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A Simple Photocell To Demonstrate Solar Energy Using Benign Household Ingredients

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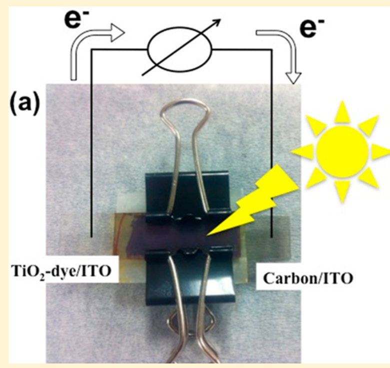
Supporting Information

ABSTRACT: A laboratory exercise for the construction of a dye-sensitized solar cell using everyday household and benign products has been developed. The simple and easy-to-assemble construction successfully demonstrates the conversion of solar energy to electrical energy. This project is intended for high school students as well as college students of chemistry, physics, or biology classes as an inexpensive hands-on exercise. A brief outline on basic measurements related to photovoltaic cell performance and its characterization is also presented, and approaches to use these concepts for demonstration are suggested.



KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Second-Year Undergraduate, Hands-On Learning/Manipulatives, Dyes/Pigments, Photochemistry, Collaborative/Cooperative Learning, Laboratory Instruction, Demonstrations, Material Science*

One of the greatest challenges that scientists and engineers must face in the coming years is the development of clean and renewable energy. As stated by the late Nobel Laureate, Richard E. Smalley, energy tops the list of global problems to address in the future.[1] By developing clean, renewable, and sustainable energy conversion systems, global problems such as clean water scarcity, food shortage, environmental pollution, poverty, and disease can subsequently be overcome.[1] As a result, Smalley has proposed the Terawatt Challenge, which is to develop and implement an array of renewable energy technologies where the energy output is equivalent to our current fossil fuel consumption. For example, in 2006 the world consumed 14 TW (14×10^{12} W) in energy from oil, coal, and natural gas.[2] As a result, the Terawatt Challenge is to implement 14 TW of renewable energy by 2050. To ensure that we meet this challenge, it is vital to inform and educate future scientists, engineers, and policy-makers of the current technologies and demonstrate them in such a way that it is easily understandable to a wide student audience. One of the promising energy technologies that have the potential to assist meeting the Terawatt Challenge posed by Smalley is solar energy. A significant amount of solar energy strikes Earth in 1 h to meet nearly all the global energy demands in one year.[3] Although this energy source can be viewed as pseudo-infinite, its use is constrained by challenges in areas such as cost/(kW h), materials, conversion efficiency, and storage.[4] Moreover, current solar energy conversion technologies require large land area. This requirement could be potentially minimized by improving photocell efficiency.

Despite the aforementioned limitations, dye-sensitized solar cell (DSSC) process, first demonstrated by O'Regan and Gratzel,[5] is an emerging and cost-effective solar energy harvesting approach that operates on principles similar to the process of natural photosynthesis. What makes the DSSC process so attractive is its price to performance ratio. The materials and manufacturing processes required to construct a DSSC can be relatively inexpensive and more environmentally friendly, compared to a silicon-based solar cell. For example, a main component of DSSC, titanium dioxide (TiO_2), is commercially available and used primarily as a pigment in paints and foods. Laboratory-constructed DSSC consisting of (i) nanosized crystalline mesoporous TiO_2, (ii) synthesized ruthenium-bipyridyl-based dyes, and (iii) platinum counter electrodes have achieved solar-to-power conversion efficiencies greater than 10% with a current density of 16 mA/cm^2.[5] However, the synthesis techniques required to achieve such high outputs can be difficult and hazardous to an untrained novice. Nonetheless, natural dyes such as chlorophyll[6] or anthocyanins[7,8] commonly found in leaves, fruits, and flowering plants can be used as light harvesting agents (sensitizers) in place of ruthenium bipyridyl dyes as well.

In this exercise, we report a laboratory-based teaching experiment intended for high school-level science students (i.e., chemistry, physics, biology, or combination thereof) to construct and test a solar cell device comprised of common

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household products. A third-year high school student carried out this laboratory exercise in a university lab setting. The concept was also validated by an entirely different student group to ensure reproducibility. The group consisted of three third-year undergraduate chemical engineering students. This project can be carried out over two, 2-h lab sessions or three, 50-min lab sessions typical in schools. Some prelab preparation (~2 h) in the form of preparing copies of assembly instructions, powering up the heater or furnace and heating the titania (see below), and ensuring all materials are available in one place, is needed. Longer preparation and testing times should be considered for larger student groups. For small groups (less than six students), individual cell construction and testing is suggested; for larger groups (greater than six students), groups of two to three students are suggested.

Several reports in the literature discuss solar cell construction in more detail,[8−10] cell performance along with characterization techniques,[8,11,12] and the basics of electron transfer in solar cell systems.[13,14] The main focus of this work is twofold: (i) to develop a laboratory exercise that is safe to carry out by high school or first-year-level college students and (ii) to demonstrate solar-to-electrical conversion using household materials. It should be noted that some types of household materials such as berry tea (i.e., raspberry or blackberry) are more desirable over others (e.g., strawberry) to demonstrate this concept in a discernible way.

■ EXPERIMENTAL OVERVIEW

Full experimental details regarding materials, solar cell device assembly, testing methods, and any hazards associated with the laboratory exercise are given in the Supporting Information. In summary, titania was obtained by calcining toothpaste to obtain anatase phase TiO_2. It was cast onto conducting glass slides and then stained with raspberry tea. This film was subsequently used as an anode in a sandwich-type solar cell assembly with a carbon-coated conducting glass slide serving as the cathode. The cathode can be made by rubbing a pencil tip on glass to create a light layer of graphite, or the glass can be held over a candle flame to form a decent conducting deposit. The anode and cathode were separated by a thin layer of a parafilm window. Figure 1 shows the schematic of the assembly process. Alcohol with dissolved iodine tablets was contained within this parafilm window and served as the electrolyte. The solar cell device was characterized under UV−visible irradiation.

A broad range of suggestions to instructors for customizing the laboratory exercise, as well as associated activities for designing objectives based on different knowledge levels of students, are given in the Supporting Information, Table S1.

Titania from Toothpaste

Different types of toothpaste (colored versus noncolored) were used to source the TiO_2. Approximately 5 g of toothpaste was heated in a crucible up to 500 °C for 3 h in air atmosphere (most of this can be started as part of the prelab by the instructor). In a typical experiment, one can obtain ~4 g of powder from ~5 g of toothpaste. The toothpaste was tested using X-ray technique (Figure S1) to ensure that TiO_2 was obtained. The brand of toothpaste for sample White-1 is Colgate Total. (The authors do not endorse any particular brand. From our analysis, this particular brand meets our desired criterion of anatase phase titanium dioxide after heat treatment.) It is worthwhile to mention here that titanium dioxide can also be obtained from food products and cosmetics.

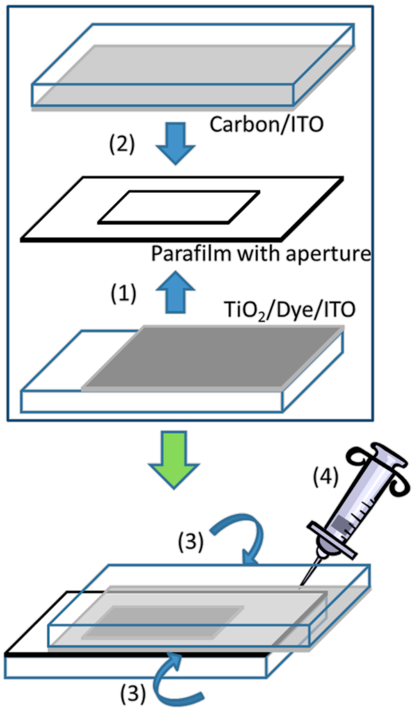

Figure 1. The scheme explaining the steps in assembling the solar cell device: (1) lay the parafilm/tape with an aperture on top of the TiO_2-dye/ITO plate; (2) place the carbon/ITO plate with the carbon side facing the TiO_2-dye/ITO; (3) attach binder clips to the edges of the assembly; (4) add a few drops of iodine mixture to the side, gently working out any air bubbles.

On the basis of the studies presented here and the work published by the Kamat group[15] (they used white powdered doughnuts as their TiO_2 source), other white colored food products are likely to contain photoactive materials for solar cell demonstrations. Other than food sources, additional options include sunscreen, which contains TiO_2 (or ZnO, another photoactive material).

■ HAZARDS

Although many chemicals used in this exercise are "household" materials, caution should still be exercised while using them. The use of proper laboratory protection equipment should be exercised. For example, when using any heating device or method, appropriate thermal protection should be used. All laboratory exercises should be carried out under the supervision of trained and qualified personnel.

■ STUDENT LEARNING OBJECTIVES

The key learning objectives are:

Synthesis: Using household products as a benign and low-cost source for developing photoactive materials.

Fabrication: Combining the synthesized and off-the-shelf materials to assemble a solar cell.

Testing: Application of simple techniques and mathematical expressions to obtain the key data that reveal the cell operation parameters.

Evaluation: Identifying and realizing the material-related issues and parameters that influence the solar cell performance.

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■ RESULTS AND DISCUSSION

The performance of the constructed device was measured indoors using a solar simulator with both UV and visible light components and a potentiostat. Examples of typical current−voltage (i−V) and power-voltage (P−V) curves of the solar cell are given in Figure 2A. Some typical parameters to examine cell performance are short circuit current (i_{SC}), open circuit potential (V_{OC}), fill factor (ff), and power conversion efficiency (η). The significance of these parameters is detailed in the Supporting Information. The cell demonstrates an i_{SC} of 1.8 μA/cm^2 and V_{OC} of 0.0105 V, with a maximum power output of 0.048 μW/cm^2 at 0.051 V. An i−t plot for two consecutive cycles recorded in light and dark conditions is shown in Figure 2B. The rapid change in photocurrent from dark (off) to light (on) demonstrates that the cell is indeed photoactive, thereby showing the photovoltaic effect, and that the results are reproducible.

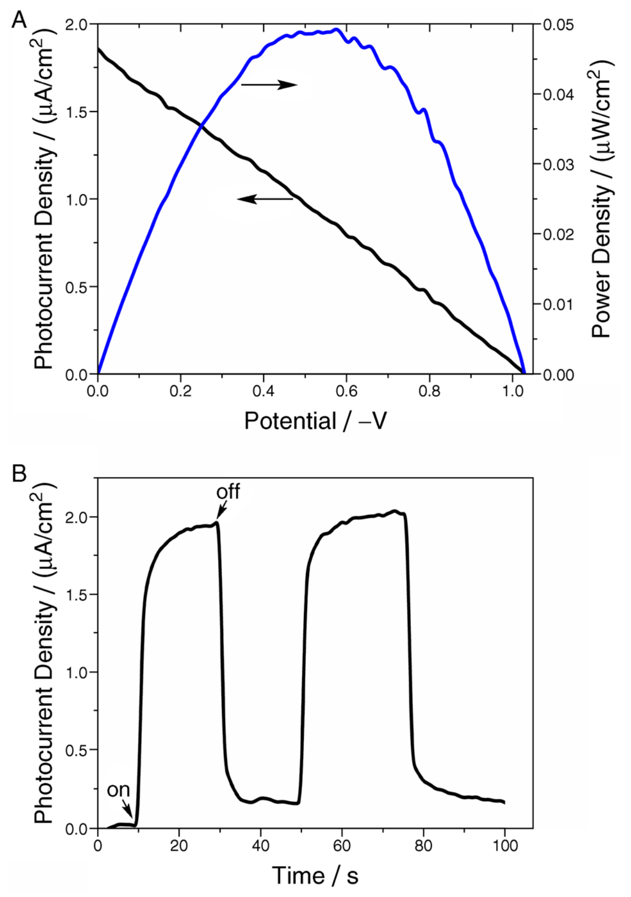

Figure 2. (A) *XYY* plot demonstrating i−V and P−V characteristics for the assembled toothpaste-based solar cell measured under a solar simulator with UV and visible light components at an intensity of ∼90 mW/cm^2. (B) i−t characteristics of the solar cell cycled through on/off photoillumination cycles.

The results using the TiO_2 obtained from the toothpaste indicate that the current, voltage, and subsequent power output of the cell is low. Specifically, ∼550 cm^2 area of an illuminated cell demonstrates a current of 0.1 mA, a fill factor (ff) of 0.26 and an overall cell efficiency (η) of ∼0.00005%. From the assembly method, as outlined in the Supporting Information, one option to increase the voltage output is to consider connecting a few cells in series. This configuration will be able to assist with increasing the voltage output so that the reading is detectable by a standard volt-ohm meter.

The low cell performance can be attributed to several factors. The materials used in the processes are crude and contain many contaminants that hinder the performance of the cell. For example, the titania source used was directly prepared from the toothpaste, which is mainly comprised of silica and only contains a small amount of titania. The titania was not separated out, resulting in a mixture of many other compounds that either do not actively participate in the photoactivity or hinder electron transfer.

As previously mentioned, there are several contaminants generated using toothpaste as the titania source. As a result, another solar cell was constructed in which pure titania was used (commercially available Degussa P25) instead of the titania from the toothpaste by the same student group to demonstrate the general application of the technique (all other components and procedures remain the same). An i−V and P−V curve of the cell are given in Figure 3A. The cell constructed using P25 titania shows an i_{SC} of 208 μA/cm^2 and V_{OC} of 0.5 V, with a maximum power output of 24.8 μW/cm^2 at 0.21 V, which corresponds to ff and η values of 0.23 and 0.03%, respectively. The i−t characteristics under visible and UV plus

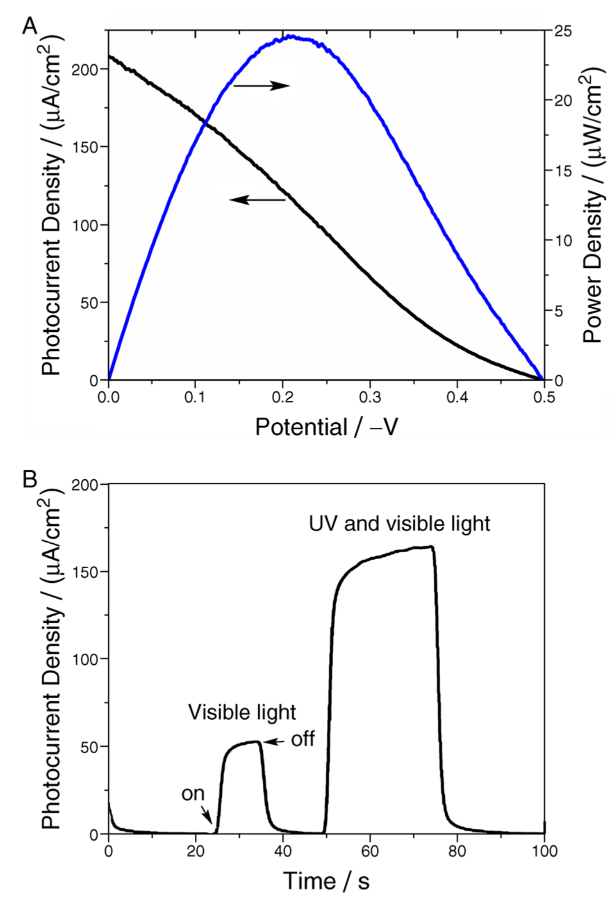

Figure 3. (A) *XYY* plot demonstrating the i−V and P−V characteristics for the assembled solar cell using commercial P25 titania, measured under a solar simulator with UV and visible light components at an intensity of ∼90 mW/cm^2. (B) i−t characteristics of commercially available titania (P25) opposed to the titania obtained from toothpaste assembled by the procedure outlined in this work. The cell was illuminated by visible light (λ > 420 nm) and UV plus visible light.

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visible light illumination of the cell are shown in Figure 3B. The UV component of the lamp was filtered out by using a band-pass filter (cut on $\lambda > 420$ nm). For visible light illumination, the photocurrent is ~55 $\mu A/cm^2$ and for UV plus visible illumination, the photocurrent is ~165 $\mu A/cm^2$. This was carried out to demonstrate the contributions of UV and visible light to the photoactivity of the cell. It was found that the visible light-absorbing component of the system (the dye) accounts for approximately 33% of the cell performance. From this construction method wherein using a more pure form of TiO_2, a substantial improvement in cell performance is observed, approximately a two to three-order magnitude increase in photocurrent and power conversion efficiency.

The laboratory exercises in the construction, power, and efficiency estimations of an alternative energy device such as this solar cell can also be extended to other energy conversion systems, such as fuel cells.[16,17] Simple calculations, as outlined in the Supporting Information, are designed to help convey vital information for the improvement of alternative energy conversion devices. Moreover, the economic feasibility of such systems is based on these example calculations. Basic solar cell operating principles and potential methods for cell improvement are discussed in further detail in the literature.[18−20]

■ SUMMARY

An introduction to solar cell characterization and a demonstration of the photovoltaic effect using household products is presented. This laboratory exercise can safely be executed by high school students and is suitable for an array of disciplines. The goal of this demonstration is not simply to motivate students about solar energy, but also to convey the parallel concepts of electron transfer in photosynthesis and energy conversion for power generation. Only through using similar concepts can a sustainable and renewable environment be developed.

■ ASSOCIATED CONTENT

Supporting Information

Details of synthesis; notes for setting up the photocell. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Smalley, R. E. Future Global Energy Prosperity: The Terawatt Challenge. *MRS Bull.* **2005**, *30*, 412−417.

(2) U.S. Energy Information Administration. International Energy, 2009. http://www.eia.gov/ (accessed Sep 2013).

(3) Lewis, N. S.; Nocera, D. G. Powering the Planet: Chemical Challenges in Solar Energy Utilization. *Proc. Natl. Acad. Sci. U.S.A* **2006**, *103*, 15729−15735.

(4) Zweibel, K. The Terawatt Challenge for Thin-Film PV, National Renewable Energy Laboratory, NREL/TP-520-38350, 2005. http://www.nrel.gov/docs/fy05osti/38350.pdf (accessed Sep 2013).

(5) O'Regan, B.; Graetzel, M. A Low-Cost, High-Efficiency Solar Cell Based on Dye-Sensitized Colloidal TiO_2 Films. *Nature* **1991**, *353*, 737−740.

(6) Kay, A.; Graetzel, M. Artificial Photosynthesis. 1. Photosensitization of Titania Solar Cells with Chlorophyll Derivatives and Related Natural Porphyrins. *J. Phys. Chem.* **1993**, *97*, 6272−6277.

(7) Tennakone, K.; Kumara, G. R. R. A.; Wijayantha, K. G. U.; Sirimanne, P. Nanoporous TiO_2 Photoanode Sensitized with the Flower Pigment Cyanidin. *J. Photochem. Photobiol., A* **1997**, *108*, 193−195.

(8) Smestad, G. P.; Gratzel, M. Demonstrating Electron Transfer and Nanotechnology: A Natural Dye-Sensitized Nanocrystalline Energy Converter. *J. Chem. Educ.* **1998**, *75*, 752−756.

(9) Martineau, D. *Dye Solar Cells for Real: The Assembly Guide for Making Your Own Solar Cells*; Solaronix: Aubonne, Switzerland, 2010.

(10) Smestad, G. P. Education and Solar Conversion: Demonstrating Electron Transfer. *Sol. Energy Mater. Sol. Cells* **1998**, *55*, 157−178.

(11) Subramanian, V. Nanostructured Semiconductor Composites for Solar Cells. *Interface* **2007**, *16*, 32−36.

(12) Gómez, R.; Segura, J. L. Plastic Solar Cells: A Multidisciplinary Field To Construct Chemical Concepts from Current Research. *J. Chem. Educ.* **2007**, *84*, 253−258.

(13) Yan, S. G.; Lyon, L. A.; Lemon, B. I.; Preiskorn, J. S.; Hupp, J. T. Energy Conversion Chemistry: Mechanisms of Charge Transfer at Metal-Oxide Semiconductor/Solution Interfaces. *J. Chem. Educ.* **1997**, *74*, 657−662.

(14) Meyer, G. J. Efficient Light-to-Electrical Energy Conversion: Nanocrystalline TiO_2 Films Modified with Inorganic Sensitizers. *J. Chem. Educ.* **1997**, *74*, 652−656.

(15) Farrow, B. A Delicious New Solar Cell Technology. Published Online 2009. http://www.youtube.com/watch?v=bVwzJEhMmD8 (accessed Sep 2013).

(16) Ramani, V.; Kunz, H. R.; Fenton, J. M. The Polymer Electrolyte Fuel Cell. *Interface* **2004**, *13*, 17−22.

(17) Shultz, M. J.; Kelly, M.; Paritsky, L.; Wagner, J. A Theme-Based Course: Hydrogen as the Fuel of the Future. *J. Chem. Educ.* **2009**, *86*, 1051−1053.

(18) Gratzel, M. Recent Advances in Sensitized Mesoscopic Solar Cells. *Acc. Chem. Res.* **2009**, *42*, 1788−1798.

(19) Gratzel, M. Photoelectrochemical Cells. *Nature* **2001**, *414*, 338−344.

(20) Hagfeldt, A.; Boschloo, G.; Sun, L.; Kloo, L.; Pettersson, H. Dye-Sensitized Solar Cells. *Chem. Rev.* **2010**, *110*, 6595−6663.