The Physics of Solar Photovoltaic Cells

R.H.B. Exell
Energy Technology Division
Asian Institute of Technology
Bangkok, Thailand

ABSTRACT

This article contains short descriptive outlines of the processes that occur in the photovoltaic effect, electrons in solids (insulators, conductors and semiconductors), electron-hole pairs, doped semiconductors, n-p junctions and photovoltaic cells.

To understand how solar photovoltaic cells work, one needs a knowledge of the quantum theory of electrons in solids. It is therefore difficult for persons with backgrounds other than a degree in physics to follow many of the texts on this subject, except those at a popular level. The aim of this article is to bridge the gap between expositions that are too elementary to be useful and those that are too advanced to be understood by the majority of engineers. The material presented is based on notes given to students in a course on solar energy in the Asian Institute of Technology.

THE PHOTOELECTRIC EFFECT

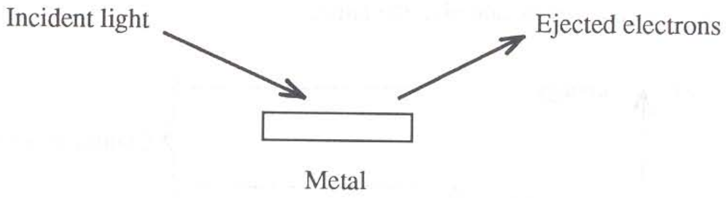

Fig. 1. Production of photo-electrons.

Experiment shows that when light falls on a metal surface, electrons may be ejected. The energy E of the ejected electrons depends on the frequency ν of the incident light according to the equation

$$E = h\nu - \phi,$$

where h is Planck's constant and ϕ is the energy required to remove the electron from the metal surface. If the electrons are collected to make an electric current, the strength of the current depends on the intensity of the incident light.

These results show that the interaction between electromagnetic radiation and matter is in the form of energy exchanges between discrete quantities of radiation and electrons. The discrete quantities of radiation are called **photons**. Each photon has energy $h\nu$, and the intensity of the radiation is determined by the number of photons received per unit time.

ELECTRONS IN SOLIDS

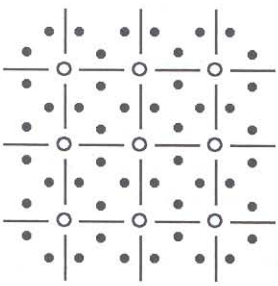

Fig. 2. Schematic diagram of silicon lattice with electron pairs (dots) in covalent bonds (lines).

The atoms of certain crystalline solids are held together in a regular lattice by covalent bonds. Each covalent bond linking two atoms consists of a pair of electrons, called valence electrons, one from each atom (Fig. 2). The valence electrons move in the space between the two atoms with energies in a certain band of energies known as the **valence band** (Fig. 3). The valence band of a solid consists of a large number of separate energy levels, one for each valence electron. The behaviour of electrons is such that when all the valence electrons are in position, no more valence electrons can be added to the lattice.

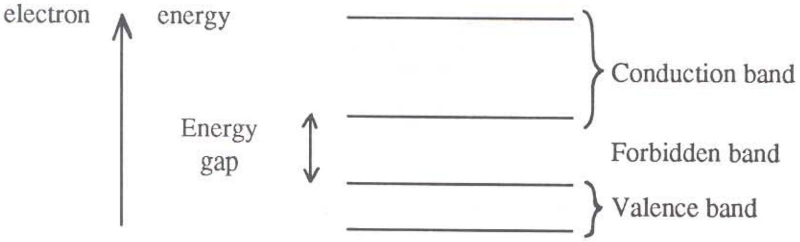

Fig. 3. Electron energy level bands in solids.

In some solids there are extra electrons moving freely through the lattice without being held in covalent bonds. These electrons are called conduction electrons because they carry electric currents through the solid. Their energies are in another band known as the **conduction band** at a higher energy level than the valence band (Fig. 3).

Between the highest energy level in the valence band and the lowest energy level in the conduction band there may be a **forbidden band** of energies. No electrons can have energies within the forbidden band. The difference between the energy at the bottom of the conduction band and the energy at the top of the valence band is called the **energy gap**.

The most convenient measure of energy in electronics is the energy gained by an electron when it is accelerated through an electric potential of one volt, called the **electron volt** (eV). Energy gaps are typically of the order 1 eV = 1.602 x 10^{-9}J.

INSULATORS, CONDUCTORS AND SEMICONDUCTORS

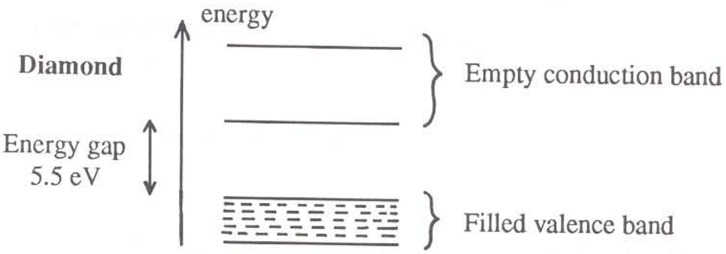

Fig. 4. Electron energies in an electrical insulator.

An **electrical insulator** has its valence band filled with electrons and its conduction band empty (Fig. 4). Therefore, there are no free electrons available to carry an electric current. Moreover, the energy gap is large so it is not possible for ordinary processes to provide enough energy for the valence electrons to break out of their valence bonds and jump into the conduction band where they might carry an electric current. Carbon in the form of diamond is an insulator with energy gap 5.5 eV.

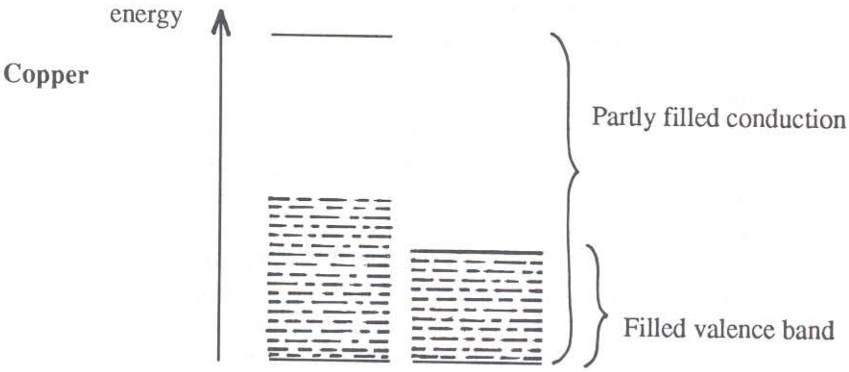

Fig. 5. Electron energies in an electrical conductor.

An **electrical conductor**, such as copper, besides having its valence band filled, also has a partly filled conduction band. Sometimes there is no forbidden band because the conduction and valence bands overlap (Fig. 5). There exist in the conduction band empty energy levels, or states of motion, into which the conduction electrons can jump with very little change of energy. Consequently, the conduction electrons are free to move through the lattice and carry an electric current.

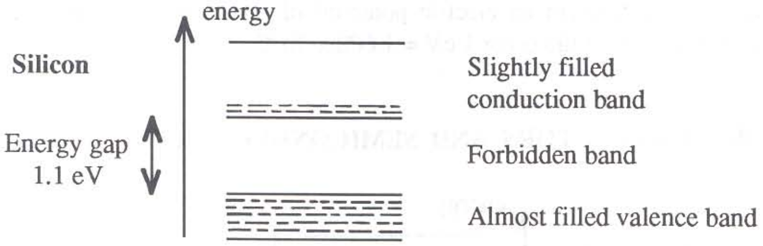

Fig. 6. Electron energies in a semiconductor.

An **intrinsic semiconductor** is a pure substance with just enough electrons to fill the valence band, but a small energy gap. It is possible for certain processes to give the valence electrons enough energy to jump across the energy gap into the conduction band where they are able to carry an electric current (Fig. 6). As there are only a few of these conduction electrons the solid is called a semiconductor. An example is silicon with an energy gap of 1.1 eV.

ELECTRON–HOLE PAIRS

When an electron jumps from the valence band to the conduction band it leaves behind a "hole", or missing electron in a covalent bond. This hole can easily be filled by an electron from an adjacent covalent bond, so the hole can move through the lattice. Thus an intrinsic semiconductor conducts electricity by means of negative charge carriers (electrons) and positive charge carriers (holes).

Electron-hole pairs may be produced by thermal excitation. The number of pairs produced depends on the energy gap E_g and on the magnitude of kT, where T is the absolute temperature and k is Boltzmann's constant 8.617×10^{-5} eV/K. At ordinary temperatures $T \approx 300$K, and so $kT \approx 0.026$ eV. This is only 2.4% of E_g for silicon but it is enough to give some conductivity.

Electron-hole pairs may also be produced by photon excitation. The rate at which pairs are produced depends on the intensity of the light, i.e. the rate at which photons are absorbed.

A photon can create an electron-hole pair only if its energy is equal to, or greater than, the energy gap. The energy of a photon is given by hc/λ, where h is Planck's constant 6.626×10^{-34}Js, c is the speed of light 2.998×10^{8} m/s and λ is the wavelength of the photon. When λ is given in µm and the photon energy E_λ is given in eV we have $E_\lambda = 1.24/\lambda$.

For photon excitation in silicon ($E_g = 1.1$ eV) we require $E_\lambda \geq 1.1$ eV, i.e. $\lambda \leq 1.13$ µm. Therefore, the photons in visible light can increase the electrical conductivity of silicon by the creation of electron-hole pairs, but the photons in the infra-red part of the spectrum with $\lambda > 1.13$ µm cannot.

DOPED SEMICONDUCTORS

The electrical conductivity of semiconductors can be greatly increased by the addition of certain impurities in concentrations of about one part per million. The process is called "doping".

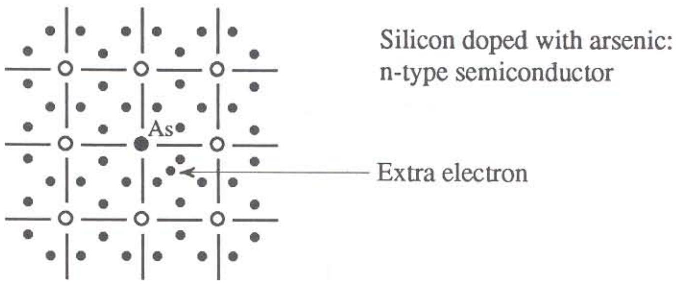

Fig. 7. Schematic diagram of an n-type semiconductor lattice.

Silicon may be doped with arsenic atoms, which have five outer electrons. Four of the outer electrons become valence electrons in the valence band, while the extra electron acts as a negative charge carrier in the conduction band (Fig. 7). The number of donated conduction electrons is much greater than the charge carriers produced from electron-hole pairs. The donated conduction electrons are therefore called **majority carriers**, while the charge carriers produced from the electron-hole pairs are called **minority carriers**. Because the majority carriers are negative the arsenic doped silicon crystal is called an **n-type semiconductor**.

Silicon may also be doped with boron atoms, which have only three outer electrons. This gives rise to missing valence electrons, or holes (Fig. 8). The holes created by the impurity atoms act as positive majority carriers, and the doped crystal is called a **p-type semiconductor**.

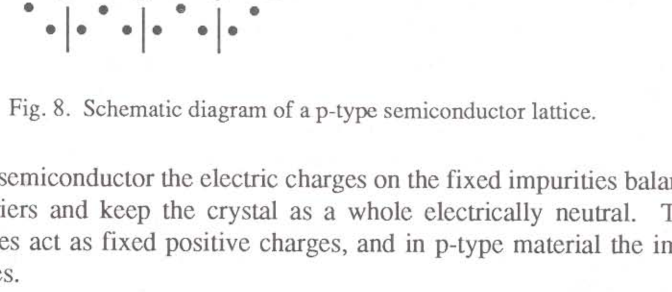

Fig. 8. Schematic diagram of a p-type semiconductor lattice.

In each type of semiconductor the electric charges on the fixed impurities balance the charges on the majority carriers and keep the crystal as a whole electrically neutral. Thus, in n-type material the impurities act as fixed positive charges, and in p-type material the impurities act as fixed negative charges.

SEMICONDUCTOR n-p JUNCTIONS

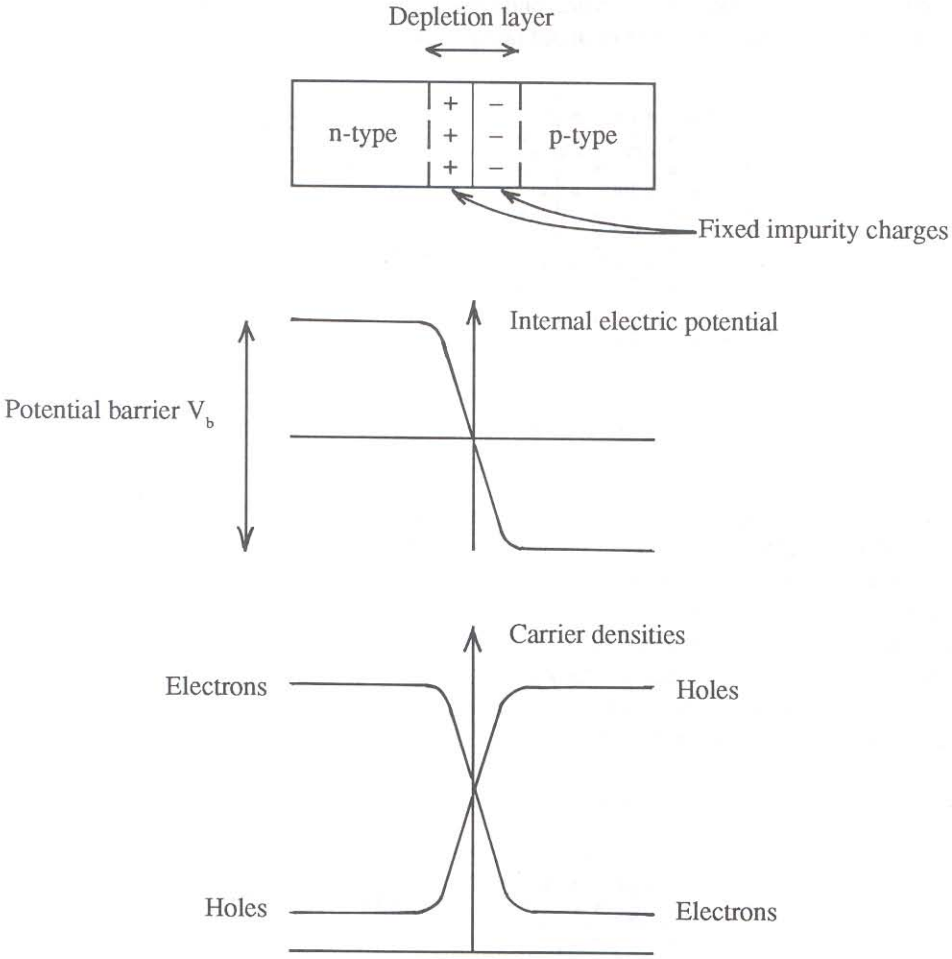

Fig. 9. The structure of a semiconductor n-p junction.

An n-p junction is a semiconductor crystal that is doped as an n-type semiconductor on one side and as a p-type semiconductor on the other side (Fig. 9).

Near the junction, free electrons from the n-type side fill the holes from the p-type side forming a **depletion layer** that is deficient in majority carriers. In this layer the fixed impurities then create an excess positive charge on the n-type side and an excess negative charge on the p-type side. This produces an electric potential barrier V_b that counterbalances further movement of majority carriers across the junction.

The height of the potential barrier V_b is somewhat less than the energy gap E_g because the fixed impurities slightly hinder the movement of the majority carriers. The potential difference across the junction produces an electric field in the depletion layer directed from the n-type side towards the p-type side.

SILICON PHOTOVOLTAIC CELLS

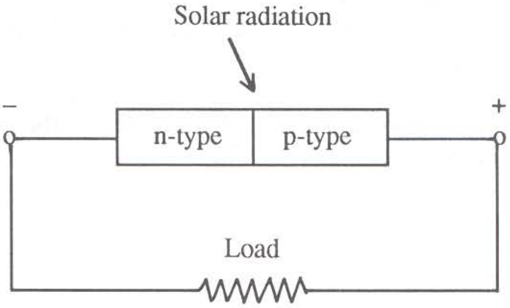

Fig. 10. The solar photovoltaic cell concept.

When solar radiation falls on a silicon n-p junction, photons with wavelength less than 1.13 μm generate electron-hole pairs. The electric field in the depletion layer separates the electrons and holes before they can recombine, driving the electrons to the n-type side. If the two sides of the junction are connected to an external circuit, these charges give rise to a current, and energy in the solar radiation is converted into electrical energy in the circuit.

The efficiency of photovoltaic conversion is limited by the relationships between the photon energies and the energy gap in the semiconductor. Photons in the ultra-violet and visible regions of the solar spectrum have energies greater than the energy gap so only part of the photon energy is converted into electrical energy by the creation of electron-hole pairs. The excess energy is dissipated as heat. Photons in the near infra-red with wavelengths 0.7 to 1.1 μm have energies only slightly greater than the energy gap so most of their energy is converted into electricity. Near infra-red photons with wavelengths greater than 1.13 μm have energies less than the energy gap and cannot produce electron-hole pairs, so they cannot contribute to the energy output of the solar cell.

Taking these facts into consideration one finds that an upper limit to the efficiency of a silicon solar cell is 45%. However, recombination of electrons and holes before they are completely separated reduces the attainable efficiency still further to about 20%.

If the external load resistance is very high we have, in effect, an open circuit in which the voltage V_b is about 0.8 V in silicon solar cells, but the current is zero so no power is delivered. If the load resistance is negligible we have, in effect, a short circuit in which the current is high since almost all of the photo-excited electron-hole pairs are separated before recombination. But again no power is delivered because the potential drop across the load is negligible. Optimum results are obtained with a potential drop across the load of about 80% of V_b, which is about 0.6 V in silicon solar cells.

FURTHER READING

There is a large volume of literature on the subject of solar photovoltaic cells covering both the physical processes involved, and also the application of photovoltaic cells in solar powered systems. Among the wide selection of books available the author has found the following texts useful for accounts of the physics involved.

Brinkworth, B.J. *Solar Energy for Man*, Compton Press, 1972. Although this book was written two decades ago, it is still one of the best introductions to the principles of solar energy as a whole, including photovoltaics.

Twidell, J. and T. Weir. *Renewable Energy Resources*, E. & F.N. Spon, 1986. This book is written for a wide readership mainly at the undergraduate level. The chapter on photovoltaics is detailed, and must be read with concentrated attention.