Photovoltaic Technology in Detail

History

In 1840, the French scientist Alexandre Edmond Becquerel discovered that some materials produce a current (electricity) when light shines on them.

Photovoltaic cells, as we know them now, were first developed in 1954 by Bell Telephone researchers and first applied to power satellites in space. Since then, cost has been decreasing continuously while efficiencies have been increasing.
PV cells are now widely used to power:

- Homes & Businesses (directly)
- The utility grid (homes and businesses indirectly)
- Satellites (the first application to use PV panels)
- Billboards and Highway signs
- Remote transmitters, pumps, and other equipment
- Construction equipment lighting
- Outdoor lights over doorways and along sidewalks
- Calculators

Types of PV Cells and Their Efficiencies

Most PV cells are made from purified silicon, which is "doped" with other elements to achieve the desired photoelectric properties. There are several basic kinds of cells:

Mono-crystalline PV Cells: Each cell is a slice of single silicon crystal: These have pretty high efficiency (10-20%), and very long lifetimes because the crystal structure is very stable. The photo at right shows such a cell. Note the uniform color, except for the white lines, which are the small wires that collect the solar electricity.

A cell like this is cut from a solid ingot of crystallized silicon. Advanced manufacturing techniques today are cutting PV cells thinner and thinner, and applying the wires in new ways that block less sunlight. These techniques are making the cells more efficient and less costly.

Polycrystalline PV Cells: Each cell is a collection of many small silicon crystals, as one can see in the photo at right. These also have pretty high efficiency (10-13%), slightly less than single crystalline cells. and very long lifetimes because the crystal structure is very stable.

These cells are made using a process called “epitaxial growth”, whereby the crystals are grown on a flat substrate, and not cut from a large ingot.

Thin film or amorphous PV Cells: Here, the PV material is made from non-crystalline thin films of silicon atoms, and typically have a uniform gray appearance. They are also flexible, as the photo at right shows. Thin film cells tend to have lower efficiencies (5-10%), and more limited lifetimes because the silicon atoms have some freedom to move around over time. On the other hand, thin film cells can be much cheaper and require much less energy to produce, and promising efforts are being made to extend their lifetimes. Some companies are now mass marketing thin film PV panels for serious power generation.

How PV Cells Work

Solar cells are mostly made of silicon, with small amounts of other materials added. Each silicon atom has four electrons in its outermost (valence) shell. To complete the shell and achieve the most stable configuration, the atom would “like” to have eight instead (this is due to the quantum mechanical properties of electron orbitals). To achieve this, each silicon atom shares each of its four electrons with four other silicon atoms. This sharing of atoms binds the atoms to each other, and these bonds are called "covalent" bonds. These covalent bonds cause the silicon atoms to form a very stable silicon crystal.

Because each of these other four atoms also each share one of their electrons with the original atom, our original atom gets to use eight electrons, and so achieves the stable configuration it likes. Because all the valence electrons are involved in the covalent bonds, they can't move from one atom to another, and therefore a pure silicon crystal is a very bad conductor of electricity.

However, the silicon crystal can be made to conduct electricity with a clever trick: We add a small number of phosphorous atoms to the silicon crystal. Each phosphorous atom has *five* electrons in its valence shell, instead of four. But only four of these electrons are needed to bond with four nearby silicon atoms, so the fifth one is left over. Because it is not involved in a bond, it is can move much more freely through the silicon.

This process of adding another element is called "doping". As we have seen, when phosphorous is the dopant, extra electrons are added. Because electrons have a negative charge, we call the doped material "n-material", where the n stands for the negative charge of the electrons. Its important to keep in mind that n-material doesn't have a *net* negative charge, because the nucleus of the phosphorous atoms have an extra proton as well (relative to silicon), and this balances out the extra electrons. What the n-material *does* have that the silicon doesn't have is charge carriers that can move, and so can conduct electricity.

Another way that charge carriers can be added to the silicon is to add an element such as boron, which has only three instead of four electrons in its valence shell. The doped silicon crystal that results will then have electron vacancies in its structure, called "electron holes". These holes can actually move, because nearby electrons can fill these holes, leaving behind a new hole nearby. This kind of material is called “p-material”, where p stands for positive, because we may think of the holes as having a positive charge.

The electron-hole concept may seem a little tricky at first. The simplest way to think of it is simply that in the p-material, the electrons can't move unless other electrons move out of their way. A hole is simply the space created by an electron moving out of the way. In any case, for either p or n type material, electrons can move, so that electricity can be conducted.

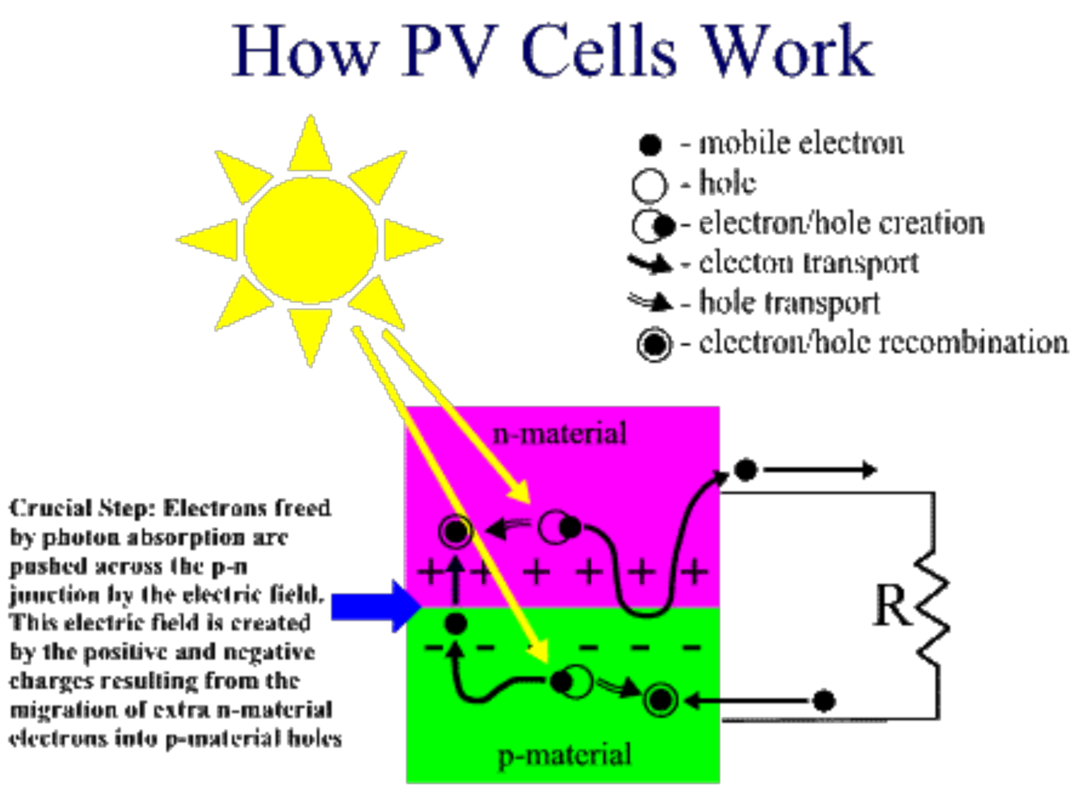
When the two types of material are brought together, say, with the n-material on the top, a very interesting thing happens. Some of the extra, mobile electrons in the n-material migrate over into the p-material and fill some of the holes there. This makes the upper layer of the p-material negatively charged, while the nearby n-material now lacks electrons and becomes positively charged. In the diagram below, these charges are symbolized with minus signs (for the negative charges), and plus signs (for the positive charges). These charges create an electric field, or voltage, across the junction of the two wafers, called a p-n junction, balances (stops) further (net) migration. This electric field remains permanently "built-in".

When there is no sunlight shining on the material, there is no net movement of electrons in the material, despite the fact that there is an electric field inside the material. When photons of light strikes the material, however, some normally non-mobile electrons in the material absorb the photons, and become mobile by virtue of their increased energy. This creates new holes too - which are just the vacancies created by the newly created mobile electrons. Because of the "built in" electric field, the new mobile electrons in the n-material cannot cross over into the p-material.

In fact, if they are created near or in the junction where the electric field exists, they are pushed by the field towards the upper surface of the n-material (such an event is shown in the diagram below). If a wire is connected from the n-material to the p-material, however, they can flow through the wire, and deliver their energy to a load.

On the other hand, the holes created in the n-material, which are positively charged, are pushed over into the p-material. In fact, what is really happening here is that an electron from the p-material, which was also made mobile by the absorption of a photon, is pushed by the electric field across the junction and into the n-material to fill the newly created hole. This completes the circuit - we now see that there are electrons flowing all the way around the circuit, dropping the energy they acquired from photons at a load.

The crucial step in the whole process is that just described - the pushing of mobile electrons across the p-n junction. This suggests a nice way to think of the PV process - like a tennis player making an overhead serve: First, an electron absorbs a photon and become mobile. This is like the first step in a tennis player’s serve, when they throw the ball upwards into the air. Secondly, the built-in electric field pushes the electron into the n-material. This is like the tennis racket crashing into the ball, and accelerating across the net.
Here is a diagram showing the whole process:



PV System Costs

The costs of typical off-grid PV system range from a few thousand for a small vacation cabin system, to about $10,000 for a small home, and upwards of $30,000 for a large home. Component costs break down roughly as follows:

- About $1 per watt for the PV panels, so for a typical 2 kilowatt system the panels cost about $2,000.
- Several hundred dollars for the charge controller.
- About $1 per watt for the inverter: a typical 2 kilowatt system would therefore need a $2000 inverter
- About $100 per kilowatt-hour of energy storage: a typical 2 kilowatt system might require 20 kWh of storage (only 10 kWh in active use to extend battery life) and therefore about $2000 worth of batteries.

Grid-Tied (Net-Metered) PV Systems

Grid-tied PV systems interconnect with the power grid and use the power grid like a battery, so these systems don't need batteries, or a charge controller. When the PV system is making more power than the system's owner can use, the extra power is fed back into the power grid, making the owner's electric meter spin backwards! This arrangement is called "net-metering": The system owner only pays for the "net" amount of electricity they use. If they use less than their system makes, then the utility gives the owner a credit on their next electric bill, or pays the system owner for their solar power.

Net-metered systems are better environmentally for two reasons: They don't need batteries, and all the solar power they generate is used by someone. The latter is not necessarily true for off-grid systems, which usually waste any solar powered after the batteries are charged up. Grid-tied systems are also cheaper than off-grid, and easier to maintain.

System Lifetimes

Today's crystalline PV panels have a very long lifetime, at least 25 years, and possibly much longer. This is because crystalline silicon is very stable (silicon crystals can remain intact on geological time scales). The primary cause of failure is due to degradation of the transparent laminates that protect the cells from the elements, and from problems such as broken contacts.

Today's batteries typically last 3-10 years before they need to be replaced. Fortunately, US law requires that the batteries be recycled. Many solar enthusiasts are hopeful that energy storage systems using hydrogen fuel cells will become available in coming decades to replace the need for short-lived batteries.

Energy Payback

A common myth is that PV panels take more energy to manufacture than they produce. In fact, according to the US Department of Energy, PV panels typically pay back their energy in 2 to 3 years, depending on the available sunlight.