Dye-Sensitized Solar Cells

Center for Nanotechnology Education

Version 062217.2

This material is based on work supported by the National Science Foundation under Grant Nos. 0802323, 1204918, and 1501878. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Abstract

In this module, you will construct a dye-sensitized solar cell (DSC). This device is essentially a photo-electrochemical cell, which means that a photo-induced chemical reaction causes electrons to travel from one material to another. DSC's consist of a nanostructured semiconductor film coated with organic dye molecules. The nanostructure intimately contacts an electrolyte solution that contains a chemical mediator. The film and solution are sandwiched between two electrodes that allow the device to be electrically connected to an external load.

Outcomes

After completing this module, students will be able to

1) Describe how a dye-sensitized solar cell works

2) Understand the benefits of TiO_2 as a solar cell constituent

3) Fabricate a simple DSC capable of converting sunlight into electricity

Prerequisites

- High school chemistry and/or physics

Science Concepts

Students should have been exposed to the following concepts prior to doing the module:

- Structure of matter (atoms and molecules)
- Knowledge of DC electricity
- Photovoltaics: creation of electricity from light

Nanoscience Concepts

- Nature and structure of matter – Atomic and molecular structure
- Size dependent properties

Background Information

Earth is the world's largest solar panel. While Earth only collects a fraction of the sun's power output of 120,000 trillion watts, it receives more energy in one hour from the sun than all the energy consumed by humans in an entire year.

Most solar panels (roughly 90%) are based on silicon. Silicon photovoltaic technology has been around for quite some time, and emerging photovoltaic materials offer a great deal of promise for higher efficiency and lower production costs. There have been intense research and development efforts in these newer technologies, in both academia and industry. These emerging technologies, like dye-sensitized solar cells, organic photovoltaics, and inorganic quantum dot solar cells have been growing exponentially.

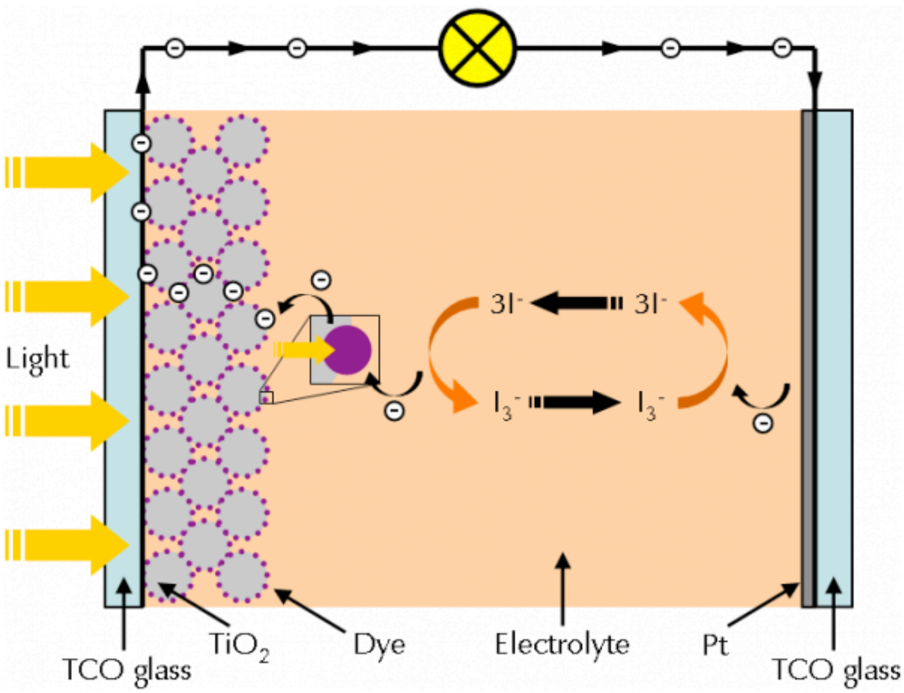
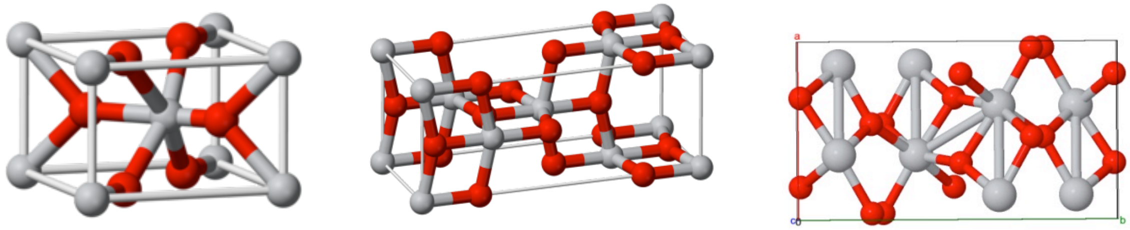


Figure 1. The structure of a dye-sensitized solar cell. *From:Gamry.com.*

Dye-sensitized solar cells consist of a nanostructured semiconductor film coated with organic dye molecules. A schematic diagram of a DSC is shown in Figure 1. The nanostructure intimately contacts an electrolyte solution that contains an iodide-triiodide mediator. The film and solution are sandwiched between two electrodes, that allows for electrical connections to an external circuit. Importantly, one electrode (the one coated with nanocrystals) must be transparent, while the other should be coated with a carbon catalyst to facilitate reduction of the iodide-triiodide mediator.



A B C

Figure 2. Representations of the crystal unit cells of titanium dioxide. (A) rutile, (B) anatase, (C) brookite. *Images from www.labspaces.net, Wikimedia Commons, and http://materials.springer.com.*

Titanium dioxide (TiO_2) is a common white pigment that can be found in everything from paint to paper products. TiO_2 exists in several crystal forms including rutile, anatase, and brookite structures. These forms differ in the spatial arrangement of titanium and oxygen atoms in the crystals, as shown in Figure 2. Since the anatase form of TiO_2 is a semiconductor with a band gap of 3.2 eV, it primarily absorbs ultraviolet light rather than visible light. Anthocyanin dyes, on the other hand, are organic molecules that absorb visible light extremely well. This gives them a deep red-purple color. When certain anthocyanin dyes come in contact with TiO_2, they can chemically react with and attach to the surface of the nanocrystals. This is depicted in Figure 3 below. The dye molecule acts as a ligand and forms bonds with titanium atoms on the TiO_2 surface. In this case, since two bonds are formed between the ligand and metal, the anthocyanin dye molecule is said to *chelate* the titanium atom. This is a particularly strong type of interaction, and it makes the dye very difficult to remove from the surface of the semiconductor. Therefore, chelating anthocyanin molecules cannot be rinsed off by solvent or the electrolyte solution during operation of the solar cell.

The proximity of the dye molecules to the TiO_2 surface allows the dye to *sensitize* the semiconductor, that is, when the dye molecules absorb visible light, they can transfer the photo-excited electrons to the TiO_2.

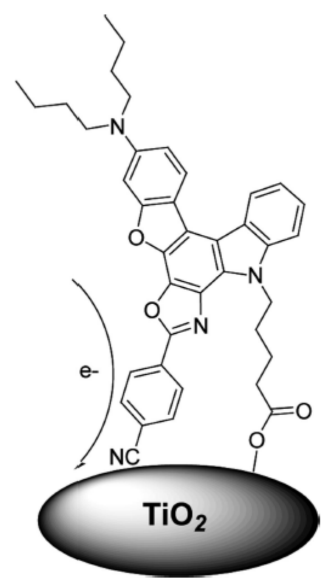


Figure 3. Molecular structure of one possible dye in a DSC. *Image from Hagfeldt et al (2010) (Reference #3 of this module).*

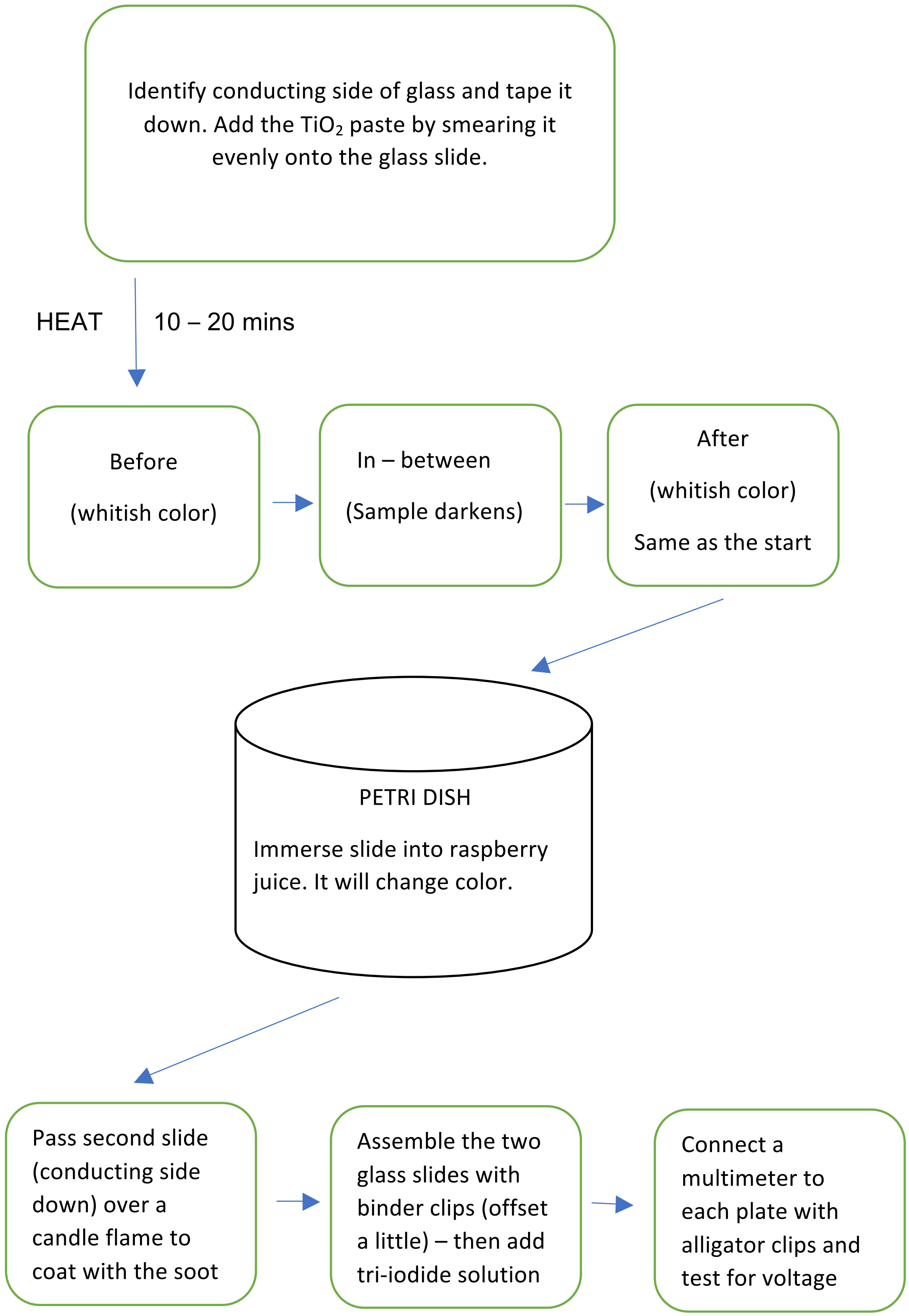
Current and Future Applications

Dye-sensitized solar cell technology has vast implications for creation of electricity from sunlight due to light absorption and charge transport phenomena. Listed below are a few current and future applications of DSC's

- Although DSC's are at best 12% efficient (silicon is 21% – 25%), they can be easily fabricated in the absence of a vacuum and with no spin coating required. Manufacturing techniques for DSC's are significantly cheaper than silicon, consume less energy, and "roll-to-roll" manufacturing is possible.
- DSC's have applications where conventional silicon solar cells might be unsuitable. DSC's work in a wide array of lighting conditions (low light – shaded and diffuse locations) whereas silicon-based technologies may be unusable under less than full sunlight illumination. Also, there is no dependence of electrical outputs on the angle of sunlight illumination, as is the case with silicon-based solar cells. Thus one application could be integrated photovoltaics. The idea is that solar panels can be built into various parts of a building's shell, not just the rooftop, which is the preferred spot for silicon panels, because DSC's work quite well in diffuse light. For that reason, thin sheets of translucent DSC's can be sandwiched between panes of glass, turning ordinary windows, skylights, and glass facades into electricity generators.
- Another advantage is that DSC's can be fabricated on a variety of substrates such as thin film, flexible or robust plastics, and applied to metal and glass substrates.
- DSC's could also power small electronic devices. One application gaining a lot of attention is the Internet of Things that refers to a network of appliances, vehicles, and other objects that are fitted with sensors and other electronics to enable them to collect and transmit data.
- In the future, some DSC companies intend to manufacture DSC powered beacons that broadcast Bluetooth signals. These devices can be used in many ways. One such example is to direct game-day attendees from the entrance of a sports stadium to ticketed seats via cell phone communication
- The drawbacks of DSC technology relate to the liquid electrolyte, that are corrosive, volatile, and prone to leaking; all of which limit the long-term stability of the cell. However, Northwestern University researchers have replaced the liquid electrolyte with a novel semiconducting inorganic solid: fluorine doped cesium tin iodide ($CsSnI_{2.95}F_{0.05}$). Implementing lab findings and improvements into the manufacturing process usually takes several years.

Dye-Sensitized Solar Cells

Activity Flow Chart



Dye-Sensitized Solar Cells Fabrication

Materials and Equipment

1. Nanocrystalline TiO_2
2. Mortar and pestle
3. Very dilute acetic acid (0.1 ml concentrated acetic acid in 50 ml water)
4. Dishwashing detergent
5. Empty syringe and parafilm
6. Conductive glass
7. Multimeter
8. Transparent tape
9. Microscope slide
10. Hotplate
11. Frozen raspberries
12. Watch glass
13. Water wash bottle
14. Ethanol wash bottle
15. Candle and matches
16. Clamp or tongs to hold glass while carbon coating
17. Cotton swabs
18. Binder clips
19. KI_3 in ethylene glycol
20. Strong light source (heat lamp, projector, or sun)

Procedure

Assemble all the materials needed on a laboratory cart, and perform the experiment under a fume hood.

1. Identify the conducting side of a tin oxide-coated piece of glass by using a multimeter to measure resistance. The conducting side will have a resistance of 20-30 ohms.
2. With the conducting side up, tape the glass on three sides to the center of a spill tray using one thickness of tape. Wipe off any fingerprints or oils using a tissue wet with ethanol. Opposite sides of tape will serve as a spacer so the tape should be flat and not

wrinkled. The third side of tape gives an uncoated portion where an alligator clip will be connected.

3. Add a small amount of titanium dioxide paste and quickly spread by pushing down and across with a microscope slide before the paste dries. If it is pressed down firmly, the tape serves as a 40-50 micrometer spacer to control the thickness of the titanium dioxide layer.
4. Carefully remove the tape without scratching the TiO_2 coating. Leave the removed tape in a spill tray for disposal.
5. Heat the glass on a hotplate in a fume hood for 10-20 minutes. The surface turns brown as the organic solvent and surfactant dries and burns off to produce a white or green sintered titanium dioxide coating. (Note: this requires a plate that gets quite hot.)
6. Allow the glass to slowly cool by turning off the hotplate. The sample will look quite similar before and after heating; the indication to look for is the darkening stage observable during heating.
7. Immerse the coating in a source of anthocyanins, in this case raspberry juice. The raspberry juice may be obtained from frozen raspberries. (Blackberries, pomegranate seeds, and Bing cherries can also be used.) The white TiO_2 will change color as the dye is absorbed and complexed to the Ti(IV).
8. Rinse gently with water to remove any berry solids and then with ethanol to remove water from the porous TiO_2. The ethanol should have evaporated before the cell is assembled.
9. Pass a second piece of tin oxide glass, conducting side down, through a candle flame to coat the conducting side with carbon (soot). For best results, pass the glass piece quickly and repeatedly through the middle part of the flame.
10. Wipe off the carbon along the perimeter of three sides of the carbon-coated glass plate using a dry cotton swab.
11. Assemble the two glass plates with coated sides together, but offset so that uncoated glass extends beyond the sandwich. Do not rub or slide the plates. Clamp the plates together with binder clips.
12. Add a drop of a triiodide solution to opposite edges of the plate. Capillary action will cause the KI_3 solution to travel between the two plates. (The KI_3 electrolyte solution consists of 0.5 M KI and 0.05 M I_2 in anhydrous ethylene glycol.) The solution can corrode the alligator clips in the next step so wipe off any excess.
13. Connect a multimeter using an alligator clip to each plate (the negative electrode is the TiO_2 coated glass and the positive electrode is the carbon coated glass).
14. Test the current and voltage produced by solar illumination, or...
15. Test the current and voltage produced by illumination from an overhead projector or heat lamp.

Discussion Questions

1. Did your solar cell work? Include the current and voltage (with units) produced by your solar cell in your conclusions. How much power is produced? (Power = energy/time; multiply the measured volts by the amps to yield power in watts.)
2. What area of solar cell would be needed to produce 1 watt? (Assume the voltage produced is constant and that the current would be proportional to the area of the solar cell.)
3. Gather together all the cells you and your classmates made. How would you assemble them together to produce a maximum voltage? What about a maximum current?
4. What is the function of each part of the solar cell you built? One way to answer this question is to follow the path of an electron through the complete circuit.
5. How could you improve the efficiency of your solar cell?

Contributors

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References

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2. "Solar Energy Conversion by Dye-Sensitized Photovoltaic Cells*," Inorg. Chem., 44, 6841-6851 (2005)*
3. "Dye-Sensitized Solar Cells", A. Hagfeldt, G. Boschloo, L. Sun, L. Kloo, H. Pettersson, Chem. Rev. 110, 6595–6663 (2010)
4. "Characteristics of the Iodide/Triiodide Redox Mediator in Dye-Sensitized Solar Cells," Acc. Chem. Research, 42,1819–1826 (2009).
5. "The future of low cost-solar cells," Chemical and Engineering New May, 2016 - Vol.94 Issue 18
6. A kit may be purchased from the Institute of Chemical Education (ICE) that contains the supplies to create five titanium dioxide raspberry solar cells: Kits may be ordered at *ice.chem.wisc.edu/Catalog/SciKits.html#Anchor-Nanocrystalline-41703)*