3

The Working Principle of a Solar Cell

In this chapter we present a very simple model of a solar cell. Many notions presented in this chapter will be new but nonetheless the general idea of how a solar cell works should be clear. All the aspects presented in this chapter will be discussed in greater detail in the following chapters.

The working principle of solar cells is based on the *photovoltaic effect*, *i.e.* the generation of a potential difference at the junction of two different materials in response to electromagnetic radiation. The photovoltaic effect is closely related to the photoelectric effect, where electrons are emitted from a material that has absorbed light with a frequency above a material-dependent threshold frequency. In 1905, Albert Einstein understood that this effect can be explained by assuming that the light consists of well defined energy quanta, called *photons*. The energy of such a photon is given by

$$E = h\nu, \tag{3.1}$$

where h is Planck's constant and ν is the frequency of the light. For his explanation of the photoelectric effect Einstein received the Nobel Prize in Physics in 1921 [23].

The photovoltaic effect can be divided into three basic processes:

1. Generation of charge carriers due to the absorption of photons in the materials that form a junction.

Absorption of a photon in a material means that its energy is used to excite an electron from an initial energy level E_i to a higher energy level E_f, as shown in Fig. 3.1 (a). Photons can only be absorbed if electron energy levels E_i and E_f are present so that their difference equals the photon energy, $h\nu = E_f - E_i$. In an ideal semiconductor electrons can populate energy levels below the so-called *valence band* edge, E_V, and above the so called *conduction band* edge, E_C. Between those two bands no allowed energy states exist, which could be
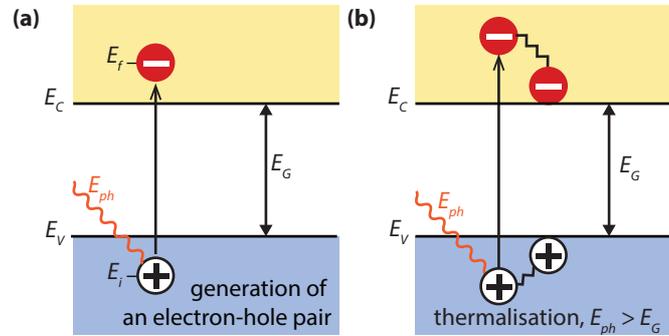
Figure 3.1: (a) Illustrating the absorption of a photon in a semiconductor with bandgap E_G. The photon with energy $E_{\mathrm{ph}} = h\nu$ excites an electron from E_i to E_f. At E_i a hole is created. (b) If $E_{\mathrm{ph}} > E_G$, a part of the energy is thermalised.

populated by electrons. Hence, this energy difference is called the *bandgap*, $E_G = E_C - E_V$. If a photon with an energy smaller than E_G reaches an ideal semiconductor, it will not be absorbed but will traverse the material without interaction.

In a real semiconductor, the valence and conduction bands are not flat, but vary depending on the so-called k-vector that describes the momentum of an electron in the semiconductor. This means, that the energy of an electron is dependent on its momentum because of the periodic structure of the semiconductor crystal. If the maximum of the valence band and the minimum of the conduction band occur at the same k-vector, an electron can be excited from the valence to the conduction band without a change in the momentum. Such a semiconductor is called a *direct bandgap* material. If the electron cannot be excited without changing its momentum, we speak of an *indirect bandgap* material. The electron can only change its momentum by momentum exchange with the crystal, *i.e.* by receiving momentum from or giving momentum to vibrations of the crystal lattice. The absorption coefficient in a direct bandgap material is much higher than in an indirect bandgap material, thus the absorbing semiconductor, often just called the *absorber*, can be much thinner [24].

If an electron is excited from E_i to E_f, a void is created at E_i. This void behaves like a particle with a positive elementary charge and is called a *hole*. The absorption of a photon therefore leads to the creation of an electron-hole pair, as illustrated in Fig. 3.2 ❶. The *radiative energy* of the photon is *converted* to the *chemical energy* of the electron-hole pair. The maximal conversion efficiency from radiative energy to chemical energy is limited by thermodynamics. This *thermodynamic limit* lies in between 67% for non-concentrated sunlight and 86% for fully concentrated sunlight [25].

The basic physics required for describing semiconductors is presented in chapter 6.

2. Subsequent separation of the photo-generated charge carriers in the junction.

Usually, the electron-hole pair will recombine, *i.e.* the electron will fall back to the initial energy level E_i, as illustrated in Fig. 3.2 ❷. The energy will then be released either as photon (*radiative recombination*) or transferred to other electrons or holes or lattice vibrations (*non-*
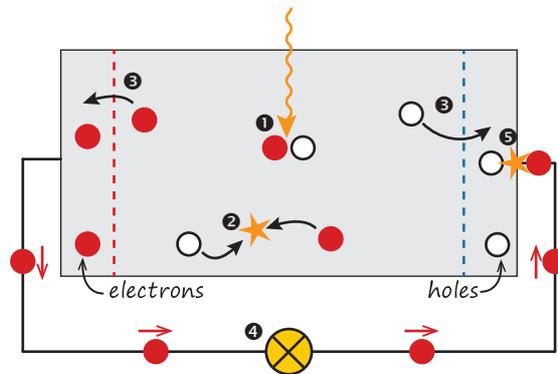
Figure 3.2: A very simple solar cell model. ❶ Absorption of a photon leads to the generation of an electron-hole pair. ❷ Usually, the electrons and holes will recombine. ❸ With semipermeable membranes the electrons and the holes can be separated. ❹ The separated electrons can be used to drive an electric circuit. ❺ After the electrons passed through the circuit, they will recombine with holes.

radiative recombination). If one wants to use the energy stored in the electron-hole pair for performing work in an external circuit, *semipermeable membranes* must be present on both sides of the absorber, such that electrons only can flow out through one membrane and holes only can flow out through the other membrane [25], as illustrated in Fig. 3.2 ❸. In most solar cells, these membranes are formed by *n*- and *p*-type materials.

A solar cell has to be designed such that the electrons and holes can reach the membranes before they recombine, *i.e.* the time it requires the charge carriers to reach the membranes must be shorter than their lifetime. This requirement limits the thickness of the absorber.

We will discuss generation and recombination of electrons and holes in detail in chapter 7.

3. Collection of the photo-generated charge carriers at the terminals of the junction.

Finally, the charge carriers are extracted from the solar cells with electrical contacts so that they can perform work in an external circuit (Fig. 3.2 ❹). The *chemical energy* of the electron-hole pairs is finally converted to *electric energy*. After the electrons passed through the circuit, they will recombine with holes at a metal-absorber interface, as illustrated in Fig. 3.2 ❺.

Loss mechanisms

The two most important *loss mechanisms* in single bandgap solar cells are the inability to convert photons with energies below the bandgap to electricity and thermalisation of photon energies exceeding the bandgap, as illustrated in Fig. 3.1 (b). These two mechanisms alone amount to the loss of about half the incident solar energy in the conversion

process [26]. Thus, the maximal energy conversion efficiency of a single-junction solar cell is considerably below the thermodynamic limit. This *single bandgap limit* was first calculated by Shockley and Queisser in 1961 [27].

A detailed overview of loss mechanisms and the resulting efficiency limits is discussed in Chapter 10.