Lesson and Lab Activity with Photovoltaic Cells

Created for CCMR RET I
Summer 2004
Dan Delorme

Lesson on Photovoltaic Cells

In this lesson you will be introduced to the history and theory of Photovoltaic (PV) cells. You will also, hopefully, begin to realize the importance of PV cells and the career opportunities available in this area of intense materials science research. In the laboratory investigation that follows, you will be asked to use PV cells to power operating circuits that they will construct in order to perform simple tasks. **Much of the text that follows was taken from various sources and those sources are credited at the end of the instruction portion of the lesson.**

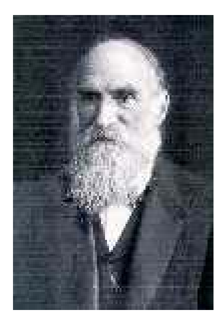
Introduction

Photovoltaic (PV) cells create electricity from sunlight and are one of the true success stories of materials science. Photovoltaic cells have grown from an area of study once viewed with skepticism to a multi-billion dollar market that promises tremendous continued growth. There are more than one billion hand-held calculators, several million watches and two or three million portable lights and battery chargers powered by PV cells. But the true area of growth is in thin film PV cells for creating electricity on such a scale as to power buildings.[1]

Currently, around 70% of U.S. solar cell production is exported making it an area that, with continued leadership in the field, the U.S. can look to as a source of employment – from basic manufacturing jobs to engineering and research positions around the country. The Department of Energy's Photovoltaics Program hopes to help make that happen. This program has, among others, the goal of reducing the price of PV electricity to roughly ten cents per kilowatt-hour and creating 50,000 high tech jobs in the US by 2010. [2] It is funding a number of materials science research endeavors to achieve this goal (listed later).

Success in this pursuit will also have major environmental ramifications, as DOE hopes that boosting production of PV cells will remove 10 million metric tons of carbon dioxide from the air each year worldwide. Greater use of PV cells may also reduce the estimated 30,000 premature deaths in the US each year attributed to power plant pollution.[3]

A Brief History



Humans have manipulated solar energy since the 7th century B.C. when magnifying glasses were used to concentrate the sun's rays to make fire and to burn ants. In 1839, Alexander Becquerel discovered the photoelectric effect.[4]
In 1873, Willoughby Smith discovered the photoconductivity of selenium. In 1876 William Adams (shown at right) and his student Richard Day

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

discover that selenium produces electricity when exposed to light. Although selenium solar cells failed to convert enough sunlight into electricity to power electrical equipment, they proved that a solid material could change light into electricity without heat or moving parts. In 1883, Charles Fritts described the first solar cells made from selenium wafers. In 1905, Albert Einstein published his paper on the photoelectric effect. In 1914, the existence of a barrier layer in photovoltaic devices is noted.[5] In 1916, Robert Millikan provided experimental proof of the photoelectric effect. In 1954, photovoltaic technology is born in the US when Daryl Chapin, Calvin Fuller, and Gerald Pearson (from left to right in photo at left) develop the silicon photovoltaic (PV) cell at Bell Labs.[6] Since then, a variety of commercial and government entities have worked to develop practical applications of photovoltaic cells while striving to increase the efficiency while decreasing the cost of these devices.

What is a PV cell?

The word Photovoltaic is a combination of the Greek Work for light and the name of the physicist Allesandro Volta. It refers to the direct conversion of sunlight into electrical energy by means of solar cells. So very simply, a photovoltaic (PV) cell is a solar cell that produces usable electrical energy. PV cells have been and are powering everything from satellites to solar powered calculators to homes and solar-powered remote-controlled aircraft as well as many, many other devices.

How does a PV Cell work?[7]

Converting Photons to Electrons

The solar cells that you see on calculators and satellites are **photovoltaic cells** or **modules** (modules are simply a group of cells electrically connected and packaged in one frame). Photovoltaics, as the word implies (photo = light, voltaic = electricity), convert sunlight directly into electricity. Once used almost exclusively in space, photovoltaics are used more and more in less exotic ways. They could even power your house. How do these devices work?

Photovoltaic (**PV**) cells are made of special materials called **semiconductors** such as silicon, which is currently the most commonly used. In fact, Over 95% of the solar cells produced worldwide are composed of the semiconductor material silicon (Si). Basically, when light strikes the cell, a certain portion of it is absorbed within the semiconductor material. This means that the energy of the absorbed light is transferred to the semiconductor. The energy knocks electrons

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

loose, allowing them to flow freely. PV cells also all have one or more electric fields that act to force electrons freed by light absorption to flow in a certain direction. This flow of electrons is a current, and by placing metal contacts on the top and bottom of the PV cell, we can draw that current off to use externally. For example, the current can power a calculator. This current, together with the cell's voltage (which is a result of its built-in electric field or fields), defines the power (or wattage) that the solar cell can produce.

That's the basic process, but there's really much more to it. Let's take a deeper look into one example of a PV cell: the single crystal silicon cell.

Silicon

Silicon has some special chemical properties, especially in its crystalline form. An atom of silicon has 14 electrons, arranged in three different shells. The first two shells, those closest to the center, are completely full. The outer shell, however, is only half full, having only four electrons. A silicon atom will always look for ways to fill up its last shell (which would like to have eight electrons). To do this, it will share electrons with four of its neighbor silicon atoms. It's like every atom holds hands with its neighbors, except that in this case, each atom has four hands joined to four neighbors. That's what forms the **crystalline structure**, and that structure turns out to be important to this type of PV cell.

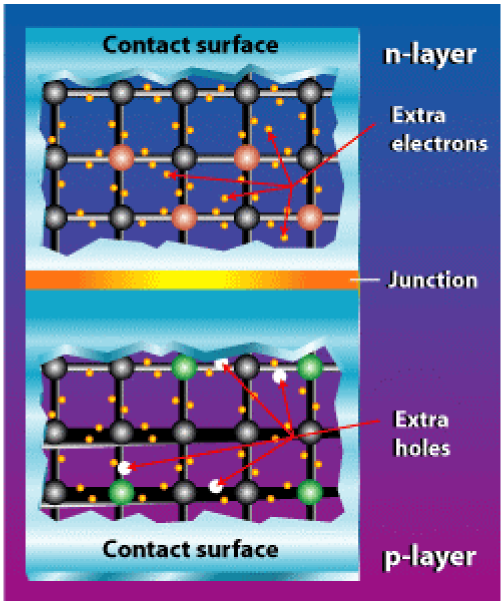
We've now described pure, crystalline silicon. Pure silicon is a poor conductor of electricity because none of its electrons are free to move about, as electrons are in good conductors such as copper. Instead, the electrons are all locked in the crystalline structure. The silicon in a solar cell is modified slightly so that it will work as a solar cell.

Silicon in Solar Cells

A solar cell has silicon with **impurities** -- other atoms mixed in with the silicon atoms, changing the way things work a bit. We usually think of impurities as something undesirable, but in our case, our cell wouldn't work without them. These impurities are actually put there on purpose. Consider silicon with an atom of phosphorous here and there, maybe one for every million silicon atoms. Phosphorous has five electrons in its outer shell, not four. It still bonds with its silicon neighbor atoms, but in a sense, the phosphorous has one electron that doesn't have anyone to hold hands with. It doesn't form part of a bond, but there is a positive proton in the phosphorous nucleus holding it in place.

When energy is added to pure silicon, for example in the form of heat, it can cause a few electrons to break free of their bonds and leave their atoms. A hole is left behind in each case. These electrons then wander randomly around the crystalline lattice looking for another hole to fall into. These electrons are called **free carriers**, and can carry electrical current. There are so few of them in pure silicon, however, that they aren't

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992



Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p/n junction at their interface, thereby creating an electric field.[8]

very useful. Our impure silicon with phosphorous atoms mixed in is a different story. It turns out that it takes a lot less energy to knock loose one of our "extra" phosphorous electrons because they aren't tied up in a bond -- their neighbors aren't holding them back. As a result, most of these electrons do break free, and we have a lot more free carriers than we would have in pure silicon. The process of adding impurities on purpose is called **doping**, and when doped with phosphorous, the resulting silicon is called **N-type** ("n" for negative) because of the prevalence of free electrons. N-type doped silicon is a much better conductor than pure silicon is.

Actually, only part of our solar cell is N-type. The other part is doped with boron, which has only three electrons in its outer shell instead of four, to become **P-type** silicon. Instead of having free electrons, P-type silicon ("p" for positive) has free holes. Holes really are just the absence of electrons, so they carry the opposite (positive) charge. They move around just like electrons do.

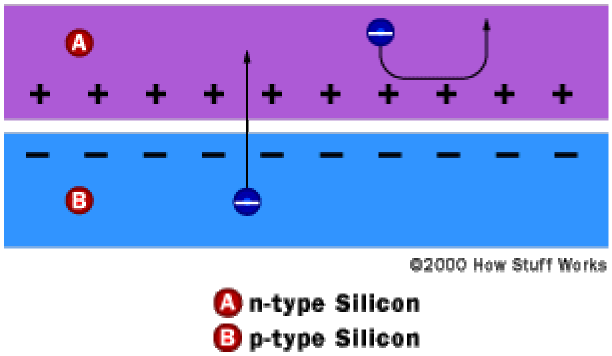
N-type Plus P-type Silicon

The interesting part starts when you put N-type silicon together with P-type silicon. Remember that every PV cell has at least one **electric field**. Without an electric field, the cell wouldn't work, and this field forms when the N-type and P-type silicon are in contact. Suddenly, the free electrons in the N side, which have been looking all over for holes to fall into, see all the free holes on the P side, and there's a mad rush to fill them in.

Before now, our silicon was all electrically neutral. Our extra electrons were balanced out by the extra protons in the phosphorous. Our missing electrons (holes) were balanced out by the missing protons in the boron. When the holes and electrons mix at the **junction** between N-type and P-type silicon, however, that neutrality is disrupted. Do all the free electrons fill all the free holes? No. If they did, then the whole arrangement wouldn't be very useful. Right at the junction, however, they do mix and form a barrier, making it harder and harder for

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

electrons on the N side to cross to the P side. Eventually, equilibrium is reached, and we have an electric field separating the two sides.



The effect of the electric field in a PV cell

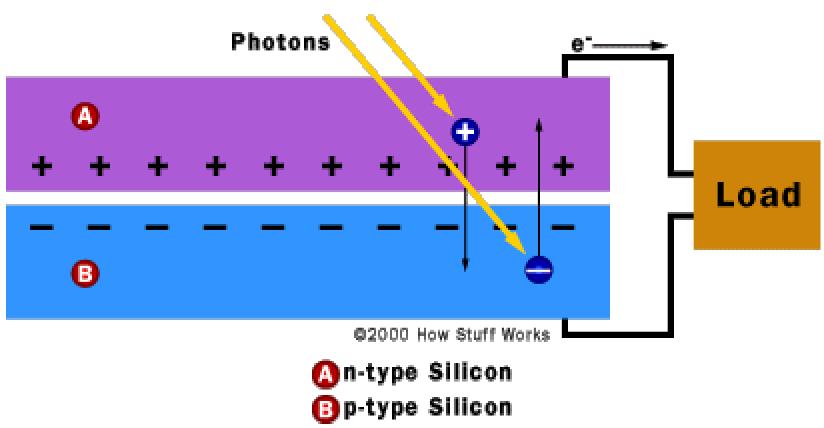
This electric field acts as a diode, allowing (and even pushing) electrons to flow from the P side to the N side, but not the other way around. It's like a hill -- electrons can easily go down the hill (to the N side), but can't climb it (to the P side).

So we've got an electric field acting as a diode in which electrons can only move in one direction. Let's see what happens when light hits the cell.

When Light Hits the Cell

When light, in the form of photons, hits our solar cell, its energy frees electron-hole pairs.

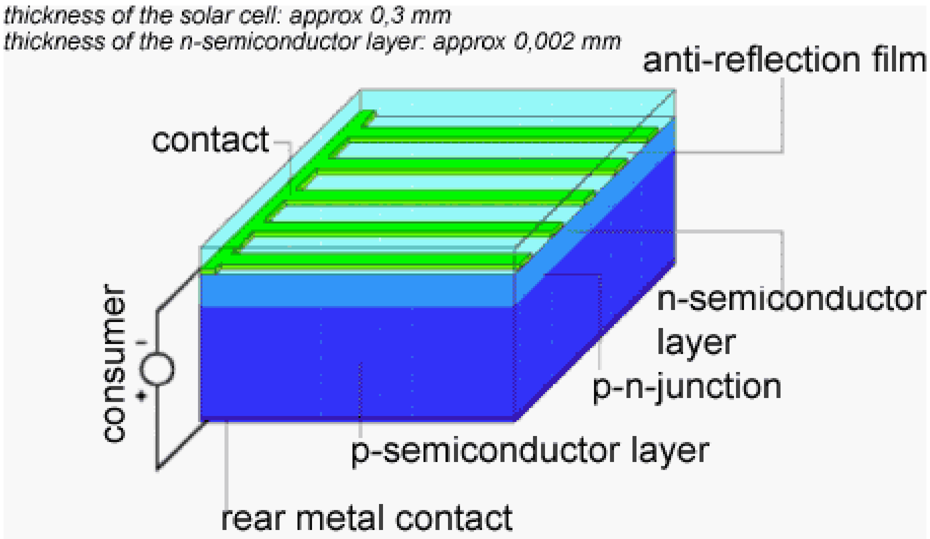
Each photon with enough energy will normally free exactly one electron, and result in a free hole as well. If this happens close enough to the electric field, or if free electron and free hole happen to wander into its range of influence, the field will send the electron to the N side and the hole to the P side. This causes further disruption of electrical neutrality, and if we provide an external current path, electrons will flow through the path to their original side (the P side) to unite with holes that the electric field sent there, doing work for us along the way. The electron flow provides the **current**, and the cell's electric field causes a **voltage**. With both current and voltage, we have **power**, which is the product of the two.



Operation of a PV cell

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

Because of the flow of electrons and holes, the two semiconductors behave like a battery, creating an electric field at the surface where they meet—what we call the p/n junction. The electrical field causes the electrons to move from the semiconductor toward the negative surface, making them available for the electrical circuit. At the same time, the holes move in the opposite direction, toward the positive surface, where they await incoming electrons. Through metal contacts, an electric charge can be tapped. If the outer circuit (consumer device in diagram) is closed, then direct current flows.



model of a crystalline solar cell[9]

How much sunlight energy does our PV cell absorb? Unfortunately, the most that our simple cell could absorb is around 25 percent, and more likely is **15 percent or less**. Why so little?

Energy Loss

Why does our solar cell absorb only about 15 percents of the sunlight's energy? Visible light is only part of the electromagnetic spectrum. Electromagnetic radiation is not monochromatic -- it is made up of a range of different wavelengths, and therefore energy levels.

Light can be separated into different wavelengths, and we can see them in the form of a rainbow. Since the light that hits our cell has photons of a wide range of energies, it turns out that some of them won't have enough energy to form an electron-hole pair. They'll simply pass through the cell as if it were transparent. Still other photons have too much energy. Only a certain amount of energy, measured in electron volts (eV) and defined by our cell material (about 1.1 eV for crystalline silicon), is required to knock an electron loose. We call this the **band gap energy** of a material. If a photon has more energy than the required amount, then the extra energy is lost (unless a photon has twice the required energy, and can

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

create more than one electron-hole pair, but this effect is not significant). These two effects alone account for the loss of around 70 percent of the radiation energy incident on our cell.

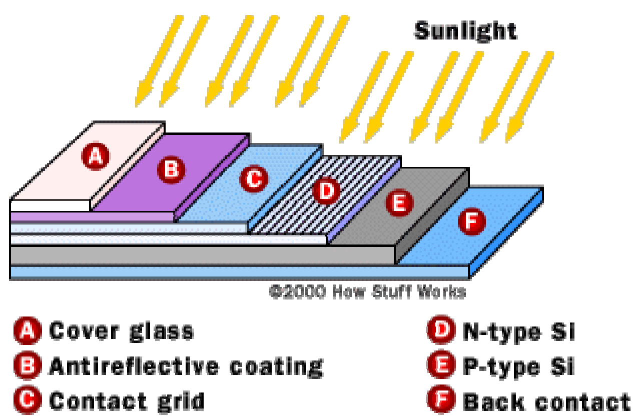
Why can't we choose a material with a really low band gap, so we can use more of the photons? Unfortunately, our band gap also determines the strength (voltage) of our electric field, and if it's too low, then what we make up in extra current (by absorbing more photons), we lose by having a small voltage. Remember that power is voltage times current. The optimal band gap, balancing these two effects, is around **1.4 eV** for a cell made from a single material.

We have other losses as well. Our electrons have to flow from one side of the cell to the other through an external circuit. We can cover the bottom with a metal, allowing for good conduction, but if we completely cover the top, then photons can't get through the opaque conductor and we lose all of our current (in some cells, transparent conductors are used on the top surface, but not in all). If we put our contacts only at the sides of our cell, then the electrons have to travel an extremely long distance (for an electron) to reach the contacts. Remember, silicon is a semiconductor -- it's not nearly as good as a metal for transporting current. Its internal resistance (called **series resistance**) is fairly high, and high resistance means high losses. To minimize these losses, our cell is covered by a metallic contact grid that shortens the distance that electrons have to travel while covering only a small part of the cell surface. Even so, some photons are blocked by the grid, which can't be too small or else its own resistance will be too high.

Finishing the Cell

There are a few more steps left before we can really use our cell. Silicon happens to be a very shiny material, which means that it is very reflective. Photons that are reflected can't be used by the cell. For that reason, an **antireflective coating** is applied to the top of the cell to reduce reflection losses to less than 5 percent.

The final step is the **glass cover plate** that protects the cell from the elements. PV modules are made by connecting several cells (usually 36) in series and parallel to achieve useful levels of voltage and current, and putting them in a sturdy frame complete with a glass cover and positive and negative terminals on the back.



Basic structure of a generic silicon PV cell

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

Single crystal silicon isn't the only material used in PV cells. Polycrystalline silicon is also used in an attempt to cut manufacturing costs, although resulting cells aren't as efficient as single crystal silicon. Amorphous silicon, which has no crystalline structure, is also used, again in an attempt to reduce production costs. Other materials used include gallium arsenide, copper indium diselenide and cadmium telluride. Since different materials have different band gaps, they seem to be "tuned" to different wavelengths, or photons of different energies. One way **efficiency** has been improved is to use two or more layers of different materials with different band gaps. The higher band gap material is on the surface, absorbing high-energy photons while allowing lower-energy photons to be absorbed by the lower band gap material beneath. This technique can result in much higher efficiencies. Such cells, called **multi-junction cells**, can have more than one electric field.

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

Some Areas of Current Materials Science Research[10]

Surface structuring to reduce reflection loss: for example, construction of the cell surface in a pyramid structure, so that incoming light hits the surface several times. New material: for example, gallium arsenide (GaAs), cadmium telluride (GdTe) or copper indium selenide ($CuInSe^2$).

Tandem or stacked cells: in order to be able to use a wide spectrum of radiation, different semiconductor materials, which are suited for different spectral ranges, will be arranged one on top of the other.

Concentrator cells: A higher light intensity will be focused on the solar cells by the use of mirror and lens systems. This system tracks the sun, always using direct radiation.

MIS Inversion Layer cells: the inner electrical field are not produced by a p-n junction, but by the junction of a thin oxide layer to a semiconductor.

Grätzel cells: Electrochemical liquid cells with titanium dioxide as electrolytes and dye to improve light absorption.

Sources
1. http://www.eere.energy.gov/
2. Ibid
3. http://www.enn.com/news/enn-stories/2001/08/08272001/tiles_44756.asp
4. http://www.solarserver.de/wissen/photovoltaik-e.html
5. http://www.eere.energy.gov/
6. http://www.californiasolarcenter.org/history_pv.html
7. Unless otherwise noted, information for this section came from http://science.howstuffworks.com
8. http://www.eere.energy.gov/
9. http://www.solarserver.de/wissen/photovoltaik-e.html
10. Ibid

Other Sources
http://www.solarbotics.net/starting/200202_solar_cells/200202_solar_cell_physics.html
http://www.etmsolar.com/roof.htm
http://www.nyseia.org/
http://www.emagazine.com/view/?851

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

Photovoltaic Cell Lab Name________________________________

The purpose of this lab is to give students experience constructing operating circuits while reviewing the following ideas/concepts:

- Voltage
- Current
- Power
- Energy/work
- Photoelectric effect
- Series/Parallel circuit design
- Efficiency

Students should be given the following materials:

- Multiple solar cells
- Two multimeters*
- A small electric motor with fan blade attached
- A small electric motor and various small masses to lift with it
- A small light bulb
- Connecting wires as necessary
- A knife switch

*The Vernier voltage and current probes can be used as well.

Students should connect their solar cells in series, in parallel, or in a series/parallel combination until they are able to perform the following tasks which are described in more detail below:

1. Make a small electric motor operate with fan blade.
2. Lift various small masses with a small electric motor.
3. Power a small light bulb.

Activity 1: Solar cell(s) and small electric fan

1. Attach a solar cell, or multiple solar cells wired in series or parallel or any combination thereof, to a small electric motor with a fan blade attached. ***Be careful not to injure yourself with the fan blade. High RPMs can be achieved even with these small motors.*** With the fan running and the solar cell(s) oriented perpendicular to the sun's rays, measure and record the voltage and current the solar cell is producing.

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

2. Compare the voltage and current actually being produced by your solar array to the optimal values provided by the manufacturer. Are your values greater or less than those provided by the manufacturer? Why might they be different (even if they are not)?

3. Calculate the power output of your solar array when operating the fan.

4. How much energy in Joules and eV would your solar array produce in an hour?

5. How many e's would pass through your fan in an hour given your measurements?

6. If 12% of the photons actually produce an electron free to move through the circuit you created, how many photons would strike your solar array in 15 minutes?

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

Activity 2: Lifting small masses with an electric motor

1. Create an operating circuit powered by a solar cell, or multiple solar cells wired in series or parallel or any combination thereof, that will allow a small electric motor to lift various small masses while measuring voltage and current. Have someone measure how long it takes to lift the mass once the circuit is completed and the motor has begun to raise the mass.

2. Record the average voltage and current produced when lifting a 10 gram mass 0.5 m and record here. Record the amount of time it took to lift the mass.

3. Calculate the average power produced by your solar array when lifting the mass.

4. Calculate the total energy produced by your solar array when lifting the mass.

5. Calculate the change in potential energy of the mass that was lifted.

6. Use your answers to questions #4 and #5 to determine the efficiency of the motor.

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

7. Repeat steps #1 - #6 two more times using different masses.

8. Use your results from question #6 for all three trials to get an average efficiency rating.

Activity 3: Powering a light bulb

1. Create an operating circuit powered by a solar cell, or multiple solar cells wired in series or parallel or any combination thereof, that will power a small light bulb with varying intensities while measuring voltage and current. By now, you should have some idea as to what voltage, current, and power different combinations of solar cells should produce. If you are not sure what your solar cell array should look like, start small and add a cell at a time or ASK YOUR TEACHER WHAT AN APPROPRIATE ARRAY MIGHT LOOK LIKE SO THAT YOU DO NOT BURN OUT THE BULB.

2. With the light bulb operating, measure the voltage and current produced by your solar cell(s).

3. Calculate the power produced by your solar cell(s). How does this compare to the power rating of the light bulb?

4. Describe the chain of events, starting with fusion in the sun, that results in the production of visible photons by the filament in the light bulb. Use additional paper if necessary.

General Questions

1. If the Sun is approximately 9.3×10^7 miles away, approximately how long (in seconds) did it take for a photon produced by the sun to strike your PV cell?

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

2. Describe the photoelectric effect. Be sure to include the terms “photon”, “threshold frequency”, “Planck’s constant”, and “photoelectron” in your discussion. Describe two ways that you could increase both the number of photoelectrons and their energy. Use drawings/sketches if needed.

Extension/Internet activities:

1. Look up “net metering” and give a brief overview of what it is. Does your state allow it and/or provide incentives for it?

2. Contact two companies that **produce** photovoltaic cells and request product information and specifications including performance parameters and cost. Find out applications they market PV cells for.

3. Investigate and describe two areas of materials science research that is underway
to improve the cost and efficiency of photovoltaic cells.

4. Create a timeline showing developments in PV cell technology.

5. Research a scientist who has been involved in the photoelectric effect or the development of photovoltaic technology and describe the importance of their achievements.

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

New York State Learning Standards met by the lesson, laboratory investigation, and extension activities (actually, many more would be met if one did all of the extension activities):

Mathematics, Science and Technology Standards
Standards 3, 4.3, 4.4, 4.5

New York State Regents Physics Core Curriculum Guide

Key Idea 4.1a
All energy transfers are governed by the law of conservation of energy.

Key Idea 4.1b
Energy may be converted among mechanical, electromagnetic, nuclear, and thermal
Forms.

Key Idea 4.1c
Potential energy is the energy an object possesses by virtue of its position or condition.

Key Idea 4.1 j Skill 4.1i and 4.1vii
Power is the time-rate at which work is done or energy is expended.

Key Idea 4.1j Skill 4.1i
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.

Key Idea 4.1m
All materials display a range of conductivity.

Key Idea 4.1n
A circuit is a closed path in which a current can exist.

Key Idea 4.1p
Electrical power and energy can be determined for electrical circuits.

Key Idea 4.1o
Circuit components may be connected in series or in parallel.

Key Idea 4.3h

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992

When a wave strikes a boundary between two media, reflection, transmission, and absorption occur.

Key Idea 4.3k
All frequencies of electromagnetic radiation travel at the same speed in a vacuum.

Key Idea 5.3a
States of matter and energy are restricted to discrete values (quantized).

Key Idea 5.3c
On the atomic level, energy is emitted or absorbed in discrete packets called photons.

Key Idea 5.3h
Behaviors and characteristics of matter, from the microscopic to the cosmic levels, are manifestations of its atomic structure. The macroscopic characteristics of matter, such as electrical and optical properties, are the result of microscopic interactions.

** Materials science in a nutshell.**

Support for Cornell Center for Materials Research is provided through NSF Grant DMR-0079992