The Photoelectric Effect in Photocells

SPN LESSON #23
TEACHER INFORMATION

LEARNING OUTCOME: After engaging in background reading on electromagnetic energy and exploring the frequencies of various colors of light, students realize that it is useful to think of light waves as streams of particles called quanta, and understand that the energy of each quantum depends on its frequency.

LESSON OVERVIEW: This lesson introduces students to the photoelectric effect (the basic physical phenomenon underlying the operation of photovoltaic cells) and the role of quanta of various frequencies of electromagnetic energy in producing it. The inadequacy of the wave theory of light in explaining photovoltaic effects is explored, as is the ionization energies for elements in the third row of the periodic table.

GRADE-LEVEL APPROPRIATENESS: This Level III Physical Setting lesson is intended for use with students in high school physics or chemistry classes.

MATERIALS: Student handout, roll of masking tape, ball of yarn, scrap paper

SAFETY: There are no safety precautions for this lesson.

TEACHING THE LESSON: Begin by explaining the structure and operation of photovoltaic cells, covering the information in the student handout and drawing from the background information below. Stake off an area of the classroom in which about two-thirds of your students can stand—it could, for example, be bounded by tape on the floor. This area is to represent a photovoltaic cell. Have half of your students form a line dividing the area in half—they represent the electrons lined up on the *p*-side of the *p-n* junction. Stretch yarn from the *n*-type semiconductor to one student chosen to represent a light bulb and from that student to the *p*-type semiconductor. The remaining half of the students represent photons. They should each hold a wad of scrap paper, which represents energy. When they are given the signal, the “photon” students are to give their wad of paper (representing energy) to an “electron” lined up on the *p*-side of the *p-n* junction. This energizes the electron on the *p*-side of the *p-n* junction to cross the junction into the *n*-type semiconductor, and it sets it into flight through the circuit. The “electron” student then is to trace the path of the yarn, giving the wad of paper to the “light bulb” student (representing the lighting of the bulb) en route before returning to the *p*-type conductor side of the photovoltaic cell. The “light bulb” student throws the wad of paper into a receptacle (to represent that the light bulb needs to be furnished energy on a continuous basis in order to stay lit). After they return to the photovoltaic cell (via the *p*-type semiconductor side), “electron” students are to line up on the *p*-side of the *p-n* junction until they receive another wad of paper (representing energy) from a “photon” student, and “photon” students are to go back for more wads of paper to represent additional energy given to the electrons the second time around.

ACCEPTABLE RESPONSES FOR DEVELOP YOUR UNDERSTANDING SECTION: Analyze your students’ essays on the basis of presence of the main points covered by the simulation.

ADDITIONAL SUPPORT FOR TEACHERS

SOURCE FOR THIS ADAPTED ACTIVITY: Chris Mason, Education Director, Northeast Sustainable Energy Association (private communication)

BACKGROUND INFORMATION: Atoms of the light elements in group 14 (carbon, silicon, and germanium) have four outermost or valence electrons. When these atoms form a solid lattice, they bond to each other covalently to form four covalent bonds of electron pairs, one from each of the two bonding atoms.

The electron energy levels in a lattice of bonded atoms are described not in terms of single energy levels but rather in terms of continuous bands, which can be considered to be equivalent to the energy levels associated with each single atom grouped together to form a continuum. There are two bands of energies that are of interest in describing the electrical properties of the lattice of bonded atoms: the *valence band*, at a lower energy, and the *conduction band*, at a higher energy. Between the two bands is a gap. Most of the electrons in a lattice of bonded atoms from group 14 are in the valence band—only a few are likely to be in the conduction band, where they are free to move and conduct an electric current when a voltage is applied. For this reason, lattices of bonded atoms in group 14 are *semiconductors* of electricity.

By themselves, lattices of bonded carbon, silicon, or germanium atoms don’t conduct much electric current or enable any of the miracles of solid-state electronics, which include photovoltaic electricity. Making a photovoltaic cell requires “doping” lattices of group 14 atoms (usually silicon, though germanium, which is more expensive, can be used)—by inserting atoms from groups 13 and 15 into them.

Atoms of group 15 have *five* outermost or valence electrons. If they are inserted to take the place of a group 14 atom, there will be one additional valence electron. Since the valence band of electron energies is already filled in a bonded lattice of group 14 atoms, this additional valence electron has no other energy level to fill except one in the conduction band. Because this added electron adds *negative* charge to what had previously occupied the conduction band, a bonded lattice of group 14 atoms “doped” with atoms of a group 15 element is called an *n*-type semiconductor (see figure 1 below).

Likewise, atoms of group 13 have only *three* outermost or valence electrons. Doping a lattice of bonded group 14 atoms with them will reduce the number of electrons in the lattice. This results in “holes” in the valence band, which can have the same ability to conduct electricity as electrons in the conduction band. Because these holes add *positive* charge to what had previously occupied the valence band, a bonded lattice of group 14 atoms doped with atoms of a group 13 element is called a *p*-type semiconductor (see figure 1).

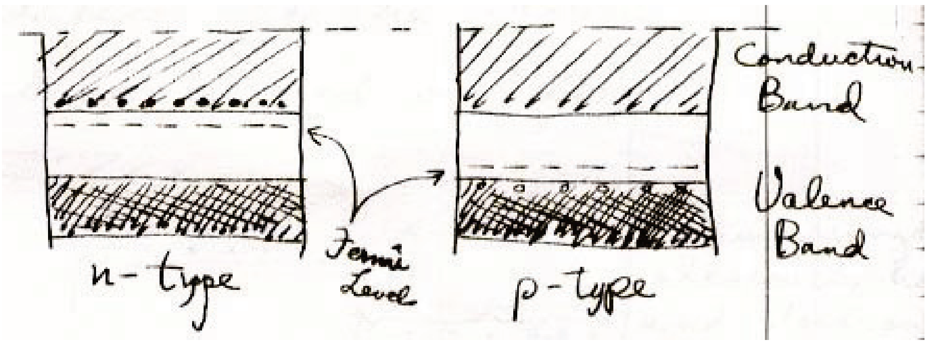

Figure 1

A photocell is formed by doping a bonded lattice of group 14 atoms so that one end is an *n*-type semiconductor and the other end is a piece of *p*-type semiconductor. Initially, the electron energy level that is 50% occupied (with higher percentage occupation below and lower percentage occupation above) is higher in the *n*-type semiconductor end than in the *p*-type semiconductor end. (This symbolic energy level, called the *Fermi level*, is named after Enrico Fermi, whose name is connected with the statistics associated with electron spin.)

However, transient flow of conduction electrons in the *n*-type end and holes in the *p*-type end "equalize" the Fermi level at both ends. This flow of electrons and holes into the "opposite" region of the bonded lattice of group 14 atoms also sets up an electric field to oppose further flow of electrons and holes. Associated with this field is a "barrier" electric potential, which causes the energy levels of the conduction and valence bands to shift in one region relative to the other (see figure 2).

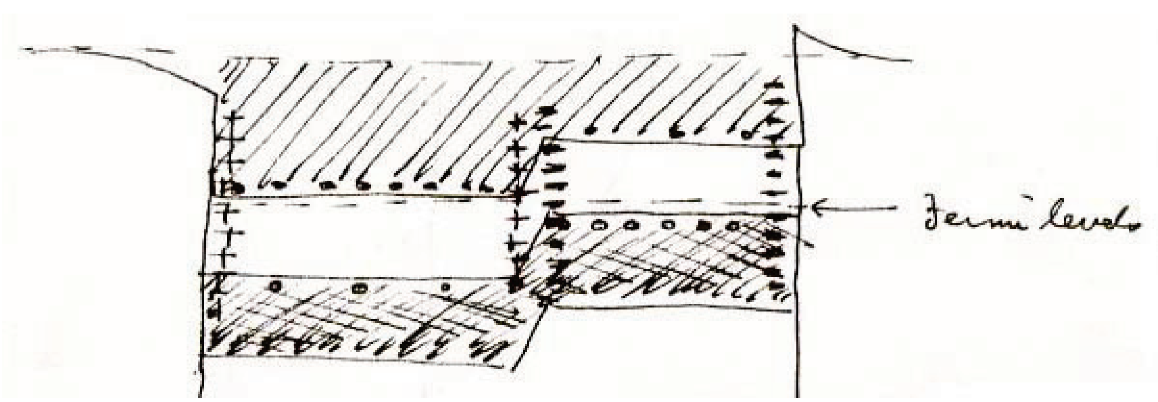

Figure 2

The incidence of light onto the material reduces this barrier potential, causing the Fermi level in the *n*-type end to rise above that in the *p*-type end. But the conduction band in the *n*-type end is still lower than in the *p*-type end. Because of the remaining barrier potential, conduction electrons in the *n*-type end cannot flow into the *p*-type end, but they can flow through a circuit and meet up with holes in the *p*-type end on the other side. In the process of doing this, they lose energy equal to the difference of the Fermi levels in the two ends of the photocell, just as they would lose energy received from a battery. Thus, light on the photocell is equivalent to a battery whose voltage equals the difference in Fermi levels at the two ends of the photocell (see figure 3).

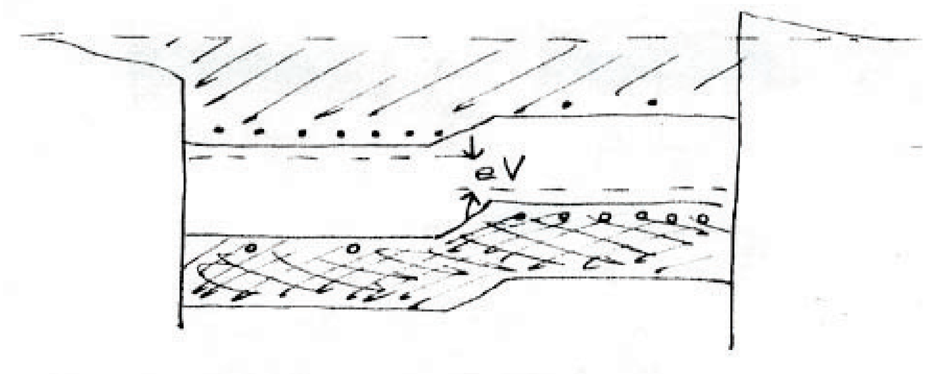

Figure 3

REFERENCES FOR BACKGROUND INFORMATION:

Curtis L. Hemenway, Richard W. Henry, and Martin Coulton, *Physical Electronics.* Wiley, New York, 1960.

John C. C. Fan, "Solar Cells: Plugging into the Sun," *Tech. Rev.*, 80(7), 14 (Aug/Sep 1978).

Energy: How Does It Impact Our Lives? New York Science, Technology, and Society Education Project, Albany, NY, 1994.

Produced by the Research Foundation of the State University of New York with funding from the New York State Energy Research and Development Authority (NYSERDA)
www.nyserda.ny.gov

(STUDENT HANDOUT SECTION FOLLOWS)

Name_____________________________________

Date _____________________________________

The Photoelectric Effect in Photocells

Photovoltaic cells are named for what they do: convert light (“photo”) to electricity (“voltaic”). They are made from the same materials as the well-known transistors of solid-state electronics—the class of substances called *semiconductors*. A semiconductor is so named because it conducts an electric current slightly when connected to a battery, but not nearly as well as a metal. A metal is a good conductor of electricity because a few electrons in its atoms are free to move and produce an electric current when a battery is connected. The corresponding electrons in the atoms of a semiconductor are not free to move unless they first acquire a certain amount of energy. For instance, they acquire this energy from light shining on the semiconductor in a photocell.

The semiconductors in a photocell are “doped” by replacing some of the atoms with others having a different number of electrons. If these substituted atoms have *more* electrons, the extra electrons increase the negative charge among the electrons, and the result is called an *n*-type semiconductor. If the substituted atoms have *fewer* electrons, there is a decrease in the negative electron charge (equivalent to an increase in positive charge), and the result is called a *p*-type semiconductor. The “deficiency” of electrons in a *p*-type semiconductor is described in terms of electron “holes.”

Photovoltaic cells are made from a piece of *n*-type semiconductor joined to a piece of *p*-type semiconductor. The region where the two types of semiconductors are joined is called a *p-n junction*. Some of the surplus electrons in the *n*-type semiconductor naturally migrate to the *p*-type semiconductor, cross into it, and line up along the junction. This migration also keeps further electrons from the *n*-type semiconductor from moving into the *p*-type semiconductor. In a similar way, “holes” from the *p*-type semiconductor migrate into the *n*-type semiconductor and line up along the junction to keep additional holes from doing the same thing (see figure 1).

p-type -
____
n-type +

Figure 1

Now let the Sun shine on the photovoltaic cell. In reacting with the photocell, the sunlight behaves as if it were made of bundles of energy called *photons,* such that the greater the frequency of the light, the greater the energy of its photons. If the photon energy is great enough to enable electrons on the *p*-side of the *p-n* junction to cross the junction into the *n*-type semiconductor, they become free to move and produce an electric current. The electrons will flow from the *n*-type semiconductor through a circuit to the *p*-type semiconductor of the photocell, just as they would in flowing from the negative terminal of a battery to the positive terminal. And the energy they have gained from the sunlight is just like the energy that electrons get from a battery (see figure 2).

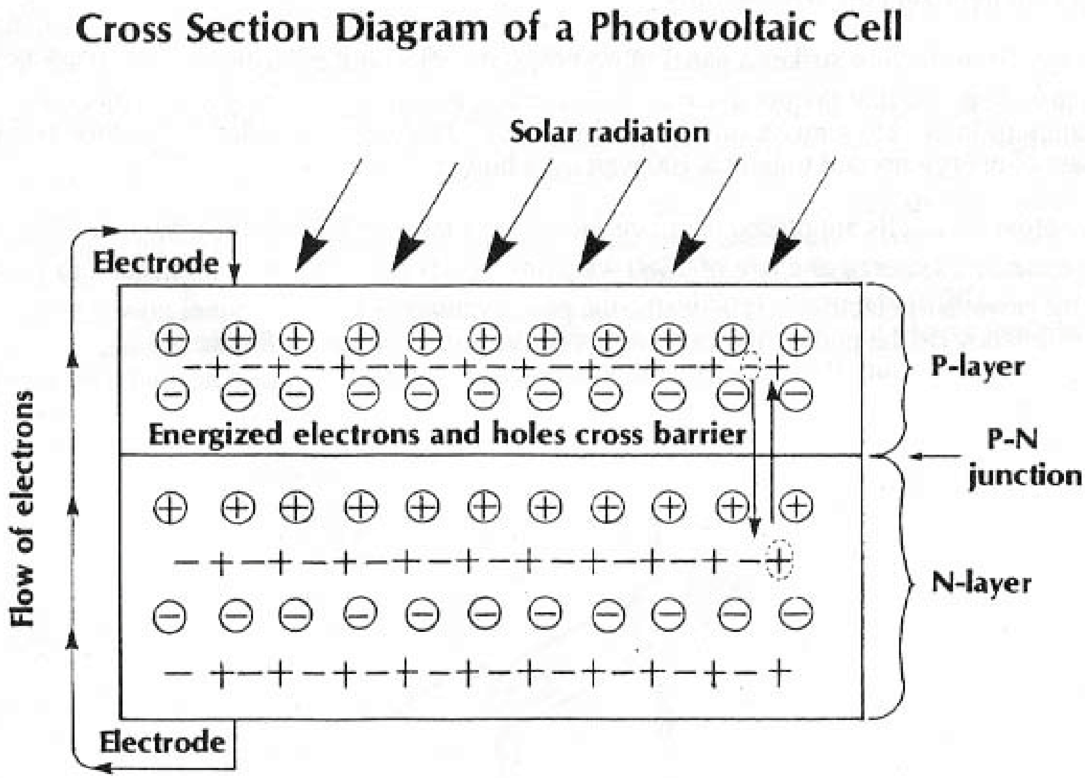

Figure 2

DEVELOP YOUR UNDERSTANDING: The following simulation is designed to enable you to experience the roles of components of a photovoltaic cell and the way it operates.

1. Your teacher will stake off an area of the classroom in which about half the students can stand—it could, for example, be bounded by tape on the floor. This area is to represent a photovoltaic cell.

2. These students form a line dividing the area in half—they represent the electrons lined up on the positive side of the *p-n* junction.

3. Yarn is to be stretched from the *n*-type semiconductor to one student chosen to represent a light bulb and from that student to the *p*-type semiconductor.

4. The remaining half of the students represent photons. They should each hold a wad of scrap paper, which represents energy. When they are given the signal, the "photon" students are to give their wad of paper (representing energy) to an "electron" student lined up on the *p*-side of the *p-n* junction. This energizes the electron on the *p*-side of the *p-n* junction to cross the junction into the *n*-type semiconductor, and it sets it into flight through the circuit. The "electron" student then is to trace the path of the yarn, giving the wad of paper to the "light

bulb" student (representing the lighting of the bulb) en route before returning to the *p*-type conductor side of the photovoltaic cell. The "light bulb" student throws the wad of paper into a receptacle (to represent that the light bulb needs to be furnished energy on a continuous basis in order to stay lit).

5. After they return to the photovoltaic cell (via the *p*-type semiconductor side), "electron" students are to line up on the *p*-side of the *p-n* junction until they receive another wad of paper (representing energy) from a "photon" student, and "photon" students are to go back for more wads of paper to represent additional energy given to the electrons the second time around.

6. On the basis of the simulation experience, compose an essay that relates the principles of atomic structure to the operation of a photovoltaic cell.