

# Nanomaterial photovoltaics

February 2, 2007

## 1 Objectives

- To construct a simple nanostructured photovoltaic cell
- To plot the cell's power output curve
- To determine its maximum power point
- To measure the fill factor of the resulting cell
- To estimate its overall light conversion efficiency

## 2 Introduction

In addition to tremendous interest in the nano-bio interface, there is also growing interest in applying nanoscale materials to the problem of solar energy conversion. It goes without saying that energy issues represent some of the most pressing problems facing us in modern times. For example, one only needs to look at the price of gasoline to see that it has risen tremendously in a very short time. An interesting example illustrating this recent price increase can be found at <http://www.randomuseless.info/gasprice/gasprice.html>. A graph from the site has been reproduced in Figure 1 (not corrected for inflation). Furthermore, we all understand that the supply of crude oil is not limitless. Coupled with an increase in global oil demand from China and India this means that the future can only bring higher oil prices. A useful article describing our current situation can be found on National Geographic's web site, <http://magma.nationalgeographic.com/ngm/0406/feature5/index.html>. In addition, global warming is attributed to the release of greenhouse gases resulting from subsequent combustion processes. Thus for all these reasons there exists a tremendous (and growing) interest in alternative energy sources.

Solar energy is one of various alternative energy resources available to us. The idea is that the sun provides a nearly limitless source of energy. Therefore if we could just learn to harvest this energy and convert it to electricity efficiently (and cheaply) we could solve a number of pressing problems facing us today.

Current photovoltaic cells are made of silicon or other combination of semiconductor materials. On exposure to light electrons and holes are created in

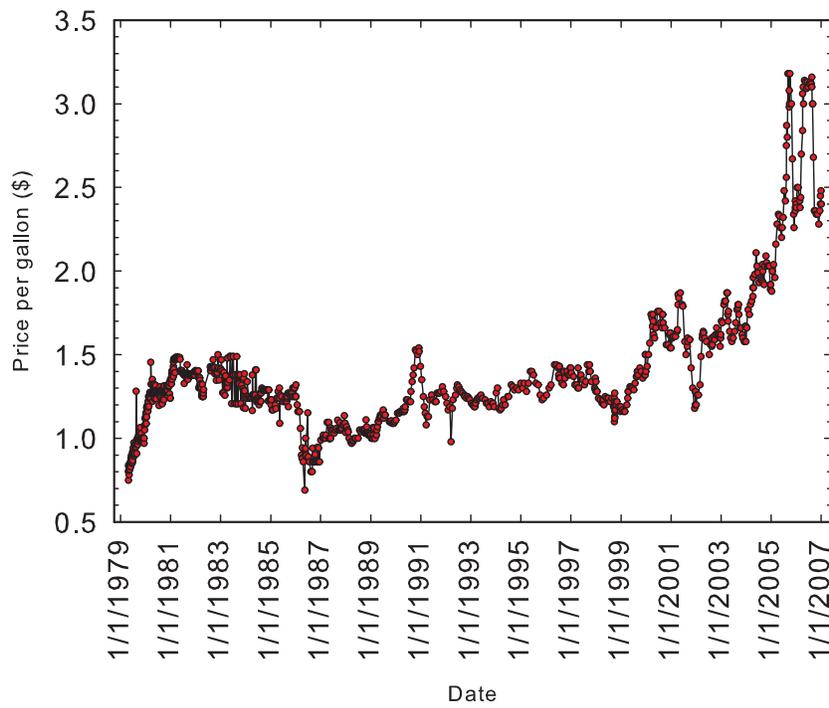


Figure 1: Gas prices in Texas over the years

the material. By design the cell is made in such a way so that the electron and its complementary hole are separated quickly to prevent them from recombining with each other. These carriers are then transported to electrodes where they become the basis of an electrical current. Although the efficiency of some of these advanced photovoltaic cells is high with conversion efficiencies near theoretical thermodynamic limits, but still less than unity, (think of the solar panels that are on the international space station) the main problem with these technologies is their high cost. If it were possible to find new materials and techniques by which to make equally (or more) efficient low cost photovoltaic cells then the demand for solar energy would increase dramatically. As of now there is still more bang for your buck burning fossil fuels.

### 3 The dye sensitized solar cell (Gratzel cell)

Because of the unique optical and electrical properties of nanomaterials there has been longstanding interest in exploring the application of nanoparticles (NPs) and other nanostructures to the problem of solar energy conversion. About 16 years ago, an important breakthrough in this area was made by Michael Gratzel and his student Brian O'Regan.[1] What they found was that one could use sintered titanium dioxide ( $TiO_2$ ) nanoparticles as a substrate on which ruthenium based organic dyes could be used as a "sensitizers" for harvesting light energy. Note that  $TiO_2$  is nearly ubiquitous in modern life. It can be found in foods (for example the white powder in powdered donuts) and even in toothpaste. However,  $TiO_2$  does not absorb visible light. Therefore a sensitizer is needed to absorb the bulk of wavelengths comprising solar radiation. An iodine-based redox couple is used to complete the circuit. A simple cartoon of the Gratzel cell is illustrated in Figure 2.

The resulting cell was found to have nearly order of magnitude higher efficiencies than other analogous photovoltaic cells of the time. External cell efficiencies were on the order of 10%, a remarkable value given the simplicity of the device. What was more important, however, was that this cell was and continues to be competitive with commercial silicon-based solar cells. Thus it has become possible to conceive of low cost, highly efficient solar cells made of nanostructured materials.

The basic idea of a dye-sensitized solar cell follows.  $TiO_2$  nanoparticles are deposited onto a transparent electrode such as indium-tin-oxide (ITO). An underlying reason why Gratzel's device is so efficient is his use of  $TiO_2$  nanoparticles (NPs) instead of planar single crystals of the same material. Because the NPs are small, they have a high surface to volume ratio. As a consequence, it is possible to have many more dye molecules (the sensitizer) in close proximity with the  $TiO_2$  electrode than in the former case of a planar substrate. Thus the fraction of photons converted to electricity can be higher leading to a more efficient solar cell. The  $TiO_2$  particles are sintered to ensure that a conductive network exists between the dye and the rest of the circuit. Furthermore, the porous  $TiO_2$  network allows the redox couple to be in more intimate contact

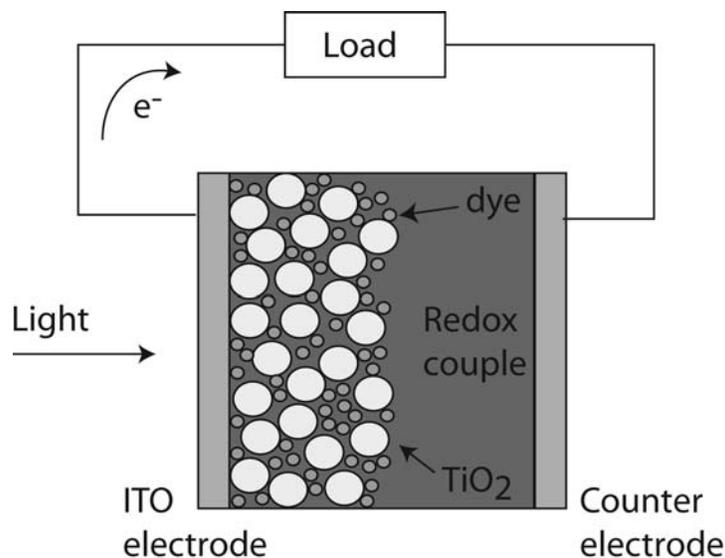


Figure 2: Cartoon illustrating the Grätzel cell

with all of the dye deposited, completing the circuit.

Fundamentally, on absorbing photons, an electronic transition into an excited state is induced in the dye molecule. This process is denoted in Figure 3. While in the excited state the molecule may undergo either radiative or non-radiative recombination to the initial (“ground”) state. The former process is referred to as fluorescence. In the presence of  $TiO_2$ , however, another relaxation pathway exists for the excited electron. This stems from the possibility of undergoing electron transfer into the underlying  $TiO_2$  layer. Provided that this relaxation pathway is competitive with the former two processes, an electron can be extracted from the dye molecule. Once in  $TiO_2$ , this carrier can then be transported to the electrode and from there into the rest of the circuit. At the same time, an iodine redox couple in solution extracts the hole from the dye molecule. (this process is really the iodine couple injecting an electron into the dye molecule). The iodine couple can then diffuse back to the opposite electrode where upon it can give up its hole. Injection of the electron and hole into opposite electrodes thus creates a current which can be used to power devices. More information about dye-sensitized solar cells (also called Grätzel cells) and the process by which they work can be found in Reference [2].

In this laboratory we will construct a rudimentary Grätzel cell using  $TiO_2$  nanoparticles and a commercial organic dye called Eosin.

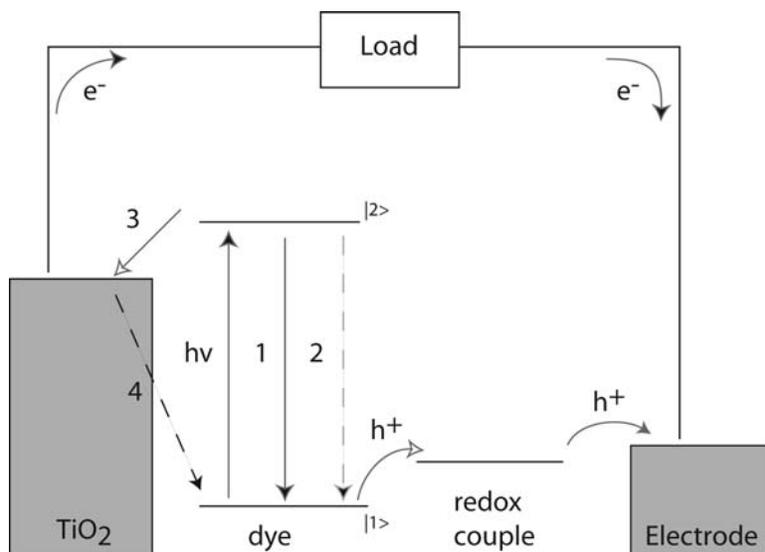


Figure 3: Energy diagram of the different electronic states involved in the Gratzel cell. Absorption of light by the sensitizer initiates the cycle. Process 1 is radiative relaxation to the ground state (fluorescence). Process 2 is nonradiative relaxation to the ground state (i.e. heat). Process 3 is the desired electron transfer process. Process 4 is an undesired “back” electron transfer process. All useful process are indicated with red arrows.

## 4 Diode model of a solar cell

Now that we see how such a cell is constructed and its underlying operating principles we want to be able to analyze how well it works. The operation of a solar cell can be modeled by what is referred to as an ideal diode model.[3,4] Figure 4 shows a very generalized cartoon schematic of the solar cell consisting of a diode, an external current source (this is the light generated current in our device) and a load (a resistor). In reality a slightly more complicated equivalent circuit for real solar cells exists, accounting for its imperfections. This is shown at the bottom of Figure 4. The only differences are the addition of what is known as a shunt resistance and a series resistance. Both of these resistors model intrinsic power losses that occur within actual solar cells. However, in this laboratory and in what follows below we will simply ignore these additional considerations and will only work with an ideal cell.

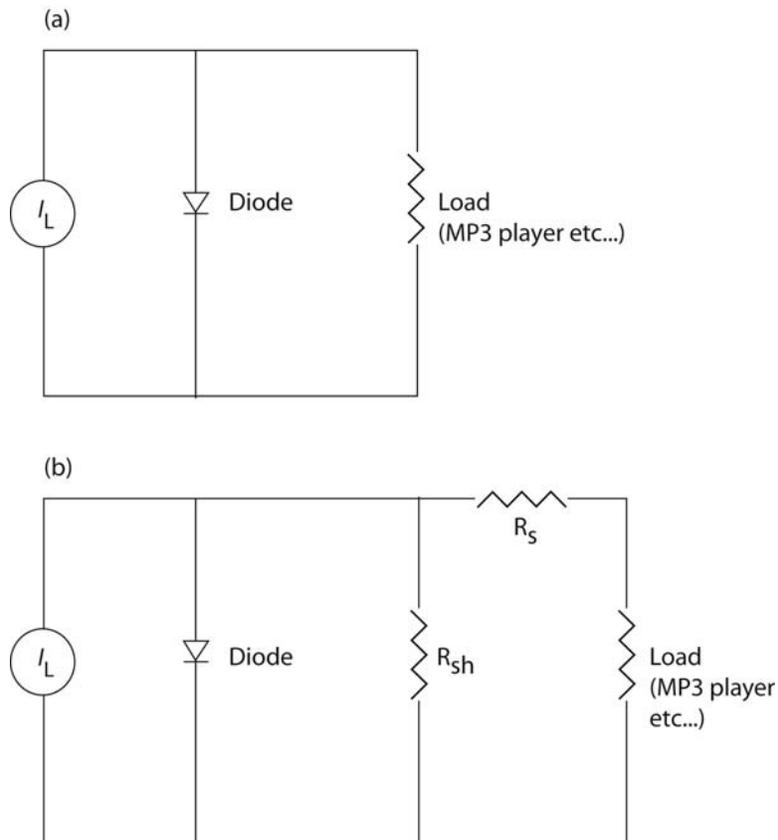


Figure 4: (a) Ideal diode solar cell model (b) More realistic diode model with shunt ( $R_{sh}$ ) and series ( $R_s$ ) resistances.

Now an equation describing the current running through a diode was derived by William Shockley a number of years ago. [Note that Schockley was apparently a colorful character. Along with John Bardeen and Walter Brattain he developed the first transistor at Bell Laboratories in 1947 (actually he developed the field effect transistor). This obviously revolutionalized the world. Look no further than your computer. All three were later to win a Nobel prize for this work. Flush with success Shockley got ambitious and later started his own company called Shockley Semiconductors out in California. It operated out of post WWII military quonset huts. Shockley was notorious for having potential employees take IQ tests to see if they were good enough to work for him. Clearly this management style eventually killed the company as most of his employees quit. One of them named Moore later started his own company which is called Intel today. You know the rest. A terrific book describing the birth of the transistor and the real behind the scenes description of how science was (and is) conducted (the rivalries, personal jealousies etc. . .) can be found in “Crystal Fire” by Michael Riordan and Lillian Hoddeson] Ok, back to the original discussion. Now when Shockley’s equation is modified to reflect how it is conventionally seen when dealing with solar cells (just a negative sign difference to reflect that a negative current implies power generation) one has

$$I = I_o \left( 1 - e^{\frac{qV}{\gamma kT}} \right) \quad (1)$$

where  $I$  is the current,  $I_o$  is called the diode reverse saturation current,  $q$  is the magnitude of charge  $q = 1.602 \times 10^{-19}C$ ,  $V$  is the potential across the diode,  $\gamma$  is a small fudge factor absent in ideal diodes but included here to account for real diodes (value between 2-3),  $k$  is Boltzmann’s constant  $k = 1.38 \times 10^{-23} J/K$  and  $T$  is the temperature in K units. Figure 5 shows the general appearance of this function.

Next, when the independent light generated current ( $I_L$ ) is tacked on to this expression, one has

$$\boxed{I = I_o \left( 1 - e^{\frac{qV}{\gamma kT}} \right) + I_L} \quad (2)$$

where the light generated current simply adds onto the existing diode current. Its effect on the general appearance of the curve can also be seen in Figure 5. (You will see that the experimental curve will look something like this, hopefully!) This is the expression that we will use to derive several important properties of a working solar cell. Namely, we will be interested in deriving expressions for the open circuit voltage ( $V_{oc}$ ), the short circuit current ( $I_{sc}$ ), an expression for the power curve, an expression for the maximum power generating voltage ( $V_{max}$ ), the corresponding maximum power current ( $I_{max}$ ) and the cell’s light conversion efficiency ( $\eta$ ) using its so called fill factor (FF). All of these parameters will be measured by you in the laboratory.

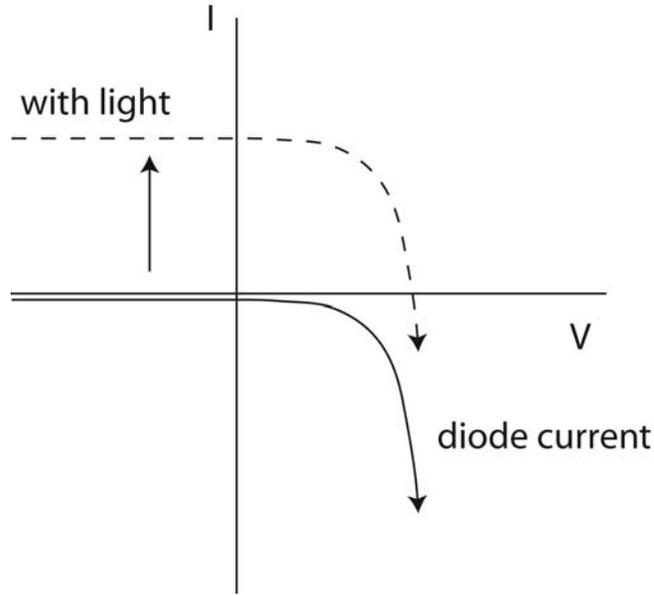


Figure 5: Diode current curve

#### 4.0.1 Open circuit voltage, $V_{oc}$

To get the cell open circuit voltage (in the lab you get this by making the load resistance really high) we set  $I = 0$  in the above equation (Equation 2) for the solar cell current. The position of the open circuit voltage can be seen in Figure 6. Our expression is

$$\begin{aligned}
 0 &= I_o \left(1 - e^{\frac{qV}{\gamma kT}}\right) + I_L \\
 0 &= I_o - I_o e^{\frac{qV}{\gamma kT}} + I_L \\
 I_o e^{\frac{qV}{\gamma kT}} &= (I_o + I_L) \\
 e^{\frac{qV}{\gamma kT}} &= \left(1 + \frac{I_L}{I_o}\right) \\
 \ln\left(e^{\frac{qV}{\gamma kT}}\right) &= \ln\left(1 + \frac{I_L}{I_o}\right) \\
 \frac{qV}{\gamma kT} &= \ln\left(1 + \frac{I_L}{I_o}\right)
 \end{aligned}$$

with the final desired expression for the open circuit voltage being

$$\boxed{V_{oc} = \frac{\gamma kT}{q} \ln\left(1 + \frac{I_L}{I_o}\right)} \quad (3)$$

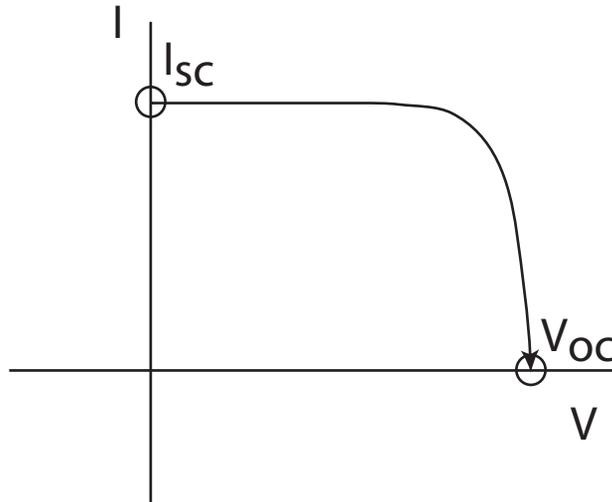


Figure 6: Important points

#### 4.0.2 Short circuit current $I_{sc}$

To get this simply set  $V = 0$  in Equation 2. (In the laboratory you measure this value by making the load resistance very small.) We get

$$\boxed{I_{sc} = I_L} \quad (4)$$

The position of the short circuit current can be seen in Figure 6.

#### 4.0.3 Power curve

Recall from introductory physics that the power can be described as the product of the current and the potential energy difference.

$$P = IV$$

Its units are watts when  $I$  is expressed in amps and  $V$  is in volts. Using our expression for  $I$  from above we then have

$$P = \left[ I_o \left( 1 - e^{-\frac{qV}{\gamma kT}} \right) + I_L \right] V$$

or

$$\boxed{P = I_o V \left( 1 - e^{-\frac{qV}{\gamma kT}} \right) + I_L V} \quad (5)$$

#### 4.0.4 Maximum power point voltage, $V_{max}$

This is the voltage at which one gets the maximum power from your solar cell and is where you will want to operate your device if using it in real life. An expression for  $V_{max}$  can be found by setting the first derivative of the above power function (Equation 5) to zero (i.e.  $\frac{dP}{dV} = 0$ ). The maximum voltage is shown in Figure 7.

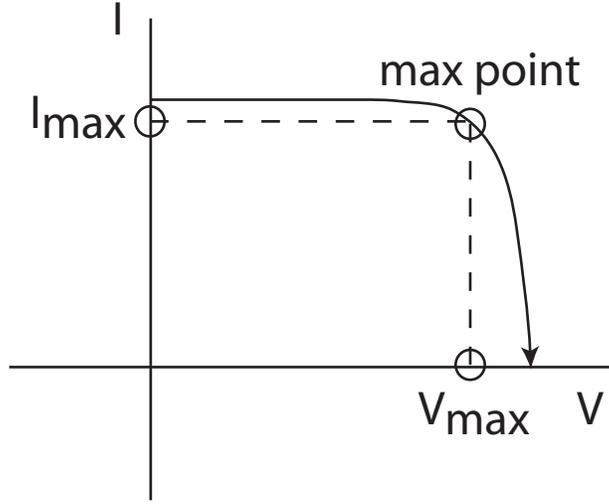


Figure 7: Maximum power points

$$\begin{aligned} \frac{dP}{dV} = 0 &= \frac{d}{dV} \left[ I_o V - I_o V e^{\frac{qV}{\gamma k T}} + I_L V \right] \\ &= (I_o + I_L) - I_o \frac{d}{dV} \left[ V e^{\frac{qV}{\gamma k T}} \right] \end{aligned}$$

Do you remember how to do this derivative? If not, think of the Chain rule.

$$\begin{aligned} 0 &= (I_o + I_L) - I_o \left[ V \left( \frac{q}{\gamma k T} \right) e^{\frac{qV}{\gamma k T}} + e^{\frac{qV}{\gamma k T}} \right] \\ 0 &= (I_o + I_L) - I_o e^{\frac{qV}{\gamma k T}} \left[ V \left( \frac{q}{\gamma k T} \right) + 1 \right] \\ (I_o + I_L) &= I_o e^{\frac{qV}{\gamma k T}} \left[ \frac{qV}{\gamma k T} + 1 \right] \end{aligned}$$

This gives us our desired final expression from which you can solve for  $V_{max}$

$$\boxed{\left( 1 + \frac{I_L}{I_o} \right) = \left( \frac{qV_{max}}{\gamma k T} + 1 \right) e^{\frac{qV_{max}}{\gamma k T}}} \quad (6)$$

#### 4.0.5 Maximum power point current, $I_{max}$

One can estimate the maximum power point current by simply plugging in the above obtained value for  $V_{max}$  into our original expression for the current ( $I$ ) produced by the solar cell (Equation 2). This current is shown in Figure 7.

#### 4.0.6 Light conversion efficiency, $\eta$

This is one of the most important parameter that characterizes the performance of a solar cell. It is basically a ratio between the cell's output power and how much (light) power was introduced. The efficiency is unity in a perfect ideal world. However, in reality you will see numbers on the order of 10% (0.1) for many commercial silicon-based solar cells. The efficiency of the cell you will make may be on the order of 1% or less. The efficiency is defined as

$$\eta = \frac{I_{max}V_{max}}{P_{in}} = \frac{I_{sc}V_{oc}FF}{P_{in}} \quad (7)$$

where  $P_{in}$  is the power (in watts) of light introduced into the cell and  $FF$  (a unitless number between 0 and 1) is the so called "fill factor" and reflects the efficiency of the cell. "FF" is defined as

$$FF = \frac{I_{max}V_{max}}{I_{sc}V_{oc}} \quad (8)$$

A geometric interpretation of the fill factor can be seen as the ratio of areas illustrated in Figure 8.

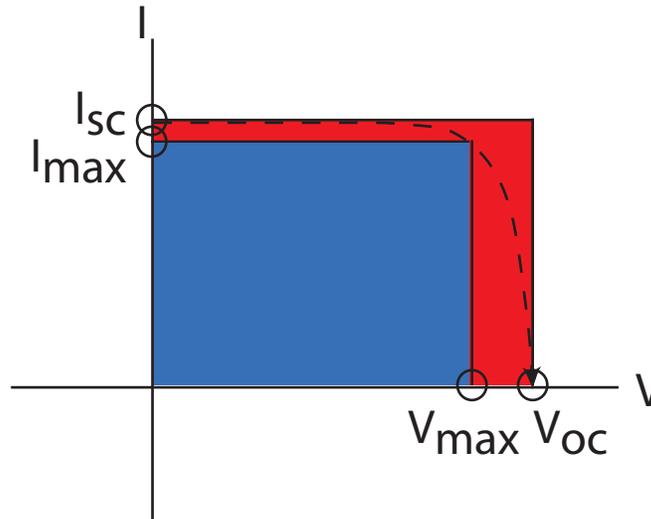


Figure 8: Geometric interpretation of the fill factor

#### 4.0.7 Theoretical fit of the measured current profile

It is possible to fit your actual data using our expression for the current output from the model diode solar cell. However, what you need to do this is some value for both  $I_o$  and  $\gamma$ . These two values can be found by taking our original expression for the current and considering the limit where  $e^{\frac{qV}{\gamma kT}} \gg 1$ . What this is really saying is that we focus only on the right side of the graph where the voltages  $V$  are large.

$$I = I_o \left(1 - e^{\frac{qV}{\gamma kT}}\right) + I_L$$

if  $e^{\frac{qV}{\gamma kT}} \gg 1$  ( $V$  is large) then

$$\begin{aligned} I &\simeq -I_o e^{\frac{qV}{\gamma kT}} + I_L \\ (I_L - I) &\simeq I_o e^{\frac{qV}{\gamma kT}} \\ \ln(I_L - I) &\simeq \ln\left(I_o e^{\frac{qV}{\gamma kT}}\right) \end{aligned}$$

You remember what the right side becomes, right?

$$\ln(I_L - I) \simeq \ln I_o + \ln\left(e^{\frac{qV}{\gamma kT}}\right)$$

or

$$\boxed{\ln(I_L - I) \simeq \left(\frac{q}{\gamma kT}\right) (V) + \ln I_o} \quad (9)$$

So plotting  $\ln(I_L - I)$  versus  $V$  should give you a straight line with a slope of  $\frac{q}{\gamma kT}$  and an intercept of  $\ln I_o$ . Thus you can find  $I_o$  and  $\gamma$  in this fashion. Finally with these two values in hand it is relatively straightforward to fit your data with our theoretical equation for  $I$  (our first equation) to see how well our idealized diode model reproduces the experimental data. After all, if the model is any good, it should provide a curve that is somewhat close to what you have measured.

## 5 An extension

Instead of the Eosin dye used in our experiment it is possible to extend this work to other substances. For example, Reference [6] describes the use of blackberries, raspberries and/or pomegranate seeds in order to extract anthocyanins that can be used as sensitizers. Alternatively, chlorophyll can be used as a dye sensitizer. In fact, plants do this all the time in a process called photosynthesis. I'm sure you've heard of it. To this end, Reference [7] describes a procedure for isolating chlorophyll from frozen spinach. It might be interesting to try this and see whether the Meijer brand not only tastes like the national brands but also produces analogous electrical currents.

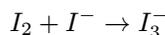
## 6 Procedure

### 6.1 Materials

- Indium tin oxide (ITO) glass slides (2 by 2 cm). You will need two of them to make a cell.
- Dye. Either Eosin Y or Eosin B.
- Titanium (IV) tetraisopropoxide
- Hot plate
- Scotch tape
- Two binder clips

### 6.2 Liquid electrolyte solution

Prepare the following solution. Add 6.69 g of lithium iodide ( $LiI$ ) in 100 mL of acetonitrile. Mix. To this add 1.27 g of iodine ( $I_2$ ). Alternatively instead of acetonitrile,  $\gamma$ -butyrolactone or 3-methoxypropionitrile can be used as a solvent. The following reaction occurs



This gives you both  $I^-$  and  $I_3^-$  which is your redox couple in the solar cell. The effective concentration of  $I^-$  is 0.45M and that of the  $I_3^-$  is 0.05M. Note that you should wear gloves when preparing and working with any iodine based solutions. These solutions will color your skin if you get them on you. In the case of accidental exposure you can rub a little lime juice (citric acid) on the affected area to prevent skin coloration.

### 6.3 $TiO_2$ paste

To prepare the  $TiO_2$  paste, suspend 3.5 grams of Degussa P25  $TiO_2$  nanopowder in 15 mL of ethanol. Sonicate the resulting mixture for approximately 30 minutes. Add 0.5 mL of titanium (IV) tetraisopropoxide into the suspension. Mix until the suspension is uniform.

### 6.4 Preparing the dye solution

Prepare a 1 mM solution of Eosin B in ethanol (20 mL total volume). Alternatively, you can prepare 20 mL of a 1mM solution of Eosin Y in ethanol. (See Figure 9)

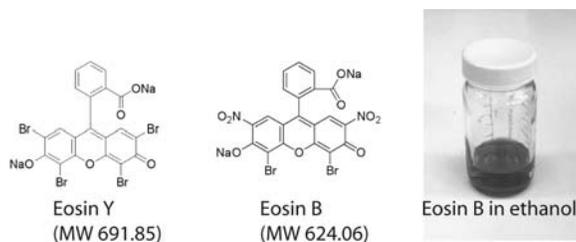


Figure 9: Dye solution

## 6.5 Preparing the spacer

Cut a small strip of parafilm having dimensions of 1.5 cm by 2 cm. In the middle of this strip cut a slightly smaller hole with dimensions of 1 cm by 0.6 cm. See Figure 10.

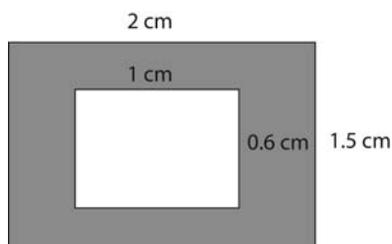


Figure 10: Spacer

You will need this to complete your Gratzel cell. Do not lose this piece.

## 6.6 Constructing the Gratzel cell

Put two strips of scotch tape on the conducting side of the ITO slide (see Figure 11). Note that the conducting side can be determined by measuring the resistance on a given side of the slide using a voltmeter. It is the side with resistance close to zero ohms. Now deposit the  $TiO_2$  paste and flatten it with a spatula on the conductive side of the ITO glass. (see Figure 12)

Place the resulting electrode on top of a hot plate and heat it at approximately  $150^\circ C$  for 10 minutes. (See Figure 13)

When done, dip your resulting  $TiO_2$  electrode into the dye solution for 10 minutes. Note that the dipping time can be varied depending on the selected dye. Furthermore, the dipped electrode can be heated mildly on the hot plate (between  $60 - 80^\circ C$ ) if the subsequent drying of the electrode proceeds too slowly.

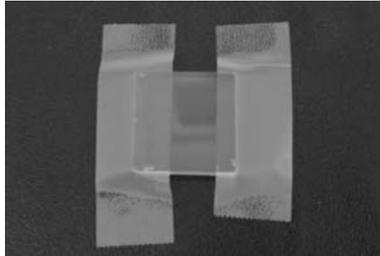


Figure 11: Photovoltaic construction

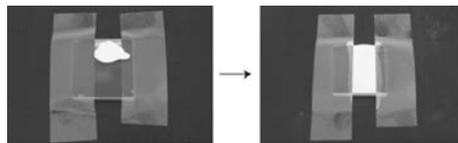


Figure 12: Photovoltaic construction



Figure 13: Photovoltaic construction

Next, on the other electrode, use a number 2 pencil to deposit a layer of graphite onto the conductive side of the second slide. (See Figure 14) What is the purpose of the graphite? Is graphite conductive? Do you think MacGyver could use number 2 pencils as wires in a homebuilt circuit?

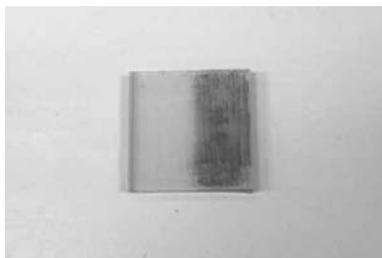


Figure 14: Photovoltaic construction

Remove the first electrode from the dye solution and wash it with fresh ethanol (i.e. dip it in a beaker full of fresh ethanol and remove it. Repeat once more.) (See Figure 15) This gets rid of any dye molecules that have not attached themselves to the  $TiO_2$  substrate. Why are unattached dye molecules not useful to us? Also note that these dye molecules attach themselves to  $TiO_2$  through their carboxy linkages.

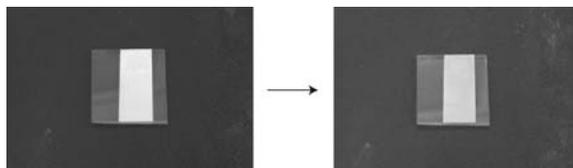


Figure 15: Photovoltaic construction

Now place the prepared parafilm spacer on the  $TiO_2$ /dye electrode and then put some drops of the electrolyte solution into the spacer's hole. This step should be done quickly (but carefully) to prevent the electrolyte solution from drying out. (See Figure 16)

Combine both electrodes, sandwiching the spacer and the electrolyte. Make sure that you try to let all of the bubbles out of the device. Note that the conductive sides of both electrodes must face each other if the cell is to work. (See Figure 17) Also while putting the two electrodes together, you should keep the edges **offset** so that you can later contact each one independently using alligator clips.

Finally, fix the electrodes with both binder clips as shown in Figure 18

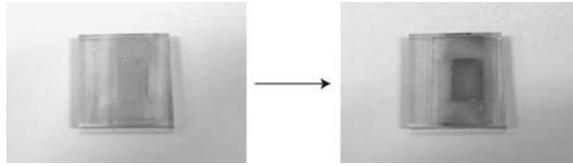


Figure 16: Photovoltaic construction

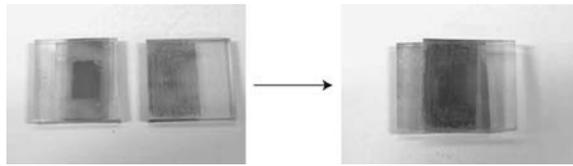
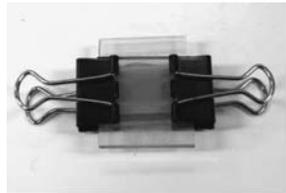
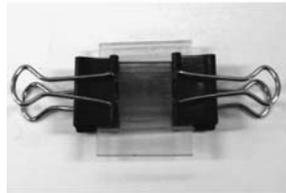


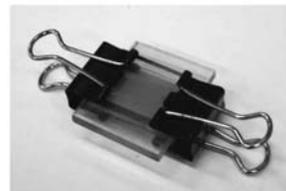
Figure 17: Photovoltaic construction



Front



Back



Resulting cell

Figure 18: Photovoltaic construction

## 6.7 Measuring the cell I-V characteristics

Once done with the Gratzel cell, construct the simple circuit shown in Figure 19. All you need is a voltmeter and an ammeter as well as a variable resistance potentiometer (a “pot”) (or just a voltmeter if no ammeter is available). Furthermore, if you don’t have a pot you can use a bunch of fixed resistances (resistors) that can be purchased at Radio Shack ( $50\Omega$ ,  $100\Omega$ ,  $200\Omega$ ,  $500\Omega$ ,  $800\Omega$ ,  $1k\Omega$ ,  $2k\Omega$ ,  $5k\Omega$ ,  $10k\Omega$ ,  $20k\Omega$ ,  $40k\Omega$ ,  $80k\Omega$ ,  $100k\Omega$ ,  $200k\Omega$ ,  $400k\Omega$  and  $800k\Omega$ ). You will also need a light source. In the absence of something like a Xe arc lamp or a quartz tungsten halogen (QTH) lamp, use an overhead projector (hopefully people still have this given the rise of powerpoint).

Illuminate your sample. Make sure the light comes into your cell from the side with the  $TiO_2$  and the dye, not the side where you coated the electrode with graphite. If using an overhead projector place the device on the top lens of the projector, not on the standard working surface where you normally put your slides. Set the resistance to its highest value. Measure the photocell’s output voltage (and current. Don’t worry, if you don’t have an ammeter just measure the voltage). The potential is measured by placing the voltmeter’s leads across points 1 and 2 in Figure 19. The associated current is measured by placing the ammeter’s leads across points 2 and 3 in Figure 19. When the pot resistance is extremely large the measured voltage will mimic the cell’s open circuit voltage ( $V_{oc}$ ).

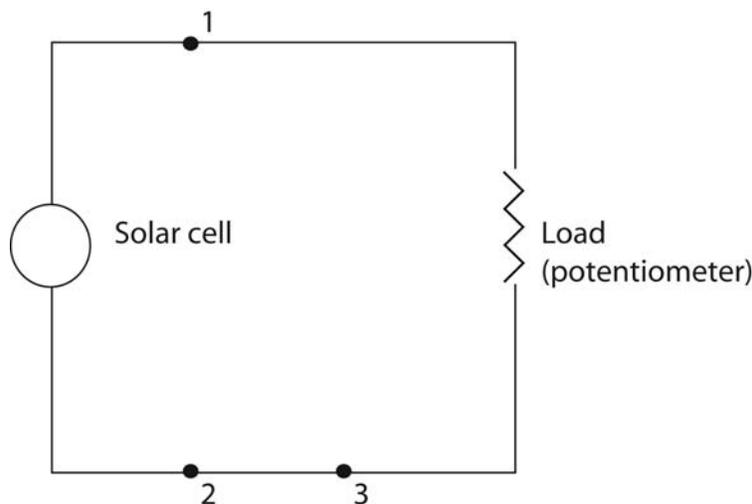


Figure 19: Solar cell

Next, you will increase the current flowing through the cell in a stepwise fashion by sequentially lowering the load resistance. Choose something on the order of 10-20 resistance values (the more points the better). At each resistance value, measure the cell’s voltage (and current if possible). Continue doing this

until you have almost no resistance on the potentiometer. The measured voltage should be very low and likewise the current should be high. This current is referred to as the short circuit current ( $I_{sc}$ ).

Now, plot all of your data on a computer spreadsheet. The x axis is your voltage and the y axis is the measured current. If you only recorded voltages then calculate for each point what the associated current was using the expression  $I = \frac{V}{R}$  where  $V$  and  $R$  were the voltage and associated resistance in the measurement. From this data one should have a graph similar to that seen in Figure 6.

Using the above derivations and actual data one should be able to determine what the maximum voltage and current points are. See the above derivation for the equations giving  $V_{max}$  and  $I_{max}$ . Experimentally, you will want to plot the voltage (x axis) versus power (y axis) and find the maximum point on this graph. The power is calculated using the expression  $P = VI$  or  $P = RI^2$  where  $V$  is the measured voltage,  $R$  is your resistance and  $I$  is the associated current measured.

Now with  $V_{oc}$  and  $I_{sc}$  as well as  $V_{max}$  and  $I_{max}$  available to you, it should be relatively straightforward to determine what the fill factor  $FF$  of the cell is. (See our derivations if you don't remember how to do this) Finally, using the above expressions one should be able to determine from the high voltage region of the plot what  $\gamma$  and  $I_o$  are. This will then allow you to compare the ideal diode current equation to the experimentally determined current curve (i.e. the theory curve can be plotted over the experimental data to see how well they agree).

Complicating an estimation of the cell efficiency  $\eta$  is the fact that it is not easy to determine what the input power into your cell is. What you need here is a measure of the intensity or irradiance (this is more modern parlance) of the light hitting your sample. The units of irradiance are watts per square centimeter. So what you really need is an optical "power meter" to get a feel for what the average power in the visible is. Unfortunately, this starts to get complicated. You can read more about the complications in Reference [4]. One way to get around this is to estimate what the average power is. Your instructor can give you a ballpark figure which can then be used to get  $\eta$  but if you don't have this available don't worry. This is just the icing on the cake. Based on past experience, any number you obtain should be on the order of 1% or less.

## 7 Clean-up

When done do the following:

- Turn in your cells to the teaching assistants. The ITO covered glass slides can be reused.
- Dispose of any unwanted iodine solution in an appropriate waste container. Larger quantities of the iodine solution should be kept since they can be reused.

- Turn in any leftover dye solution since it can be reused as well.
- Turn in all electronic components to the teaching assistants.

## 8 Laboratory report points to consider

- Consider our prior discussion on molar extinction coefficients. For a better solar cell, would a molecule with a bigger cross section or molar extinction coefficient be better? Why?
- We mentioned that when the dye sensitizer is excited there are various processes which compete with electron transfer. Would a highly fluorescent molecule be likely to be a good sensitizer? Why or why not?
- If the radiative lifetime of most fluorescent molecules is in the range of 1 ns (the associated rate is  $10^9 s^{-1}$ ), what are ballpark rates for the electron transfer process?
- Do you suppose that there is something else other than  $TiO_2$  that one could use in the Gratzel cell?
- The solar spectrum is pretty broad. How broad is it and what part of the solar spectrum appears to be underutilized?

## 9 References

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