CNS Institute for Physics Teachers

Title:	**Photovoltaic Cells: Getting a Charge Out of Light:** **Indoor Version**
Original: **Revision:**	1 December 2007 30 June 2008
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Appropriate Level:	Regents and AP Physics
Abstract:	Students develop an understanding of how photovoltaic solar cells work. They calculate the IV characteristics for the cell, measure the peak power produced as a function of a load resistor, and calculate the efficiency of the solar cell.
Time Required:	Two 40 minute lab periods Materials are provided which can form the basis of a pre-lab lecture and discussion, or which can be assigned as homework.
NY Standards Met:	4.1 Energy exists in many forms, and when these form change energy is conserved. 4.1a. All energy transfers are governed by the law of conservation of energy. 4.1b. Energy may be converted among mechanical, electromagnetic, nuclear, and thermal forms. 4.1i Power is the time-rate at which work is done or energy is expended. 4.1j Energy may be stored in electric or magnetic fields. This energy may be transferred through conductors or space and may be converted to other forms of energy. 4.1n A circuit is a closed path in which a current can exist. 4.1o Circuit components may be connected in series or in parallel. 4.1p Electrical power and energy can be determined for electrical circuits. S3.1 Use various means of representing and organizing observations to insightfully interpret the organized data.
Special Notes:	**Photovoltaic Cells** is a kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/. For the indoor version, the solar cell is illuminated with a construction worker's halogen work light (minimum 500W).

Behavioral Objectives:

Upon completion of this lab activity, students should be able to:

- Explain in very basic terms how a solar cell functions (this assumes the teacher introduces this material before teaching the lab)

- Understand how solar energy fits into the US energy landscape

- Wire a basic solar cell circuit and take data from it

- Interpret graphical data and calculate the efficiency of a solar cell

Class Time Required:

- Two 40 minute lab periods

Teacher Preparation Time:

- It is recommended that teachers familiarize themselves with some basics of solar cell operation to more effectively teach this lab to their students.

Tips For a More Fun Lab Experience:

- Use the solar cell to run something during the lab. A boom box is good (but you have to make sure that you don't fry it – we have done this – pay attention to the voltage of the cell and the maximum voltage of the radio!).

- If you have a CIPT resonator, pull apart the box with the switch and speed control knob to attach the motor directly to the solar cell. The rheostat is a much better speed control knob than the one connected to the resonator.

- If you think of a more fun thing to run off the solar cell, please send an email to the CIPT and let us know what you did!

- If you want to do this outside, go to the CIPT website and download the outdoor version of the lab since there are directions specific to setting up the cell outdoors. The performance of the cell is better when illuminated with the sun, but the weather in upstate NY deems necessary an indoor alternative!

Assumed Prior Knowledge of Students:

- Basic circuit knowledge is required.

- An understanding of the wave model of light is required.

- A basic familiarity with the electromagnetic spectrum is also necessary.

Background Information for Teacher:

Photovoltaic Cells: An introduction to semiconductors and *p-n* junctions

A photovoltaic cell is made from a junction between semiconductors with different chemical potentials (or Fermi levels.) A "*p* type" semiconductor has a tiny fraction of its atoms substituted by dopant atoms with one fewer valence electrons, resulting in a slightly reduced number of mobile electrons compared with an undoped *intrinsic (i)* sample. An "*n* type" semiconductor has a tiny fraction of its atoms substituted by dopant

atoms with one more valence electron, resulting in a slightly increased number of mobile electrons compared with an *intrinsic* sample. The *intrinsic* material is actually an insulator which has a *band gap* such that there are no empty states near the valence electrons at room temperatures, but the *p* and *n* materials behave as if they have freely moving positive and negative charge carriers respectively created by the dopants. The details of this are too complex to cover here, but you can think of the shortage of electrons as being positively charged "*holes*" in contrast with the surplus of electrons. The difference in the signs of the mobile charges creates significant changes when they are brought together, as the mobile charges *near the junction* (called the *depletion region*) move across the junction to create a new equilibrium. Once this equilibrium is reached (very fast), no current flows from the junction since the charges hold each other, on average, in place. This region becomes similar to the *intrinsic* semiconductor with no mobile charges of either sign. The new equilibrium has a charge inversion at the boundary with an excess of negative charge in the *p* side and an excess of positive charge in the *n* side, creating a built in electric potential and an electric field in this *depletion region*. This is shown in Figure 1.
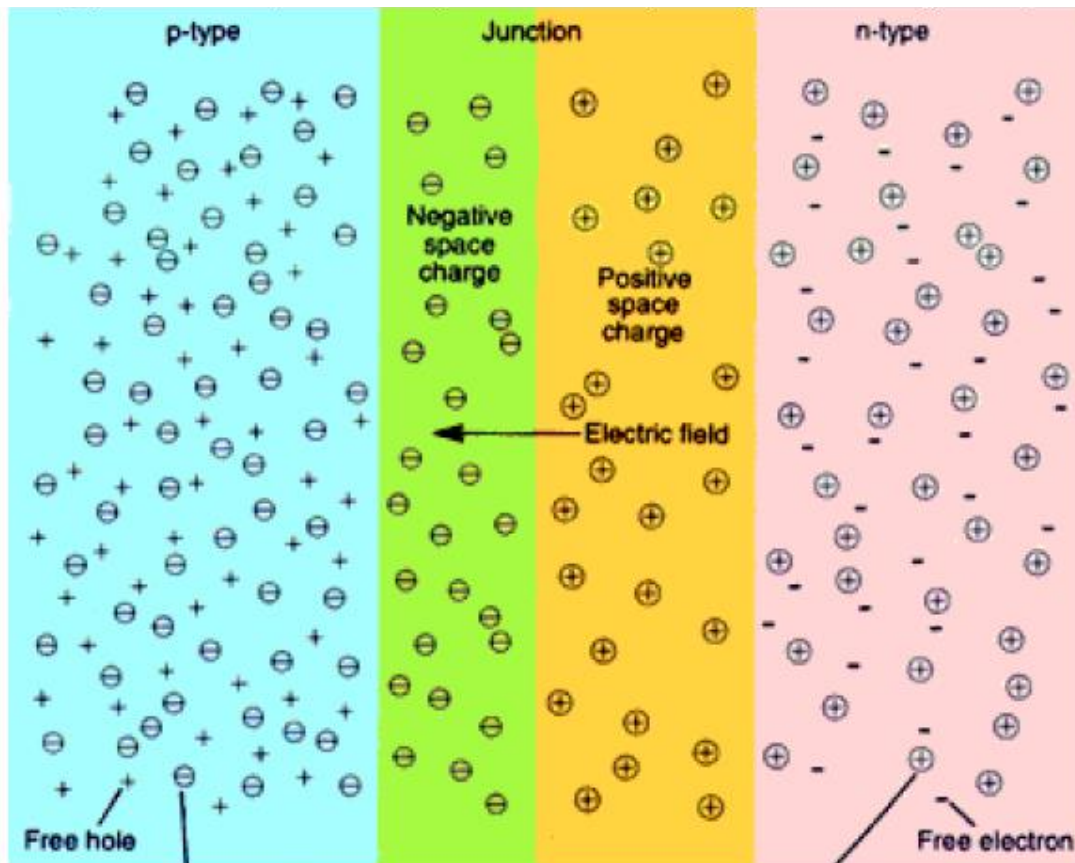

Figure 1: Schematic of charge distribution in a pn junction.

When a photon with an energy larger than the *band gap* is absorbed near this junction it can create both an electron and a *hole* (the net charge must be conserved) and while these charges could recombine (as the do in the bulk semiconductor), there is a much higher

probability that the electron will be driven by the built-in field into the *n* type material and the *hole* into the *p* type material. Once this happens, these charges are excess beyond the equilibrium charge distribution, so they move out away from the junction. If the cell is isolated, the excess electrons and *holes* move out to the surfaces of the bulk *n* and *p* regions respectively, just as excess charges do on a metal, but with the result that the *n* material has a lower potential than the *p* material. This difference in potential is the *open circuit voltage, V_{oc}*, of the solar cell (analogous to the rated potential of a chemical cell or battery.) If the solar cell is placed in a circuit, the electrons that were driven out from the *depletion region* into the *n* region will move through the circuit to the *p* region where they can now recombine with the positive charges that were piling up after being driven out the other side of the depletion region.   If the number of photons absorbed increases, the number of excess charges increases and the current flowing in the circuit will be larger. The resistance of the circuit (typically referred to as the *load*) also matters, as that portion of the circuit must satisfy Ohm's Law. If this resistance approaches zero the current will increase to the *short circuit current,I_{sc},* for a fixed illumination of the cell. An ideal PV cell would provide an *ideal maximum power,*

$$P_{max\ ideal} = I_{sc}\ V_{oc} \qquad\qquad\qquad \text{(Eqn. 1)}$$

Finally, it should be noted that *p-n* junctions are in all modern electronics. The solar cell absorbs photons and generates a current in the *forward* direction. If instead we take a *p-n* junction and connect it to a battery that drives current in this direction, we will drive electrons and *holes* from the bulk regions into the junction region where they can recombine and create photons with an energy equal to the *band gap*. This is known as a light emitting diode. The *p-n* diode is a nonlinear electronic device akin to a one-way valve for current.   If one connects a battery to try and move current in the *reverse* direction in a diode the mobile charges are driven away from the junction and no current can flow. Transistors are made by placing two diodes back to back (*pnp* or *npn*) and creating a third terminal (called the *gate*) that can modulate when the current can flow by adding an electrical bias to the middle segment between the two junctions. While these topics are beyond the material covered in regents or AP physics, they are critical technology in our world today, having enabled the creation of computers and modern electronics.

Additional Notes:

While you have been working with a single PV panel which creates ~20 watts of DC power, most home and commercial solar installations are significantly larger and tied to the AC power grid. This requires an inverter to convert the DC power to AC power similar to what you draw from the power company. A major advantage of this approach is that the federal government requires all local electric utility companies to buy back excess power residential customers generate at the same price that they charge these customers for the power. Effectively this means that when a residential power system creates more energy than is in use at the site, the power meter at the residence actually runs backwards lowering the electricity bill. PV power is generated under direct sun, which corresponds to the peak demand period for electric utility companies. The

advantage of this approach is that there is no need to store the power generated on site, which is a significant hassle. (The major exception to this is when PV panels are used for power on boats or remote cabins far from the power grid. In these cases the panels are usually used to charge a battery bank enabling users to store the energy for use even after dark or on cloudy days.)

There are a wide variety of PV materials and cell designs. The highest efficiency cells use exotic materials and light concentrators (mirrors or lenses) and achieve efficiencies over 30%. The best single crystal silicon cells are over 20% efficient, and thin film solar cells of various materials can be much more cost effective despite lower efficiencies of 8-16%. Many of these technologies are quite mature and in manufacturing is ramping up. However, in the past few years two new types of PV cells, based dye-sensitized nanocrystalline TiO_2 and organic polymers (plastics) have been making major advances, and may become disruptive technologies.

Answers to Questions: *send email to cipt_contact@cornell.edu to request answers*

Recommended Online References/Resources:

http://www.eia.doe.gov/	*DOE Official Energy Statistics*
http://www.nrel.gov/learning/	*Nat. Renewable Energy Lab NREL*
http://www.eere.energy.gov/solar/pv_basics.html	*Dept. of Energy Solar Tech. info.*
http://www.nrel.gov/ncpv/documents/pvpaper.html	*1993 Physics Today article on PVs*
http://www.nrel.gov/docs/legosti/old/16319.pdf	*NREL Photovoltaics Fundamentals*
http://www.uni-solar.com/interior.asp?id=36	*Uni-Solar literature*
http://www.homepower.com/	*magazine for home power systems*

# Photovoltaic Cells: Getting a Charge Out of Light
Indoor Version

Equipment List

Item Number	Quantity	Item
1	1	Shop light
2	1	SunWize SolCharger solar cell (18.7 Volts, 0.6 Amperes, 12 Watts)
3	1	small ring stand (plate and metal rod)
4	1	ruler
5	1	plastic tubing to secure solar cell against the table
6	1	rheostat (rated for ~ 1 A, variable resistance 0 - 200 Ohms)
7	5	patch cords with banana clip ends
8	2	digital multimeters

Photovoltaic Cells: Getting a Charge Out of Light
Indoor Version
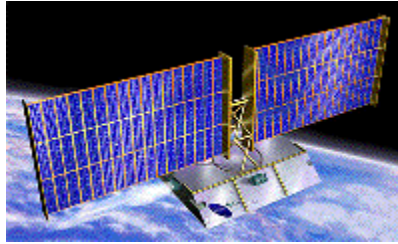
Pre-lab Assignment

While most circuits use batteries or power from the electric grid, an illuminated solar cell creates a voltage source that can be used to drive current through a circuit. No chemical reactions occur in a solar cell (i.e. it is never used up like a battery), it creates no CO_2 emissions, and it is a truly renewable resource. Photovoltaic (PV) panels are generally considered the cleanest (no emissions) and most environmentally benign way to generate electrical power, but are not currently cost competitive with other forms of power generation. The total of PV generated electricity is currently a tiny, but growing, fraction of our electricity supply. Some interesting energy facts are shown in Figure 1 below.

Figure 1
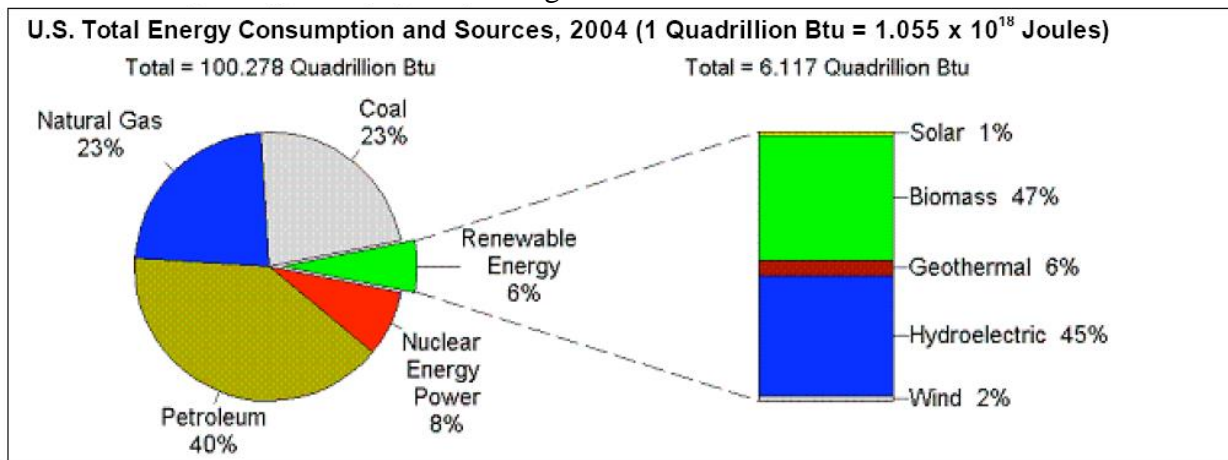
The average US home uses 29.5 kWhr of electricity each day, but the variations are very large, depending upon habits, region, types of appliances, etc. Figure 2 shows where this energy is used.

Figure 2

Percent of Total Electricity Consumption in U.S. Housing Units, 2001

Lighting 8.8
Water Heating 9.1
Space Heating 10.1
Air-Conditioning 16
Refrigerator 13.7
Other 42.2
All Others 26.7
Color TVs 2.9
Furnace Fans 3.3
Freezers 3.5
Clothes Dryers 5.8

Source: Energy Information Administration, Form EIA-457A, B, C. E. and H of the 2001 Residential Energy Consumption Survey.
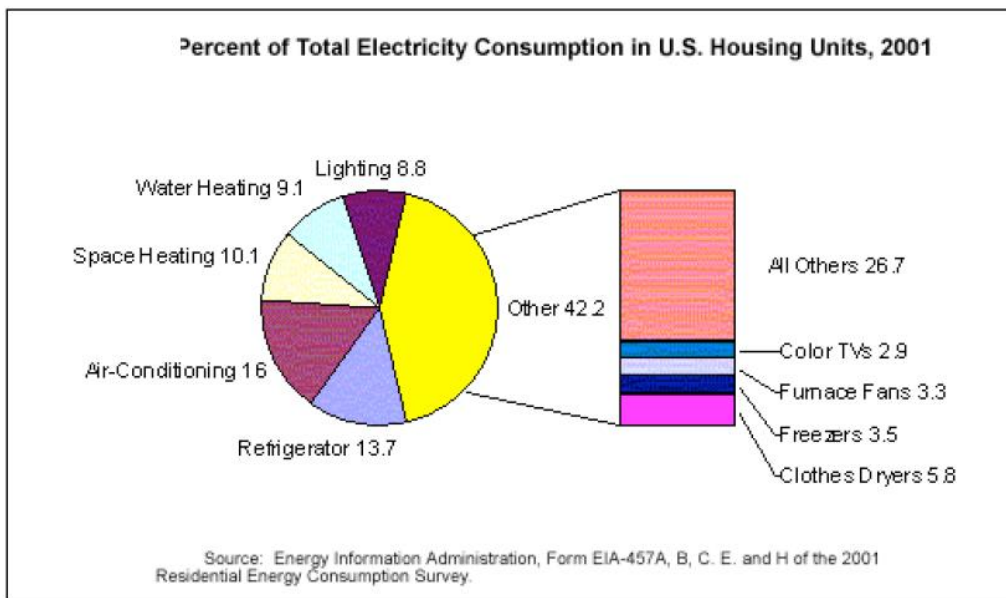
In direct sunlight, the power that lands on the earth's surface is ~1000 Watts/m^2. Because of clouds, night time, etc., the long term average value is ~200 Watts/m^2.

Remember:

Power = Energy/time
1 Watt = 1 Joule/sec
1kWhr=1000J/s*3600 s = 3.6x10^6 J

1. Use the data in Figure 1 to calculate the average power consumption in the US over the course of a year.

2. If the total of US *electricity* consumption is currently ~ 4x10^{11} Watts, what fraction of our total power consumed is used in the form of electricity?

3. If there are a total of 107 million households in the US, what fraction of this electricity consumption is residential usage?

4. Assuming a PV array has 20% efficiency converting sunlight into usable electricity, what is the net area a PV array would need to fully power an average household?

5. What fraction of the total US land area would need to be covered with 20% efficiency solar cells to provide full power needs of the US? (Use your answer to question 1, and note the land area of the US is: 9,161,923 sq km according to the CIA World Factbook.

Experimental Section

Introduction

In this lab you will test how the current, *I*, and the voltage, *V*, generated by a solar panel vary under a wide variety of conditions. You can calculate the power, *P=IV,* or the *load resistance*, *R=V/I,* at any time. While you cannot control the solar power available from the sun during lab, you can control the *load resistance.* This will be your independent variable for this study.

Before you begin to test the circuit as a function of the load resistance, you will first explore the current generated by the room light. Then you will take two very important data points using the halogen light. First, you will measure the open circuit voltage and then the short circuit current.

Exploring the dependence of the short circuit current on the ambient lighting
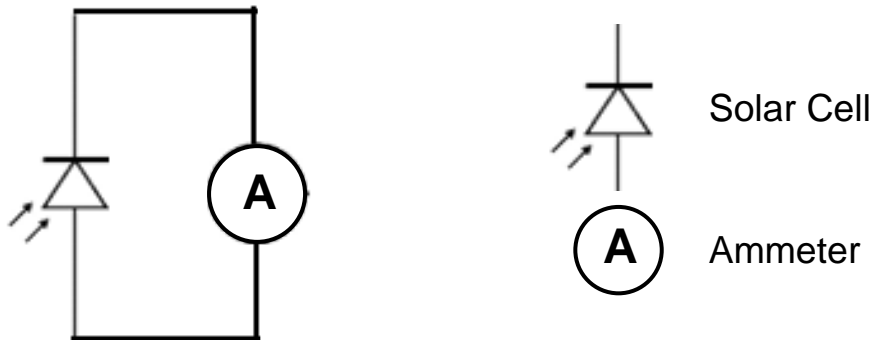
- The *short circuit current, I_{SC}*, is the current the solar cell generates when there is no resistive load (maximum current flow).
- Use a black patch cord to connect the black terminal from the solar cell to the "com" socket of the multimeter.
- Use a red patch cord to connect the red terminal from the solar cell to the "VΩmA" socket of the multimeter.
- Set the dial on the multimeter to the "200mA" setting. You are now using the multimeter as an ammeter. A digital multimeter measuring current will have a low resistance of less than an ohm, so that maximum current flows through it.
- Carefully move around the solar cell. Point it toward lights, windows, the floor, etc. and observe how the current varies.

1. When more light hits the solar cell, is the current higher or lower? _____

2. Suggest an explanation for your observation_____

_____

3. What is the maximum current you measured (include units)? _____
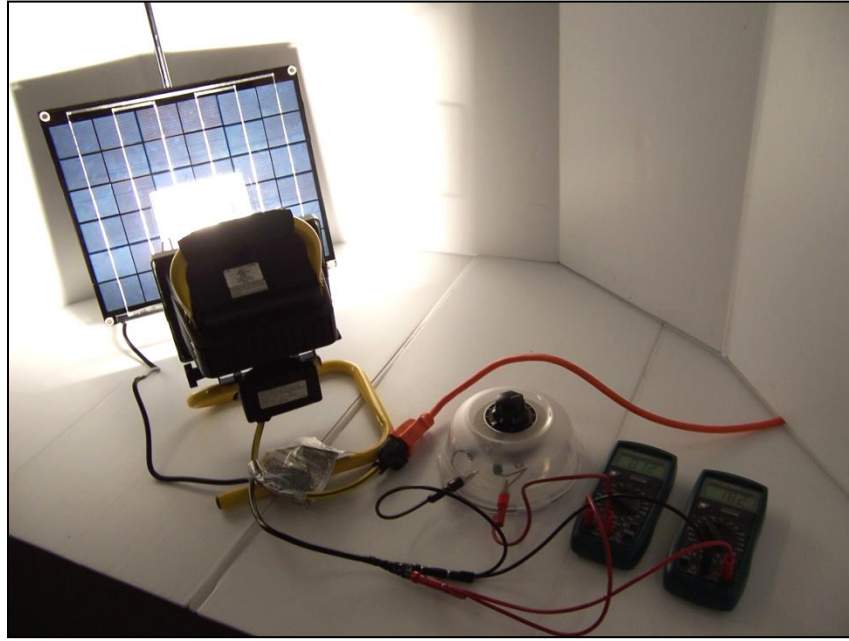
Assembled Solar Lab Set-up

Maximizing the Short Circuit Current, I_{SC}

- See the picture above to guide you in setting up the lab assembly.
- Now slide the plastic tubing under the bottom edge of the solar cell to prevent it from slipping and lean the solar cell against the assembled ring stand.
- Place the halogen lamp in front of the solar cell and turn it on.
- Measure *Isc*, **the short circuit current**, by moving the red patch cord from the "VΩmA" socket to the "10ADC" socket of the multimeter and moving the dial to the "10A' setting. The multimeter is now an ammeter in the high current mode.
- Note that much higher currents are generated when the halogen light shines on the solar cell than when the cell is only illuminated by room light.
- Explore how the current changes with the position of the halogen lamp with respect to the solar cell.
- Position the halogen lamp to maximize the current.
- Record your result in the space below.
- **Make sure you do not move your solar cell or halogen lamp now that you have started taking measurements.**

4. Short Circuit Current (*Isc*): _____ (include units!)

Measuring the Open Circuit Voltage, *Voc*

Solar Cell
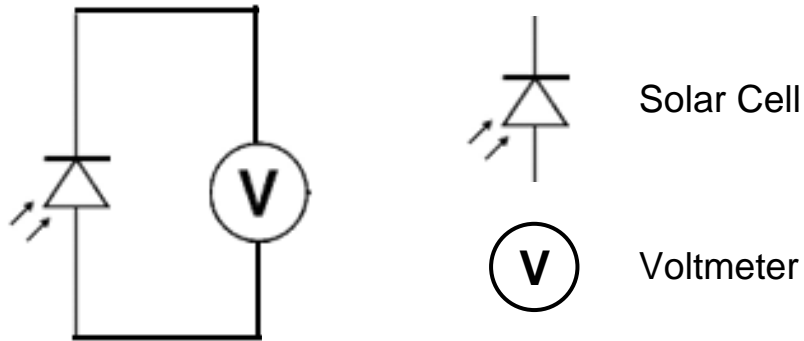
V   Voltmeter

- Move the red patch cord from the "10ADC" socket to the "VΩmA" socket of the multimeter
- Turn the dial on the multimeter to the "200 V DC" setting. You are now using the multimeter as a voltmeter, which has a large resistance (~ 1MΩ), and virtually no current flows through it.
- The multimeter is now reading the **open circuit voltage, *Voc*,** which is the maximum voltage generated by the circuit when no current flows through it**.**
- Record your result below.

5. Open circuit voltage (*Voc*): _____ (include units!)

Measuring the Load Resistance of the Solar Cell

Rheostat

Solar Cell

A   Ammeter

V   Voltmeter
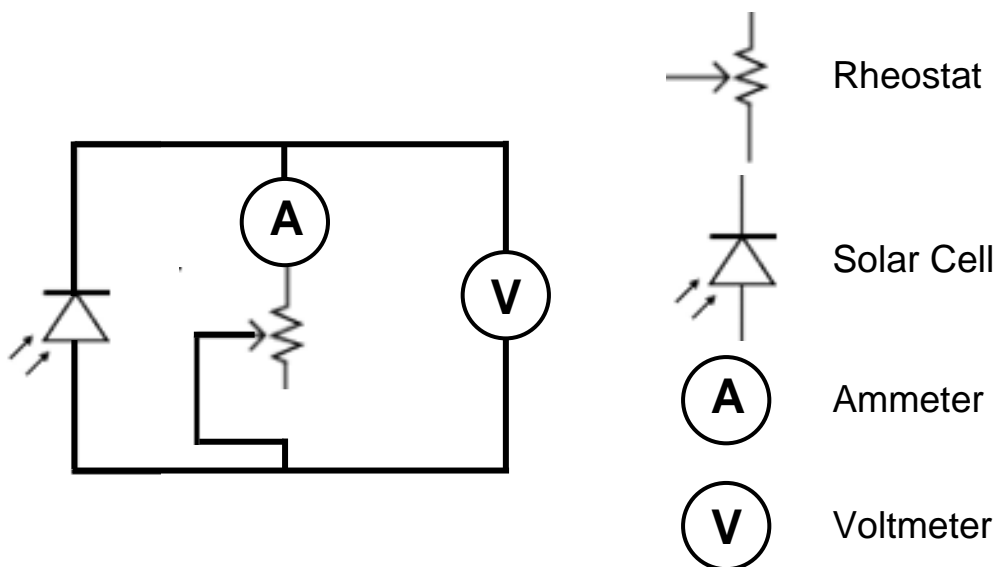
- Remember that you must not move the solar cell or the halogen lamp since the illumination must remain constant for your data to be valid.
- Now that you have measured the maximum current and voltage values, you will examine how current and voltage change as a function of applied load resistance.
- The load in this circuit is a rheostat, which is just a variable resistor with resistance ($0 < R < 200$ Ohms).
- Wire the circuit as shown in the diagram above. If you get a negative voltage or current, then simply reverse the connections to the multimeter.
- The rheostat has markings from 0 to 100. These are the percentage of the resistance of the rheostat. Since the maximum resistance is 200 ohms, 10% is 20 ohms. Thus 10 on the rheostat is 20 ohms, 20 on the rheostat is 40 ohms, etc. up to 200 ohms at a setting of 100.
- Collect data from 0 to 200 ohms in 10 ohm intervals by setting the rheostat dial from 0 to 100% in intervals of 5%. For each 10 ohm interval, record the voltage and current in the table on the next page.
- Once the first three columns are complete, use a calculator to compute the power ($P = IV$) and the resistance ($R = V/I$).

Solar cell data table

Rheostat setting	Rheostat resistance (Ω)	*Voltage Volts (V)*	*Current Amps (A)*	*P=IV watts (W)*	*$R_{circuit}$=V/I ohms (Ω)*
0	0				
5	10				
10	20				
15	30				
20	40				
25	50				
30	60				
35	70				
40	80				
45	90				
50	100				
55	110				
60	120				
65	130				
70	140				
75	150				
80	160				
85	170				
90	180				
95	190				
100	200				

Note that the resistance value from the rheostat is less than the circuit resistance you calculated from the current and voltage measurements.

6. Suggest a way to explore the rheostat as a source of this error using the equipment provided in this lab.

7. Do it! Show your data in the space below. Did it resolve all, part, or none of the error?

8. What other part of the circuit could be the source of the additional resistance?

Plotting Your Results

- Plot the current, I, on the y-axis and the voltage, V, on the x-axis (*I* vs. *V*).
- Plot the power, *P*, on the y-axis and the rheostat resistance in the second column, R, on the x-axis (P vs. R).
- You will need to figure out appropriate scales for the axes. If you prefer, you could use a computer to plot the data.

Post-lab Analysis

1. There should be a clear peak in the power vs. resistance curve. This peak corresponds to the conditions for maximum power generation. How much is this power?

2. Estimate the current and voltage that correspond to the maximum power on the P vs. R curve. Now mark this point on your *IV* curve. Draw a vertical and horizontal line from this point to the x and y axes, and label these intercepts V_{mp} and I_{mp} (mp = maximum power). The area of the resulting rectangle is the maximum power produced by the solar cell.

3. Theoretically, it would be great if you could generate power with the short circuit current, *Isc*, and open circuit voltage, *Voc*. Please label *Isc* and *Voc* on your *IV* curve. Draw the rectangle on the *IV* curve that corresponds to this <u>ideal</u> power and calculate its value. How does this compare to your answer to question 1?

4. Using the ruler provided, find the area of the solar cell.

$$A_{solar\ cell} = \underline{\hspace{2cm}} m^2$$

5. If you used your solar cell outside, you could assume that solar power that lands on the earth's surface is approximately 1000 Watts/m^2. Using this number and your answer from question 4, calculate the maximum solar power the cell could absorb. Show your work.
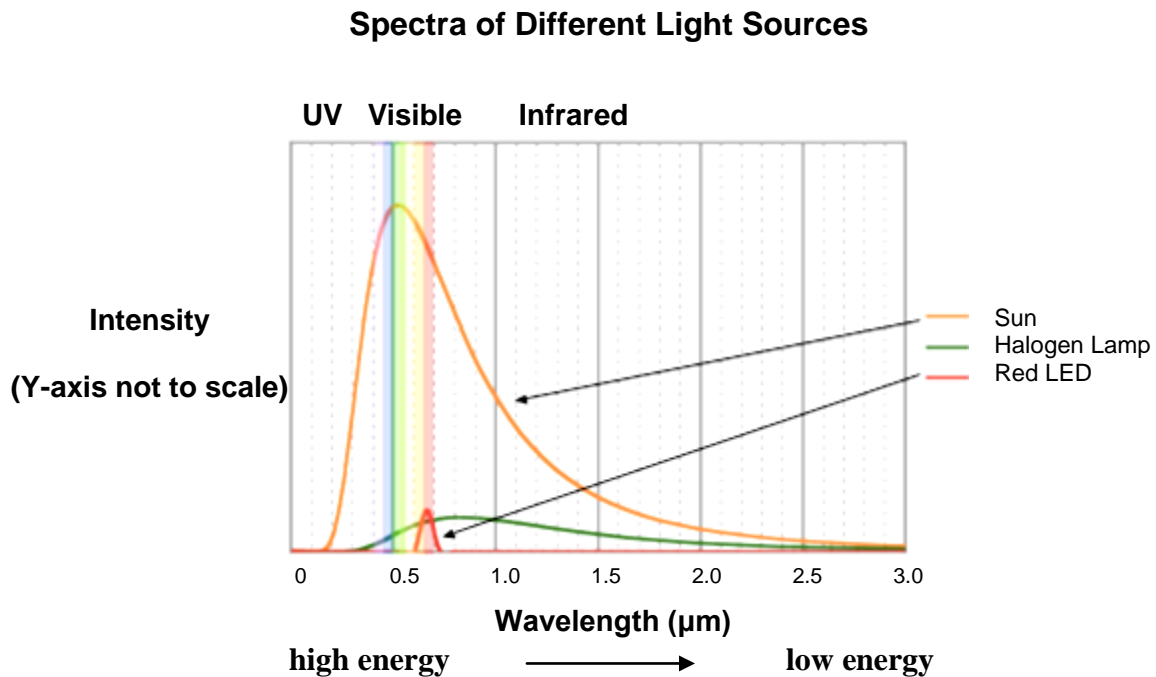
$$Max\ Power_{solar\ cell} = \underline{\hspace{2cm}} Watts$$

6. If you ran this experiment outside in the sun, instead of inside with the halogen light source, the maximum power you would observe is approximately 8.3 Watts.

   Use this value and the power calculated in question 5 to determine the efficiency of the solar cell in the sun. Show your calculations.

$$Efficiency = \underline{\hspace{2cm}}$$

7. Did you notice how hot the solar cell became while you were illuminating it with the halogen light? The graph below explains why that is the case. Infrared radiation is heat. Based upon this graph, is the halogen lamp a more efficient heat source or a more efficient light source? Explain your answer.

Spectra of Different Light Sources

UV   Visible   Infrared

Intensity

(Y-axis not to scale)

Sun
Halogen Lamp
Red LED

0   0.5   1.0   1.5   2.0   2.5   3.0

Wavelength (µm)

high energy   ⟶   low energy

8. Based upon the same plot, explain why is the sun a better power source for a solar cell than a halogen light.

Current *I*
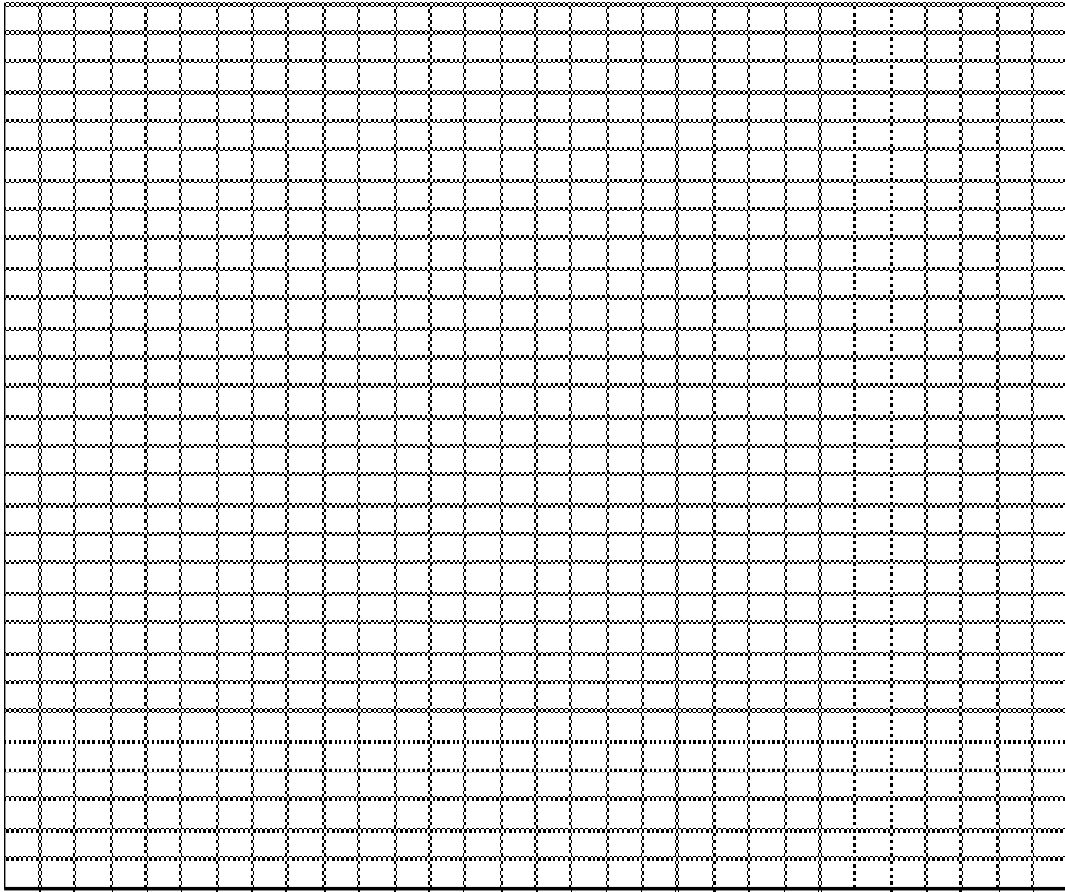
Voltage *V*
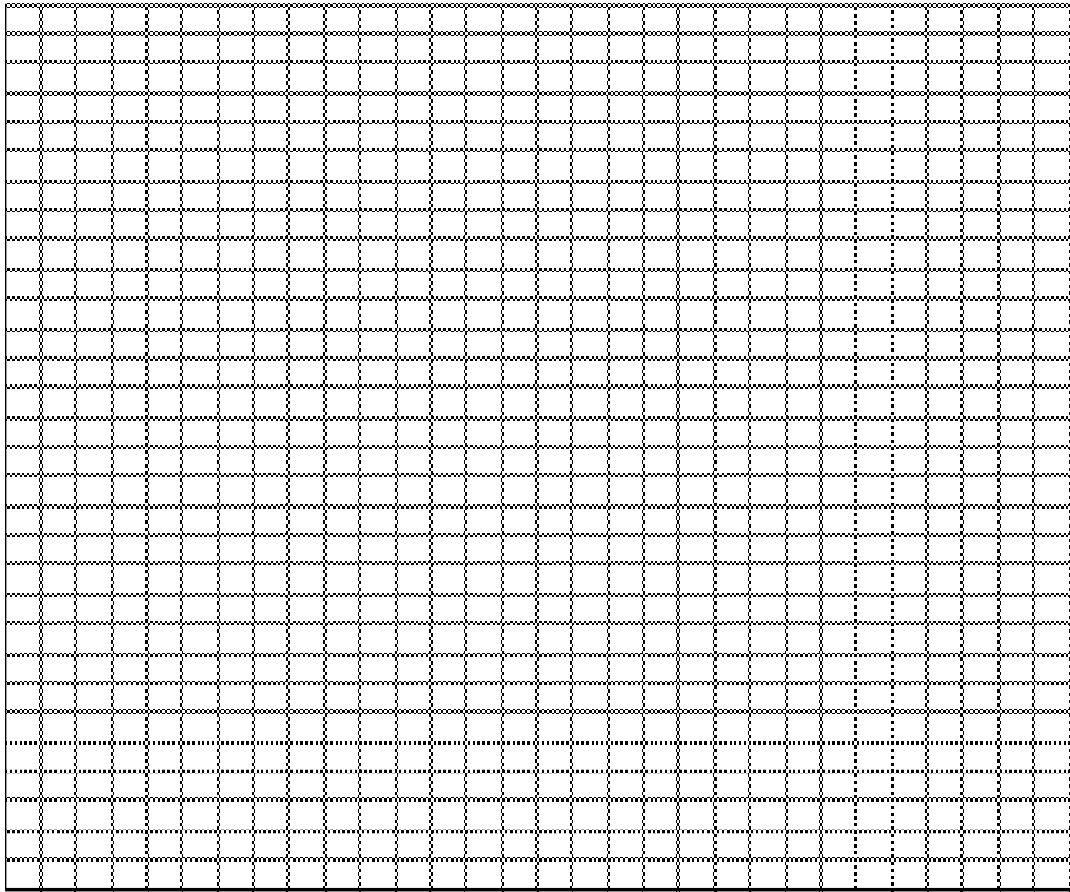
Graph of *current* vs. *voltage*.

Power *P=VI*

Resistance *R=V/I*

Graph of *Power* vs. *Resistance*.