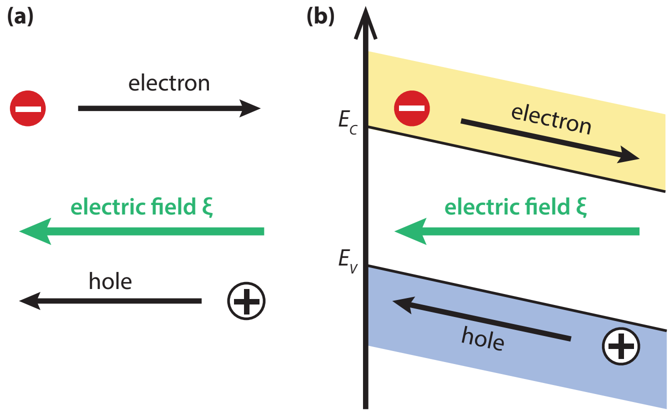

Figure 6.8: Visualisation of (a) the direction of carrier fluxes due to an electric field and (b) the corresponding band diagram.

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

$$\mathbf{v}_{dn} = -\mu_n \xi, \qquad (6.23a)$$
$$\mathbf{v}_{dp} = \mu_p \xi. \qquad (6.23b)$$

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

$$\mathbf{J}_{n,\,\text{drift}} = -qn\mathbf{v}_{dn} = qn\mu_n \xi, \qquad (6.24a)$$
$$\mathbf{J}_{p,\,\text{drift}} = qp\mathbf{v}_{dp} = qp\mu_p \xi. \qquad (6.24b)$$

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

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

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

$$\mu_n \approx 1\,360\,\text{cm}^2\text{V}^{-1}\text{s}^{-1},$$
$$\mu_p \approx \quad 450\,\text{cm}^2\text{V}^{-1}\text{s}^{-1}.$$

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

$$\mathbf{J}_{n,\,\text{diff}} = qD_n\nabla n, \tag{6.26a}$$
$$\mathbf{J}_{p,\,\text{diff}} = -qD_p\nabla p, \tag{6.26b}$$

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

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

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

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{k_B T}{q}. \tag{6.28}$$

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,

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

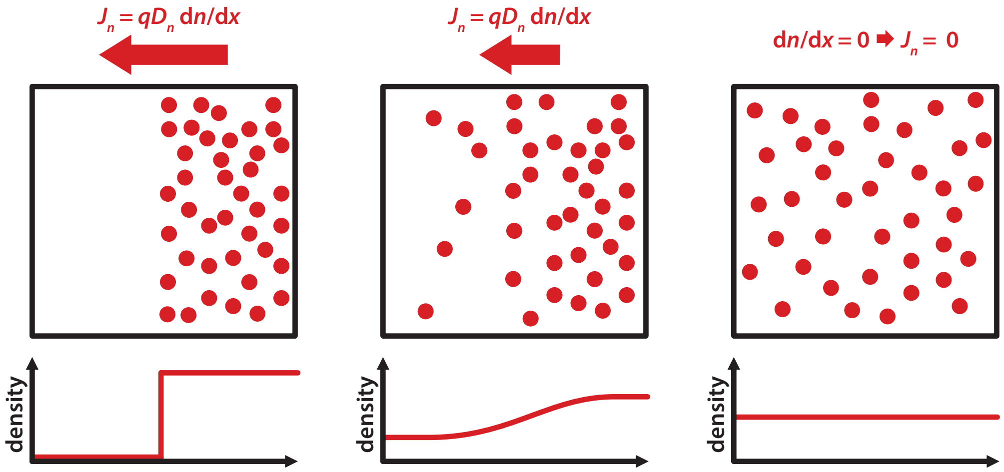

Figure 6.9: Visualisation of electron diffusion.

Example

To obtain some idea about values of diffusion coefficients, let us assume a c-Si wafer at room temperature, doped with donors, $N_D = 10^{14}\,\mathrm{cm}^{-3}$. *According to Eq. (6.28),*

$$D_N = \frac{k_B T}{q}\mu_n = 0.0258\,\mathrm{V} \times 1360\,\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1} = 35\,\mathrm{cm}^2\mathrm{s}^{-1}.$$