Environmental Science Institute
UNIVERSITY OF TEXAS AT AUSTIN

LESSON PLAN - How Do Solar Cells Work?[1]

Title of Lesson: How Do Solar Cells Work?
Description of class: Middle School science or High School physics, chemistry or electronics classes
Length of Lesson: 90 minutes
Purpose: In this lesson, students are introduced to the basic physics and chemistry behind the operation of a solar cell. They will learn how a single crystal silicon cell accepts energy from light and turns it into electricity.

Objectives: Students will be able to:
- **(a)** Explain the atomic properties of Silicon, Boron and Phosphorus that make them suitable for use in Photovoltaic Solar cells
- **(b)** Explain what electricity is and describe the movement of electrons in a solar cell
- **(c)** Analyze data in graphs and draw conclusions

Student background: Students should be familiar with the electron-proton-neutron model of the atom and with the basic ideas of bond formation involving shared pairs of electrons. It is also assumed that they know about the idea of valence electrons. The notion that like charges repel and opposites attract is also assumed.

TEKS addressed
§112.33. Astronomy, Beginning with School Year 2010-2011
(c) (8) (C) recognize that the angle of incidence of sunlight determines the concentration of solar energy received on the Earth at a particular location
§112.35. Chemistry, Beginning with School Year 2010-2011
(b) (1) Chemistry
(c) (5) (C) use of periodic table; 6) E) express the arrangement of electrons
§112.37. Environmental Systems, Beginning with School Year 2010-2011
(c) (6) (B) describe and compare renewable and non-renewable energy derived form natural and alternative sources
§112.38. Integrated Physics and Chemistry, Beginning with School Year 2010-2011
(c) (5) (A) recognizes that substances in motion have kinetic energy
§112.39. Physics, Beginning with School Year 2010-2011
(c) (8) simple examples of atomic phenomena

Equipment and Supplies: Solar Racers (possible brand: Solar Racers™ Sun Powered Micro Vehicles Outdoor Racing Set, price: $19.99 a pair) or a small solar panel (Wal-Mart carries camping solar panels in the range of $20 to $80 for a single panel), A mulitmeter, similar to the Extech MN36, which can be purchased for about $40, Periodic Table, and a computer with

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[1] Originally prepared for the Oregon Million Solar Roofs Coalition, November, 2000, by Frank Vignola, University of Oregon Solar Radiation Monitoring Lab; John Hocken, South Eugene High School; and Gary Grace, South Eugene High School. Modified November 2009, by Eric W. James, University of Texas at Austin Environmental Science Institute with support from the Texas State Energy Conservation Office.

internet access. **These are suggestions for activity supplies and do not serve as an endorsement of any particular brand by ESI, SECO, or UT Austin.

Methodology:
If possible, take the students outside (or set up one or two clamped, incandescent lamps in two areas of the room). Assign groups of students to stations where they get to play with solar toys and measure the voltage output of the solar panels. For example, each station could have a solar car toy or a solar panel plugged into a digital multi-meter to read the voltage on a solar panel. Students might be tasked with figuring out how to optimize the performance of the toys. The question we what to come to mind is, "How do these devices make electricity?"

Review the Periodic Table and the concept of valence electrons using the Socratic method. Explain the figures in the student handout and check for understanding of valence electrons with questions about the periodic table and figures in the handout.

Divide the class into groups of 3-5 students. Distribute the student worksheets to the groups and assign each group of students one question (in 1-6) to answer and present back to the class. Provide time for the groups to read and assist each with discovering the solution and framing their explanation.

Have each group present the answer to their question and discuss among the students. Introduce the class to the Soltrex website and data: www.soltrex.com and lead a class discussion based on question 7 in the handout.

--STUDENT WORKSHEET--

How Solar Cells Turn Sunlight into Electricity

Solar cells are materials that turn sunlight into electricity. This effect was first recorded by E. Becquerel, in 1839. The first solid state device was recorded to show such an effect in 1877. However, it was in 1954 at Bell Labs when the solar electric effect was demonstrated in silicon (Si) that the idea of producing useable amounts of electricity from solar cells began.

The question is, how do solar cells produce electricity?

Two facts are important to the understanding of how solar cells work.

- First, sunlight is composed of photons of various energies.
- Second, photons can interact with atoms, and if a photon has sufficient energy, it can break the bond between an electron and the atom (Figure 1).

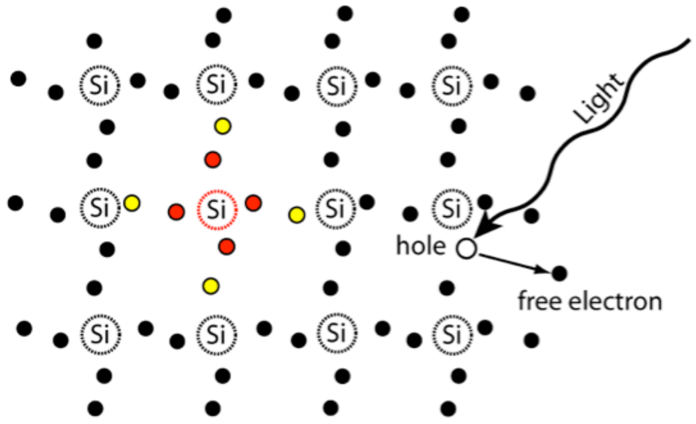

Figure 1. A diagrammatic representation of atoms in a Si crystal. The electrons in red represent the four valence electrons of the Si atom shown in red. The yellow electrons are covalently shared with the adjacent Si atoms.
Light of sufficient energy can dislodge an electron from its bond in the crystal, creating a positive hole (a bond missing an electron) and a free electron. Without an electrical field to make them move apart the hole and electron will recombine quickly.

The trick to making solar cells produce electricity is the ability to "collect" the electron once it has been separated from the atom. The resulting flow of electrons is called the photocurrent.

The example of solar cells made from single crystal silicon (like Figure 1) will be used to illustrate the general principles.

Silicon is an atom with four valence electrons. In a silicon crystal, each of the valence electrons forms a bond with a valence electron of a neighboring silicon atom. This electron-to-electron bond is very strong and in a perfect crystal there are no free valence electrons waiting to bond with another electron. Electrons bond in pairs when possible (it's lower energy state).

Pure single crystal silicon is a very poor conductor because all the valence electrons are bonded with their neighbors.

To collect the photocurrent, solar cells are constructed like a battery. This is done by taking two semiconductors of opposite charge and putting them together (Figure 2).

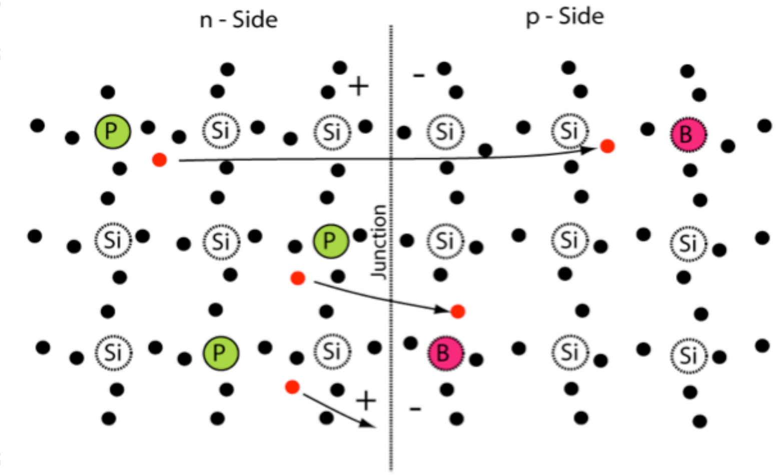

Figure 2. A diagrammatic representation of a simple solar cell. When n- (doped with P) and p-type (doped with B) silicon come into contact, electrons move from the n-side to the p-side. This causes a positive charge to build on the n-side of the interface (or p-n junction) and a negative charge to form on the p-side.

from silicon approximately $2x10^{16}/cm^3$ acceptor atoms (atoms with three valence electrons such as boron, B) or approximately $10^{19}/cm^3$ donor atoms (atoms with five valence electrons such as phosphorous, P) are substituted for the silicon atoms with four valence electrons.

When phosphorous is substituted for a silicon atom, four of the five valence electrons form strong bonds with the nearest silicon electrons and the remaining electron is very loosely bound by the slightly more positive charge of the nucleus of the phosphorous atom. However, this electron travels easily around the crystal lattice in the area of the phosphorous atom. Silicon that contains atoms with an extra valence electron is called n-type silicon (n is for negative). The process of substituting boron or phosphorous atoms for silicon atoms is called **doping**. This is often done by thermal diffusion.

If a boron atom is substituted for a silicon atom, the three valence electrons form strong bonds with the nearest silicon electrons, but there is one silicon electron that is left looking for a partner to bond with. This missing electron that is being sought for bonding, is called **a hole**. Because the hole is a missing electron, it can be treated mathematically like the free electron when phosphorous is substituted, but it effectively has a positive charge (the absence of an negative electron). Silicon that contains atoms with one less valence electron is called p-type silicon (p is for positive).

A solar battery is created when n and p type silicon are placed next to each other. The extra electrons from the phosphorous are attracted to the holes created by the doping of the silicon with boron (Figure3). This occurs because binding of the electron pairs is much stronger than the electromagnetic attraction between the outer electrons and the nucleus of the atoms that is masked by the electrons that are surrounding each atom in the crystal structure.

Near the junction of the n and p type material, holes on the p-side are filled with the free electrons from the n-side forming strong, stable electron pair bonds (Figure 3). This results in a shift in charge that creates an electric field in the material. When the free valence electron from the n-side combines with the single bound valence electron on the p-side, the phosphorus atom is surrounded by one less electron than there are positive protons in the phosphorus nucleus. Similarly, the boron atom is surrounded by one more electron than there are positive protons in the boron nucleus. While this n-p '**junction**' is only a few atoms thick, the resulting electric field creates a barrier that prevents additional crossover of holes from the p-side and electrons from the n-side. This electric field (resulting in an electromotive force, EMF, of approximately 0.5 volts) makes it possible to create the photocurrent when light breaks the electron-electron pair bond. All that is need now is light energy to make electricity.

This lesson plan created by the Environmental Science Institute with funding from the State Energy Conservation Office (SECO)

SECO
State Energy Conservation Office

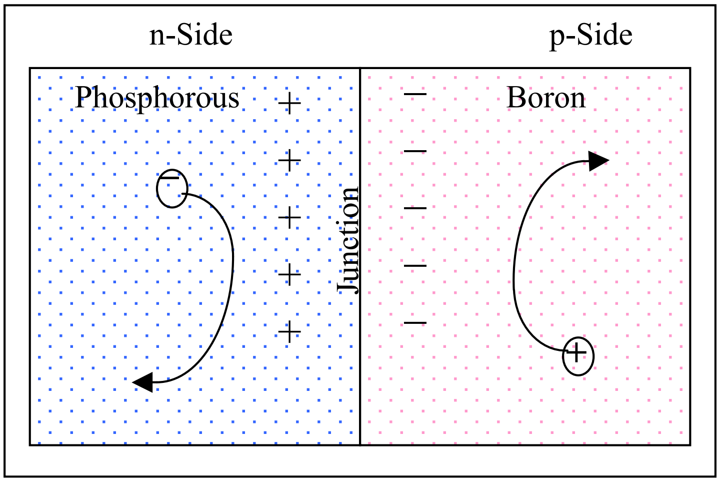

Figure 3. The buildup of excess positive and negative charges on either side of the junction creates an electric field across the interface; the strength of this field depends on the amount of dopant in the silicon. At equilibrium, the electric field repels any additional crossover of holes from the p-side or electrons from the n-side.

Now, when the photon enters the material and breaks apart an electron pair (Figure 4), a negative electron and a positive hole are created. If it weren't for the electric field, the electron and the hole would attract and recombine. With the electric field, the negative electron goes one direction and the positive hole goes the other direction. The electric field acts as a diode, allowing electrons to flow only from the p side to the n side, but not the other way. This is the source of the electricity of a solar cell. The movement of electrons in one direction (and positive holes in the other) is the definition of electrical current. Solar cells have grids of conductive wire near the surface (not shown in the diagrams) to lead this current to the electrical system to be powered or to charge batteries.

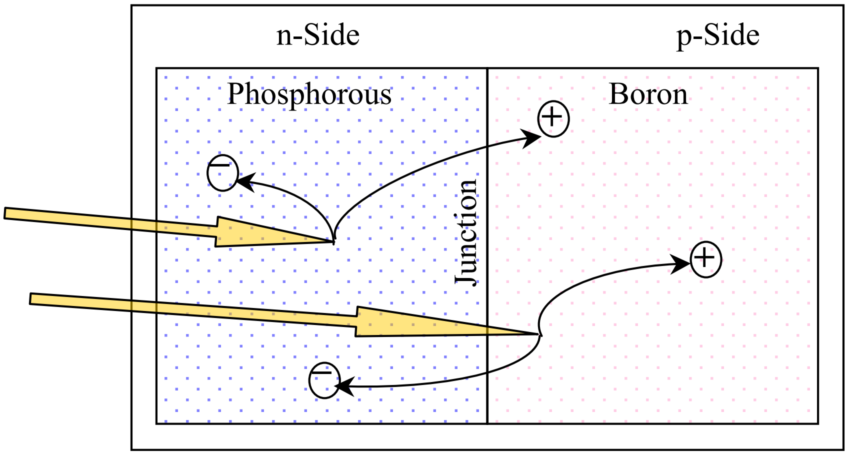

Figure 4. When sunlight striking a cell creates charge carriers (electrons and holes), the electric field pushes new electrons to one side of the junction and new holes to the other. This sorting-out process is what drives the charge carriers in an electric circuit.

The minimum energy that it takes to break up the electron-electron bond is called the **band gap**. Photons with energy less than the band gap won't separate the electron pairs. Photons with more energy than necessary to separate the electron pairs result in electrons and holes with more kinetic energy. The term band gap refers to the energy necessary to separate the electron pair. It can also be thought of as the energy necessary to make an electron in the valence band jump into the conduction band. The valence band is where the electrons are bonded and the conduction band is where the electrons are free to flow as a current. When the electron pairs are separated by a photon, any energy of the photon above the band gap energy goes into the kinetic energy of the electron.

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When solar cells get hot, the electrons and atoms are vibrating faster and the effectiveness of the electric field to separate the electrons and holes is diminished. The randomly directed kinetic energy becomes the dominant factor governing the motion of the electrons and holes. Typical loss in efficiency is about 0.1%/degree C measured solar cell temperature. (A solar cell that is 16% efficient at 25º C will be 9% efficient at 100º C)

[*Figures based on slides from the National Renewable Energy Laboratory*]

Questions for group or individual consideration:

1) What atomic property makes Si a useful material for making solar cells? Is there another element that might be used for the same reasons?
2) Similarly, what atomic properties of B and P are exploited when they are added in small amounts to Si photovoltaic cell materials?
3) What is p-type Si ? n-type? What do the p and n stand for?
4) What is a "hole" in a Si crystal?
5) Describe the movement of electrons and holes when p-type and n-type Si are joined together. Do all the electrons and holes travel across the p-n junction to balance charges? Why or why not?
6) What happens when energetic light photons interact with the Si in a p and n type solar cell? What "sorts out" or drives the electrons away from the holes so they don't re-combine?
7) Let's consider some real-world data. Go to the website http://www.soltrex.com/index.cfm. Get you teacher's permission first (she may have already registered) then register to use the system (bottom of the orange box on the right). When you have logged in, click on EXPLORE SYSTEMS on the upper black banner. Type in Bryker to get to the solar data being collected by Bryker Woods Elementary School's solar power system. On the page that comes up click on the blue Bryker Woods link. A graph of power output will be displayed for the PV system. You can roll over the other types of graphs to get an idea of what current conditions are like. Next, click on the "Custom" button to the right of the graph. In the Graph Controls orange box on the right enter the date range 01/01/2008 to 12/31/2008 (or any year period you like), set the Interval to "Day" and the Data Set to "Energy Production (kWh)".
    a. What times of the year have the highest <u>daily</u> energy outputs?
    b. What times of the year have the most day-to-day-variability? Why?
    c. It was noted above that solar cells become less efficient as temperature rises. Is the summer to winter temperature difference (approximately 30°C) enough to account for the monthly difference in energy production?
    d. Consider where the sun is in the sky in summer versus winter. How would you align and tilt a solar panel to get the most power over the whole year? This is not a simple question! Change the Interval on the graph to month or quarter and you'll see that this solar power system has been set up to even out much of the variation in power production over a year, but to get a little more in the summer. When in the year do you think energy demand is highest in Austin Texas?

Further resources and follow up: There are numerous websites with information on this topic. The University of Oregon's Solar Radiation Monitoring Lab maintains a site at http://solardat.uoregon.edu/ that has solar data, information about solar monitoring, and lists and links to many other sites. A nice supplement to the teaching

Useful Web Sites:

http://science.howstuffworks.com/solar-cell.htm

http://www.soltrex.com/index.cfm.

http://www.nrel.gov/ncpv/

http://www.ascensiontech.com/RTD/ashlandrtd.html

http://www.ascensiontech.com/RTD/pge.html

http://www.ases.org/

http://www.seia.org/main.htm

http://www.pvwatts.org/

For further reading:

The Solar Electric House by Steven J. Strong with William G. Scheller, Sustainability Press, Still River, Massachusetts 01467-0143, 1987.

From Space to Earth – The Story of Solar Electricity, John Perlin, aatec publications, Ann Arbor, MI 48107, 1999.

T*he Solar Electricity Handbook 2009: A Simple, Practical Guide to Using Electric Solar Panels and Designing and Installing Photovoltaic Solar PV Systems* by Michael Boxwell: CodeGreen Publishing, Ryton on Dunsmore, UK,.

Sample Answers

1) What atomic property makes Si a useful material for making solar cells? Only 4 electrons in the outer shell Is there another element that might be used for the same reasons? Ge has the same outer shell structure.
2) Similarly, what atomic properties of B and P are exploited when they are added in small amounts to Si photovoltaic cell materials? P has 5 valence electrons (making it a donor) B has 3 (making it an acceptor)
3) What is p-type Si ? n-type? P-type Si is doped with (has trace amounts of) boron, B and s-type is doped with phosphorus, P. What do the p and n stand for? Positive and negative
4) What is a "hole" in a Si crystal? The site where a valence electron has been removed, a "missing" electron.
5) Describe the movement of electrons and holes when p-type and n-type Si are joined together. Electrons move from the n-side to the p-side, holes move the opposite way Do all the electrons and holes travel across the p-n junction to balance charges? No Why or why not? Local equilibrium is established at the junction forms an electric field.

6) What happens when energetic light photons interact with the Si in a p and n type solar cell? Knocks an electron loose and forms a hole. What “sorts out” or drives the electrons away from the holes so they don’t re-combine? The electric field established across the p-n junction, see 5.
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    a. What times of the year have the highest daily energy outputs? Feb. through Mar and Sept through Oct.
    b. What times of the year have the most day-to-day-variability? Roughly, winter into spring Why? Most variability in cloud cover.
    c. It was noted above that solar cells become less efficient as temperature rises. Is the summer to winter temperature difference (approximately 30°C) enough to account for the seasonal difference in energy production, ignoring cloudy days? No, it would only make about a 3% difference
    d. Consider where the sun is in the sky in summer versus winter. How would you align (to the S) and tilt a solar panel (the optimum angle changes by month, http://www.solarpaneloptimizer.com/html/about.html) to get the most power over the whole year? This is not a simple question! Change the Interval on the graph to month or quarter and you’ll see that this solar power system has been set up to even out much of the variation in power production over a year, but to get a little more in the summer. When in the year do you think energy demand is highest in Austin Texas? During the long, hot summers.

WORKSHEET – How PV Solar Works

How Solar Cells Turn Sunlight into Electricity

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The question is, how do solar cells produce electricity?

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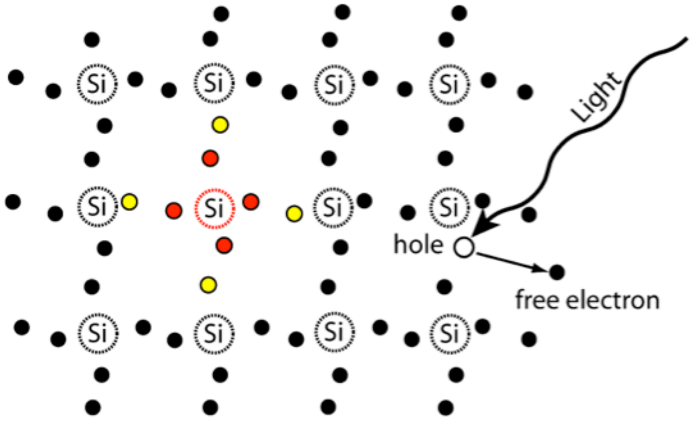

Figure 1. A diagrammatic representation of atoms in a Si crystal. The electrons in red represent the four valence electrons of the Si atom shown in red. The yellow electrons are covalently shared with the adjacent Si atoms.
Light of sufficient energy can dislodge an electron from its bond in the crystal, creating a positive hole (a bond missing an electron) and a free electron. Without an electrical field to make them move apart the hole and electron will recombine quickly.

The trick to making solar cells produce electricity is the ability to "collect" the electron once it has been separated from the atom. The resulting flow of electrons is called the photocurrent.

The example of solar cells made from single crystal silicon (like Figure 1) will be used to illustrate the general principles.

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Pure single crystal silicon is a very poor conductor because all the valence electrons are bonded with their neighbors.

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To collect the photocurrent, solar cells are constructed like a battery. This is done by taking two semiconductors of opposite charge and putting them together (Figure 2).

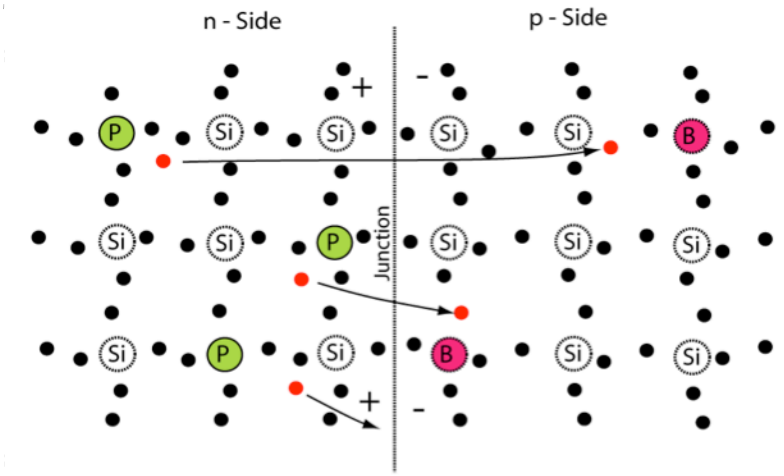

Figure 2. A diagrammatic representation of a simple solar cell. When n- (doped with P) and p-type (doped with B) silicon come into contact, electrons move from the n-side to the p-side. This causes a positive charge to build on the n-side of the interface (or p-n junction) and a negative charge to form on the p-side.

from silicon approximately $2x10^{16}/cm^3$ acceptor atoms (atoms with three valence electrons such as boron, B) or approximately $10^{19}/cm^3$ donor atoms (atoms with five valence electrons such as phosphorous, P) are substituted for the silicon atoms with four valence electrons.

When phosphorous is substituted for a silicon atom, four of the five valence electrons form strong bonds with the nearest silicon electrons and the remaining electron is very loosely bound by the slightly more positive charge of the nucleus of the phosphorous atom. However, this electron travels easily around the crystal lattice in the area of the phosphorous atom. Silicon that contains atoms with an extra valence electron is called n-type silicon (n is for negative). The process of substituting boron or phosphorous atoms for silicon atoms is called **doping**. This is often done by thermal diffusion.

If a boron atom is substituted for a silicon atom, the three valence electrons form strong bonds with the nearest silicon electrons, but there is one silicon electron that is left looking for a partner to bond with. This missing electron that is being sought for bonding, is called **a hole**. Because the hole is a missing electron, it can be treated mathematically like the free electron when phosphorous is substituted, but it effectively has a positive charge (the absence of an negative electron). Silicon that contains atoms with one less valence electron is called p-type silicon (p is for positive).

A solar battery is created when n and p type silicon are placed next to each other. The extra electrons from the phosphorous are attracted to the holes created by the doping of the silicon with boron (Figure3). This occurs because binding of the electron pairs is much stronger than the electromagnetic attraction between the outer electrons and the nucleus of the atoms that is masked by the electrons that are surrounding each atom in the crystal structure.

Near the junction of the n and p type material, holes on the p-side are filled with the free electrons from the n-side forming strong, stable electron pair bonds (Figure 3). This results in a shift in charge that creates an electric field in the material. When the free valence electron from the n-side combines with the single bound valence electron on the p-side, the phosphorus atom is surrounded by one less electron than there are positive protons in the phosphorus nucleus. Similarly, the boron atom is surrounded by one more electron than there are positive protons in the boron nucleus. While this n-p ‘**junction**’ is only a few atoms thick, the resulting electric field creates a barrier that prevents additional crossover of holes from the p-side and electrons from the n-side. This electric field (resulting in an electromotive force, EMF, of approximately 0.5 volts) makes it possible to create the photocurrent when light breaks the electron-electron pair bond. All that is need now is light energy to make electricity.

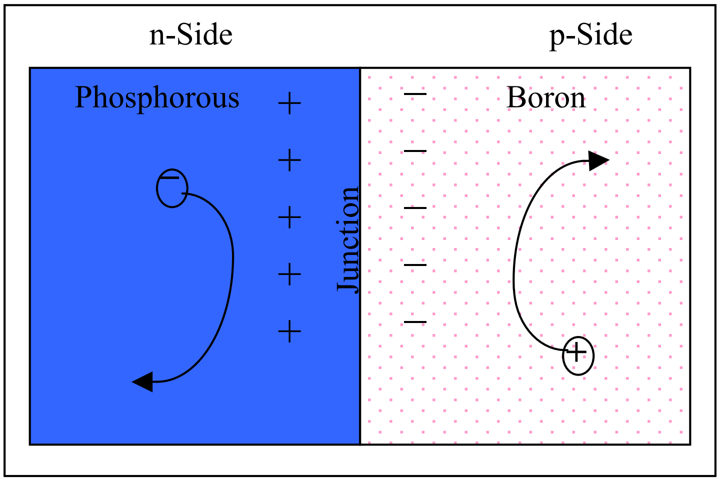

Figure 3. The buildup of excess positive and negative charges on either side of the junction creates an electric field across the interface; the strength of this field depends on the amount of dopant in the silicon. At equilibrium, the electric field repels any additional crossover of holes from the p-side or electrons from the n-side.

Now, when the photon enters the material and breaks apart an electron pair (Figure 4), a negative electron and a positive hole are created. If it weren’t for the electric field, the electron and the hole would attract and recombine. With the electric field, the negative electron goes one direction and the positive hole goes the other direction. The electric field acts as a diode, allowing electrons to flow only from the p side to the n side, but not the other way. This is the source of the electricity of a solar cell. The movement of electrons in one direction (and positive holes in the other) is the definition of electrical current. Solar cells have grids of conductive wire near the surface (not shown in the diagrams) to lead this current to the electrical system to be powered or to charge batteries.

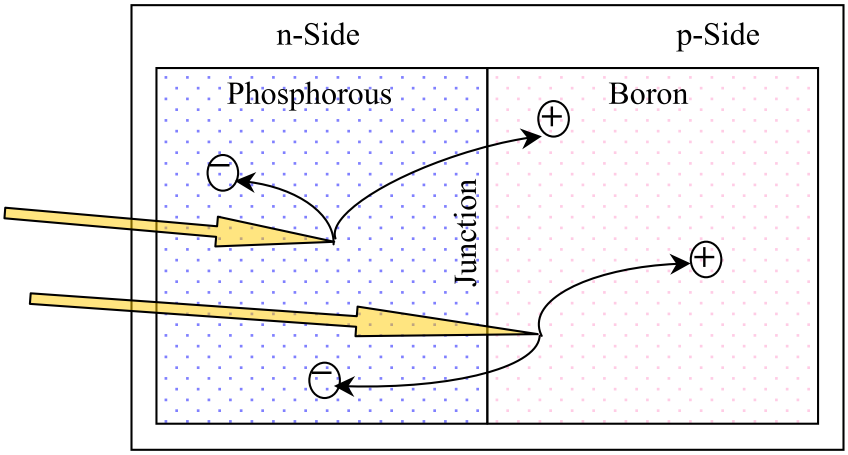

Figure 4. When sunlight striking a cell creates charge carriers (electrons and holes), the electric field pushes new electrons to one side of the junction and new holes to the other. This sorting-out process is what drives the charge carriers in an electric circuit.

The minimum energy that it takes to break up the electron-electron bond is called the **band gap**. Photons with energy less than the band gap won't separate the electron pairs. Photons with more energy than necessary to separate the electron pairs result in electrons and holes with more kinetic energy. The term band gap refers to the energy necessary to separate the electron pair. It can also be thought of as the energy necessary to make an electron in the valence band jump into the conduction band. The valence band is where the electrons are bonded and the conduction band is where the electrons are free to flow as a current. When the electron pairs are separated by a photon, any energy of the photon above the band gap energy goes into the kinetic energy of the electron.

When solar cells get hot, the electrons and atoms are vibrating faster and the effectiveness of the electric field to separate the electrons and holes is diminished. The randomly directed kinetic energy becomes the dominant factor governing the motion of the electrons and holes. Typical loss in efficiency is about 0.1%/degree C measured solar cell temperature. (A solar cell that is 16% efficient at 25º C will be 9% efficient at 100º C)
[*Figures based on slides from the National Renewable Energy Laboratory*]

Questions for group or individual consideration:

1) What atomic property makes Si a useful material for making solar cells? Is there another element that might be used for the same reasons?
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4) What is a "hole" in a Si crystal?
5) Describe the movement of electrons and holes when p-type and n-type Si are joined together. Do all the electrons and holes travel across the p-n junction to balance charges? Why or why not?
6) What happens when energetic light photons interact with the Si in a p and n type solar cell? What "sorts out" or drives the electrons away from the holes so they don't re-combine?
7) Is the current from a solar cell AC or DC?
8) Let's consider some real-world data. Go to the website http://www.soltrex.com/index.cfm. Get you teacher's permission first (she may have already registered) then register to use the system (bottom of the orange box on the right). When you have logged in, click on EXPLORE SYSTEMS on the upper black banner. Type in Bryker to get to the solar data being collected by Bryker Woods Elementary School's solar power system. On the page that comes up click on the blue Bryker Woods link. A graph of power output will be displayed for the PV system. You can roll over the other types of graphs to get an idea of what current conditions are like. Next, click on the "Custom" button to the right of the graph. In the Graph Controls orange box on the right enter the date range 01/01/2008 to 12/31/2008 (or any year period you like), set the Interval to "Day" and the Data Set to "Energy Production (kWh)".
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    b. What times of the year have the most day-to-day-variability? Why?

c. It was noted above that solar cells become less efficient as temperature rises. Is the summer to winter temperature difference (approximately 30°C) enough to account for the monthly difference in energy production?

d. Consider where the sun is in the sky in summer versus winter. How would you align and tilt a solar panel to get the most power over the whole year? This is not a simple question! Change the Interval on the graph to month or quarter and you'll see that this solar power system has been set up to even out much of the variation in power production over a year, but to get a little more in the summer. When in the year do you think energy demand is highest in Austin Texas?

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http://science.howstuffworks.com/solar-cell.htm

http://www.soltrex.com/index.cfm.

http://www.nrel.gov/ncpv/

http://www.ascensiontech.com/RTD/ashlandrtd.html

http://www.ascensiontech.com/RTD/pge.html

http://www.ases.org/

http://www.seia.org/main.htm

http://www.pvwatts.org/

For further reading:

The Solar Electric House by Steven J. Strong with William G. Scheller, Sustainability Press, Still River, Massachusetts 01467-0143, 1987.

From Space to Earth – The Story of Solar Electricity, John Perlin, aatec publications, Ann Arbor, MI 48107, 1999.

T*he Solar Electricity Handbook 2009: A Simple, Practical Guide to Using Electric Solar Panels and Designing and Installing Photovoltaic Solar PV Systems* by Michael Boxwell: CodeGreen Publishing, Ryton on Dunsmore, UK,.

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