CHAPTER 2

DEVICE PHYSICS OF SILICON SOLAR CELLS

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No, 'tis not so deep as a well, nor so wide as a church-door; but 'tis enough, 'twill serve.
Romeo and Juliet, William Shakespeare, *c.* 1594.

2.1 Introduction

As shown in Chapter 1, a semiconductor solar cell is based on a simple *p-n* junction. An elementary description of cell performance can therefore be given in terms of a very simple model based on the Shockley diode equation in the dark and under illumination. This model is sufficient for understanding the basic mechanisms in the cell and roughly predicting the performance parameters of a solar cell. For some types of cells that perform far below their theoretical efficiency limit, this basic description may be adequate. However, for advanced solar cells such as high-efficiency monocrystalline silicon (c-Si) or gallium arsenide (GaAs) cells, which have been developed almost to their theoretical upper limit, these simple models are not sufficient to understand the subtleties of the device physics. Indeed, in the past few years improved methods of solar cell modelling have added immensely to a better understanding and performance of high efficiency cells.

Unfortunately, detailed solar cell models are too complicated to be handled by analytical mathematical methods. One has to use numerical techniques that may be complex and time consuming. Therefore in a typical R&D laboratory, simple and detailed device models are used in parallel. The choice of model depends on the problems that have to be solved.

In this chapter the device physics of solar cells is presented in several steps of increasing complexity. A schematic diagram representing the structure of the sections is shown in Fig. 2.1 Starting from the fundamental equations that describe semiconductor devices (Section 2.2), solutions are first discussed for the most simple cell model: the device equations are solved for a simple *p-n* junction cell consisting of

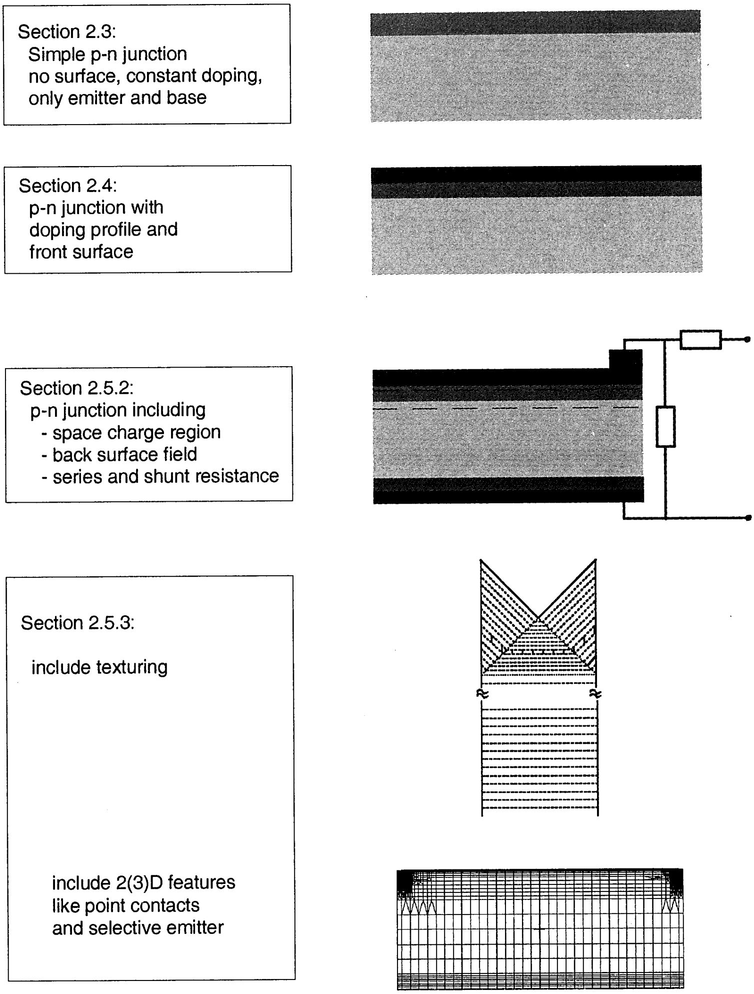

Figure 2.1 From top to bottom: solar cell models of increasing complexity as analysed in this chapter.

an emitter and a base, each with a constant doping profile, with no boundaries taken into account (Section 2.3). In this most simple model, the ideal current–voltage characteristic of a solar cell is obtained. In Section 2.3 a basic skeleton of equations governing the device physics of solar cells is presented. A thorough derivation of the ideal *p-n* junction characteristics as presented in Section 2.3 is given by Archer *et al.* (1996).

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 ρ

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

where ϕ is the electrostatic potential, ϵ_o is the permittivity of free space and ϵ_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

$$i_e(x) = +qD_e\frac{dn(x)}{dx} + qu_e n(x)\mathcal{E}(x) \tag{2.2}$$

$$i_h(x) = -qD_h\frac{dp(x)}{dx} + qu_h p(x)\mathcal{E}(x) \tag{2.3}$$