Photovoltaic effect: Diode IV-characteristics
Laboration Condensed Matter Physics / Solid State Physics

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April 25, 2005

This lab is intended to explore the working details of a solar cell and to illustrate the underlying physics.

1 Introduction to the photovoltaic effect and solar cells

The photovoltaic effect in semiconductors refers to the appearance of a voltage over a $p-n$ junction under illumination. A homogenous $p-n$ junction consists of a semiconductor where one part is doped with acceptor atoms (the p-side) and the other with donor atoms (the n-side). In a small interface region, electrons from the n-side will diffuse to the acceptors on the p-side and holes from the p-side will diffuse to the donors on the n-side. This diffusion of charges continues until the electric potential between the negatively charged p-side and the positively charged n-side cancels the effect of the doping concentration gradient. The $I-V$ characteristics of a diode follow the *diode equation* (sign convention is specific to this measurement setup)

$$I = I_{\text{sat}} \left(1 - \exp\left(-\frac{eV}{nk_B T}\right)\right), \tag{1}$$

where n is the *ideality factor*.

Now assume that we have a semiconductor whose bandgap energy is comparable to the energy of visible light. The photon energy associated with the light is then sufficient to excite electrons to the conduction band leading to the creation of a free electron and a free hole. If this happens in a homogenous semiconductor the electron and hole will soon recombine but in a $p-n$ junction, if the electron or hole is close enough to the interface to feel the electric field, they will be accelerated by the built-in field in two different directions. If the n and p sides are now short circuited a current will flow as electrons accelerated to the n side continue to the p side to recombine with the holes. This process is illustrated in figure 1. Note that the direction of this current is opposite to that of the "allowed" direction in a diode. This is because we are generating minority carriers which are otherwise absent.

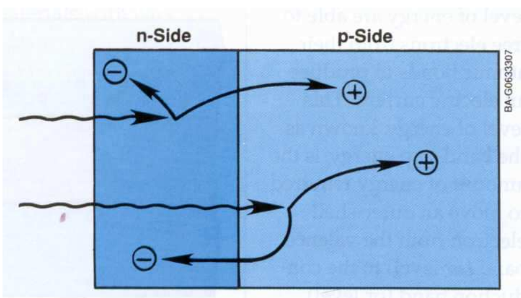

Figure 1: Illustration of photo-generation of carriers and subsequent acceleration by the built-in electric field in a $p-n$ junction. Image courtesy of Sandia National Laboratories.

A solar cell is simply put a very large $p-n$ junction oriented with the n side on top. On the bottom of the junction we have a large metallic contact covering the entire area, while on the top of the junction there is a grid of electrical contacts designed to minimize resistive losses while not preventing light to reach the interior of the solar cell. The cell is then covered with an antireflective coating and finally some transparent material for protection.

2 Experimental setup

The photovoltaic cell used in this laboration is a polycrystalline silicon thin film made for solar cell applications. As shown in figure 2, electrical contacts to the top and bottom are available at the front of the box. Illumination is provided with a standard desk lamp.

A Power Cassy$^{\text{TM}}$ will be used to measure current under applied bias. Unlike, for example, a hand held multimeter this unit is capable of sourcing different waveforms $V_{\text{out}}(t)$ and then

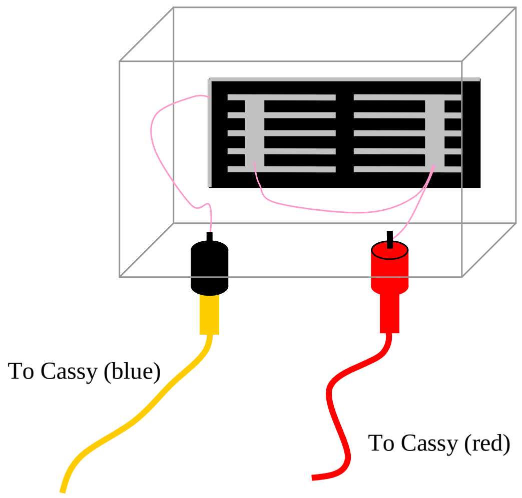

Figure 2: Schematic of solar cell and protective box. Note the grid-like arrangement of top contacts.

recording the current response as a function of time. The input resistance of the unit is 0 so it acts as a completely ideal voltage source.

For a *very* simplified model of the Power Cassy connected to the solar cell we introduce the circuit on the left of figure 3. With the directions as defined in the figure we have $U = U_0 - IR_0$ so that the applied voltage has the same effect as applying an external load with resistance $R = -U/I$. The power done *on* the load resistor in this case is $P = (-U)I$. A more exact model of the solar cell is provided by the circuit in the right of figure 3, consisting of a parallel connected ideal diode and ideal current source. Only the first model shall be used later to analyze the behavior of the solar cell.

The following materials is needed to perform the laboration:

- 1 power Cassy,
- 1 black power cable,
- 1 RS232 cable
- 1 solar Cell in plastic box,
- 2 cables with banana plugs,
- 1 large ruler,
- 1 desk lamp, and
- 1 computer with Cassy Lab installed.

3 Laboration procedure

3.1 Preparations

Connect Cassy to the solar cell, to the computer (with RS232 cable) and to a power outlet. Position the lamp directly over the solar cell so that it is possible to adjust its height. Start Cassy Lab on the computer and close the information box that appears on screen.

You should now see the `Settings` dialog box as shown in figure 4. Under the `General` heading, make sure that the Cassy unit is assigned to the appropriate computer port. Load the pre-programmed `SolarCell.lab` module by hitting F3.

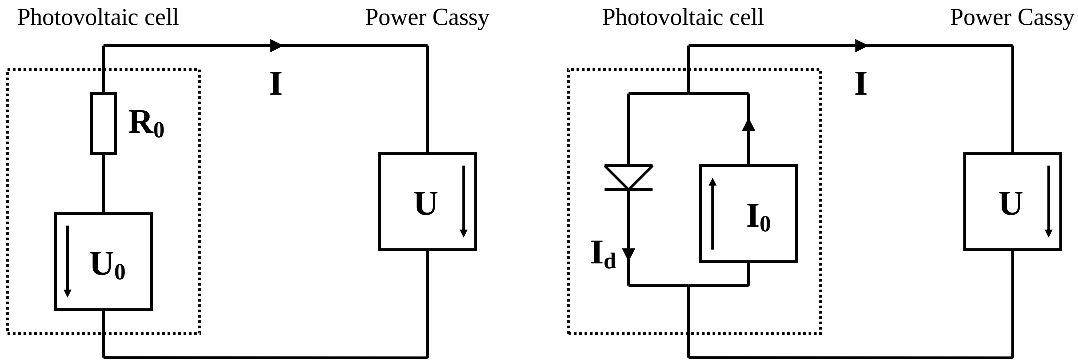

Figure 3: Two circuit models of the system under study. Directions of current and voltages are consistent with a solar cell performing work on the load.

3.2 Measurements

3.2.1 Without applied bias

Click on one of the channels to set your measurements (the red and blue dots on the Cassy picture shown). This will open the `Function Generator Settings` which should be set to the values shown in figure 5.

Important: Make sure that the Output range and Measurement Range is set properly. High currents may damage the solar cell!

Click on `Display measurement parameters` and set to the values shown in figure 5. The program is now set to source a constant DC voltage of `Vp = 0` V and measure the current at 500 points separated by 200 μs. Make sure the lamp is off and click the measurement button which is shaped like a clock (see figure 4). Since no bias was applied and no light provided both current and voltage should be zero.

Now position the lamp close to the solar cell, turn it on and click the measurement button again. After the measurement is done turn off the lamp.

Important: Always turn off lamp between measurements to avoid heating the solar cell and box.

Now what do you see? How can you explain this? Is the frequency what you expected? To save this measurement, click F2 and save it in ASCII format.

3.2.2 IV-characteristics

Set the `Function Generator Settings` and `Measuring Parameters` to those shown in figure 6.

Important: Make sure that the Output range and Measurement Range is set properly. High currents may damage the solar cell!

The program is now set to source a triangular wave with amplitude `Vp = 0.57` V and frequency 0.2 Hz. Open the `Settings` by clicking on little toolbox. Under the heading `Display` you can change what parameters are to be plotted. If you choose more than one parameter to plot on the y-axis there will be buttons along the left and right side of the axes that determine what is being plotted. Set the program to plot current versus voltage.

Now perform this measurement both with and without illumination. Under illumination the curve shows the “noise” observed in the first current measurement. To get rid of this we can introduce a new parameter which is an average value of the current over some time interval. Open `Settings Parameter/Formula/Display` and define a new quantity `Iav` by choosing `New Quantity` and clicking the `Mean value` button. Let the mean value be formed over 10 ms and have 4 digits. Also introduce a suitable name and unit for this quantity.

Now you can display the measured current and the averaged current in the same plot by plotting them on the left and right y-axis respectively. By right clicking on the right and left

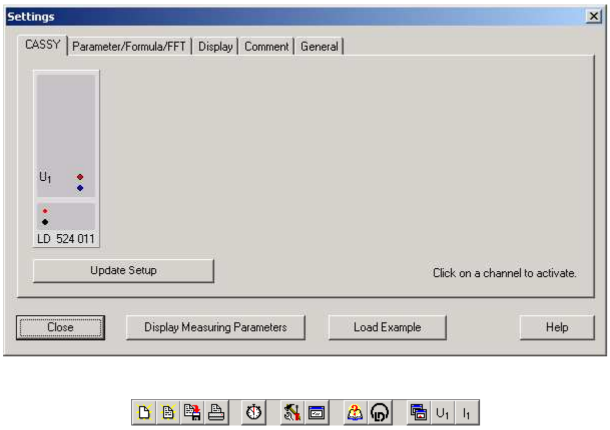

Figure 4: Settings dialog box and important buttons in Cassy lab.

side of the plot you can change the scale on the axes. The `Find minimum and maximum` button rescales the axis automatically.

As mentioned above we are also interested in the power delivered by the cell. Introduce a new quantity for power but use the `Formula` field to define its value. Take care to get the correct sign of the power. Plot this quantity and find the point of maximum power. By simply clicking on the graph, the tabulated values corresponding to that point will be marked.

3.2.3 Power dependence on distance

The maximum power delivered by the solar cell will depend on the total radiative power received and thus on the distance to the lamp. Derive the expression for the power delivered to the surface of the cell as a function of the table-to-lamp edge distance. Introduce any unknowns as fitting parameters.

To measure the power dependence on distance you should measure IV-characteristics at different table-to lamp edge distances. How should you choose your measurement points? With linear relationships equidistant points are a good choice. How should the points be chosen in this case? Hint: I want to plot Power vs f(distance) with f chosen such that the curve is a straight line with equidistant points. Discuss with the assistant if you are not sure how to do this.

When turning on the lamp, take care not to move it vertically. Also make sure that when repositioning the lamp, the bulb is always exactly above the solar cell. Perform measurements at approximately 10 different distances. Remember to save your files after each measurement.

4 Post-processing of data

Before starting to work with the measurement data we must remove some extra information in the text files. Open the measurement files in any text editor and remove the first five lines which simply contain information about the measurement.

4.1 Diode equation

Fit the IV curve without illumination to the diode equation. To make this process easier there is a matlab function file called `diode.m` which can be downloaded from the course homepage which can be used together with the following lines of code to get the fitting parameters I_{sat} and $V_0 = nk_BT/e$:

```
format long
data = load('foo.txt');
U = data(:,2);
```

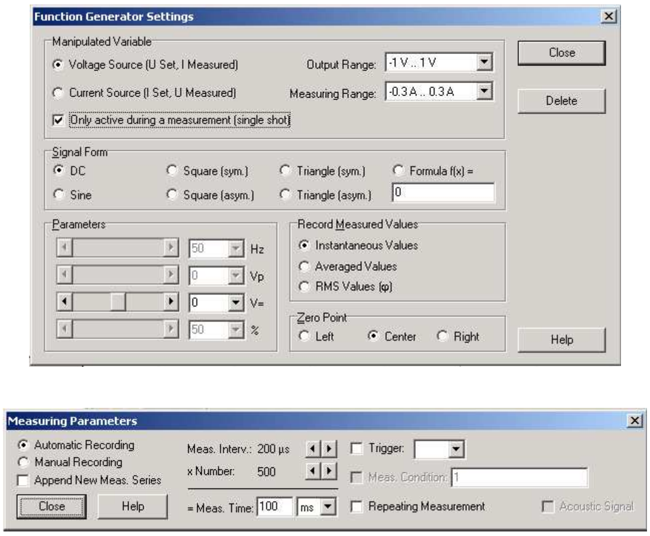

Figure 5: Settings for measurement of photocurrent under 0 applied bias.

```
I = data(:,3);
initials=rand(1,2);
options=optimset('Display','iter');
params = fminsearch(@diode,initials,options,U,I)
```

where `foo.txt` should be substituted for the name of your data file. The matlab function takes the parameters I_{sat} and V_0 and the measurement data U, I as inputs and then outputs the squared error $(I - I_{\mathrm{sat}}\,(1 - \exp(-U/V_0)))^2$ summed over all voltages U. This functions is then minimized with respect to the parameters with the built-in matlab function `fminsearch`.

Plot the measured data and the fitted function in the same plot.

4.2 IV-characteristics and Power at different distances

Make the following two plots: a family of I versus V curves at different distances, and a family of P versus V curves at different distances. Then extract, using e.g. `ginput`, the maximal power $P_{\max}$ delivered by the solar cell for all distances.

You have derived the functional dependence $P_{\max} = f(d)$ containing two unknown parameters (question 4). In the course homepage there is the matlab function `diodedist.m` which takes as inputs the distances d and the power $P_{\max}$ and finds the unknown fitting parameters. Use it in the same way as when you fitted your data to the diode equation. It is now possible to make a plot of $P_{\max}$ versus $f(d)/f(0)$. Discuss what the $f(d)/f(0)$ parameter should be with your assistant if you are not sure. If the formula you derived is valid, this curve should be linear.

5 Question to answer

The following questions should be answered and included in the lab report. Write the lab report in the style of a technical article and try to include questions, answers and relevant plots in a natural way in the text.

1. Assume you want to run this solar cell with a monochromatic light source. What is the minimum frequency needed?

2. Explain the behavior of the current at zero bias. Illustrate with a figure.

3. Do the IV characteristics in the non-illuminated state agree with the diode equation? What is the ideality factor? Illustrate with a figure.

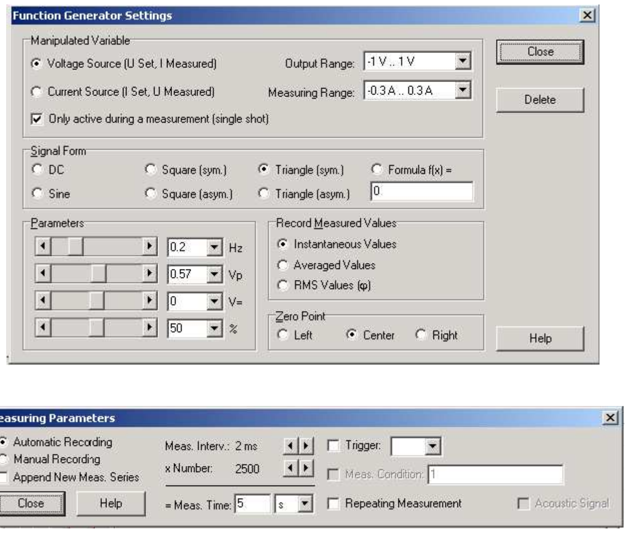

Figure 6: Settings for measurement of current under the application of a triangular wave with amplitude 0.57 V and frequency 0.2 Hz.

4. Derive the relation between power delivered to solar cell and desk-to-lamp edge distance. The expression should include two parameters, one of which has the dimension of length. What is the physical meaning of this parameter? Is the derived relation valid in this experiment? Illustrate with the figure mentioned in 4.2.

5. Show that for a voltage source with internal resistance R_0, the optimal load which maximizes the power output is R_0. What should the voltage U be at the point of maximum power? Is this fulfilled in your measurements? This corresponds to the predictions of the circuit model in the left of figure 3.

6. An important parameter of a solar cell is the efficiency η defined by

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{P_o}{P_i}. \tag{2}$$

Using very simple statistical mechanics arguments it is possible to find a theoretical upper limit to η for a pn-junction solar cell operating at 0 K with a bandgap E_g and illuminated by a blackbody at temperature T. One finds that the efficiency is a function of the dimensionless variable $x_g = E_g/(k_B T)$ as plotted in figure 7.

   - What semiconductor appears to be ideal for solar cells and why? Use figure 7 and e.g. tabulated values in Kittel p. 201 (1996).
   - Make a rough estimate of the efficiency of the present solar cell and compare it to the theoretical maximum for the present working conditions.

   Optional: For the diligent student who wants to perform the calculation of $\eta(x_G)$ him-/herself a step-by-step guide following the paper by Shockley and Queisser (1961) is included in the appendix.

6 References

- Bowley, R. and Sánchez, M., *Introductory statistical mechanics*, Oxford university press, 1999.
- Kittel, C., *Introduction to solid state physics*, Wiley, 1996.

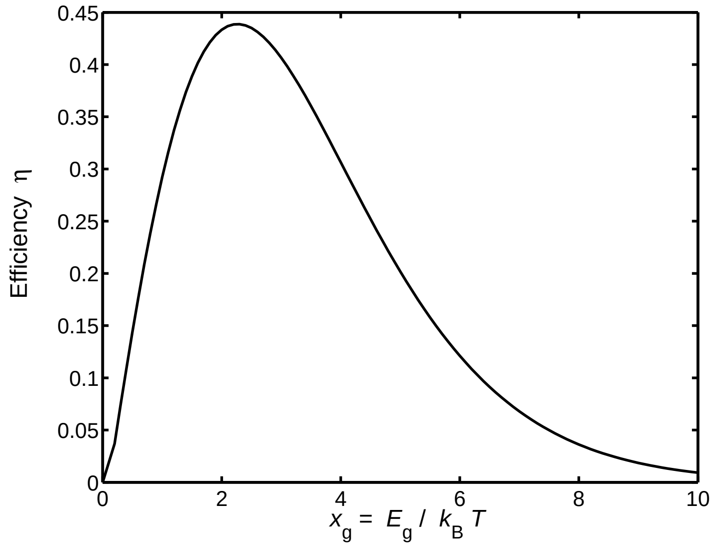

Figure 7: Upper limit of efficiency of pn-junction solar cell η at 0 K versus $E_g/(k_B T)$ where T is the temperature of a blackbody illuminating the solar cell and E_g is the band gap of the semiconductor..

- Photovoltaic systems research and development at Sandia National Laboratories, accessed 050207, `http:www.sandia.gov/pv`.
- Shockley, W. and Queisser H. J., *Detailed balance limit of efficiency of p-n junction solar cells*, J. Appl. Phys. **32**, pp. 510-519.

7 Appendix: Theoretical upper limit of the efficiency

1. The incoming power to the solar cell is given by the product of the area and the intensity I radiated by a black body at temperature T, as given by Stefan-Boltzmanns law (Bowley and Sanchez p. 168 (2000))

$$I = \frac{2\pi^5}{15c^2h^3}(k_B T)^4 . \tag{3}$$

2. Assume that every photon with energy larger than the bandgap $E_g = h\nu_g$ is absorbed and its energy completely converted to output energy of the device. The total output power is then given by the product of the area, this energy E_g and the number of incident photons with frequency $> \nu_g$ per unit time and unit area, Q.

3. Plancks law states that the contribution to the *energy density* from a frequency interval $[\nu, \nu + d\nu]$ is

$$u(\nu)d\nu = 8\pi h\nu^3/(c^3(\exp(h\nu/k_B T) - 1)d\nu. \tag{4}$$

Dividing by the energy for a photon $h\nu$ gives the contribution to the *number density* in this interval

$$n(\eta) = \frac{u(\nu)}{h\nu}d\nu \tag{5}$$

and the contribution to the number of particles that hit a unit area per unit time is given by the flux (Bowley and Sanchez p. 167 (2000))

$$\phi(\nu) = \frac{1}{4}cn(\nu)d\nu. \tag{6}$$

Integrate the flux over all frequencies above the bandgap to obtain the total number of photons of energy $> E_g$ hitting a unit area in unit time, i.e. Q.

4. Now write down the expression for η in its most simple form (this may include integrals) and plot η versus $x_g = E_g/(k_B T)$ in a suitable range.