Solar cell structure diagram

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The theory of solar cells explains the process by which light energy in photons is converted into electric current when the photons strike a suitable semiconductor device. The theoretical studies are of practical use because they predict the fundamental limits of a solar cell, and give guidance on the phenomena that contribute to losses and solar cell efficiency.

When a photon hits a piece of semiconductor, one of three things can happen:

When a photon is absorbed, its energy is given to an electron in the crystal lattice. Usually this electron is in the valence band. The energy given to the electron by the photon "excites" it into the conduction band where it is free to move around within the semiconductor. The network of covalent bonds that the electron was previously a part of now has one fewer electron. This is known as a hole, and it has positive charge. The presence of a missing covalent bond allows the bonded electrons of neighboring atoms to move into the "hole", leaving another hole behind, thus propagating holes throughout the lattice in the opposite direction to the movement of the negatively electrons. It can be said that photons absorbed in the semiconductor create electron-hole pairs.

A photon only needs to have energy greater than that of the band gap in order to excite an electron from the valence band into the conduction band. However, the solar frequency spectrum approximates a black body spectrum at about 5,800 K,[1] and as such, much of the solar radiation reaching the Earth is composed of photons with energies greater than the band gap of silicon (1.12eV), which is near to the ideal value for a terrestrial solar cell (1.4eV). These higher energy photons will be absorbed by a silicon solar cell, but the difference in energy between these photons and the silicon band gap is converted into heat (via lattice vibrations -- called phonons) rather than into usable electrical energy.

The most commonly known solar cell is configured as a large-area p-n junction made from silicon. As a simplification, one can imagine bringing a layer of n-type silicon into direct contact with a layer of p-type silicon. n-type doping produces mobile electrons (leaving behind positively charged donors) while p-type doping produces mobile holes (and negatively charged acceptors). In practice, p-n junctions of silicon solar cells are not made in this way, but rather by diffusing an n-type dopant into one side of a p-type wafer (or vice versa).

Once equilibrium is established, electron-hole pairs generated in the depletion region are separated by the electric field, with the electron attracted to the positive n-type side and holes to the negative p-type side, reducing the charge (and the electric field) built up by the diffusion just described. If the device is unconnected (or the external load is very high) then diffusion current would eventually restore the equilibrium charge by bringing the electron and hole back across the junction, but if the load connected is small enough, the electrons prefer to go around the external circuit in their attempt to restore equilibrium, doing useful work on the way.

These two "forces" may work one against the other at any given point in the cell. For instance, an electron moving through the junction from the p region to the n region (as in the diagram at the beginning of this article) is being pushed by the electric field against the concentration gradient. The same goes for a hole moving in the opposite direction.

It is easiest to understand how a current is generated when considering electron-hole pairs that are created in the depletion zone, which is where there is a strong electric field. The electron is pushed by this field toward the n side and the hole toward the p side. (This is opposite to the direction of current in a forward-biased diode, such as a light-emitting diode in operation.) When the pair is created outside the space charge zone, where the electric field is smaller, diffusion also acts to move the carriers, but the junction still plays a role by sweeping any electrons that reach it from the p side to the n side, and by sweeping any holes that reach it from the n side to the p side, thereby creating a concentration gradient outside the space charge zone.

In thick solar cells there is very little electric field in the active region outside the space charge zone, so the dominant mode of charge carrier separation is diffusion. In these cells the diffusion length of minority carriers (the length that photo-generated carriers can travel before they recombine) must be large compared to the cell thickness. In thin film cells (such as amorphous silicon), the diffusion length of minority carriers is usually very short due to the existence of defects, and the dominant charge separation is therefore drift, driven by the electrostatic field of the junction, which extends to the whole thickness of the cell.[2]

Once the minority carrier enters the drift region, it is "swept" across the junction and, at the other side of the junction, becomes a majority carrier. This reverse current is a generation current, fed both thermally and (if present) by the absorption of light. On the other hand, majority carriers are driven into the drift region by diffusion (resulting from the concentration gradient), which leads to the forward current; only the majority carriers with the highest energies (in the so-called Boltzmann tail; cf. Maxwell-Boltzmann statistics) can fully cross the drift region. Therefore, the carrier distribution in the whole device is governed by a dynamic equilibrium between reverse current and forward current.

Ohmic metal-semiconductor contacts are made to both the n-type and p-type sides of the solar cell, and the electrodes connected to an external load. Electrons that are created on the n-type side, or created on the p-type side, "collected" by the junction and swept onto the n-type side, may travel through the wire, power the load, and continue through the wire until they reach the p-type semiconductor-metal contact. Here, they recombine with a hole that was either created as an electron-hole pair on the p-type side of the solar cell, or a hole that was swept across the junction from the n-type side after being created there.

The voltage measured is equal to the difference in the quasi Fermi levels of the majority carriers (electrons in the n-type portion and holes in the p-type portion) at the two terminals.[3]

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