How Does A Photovoltaic Cell Works

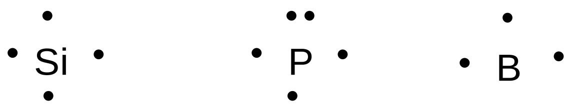
It all starts with sunlight. Sunlight is composed of photons. Photons have different energies, we notice this when looking at a rainbow and see different colors; each colors represents a photons with a different energy. When one of these photons sticks an atom in a photo voltaic (PV) cell, the photon frees one electron from the atom. The freed electron begins to wander around the PV cell, ultimately finding its way to the opposite side of the PV cell where it comes into contact with a metal wire. Einstein won the Noble Prize for describing the photovoltaic effect. The electron continues its journey through the wire. The wire connects things that need electricity like a computer, light bulb, batteries or refrigerators. Chances are the electricity you're using now got its start from a freed electron created by a photon from the sun.

Silicon solar cell

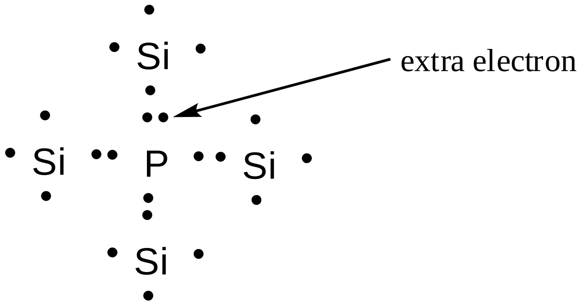
Pure silicon is not a very good conductor of electricity, though it conducts some electricity; hence called a semi-conductor. To increase its conductivity **impurities** are added; this is called **doping**. We'll see in the next few paragraphs why adding impurities like either phosphorous or boron atoms to silicon are desirable as well as what happens when these two different types of doped-silicon are sandwiched together.

Digging back into our chemistry knowledge we know atoms have protons and neutrons at the center or nucleus of the atom, and electrons whirling around the nucleus. Electrons move in a predictable fashion, in fact we know there movement is confined to well defined zones around the nucleus. It's easiest to picture in our mind that these electron-zones most resemble a cross section of an onion, where each onion layers represents a different zone where we find electrons. In chemistry it's the last onion layer that we're interested in because it's in that layer where electrons are moving between atoms.

Looking at phosphorous on the atomic level we see that phosphorous has three onion layers. Again, we're only interested in the last onion layer; these layers in chemistry are often referred to as shells. So in phosphorous, the last onion layer or shell we see that phosphorous has 5 electrons in its last shell. Boron has 2 shells, and again we're only interested with the last shell in which boron has 3 electrons in its last shell. Silicon happens to have 3 onion layers and in its last shell, it has 4 electrons which is a number right between phosphorous and boron. Below is a picture of what the last shell of each atom would look like; silicon with 4 electrons or 4 dots (each dot is an electron), 5 for phosphorous, and 3 for boron. A more technical term for these last electrons in an atom is a **valance electron**.

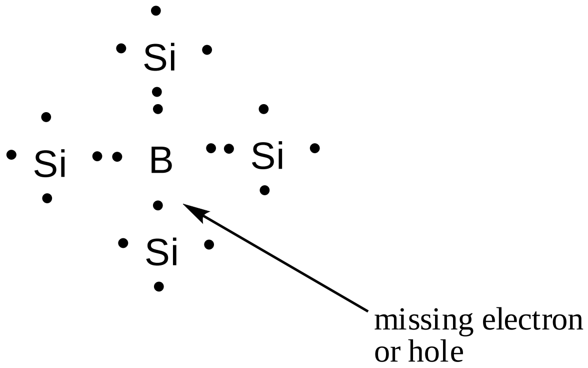


What we're going to do next is make two different types of silicon. To one type we'll add phosphorous. To the other we'll boron. Our goal is to sandwich together these two different types of silicon, one doped with phosphorous, the other silicon doped with born to make a PV cell. Before doing this, we better review a little more chemistry, specifically bonding. To make a bond between atoms, you need 2 electrons. There are a maximum number of bonds an atom wants to make, and for the vast majority of molecules it's 4 bonds. Silicon is always looking to form four bounds so when silicon forms its four bonds to a phosphorous atom it would look like the picture below. Remember, 2 electrons per bond, now referring to the valance electron picture above for silicon and phosphorous we end up with a picture below. Notice in the picture below, phosphorous ends up with one extra electron, that extra electron can't bond to anything else.



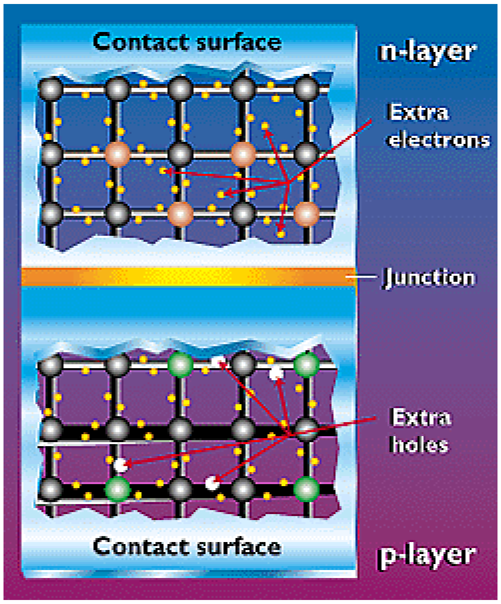
This extra electron creates a negative charge in the silicon-phosphorous doped semiconductor. Whenever silicon is mixed with phosphorous this negative charge is produced and this type of silicon is referred to as an n-type conductor, the "n" referring to negative charge. N-type conductors have an excess of electrons.

A similar analogy applies to boron. When boron binds to silicon, boron only has 3 electrons and silicon has 4 electrons. So what ends up happening is silicon is stuck without being able to make four bonds. In this case, the silicon, is trying to make another bond, and it can't. Silicon comes up short one electron. It would look like this:



Since the silicon atom is short one electron a positive charge forms on the silicon atom. Whenever silicon is mixed with boron positive charge is produced. This type of silicon-boron semiconductor is called a p-type conductor, the "p" referring to the positive charge. P-type conductors lack electrons. From this point forward, it is best to think of the boron doped silicon, where the missing electron is really just a **hole** and this hole is looking for another electron to fill it up. Therefore, the p-type material has an excessive number of positive holes to fill (that’s the end of our chemistry review).

p-Types, n-Types



To create a PV cell, two different types of semiconductors are sandwiched together. The "n" and "p" types of semiconductors correspond to "negative" abundance of electrons and "positive" abundance of holes (really just an absence of electrons).

Although both materials are electrically neutral, sandwiching these together creates a p/n junction at their interface, thereby creating a one-way electric field or diode which we’ll discuss later.

The p-n junction

The region in the solar cell where the n-type and p-type layers meet is called the p-n junction. When p-type and n-type materials are placed in contact with each other, a junction is automatically formed. An interesting interaction occurs at the p-n junction of a solar cell when the n-type layer comes into contact with the p-type layer. Electrons will only flow in one direction (forward biased) but not in the other (reverse biased).

How is this junction produced?

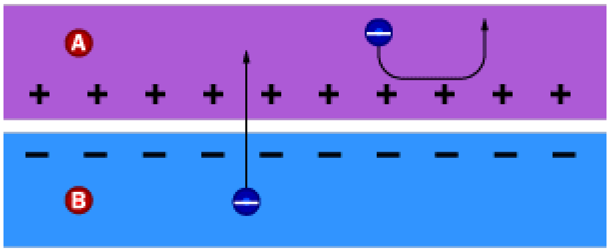
Remembering back to the n-type, phosphorous doped silicon with its extra electron, and the p-type, boron doped silicon with its missing electron. When the p-type and n-type semiconductors are sandwiched together, the point at which they touch, a sudden, mad-rush of an extra free electrons in the n-type layer, fall into a holes on the p-type side.

What does this produce? Before now, our two separate pieces of silicon were electrically neutral; the interesting part begins when you put them together. What is created is an **electric field**. The electric field forms when the mad-rush of free electrons on the N side to the holes on the P side. Do all the free electrons fill all the free holes? No, just the atoms right at the **junction**, they mix forming something of an electrical barrier, making it harder and harder for electrons on the N side to cross over to the P side. Eventually, an equilibrium of positive and negative produces an electric field on each side of the junction.

In the picture below, you can see how all of the extra electrons, at the junction, on the phosphorous side, Pink, jumped over to the boron side colored blue. When the extra electron on the phosphorous mad-rushes or jumps into the boron hole, the phosphorous leaves behind a positive hole. To you and I it looks like a hole is also moving, however this is best described as to what happens when looking at a bubble moving in a liquid. Although it's the liquid that is actually moving, it's easier to describe the motion of the bubble as it moves in the opposite direction or as we say rising. So applying our bubble analogy to positive holes moving, it looks like positive holes are moving and in reality, it's the electrons jumping, leaving behind a hole, so as more and more electrons jump into holes, holes appear to be moving. The funny thing is, we want the hole and electron to move in opposite directions. We want the hole to move to the p-type silicon, all the way to the bottom of the layer, to the opposite of the p-n junction. And, we want the electron to move through the n-type silicon, all the way to the opposite side of the p-n junction.

Combining a p-Types, n-Types produces a diode

At the junction all of the phosphorous electrons jump to the boron side, creating a negative charge on the boron side, leaving behind holes or positive charge on the opposite side. This separation of charge creates an electric field. This electric field is the exact location where energy or work is extracted from the PV cell. The reason is the electric field acts as a **diode**, allowing (and even pushing) electrons to flow from the P side (colored Blue below) to the N side (colored Pink below), 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).



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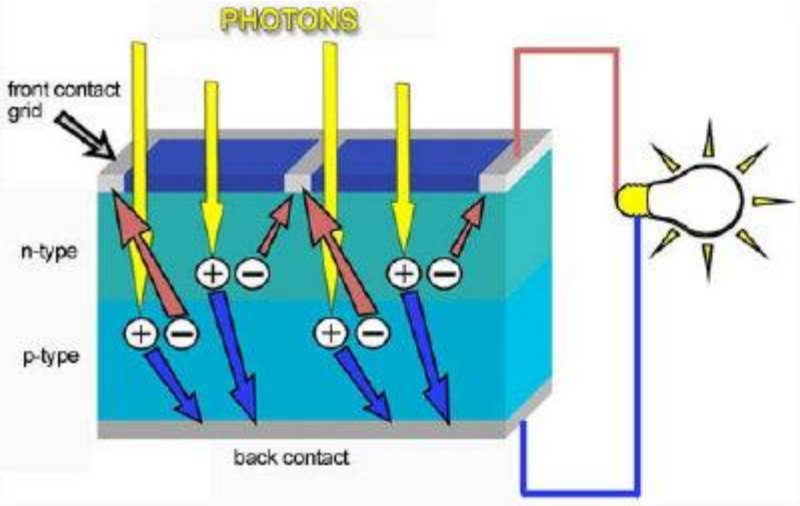
Ⓐ n-type Silicon
Ⓑ p-type Silicon

The effect of the electric field in a PV cell

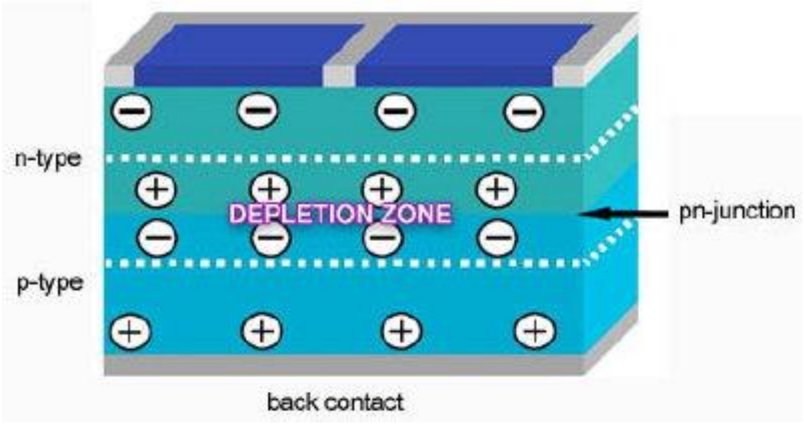
Through this flow of electrons and holes, the two halves of the semiconductors act as a battery, creating an electric field at the surface where they meet (known as the "junction"). It's this field that causes the electrons to jump across the junction, and then pushes the electrons further out toward the outer surface of the semiconductor. Once the electrons have reached the surface of the semiconductor, they are available for the electrical circuit. Remembering though, that as the electron jumped across the junction, what it leaves behind is a hole. So as the electron is weaving its way up to the surface of the n-type material, the hole it created on the p-type side begins moving in the opposite direction, toward the positive surface, where, ultimately the electron and hole will meet up again to finish the circuit.

Anatomy of a Solar Cell

Light, in the form of photons, hits our solar cell. When a photon of sunlight strikes an atom in either layer, it knocks loose an electron. If the photon has enough energy, the photon will strike a valence electron, releasing the electron and creating a positive hole. Normally one photon will free exactly one electron, unless the photon has twice the energy in which case it will release two electrons and create two positive holes.



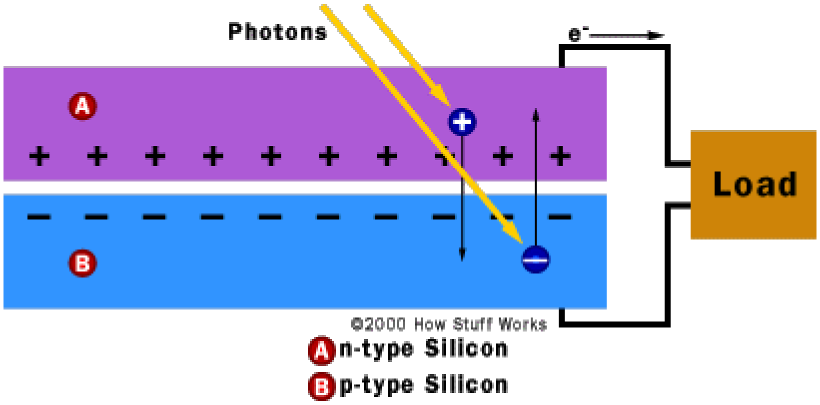
Freed electrons in the P-layer easily cross, even pulled through the electrical field into the n-layer, and holes move, even pulled to the p-layer. As a result, an excess of free electrons build up in the N-layer. The movement of electrons to the N side and holes to the P side causes a disruption of electrical neutrality in the junction sometimes referred to as the **depletion zone**. In the depletion zone (p-n junction) acts as a diode, **it's a one-way road**, only allowing electrons to move in one direction. N-layer electrons aren't able to cross the electrical field into the P-layer and vice-a-versa for the holes.



The electrical imbalance at the junction or depleted zone is about 0.6 to 0.7 volts. So due to the p-n junction, a built in electric field is always present across the solar cell. Another way to think of it is to say that that is the strength of a photon you'll need to knock an electron free, to make it jump the p-n junction gap. You could also say that's how much electricity you'll get from your PV cell. Knowing the voltage allows you to calculate the energy of all the photons, from the sun, striking your PV cell with 0.6 to 0.7 volts to knock an electron lose; that will give you the theoretical efficiency of a PV cell.

So we've got an electric field acting as a diode in which electrons can only move in one direction.

A metal wire attached to the N-layer gives excess electrons somewhere to go. Harnessing electrons powers electrical appliances in homes, offices, schools and factories. Forcing electrons through these paths creates an electric current. The circuit is complete when the free electrons recombines with a hole in the P-type layer.



Operation of a PV cell

P = V × I

The number of electrons moving are called **current**, symbol “I.” A cell's electric field causes a **voltage**, symbol “V.” With both current and voltage, we have **power**, which is the product of the two. Since voltage, in our above example is fixed at 0.6 to 0.7 volts, the only current is variable; so the brighter the day the more photons you’ll have, creating more current, making more power.

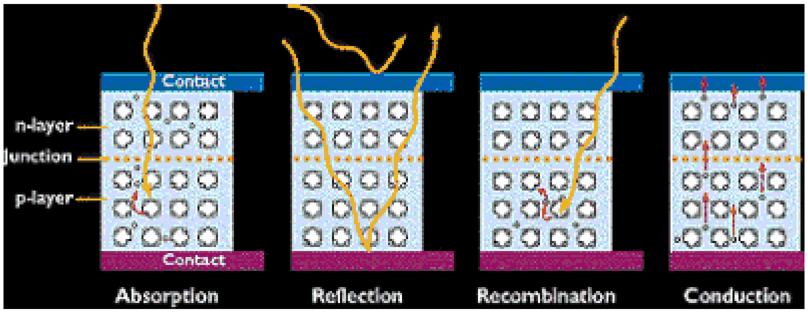
A Photon causes the Photoelectric Effect in more detail.

Band Gap

Today's most common PV devices use a single junction, or depleted region, to create an electric field. In our previous example of phosphorous and boron, the measure of energy across the junction or depleted region was between 0.6 to 0.7 volts. Therefore, only photons whose energy is equal to or greater than 0.6 to 0.7 volts can free an electron to make our electric circuit. The 0.6 to 0.7 volts is referred to as the **band gap**. If the photon's energy is at least as large as the material's energy band gap, the energy from the photon creates an electron-hole pair. Close to the junction, in the presence of an electric field, the junction acts more like a magnet, attracting and repelling negatively charged electron and the positively charged hole. Further away from the junction what typically happens is electrons and holes stay together, in a process called **recombination**, because the electron or holes doesn’t have enough energy to make it all the way to junction.

Absorption and Conduction

In a PV cell, photons are absorbed in the p layer. It's very important to "tune" this layer to the properties of the incoming photons to absorb as many as possible and thereby free as many electrons as possible. Another challenge is to keep the electrons from meeting up with holes and "recombining" with them before they can escape the cell. To do this, we design the material so that the electrons are freed as close to the junction as possible, so that the electric field can help send them through the "conduction" layer (the n layer) and out into the electric circuit. By maximizing all these characteristics, we improve the conversion efficiency of the PV cell.



To make an efficient solar cell, we try to maximize absorption, minimize reflection and recombination, and thereby maximize conduction. Junctions in semiconductors create electrical fields. A junction can be formed at the border between *p*-and *n*-doped regions, or between different semiconducting materials (a heterojunction), or between a semiconductor and certain metals (forming a Schottky barrier).

You can also try to capture more photons with different amounts of energy. You can probably envision doping silicon with elements other than phosphorous or boron. Changing the type of atom combinations will give a different band gap voltage other than our 0.6 to 0.7 volts for phosphorous or boron. It is possible to make stacks all of these different cells together to create a multi-junction cell. The advantage being that by changing the atom combination, you can change the voltage in the band gap, thereby effectively creating a PV cell that can capture all the photons with different energies.

The conversion efficiency of a PV cell is the proportion of sunlight energy that the cell converts to electrical energy. This is very important when discussing PV devices, because improving this efficiency is vital to making PV energy competitive with more traditional sources of energy (e.g., fossil fuels). Naturally, if one efficient solar panel can provide as much energy as two less-efficient panels, then the cost of that energy (not to mention the space required) will be reduced. For comparison, the earliest PV devices converted about 1%-2% of sunlight energy into electric energy. Today's PV devices convert 7%-17% of light energy into electric energy. Of course, the other side of the equation is the money it costs to manufacture the PV devices. This has been improved over the years as well. In fact, today's PV systems produce electricity at a fraction of the cost of early PV systems.

Energy Loses

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 pure 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 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, many just the physical design of a solar panel. Here is an example. Once our electron is free we want the electron to go to a wire which is more conductive than metal. So where do we place the metal. It's not possible to completely cover the top and bottom of the PV cell with metal otherwise our photons will never hit the PV cell. Placing the wires to far apart will cause our electrons to travel extremely long distances. The more time an electron spends by itself the great the chance it will recombine with its hole, and other problem being, silicon is a semiconductor -- it's not nearly as good as a metal for transporting current.

On the Horizon

Putting PV cell production at the same level of production as automobiles will decrease the cost of a PV cell. A MIT professor said the cost of materials in a PV cell is less than the cost of paint on some of the newer automobiles being produced today.

Another MIT professor said 65% of the cost of a PV cell is installing it on someone's house. A more efficient way of putting solar panels on a house would reduce the cost.

Current PV cells are as efficient as nuclear energy. The largest barrier is overcoming the cheap cost of burning fossil fuels.