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Solar energy from spinach and toothpaste: fabrication of a solar cell in schools

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Abstract. We will show how pupils can make a solar cell with spinach, toothpaste and a few other items found in any school laboratory. This device is called a Graetzel cell, and could trigger off a revolution in photovoltaic technology.

Great star! What would your happiness be,
if you had not those for whom you shine!

Thus spake Zarathustra

1. Introduction

An ancient Jewish prayer says: ‘If work be thy curse, how sweet must be thy blessing!’ Yet mankind has constantly tried to free himself from the yoke of manual work. Thus in the Middle Ages the Indians conceived the *perpetuum mobile* (see figure 1), an image of the wheel of life, the sunwheel, the chakra, which turns eternally. Balls roll along grooves around the circumference and the centreline of the petal-shaped spokes, approaching the hub from the left, and moving away from it on the right. Numerous such wheels were constructed, and the Deutsches Museum in Munich houses several good examples. Unfortunately, the self-sustained rotation is an illusion, regardless of the amount of research money invested. In 1726 Jakob Leupold calculated that the sum of the torques exerted by the balls equals zero.

The dream of constructing the *perpetuum mobile* leads us to the law of energy conservation, almost as the search for a shorter sea route to India led to Columbus’ discovery of America. It shows the need to search for sources of energy. Today the focus has shifted away from the sunwheel to solar energy as a possible inexhaustible energy source.

1.1. Reasons for selecting this topic

Solar energy is so widely used today that it is astonishing how little attention it receives in school physics textbooks. Very good instructive material is available, however, from energy supply

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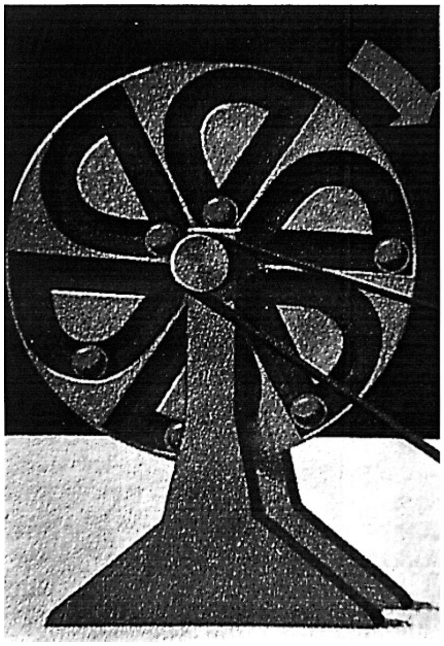

Figure 1. *Perpetuum mobile* (reproduced from Sexl *et al* (1990), page 57).

companies. Yet it is only possible to purchase ready-made solar cells which are extremely difficult to produce. Thus, we would like to show how a solar cell can be manufactured at school, using the simplest of ingredients (see figure 2). However, before doing so, the historical development of this technique will briefly be discussed.

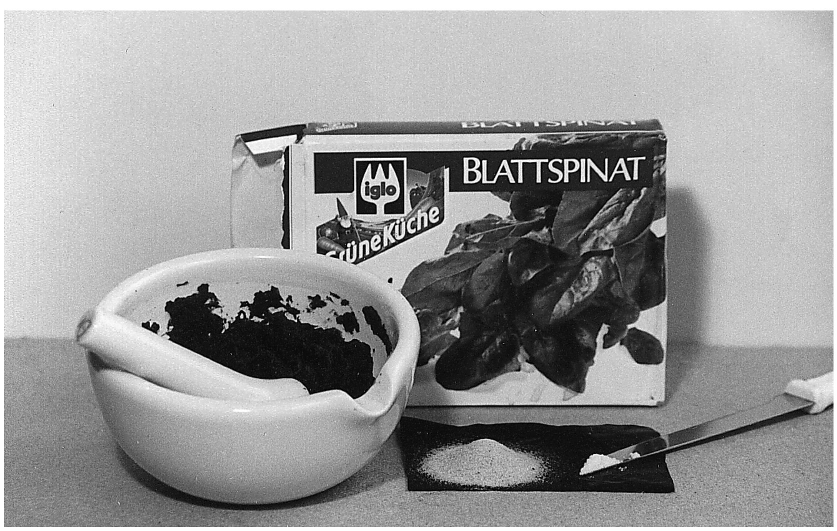

Figure 2. Materials for the Graetzel cell: spinach, titanium dioxide (e.g., toothpaste), a knife tip of calcium carbonate.

It began with the French scientist A E Becquerel (1820–1891), who discovered in 1839 that an electrical current could be created when light ‘hits’ certain structures. Thus, he is considered the ‘Father of Photovoltaics’. The second important step was completed in 1876 when the American physicists Adams and Day discovered Becquerel’s effect on a selenium crystal. It then took a further 80 years (until 1958), before the Americans placed 108 solar-cells on the Satellite Vanguard I to provide electrical energy for this little ‘spaceship’. The real breakthrough in this technique came with the oil crisis in 1973/74, when alternatives to oil as a primary energy source were sought.

In this paper we describe a method of building solar cells from the everyday materials of toothpaste and spinach, which is suitable for pupils to carry out at school (see figure 2). Of the many different types of solar cell, we have selected the Graetzel cell. According to reports in *Der Spiegel* (issue 51 of 1995, page 160) and other magazines, this idea could even spark off a revolution in photovoltaic (PV) technology. A spin-off of getting involved in a project such as this is that one also learns to assess press reports critically.

The ‘Graetzel cell’ is a suitable material for a week-long project. An obvious way of attempting to utilize solar energy would be to imitate the way plants do it. Many of the details of the experiment need to be explained to the pupils, which is customary at school anyway—whether investigating the period of the pendulum with a quartz clock, gravitation using electro-optical apparatus, or an electrical circuit using a voltmeter. The amount of assistance required depends on the extent of the pupils’ knowledge of chemistry and biology. As far as the physics syllabus is concerned, the ‘solar energy’ project would dovetail well with the study of the galvanic cell.

The Graetzel cell converts light to electrical energy by means of chlorophyll and a universal colouring agent, titanium dioxide (the white colouring in toothpaste). We shall now describe the principle and construction of the Graetzel cell.

1.2. The principle of a semiconductor solar cell

Provided the energy of the photons is adequate, light in semiconductors causes negative charge carriers (electrons) and positive charge carriers (holes) to move. If an electric field separates these carriers, a current-source results. This electric field is produced when two different materials come in contact: an n-conductor (movable electrons) and a p-conductor (movable holes). The electrons diffuse into the p-conductor, where both recombine. The stationary charges remain and are the source of the required electric field.

1.3. The principle of the Graetzel cell

It is difficult to reduce the workings of a solar cell to its elementary processes. About 10 years ago the mayor of Duisburg stated that, for him, ‘semiconductor physics was like theology, in that both were concerned with omnipotent forces which defy comprehension. . .’ However, we shall attempt the following explanation for the teacher.

Light excites the electrons in the chlorophyll, which tunnel through to the conduction band of the semiconductor titanium dioxide. The latter thus acquires a negative charge and donates its excess electrons to the front electrode (a transparent conductor), from which they flow through a resistive load, via the counter-electrode, to the electrolyte. The chlorophyll (F) regains the electrons (e) lost through tunnelling by reacting with iodine (I for iodine):

$$2e^- + I_3^- \rightarrow 3I^-$$

$$3I^- + 2F^+ \rightarrow I_3^- + 2F$$

($I \equiv$ iodine, $e^- \equiv$ electron, $F \equiv$ dye material, with graphite on the electrode as a catalyst). A functional diagram of the Graetzel cell is shown in figure 3.

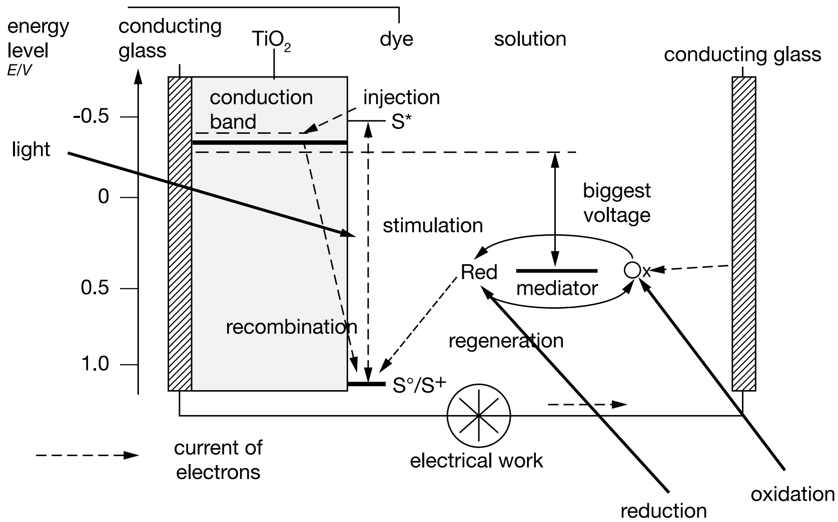

Figure 3. Functional diagram of the Graetzel cell (reproduced from *Entwicklung neuartiger Solarzellen auf der Grundlage Farbstoff-sensibilisierter nanokristalliner Halbleiterfilme* (1994), page 2).

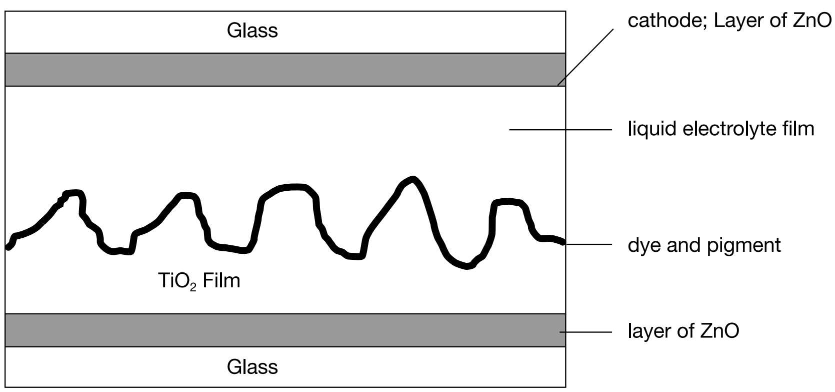

Figure 4. Construction of a Graetzel cell (reproduced from Volker and Hoffmann (1996)).

2. Construction of a cell

The construction of a Graetzel cell is shown schematically in figure 4. In what follows we detail the steps needed to construct a practical device according to our design.

2.1. Chlorophyll extraction

Every green leaf contains the green substance, chlorophyll. The deeper the colour green, the higher the chlorophyll content. Spinach is particularly well-suited for the extraction of chlorophyll, because the chlorophyll is highly concentrated in the leaves and is easily dissolved. The spinach may be either deep-frozen or fresh. Hexane is used as a non-polar solvent. Diethyl ether (as also suggested in the literature) is not suitable for use in schools, because it is highly explosive. Polar solvents such as alcohols, water or acetone are unsuitable, because they inhibit the attachment of the chlorophyll to the hydrophilic TiO_2 surface.

50 g of spinach is cut up using a pair of scissors. A pinch of fine sea-sand and a knifetip of calcium carbonate are added and ground in a mortar. 100 ml of ethanol is then added and the leaves are ground for a further 2–4 min until very fine. The sand ruptures the cell walls and so releases the chlorophyll. Calcium carbonate reduces the amount of oxidation upon contact with air. We recommend that the work be carried out in a darkened room, as the chlorophyll released from the cells easily decomposes in the presence of light. The preparation is then transferred to a flask and mixed for a further 10 min using a magnetic stirrer. It is then strained through filter paper and a wad of cotton wool. Because ethanol evaporates easily, it may be necessary to add more from time to time.

The remaining filtrate is poured together with 15 ml hexane into a glass cylinder containing a further 15 ml of hexane; the non-polar and lighter hexane remains on the top of the liquid column. Then 20 ml of distilled water are added dropwise and the mixture is stirred vigorously; the originally clear mixture becomes visibly turgid.

After refrigerating for one hour the mixture in the glass cylinder separates out into three layers: the bottom layer looks yellowish-green and consists of ethanol, water, carotene, xantophylle and cell residues; the top layer is a deep dark green, consisting, of hexane and the chlorophyll. Between these two layers is a thin, light-yellow-looking layer containing viscous, flaky cell-remains, which will drop to the bottom after some time. (According to the literature, the chlorophyll should have settled in the alcohol-containing layer; here it does not, because as mentioned before, in our case ethanol and hexane are used instead of methanol and dioxane) The next step consists of removing the chlorophyll-containing top layer with the aid of a pipette. If this layer still contains cell remains, the procedure can be repeated. It is advisable to run the chlorophyll layer into a light-proof vessel and, once sealed, store this in a refrigerator for the time being.

2.2. The layer of titanium dioxide

Apart from the chlorophyll as electron donor, the semiconductor titanium dioxide is necessary for the functioning of the cell. As mentioned above, toothpaste contains this compound, but instead of extracting it from the paste fine-grained titanium dioxide can be purchased (e.g., Degussa P25, particle size 25 nm). In this way we get the fineness we need for an appropriately large *semiconductor surface*. This surface functions like a sponge, which is one of the essential characteristics of the Graetzel cell.

First of all 5 g of TiO_2 are ground in a mortar for at least 10 min to remove the lumps. This step is repeated after adding 2.5 g of distilled water and 10 drops of acetic acid or vinegar, which prevents lumping. Too much acetic acid results in cracking of the surface. This paste and its ‘grinding power’ now provide the appropriate fineness for an optimal surface. Finally 7.5 g of water are added, resulting in a mixture in the ratio $1:2 \equiv TiO_2:H_2O$. This suspension is spread thinly on the conductive side of the plate we used for our cell. The layer must be homogenous, without any lumps or bubbles. The optimal thickness is 10 μm; the film appears milky but transparent. Now the air-dried TiO_2 layer must be sintered by a hot-air gun at 500 °C for approximately 30 min. The melting point of TiO_2 is above 1500 °C; but at 500 °C the particles will be sintered so as to cling to the electrically conducting tin oxide layer of the electrode.

2.3. Size of the electrodes

The achievable amperage is proportional to the area of the electrode, in contrast to the voltage. Whilst sintering the TiO_2 layers with the hot-air gun the rise in temperature is concentrated at points rather than distributed over areas, thus causing damage to the glass. Sintering, however, means merely baking together the granular material—so care must be taken! This is also the reason for the recommended electrode size being 10 cm^2. It is also possible to combine several small cells to produce larger cells as needed.

2.4. Colouring of the titanium dioxide layer

The glass plate with the semiconducting TiO_2 layer is now dipped into the non-polar dye solution of the manually extracted chlorophyll at 80 °C. This temperature is *essential*: at lower temperatures condensing air moisture could prevent the dye process in the non-crystalline pores of the electrode surface; at higher temperatures the glass could burst. The layers should be left in the refrigerator for eight hours to prevent ingression of air.

2.5. The catalyst

The counter-electrode must be layered with carbon. This process can be carried out quite easily by using a very soft graphite pencil (hardness B9), covering the glass as evenly and completely as possible.

2.6. Production of the electrolyte

For the total cell area, of up to 1 m^2, 50 ml of the electrolyte are needed as follows: 50 g of iodine and 4.15 g of potassium iodite, dissolved in 40 g of ethylene carbonate and 10 g of propylene carbonate. Because of the latter, the mixture must be heated to 100 °C while stirring vigorously. The result is a rather brown liquid. (Use safety glasses!)

2.7. Sealing of the cell

Immediately after the coloured TiO_2 film has dried, the two electrodes are placed with the layered sides together, so that the white unlayered edges are visible. The electrodes should then be closed on three sides with tape. The open side is used to drip the electrolyte between the electrodes. It is advisable not to press the electrodes together while taping them, because bubbles could be created if the pressure is released. If the electrolyte evaporates, or even the plates separate, the electrolyte can simply be refilled or the electrodes can be stuck together again. The resulting cell looks like that shown in figure 5.

3. The result

What can one expect after all this work? When we carried out this experiment we were rather disappointed, because the measured current–voltage characteristic of our home-made Graetzel cell was far below the expected value. We used a halogen light (a diascope) as an energy source, which produced 0.1 W from our cell, creating 60 μA at 200 mV. This means an efficiency of 0.005%, although the appropriate literature (using other dye materials) gives 10%. The reason for the large difference is the fact that we have used chlorophyll as the electron supplier, which is very impressive for public relations but not the most suitable dye for this process. *Unfortunately the other dye materials are expensive in small quantities*. Nevertheless, our four Graetzel cells supply sufficient voltage (1.5 V) and current (0.1 mA) for a sound-chip, such as those used in greetings cards. The music sounds quite impressive.

Acknowledgments

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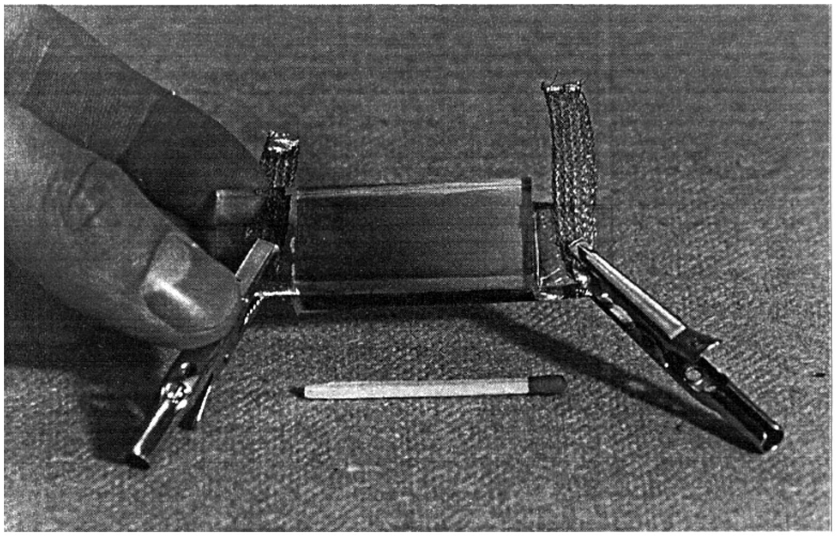

Figure 5. Our Graetzel cell.

Appendix

To assemble a spinach cell you will need

- 1 mortar
- 3 or 4 test tubes (latter centrifuge)
- 50 g spinach, fresh or deep frozen
- Refrigerator with ice box
- 1 digital balance
- 1 magnetic stirrer
- 1 cup of fine sand
- 0.1 ml acetic acid
- 30 ml hexane
- 200 ml ethanol
- small film-boxes
- 1 knife-tip of calcium hydrocarbonate or calcium carbonate
- Light-proof vessel, for storing the dissolved chlorophyll
- Funnel
- 50 ml and 100 ml flask
- Glass breaker
- Kitchen knife and plate

For the layer of titanium dioxide

- 5 g titanium dioxide (TiO_2), Degussa P25
- 1 digital balance
- Acetic acid or vinegar
- 0.5 l distilled water
- 0.5 l alcohol for cleaning
- 1 glass rod
- 2 supports
- Spatula or spoon
- Diascope
- Hot-air gun, 500 °C
- Forceps
- Self-adhesive peel-off wrapper

For the electrolyte

- 10 g propylene carbonate
- 40 g ethylene carbonate
- 0.5 g iodine
- 4.15 g potassium iodate

For the electrodes

- Glass plate
- Graphite pencil (non-rigid)
- Glass cutter
- Adhesive tape
- Thin, double-sided adhesive tape

Addresses for materials

For TiO_2:

Degussa AG
Weißfrauenstr. 9
D-60287 Frankfurt am Main
Germany

Tel.: 00 49 69-218-01

For glass slabs as transparent conductor:

Flachglas AG
Auf der Reihe 2
D-45884 Gelsenkirchen
Germany

Tel.: 00 49-209-168-1

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