

Simple photovoltaic cells for exploring solar energy concepts

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Abstract

Low-efficiency solar cells for educational purposes can be simply made in school or home environments using wet-chemistry techniques and readily available chemicals of generally low toxicity. Instructions are given for making solar cells based on the heterojunctions Cu/Cu₂O, Cu₂O/ZnO and Cu₂S/ZnO, together with a modified Grätzel cell.

Introduction

It appears to be becoming much more difficult to interest young people in learning about science, particularly fields of science involving abstract concepts which are far removed from day-to-day experiences, such as semiconductor physics. Although the reasons for this are probably complex and linked to changing social values and expectations, one factor could be that it is becoming increasingly difficult to access some of the concepts through simple home- or school-based experiments. This is especially the case for current research on semiconductors for solar energy conversion. In pursuit of increasing energy conversion efficiency, devices for generating electricity from solar energy are increasingly being made with materials and sophisticated manufacturing techniques that are largely inaccessible to the general public.

The inaccessibility of some scientific ideas and materials could create problems for experiential learners who actually need to feel the thrill of the chase in tracking down materials from the local shopping centre or scrap-heap and carrying out an experiment at home before a concept makes any sense. Many of today's scientists became hooked on their professions through the many hours they

spent at home tinkering with chemistry and electronic sets when they were young(er), and that same sense of fun and adventure may be needed to encourage more people to pursue careers in science.

I have tried recapture some of this spirit with the solar cells below, which introduce the concept of the photovoltaic effect at semiconductor-metal and semiconductor p-n junctions, and in a modified dye-sensitized Grätzel solar cell. The four solar cells I have described below are all very easy to make using readily available materials of generally low toxicity, and are meant to be points of departure for further exploration rather than complete ends in themselves. The cells have been tested under home conditions and I have used kitchen units of measurement (teaspoons etc) rather than standard school laboratory measurement units to encourage home exploration, perhaps after the concepts have been introduced at school.

Introduction to semiconductors and solar cells

Photovoltaic cells, also commonly known as solar cells, have the property of being able to directly convert the energy from sunlight into

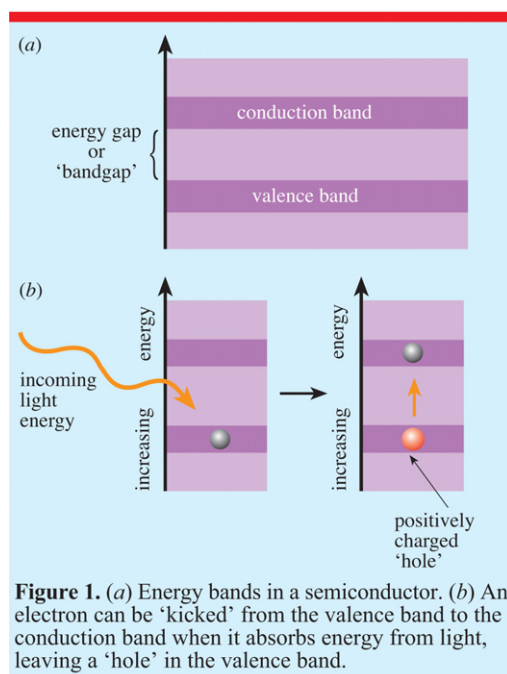


Figure 1. (a) Energy bands in a semiconductor. (b) An electron can be 'kicked' from the valence band to the conduction band when it absorbs energy from light, leaving a 'hole' in the valence band.

electricity. They are able to do this because of the special characteristics of certain semiconductors, materials which share some of the properties of insulators, where constituent atoms have tightly bound electrons that limit electrical conductivity, and metals, which contain atoms with more loosely bound electrons that allow a much higher electrical conductivity.

The ability of semiconductors to conduct electricity emerges from the way that electrons are arranged in the constituent atoms of these materials. According to the quantum theory of matter, the quantity of energy possessed by any given electron in a material will lie within one of several discrete levels or 'bands'. The electrons that are involved with forming covalent chemical bonds within the compound are said to be occupying the 'valence band' (figure 1(a)) and are not available for conducting electricity. Current flow is only possible when sufficient energy is available to allow a large number of electrons to jump across an energy gap ('bandgap') into the 'conduction band' (figures 1(a) and 1(b)).

In chemical compounds that are insulators, this energy gap is prohibitively large under most circumstances, whereas in metals the valence and conduction bands overlap, which allows electrons to be very mobile and enables good

electrical conductivity. Chemical compounds or elements that are semiconductors are often weak conductors of electricity, but the conductivity can be improved by adding ('doping with') trace amounts of elements that effectively add or remove electrons from the semiconductor. A surplus of electrons creates n-type semiconductors, and a deficit of electrons creates p-type semiconductors. Some chemical compounds with semiconductor properties naturally adopt p or n behaviour because one or more of the constituent elements may be in deficit or surplus in the crystal lattice of the compound (i.e. the compound is not perfectly stoichiometric).

In conventional solar cells, the bandgaps of semiconductors need to be sufficiently small that photons of light in the visible range can 'kick' electrons into the conduction band (figure 1(b)), leaving a positively charged 'hole' behind. This equates to bandgaps in the range of about 1.0–1.5 eV for semiconductors with photovoltaic properties (for example, the most widely used semiconductor in solar cells, silicon, has a bandgap of 1.1 eV). These solar cells consist of thin slices of n- and p-type semiconductors (typically doped silicon) which are fused together. At the junction between the two semiconductors, their energy bands combine (figure 2(a)) and create an electrical field across the junction which can drive current flow. Electrons that jump to the conduction band move under the influence of this field towards the n region, while the positively charged holes in the valence band migrate in the opposite direction (figure 2(b)).

Under some circumstances, photovoltaic behaviour can occur at the junction between an n- or p-type semiconductor and a metal, and the semiconductor–metal contact behaves as a semiconductor with the opposite characteristics. This property enabled the combination of a galena crystal and a copper wire 'cats-whisker' to be an effective signal detector in the first radio receivers ('crystal sets'), and is the basis for the copper–cuprous oxide solar cell outlined in a later section.

The operating principles behind the Grätzel solar cell are quite different to conventional p–n junction solar cells. Unlike conventional cells, Grätzel cells use liquid electrolytes, and the semiconductors used (generally titanium dioxide (TiO_2) or zinc oxide) have large bandgaps that have to be 'sensitized' to visible light photons by

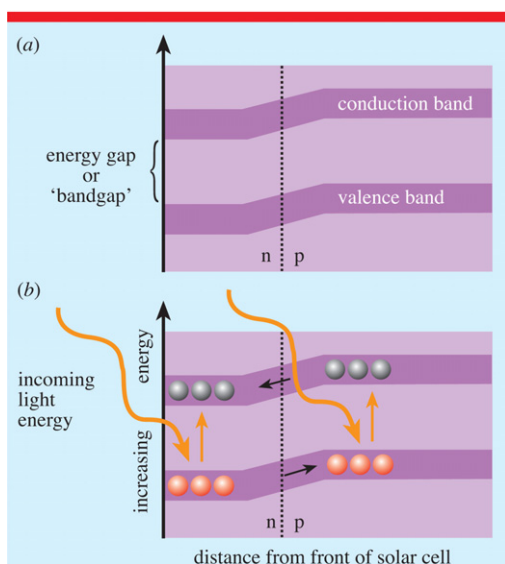
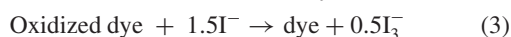
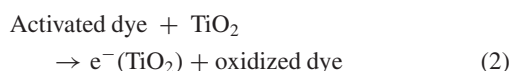


Figure 2. (a) The creation of a p–n junction creates a new energy distribution as the energy bands of the two semiconductors merge at the junction. An electric field is created across the junction that is able to drive current flow. (b) Electrons that jump to the conduction band migrate under the influence of the electric field towards the n-region, and ‘holes’ left behind in the valence band move in the opposite direction.

adsorbed dye molecules, which donate electrons to the semiconductor [1, 2]. The electrons lost by the dye via light adsorption are replaced by a ‘mediator’ electrolyte (usually containing iodide and iodine). The key reactions in a Grätzel cell are [2]



Grätzel cells are often made by sandwiching dye-treated nanocrystalline TiO_2 and an iodine/iodide solution between specially prepared conductive glass sheets which act as transparent electrodes. Kits containing these materials are available for school science projects [2], but are not an essential prerequisite for exploring this technology. A much simpler (and far less efficient) Grätzel cell is described in a following section; it is made using common household items and can be made in a fraction of the time required by the standard school kit.

Currently, most solar cells are made of silicon because the raw materials for manufacturing these cells are widely available (the silicon is usually made by reducing pure quartz sand, SiO_2 , with carbon). Additionally, the conductivity of silicon can be readily manipulated by doping with other elements at high temperatures to give a high efficiency of conversion of light energy to electricity. Special laboratory facilities are needed to do this, so the manufacture of silicon solar cells is not something that could be done in a school laboratory or in a home environment. However, a wide range of other inorganic materials are also known to have photovoltaic properties, some of which are potentially accessible for school- or home-based experimentation. Some of these are listed in table 1 together with possible sources, and some of these materials are also the basis for the four solar cell ‘recipes’ outlined in the following sections.

Making solar cells using wet-chemistry techniques

Commercial solar cells are typically manufactured to be solid-state devices. That is, contacts between different semiconductors and with electrodes are fused together at high temperature to form a solid slab of material which is extremely durable. This is not practicable in a school or home environment, but it is often possible to make simpler versions of the same cells by using wet-chemistry techniques, and by using aqueous solutions and a salt-bridge to create the p–n junction. Solar cells made this way are typically very inefficient by comparison with their solid-state equivalents, and may only work for a few days because of corrosion reactions within the cell.

However, these cells are generally very simple, cheap and quick to make (i.e. they can provide a degree of ‘instant gratification’). The fact that they work at all is often sufficient incentive to motivate students to find out what makes them function, and to explore ways of improving their performance. By contrast, there is an unfortunate trend in some texts of focusing solely on the efficiency of conversion of light to electricity, and being dismissive of technologies that do not ‘make the grade’. This can be a major disincentive for anyone wishing to explore the field in any depth by experimental means.

Table 1. Some inorganic chemicals that are known to have photovoltaic properties and possible sources of these materials.

Compound	Common name	Sources and comments
Cadmium selenide ^a	Red overglaze, cadmium red, pigment red 108	Art and craft shops
Cadmium sulfide ^a	Yellow overglaze, cadmium yellow, pigment yellow 35, 36	Art and craft shops
Copper(I) oxide (cuprous oxide)	Red copper oxide, cuprite	Art and craft shops. Can also be made from copper sulfate, which is available from hardware or garden supply shops
Copper(I) iodide (cuprous iodide)		Can be made by reacting copper sulfate with potassium iodide (available from shops that supply materials for saltwater aquariums)
Copper(I) sulfide (cuprous sulfide)	Chalcocite	Can be made from copper sulfate
Lead sulfide ^a	Galena	Mineral and rock shops. Can also be made by reacting lead acetate paper with hydrogen sulfide
Tin(II) sulfide (stannous sulfide)		Can be made from the reaction of tin with sulfides
Titanium dioxide	Anatase	White pigment in correction fluid ('white out'), white paint. Also in some sunscreen creams
Zinc oxide		Art and craft shops. Also pharmacies—a constituent of some sunscreen creams ('white zinc') and can be made by heating calamine (zinc hydroxy carbonate), or adding acid to a solution of zinc acetate in a water/alcohol mixture
Zinc sulfide	Sphalerite, zinc-blende	Can be made from the reaction of zinc sulfate (available in garden supply shops) with hydrogen sulfide

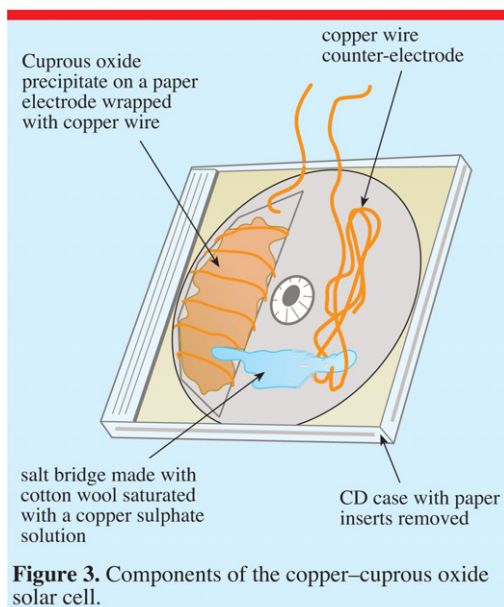
^a This compound is very toxic and must be handled with care. There may be a school policy against using this chemical.

Instructions for making a number of different types of solar cells using wet-chemistry techniques are outlined below. It is recommended that standard laboratory safety practices are used when making all of the solar cells described below. This includes ensuring safety glasses are worn at all times while making the cells, and ensuring that arms, legs and feet are covered by appropriate clothing and shoes (i.e. lace-up shoes, not sandals or open shoes with straps). It is also recommended that disposable gloves are worn when handling the solutions and wet electrodes that are made to assemble the solar cells described below. Experiments carried out at home should be carried out next to a laundry sink or in a well ventilated shed or garage, not in the kitchen. Please use disposable plastic spoons and containers and not the utensils that will be used for your next meal!

Copper–cuprous oxide solar cell

Wilhelm Hallwachs discovered in 1904 that a thin film of cuprous oxide (Cu_2O) on copper was photosensitive, and there has been intermittent interest since then in trying to develop commercially viable solar cells from these materials. However, the efficiency of energy conversion is too low by comparison to many other semiconductors for this particular cell design to be widely adopted. The cell works because cuprous oxide typically behaves as a p-type semiconductor due to a stoichiometric excess of oxygen, which commonly occurs in the oxide film [3].

The cuprous oxide film is usually made by heating a sheet of copper to about 1000°C in air until a uniform black coating of cupric oxide (CuO) has formed [3]. The sheet is then allowed to cool slowly, and black scales of cupric oxide are



removed, exposing an underlying reddish-brown layer of cuprous oxide. Most of the available references on the internet refer to this as a method of making 'home made' solar cells.

However, a Cu_2O electrode for a copper-cuprous oxide solar cell can be much more easily and safely made at room temperature using a piece of aluminium foil to reduce cupric ions in a copper sulfate/sodium chloride solution. The foil gradually disintegrates and is replaced by a fine precipitate of copper, which in turn is partially oxidized to form reddish-brown cuprous oxide according to the following reactions:



The instructions for making this solar cell are given in box 1, and the components of the cell are illustrated in figure 3.

Cells that I made (figure 4) had a voltage of about 0.05–0.15 V and produced up to $100 \mu\text{A}$ of current in sunshine (or about $2 \mu\text{A cm}^{-2}$ of electrode area). This is comparable to copper-cuprous oxide solar cells produced by the heating method, but is only a tiny fraction of the power output of an equivalently sized silicon solar cell.

The power output from this solar cell will depend to a large extent on the semiconductor



properties of the cuprous oxide precipitate. This may be altered by changing the physical and chemical conditions under which the precipitate forms. Possible things to try include the following:

- changing the temperature of the solution (alters the reaction rate and may change the degree of crystallinity of the precipitate);
- changing the pH of the solution (some literature suggests that the semiconductor behaviour of Cu_2O is very sensitive to pH changes);
- adding copper(II) complexing agents such as tartaric acid (which can alter the reaction rate and the way that individual Cu_2O crystals grow); and
- adding small amounts of other metal ions to the copper sulfate solution (the behaviour of a semiconductor can often be changed through the incorporation of other metals into a crystal lattice, or through the formation of intergrowths of different chemical compounds).

Cuprous oxide-zinc oxide solar cell

Zinc oxide (ZnO) is typically deficient in oxygen atoms and behaves as an n-type semiconductor [3]. This can be combined with cuprous oxide to form a solar cell with a p-n junction using the procedures outlined in box 2. The cuprous oxide-zinc oxide solar cell that I made had a voltage of about 0.1 V

Box 1. Copper–cuprous oxide solar cell**You will need:**

- an empty CD case (paper inserts removed);
- 0.5 mm diameter uncoated single-core copper wire;
- copper sulfate (available from a hardware shop or garden supply shop);
- salt (table salt);
- honey;
- good quality absorbent paper with plenty of body (I used water-colour paper);
- aluminium foil;
- disposable plastic spoons and plastic containers;
- sticky tape or rubber bands;
- cotton wool;
- a multimeter.

Method

Cut a strip of paper to fit neatly into the well on one side of the CD case. Cut a piece of aluminium foil to cover the paper, and bind the two together by winding with a few coils of copper wire. Ensure that there is at least 20 cm excess wire to form the electrical connection to what will become the cuprous oxide electrode. Put the wire-wrapped assemblage foil side up in a small plastic container which contains just enough cold water to cover the foil, and spread 1/4 teaspoon of salt and 2 teaspoons of copper sulfate crystals over the foil to push the electrode assemblage beneath the water surface.

It may take a minute or two before anything happens, but eventually you will see small bubbles of hydrogen gas growing on the foil, and a reddish-brown precipitate forming. As the reaction proceeds, small pieces of aluminium foil will float off the paper, buoyed by hydrogen bubbles, but the cuprous oxide precipitate will remain. When the foil has gone, carefully lift the paper out of the water without spilling the precipitate and insert face-up into the well in the CD case. Decant the liquid out of the plastic container, and spoon out any residual brown precipitate back onto the paper electrode. Spread the precipitate evenly over the paper surface and remove any remaining fragments of foil. Ensure that there is good electrical contact between the cuprous oxide and the copper wire. Spoon a small amount of honey over the cuprous oxide precipitate—the fructose and glucose in the honey are reducing agents that inhibit the oxidation of Cu_2O to form cupric salts.

The copper counter-electrode is made by loosely winding a few coils of copper wire around your hand and squeezing the bundle into the opposite side of the well of the CD case to the cuprous oxide electrode (figures 3 and 4). Ensure that the two electrodes do not touch each other. Once again, make sure that there is at least 20 cm of excess wire to form the electrode connection.

The two electrodes are connected in the CD case with a salt bridge made by soaking a piece of cotton wool in a solution consisting of 1 teaspoon of copper sulfate in 1 teaspoon of water. Ensure that the electrode connections poke out of the CD case, and then close the transparent lid of the case and secure with a few pieces of sticky tape or with rubber bands.

Connect the copper electrode to the negative terminal of the multimeter and the cuprous oxide electrode to the positive terminal of the multimeter.

and produced up to $250 \mu\text{A}$ of current in sunshine (or about $6 \mu\text{A cm}^{-2}$ of electrode area).

You may be able to change the behaviour of this solar cell by changing the way that the zinc oxide precipitate is prepared, which may alter its properties as a semiconductor. For instance, try dissolving some calamine lotion (an

aqueous suspension of zinc hydroxy carbonate and bentonite used to soothe irritated skin) in vinegar. Filter to remove the residue and allow the solution to evaporate to dryness in the sun. Then dissolve the residue in methylated spirits (denatured alcohol) and add a few pellets of household sodium hydroxide. This will cause

Box 2. Cuprous oxide–zinc oxide solar cell**You will need:**

- the ingredients and items outlined in box 1;
- two small glass jars;
- a small plastic funnel;
- ‘white zinc’ sunscreen cream (containing about 25% of ZnO);
- ‘white spirits’ (volatile hydrocarbon fluid for household dry cleaning and stain removal);
- ‘methylated spirits’ (denatured ethanol);
- household sodium bicarbonate (‘bicarbonate of soda’).

Method

Make up the cuprous oxide electrode using the procedures outlined in box 1 and insert into a CD case. The only difference between this cell and the copper–cuprous oxide solar cell described in box 1 is that the copper counter-electrode will be replaced with another paper electrode with the same dimensions as the cuprous oxide electrode.

The base of the electrode is made by cutting a piece of paper to the same size as the cuprous oxide electrode, and wrapping this with copper wire as before (but without inserting aluminium foil underneath the wire).

Put a teaspoon-full of sunscreen in the glass jar, and pour in enough white spirits to cover the cream (do this in a fume-hood or in a well ventilated place). Stir the mixture with a plastic spoon until the cream has all dissolved. Put a small piece of cotton wool in the funnel and place on the second glass jar, and then slowly pour through the sunscreen solution to filter out the oily emulsion that contains the zinc oxide particles. Rinse the precipitate in the funnel with a small amount of methylated spirits, and then spoon out the white slurry evenly over the prepared electrode and allow this material to dry for a few minutes.

In a small plastic container mix a teaspoon of sodium bicarbonate with a small amount of water to make a paste. Spread this evenly over the zinc oxide on the paper electrode to saponify the remaining oily compounds that coat zinc oxide particles so that these particles are able to conduct electricity.

Insert the zinc oxide electrode in the CD case and connect to the cuprous oxide electrode using a salt bridge made in the way described in box 1. Connect the cuprous oxide electrode to the positive lead of a multimeter, and the zinc oxide electrode to the negative lead.

a cloudy suspension of zinc oxide to form. Alternatively, heat the dry zinc acetate in a crucible over a Bunsen burner/gas flame (preferably in a fume hood or outdoors) to drive off carbon dioxide and water and leave a white powder (yellowish when hot) of zinc oxide.

Cuprous sulfide–zinc oxide solar cell

Cuprous sulfide (nominally Cu_2S , or chalcocite) is a naturally occurring metal sulfide that is being intensively studied as a possible component of thin-film solar cells, usually in combination with cadmium sulfide (CdS). Cuprous sulfide is typically a p-type semiconductor [4] that is often associated with other cuprous/cupric sulfides with similar properties including $\text{Cu}_{1.95}\text{S}$

(djurteite), $\text{Cu}_{1.8}\text{S}$ (digenite), $\text{Cu}_{1.7}\text{S}$ (anilite) and CuS (covellite) [4].

A brown to bluish-black precipitate with a metallic sheen containing Cu_2S and minor amounts of other copper sulfides can be made by reacting copper compounds with sulfides in solution under reducing conditions. The most accessible source of soluble sulfides for the home experimenter is likely to be ‘lime sulfur’ fungicide, a solution containing calcium polysulfides, CaS_x (where $x = 2-5$). This is usually sold in shops that sell garden supplies. Although sulfides can be hazardous to use under acidic conditions because of the risk of generating large amounts of toxic hydrogen sulfide gas, this risk is negligible when alkaline compounds such as calcium polysulfides are used and strong acids are avoided.

Box 3. Cuprous sulfide–zinc oxide solar cell

You will need:

- the ingredients and items outlined in boxes 1 and 2;
- ‘lime sulfur’ (calcium polysulfide) solution.

Method

Start making a cuprous oxide electrode using the procedures outlined in box 1 and commence the reaction with copper sulfate and salt as previously described. When hydrogen gas bubbles start forming on the aluminium foil and copper precipitation commences, add about 5 teaspoons of the calcium polysulfide solution. The reaction rate in solution will slow and a brown to bluish black precipitate of cuprous sulfide will start forming on the foil (there may also be a brief faint smell of hydrogen sulfide as the polysulfide solution is added). Allow the reaction to continue for several minutes, and then remove the remaining aluminium foil (use disposable gloves and eye protection because the solution is very caustic). Spread the precipitate evenly over the paper electrode, and then place it in an empty CD case with a zinc oxide electrode made with the procedures described in box 2. Connect the electrodes in the CD case with a copper sulfate saturated salt bridge as previously described. Connect the copper wire from the cuprous sulfide electrode to the positive terminal of a multimeter, and the zinc oxide electrode to the negative terminal.

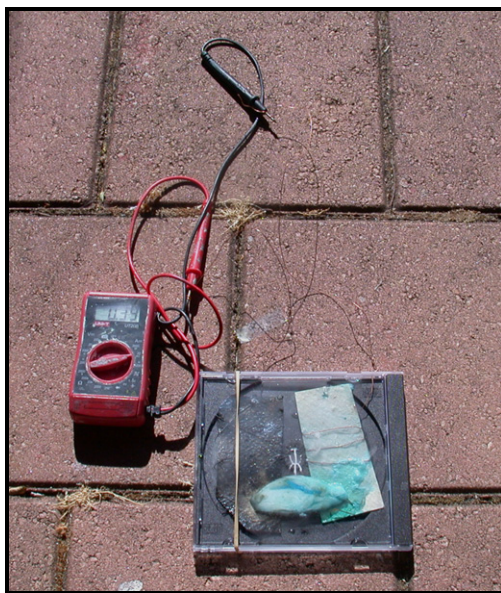


Figure 5. Photograph of a cuprous sulfide–zinc oxide solar cell showing an output current of 0.39 mA.

Box 3 describes a method for making cuprous sulfide–zinc oxide solar cells using calcium polysulfide as a sulfide source. A solar cell that I made by this method (figure 5) had a voltage of about 0.08 V and produced up to 400 μA of

current in bright sunshine (or about $11 \mu\text{A cm}^{-2}$ of electrode area).

You may consider replacing the zinc oxide electrode with one made of zinc sulfide. This can be done by reacting a soluble zinc compound (calamine dissolved in vinegar as previously described, or zinc sulfate, which is available as a crystalline solid in shops that sell garden supplies) with a calcium polysulfide solution. A white precipitate of zinc sulfide will form, which can be spread on a paper electrode in the same way as the zinc oxide electrode described in box 2.

Modified Grätzel solar cell

I had to modify the general layout used in the solar cells described because the water-colour paper I had been using had a starch filler, which reacted with the iodine used in the Grätzel cell. The iodine reacted with the starch in the paper to form an intense blue coloured complex that effectively removed I_2 from solution and prevented the cell from working properly.

As a consequence of this, the cell design for the Grätzel cell shown in figure 6 evolved, where paper electrodes were replaced by a kitchen sponge (made of a synthetic polymer) which provided a porous medium for all of the electrolytes in the cell without the need for a salt-bridge. Other modifications made to the Grätzel

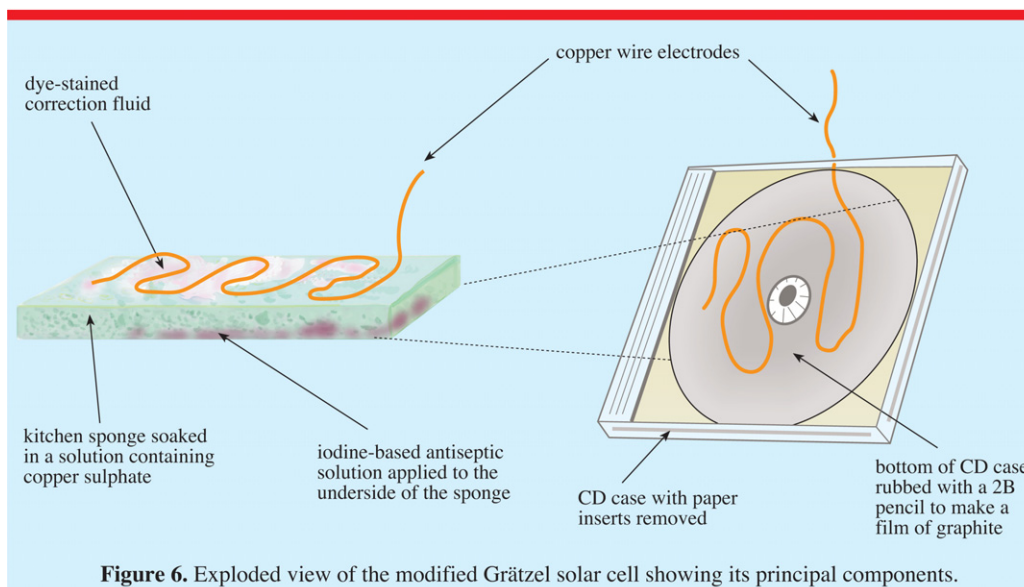


Figure 6. Exploded view of the modified Grätzel solar cell showing its principal components.

cell normally used in school science programs [2] were the following:

- Replacing nanocrystalline titanium dioxide powder with a more readily available source of TiO_2 particles—typing correction fluid. Correction fluid contains up to 30% by volume of TiO_2 mixed with a plastic filler in suspension in the chlorinated solvent trichloroethane.
- Replacing tin oxide-coated conducting glass electrodes with copper wire electrodes.
- Eliminating the need to bond TiO_2 particles together and to a glass substrate by heating on a hot plate.
- Replacing potassium iodide with a more readily available source of iodine, an antiseptic containing the organo-iodine compound povidone (which releases I_3^- into solution). Antiseptics containing about 10% of povidone are generally available in pharmacies or supermarkets.
- Replacing the juice of crushed blackberries or raspberries (a source of natural anthocyanin dyes) with a synthetic food colouring (food additive number 122, the azo-dye azorubine, also known as carmoisine).
- Adding cupric ions to the electrolyte solution.

The procedures used to make the solar cell are outlined in box 4, and the components of the cell

are illustrated in figure 6. The cell that I made had a voltage of 0.15 V, and produced 1.5 mA in bright sunshine (or about $40 \mu\text{A cm}^{-2}$ of electrode area).

It is not immediately obvious why copper sulfate should be a good electrolyte for this solar cell, but the addition of even a few crystals of this compound immediately increased the current output of the cell by a factor of 100. If you only looked at the oxidation–reduction chemistry involved in the reaction of cupric ions with iodide ions, you would reasonably expect that the efficiency of the cell would decline because iodide is progressively lost from solution by the precipitation of cuprous iodide by the following oxidation–reduction reaction:



However, CuI is also a p-type semiconductor [5], and it is likely that this chemical compound is replacing at least part of the function of the I^-/I_3^- mediator electrolyte in the solar cell. A number of research groups are currently investigating p-type conductors like CuI as a possible replacement for an aqueous iodide electrolyte in so-called solid-state dye-sensitized solar cells [6].

There are lots of avenues that could be explored to change the behaviour of this version of a Grätzel cell. One avenue worth exploring is to change the source of the n-type semiconductor

Box 4. A modified Grätzel solar cell

You will need

- CD case, copper wire, rubber band, and plastic spoons and containers as previously described;
- a 2B pencil
- a kitchen sponge (about 1 cm thick);
- typing correction fluid;
- copper sulfate;
- antiseptic solution containing povidone;
- food colouring or natural vegetable dye

Method

Use a 2B pencil to cover the base of the CD container with a uniform film of graphite, and assemble the copper wire counter-electrode on top of this layer as illustrated in figure 6. Also prepare a copper wire electrode to sit on top of the kitchen sponge (figure 6).

Soak the kitchen sponge in a copper sulfate solution made by adding about 1 teaspoon of copper sulfate crystals to a cup of water. In a fume hood or well ventilated space, spread correction fluid on the top of the wet sponge using the brush provided in the bottle (not on the dry sponge—you will get an impermeable plastic layer that will not conduct electricity or absorb dye). Use a plastic teaspoon to drip dye solution over the wet correction fluid and then mix the dye into the correction fluid with the back of the spoon. (Caution! Wear old clothes or a lab coat, or family relationships could be under considerable strain if you spill dye or correction fluid on your clothes!) Generously spread antiseptic containing povidone on the underside of the sponge (also a staining hazard) and place this side of the sponge on top of the electrode in the CD container.

The next stage of assembling the solar cell is best done over a sink or a bucket. Place the second wire electrode on top of the sponge, and close the transparent lid of the CD container. You will squeeze some liquid out of the sponge, and you will need to keep the lid of the CD container closed using a rubber band.

Connect the electrode on top of the sponge to the negative terminal of a multimeter, and the bottom electrode to the positive terminal.

(the TiO_2) in the cell, because it is currently being delivered in an organic solvent, which makes it difficult for this material to interact with aqueous electrolytes in the cell. It may be worth replacing the titanium dioxide with zinc oxide made from zinc acetate (see the section 'Cuprous sulfide–zinc oxide solar cell') as this would be in a much more hydrophilic form. It may also be possible to obtain titanium dioxide in powdered form, which would greatly improve its performance in an aqueous medium.

Another path worth exploring is to change the dye in the cell. I used a synthetic food colouring dye because it was available in my kitchen, but there is a large range of naturally occurring dyes that can be used in place of the food colouring in the cell. For example, anthocyanin dyes are commonly used as the sensitizing agents in Grätzel cells. These dyes occur in berry-fruit

such as raspberries, blackberries and blueberries, in red cabbage and in flowers such as roses, hibiscuses and hydrangeas. Other vegetable dyes you could try include chlorophylls, carotenes and curcumins (curcumins may be obtained by the extraction of turmeric with alcohol—this is a major staining hazard, so be careful or your family may completely disown you).

Using the solar cells in education programs

Apart from their value as informal exploration tools, one or more of the cells described here could be incorporated into existing science programs in secondary school. They could be useful aids for introducing concepts like oxidation–reduction chemical reactions, the relationship between light wavelength and energy, and photosynthesis. Projects based around making,

testing and improving the cells could also help students to develop some basic laboratory and literature research skills. Most importantly, they are a good way of having some serious fun. Happy exploring.

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