

5. Semiconductors and P-N junction

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Learning Outcomes

- Get the picture of a silicon crystal
- Understand the concept of the energy band diagram
- Figure out the movement of charge carriers in a crystal
- Recognize an intrinsic semiconductor
- Comprehend an n-type and a p-type extrinsic semiconductor
- Recognize the p-n junction under thermal equilibrium
- Realise the p-n junction behaviour when applying a DC-voltage
- Understand the physical mechanism within the p-n junction under sunlight

Physical background of semiconductors

The silicon crystal

In 2013, the global annual photovoltaic (PV) production was close to 40 GWp. 90% of the fabricated PV modules are based on silicon elements [1]. It is then understood that most of the solar cells fabricated today use silicon as their base material. Thus, in order to understand the underlying principle of solar cell power, we must focus our attention on the silicon crystal.

A crystal is characterized by a regular and ordered arrangement of its atoms. Its lattice results from a periodic repetition of an elementary geometric pattern in all three dimensions of the space.

The silicon crystal is solid, dark gray and has a mass/volume of 2.328 g/cm^3 . It presents a diamond like lattice. The coherence of the silicon crystal is ensured by covalent bounds linking each atom to its four nearest neighbours. Such bounds results from the fact that two atoms share two valence electrons. Valence electron means an electron in the outer shell of the atom. Fig. 1 represents a 2-D plane of the crystal: at a given time, the valence electrons a and b (having opposite spin) must be considered to belonging to both atom 1 and atom 2.

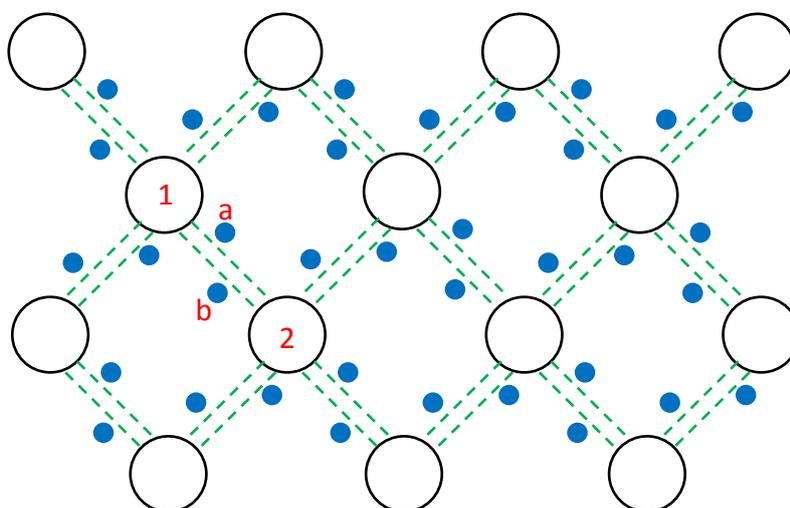


Fig. 1: 2-D representation of the silicon lattice

All electrons are necessary to ensure all the bounds, or, in other words, the coherence of the crystal; but this does not mean that the electrons cannot move individually from one bound to another. Each time an electron changes a bound, it is then replaced by another electron. We can say that the valence electrons are enslaved to a given task, but they are free to move.

The energy bands

The Bohr model tells us that the electrons from the silicon **atom** can only take on certain discrete values of energy. Within the silicon **crystal**, the energy levels are modified compared to those of a single isolated atom. This is particularly true for the valence electrons. The valence electrons need to ensure the bounds while, at the same time, they can move around the crystal like gas molecules in a closed volume. Due to this delocalisation of the valence electrons, the rules of quantum mechanics imply that the initial energy levels are separated into energy bands that consist of all the possible energy levels. We can distinguish two bands, the valence band and the conduction band (see Fig. 2). The energy band between the valence band and the conduction band is called bandgap and within this bandgap no energy levels are allowed. This bandgap is about 1.1eV at ambient temperature for a silicon crystal.

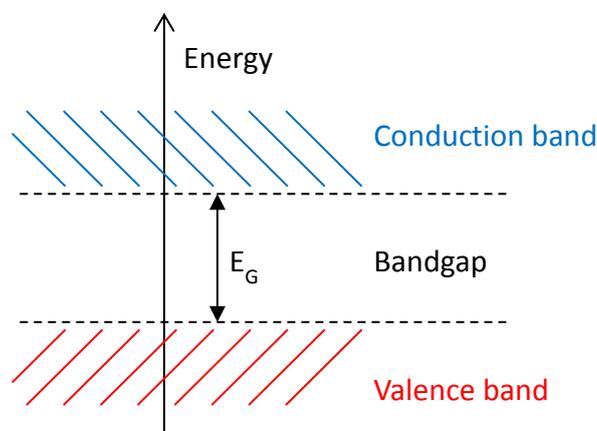


Fig. 2: Energy band representation of a silicon crystal

Charge carriers

Assuming zero temperature, all electrons of the crystal are bound, all the states in the valence band are occupied and, consequently, all the states in the conduction band are unfilled. If we apply an electric field to the crystal, no current will flow since all allowed states are occupied. At zero Kelvin, the silicon crystal is a perfect isolator.

When temperature changes, some of the valence electrons get enough thermal energy to break the bound and become free electrons (they are no more enslaved to the task of ensuring the coherence of the crystal). A schematic view is show in the Fig. 3.

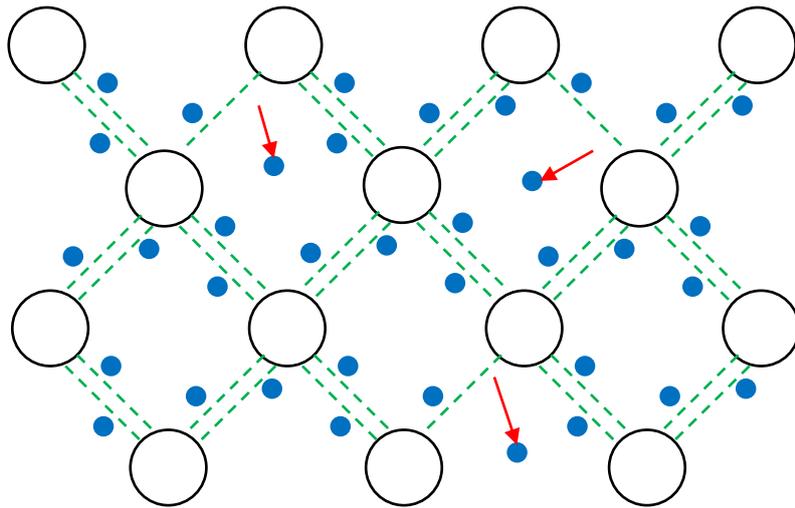


Fig. 3: Free electrons in a silicon crystal

The thermal energy must be higher than the bandgap E_G for the electrons to occupy a state in the conduction band. Correspondingly, they leave free states behind in the valence band. A schematic presentation is given in the Fig. 4.

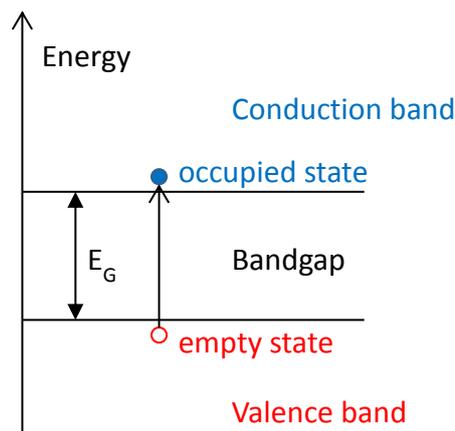


Fig. 4: Energy band diagram

Now, let us see what happens when an electric field is applied. The number of free electrons occupying the states in the conduction band is much lower compared to all the states available in the conduction band. Consequently, they will move when an electric field is applied, resulting in a global charge transfer corresponding to an electric current. Furthermore, the presence of unoccupied states in the valence band allows the electrons in the valence band – these electrons are also subject to the macroscopic applied electric field – to contribute to the global charge transfer (and to the current). This way, the unoccupied states move in the opposite direction. This mechanism is highlighted in Fig. 5.

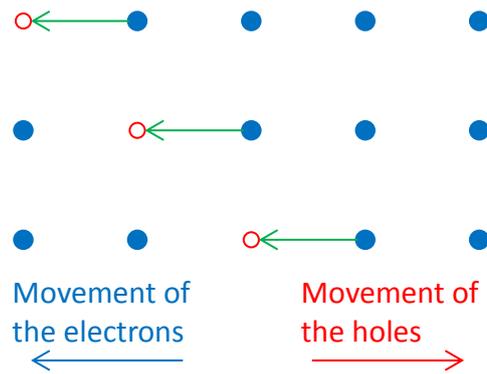


Fig. 5: Movement of electrons and holes in a silicon crystal

The number of the unoccupied states is small compared to the number of the electrons in the valence band. It is very common to consider these unoccupied states as free particles (such as the electrons in the conduction bands) with opposite charge. These unoccupied states are called **holes**. A hole has a positive charge q equal to $1.6 \times 10^{-19}\text{C}$, the same amount as an electron charge, but has opposite sign.

We can conclude that in a silicon crystal (semiconductor) the charge transport (the current flow) is realised by two types of carriers:

- free electrons with negative charge $-q$ that move (occupy the states) in the conduction band
- free holes with positive charge $+q$ that move (occupy the states) in the valence band

The intrinsic semiconductor

Absolutely pure semiconductors without any impurities inside the crystal lattice are called intrinsic. The fundamental characteristic of a pure semiconductor is the absolute equality of the number of free electrons and free holes at any temperature. These carriers are thermally or optically (absorption of a photon – the fundamental process in a PV cell) generated.

The concentration (number per unit volume) n of the free electrons and p of the free holes are equal and called the intrinsic carrier density.

$$n = n_i = p$$

It can be shown that: $n_i = A T^{\frac{3}{2}} \exp\left(-\frac{E_G}{2kT}\right)$

With: T: Temperature

E_G : Bandgap

k: Boltzmann constant

A: constant

As can be seen from the above expression, n_i is strongly temperature dependent. Consequently, the resistivity of an intrinsic semiconductor decreases rapidly when the temperature increases due to the strong increase of the number of created electron-hole pairs.

At ambient temperature (300 K), the intrinsic carrier density of silicon is $n_i = 1.45 \times 10^{10} \text{ cm}^{-3}$. It can be considered to be very small compared to the number of atoms in a silicon crystal (equal to $5 \times 10^{22} \text{ cm}^{-3}$).

The extrinsic semiconductor

An extrinsic semiconductor or doped semiconductor is obtained by introducing well defined impurities (in a well-controlled manner) in an intrinsic semiconductor. The aim of this process is to modify the electrical characteristic of the semiconductor and it is the most fundamental step in the creation of electron devices.

n-type semiconductor

Hypothesise that we dope the silicon crystal using an element from the 5th column of the periodic table {e.g. phosphorus (P) or arsenic (As)}.

The impurities are placed inside the crystal lattice by substitution as shown in Fig. 6:

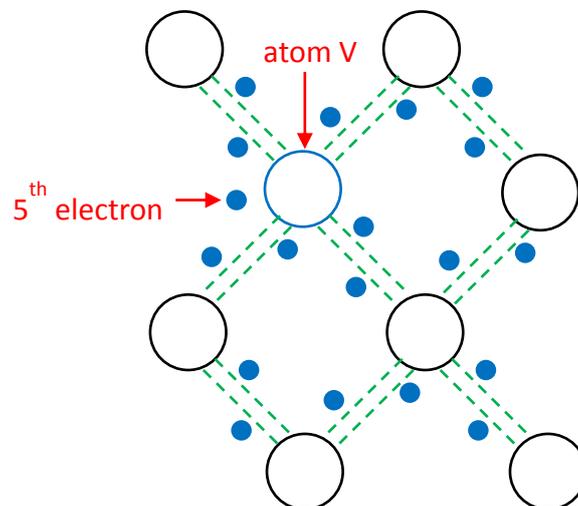


Fig. 6: Schematic presentation of n-doped silicon

An element of the fifth column is pentavalent, meaning that it has five electrons in its outer shell. Four of them are used to ensure the covalent bonds with the four other neighbouring Si-atoms. The 5th electron does not take part to the cohesion of the crystal, it is only very weakly bound to its original atom and a very low additional (mostly thermal) energy is sufficient to make it completely unbound, meaning that it can contribute to charge conduction.

The remaining impurity is qualified as donor and is now a positive charge fixed ion.

In a wide temperature range (from 150 K to 600 K), the number of free electrons is much larger than the number of free holes. For that reason, these free electrons are called majority carriers and the holes minority carriers. This semiconductor is called n-type.

p-type semiconductor

Consider now the doping of silicon by using an atom of the 3rd column of the periodic table {e.g. boron (B)}. Here again, the doping atoms are placed inside the crystal by substitution of the original atoms, as shown in the figure 7:

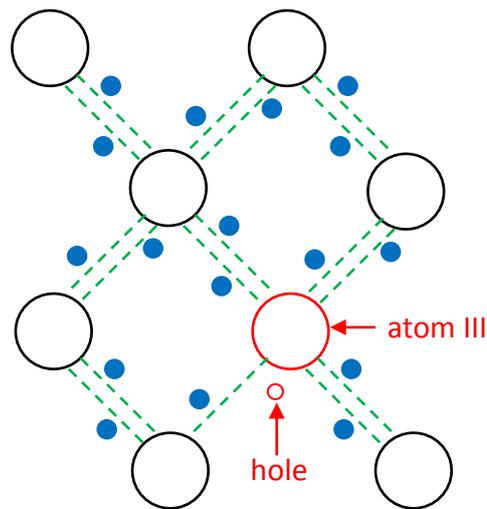


Fig. 7: Schematic presentation of p-doped silicon

With three electrons on its outer shell, the element of the 3rd column (trivalent) can only satisfy three covalent bounds of its four neighbouring atoms. The 4th bound is not complete, a void exists.

A very small amount of energy permits a valence electron to fill in this void, which thereby has moved. A hole has been created that can participate to charge conduction.

The remaining impurity is qualified as acceptor and is now a negative charge fixed ion.

As with the n-type material, but in an opposite manner, here the number of free holes is much larger than the number of free electrons in a wide temperature range. For that reason, these holes are called majority carriers and the electrons are called minority carriers. This semiconductor is called p-type.

The p-n junction

The p-n junction at thermal equilibrium

The thermal equilibrium is defined by a constant temperature distribution and no electrical, optical, mechanical or chemical excitation is applied from the outside world.

The thermal equilibrium is a dynamic state in which each phenomenon is compensated by its inverse phenomenon. Thus, at each point in time, the number of generated carriers is compensated by the same number of recombination; the flux of electrons (or holes) in one direction is exactly compensated by the same flux of the same type of carriers in the other direction.

Now, let us proceed with a qualitative study of the p-n junction.

Hypothesize that we are realizing a p-n junction by bringing together two regions: one region is n-type doped and the other region is p-type doped. Both regions were electrically neutral. We consider constant doping for the sake of simplification. Each region has a large number of majority carriers (nearly as many as ionized impurities or dopants) and a very small number of minority carriers, in such a way that the following relationship holds:

$$n * p = n_i^2$$

A schematic representation of each region is shown in Fig. 8. The ionized fixed impurities, the majority carriers and the minority carriers are represented in each region.

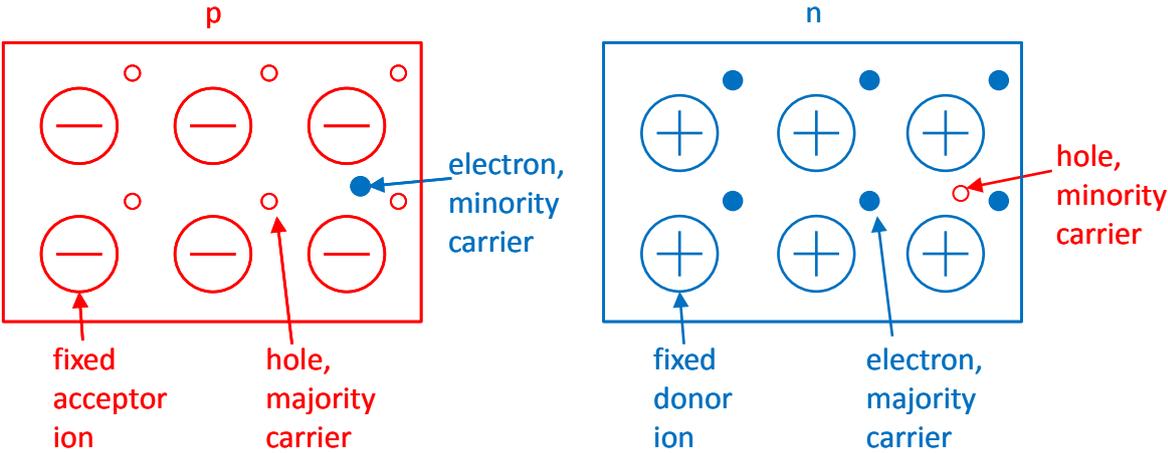


Fig. 8: Schematic presentation of the p-region and the n-region

Each region is electrically neutral, so we can write:

For the p-region (with p: majority carrier, n: minority carrier, N_A : ionized fixed impurities):

$$p - n - N_A = 0$$

For the n-region (with n: majority carrier, p: minority carrier, N_D : ionized fixed impurities):

$$p - n + N_D = 0$$

Now, hypothesize that both regions are brought into contact. A huge gradient of the carrier concentration appears at the border of the two regions. Consequently, an enormous carrier

flux of electrons and holes turns up in such a way, that the carriers tend to generate a uniform distribution of the concentration of each carrier inside the structure (Fig. 9).

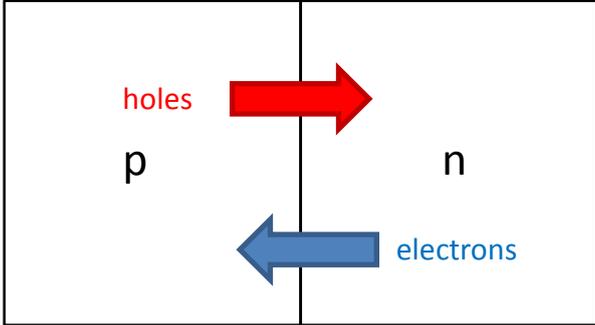


Fig. 9: Schematic presentation of the carrier flux

However, the uniformity is never reached, because another phenomenon impedes this tendency. In fact, the holes are diffusing from the p-type region versus the n-type region and the electrons are diffusing from the n-type region versus the p-type region; they let behind ionized fixed impurities (the respective dopants) whose charge is not compensated anymore.

Thus, a space charge region will arise on each side of the junction (Fig. 10):

- it is positive near the junction in the n-type region due to ionized positive donors
- it is negative near the junction in the p-type region due to ionized negative acceptors

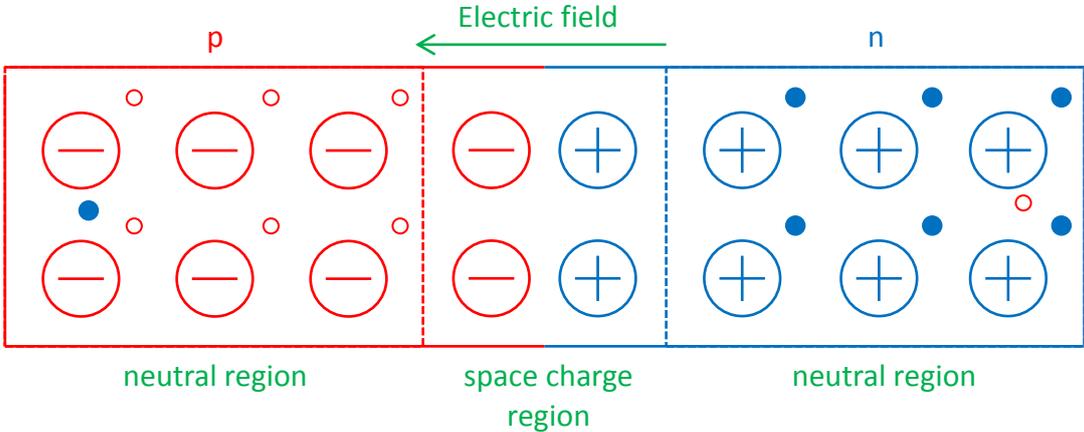


Fig. 10: Schematic presentation of the space charge region inside the p-n junction

Due to the space charge region, an electric field is created oriented from the n-type region opposing the p-type region. It results to an internally potential distribution, also called “built-in” potential. The electric field tends to repel the holes in the p-type region and the electrons in the n-type region. It attenuates the **diffusion** process of both types of **majority** carriers. At the same time, it causes the movement of the **minority** carriers by **conduction**; the holes move from the n-type region to the p-type region, the electrons the other way around.

The thermal equilibrium is reached when the tendency of electrons and holes to continue diffusing down their respective concentration gradients is cancelled out by the electric field repelling the diffusion of majority carriers. Under this condition, there are no more free carriers close to the border of the junction and a so-called depletion region is created.

The biased p-n junction

Now let us apply an external positive voltage to the p-side and a negative voltage to the n-side (Fig. 11)

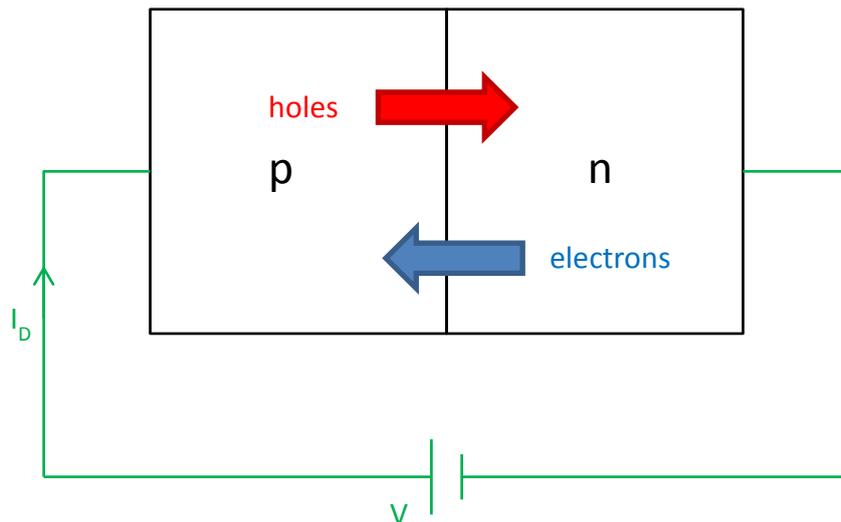


Fig. 11: Schematic of a voltage source applied to the p-n junction

This external voltage, also called forward bias, reduces the internal electric field and, consequently, the “built-in” potential. Thus, the majority carriers can diffuse over the junction resulting in a direct or forward current flow.

On the other hand, when we are inverting the external voltage, we are increasing the internal potential barrier, the “built-in” voltage and no diffusion current can flow anymore. Only the minority carriers that are present on each region will contribute to the current by conduction. The number of these carriers is very small; they are due to thermally generated electron/hole pairs and the resulting current flow is most of the time negligible. That way the p-n junction is a diode, an electronic device that conducts the current in one direction only.

Fig. 12 shows the diode characteristic. The current I_D increases when a positive bias is applied, especially when the built-in voltage of roughly 0.6 V is offset - but under negative bias the reverse current is negligible and equal to the saturation current I_S .

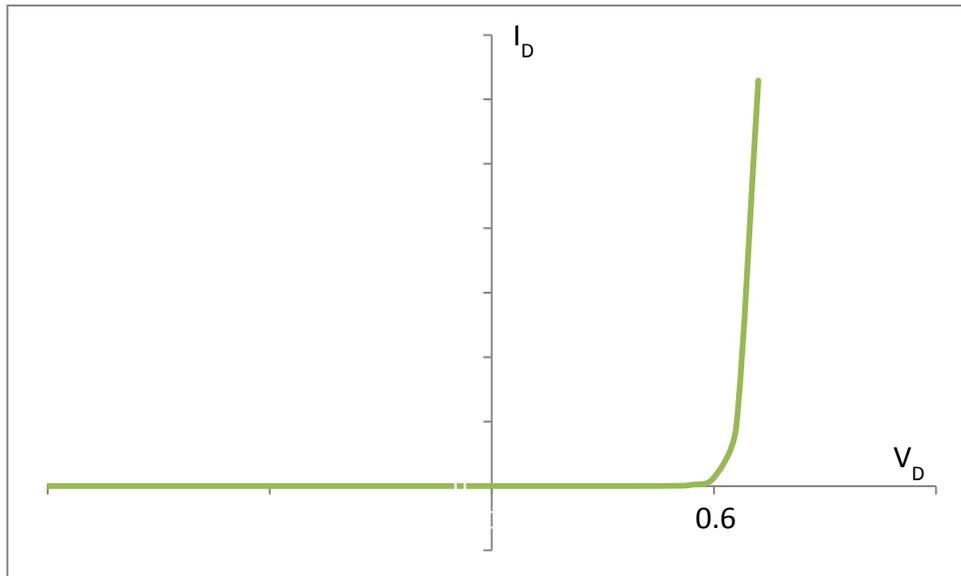


Fig. 12: Current-voltage characteristic of the diode

Applied semiconductor physics give us the following relationship for the current-voltage characteristic of the p-n junction:

$$I_D = I_S \left(e^{\frac{qV}{kT}} - 1 \right)$$

where q is the charge on an electron, k is Boltzmann's constant, T is the absolute temperature and I_S the saturation current.

We will see in the next section why all this theory about majority and minority carriers, electrons and holes, space charge region and built-in potential is essential for revealing the secrets of photovoltaics.

The p-n junction under sunlight

We have already discussed the creation of electron-hole pairs in a crystal by thermal excitation. It is also possible to create electron-hole pairs when the crystal interacts with photons. These mechanisms are highlighted in Fig. 13.

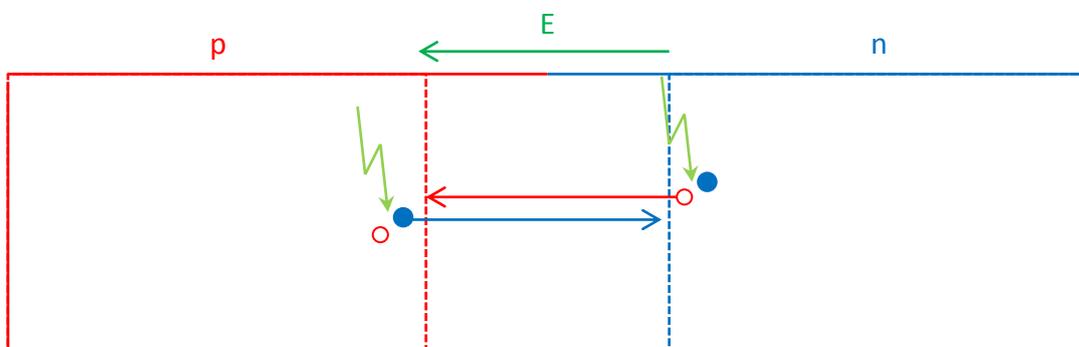


Fig. 13: Schematic representation of an creation by photons of electron-hole pairs

In fact, if the energy of the photon is high enough (greater than the bandgap), this energy can be absorbed through the creation of an electron-hole pair: an electron from the valence band is brought to the conduction band leaving behind a hole. Both carriers have now enough energy to be considered as free and they can move around (they have a lifetime of about $1\mu\text{s}$, and then they recombine.) If the created electrons come close to the depletion region in the p-type region where they are minority carriers, they will be accelerated by the internal electric field and swept over to the depletion region; the same is true for holes arriving on the n-side of the depletion region. Both carrier types contribute to charge transport and this mechanism can be considered as a current generator and is electrically represented as a current source.

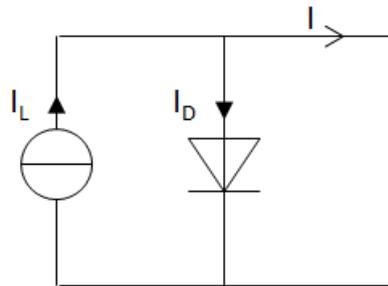


Fig. 14: Equivalent circuit of the p-n junction under sunlight

Fig. 14 shows an equivalent circuit summarizing the cell's behaviour. We can see a diode symbol representing the current-voltage characteristic without sunlight; we added a current source representing the light-generated current I_L .

Without any light and under external bias condition, the cell behaves like any semiconductor diode and the current I_D is flowing from anode to cathode. Under sunlight, electron-hole pairs are created and are generating a current I_L as indicated by the arrow. At constant temperature insolation conditions, I_L is constant.

We can calculate the current I , flowing out of the solar cell, using Kirchhoff's current law:

$$I = I_L - I_D$$

and using the expression above:

$$I = I_L - I_S \left(e^{\frac{qV}{kT}} - 1 \right)$$

Finally, the current-voltage characteristic of the solar cell is sketched in Fig. 15.

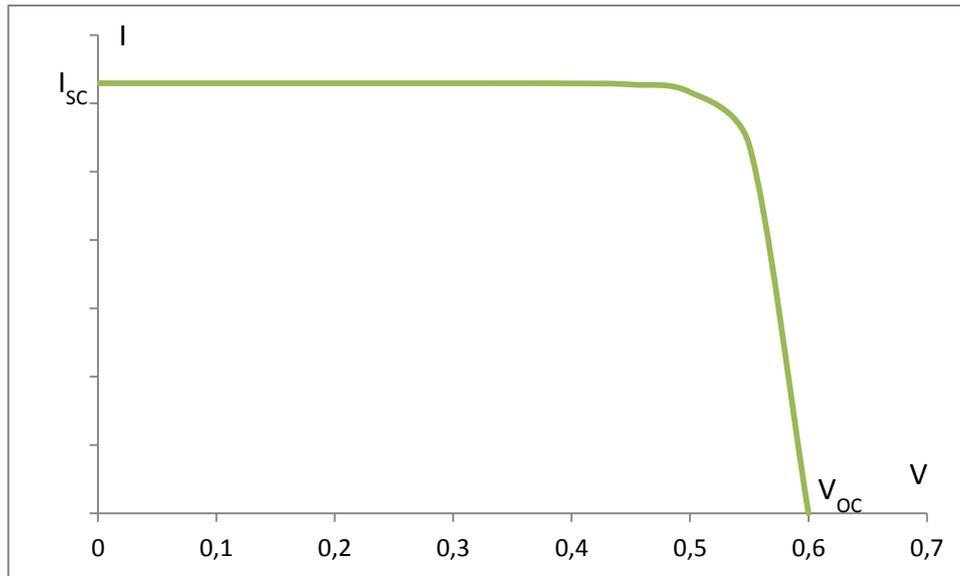


Fig. 15: Current-voltage characteristic of the solar cell

From Fig. 15, we can determine two fundamental characteristic figures of importance to the function of a solar cell:

- (i) The maximum voltage (or open-circuit voltage, V_{oc}) produced by a silicon solar cell is about 0.6 V; this implies that many cells must be connected in series to provide the higher voltages required for most applications.
- (ii) Under constant insolation, the current is constant over a wide range: the solar cell can be considered as a current source. Furthermore, the maximum cell current also defined as its short-circuit current (I_{sc}) and is given by the intercept on the current axis. I_{sc} depends on temperature and insolation strength.

A detailed study of the electrical characteristics of solar cells and modules is given in chapter 7.

References

- [1] Fraunhofer Institute for Solar Energy Systems ISE, “Photovoltaics Report”, 24 October 2014, <http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf>
- [2] Philippe Cazenave, “Physique des matériaux semiconducteurs”, Fascicule de cours, Université de Bordeaux 1, filière EEA – Licence, 1998
- [3] Philippe Cazenave, “La jonction pn”, Fascicule de cours, Université de Bordeaux 1, filière EEA – Licence, 1997
- [4] Paul A. Lynn, Electricity from Sunlight: “An Introduction to Photovoltaics”, John Wiley & Sons, 2010
- [5] Hans K. Köthe, “Stromversorgung mit Solarzellen”, Franzis-Verlag GmbH, Feldkirchen, 1996