

6

Basic Semiconductor Physics

6.1 Introduction

With this chapter we start with the discussion of some important concepts from *semiconductor physics*, which are required to understand the operation of solar cells. After giving a brief introduction into semiconductor physics in this chapter, we will discuss the most important *generation and recombination* mechanisms in Chapter 7. Finally, we will focus on the physics of *semiconductor junctions* in Chapter 8.

The first successful solar cell was made from crystalline silicon (c-Si), which still is by far the most widely used PV material. Therefore we shall use c-Si as an example to explain the concepts of semiconductor physics that are relevant to solar cell operation. This discussion will give us a basic understanding of how solar cells based on other semiconductor materials work.

The *central semiconductor parameters* that determine the design and performance of a solar cell are:

1. Concentrations of doping atoms, which can be of two different types: *donor atoms*, which donate free electrons or *acceptor atoms*, which accept electrons. The concentrations of donor and acceptor atoms are denoted by N_D and N_A , respectively, and determine the width of the space-charge region of a junction, as we will see in Chapter 8.
2. The mobility μ and the diffusion coefficient D of charge carriers is used to characterise the transport of carriers due to drift and diffusion, respectively, which we will discuss in Section 6.5.
3. The lifetime τ and the diffusion length L of the *excess carriers* characterise the recombination-generation processes, discussed in Chapter 7.

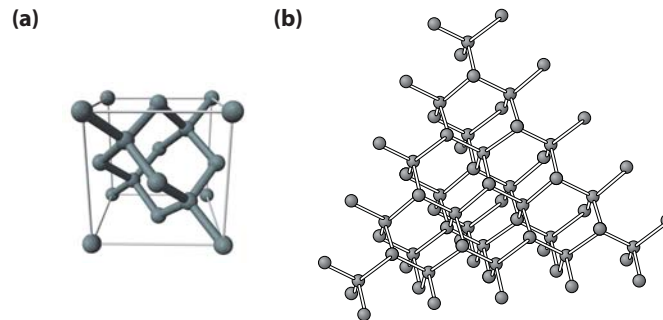


Figure 6.1: (a) A diamond lattice unit cell representing a unit cell of single crystal Si [30], (b) the atomic structure of a part of single crystal Si.

4. The band gap energy E_g , and the complex refractive index $n - ik$, where k is linked to the absorption coefficient α , characterise the ability of a semiconductor to absorb electromagnetic radiation.

6.2 Atomic structure

The *atomic number* of silicon is 14, which means that 14 electrons are orbiting the nucleus. In ground state configuration, two electrons are in the first shell, both in the 1s orbital. Further, eight electrons are in the second shell, two in the 2s and six in the 2p orbitals. Hence, four electrons are in the third shell, which is the outermost shell for a Si atom. Only these four electrons interact with other atoms, for example via forming chemical bonds. They are called the *valence electrons*.

Two Si atoms are bonded together when they share each other's valence electron. This is the so called *covalent bond* that is formed by two electrons. Since Si atoms have four valence electrons, they can be covalently bonded to four other Si atoms. In the crystalline form each Si atom is covalently bonded to four neighbouring Si atoms, as illustrated in Fig. 6.1.

In the ground state, two valence electrons live in the 3s orbital and the other two are present in the three 3p orbitals (p_x , p_y and p_z). In this state only the two electrons in the 3p orbitals can form bonds as the 3s orbital is full. In a silicon crystal, where every atom is *symmetrically* connected to four others, the Si atoms are present as so-called *sp₃ hybrids*. The 3p and 3s orbitals are mixed forming 4 sp₃ orbitals. Each of these four orbitals is occupied by one electron that can form a covalent bond with a valence electron from a neighbouring atom.

All bonds have the same length and the angles between the bonds are equal to 109.5°. The number of bonds that an atom has with its immediate neighbours in the atomic structure is called the *coordination number* or *coordination*. Thus, in single crystal silicon, the coordination number for all Si atoms is four, we can also say that Si atoms are fourfold coordinated. A *unit cell* can be defined, from which the crystal lattice can be reproduced by duplicating the unit cell and stacking the duplicates next to each other. Such a regular atomic arrangement is described as a structure with *long range order*.

A diamond lattice unit cell represents the real lattice structure of monocrystalline silicon. Figure 6.1 (a) shows the arrangement of the unit cell and Fig. 6.1 (b) the atomic structure of single crystal silicon. One can determine from Fig. 6.1 (a) that there are eight Si atoms in the volume of the unit cell. Since the lattice constant of c-Si is 543.07 pm, one can easily calculate that the density of atoms is approximately $5 \times 10^{22} \text{ cm}^{-3}$. Figure 6.1 (a) shows the crystalline Si atomic structure with no foreign atoms. In practice, a semiconductor sample always contains some impurity atoms. When the concentration of impurity atoms in a semiconductor is insignificant we refer to such semiconductor as an *intrinsic semiconductor*.

At practical operational conditions, e.g. at room temperature,¹ there are always some of the covalent bonds broken. The breaking of the bonds results in liberating the valence electrons from the bonds and making them mobile through the crystal lattice. We refer to these electrons as free electrons (henceforth simply referred to as electrons). The position of a missing electron in a bond, which can be regarded as positively charged, is referred to as a hole. This situation can be easily visualised by using the *bonding model* illustrated in Fig. 6.2.

In the bonding model the atomic cores (atoms without valence electrons) are represented by circles and the valence or bonding electrons are represented by lines interconnecting the circles. In case of c-Si one Si atom has four valence electrons and four nearest neighbours. Each of the valence electrons is equally shared with the nearest neighbour. There are therefore eight lines terminating on each circle. In an ideal Si crystal at 0 K all valence electrons take part in forming covalent bonds between Si atoms and therefore no free electrons are present in the lattice. This situation is schematically shown in Fig. 6.2 (a).

At temperatures higher than 0 K the bonds start to break due to the absorption of thermal energy. This process results in the creation of mobile electrons and holes. Figure 6.2 (b) shows a situation when a covalent bond is broken and one electron departs from the bond leaving a so-called *hole* behind. A single line between the atoms in Fig. 6.2 (b) represents the remaining electron of the broken bond. When a bond is broken and a hole created, a valence electron from a neighbouring bond can “jump” into this empty position and restore the bond. The consequence of this transfer is that at the same time the jumping electron creates an empty position in its original bond. The subsequent “jumps” of a valence electron can be viewed as a motion of the hole, a positive charge representing the empty position, in the direction opposite to the motion of the valence electron through the bonds.

Since the breaking of a covalent bond leads to the formation of an electron-hole pair, in intrinsic semiconductors the concentration of electrons is equal to the concentration of holes. In intrinsic silicon at 300 K approximately $1.5 \times 10^{10} \text{ cm}^{-3}$ broken bonds are present. This number then gives also the concentration of holes, p , and electrons, n . Hence, at 300 K, $n = p = 1.5 \times 10^{10} \text{ cm}^{-3}$. This concentration is called the *intrinsic carrier concentration* and is denoted as n_i .

¹In semiconductor physics most of the time a temperature of 300 K is assumed.

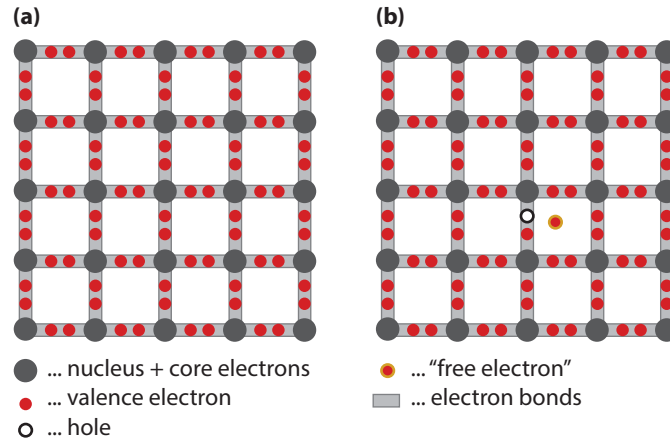


Figure 6.2: The bonding model for c-Si. (a) No bonds are broken. (b) A bond between two Si atoms is broken resulting in a free electron and hole.

6.3 Doping

The concentrations of electrons and holes in c-Si can be manipulated by *doping*. Doping of silicon means that atoms of other elements substitute Si atoms in the crystal lattice. The substitution has to be carried out by atoms with three or five valence electrons, respectively. The most used elements to dope c-Si are boron (B) and phosphorus (P), with atomic numbers of 5 and 15, respectively.

The process of doping action can best be understood with the aid of the bonding model and is illustrated in Fig. 6.3. When introducing a phosphorus atom into the c-Si lattice, four of the five phosphorus atom valence electrons will readily form bonds with the four neighbouring Si atoms. The fifth valence electron cannot take part in forming a bond and becomes rather weakly bound to the phosphorus atom. It is easily liberated from the phosphorus atom by absorbing the thermal energy, which is available in the c-Si lattice at room temperature. Once free, the electron can move throughout the lattice. In this way the phosphorus atom that substitutes a Si atom in the lattice "*donates*" a free (mobile) electron into the c-Si lattice. The impurity atoms that enhance the concentration of electrons are called *donors*. We denote the concentration of donors by N_D .

An atom with three valence electrons such as boron cannot form all bonds with four neighbouring Si atoms when it substitutes a Si atom in the lattice. However, it can readily "*accept*" an electron from a nearby Si-Si bond. The thermal energy that the c-Si lattice contains at room temperature is sufficient to enable an electron from a nearby Si-Si bond to attach itself to the boron atom and complete the bonding to the four Si neighbours. In this process a hole is created that can move around the lattice. The impurity atoms that enhance the concentration of holes are called *acceptors*. We denote the concentration of acceptors by N_A .

Note that by substituting Si atoms with only one type of impurity atoms, the concentration of only one type of mobile charge carriers is increased. Charge neutrality of the

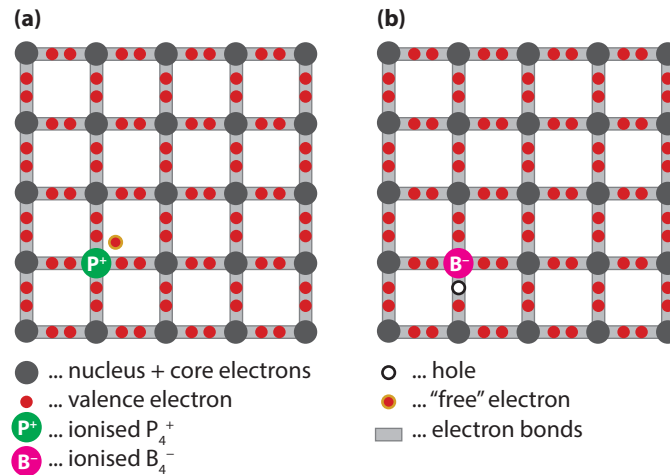


Figure 6.3: The doping process illustrated using the bonding model. (a) A phosphorus (P) atom substitutes a Si atom in the lattice resulting in the positively-ionised P atom and a free electron, (b) A boron (B) atom substitutes a Si atom resulting in the negatively ionised B atom and a hole.

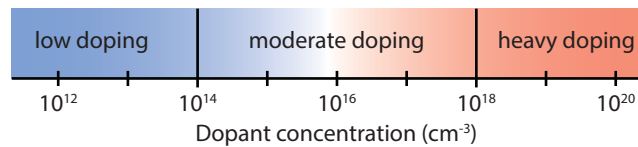


Figure 6.4: The range of doping levels used in c-Si.

material is nevertheless maintained because the sites of the bonded and thus fixed impurity atoms become charged. The donor atoms become positively ionised and the acceptor atoms become negatively ionised.

The possibility to control the electrical conductivity of a semiconductor by doping is one of the most important semiconductor features. The electrical conductivity in semiconductors depends on the concentration of electrons and holes as well as their mobility. The concentration of electrons and holes is influenced by the amount of the doping atoms that are introduced into the atomic structure of the semiconductor. Figure 6.4 shows the range of doping that is used in case of c-Si. We denote a semiconductor as *p*-type or *n*-type when holes or electrons, respectively, dominate its electrical conductivity. In case that one type of charge carriers has a higher concentration than the other type these carriers are called majority carriers (holes in the *p*-type and electrons in the *n*-type), while the other type with lower concentration are then called minority carriers (electrons in the *p*-type and holes in the *n*-type).

6.4 Carrier concentrations

6.4.1 Intrinsic semiconductors

Any operation of a semiconductor device depends on the concentration of carriers that transport charge inside the semiconductor and hence cause electrical currents. In order to determine and to understand device operation it is important to know the precise concentration of these charge carriers. In this section the concentrations of charge carriers inside a semiconductor are derived assuming the semiconductor is under *thermal equilibrium*. The term equilibrium is used to describe the unperturbed state of a system, to which no external voltage, magnetic field, illumination, mechanical stress, or other perturbing forces are applied. In the equilibrium state the observable parameters of a semiconductor do not change with time.

In order to determine the carrier concentration one has to know the function of density of allowed energy states of electrons and the occupation function of the allowed energy states. The density of energy states function, $g(E)$, describes the number of allowed states per unit volume and energy. Usually it is abbreviated with *Density of states* function (DoS). The occupation function is the Fermi-Dirac distribution function, $f(E)$, which describes the ratio of states filled with an electron to total allowed states at given energy E . In an isolated Si atom, electrons are allowed to have only discrete energy values. The periodic atomic structure of single crystal silicon results in the ranges of allowed energy states for electrons that are called *energy bands* and the excluded energy ranges, forbidden gaps or *band gaps*. Electrons that are liberated from the bonds determine the charge transport in a semiconductor. Therefore, we further discuss only those bands of energy levels, which concern the valence electrons. Valence electrons, which are involved in the covalent bonds, have their allowed energies in the *valence band* (VB) and the allowed energies of electrons liberated from the covalent bonds form the *conduction band* (CB). The valence band is separated from the conduction band by a band of forbidden energy levels. The maximum attainable valence-band energy is denoted E_V , and the minimum attainable conduction-band energy is denoted E_C . The energy difference between the edges of these two bands is called the band gap energy or band gap, E_g , and it is an important material parameter.

$$E_G = E_C - E_V. \quad (6.1)$$

At room temperature (300 K), the band gap of crystalline silicon is 1.12 eV. A plot of the allowed electron energy states as a function of position is called the energy band diagram; an example is shown in Fig. 6.5 (a).

The density of energy states at an energy E in the conduction band close to E_C and in the valence band close to E_V are given by

$$g_C(E) = 4\pi \left(\frac{2m_n^*}{h^2} \right)^{\frac{3}{2}} \sqrt{E - E_C}, \quad (6.2a)$$

$$g_V(E) = 4\pi \left(\frac{2m_p^*}{h^2} \right)^{\frac{3}{2}} \sqrt{E - E_V}, \quad (6.2b)$$

where m_n^* and m_p^* is the *effective mass* of electrons and holes, respectively. As the electrons and holes move in the periodic potential of the c-Si crystal, the mass has to be replaced

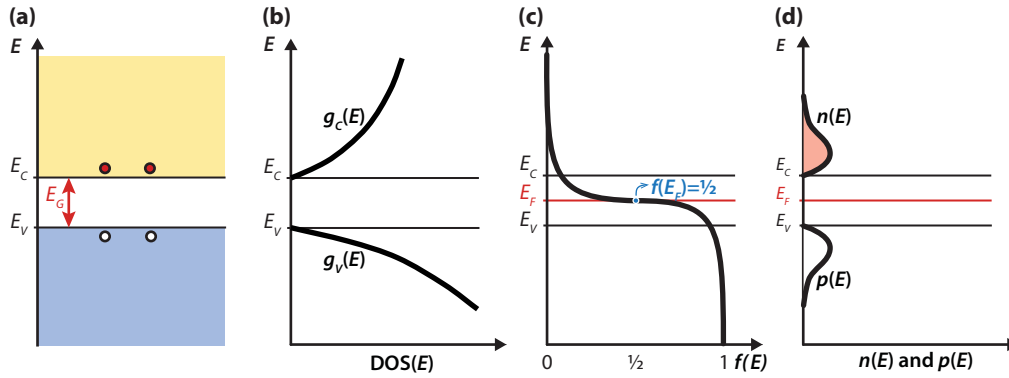


Figure 6.5: (a) The basic energy band diagram with electrons and holes indicated in the conduction and valence bands, respectively. (b) The density of states (DOS) functions g_C in the conduction band and g_V in the valence band. (c) The Fermi-Dirac distribution. (d) The electron and hole densities in the conduction and valence bands, respectively, obtained by combining (b) and (c).

by the effective mass, which takes the effect of a periodic force into account. The effective mass is also averaged over different directions to take anisotropy into account. Both g_C and g_V have a parabolic shape, which is also illustrated in Fig. 6.5 (b).

The Fermi-Dirac distribution function is given by

$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)}, \quad (6.3)$$

where k_B is Boltzmann's constant ($k_B = 1.38 \times 10^{-23}$ J/K) and E_F is the so-called *Fermi energy*. $k_B T$ is the *thermal energy*, at 300 K it is 0.0258 eV. The Fermi energy — also called *Fermi level* — is the electrochemical potential of the electrons in a material and in this way it represents the averaged energy of electrons in the material. The Fermi-Dirac distribution function is illustrated in Fig. 6.5 (c). Figure 6.6 illustrates the Fermi-Dirac distribution at different temperatures.

The carriers that contribute to charge transport are electrons in the conduction band and holes in the valence band. The concentration of electrons in the conduction band and the total concentration of holes in the valence band is obtained by multiplying the density of states function with the distribution function and integrating across the whole energy band, as illustrated in Fig. 6.5 (d).

$$n(E) = g_C(E)f(E), \quad (6.4a)$$

$$p(E) = g_V(E)[1 - f(E)]. \quad (6.4b)$$

The total concentration of electrons and holes in the conduction band and valence band,

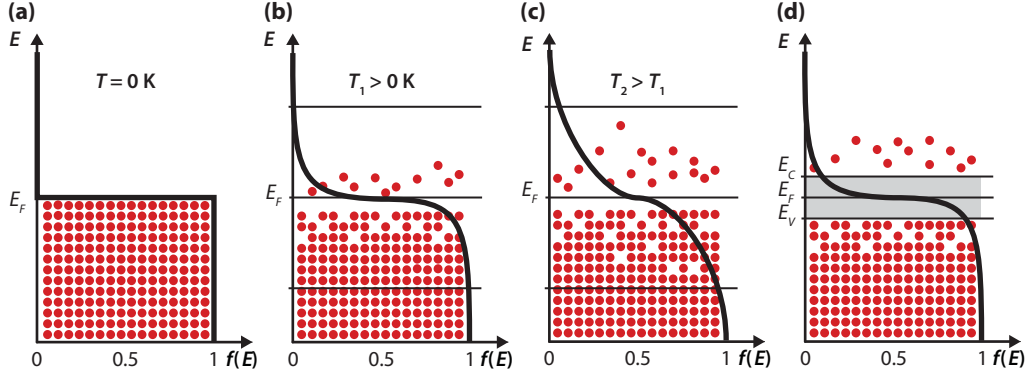


Figure 6.6: The Fermi-Dirac distribution function. (a) For $T = 0$ K, all allowed states below the Fermi level are occupied by two electrons. (b, c) At $T > 0$ K not all states below the Fermi level are occupied and there are some states above the Fermi level that are occupied. (d) In an energy gap between bands no electrons are present.

respectively, is then obtained via integration,

$$n = \int_{E_C}^{E_{\text{top}}} n(E) dE, \quad (6.5a)$$

$$p = \int_{E_{\text{bottom}}}^{E_V} p(E) dE. \quad (6.5b)$$

Substituting the density of states and the Fermi-Dirac distribution function into Eq. (6.5) the resulting expressions for n and p are obtained after solving the equations. The full derivation can be found for example in Reference [24].

$$n = N_C \exp\left(\frac{E_F - E_C}{k_B T}\right) \quad \text{for} \quad E_C - E_F \geq 3k_B T, \quad (6.6a)$$

$$p = N_V \exp\left(\frac{E_V - E_F}{k_B T}\right) \quad \text{for} \quad E_F - E_V \geq 3k_B T, \quad (6.6b)$$

where N_C and N_V are the *effective* densities of the conduction band states and the valence band states, respectively. They are defined as

$$N_C = 2 \left(\frac{2\pi m_n^* k_B T}{h^2} \right)^{\frac{3}{2}} \quad \text{and} \quad N_V = 2 \left(\frac{2\pi m_p^* k_B T}{h^2} \right)^{\frac{3}{2}} \quad (6.7)$$

For crystalline silicon, we have at 300 K

$$N_C = 3.22 \times 10^{19} \text{ cm}^{-3}, \quad (6.8a)$$

$$N_V = 1.83 \times 10^{19} \text{ cm}^{-3}. \quad (6.8b)$$

When the requirement that the Fermi level lies in the band gap more than $3k_B T$ from either band edge is satisfied the semiconductor is referred to as a *nondegenerate* semiconductor.

If an intrinsic semiconductor is in equilibrium, we have $n = p = n_i$. By multiplying the corresponding sides of Eqs. (6.6) we obtain

$$np = n_i^2 = N_C N_V \exp\left(\frac{E_V - E_C}{k_B T}\right) = N_C N_V \exp\left(-\frac{E_g}{k_B T}\right), \quad (6.9)$$

which is independent of the position of the Fermi level and thus valid for doped semiconductors as well. When we denote the position of the Fermi level in the intrinsic material E_{Fi} we may write

$$n_i = N_C \exp\left(\frac{E_{Fi} - E_C}{k_B T}\right) = N_V \exp\left(\frac{E_V - E_{Fi}}{k_B T}\right). \quad (6.10)$$

From Eq. (6.10) we can easily find the position of E_{Fi} to be

$$E_{Fi} = \frac{E_C + E_V}{2} + \frac{k_B T}{2} \ln\left(\frac{N_V}{N_C}\right) = E_C - \frac{E_g}{2} + \frac{k_B T}{2} \ln\left(\frac{N_V}{N_C}\right). \quad (6.11)$$

The Fermi level E_{Fi} lies close to the midgap $[(E_C + E_V)/2]$; a slight shift is caused by the difference in the densities of the valence and conduction band.

6.4.2 Doped semiconductors

It has been already mentioned in Section 6.3 that the concentrations of electrons and holes in c-Si can be manipulated by doping. The concentration of electrons and holes is influenced by the amount of the impurity atoms that substitute silicon atoms in the lattice. Under the assumption that the semiconductor is uniformly doped and in equilibrium a simple relationship between the carrier and dopant concentrations can be established. We assume that at room temperature the dopant atoms are ionised. Inside a semiconductor the local charge density is given by

$$\rho = q(p + N_D^+ - n - N_A^-), \quad (6.12)$$

where q is the elementary charge ($q \approx 1.602 \times 10^{-19}$ C). N_D^+ and N_A^- denote the density of the *ionised donor and acceptor* atoms, respectively. As every ionised atom corresponds to a free electron (hole), N_D^+ and N_A^- tell us the concentration of electrons and holes due to doping, respectively.

Under equilibrium conditions, the local charge of the uniformly doped semiconductor is zero, which means that the semiconductor is charge-neutral everywhere. We thus can write:

$$p + N_D^+ - n - N_A^- = 0. \quad (6.13)$$

As previously discussed, the thermal energy available at room temperature is sufficient to ionise almost all the dopant atoms. We therefore may assume

$$N_D^+ \approx N_D \quad \text{and} \quad N_A^- \approx N_A, \quad (6.14)$$

and hence

$$p + N_D - n - N_A = 0, \quad (6.15)$$

which is the common form of the *charge neutrality equation*.

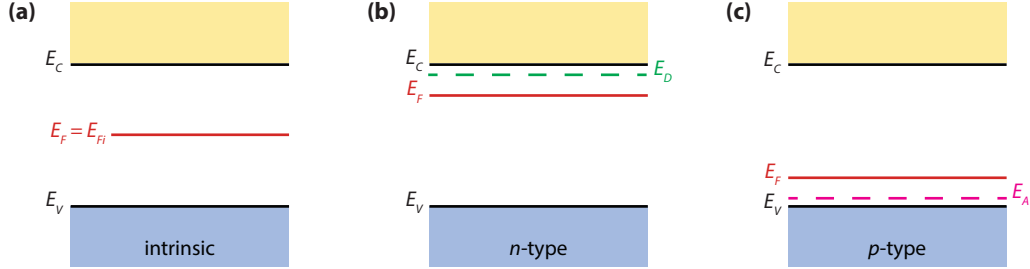


Figure 6.7: A shift of the position of the Fermi energy in the band diagram and the introduction of the allowed energy level into the bandgap due to the doping.

Let us now consider an n -type material. At room temperature almost all donor atoms N_D are ionised and donate an electron into the conduction band. Under the assumption that $N_A = 0$, Eq. (6.15) becomes

$$p + N_D - n = 0, \quad (6.16)$$

Further, assuming that

$$N_D \approx N_D^+ \approx n, \quad (6.17)$$

we can expect that the concentration of holes is lower than that of electrons, and becomes very low when N_D becomes very large. From Eq. (6.9), we can calculate the concentration of holes in the n -type material more accurately,

$$p = \frac{n_i^2}{n} \approx \frac{n_i^2}{N_D} \ll n. \quad (6.18)$$

In case of a p -type material almost all acceptor atoms N_A are ionised at room temperature. Therefore, they accept an electron and leave a hole in the valence band. Under the assumption that $N_D = 0$, Eq. (6.15) becomes

$$p - n - N_A = 0. \quad (6.19)$$

Further, when assuming that

$$N_A \approx N_A^- \approx p, \quad (6.20)$$

we can expect that the concentration of electrons is lower than that of holes. From Eq. (6.9), we can calculate the concentration of electrons in the p -type material more accurately,

$$n = \frac{n_i^2}{p} \approx \frac{n_i^2}{N_A} \ll p. \quad (6.21)$$

Inserting donor and acceptor atoms into the lattice of crystalline silicon introduces allowed energy levels into the forbidden bandgap. For example, the fifth valence electron of the P atom does not take part in forming a bond, is rather weakly bound to the atom and is easily liberated from the P atom. The energy of the liberated electron lies in the CB. The energy levels, which we denote E_D , of the weakly-bound valence electrons of the donor atoms have to be positioned close to the CB. Note that a dashed line represents the E_D . This means that an electron, which occupies the E_D level, is localised in the vicinity of the

donor atom. Similarly, the acceptor atoms introduce allowed energy levels E_A close to the VB.

Doping also influences the position of the Fermi energy. When we increase the electrons concentration by increasing the donor concentration the Fermi energy will increase, which is represented by bringing the Fermi energy closer to the CB in the band diagram. In the p -type material the Fermi energy is moved closer to the VB. A change in the Fermi-energy position and the introduction of the allowed energy level into the bandgap due to the doping is illustrated Fig. 6.7.

The position of the Fermi level in an n -type semiconductor can be calculated with Eqs. (6.6a); in a p -type semiconductor Eqs. (6.6b) and (6.20) can be used:

$$E_C - E_F = k_B T \ln \left(\frac{N_C}{N_D} \right) \quad \text{for } n\text{-type}, \quad (6.22a)$$

$$E_F - E_V = k_B T \ln \left(\frac{N_V}{N_A} \right) \quad \text{for } p\text{-type}. \quad (6.22b)$$

Example

This example demonstrates how much the concentration of electrons and holes can be manipulated by doping. A c-Si wafer is uniformly doped with $1 \times 10^{17} \text{ cm}^{-3}$ P atoms. P atoms act as donors and therefore at room temperature the concentration of electrons is almost equal to the concentration of donor atoms:

$$n = N_D^+ \approx N_D = 10^{17} \text{ cm}^{-3}.$$

The concentration of holes in the n -type material is calculated from Eq. (6.17),

$$p = \frac{n_i^2}{n} = \frac{(1.5 \times 10^{10})^2}{10^{17}} = 2.25 \times 10^3 \text{ cm}^{-3}.$$

We notice that there is a difference of 14 orders of magnitude between n (10^{17} cm^{-3}) and p ($2.25 \times 10^3 \text{ cm}^{-3}$). It is now obvious why electrons in n -type materials are called the majority carriers and holes the minority carriers. We can calculate the change in the Fermi energy due to the doping. Let us assume that the reference energy level is the bottom of the conduction band, $E_C = 0 \text{ eV}$. Using Eq. (6.11) we calculate the Fermi energy in the intrinsic c-Si.

$$E_{Fi} = E_C - \frac{E_g}{2} + \frac{k_B T}{2} \ln \left(\frac{N_V}{N_C} \right) = -\frac{1.12}{2} + \frac{0.0258}{2} \ln \left(\frac{1.83 \times 10^{19}}{3.22 \times 10^{19}} \right) = -0.57 \text{ eV}.$$

The Fermi energy in the n -type doped c-Si wafer is calculated from Eq. (6.6a)

$$E_F = E_C + k_B T \ln \left(\frac{n}{N_C} \right) = 0.0258 \times \ln \left(\frac{10^{17}}{3.22 \times 10^{19}} \right) = -0.15 \text{ eV}.$$

We notice that the doping with P atoms has resulted in the shift of the Fermi energy towards the CB. Note that when $n > N_C$, $E_F > E_C$ and the Fermi energy lies in the CB.

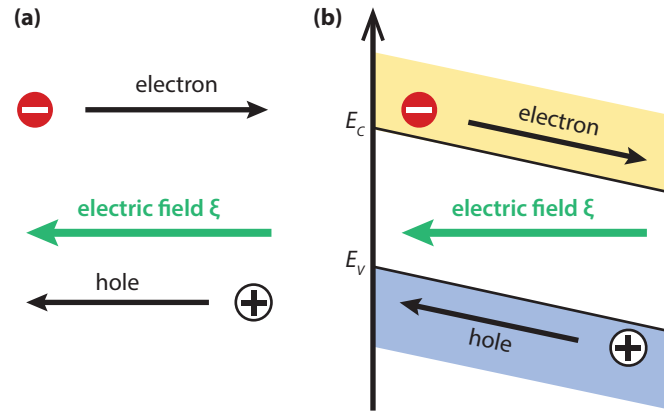


Figure 6.8: Visualisation of (a) the direction of carrier fluxes due to an electric field and (b) the corresponding band diagram.

6.5 Transport properties

In contrast to the equilibrium conditions, under operational conditions a net electrical current flows through a semiconductor device. The electrical currents are generated in a semiconductor due to the transport of charge by electrons and holes. The two basic transport mechanisms in a semiconductor are *drift* and *diffusion*.

6.5.1 Drift

Drift is charged-particle motion in response to an electric field. In an electric field the force acts on the charged particles in a semiconductor, which accelerates the positively charged holes in the direction of the electric field and the negatively charged electrons in the direction opposite to the electric field. Because of collisions with the thermally vibrating lattice atoms and ionised impurity atoms, the carrier acceleration is frequently disturbed. The resulting motion of electrons and holes can be described by average drift velocities \mathbf{v}_{dn} and \mathbf{v}_{dp} for electrons and holes, respectively. In case of low electric fields, the average drift velocities are directly proportional to the electric field ξ as expressed by

$$\mathbf{v}_{dn} = -\mu_n \xi, \quad (6.23a)$$

$$\mathbf{v}_{dp} = \mu_p \xi. \quad (6.23b)$$

The proportionality factor is called mobility μ . It is a central parameter that characterises electron and hole transport due to drift. Although the electrons move in the opposite direction to the electric field, because the charge of an electron is negative the resulting electron drift current is in the same direction as the electric field. This is illustrated in Fig. 6.8.

The electron and hole drift-current densities are then given as

$$\mathbf{J}_{n, \text{drift}} = -qn\mathbf{v}_{dn} = qn\mu_n \xi, \quad (6.24a)$$

$$\mathbf{J}_{p, \text{drift}} = qp\mathbf{v}_{dp} = qp\mu_p \xi. \quad (6.24b)$$

Combining Eqs. (6.24a) and (6.24b) leads to the total drift current,

$$\mathbf{J}_{\text{drift}} = q(p\mu_p + n\mu_n)\boldsymbol{\xi}. \quad (6.25)$$

Mobility is a measure of how easily the charge particles can move through a semiconductor material. For example, for c-Si with a doping concentration N_D or N_A , respectively, at 300 K, the mobilities are

$$\begin{aligned} \mu_n &\approx 1360 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}, \\ \mu_p &\approx 450 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}. \end{aligned}$$

As mentioned earlier, the motion of charged carriers is frequently disturbed by collisions. When the number of collisions increases, the mobility decreases. Increasing the temperature increases the collision rate of charged carriers with the vibrating lattice atoms, which results in a lower mobility. Increasing the doping concentration of donors or acceptors leads to more frequent collisions with the ionised dopant atoms, which results in a lower mobility as well. The dependence of mobility on doping and temperature discussed in more detail in standard textbooks for semiconductor physics and devices, such as References [24, 31].

6.5.2 Diffusion

Diffusion is a process whereby particles tend to spread out from regions of high particle concentration into regions of low particle concentration as a result of random thermal motion. The driving force of diffusion is a *gradient* in the particle concentration. In contrast to the drift transport mechanism, the particles need not be charged to be involved in the diffusion process. Currents resulting from diffusion are proportional to the gradient in particle concentration. For electrons and holes, they are given by

$$\mathbf{J}_{n, \text{diff}} = qD_n \nabla n, \quad (6.26a)$$

$$\mathbf{J}_{p, \text{diff}} = -qD_p \nabla p, \quad (6.26b)$$

Combining Eqs. (6.26a) and (6.26b) leads to the total diffusion current,

$$\mathbf{J}_{\text{diff}} = q(D_n \nabla n - D_p \nabla p). \quad (6.27)$$

The proportionality constants, D_n and D_p are called the electron and hole *diffusion coefficients*, respectively. The diffusion coefficients of electrons and holes are linked with the mobilities of the corresponding charge carriers by the *Einstein relationship* that is given by

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{k_B T}{q}. \quad (6.28)$$

Figure 6.9 visualises the diffusion process as well as the resulting directions of particle fluxes and current.

Combining Eqs. (6.25) and (6.27) leads to the total current,

$$\begin{aligned} \mathbf{J} &= \mathbf{J}_{\text{drift}} + \mathbf{J}_{\text{diff}} \\ &= q(p\mu_p + n\mu_n)\boldsymbol{\xi} + q(D_n \nabla n - D_p \nabla p). \end{aligned} \quad (6.29)$$