The physics of the photovoltaic process

Some notions of modern physics concerning the nature of the electromagnetic radiation and the structure of the atom are necessary in order to understand how the photo-conversion process works, i.e. how the solar radiation energy can be transferred to an electronic current.

The direct conversion of solar energy into electric energy by means of a photovoltaic cell is based on the interaction between light radiation and the valence electrons of a semiconductor material: this physical phenomenon is called *photovoltaic effect*. The *photovoltaic effect* highlights the corpuscular nature of light: indeed, physicists discovered that the required energy for activating the process is provided by the photon, a particle associated to electromagnetic waves. Whatever the material used, the mechanism that allows the cell to transform solar into electric energy is essentially the same.

Let us consider the simple case of a conventional photovoltaic cell of crystalline silicon. The silicon atom has 14 electrons, four of which are valence electrons, which can participate in the interaction with other atoms, being them of silicon or other elements. In a crystal of pure silicon, each atom is covalently bonded to four other atoms: thus two adjacent atoms of a crystal of pure silicon have in common a pair of electrons, one of which belongs to the atom in question and the other the atom nearby (Fig. 1).

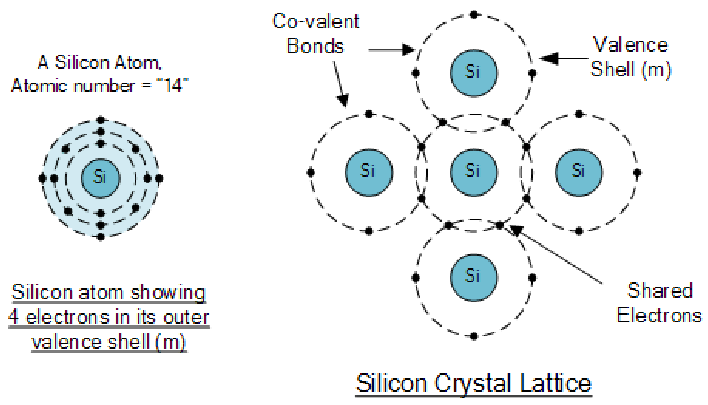

Figure 1: Sketch of Si atom (left) and of Si –Si bond in a pure Si single crystal (right).

Therefore, there is a strong electrostatic bond between an electron and the two atoms. A certain quantity of energy can enable electrons to move to a higher energy level: from the valence band to the conduction band by overcoming the forbidden energy gap. The required energy for silicon is 1.1 eV (eV means electron volts, 1 eV = 1.602 * 10^{19} J). If this energy is provided to the Si crystal, the electron is brought to a higher energy level (conduction band) where it is free to move and to contribute to the current flow.

When an electron is promoted to the conduction band, a hole is left in the valence band, where an electron is missing. Therefore, when a light flux invests the crystal lattice of the silicon, a number of electrons is released and an equal number of holes is formed. In the process of recombination, each electron in the vicinity of a hole can occupy it, by releasing a portion of its kinetic energy in the form of heat.

A coherent motion of electrons (and holes), called current, must be created to exploit electrical energy. Inside the cell, this is made by means of an internal electric field. The field is realized with special physical and chemical treatments: in particular, an excess of positively charged atoms in a part of the semiconductor and an excess of negatively charged atoms in the other are created (this is called a *pn* junction).

In order to produce a *pn* junction, it is necessary to introduce into silicon a small amount of atoms belonging to the third or fifth group of the periodic system of the elements to obtain two different structures, one with an insufficient number of electrons, the other with an excessive number of electrons with respect to intrinsic silicon. This treatment is called doping and the amount of introduced impurities is of the order of one part per million. Generally, boron (third group) and phosphorus (fifth group) are used to obtain *p*-type (with an excess of holes) and *n*-type (with an excess of electrons) Si, respectively.

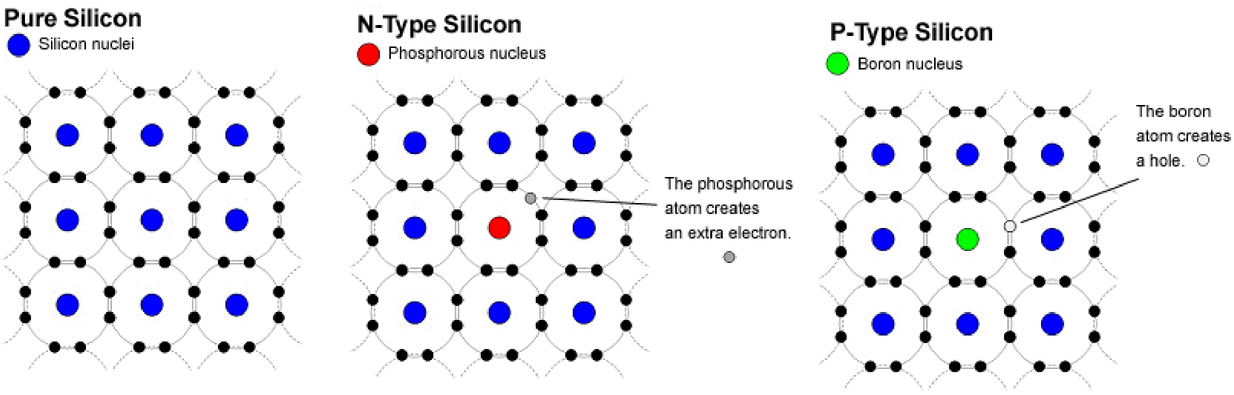

Figure 2: Sketch of the chemical bonds in intrinsic Si, (left), n-type Si (center) and p-type Si (right).

In the layer doped with phosphorus, which has five valence electrons instead of the four electrons of intrinsic silicon, a weakly bound negative excess charge (electron) is present; while a weakly bound excess positive charge (hole) is present in the layer doped with boron, which has three valence electrons. The layer with a number of excess electrons is denoted by *n*, while the one with a number of excess holes with *p* (Fig. 2). These two regions form the *pn* junction.

In both cases the material is electrically neutral; however, by placing in contact the two types of structures, an electronic flow between the two layers (from zone *n* to zone *p*) is activated: once the electrostatic balance is reached, there is an excess of fixed positive charge in the *n*-zone (due to the positively ionized phosphorus atoms without an electron) and an excess of fixed negative charge in the *p*-zone (due to the fixed negatively ionized boron atoms with an extra electron). In other words, the electrons present in the *n*-type silicon move for a short distance in the *p*-type silicon: the *n*-type silicon get positively charged, the *p*-type get negatively charged and an intermediate region called *depletion region* (which is depleted of free carriers) or space charge is created (Fig. 3). The result is that an internal electric field is generated in a region of a few micrometers within the device.

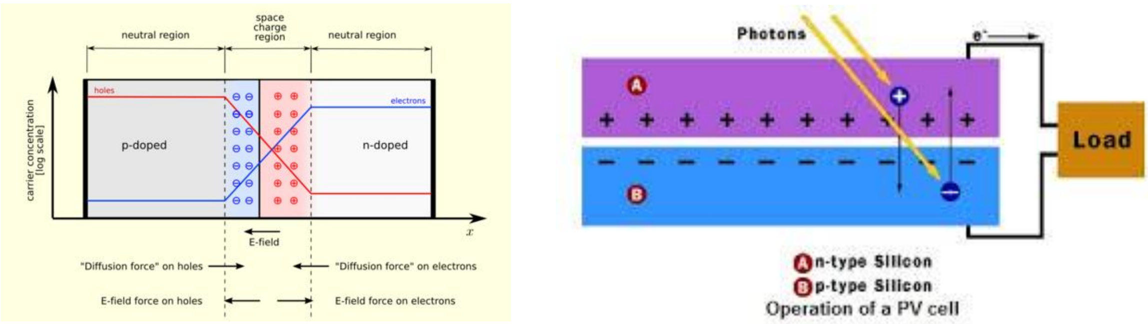

Figure 3: Sketch of a pn junction (right), sketch of the photo generation process (left).

When the *pn* junction is illuminated, electron-hole pairs are generated both in zone *n* and *p* (fig 3b). The electric field separates the electrons and holes which travel in opposite directions (the electrons towards the *n*-zone and the holes toward the *p*-zone).

If the *pn* junction is connected with a load, a flow of electrons from *n*-layer (greater potential) to the *p*-layer (lower potential) is generated in the external circuit. As far as the cell is exposed to light, free carriers flow regularly in the form of continuous current. It is important that the thickness of the *top layer* is small enough to ensure the maximum absorption of incident photons in close to the junction. For silicon, this thickness must be 0.5 mm, while the total thickness of the cell must not exceed 250 mm.

Summarizing: the conversion from solar to electrical energy carried out by the photovoltaic cell is based on the fact that free charge carriers (electrons and holes) are generated by light and pushed in opposite directions by the internal electric field created through the junction. The charges cannot change direction due to the presence of the electric field which prevents them from recombining. The holes travel towards one side of the cell and the electrons towards the other. If the two sides (top and bottom of the cell) are connected to a load, an electric current can be obtained. As far as the cell is exposed to light, charged carriers flow and form a continuous current. Therefore, a solar cell behaves like a current generator (Fig. 4).

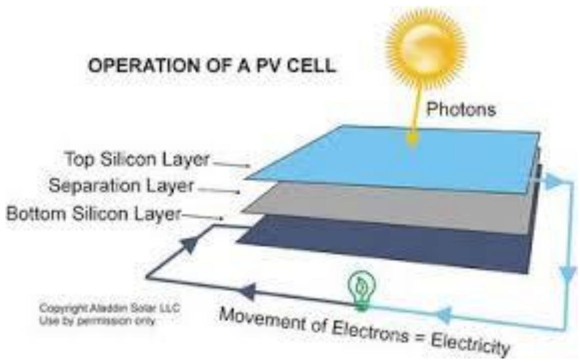

Figure 4: Principle of operation of a solar cell.

The solar cell is able to convert only a certain fraction of the total solar energy. The fraction of the electrical power obtained over the total incident power is defined as the conversion efficiency. The conversion efficiency for silicon commercial cells is generally between 15% and 20%, while high efficiency solar cells for space application reach values around 45%.

The reasons for the limited efficiency of Si based solar cells are numerous and can be grouped into four categories:

- reflection: not all the photons impinging over the cell are absorbed as some of the photons can be reflected by the surface or impinge over the metal contacts;
- photons of too high or too low energy: in order to jump from the valence band to the conduction band, a certain energy is required (above 1.1 eV for Si) and not all the incident photons have sufficient energy. On the other hand, photons with excess energies generate energetic electrons which rapidly thermalize with the crystal lattice, losing their energy in form of heat;
- recombination: not all the generated electron-hole pairs are collected by the electric field of the junction and sent to the external load since they may recombine with opposite charges in the path from the point of generation to the junction;
- parasitic resistance: the charges generated and collected by the electric field in the depletion region must be collected by the external contacts. The contacts are usually made by Si-Al alloys. However, a certain resistance at the interface remains, which causes loss of current, thus reducing the power transferred to the load.

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