How Photovoltaic Cells Work

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Photovoltaics are indeed magical devices - who would think, really, that you could put a shiny blue flat thing out in the sun and get electricity from it? They do work. Moreover, they need not be mysterious. It does take a little patience (you may need to read over this twice or more to get comfortable with the terms) but you do not need to be a semiconductor physicist to understand qualitatively how PVs convert light into electricity.

Atomic Model for Semiconductors

Ninety-nine percent of today's solar cells are made of silicon (Si), and other solar cells are governed by basically the same physics as Si solar cells. Since it is helpful to be concrete, I'll explain solar cells with reference to silicon. A silicon atom has 14 electrons. Four of them are valence electrons, meaning they are available to associate with other atoms. In a pure silicon crystal, each atom shares these valence electrons with four neighbor atoms in covalent bonds. This fairly strong electrostatic bond between an electron and the two atoms it is helping to hold together can be broken by input of sufficient energy: 1.1 electron volts (eV) or more. This corresponds to a photon of light of wavelength 1.12µm or less - all colors in the visible spectrum, and well into the infrared. This freed electron now roams the crystals much the way an electron in a metal travels freely, not attached to any one atom. It is free to accelerate in the presence of an electric field; that is to say it takes a part in the conduction of electricity. In making this transition it leaves behind a "hole", a place lacking an electron. Neighboring electrons can leave their bonds to fill the hole, essentially switching places with it. Hence both electron and hole can move through the crystal. This is called the photoconductive effect.

If nothing is done, within a certain time **t**, called the minority carrier lifetime, the electron is expected to recombine with a hole, producing a photon (heat). This is not very exciting, and it certainly is not useful for creating electricity. Loosely, what is needed is a way to separate the electrons and the holes so that they won't recombine in the crystal, and a path to funnel these electrons out to do work on a load. The former is provided by a semiconductor junction between two semiconductors with different electrostatic charges. The latter, simply by metal contacts to the cell on opposite side of the junction.

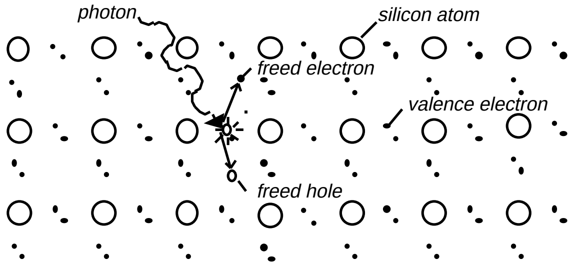

Figure 1 Photoconductive effect in silicon

Doping

If we add a small amount (on the order of one part per million) of phosphorous to the silicon crystal as it is forming so that the phosphorous atoms fill sites in the silicon crystal lattice, then we are said to have 'doped' the crystal with phosphorous. Phosphorous is group V on the chemical chart, so it has five valence electrons - one more than silicon. The phosphorous nucleus and inner electrons settle happily into the lattice site, and four of phosphorous's electrons participate in the covalent bonding with electrons from the four neighboring silicon atoms. But in the crystal the fifth electron is very loosely bound to the phosphorous atom, so loosely in fact that at room temperatures it is thermally excited into the wandering free state. Doping with elements like phosphorous with one valence electron more than the original atom is called n type doping (n for 'negative'), and the dopant is called a 'donor' because it easily gives up electrons.

Doping silicon with boron has exactly the opposite effect. Boron is group III, so it has three valence electrons - one less than silicon. It fills a silicon lattice site, but has enough electrons for only three covalent bonds with

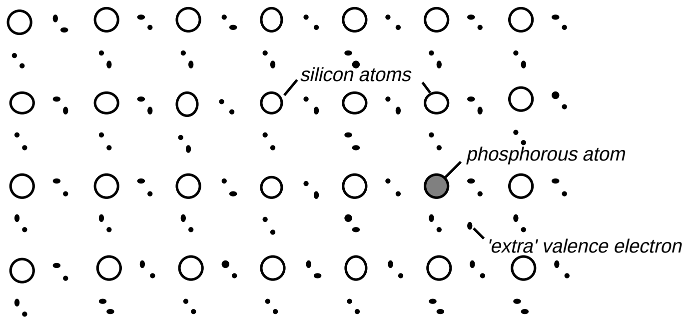

Figure 2 n type (phosphorous) doped silicon

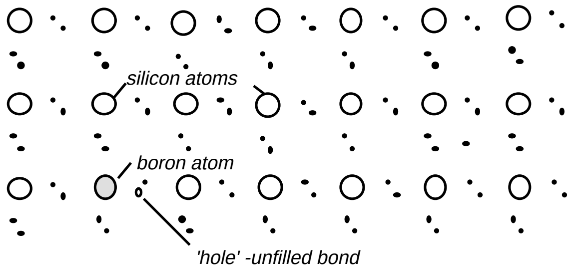

Figure 3 p type (boron) doped silicon

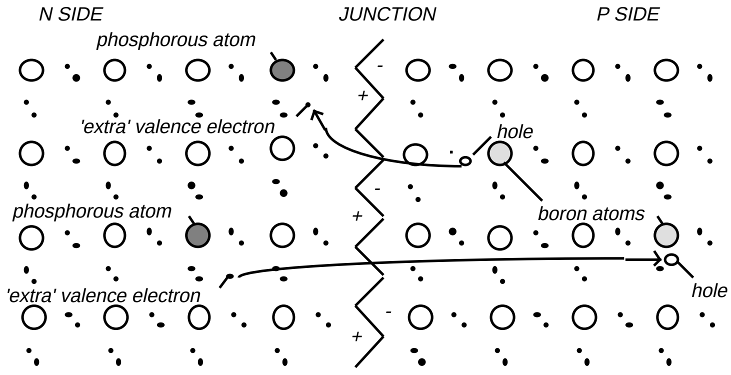

Figure 4 Junction forming

neighboring atoms, leaving a hole. This hole, identical to the photogenerated hole explained above in the discussion on photoconduction, is thermally excited at room temperature into freedom to roam about the crystal. For silicon, boron is a p type (positive) dopant, and called an acceptor because its unfilled bond (hole) readily takes in free electrons.

Diodes

Photovoltaic cells are diodes with a large surface area exposed to the sun. A diode is just an n - type layer slapped onto a p layer. The space where the two layers meet is called the junction. The instant the diode is formed, the billions of free electrons near the junction in the n-type material immediately rush over to fill the holes in the p-type material, leaving the n side (which had been electrostatically neutral) with a net positive charge. Likewise, holes on the p side migrate to the n type material, leaving the p side of the junction with a net negative electrostatic charge.

Within milliseconds the process reaches equilibrium as the statistical force pushing electrons on the n side to fill holes on the p side is balanced by the force from the electric field created by the electrons and holes when they have moved from their original materials. Loosely you can think of the n- side as having a high "electron pressure" and the p-side as having a low electron pressure. Forming the junction "opens the valve" for this electron gas to flow to the region of lowest pressure. The electric field of the junction presents a barrier to further crossover of majority carriers: in the n type material, electrons are the majority carriers, and in the p type, holes are the majority carriers. As figure 5 shows, the junction does not impede the flow of minority carriers; if there are electrons in the p side (and there won't be many because holes are so common there) and they wander into the junction they will be accelerated across to the n side. Actually this wandering is not entirely random: those electrons on the p side which make it to the junction are whisked across, and their absence on the p side near the junction encourages a drift of electrons from farther in the p side to take their place. This current is called a diffusion current. Vice versa for holes (minority carriers on the n side).

Sunlight into Electricity

Now recall the photoconductive effect: a photon hits an atom (a silicon atom most likely since there are millions more of them, but also possibly a phosphorous or boron atom) and frees an electron leaving behind a hole. Suppose this creation of an 'electron hole pair' takes place in the p type material. The electron and the hole wander around the lattice with a speed determined by a material dependent parameter called the mobility. An electron from such an electron-hole pair has a relatively short time that it is free because it is very likely to recombine with one of the numerous holes on the p-side. If the electron-hole pair is created close enough to the junction, chances are pretty good, however, that it will diffuse into the junction, and when it does it will be

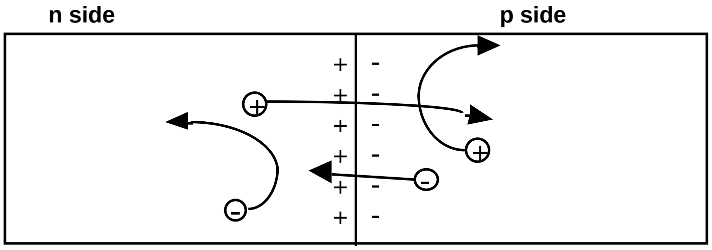

Figure 5 junction formed

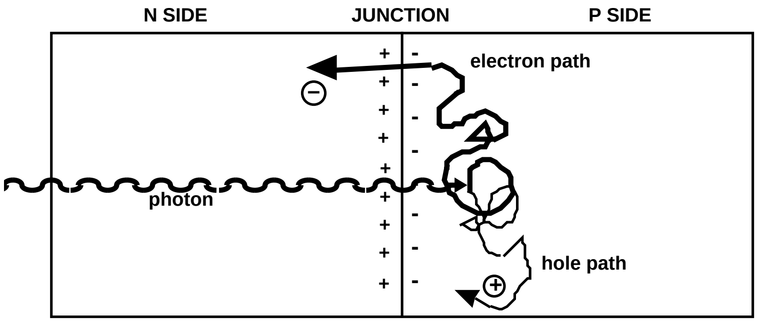

Figure 6 The junction in action

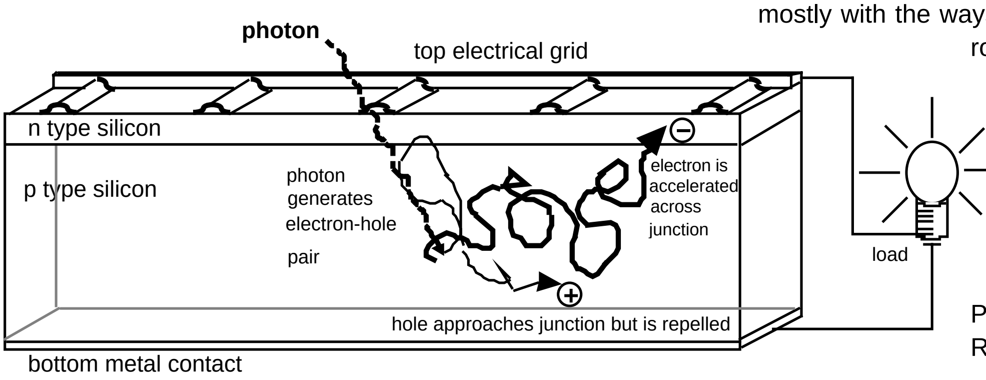

Figure 7 schematic of a pv cell.

accelerated across by the electric field. If the hole happens to wander into the junction, it will be repelled.

The electron, once it has gone across, will stay on the n-side since only rarely does it have the energy to climb the barrier back to the p side. It has little danger of recombining with a hole because there are very few holes on the n side. A similar situation occurs when the electron-hole pairs are created by light on the n side. In this case the hole, if it diffuses into the junction will be accelerated across to the p side where there are very few electrons. The only work performed by the light was the separation of electrons from the holes at some atom. As the electrons and holes wandered around the crystal, the minority carriers (electrons on the p side, holes on the n side) that came upon the junction were accelerated through to the other side by the 'frozen in' electric field of the junction. The charge imbalance in an illuminated cell (electrons piled up on the n-side, holes on the p side) creates a voltage difference, and if the two sides are connected by a wire, a current of electrons will flow from the n-side to the less electron crowded p-side doing work against an external load. Actually this last sentence is not rigorous enough to account for the current and the voltage of the cell. The electrons lose potential energy as they cross the junction, just as a ball loses potential energy as it rolls downhill. The electrons remain, however, free, and as such they have a higher potential energy than the bound electrons on the p side. Since most of the electrons on the p side are bound, and most on the n side are free, taking the material as a whole, the higher energy of n side electrons creates a voltage difference between the p and n sides. Connecting the two sides with an electrical load, the photogenerated electrons will flow from the n side through the load to the lower energy p side.

Further Reading

Physicists use other models to design and predict the voltage and current of a solar cell. They are concerned mostly with the ways electrons and holes can recombine, robbing a cell of its output. If you're interested, there are a number of more deeply into this. I recommend R. J. Van Overstraeten and R. P. Mertens, Physics, Technology and Use of Photovoltaics, (Adam Hilger Ltd, Bristol 1986) and Kenneth Zweibel, Basic Photovoltaic Principles and Methods, (Van Nostrand Reinhold Co.), 1984

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