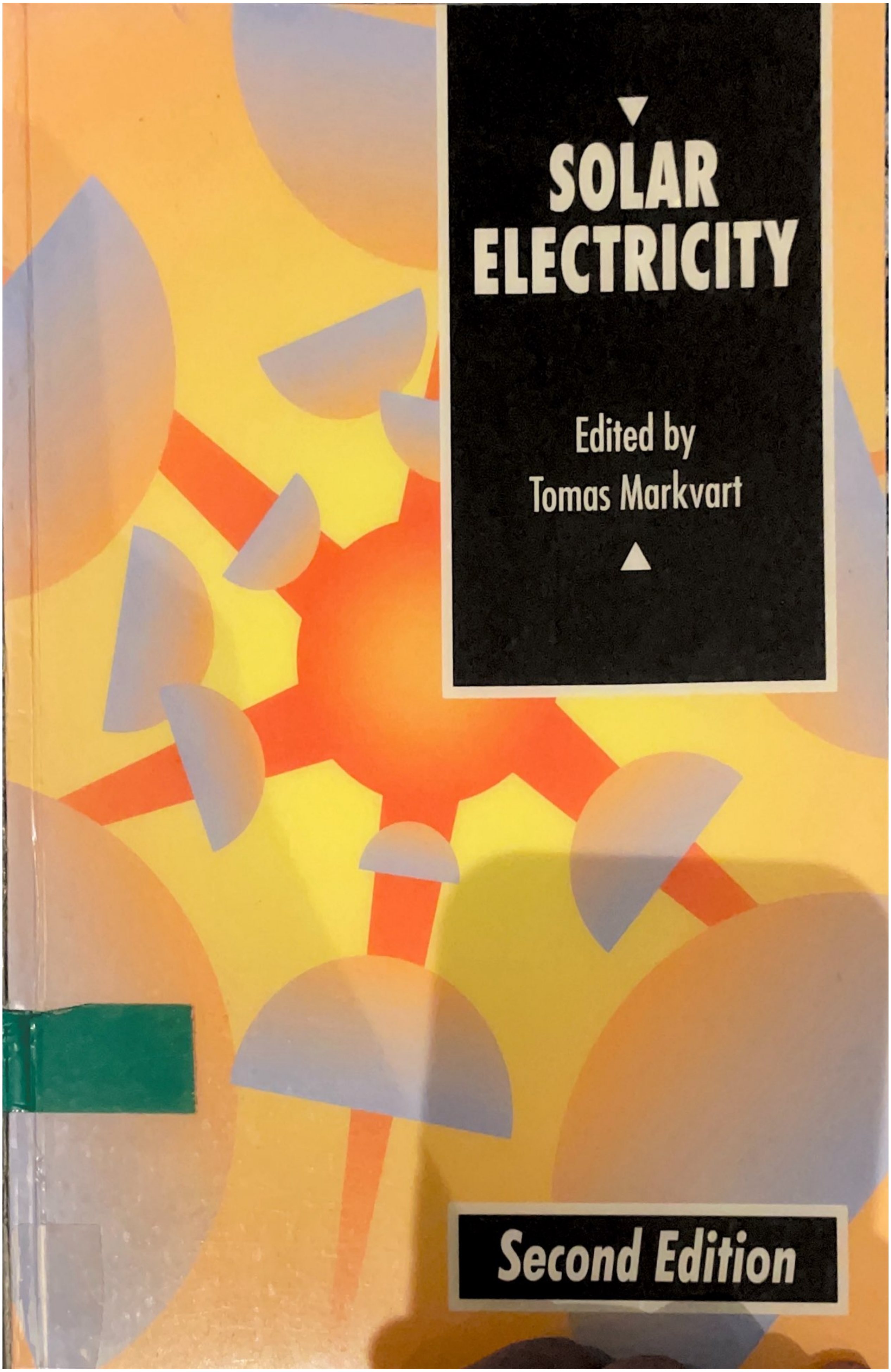

SOLAR ELECTRICITY

Edited by
Tomas Markvart

Second Edition

3
Solar Cells

AIMS

The aims of this unit are to explain how solar cells work and how they are manufactured.

OBJECTIVES

When you complete this unit you should be able to:

1. analyse the structure of a solar cell,
2. explain the power output from a cell in terms of the incident energy flux and the electronic structure of the semiconductor,
3. evaluate the cell performance by using its current–voltage characteristic,
4. assess the operation of practical devices and limits imposed on their performance,
5. identify the technological steps which are used in the manufacture of solar cells.

NOTATION AND UNITS

Symbol		SI unit	Other unit
A	Surface area of the cell	m^2	
c	Speed of light in vacuum	m/s	
E_c	Energy of the bottom of the conduction band	J	eV
E_v	Energy of the top of valence band	J	eV
E_g	Energy gap	J	eV
$E_{ph}(\lambda)$	Photon energy	J	eV
FF	Fill factor		

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3.1 INTRODUCTION

In this chapter, you will learn how solar cells work and how they are manufactured. A broad overview of the available solar cells will be given in section 3.2. You will then be shown in section 3.3 how solar cells work. Starting with the electronic properties of semiconductors we shall examine the overall structure of the cell and explain how it produces electricity. Various practical devices will be discussed, together with power losses which occur during their operation.

The devices that you are most likely to encounter—the silicon and thin-film solar cells—will then be analysed in detail in sections 3.4 and 3.5. You will be shown how they are manufactured, from raw materials to the final device. Emphasis will be placed not only on the electrical properties of the device, but also on the economic aspects of the technology.

3.2 WHAT ARE SOLAR CELLS?

Solar cells represent the fundamental power conversion unit of a photovoltaic system. They are made from semiconductors, and have much in common with other solid-state electronic devices, such as diodes, transistors and integrated circuits. For practical operation, solar cells are usually assembled into modules.

Many different solar cells are now available on the market, and yet more are under development (Fig. 3.1). The range of solar cells spans different materials and different structures in the quest to extract maximum power from the device while keeping the cost to a minimum. Devices with efficiency exceeding 30% have been demonstrated in the laboratory. The efficiency of commercial devices, however, is usually less than half this value.

Crystalline silicon cells hold the largest part of the market. To reduce the cost, these cells are now often made from multicrystalline material, rather than from the more expensive single crystals. Crystalline silicon cell technology is well established. The modules have a long lifetime (20 years or more) and their best production efficiency is approaching 18%.

Cheaper (but also less efficient) types of silicon cells, made in the form of amorphous thin films, are used to power a variety of consumer products. You will be familiar with the solar-powered watches and calculators, but larger amorphous silicon solar modules are also available.

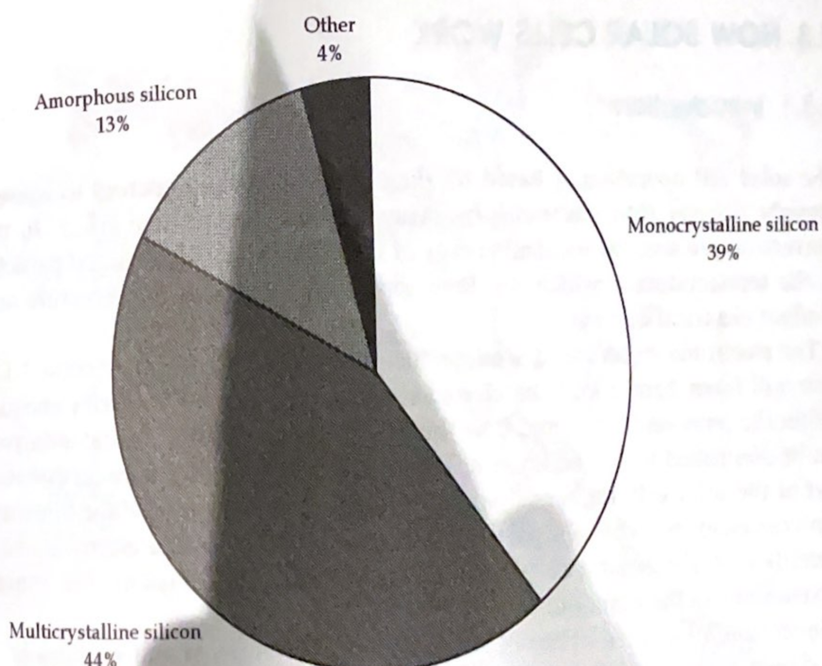

Fig. 3.1 Market share of the principal photovoltaic technologies (1998). 'Other' technologies include crystalline silicon cells for concentrator systems, cells based on ribbon silicon, cadmium telluride and silicon on low-cost substrates (Source: Paul Maycock, PV News).

A variety of compound semiconductors can also be used to manufacture thin-film cells (for example, cadmium telluride or copper indium diselenide). These modules are now beginning to appear on the market and hold the promise of combining low cost with acceptable conversion efficiencies.

A particular class of high-efficiency solar cells from single crystal silicon or compound semiconductors (for example, gallium arsenide or indium phosphide) are used in specialised applications, such as to power satellites or in systems which operate under high-intensity concentrated sunlight. The operation and applications of these devices will be reviewed in Chapters 5 and 7.

Photovoltaic materials are not restricted to semiconductors. Solar cells are now available which convert light to electricity by organic molecules, with best conversion efficiency exceeding 10%. The principles of this novel type of solar energy conversion are summarised briefly in Section 3.3, and discussed in detail in Section 7.3.

Summary

Various types of solar cells have been introduced: crystalline and amorphous silicon cells, compound thin-film devices, and high-efficiency cells for specialised applications.

3.3 HOW SOLAR CELLS WORK

3.3.1 Introduction

The solar cell operation is based on the ability of semiconductors to convert sunlight directly into electricity by exploiting the *photovoltaic effect*. In the conversion process, the incident energy of light creates mobile charged particles in the semiconductor which are then separated by the device structure and produce electrical current.

The electronic structure of semiconductors will be reviewed in section 3.3.2. You will learn here about the characteristic distribution of electron energies within the semiconductor, and how the electrical properties of semiconductors can be controlled by the addition of impurities. We shall introduce an essential part of the solar cell, the semiconductor junction, and show how the illumination creates mobile charged particles, electrons and holes. The electrical characteristics of the solar cell will then be obtained by analysing the charge currents across the junction.

In section 3.3.4, various device structures will be reviewed and we show how the device design aims to minimise the losses of power which occur during the cell operation. We shall also examine how the operation of the cell is affected by practical operating conditions, particularly by variable temperature and irradiance.

3.3.2 Electronic structure of semiconductors

3.3.2.1 *Band structure, doping*

The principles of semiconductor physics are best illustrated by the example of silicon, a group 4 elemental semiconductor. The silicon crystal forms the so-called *diamond lattice* where each atom has four nearest neighbours at the vertices of a tetrahedron. The four-fold tetrahedral coordination is the result of the bonding arrangement which uses the four outer (valence) electrons of each silicon atom (Fig. 3.2). Each bond contains two electrons, and you can easily see that all the valence electrons are taken up by the bonds. Most other industrially important semiconductors crystallise in closely related lattices, and have a similar arrangement of the bonding orbitals.

This crystal structure has a profound effect on the electronic and optical properties of the semiconductor.

According to the quantum theory, the energy of an electron in the crystal must fall within well-defined *bands*. The energies of valence orbitals which form bonds between the atoms represent just such a band of states, the *valence band*. The next higher band is the *conduction band* which is separated from the valence band by the *energy gap*, or *bandgap*. The width of the bandgap $E_c - E_v$ is a very important characteristic of the semiconductor and is usually denoted by E_g. Table 3.1 gives the bandgaps of the most important semiconductors for solar-cell applications.

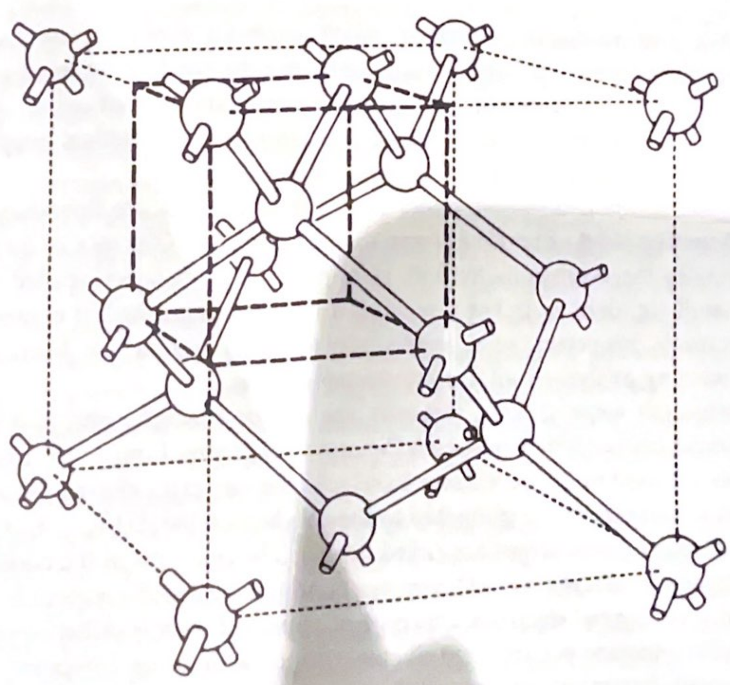

Fig. 3.2 The diamond lattice

Table 3.1 Energy gaps of principal semiconductors for photovoltaic applications (gap values given at room temperature)

Material	Energy gap (eV)	Type of gap
crystalline Si	1.12	indirect
amorphous Si	~1.75	direct
$CuInSe_2$	1.05	direct
CdTe	1.45	direct
GaAs	1.42	direct
InP	1.34	direct

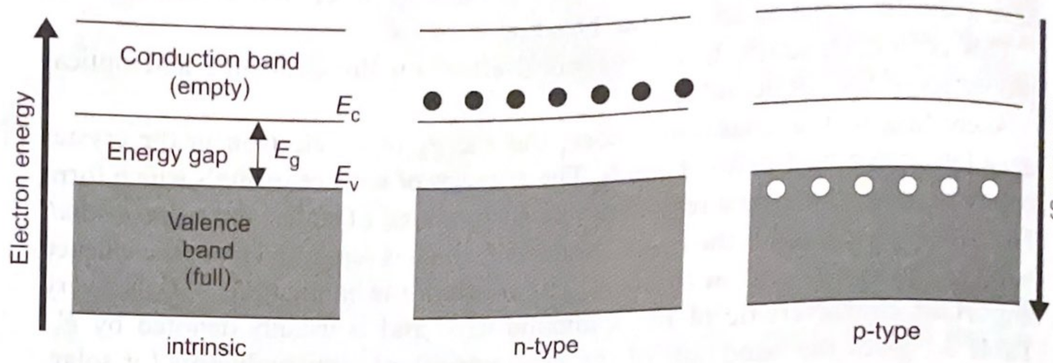

Fig. 3.3 Band diagram and electron–hole distribution in semiconductors

A pure semiconductor (which is called *intrinsic*) contains just the right number of electrons to fill the valence band, and the conduction band is therefore empty (Fig. 3.3). Electrons in the full valence band cannot move—just as, for example, marbles in a full box with a lid on top. For practical purposes, a pure semiconductor is therefore an insulator.

Semiconductors can only conduct electricity if carriers are introduced into the conduction band or removed from the valence band. One way of doing this is by alloying the semiconductor with an impurity. This process is called *doping*. As we shall see, doping makes it possible to exert a great deal of control over the electronic properties of a semiconductor, and lies at the heart of the manufacturing process of all semiconductor devices.

Suppose that some group 5 impurity atoms (for example, phosphorus) are added to the silicon melt from which the crystal is grown. Four of the five outer electrons are used to fill the valence band and the one extra electron from each impurity atom is therefore promoted to the conduction band (Fig. 3.3). For this reason, these impurity atoms are called *donors*. The electrons in the conduction band are mobile, and the crystal becomes a conductor. Since the current is carried by negatively charged electrons, this type of semiconductor is called *n-type*.

A similar situation occurs when silicon is doped with group 3 impurity atoms (for example, boron) which are called *acceptors*. Since four electrons per atom are needed to fill the valence band completely, this doping creates electron deficiency in this band (Fig. 3.3). The missing electrons—called *holes*—behave as positively charged particles which are mobile, and carry current. A semiconductor where the electric current is carried predominantly by holes is called *p-type*.

The prevailing charge carriers in a given semiconductor are called *majority carriers*. Examples of majority carriers are electrons in an n-type semiconductor and holes in the p-type. The opposite type of carriers whose concentration is generally much lower, are called *minority carriers*.

3.3.2.2 Semiconductor junctions

The operation of solar cells is based on the formation of a *junction*. Various examples of junctions are shown in Fig. 3.4. Perhaps the simplest is the *p-n junction*, an interface between the n and p regions of one semiconductor. A layer of intrinsic material is sometimes incorporated between the n- and p-type regions, resulting in a wider transition zone. In contrast with these *homojunctions*, a *heterojunction* is formed by two different semiconductors—note the difference in the bandgaps on the two sides of the junction.

An interface between a metal and a semiconductor may also form a junction, called the *Schottky barrier*. In general, the properties of metal contacts with a semiconductor depend on the actual materials in question. For each semiconductor, some metals form a Schottky barrier but some form an *ohmic contact* where the barrier is absent. These contacts are used to extract electrical current from the device.

The important feature of all junctions is that they contain a strong electric field. To illustrate how this field comes about, let us imagine the hypothetical situation where the p-n junction is formed by joining together two pieces of semiconductor, one p-type and the other n-type (although this manner of junction formation is not normally employed in practice, it is a convenient means to demonstrate the relevant principles). In separation, there is electron surplus in the n-type material and hole surplus in the p-type. When the two pieces are brought into contact, electrons from the n region near the interface diffuse into the p side, leaving behind a layer which is positively charged by the donors. Similarly, holes diffuse in the opposite direction, leaving behind a negatively charged layer stripped of holes. The resulting junction region then contains practically no mobile charge carriers (Fig. 3.5), and the fixed charges of the dopant atoms create a potential barrier acting against a further flow of electrons and holes. Note that the electric field in the junction pulls the electrons and holes in opposite directions.

Figure 3.6 shows the band diagram of a p-n junction diode in equilibrium, and when external voltage is connected to the diode. Without bias, of course, there is no current through the junction. We may imagine this zero net current as consisting of two very small opposite currents I_o and $-I_o$ which remain from the current flow prior to the junction formation. These currents are very small indeed, corresponding to a current density of the order of $10^{-14}\,\mathrm{A/cm^2}$ in a good silicon diode.