a function of the distance between Ag lines.
connected to each other in a parallel configuration. For the 4S mini-module, the TiO2 strips were isolated by removing the conductive oxide layer on the FTO, and there was no connection between Ag lines. Therefore, the performance of just one strip cell could be studied. After characterizing the strip cells individually, the Ag lines were connected in order to study the performance of entire mini-module, also in a parallel configuration.

FIG. 7. (a) Nyquist plots for the solar test cells as a function of the distance between the Ag collector lines from 14 to 104 mm. The amplitude was 10 mV, and the frequency range was from $10^{-1}$ to $10^5$ Hz. The inset shows the equivalent circuit generally used for the interpretation of EIS measurements on DSSCs: $R_s$ is the FTO series resistance; $R_{FTO}$ and $C_{FTO}$ correspond to the substrate not covered by the TiO2 nanoparticles; $R_e$ represents the resistance for electron transport; $R_r$ is the charge transfer or recombination resistance; $C_{el}$ is the chemical capacitance; $Z_d$ is the Warburg impedance corresponding to diffusion of the redox species in the electrolytic solution; $R_m$ stands for the charge transfer resistance; and $C_m$ for the Helmholtz capacitance at the counter electrode/electrolyte interface. (b) Test cell series resistance versus Ag line distance.

FIG. 8. (a) Solar mini-modules with 4 TiO2 strips. (b) Solar mini-module with 7 TiO2 strips. The left side shows the working electrode with sensitized TiO2, and the right side shows the counter electrode with Ag lines and the platinum electrocatalyst. (c) Solar mini-modules after assembly: left side, 4S mini-module and right side, 7S mini-module.
F. Solar mini-modules: Performance

Figure 9 shows the current versus voltage curves under 1 sun illumination for the 4S mini-module after connection between Ag lines (red curve) and for 7S mini-module with connected Ag lines (black curve), both in a parallel configuration. In Table II, the results for the solar cells and mini-modules are listed.

In Table II, the parameters for separated strips are the average values of the 4 strips, with the best strip showing an efficiency of 5.85%.

From Table II, we can conclude that the efficiency for the best strip and that of the 7S mini-module is actually somewhat higher than for the small cell, indicating that we have achieved a viable scale-up of the 0.5 cm² cell to a 3.4 cm² strip cell and a 23.8 cm² mini-module. These results are related to the smaller distance between the Ag collector lines in the module design than in the small cell design. However, the 4S mini-module had a somewhat lower efficiency, which is due to a lower current density than for the best strip cell and a lower fill factor. This is most likely related to variations in the performance between the 4 strips. As a consequence, the performance of the mini-module in a parallel connection of the strips is limited by the lower current density and lower fill factor of one or more strips. This is also observed for the 7S mini-module: both the short circuit current density and the fill factor are somewhat lower than for the best strip cell (of the 4S mini-module); however, the final efficiency is very promising, as it is still higher than that of the small laboratory solar cell of 0.5 cm². The area of the sealed 7S mini-module is 45.6 cm², hence, the active area of the mini-module design corresponds to 52% of the geometric area, which compares well to other module designs in the literature.\textsuperscript{7,13,23} It should be noted that current high-efficiency solar cells with area $<0.5$ cm² are characterized by a short circuit current density of about 18 mA cm$^{-2}$, hence,
the higher current density may affect the optimization parameters of the module design. However, the general conclusions obtained with the cells and mini-modules presented in this work remain valid and provide a framework for scale-up of the DSSC.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.

IV. CONCLUSIONS

An important challenge in the scale-up of the dye-sensitized solar cell is related to the significant effect of ohmic losses due to the transparent conducting oxide substrate upon increase in substrate area. This effect can be minimized by incorporating silver collector lines on both the working and the counter electrode. Hence, the width and distance of Ag lines are important factors in the optimal design of a dye sensitized solar mini-module.

In this work, a mini-module with 7 strips of TiO2 with total active area of 23.8 cm² and optimum width for Ag line of 0.60 mm showed a better performance than a small laboratory dye-sensitized solar cell incorporating Ag collector lines is a viable option.