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FINAL PROJECT REPORT
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“Dye Sensitized Tandem Photovoltaic Cells”

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DYE SENSITIZED TANDEM PHOTOVOLTAIC CELLS

Final Report

CONTAINS INTELLECTUAL PROPERTY INFORMATION

September 2005 - May 2009

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Summary of Final Research, 9/05-5/09

Funds provided by this DOE grant have been used to support the principal investigator, a postdoc, a graduate student and an undergraduate student studying the photochemistry and photoelectrochemistry of nanometer grained TiO_2 dye sensitized solar cells (DSSC) to be used in a hybrid DSSC-Si concentrator array. This hybrid system offers a potentially interesting alternative to conventional DSSCs or Si systems in that it combines the diffuse power generation of conventional flat plate cells within a concentrator array for the Si cell. These arrays are potentially interesting for photoelectrochemistry because in principle they could allow a higher power output at a lower cost per unit area, allow each component of the system to be optimized individually, and demonstrate that although visible responsive photoelectrochemical cells cannot be made more efficient than silicon, they can be as efficient as silicon over the visible spectrum. Although it was the primary objective to demonstrate the advantages of a tandem hybrid concentrator system, much of this research ended up being devoted to addressing processing, chemical synthesis, and extending the absorption problems of TiO_2 based DSSCs. Some highlights we accomplished during this funding:

General Procedure for synthesis of $> 5.5\%$ TiO_2 DSSCs: The major challenge in the construction of the tandem cell has been the production and reproducibility of efficient DSSCs. In our research, we have found that individual cell performance depends critically on the nanocrystalline TiO_2 paste synthesis procedure, the addition of a dense TiO_2 underlayer, the addition of a light scattering layer, and an aqueous titanium tetrachloride post treatment or a core shell arrangement. In addition, all of these are all necessary for the production of efficient DSSCs consistent with reports by Graetzel, et al., Frank, et al., and the numerous literature reports.

However, it has also been demonstrated the environment in which the titania paste is sintered can significantly affect the efficiency of DSSCs as shown in Fig. 1. In this research, a commercially available anatase powder (Alfa Aesar, 32 nm) was processed into a paste (2 g TiO_2 /1 g hydroxypropylcellulose/14 g water) and then processed either in a tube furnace with a controlled oxygen-water vapor environment or an open air box furnace. As shown, it is clear the controlled atmosphere environment yielded higher performing devices compared to the best device processed in air. As detailed at the 30th DOE Solar Hydrogen meeting, the improvement seems to be due to either lower trap density or improved sintering. These findings coupled with the above results are consistent with the idea that the interconnectivity of TiO_2 nanoparticles and the porosity of the mesopores are crucial factors in optimizing DSSC energy conversion efficiencies.

Further evidence for the effect of processing on the efficiency of overall DSSC performance has been collected over the past year while working with a commercially available anatase paste (Solaronix, Switzerland). Despite developing procedures to make 10-14 μm thick films of nanocrystalline titania with or without an appropriate scattering layer, devices made with this commercially available paste can have lower or similar efficiency compared to the DSSCs made with the anatase paste using the procedure developed at NREL (much thanks to Art Frank and Nathan Neale of NREL without whose help this work would not be possible) as shown in Table 1. Thus, despite what is suggested in the literature regarding the simplicity of this technology, efforts and results obtained in this laboratory suggest the overall procedure to make highly efficient DSSCs is not a straightforward and simple procedure.

Fig. 1. Observed efficiencies of DSSCs fabricated from a commercially available powder showing the effect of processing atmosphere and temperature.

Table 1. Results of DSSCs produced with a variety of processing conditions using a commercially available anatase paste showing that processing and environmental conditions play a significant role in efficient DSSC production.

Heat at 3C per min with steps								
3800 rpm 0.1 M TiAcAc over entire substrate								
1 Scotch Tape								
	Area (cm ²)	Thickness (µm)	Voc (V)	Isc (mA)	Jsc (mA/cm ²)	Fill Factor	Power (mW)	Efficiency
No Scatt #2	0.65	12-14	0.724	3.850	5.923	0.688	1.910	2.94
With Scatt #1	0.63	16-17	0.726	4.833	7.671	0.667	2.341	3.72
With Scatt #2	0.63	16-17	0.714	4.874	7.737	0.679	2.363	3.75
Heat at 5 C/min with 5 min holds steps								
3600 rpm 0.1 M TiAcAc over ALL substrate or LOCAL area under TiO ₂ only								
1 Scotch Tape								
No Scatt 1 ALL	0.63		0.736	4.470	7.098	0.639	2.100	3.33
No Scatt 2 ALL	0.70	10-11	0.725	4.329	6.185	0.656	2.056	2.94
No Scatt 1 Local	0.63	12	0.732	5.597	8.884	0.599	2.452	3.89
No Scatt 2 Local	0.80	12	0.714	6.599	8.248	0.634	2.988	3.74
Heat at 5 C/min with 10 minutes hold								
0.1 M TiAcAc prebake local to area in form of long strip								
1 Scotch Tape with no scattering particles								
2000 rpm (~200 nm UL)	0.69		0.753	4.728	6.869	0.680	2.423	3.53
2500 rpm	0.70		0.752	4.756	6.834	0.668	2.390	3.43

3000 rpm (100-150 nm UL)	0.73	0.750	4.858	6.897	0.675	2.460	3.39
3500 rpm (50-100 nm UL)	0.69	0.762	4.427	6.426	0.678	2.289	3.32

Heat at 5 C/min with 10 minute holds
0.1 M TiAcac 3000 rpm all area prebake
1 Scotch Tape with scattering particles

50C EtOH soak 1	0.80	0.748	6.281	7.862	0.661	3.106	3.89
50C EtOH soak 2	0.78	0.737	6.573	8.452	0.653	3.188	4.07
Acn-tBuOH 12hrs soak 1	0.76	0.745	6.267	8.391	0.651	3.041	4.07
Acn-tBuOH 12hrs soak 2	0.78	0.743	6.143	7.836	0.674	3.077	3.92

Heat at 5 C/min with 10 minute holds
0.1 M TiAcac 3000 rpm all area prebake
1 Scotch Tape with scattering particles TiO₂ 70C 30min

Acn-tBuOH soak New dye	0.71	0.649	7.045	9.662	0.609	2.786	3.90
EtOH soak Refresh Rubby	0.71	0.678	7.371	10.375	0.641	3.202	4.51

Heat at 5 C/min with 15 minute holds with 50 mL per min O₂ flowing
0.1 M TiAcac 3000 rpm all area 325 C prebake 10 minutes
1 Scotch Tape 8 min dry RT 125 C for 10 minutes No Scat

Acn-tBuOH soak 1	0.73	0.673	4.967	6.810	0.706	2.358	3.23
Acn-tBuOH soak 2	0.75	0.677	3.691	4.939	0.696	1.739	2.33
EtOH 50C soak 1	0.74	0.695	5.282	7.063	0.669	2.446	3.26
EtOH 50C soak 2	0.75	0.709	4.630	6.415	0.710	2.430	3.23

Production of titanium foils bonded to transparent conducting oxides. Literature reports of dye-sensitized cells made from titania nanotube arrays show that anodized tubes may provide high performing DSSCs. However, the production of these electrodes by using evaporated or sputtered Ti films is not manufacturable, and the anodization of Ti foils requires backside illumination of the DSSC. In order to address these problems, we have developed low temperature methods for bonding readily available low cost titanium foils to transparent conducting oxide substrates. In particular, 0.025 mm thick (0.001") titanium foils have been bonded to rough FTO substrates through the use of Sn, Sb-Sn, Sb-Sn-Zn, and sol-gel deposited oxide interlayers by vacuum and inert atmosphere hot pressing at low temperatures and pressures. Anodic titania nanotube arrays have been

successfully made from titanium foils bonded to the FTO by the anodization methods developed by the Grimes group at Penn State. A general procedure with the use of tin based compounds is shown in Fig. 2a while Fig. 2b is an electron microscopy image of an anodized titanium foil that was bonded to FTO through the procedure outlined in Fig. 3a. Other intermetallic alloys that are compatible with DSSCs have also been investigated as bonding agents. Despite being able to reduce the complexity and processing time for titanium on a TCO, significant processing challenges remain. Also, based upon literature results, it seems the diffusivity of an electron in the titania nanotubes is not any faster than diffusion of an electron through an equivalent particle size polycrystalline film. Thus, the thought of enhanced electron transport in low dimensional anatase solid structures does not seem to be possible in the dye cell's current architecture.

Fig. 2: (a, left image). Overall process for bonding of Ti to FTO and fabrication of TiO_2 nanotubes and (b, right image) resulting nanotubes after anodization.

Evaluation of inverse opal photonic crystals as scattering layers in DSSCs. One of the important factors limiting the performance of DSSCs is their poor spectral response, especially in the red and near-infrared. Scattering particles have been used for to enhance the red response of DSSCs. In 2003, we showed that by coupling titania inverse opals to conventional nano- TiO_2 layers, one could attain particularly strong enhancement of light absorption by the dye in the red part of the visible spectrum,

presumably because of light localization in the inverse opal. Other groups have since verified that photonic crystal scattering layers provide strong red enhancement.

One problem with our previous study and those of other groups is they compare spectral responses in poorly performing DSSCs. Thus the photonic crystal effect has not been quantified in efficient cells. Because of the need to make efficient DSSCs for the hybrid testing, we attempted to quantify the increase in efficiency that could be achieved in photonic crystal bilayer cells and to understand the mechanism of the enhancement by comparing several different cell geometries. Enhancement of the spectral response of the DSSC is necessary for improving the performance of the hybrid concentrator system.

Figure 3 illustrates a procedure we developed for growing TiO_2 inverse opals on top of nanocrystalline anatase films. Our previous studies had the order of the layers reversed, which necessitated illumination from the cathode side of the cell. However, anode side illumination is preferred for high cell efficiency, because light is absorbed closer to the FTO collector electrode and absorption of blue light by I_3^- is minimized.

Fig. 3. Fabrication of a nanocrystalline TiO_2 /inverse opal TiO_2 bilayer anode for the DSSC.

In this procedure a polymer is spin-coated over the “green” anatase film prior to growth and infiltration of the polystyrene colloidal crystal with TiO_2 . This polymer film prevents loss of porosity in the nano- TiO_2 layer. We find that bilayers prepared in this way, when illuminated from the anode side, give strong enhancement of the IPCE in the red, as shown in Fig. 4. This enhancement is consistent with modeling studies performed by Miguez and coworkers. The Miguez model involves optical coupling of the two layers. This is essentially a waveguide effect, in which light localized in the inverse opal is backscattered into the nano- TiO_2 layer. The Miguez model addresses the paradox of the large photocurrent enhancement (15-20% in the red), which cannot be attributed solely to light localization in the photonic crystal layer, because almost all of the dye resides in the higher surface area nano- TiO_2 layer. A good diagnostic of this model is to observe the effect of decoupling the two layers by growing one on the anode and the other on the cathode side of the cell. In this case, the action spectrum resembles that of the nano- TiO_2 layer alone, as illustrated in Fig. 4.

Fig. 4. Normalized IPCE spectra of bilayer (orange curve) and split-layer inverse opal DSSCs. The spectral shape for the split-layer cell is essentially the same as that of a single-layer DSSC.

We find this decoupling effect occurs even when the two layers are grown together, as shown in Fig. 4, unless a second TiO_2 growth step (from TiCl_4 or borate/ TiF_6^{2-}) is

performed to join the two layers after calcination. Apparently the ~200 nm thick polymer layer and the roughness of the inverse opal are together sufficient to destroy the optical coupling between layers.

Measurements of i-V curves of single-layer and bilayer cells were performed to quantify the performance of the scattering layers in high quality cells. In these experiments, care was taken to compare cells containing similar amounts of adsorbed dye, which generally meant comparing cells that contained similar thicknesses of the nano-TiO₂ layers. As expected, the enhancement effect was greatest (up to 25% in overall efficiency) for relatively thin nano-TiO₂ layers, which absorb well near the absorbance maximum of the dye but poorly in the red. With thicker (10-15 micron) nano-TiO₂ layers, there is better light absorption across the visible, but losses in both open circuit photovoltage and short circuit photocurrent result from the longer electron transport pathway, which leads to more charge recombination. Table 2 shows a typical comparison of single-layer and bilayer cells.

Table 2. Solar performance data for single layer and inverse opal bilayer DSSCs. The surface coverage of the surface coverage is nmol/cm².

	N719 Surface Coverage	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
Standard DSSC	154	14.70	0.720	0.61	6.5
Bilayer PC291	159	15.11	0.752	0.70	7.9
Bilayer PC327	155	15.56	0.747	0.68	7.9
Disordered bilayer	156	15.13	0.757	0.68	7.8

For these high quality DSSCs, the inverse opal layer increases the AM 1.5 power conversion efficiency from 6.5 to 7.8-7.9%, i.e., by about 20%. As we noted in an earlier study, the increase is surprisingly insensitive to the degree of order of the inverse opal. A

disordered scattering layer (made from a template with two different sphere sizes) gives no observable stop band, but has the same effect on the absorbance of the bilayer and the I-V properties of the cell. This behavior does not follow in a straightforward way from the period crystal (i.e., Bloch function) model used by Miguez and it is not clear as to why the enhancement is across the entire spectral range.

Growth of Oriented Anatase-like TiO_2 nano- to micro-structures. As noted previously in this report, although the use of nanotube arrays of anatase provided some enhancement in efficiency compared to thin films of nanocrystalline anatase particles, the enhancement was due to lower back electron recombination. Thus because of the nature of the project to have high efficiency DSSCs, effort was devoted to developing the growth of single crystal anatase nanorods as it is well known the limiting factor affecting dye cell performance is the overall electron transport rate through the titania to the anode transparent conductor via trap-to-trap hopping^{19,20}. It is thought that by growing single crystal anatase and eliminating grain boundaries, which contain significant number of defect sites, electron transport and hence efficiency would be enhanced. We have verified well aligned vertical columns of sodium titanates may be grown by hydrothermally treating Ti foil to 1 M aqueous NaOH at temperatures above 180 °C. These sodium titanates may then be transformed to hydrogen titanates through an ion exchange process and then anatase through dehydration at elevated temperatures. Although a procedure was not developed during this research period to mate this processing to the production of these nanowires on FTO, it is strongly believed this procedure offers significant potential.

Separately from these recent reports, we have grown vertically aligned titania nanowires on FTO by 2 different template free techniques. In the first technique, titanium trichloride is hydrothermally treated in aqueous NaCl at 200 °C for several hours. We

have also grown vertically aligned titanium glycolate rods on FTO. What is intriguing regarding the glycolate rods is they may be converted to anatase through hydrolysis but they are already 1-D titania nanowires and can be grown 10's of micrometers long as a single wire. As originally detailed at the June 2008 30th DOE Solar Hydrogen Meeting, this program was the first to report the production of these and hydrolytically condensed single phase anatase like nanowires as well as the synthesis of perovskite on FTO as shown in the x-ray diffraction patterns in Fig. 5.

Fig. 5. Observed X-ray diffraction pattern of oriented titania and perovskite on polycrystalline FTO through controlled hydrolysis of organic precursors.

Testing of the Overall Hypothesis of the System. As the primary mission of this research program is to develop photoelectrochemical production of hydrogen using a

hybrid dye sensitized-silicon concentrator system, several measurements were undertaken to establish the baseline performance of the system.

The initial efforts used low efficiency DSSCs (approximately 3-4% active area efficiency) in a parabolic concentrator arrangement. In this test, 12 DSSCs (each approximately 0.4 cm^2 active area) were fabricated with large sealing borders so that the active area was approximately 20% of the total. Hot mirror coatings were fabricated on the non-conductive side of TEC 15 glass by Evaporated Coatings, Inc. (Willow Grove, PA) with 750 nm normal incidence cutoff. Before the nanocrystalline TiO_2 film was applied to the evaporated hot mirror/FTO slides, the conductive side was polished with $1 \text{ }\mu\text{m}$ alumina paste until the conductivity reached 30 ohm/sq . The sealing borders of the DSSC array was masked with black tape and the NIR light from the unmasked active area (4.30 cm^2) was focused onto a silicon concentrator test cell (1.44 cm^2). Thus the effective concentration ratio of this initial system was approximately 3.0. Although this system was tested during the first year of funding, subsequent testing showed the measurements and calculations were incorrect.

Despite these results, the next stage of the project required optimization of the preparation of the DSSCs to maximize the active area efficiency and to minimize the sealing area so that more realistic module efficiencies (calculated on the basis of total DSSC areas) could be measured. As stated earlier in this report, development of a complete 'production' processing procedure was the most time-consuming part of the project since the optimization of the DSSCs involved many fabrication parameters. Despite improving our active area DSSC over small areas (0.25 cm^2), when scaled to 1 cm^2 of active device area, our device performance was lower. Furthermore, it was soon discovered device efficiency depended on the wired electrical contacts geometry with

single edge contacts performing ~ 1% less efficient than 2 sided 'L-shaped' contacts. Despite this result, one-sided rectangular contacts were used for simplicity.

Using a reflective optics based system, another two outdoor measurements were attempted with dye sensitized solar cells with global efficiencies of ~5.3% and a silicon cell with a global efficiency of ~17% measured using a hand held power meter. These small cells had a 1 mm wide wire bonding border on the platinized counter electrode and exhibit typical fill factors of 0.55, which is much lower than the measured fill factor of 0.70-0.75 for high efficiency cells. As a result, these small cells have significant voltage loss at the maximum power point and thus suffer from a series resistance loss problem. In particular, the problem seems to be a sealing problem compounded by attaching lead wires to the 1 mm wide border on the platinized counterelectrode with a hand soldering iron. Furthermore, the measurements suffered from an inaccurate irradiance global measurement as well as a significantly high albedo reflectance on the silicon cell from the equipment used to make the concentrator arrangement thus negating any ability to calculate system efficiency. Lastly, measurements under a variety of direct and diffuse conditions were not undertaken.

Testing the Hypothesis of DSSC Efficiency versus Single Crystal Silicon over Visible Radiation. As noted, several measurements were attempted to evaluate the performance of the tandem DSSC-Si system in a reflective concentrator arrangement of which a representative schematic is shown in Fig. 6. Testing was scaled back to just compare the power generated by a DSSC versus a silicon cell over the visible part of the spectral range as well as to study the effect of commercially available optical filters on the performance of DSSCs. A 1 cm² Si solar cell, generously donated by Dr. Martin Green and his lab at the University of New South Wales and a dye sensitized solar cell,

graciously donated by Dr. Michael Graetzel of Ecole Polytechnique Fédérale de Lausanne (EPFL) and his lab were used in this investigation. The silicon cell was nominally 1 cm x 1 cm but due to having to make contact to it, the active area was approximated as 0.94 cm². Similarly, the dye cell had a measured active area of 0.865 cm². In the tandem hybrid arrangement proposed in Fig. 6., each DSSC would reflect red and infrared radiation to a silicon cell at the focal point of the DSSCs. Since there are many filters available, it became necessary to investigate the performance of a DSSC under several commercially available filters.

Fig. 6. Schematic showing a potential representation of a DSSC-Si tandem hybrid system.

The tandem hybrid set-up investigated the use of 2 wavelength selective coatings: a precision short bandpass 650 nm filter and a hot mirror [14]. The precision short bandpass 650 nm filter was obtained from Edmond Optics (12.5 mm diameter, Barrington, NJ, USA). The hot mirror coating was fabricated onto a 1 mm thick microscope glass slide by Evaporated Coatings (West Chester, PA, USA) and was cut into ~ 11 mm squares so as to slightly overfill the silicon cell. No air bubbles were visible

between the filters and the DSSC cell when each filter was individually placed on the front surface of the DSSC through index matching fluid. The transmission spectrum of the 650 nm short bandpass filter and hot mirror filter are shown in Fig. 7. The measured transmission of the short bandpass 650 nm filter appears to be about 3-4% lower than what is reported by the manufacturer. However the transmission of the hot mirror coating past 800 nm appears to be higher than what is expected for a hot mirror coating. The errors may be due to an alignment issue as the reflectors had to be manually held in the beam path during the measurement with a UV-VIS spectrophotometer but the general trend of the cut-off location and spectral dips remains the same. It should be noted the hot mirror coating contained a drop in transmission over the 360-425 nm range.

Fig. 7. Normal incidence transmission curves for the hot mirror (red) and 650 nm short bandpass filters used in the indoor and outdoor measurements.

In this test, each cell was measured indoors under AM 1.5G 1 sun conditions (Newport Oriel, Class A, 1000 W Solar Simulator). To verify the solar simulator was operating properly, a 0.979 cm² silicon solar cell (Burdick Technologies Unlimited, Lakewood, CO, USA) that had been measured at the National Renewable Energy

Laboratory (NREL) was measured under the solar simulator. This reference Si cell was measured to be 11.73% efficient. Although this efficiency is higher than the NREL measured efficiency of 11.44%, this slightly higher efficiency is attributable to a cooler ambient room/cell temperature of 20.5-21.0 °C versus 25 ± 1 °C during testing at NREL. A lower Si cell temperature should have a higher open circuit voltage and this was observed as listed in Table 3. It should also be noted the short circuit current matched to within 300 μ A thus suggesting the photon flux over the response of the silicon cell solar matched the NREL solar simulator well. The full solar characteristics of this cell measured at NREL and at Penn State are listed in Table 3.

The 1 sun indoor efficiency of the UNSW Si cell was measured to be 18.10% with an average current density of 39.40 mA/cm². The indoor efficiency of the dye sensitized solar cell (DSSC) was 9.03% with a current density of 15.58 mA/cm². The full indoor solar characteristics of these cells are listed in Table 3. This DSSC was also tested indoors with the wavelength selective filters covering the cell. It can be seen from the data in Table 1, there is only a small drop in performance of < 0.5% efficiency or < 1 mA when the DSSC was covered with the precision bandpass 650 nm filter. However, a substantial drop of -3.5 mA or 1.5% in efficiency was observed when the hot mirror was covering the DSSC. This is believed to be due to the dip in transmission over the 350-450 nm range. However, these results suggest that despite the significantly lower current using the hot mirror coating filter, which has a solar weighted reflectance of 62%, the efficiency of this 'global' 9.03% cell is actually 24.0% over the transmitted power density of 38 mW/cm² through the hot mirror filter covering the DSSC front surface. This result

is clearly important in proving that a photoelectrochemical cell can be more efficient than silicon over their corresponding spectral ranges.

Table 3. Indoor 1 sun solar cell performance characteristics of the dye sensitized solar cell (DSSC) and silicon solar cell as a function of. A National Renewable Energy Laboratory certified silicon reference cell measured at Penn State is also shown.

Cell and Location of Measurement	V_{oc} (V)	I_{sc} (mA)	J_{sc} (mA/cm ²)	Fill Factor (%)	Power max (mW)	Efficiency (%)
Si Reference cell - NREL	0.540	32.662	33.363	63.48	11.20	11.44
Si Reference cell - PSU	0.547	32.328	33.021	64.97	11.49	11.77
DSSC PSU	0.841	13.481	15.585	69.64	7.89	9.03
Si #5 PSU - 0.94 cm ²	0.651	36.250	39.401	72.10	17.01	18.10
DSSC - Hot Mirror filter - global	0.834	10.501	12.139	72.42	6.34	7.25
DSSC - Hot Mirror using just the transmitted power density through the hot mirror filter	0.834	10.501	12.139	72.42	6.34	24.00
DSSC - 650 nm short bandpass filter	0.843	12.738	14.726	70.73	7.59	8.78

As the other cornerstone of the tandem hybrid concentrator is that the performance of the silicon cell will improve with irradiance and the mirrors will not affect the performance of the DSSC cells. Outdoor performance data of the silicon cell from November 7, 2008 is shown in Fig. 7. In this work compared to the outdoor results mentioned previously, the albedo incident on the silicon cell has been reduced by a factor of 3. All data was collected with the irradiance between 81.3-84.8 mW/cm² on the handheld power meter. However, since the meter is line-of-sight and unable to collect all diffuse and albedo radiation incident on the silicon cell in the global and concentrator configuration, efficiency values can not be calculated directly. What is noteworthy is that each of 'red-to-infrared reflectors' reflect about half of the current density of the silicon cell under global conditions and the linear scaling of the photocurrent with each reflector.

Under these outdoor conditions the solar performance characteristics of the 0.865 cm² DSSC from Dr. Grätzel's lab were also investigated. Using this measured DSSC power and adjusting it to the same active area as the Si cell, the simulated tandem hybrid system would produce 100.3% of the power per unit area produced by the Si cell under the same global conditions. Based upon this work, further work with more efficient cells over the visible part of the solar spectrum would yield even higher performing systems than the single crystal silicon investigated here.

Fig. 7. I-V sweeps of a silicon cell under global and a concentrator arrangement with 1 and 2 reflectors incident upon it under an irradiance of 81.3-84.8 mW/cm².

Summary

This work provided a new way to look at photoelectrochemical cells and their performance. Although thought of as low efficiency, the internal efficiency of a 9% global efficiency dye sensitized solar cell is approximately equal to an 18% efficient silicon cell when each is compared to their useful spectral range. Other work undertaken with this contract also reported the first growth oriented titania and perovskite columns on a transparent conducting oxide. Other work has shown that significant performance enhancement in the performance of dye sensitized solar cells can be obtained through the use of coupling inverse opal photonic crystals to the nanocrystalline dye sensitized solar cell. Lastly, a quick efficient method was developed to bond titanium foils to transparent conducting oxide substrates for anodization. Lastly, the authors would like to thank Dr. Mark Spitler of the Department of Energy for the opportunity to pursue such diverse research topics for the solar hydrogen program.

Statement of Unobligated Funds

No unobligated funds are anticipated at the end of the current project period.

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