

In Section 2.4 the most critical assumptions used in the derivation of the current-voltage characteristics are discussed and the ideal solar cell model is extended to include the front and rear surfaces and a diffused emitter. For these models the device equations can still be solved analytically. The contents of Sections 2.2, 2.3 and 2.4 can be found in standard textbooks on solar cell physics (e.g. Hovel, 1975; Green, 1982).

The semiconductor device equations can be solved with higher accuracy by applying numerical methods, to which we turn in Section 2.5, first for a one-dimensional model (Section 2.5.2). In high-efficiency solar cells, two- and three-dimensional features such as point contacts and selective emitters have to be included in the calculation, so 2D- and 3D-numerical models must be used. These models are introduced in Section 2.5.3. In this section optical reflection and absorption in a high-efficiency silicon solar cell, calculated by means of ray tracing simulation, are also discussed. Furthermore, front side texturisation is taken into account and the optical carrier generation rate in high efficiency silicon solar cells is modelled.

## 2.2 Semiconductor device equations

Five equations describe the behaviour of charge carriers in semiconductors under the influence of an electric field and/or light, both of which cause deviations from thermal equilibrium conditions. These equations are therefore called the basic equations for semiconductor device operation. In the following they are simplified to one dimension.

The Poisson equation relates the static electric field  $\mathcal{E}$  to the space-charge density  $\rho$

$$\frac{d^2\phi(x)}{dx^2} = -\frac{d\mathcal{E}(x)}{dx} = -\frac{\rho(x)}{\epsilon_0\epsilon_s} \quad (2.1)$$

where  $\phi$  is the electrostatic potential,  $\epsilon_0$  is the permittivity of free space and  $\epsilon_s$  is the static relative permittivity of the medium. The electron current density  $i_e$  and the hole current density  $i_h$  are given by eqs. 2.2 and 2.3

$$i_e(x) = +qD_e \frac{dn(x)}{dx} + qu_en(x)\mathcal{E}(x) \quad (2.2)$$

$$i_h(x) = -qD_h \frac{dp(x)}{dx} + qu_hp(x)\mathcal{E}(x) \quad (2.3)$$

where  $n$  and  $p$  are electron and hole densities,  $u_e$  and  $u_h$  are the electron and hole mobilities and  $D_e$  and  $D_h$  are the electron and hole diffusion constants. The first terms on the right hand side of eqs. 2.2 and 2.3 are diffusion currents driven by a concentration gradient, and the second terms are drift currents driven by the electric field  $\mathcal{E}$ .

The divergence of the current density  $i$  is related to the recombination and generation rates of charge carriers by the *continuity equation*. The electron and hole continuity equations may be written as

$$+ \frac{1}{q} \frac{di_e(x)}{dx} - r_e(x) + g_e(x) = 0 \quad (2.4)$$

$$- \frac{1}{q} \frac{di_h(x)}{dx} - r_h(x) + g_h(x) = 0 \quad (2.5)$$

where  $r(x)$  and  $g(x)$  are the position-dependent volume recombination and photo-generation rates, respectively.

Substitution of the current densities eqs. 2.2 and 2.3 into the continuity equations 2.4 and 2.5 gives a coupled set of differential equations, the *transport equations*

$$D_e \frac{d^2 n}{dx^2} + u_e \mathcal{E} \frac{dn}{dx} + nu_e \frac{d\mathcal{E}}{dx} - r_e(x) + g_e(x) = 0 \quad (2.6)$$

$$D_h \frac{d^2 p}{dx^2} - u_h \mathcal{E} \frac{dp}{dx} - pu_h \frac{d\mathcal{E}}{dx} - r_h(x) + g_h(x) = 0 \quad (2.7)$$

The electron and hole transport equations 2.6 and 2.7 are coupled by the electric field  $\mathcal{E}$ . The coupled set of differential equations 2.1, 2.6 and 2.7 can be solved with different degrees of accuracy. The most basic approach will be discussed in the next section.