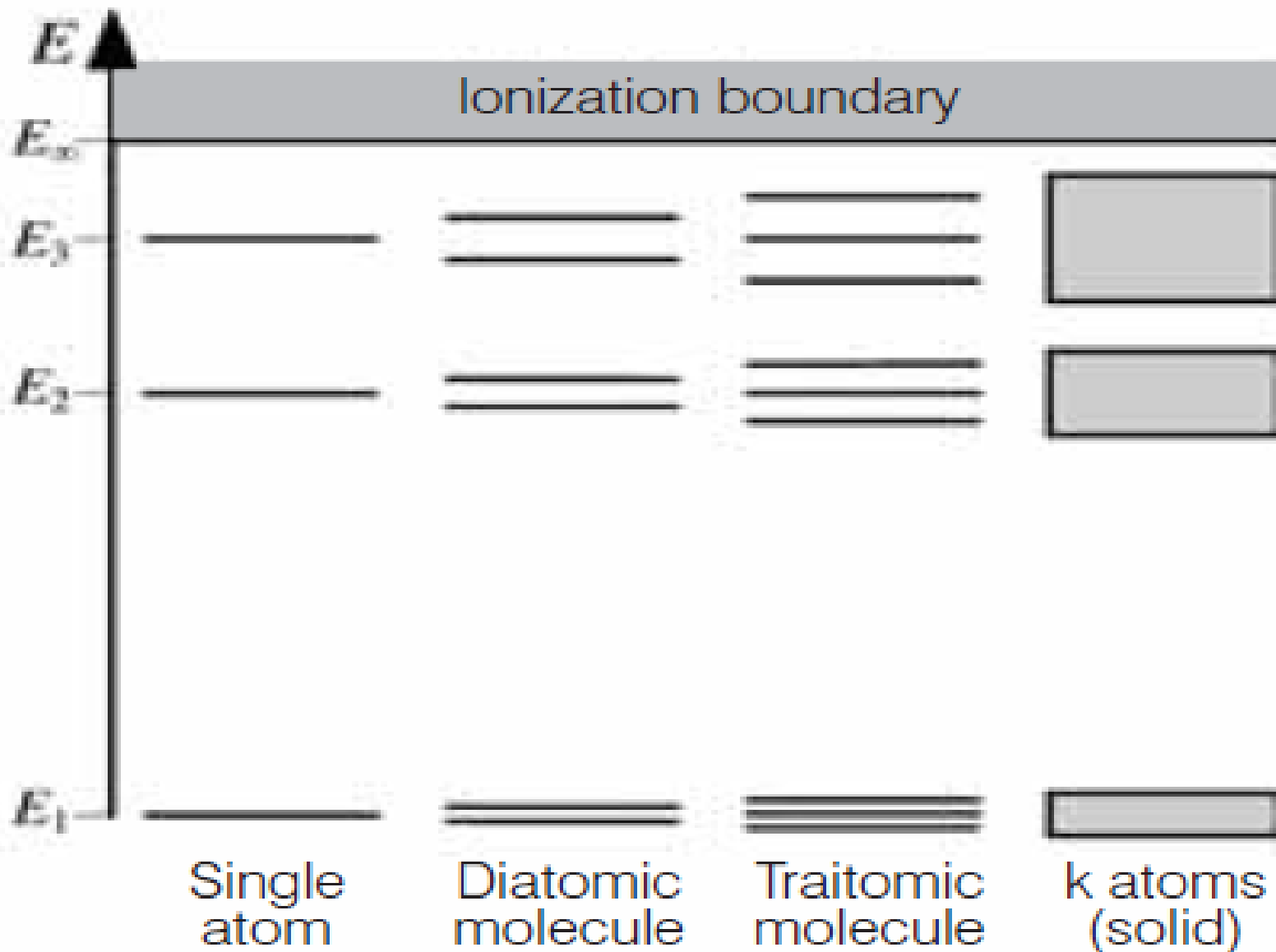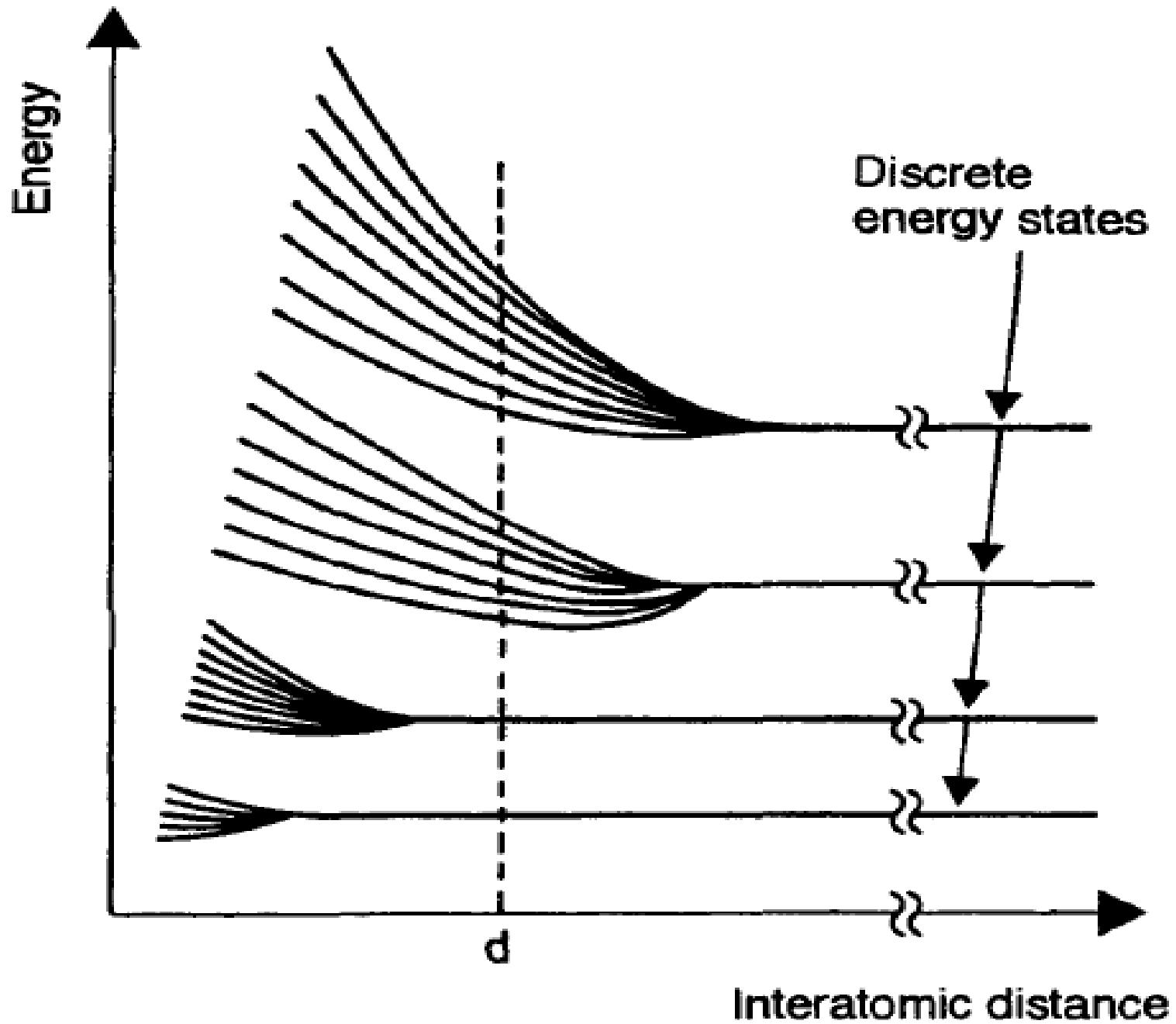**Figure 4.2** *Energy States of Electrons in Atoms, Molecules and Solids*

In the energy band model, electrons fill the bands one after another starting with the first, lowest energy band. The highest fully occupied band is called the *valence band* (VB). The next highest band, which can be partially occupied or totally empty, is called the *conduction band* (CB). The space between the valence band and conduction band contains forbidden energy states and is therefore called the *forbidden band* (FB). The energy gap between the bands is called the *band gap* E_g.
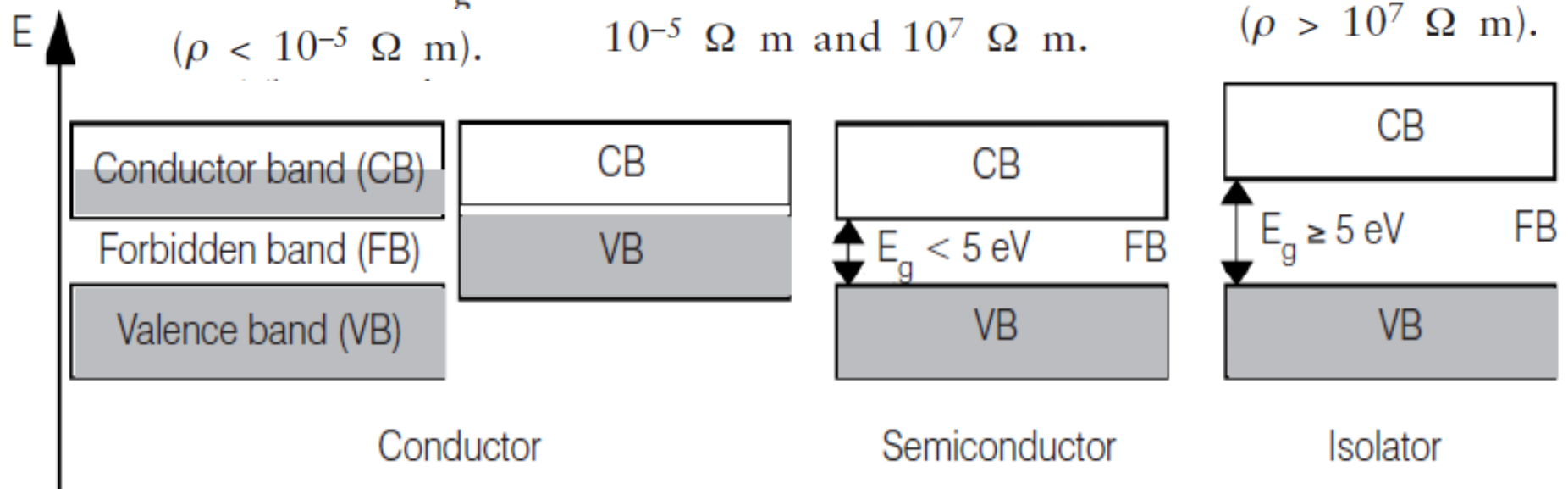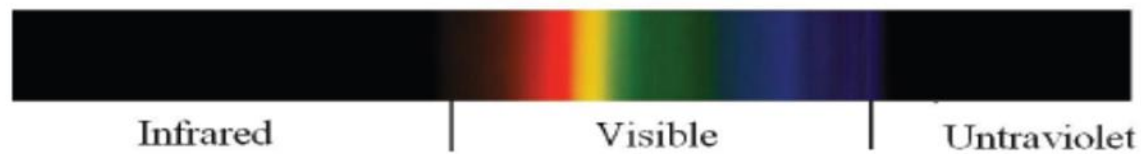
$(\rho < 10^{-5} \ \Omega \ m)$. $10^{-5} \ \Omega \ m$ and $10^7 \ \Omega \ m$. $(\rho > 10^7 \ \Omega \ m)$.

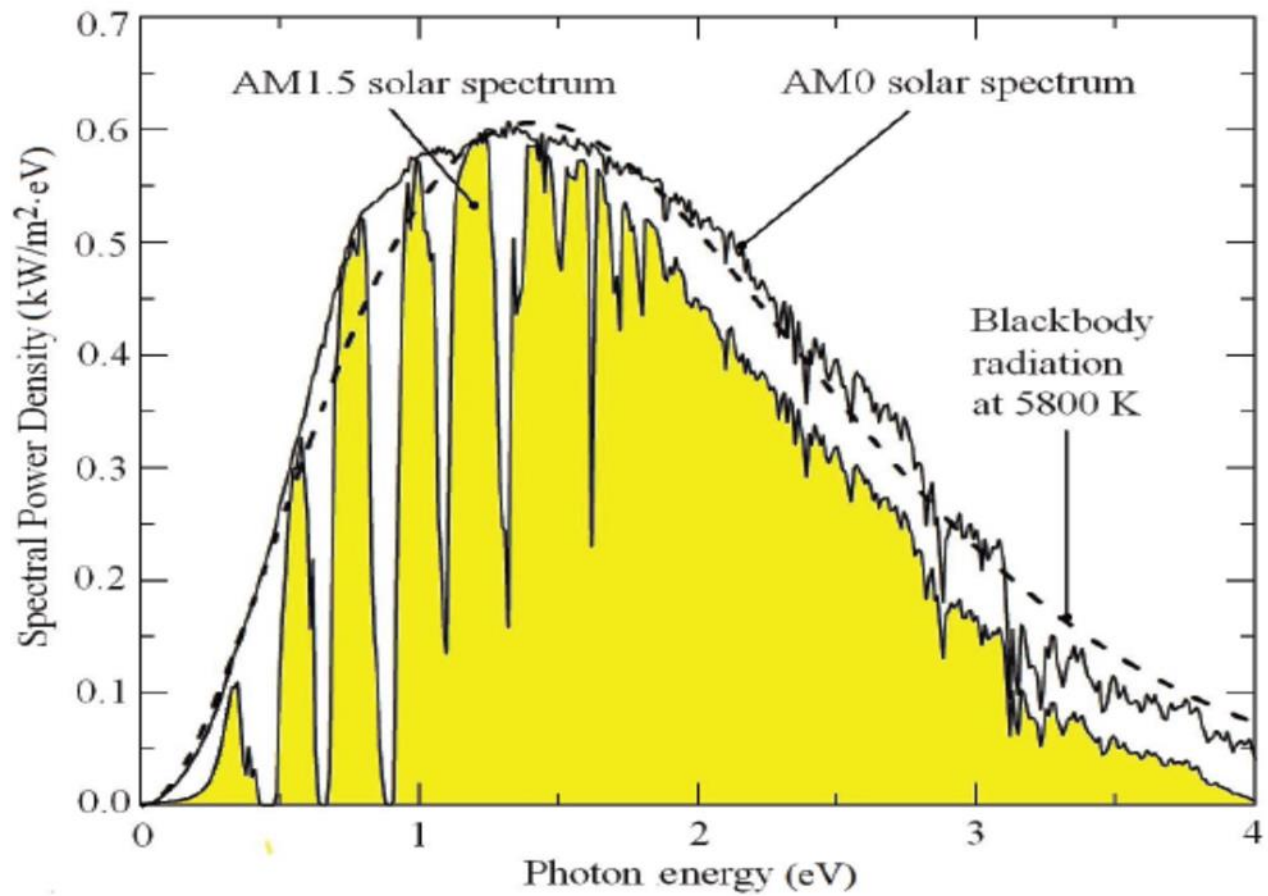| E			
Conductor band (CB)	CB	CB	CB
Forbidden band (FB)	VB	$E_g < 5$ eV FB	$E_g \geq 5$ eV FB
Valence band (VB)		VB	VB
Conductor		Semiconductor	Isolator

Figure 4.3 *Energy Bands of Conductors, Semiconductors and Isolators*
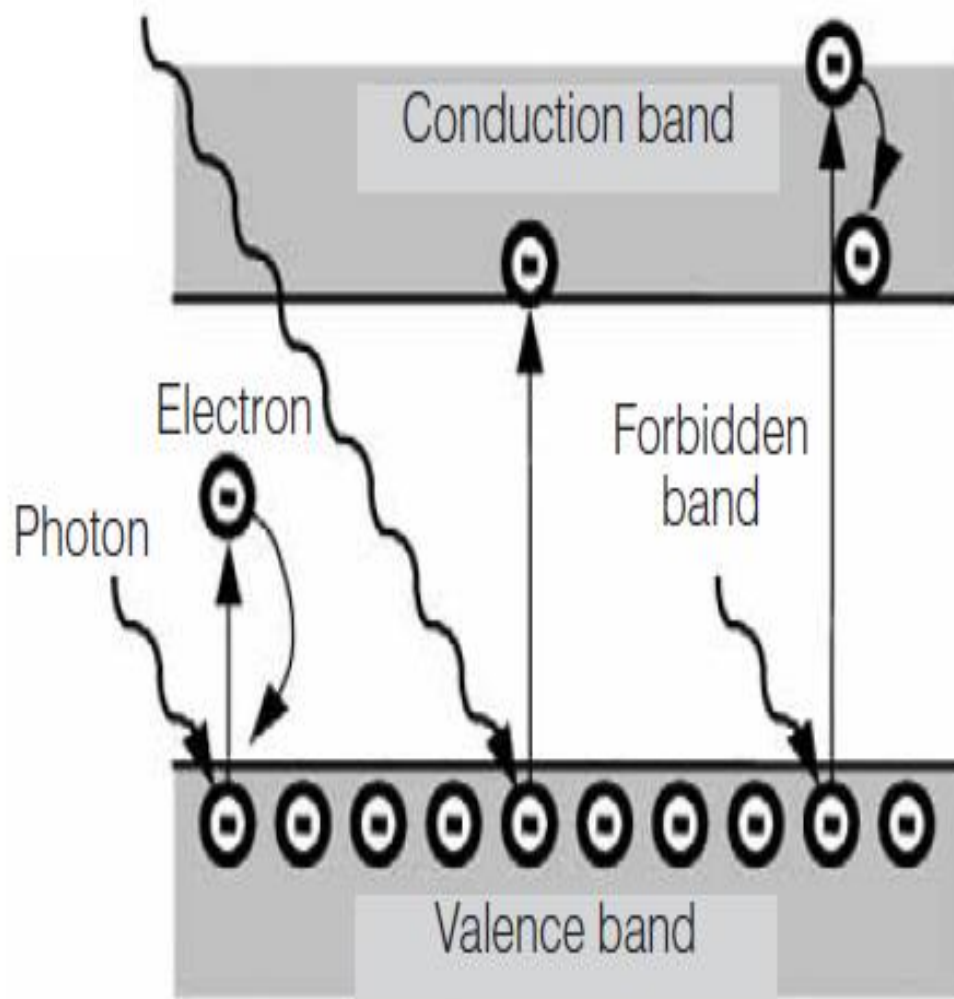
$$E = \frac{h \cdot c}{\lambda}$$

Figure 4.4 *The Lifting of Electrons from the Valence Band to the Conduction Band Caused by Light Energy in a Semiconductor (Inner Photo Effect)*

An incident photon can have several effects: photon energy lower than the band gap will not elevate an electron because it cannot bridge the band gap. Photons with energy larger than the band gap can elevate electrons into the conduction band with a part of its energy. Surplus energy is lost, because the electron falls back to the edge of the conduction band.

Photoresistors, which change their resistance depending on the irradiance, use the internal photo effect. Photovoltaic cells also use the internal photo effect for generating current.

Table 4.2 *Band Gap for Various Semiconductors at 300 K*

IV semiconductors		III-V semiconductors		II-VI semiconductors	
Material	E_g	Material	E_g	Material	E_g
Si	1.107 eV	GaAs	1.35 eV	CdTe	1.44 eV
Ge	0.67 eV	InSb	0.165 eV	ZnSe	2.58 eV
Sn	0.08 eV	InP	1.27 eV	ZnTe	2.26 eV
		GaP	2.24 eV	HgSe	0.30 eV

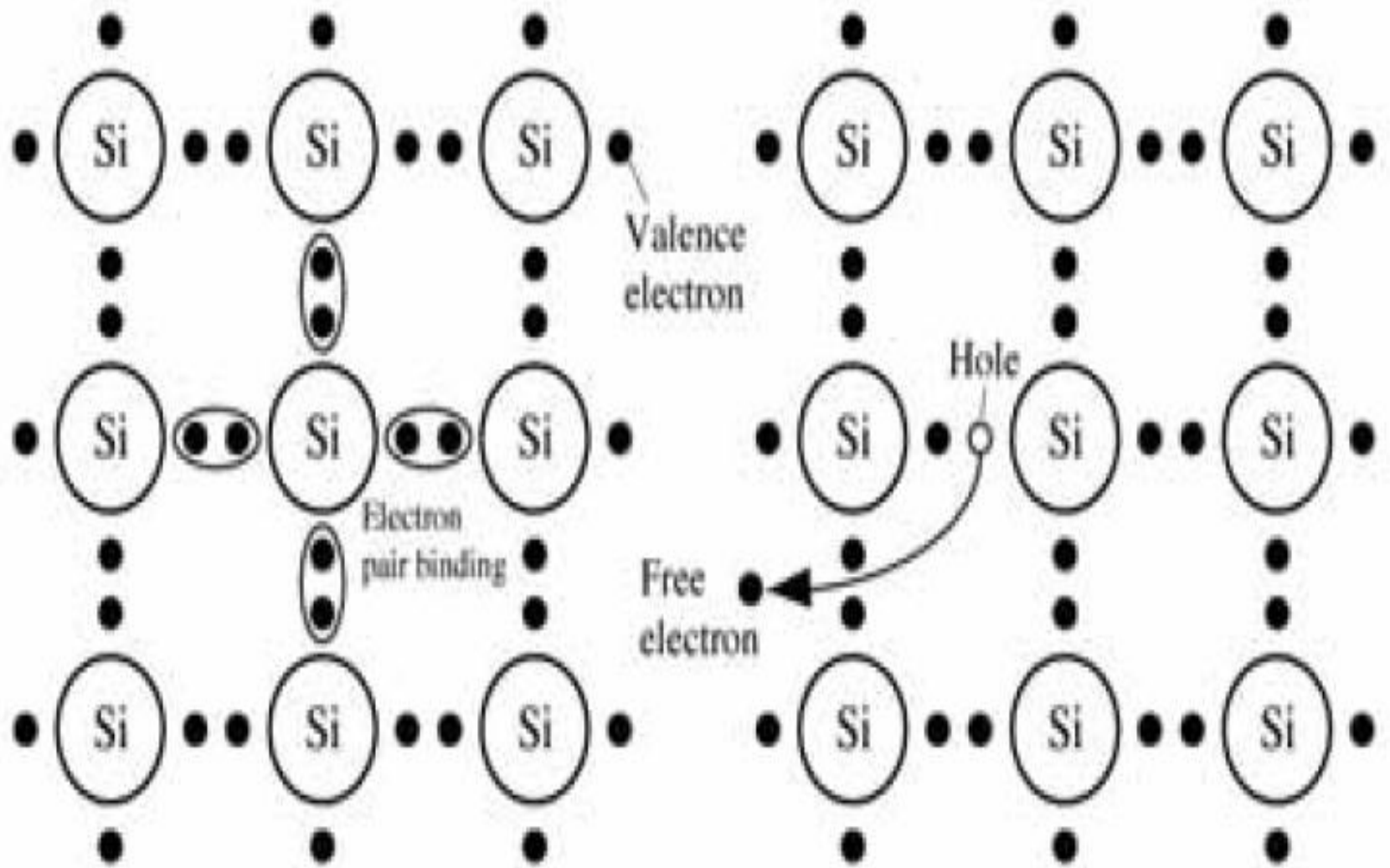*Source: data from Lechner, 1992*

Figure 4.5 *Crystal Structure of Silicon (left), Intrinsic Conduction due to Defect Electron in the Crystal Lattice (right)*

electron density n and hole density p:

$$n = p$$

intrinsic carrier density

$$n \cdot p = n_i^2 = n_{i0}^2 \cdot T^3 \cdot \exp\left(-\frac{E_g}{k \cdot T}\right)$$

$$k = 1.380658 \cdot 10^{-23} \ \text{J/K}$$

The value for silicon is $n_{10} = 4.62 \cdot 10^{15}$ cm^{-3} K$^{-3/2}$. No free electrons and holes exist at a temperature of absolute zero ($T = 0$ K $= -273.15°C$). With increasing temperature their number rises rapidly.

If an electrical voltage is applied to the silicon crystal externally, negatively charged electrons will flow to the anode. Electrons neighbouring a hole can move into the hole created by this current. Thus, holes move in the opposite direction to the electrons. The *mobility* μ_n and μ_p of electrons and holes in the semiconductor depends also on the temperature. μ_n and μ_p can be calculated for silicon with μ_{0n} = 1350 cm^2/(V s) and μ_{0p} = 480 cm^2/(V s) at T_0 = 300 K by:

$$\mu_n = \mu_{0n} \cdot \left(\frac{T}{T_0} \right)^{-3/2}$$

$$\mu_p = \mu_{0p} \cdot \left(\frac{T}{T_0} \right)^{-3/2}$$

$$\kappa = \frac{1}{\rho} = e \cdot (n \cdot \mu_n + p \cdot \mu_p) = e \cdot n_i \cdot (\mu_n + \mu_p)$$

The influence of light also changes the electrical conductivity. This effect is used in light sensible photoresistors. For their application, an electrical voltage must be applied externally. However, this effect is not relevant to the photovoltaic generation of electrical current. Therefore, another effect must be used: the so-called extrinsic or *defect conduction* (Figure 4.6).

atoms from group V is called n-doping.   p-doping

$$p = \sqrt{\frac{n_A \cdot N_V}{2}} \cdot \exp\left(-\frac{E_A}{2 \cdot k \cdot T}\right)$$

If p-type and n-type semiconductors are placed in contact, a so-called *p-n junction* is created. Owing to the different majority carriers, electrons will diffuse from the n-region into the p-region, and holes from the p-region into the n-region (Figure 4.7).

Charge distribution
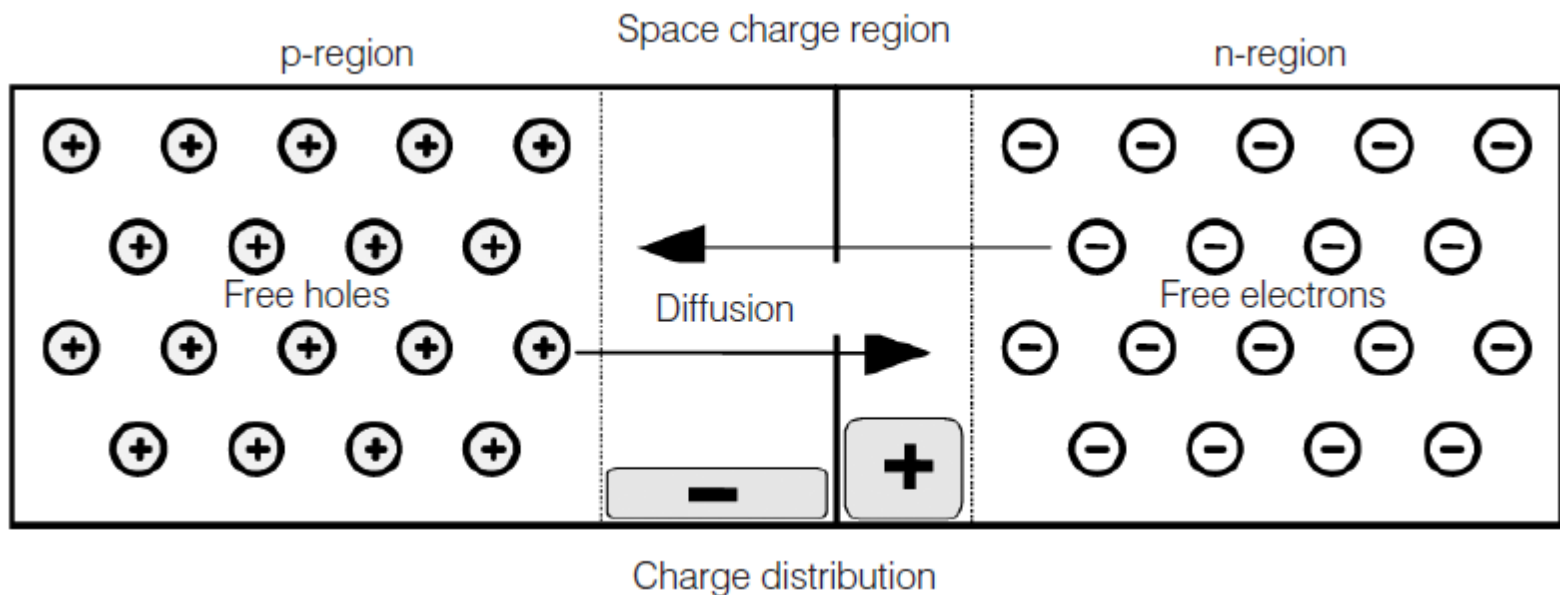
a *diffusion voltage*

$$V_d = \frac{k \cdot T}{e} \cdot \ln \frac{n_A \cdot n_D}{n_i^2}$$

is created. The charge neutrality within the boundaries d_n and d_p of the space charge region in the n-type and p-type semiconductor region leads to:
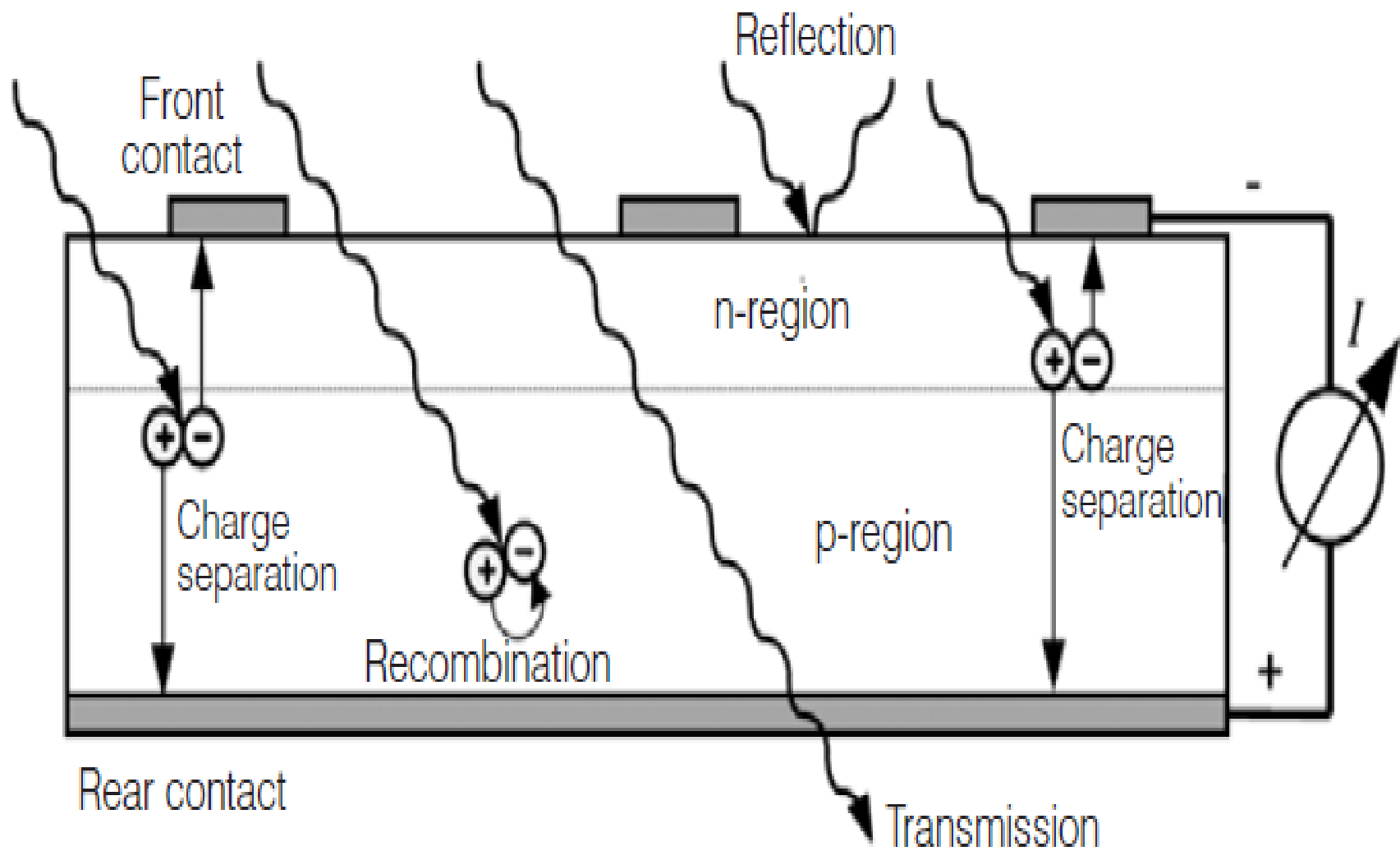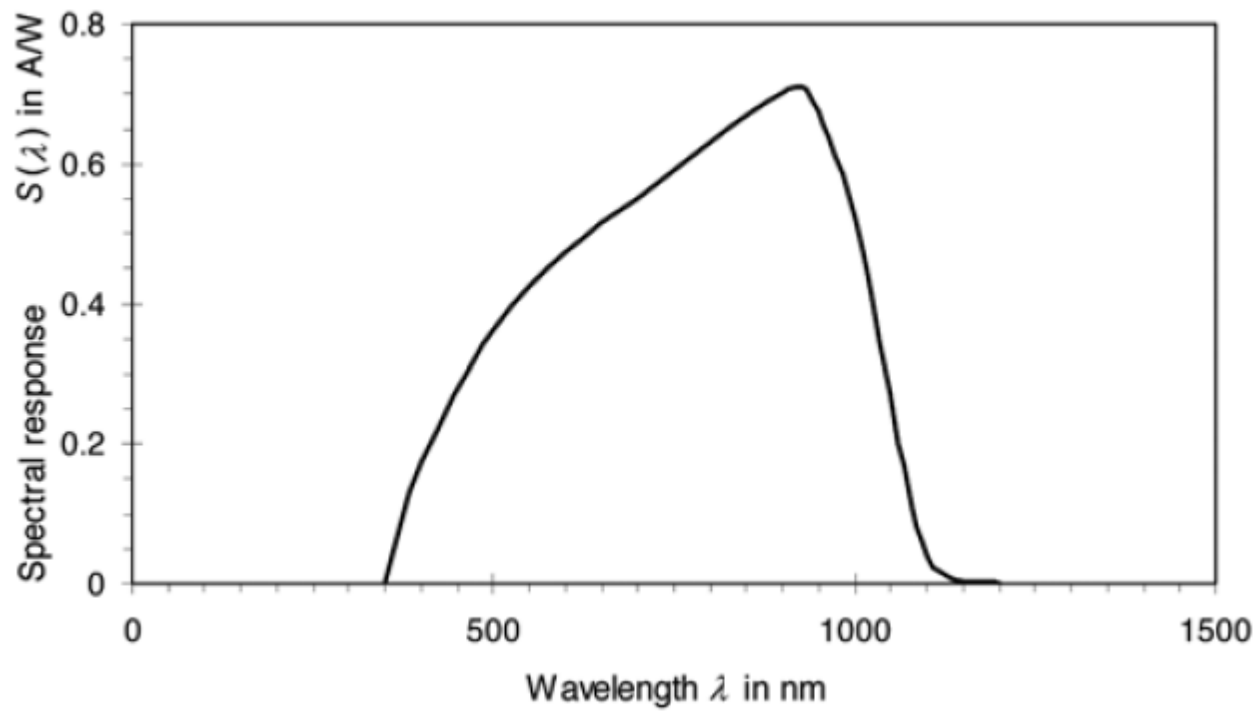
$$d_n \cdot n_D = d_p \cdot n_A.$$

Figure 4.9 *Processes in an Irradiated Solar Cell*

In the absence of an external field, i.e. if a solar cell is short-circuited, the *photocurrent* I_{ph} is generated. This current can be calculated using the solar cell area A, the spectral sensitivity S and the spectrum of sunlight $E(\lambda)$ (e.g. the air mass AM 1.5 spectrum of Chapter 2):

absorption coefficient α

$$E = E_0 \cdot (1 - \exp(-\alpha \cdot d))$$
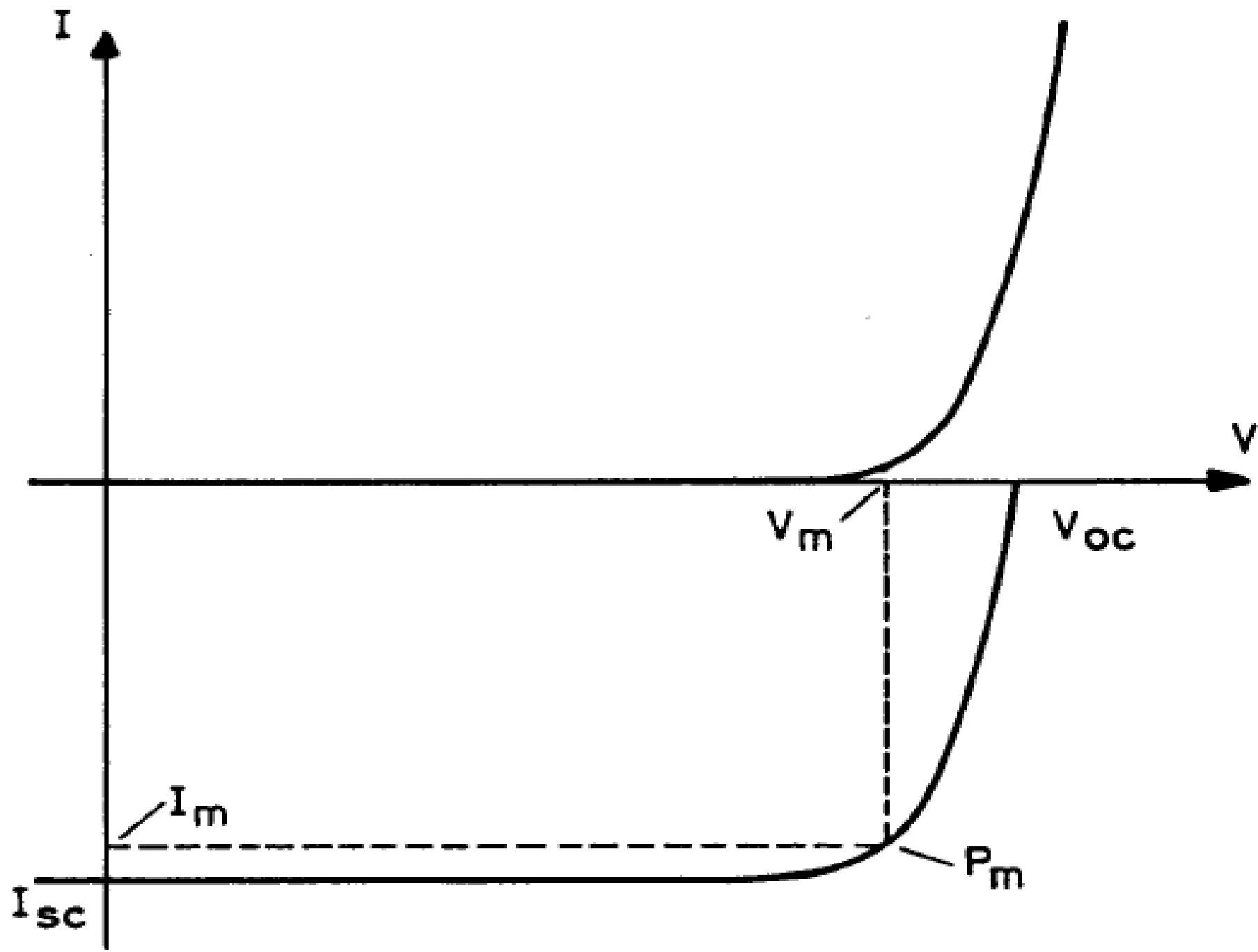
5.1.1.1   Short Circuit Current

As its name suggests, this current is obtained if the solar cell is short circuited, i.e. there is no voltage at the cell. This current is designated I_{sc} (from short circuit current).

From equation (5.1.8) we find that $I_{sc} = -I_L$, i.e. the short circuit current is equal to the absolute light–current amount. We note here that the

magnitude of the current, disregarding all losses in the cell, with AM1.5 radiation, can reach a peak of 44 mA/cm².

5.1.1.2   Open Circuit Voltage

The open circuit voltage V_{oc} is obtained when no current is drawn from the solar cell. From (5.1.8) this is found to be

$$V_{oc} = U_T \ln \left(I_L / I_0 + 1 \right) \qquad (5.1.9)$$

Since even at very low current densities we can disregard the value 1 compared with I_L/I_0 and $I_L \approx I_{sc}$, we find that for V_{oc}

$$V_{oc} \approx U_T \ln \left(I_{sc} / I_0 \right) \qquad (5.1.10)$$

i.e. the open circuit voltage is proportional to the logarithm of the ratio of short circuit current to dark current. Since in good solar cells the short circuit current very quickly nears a saturation value, the increase in the

open circuit voltage and thus efficiency is basically a question of reducing the saturation current. From equation (4.3.25), following (5.2.13) we find that for small dark current values the following three conditions must be fulfilled:

- diffusion length of minority charge carriers as high as possible,
- doping concentration N_A, N_0 high, and
- crystal volume as low as possible (thin wafer).

The first two parameters are linked to each other to some degree. Considerations about optimal parameter combinations are dealt with in Chapter 6.

5.1.1.3 Fill Factor

As always in electrical engineering, optimal power output requires a suitable load resistor R_a, which corresponds to the ratio V_m/I_m (Figure 5.2). V_m and I_m are, by definition, the voltage and current at the optimal operating point and P_m is the maximum achievable power output. We now form the ratio of peak output ($V_m I_m$) to the variable ($V_{oc} I_{sc}$) and call this ratio the fill factor FF of a solar cell:

$$FF = V_m I_m / V_{oc} I_{sc} \qquad (5.1.11)$$

The fill factor is so named because when graphically represented it indicates how much area underneath the I–V characteristic is filled by the rectangle $V_m I_m$ in relation to the rectangle $V_{oc} I_{sc}$. The fill factor normally lies in the range 0.75 to 0.85.

5.1.1.4　Efficiency

The efficiency of a solar cell is defined as the ratio of the photovoltaically generated electric output of the cell to the luminous power falling on it:

$$\eta = \frac{I_m V_m}{P_{light}} = \frac{FF\, I_{sc} V_{oc}}{P_{light}}$$

The current record for efficiency is held by a solar cell made of monocrystalline silicon using very complex technology at approximately 23–24% (area 2×2 cm², radiation AM1.5). Commercially produced cells currently have an efficiency of between 14% and 16%. In individual special cases large area cells (and modules) have been produced with 17%

–19%. The significance of high efficiency for reducing the cost of a complete solar array will be described in Chapter 6.

In general, the efficiency of photovoltaic energy conversion is very limited for physical reasons. Around 24% of solar radiation has such a long wavelength that it is not absorbed. A further 33% is lost as heat, as the excess photon energy (in the short wavelength region) is converted into heat. Further losses of approximately 15–20% occur because the cell voltage only reaches around 70% of the value which corresponds to the energy gap.

Name	Symbol	Unit	Remarks
Open circuit voltage	V_{OC}	V	$V_{OC} \sim \ln E$
Short circuit current	I_{SC}	A	$I_{SC} \approx I_{Ph} \sim E$
MPP voltage	V_{MPP}	V	$V_{MPP} < V_{OC}$
MPP current	I_{MPP}	A	$I_{MPP} < I_{SC}$
MPP power	P_{MPP}	W or W_p	$P_{MPP} = V_{MPP} \cdot I_{MPP}$
Fill factor	FF		$FF = P_{MPP} / (V_{OC} \cdot I_{SC}) < 1$
Efficiency	η	%	$\eta = P_{MPP} / (E \cdot A)$

Temperature dependence

$$I_{s1} = c_{s1} \cdot T^3 \cdot \exp\left(-\frac{E_g}{k \cdot T}\right)$$

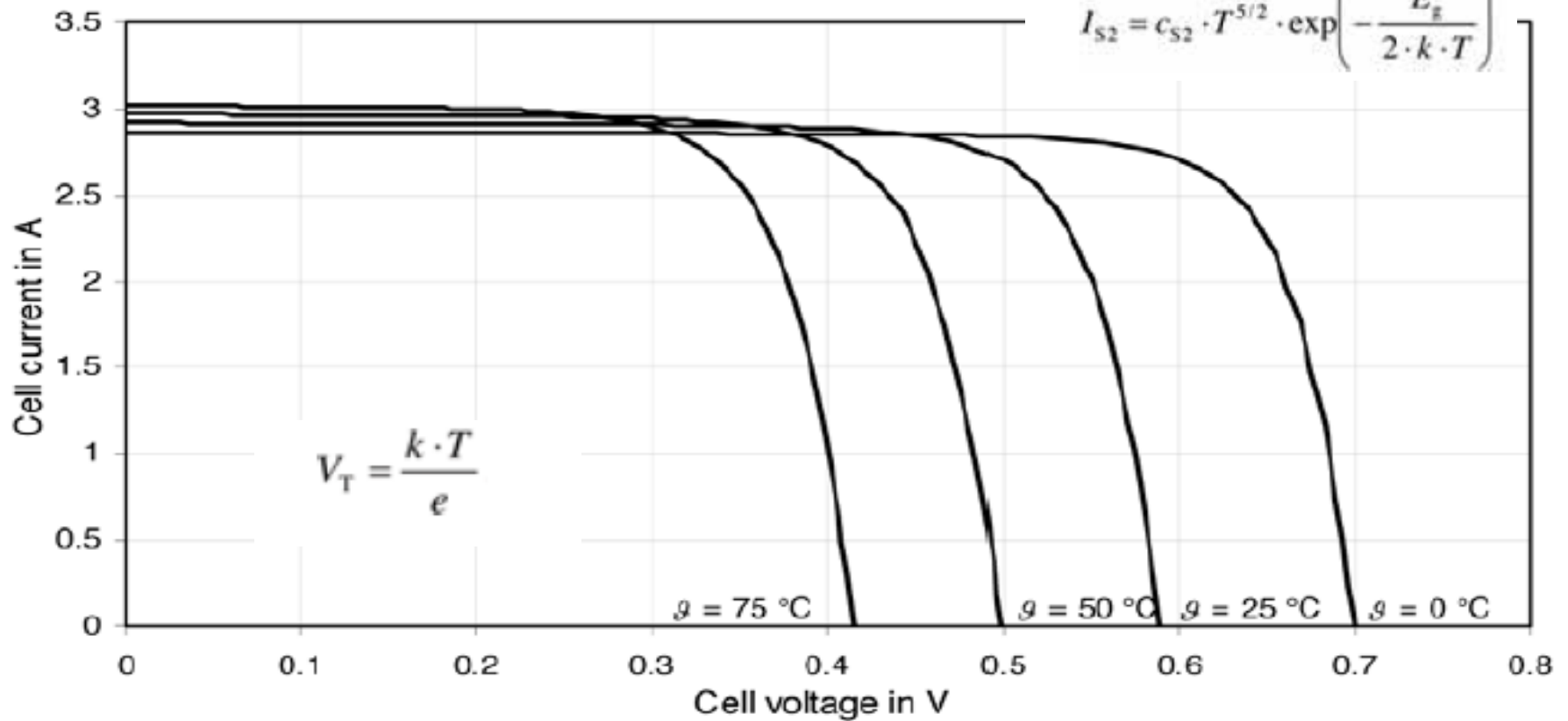$$I_{s2} = c_{s2} \cdot T^{5/2} \cdot \exp\left(-\frac{E_g}{2 \cdot k \cdot T}\right)$$

$$V_T = \frac{k \cdot T}{e}$$

Figure 4.22 *Temperature Dependence of Solar Cell Characteristics*

ELECTRICAL DESCRIPTION OF SOLAR CELLS
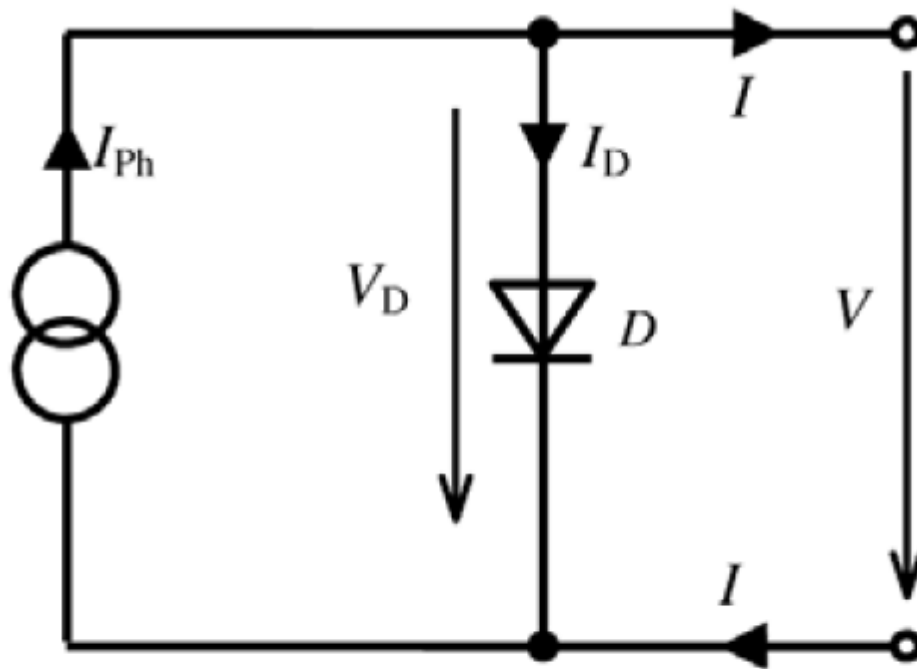
Simple equivalent circuit

Figure 4.13 *Simple Equivalent Circuit of a Solar Cell*

$$I = -I_D = -I_S \cdot \left(\exp\left(\frac{V_D}{m \cdot V_T} \right) - 1 \right)$$

The equation of the cell current I depends on the cell voltage (here $V = V_D$) with the saturation current I_S and the diode factor m:

the photocurrent I_{Ph} can be

assumed to be equal to the short circuit current I_{SC}.

The diode factor m of an ideal diode is equal to 1

Hence two parameters are already estimated (I_{Ph} =

I_{SC} and m = 1). The *diode saturation current* I_S can be calculated from equation (4.34) using the open circuit conditions:

A series resistance R_S expresses this voltage drop.

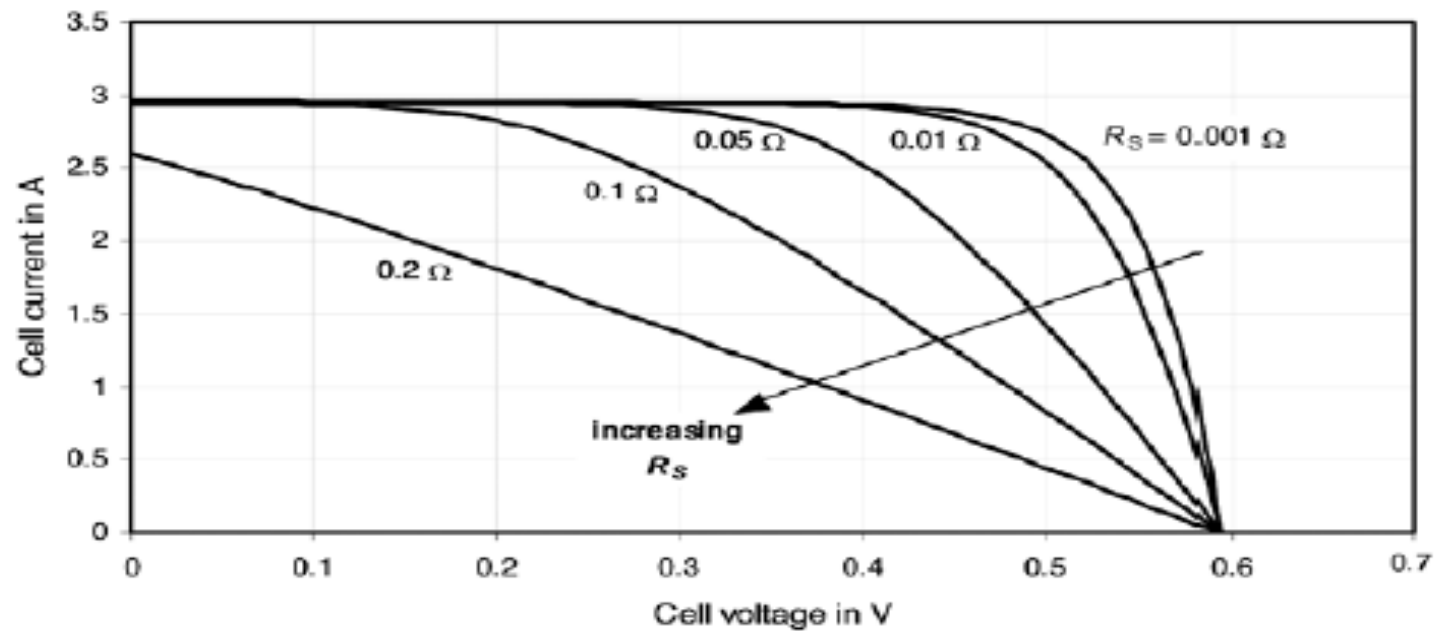$$R_S \approx \left.\frac{\partial V}{\partial I}\right|_{V \gg V_{OC}}$$

Figure 4.16 *Influence of the Series Resistance* R_S *on the I-V Characteristics of a Solar Cell*

around or beyond the open circuit voltage provides the *series resistance* R_S:

additional *parallel resistance* R_p describes the leakage currents at the cell edges.

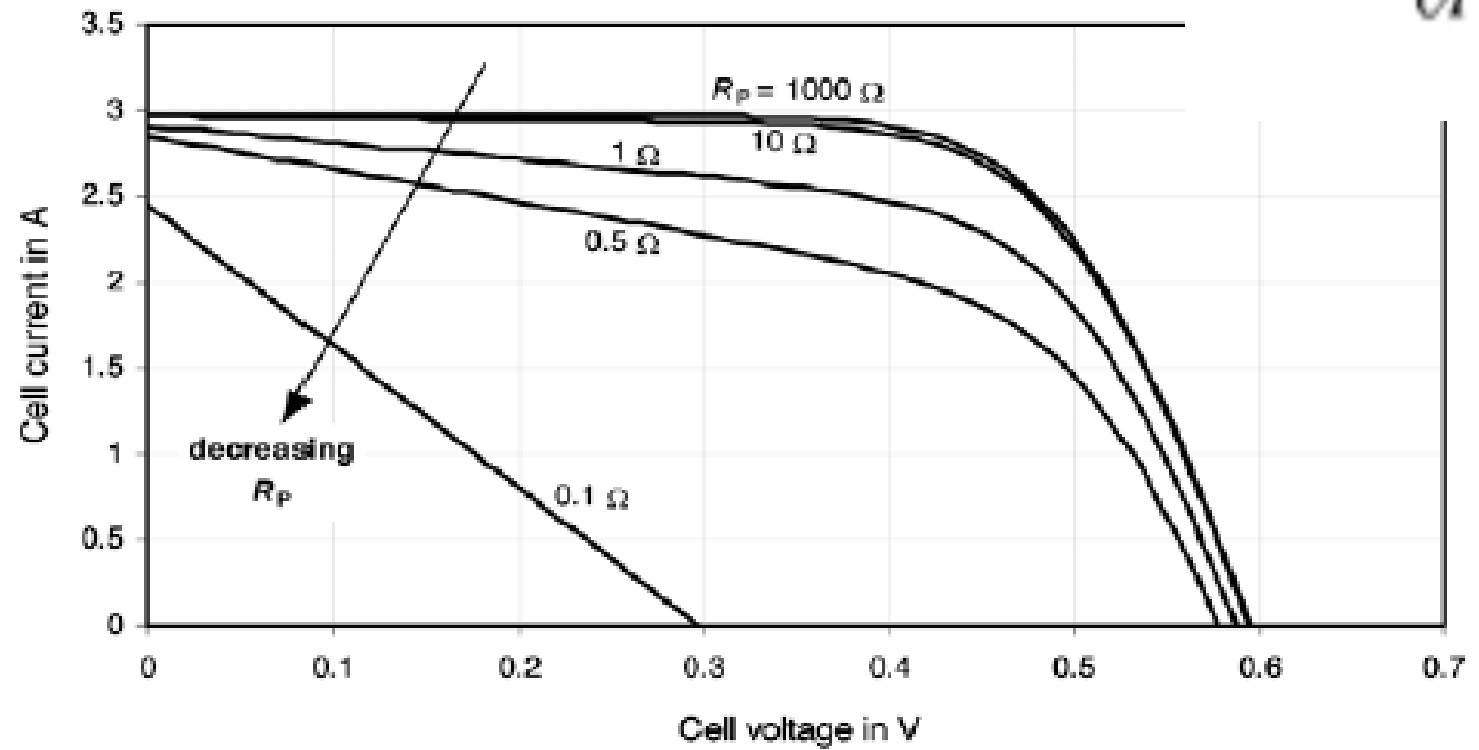$$R_p \approx \left. \frac{\partial V}{\partial I} \right|_{V=0}$$

Figure 4.17 *Influence of the Parallel Resistance* R_p *on the I-V Characteristics of a Solar Cell*

The *parallel resistance* R_p can be estimated by the negative slope of the I-V characteristic under short circuit conditions.

Series connection of solar cells
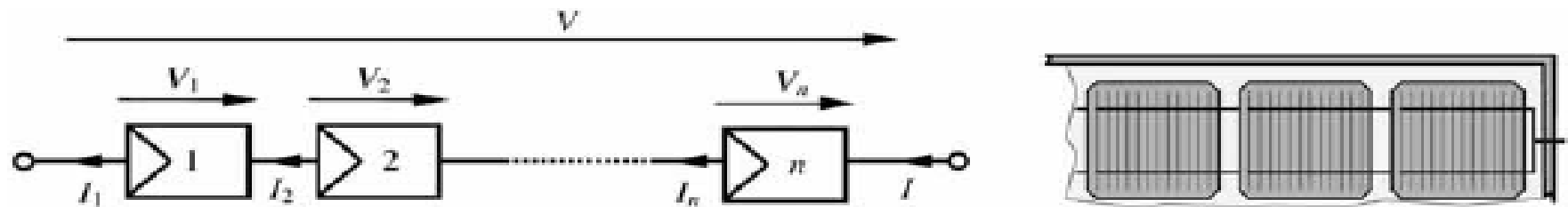
of 32–40 silicon cells is

Figure 4.23 *Series Connection of Photovoltaic Solar Cells (left: Electrical Symbols, Currents and Voltages; right: Top View of a Part of a Module with Crystalline Cells)*

$$I = I_1 = I_2 = \ldots = I_n$$

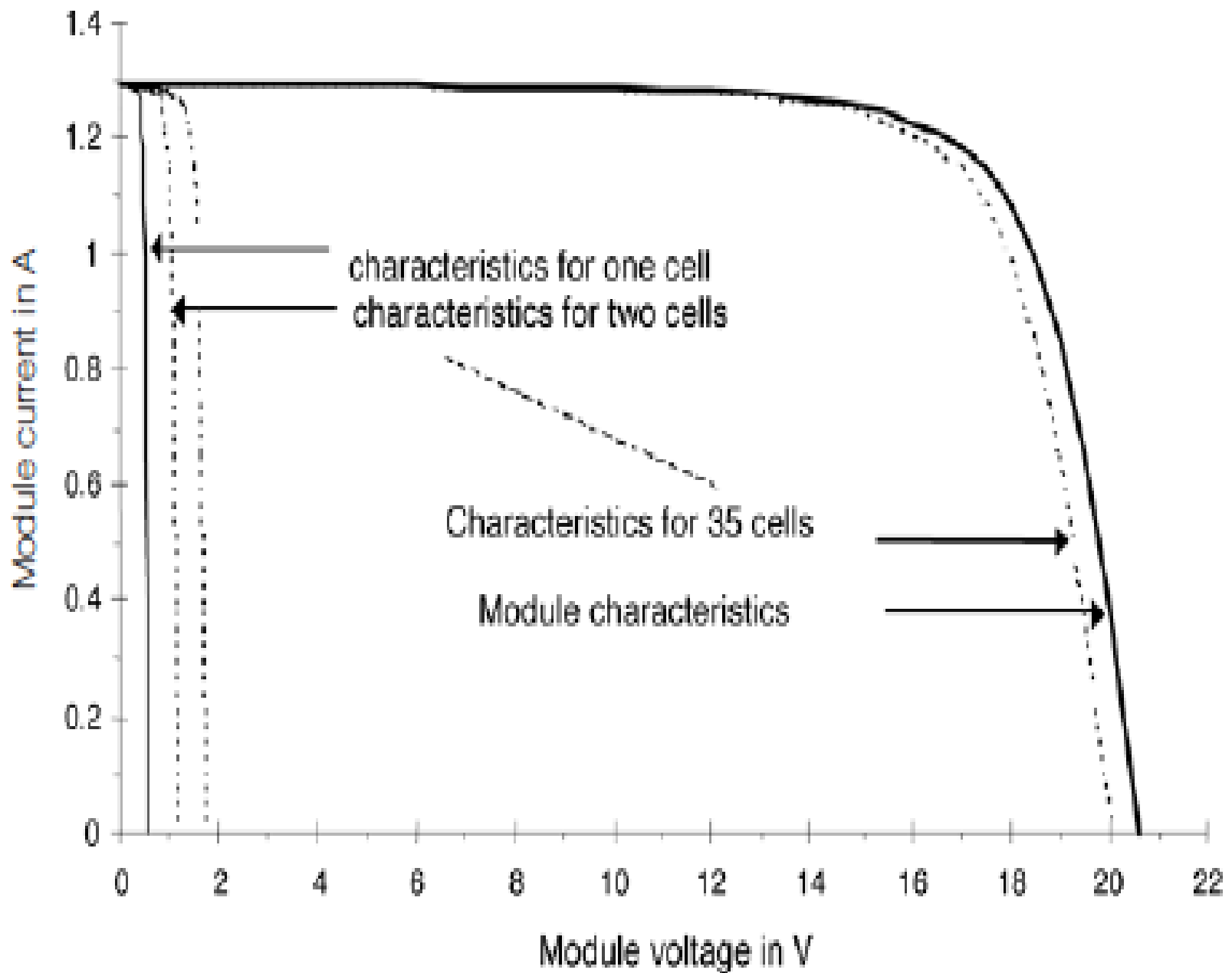$$V = \sum_{i=1}^{n} V_i$$

Figure 4.24 Comparison of Module Characteristics with 36 Cells to a di...
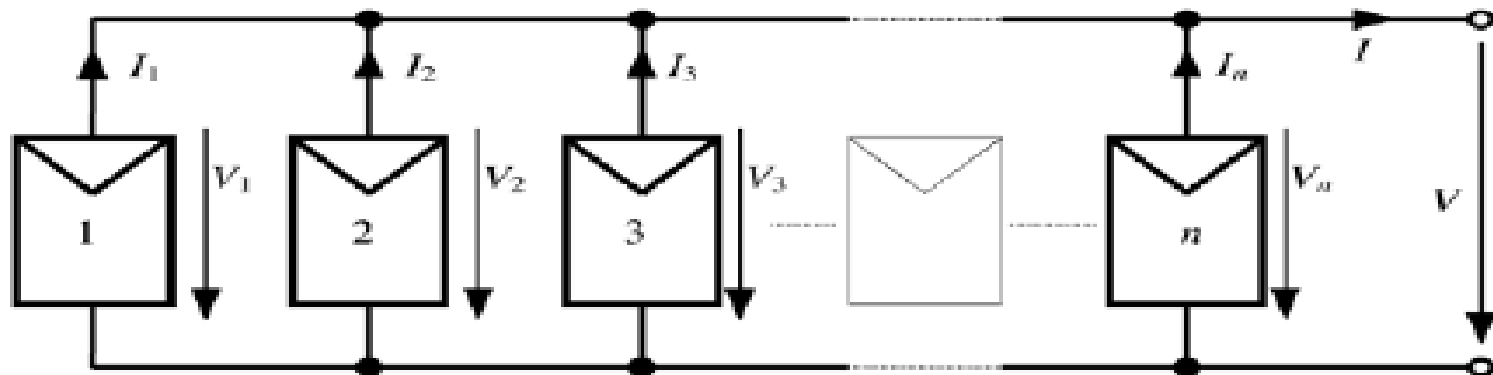
Parallel connection of solar cells

Figure 4.29 *Parallel Connection of* n *Solar Cells*

$$V = V_1 = V_2 = \ldots = V_n$$

$$I = \sum_{i=1}^{n} I_i$$

Types of batteries

long-term storage

short-term storage

Secondary electrochemical elements are mainly used for storage over short- and medium-term periods; they are usually called batteries. For economic reasons, the lead–acid battery dominates the current market. When higher energy densities are needed due to weight considerations, for example, in laptop computers, other batteries such as nickel–cadmium (NiCd) or nickel–metal hydride (NiMH) are used. Other batteries such as sodium–sulphur (NaS) have been tested for use in electrical (battery-powered) vehicles but are no longer being developed. Table 4.7 summarizes the data for various types of rechargeable battery.

Table 4.7 Data for Various Types of Rechargeable Battery

	Lead–acid	NiCd	NiMH	NaS
Positive electrode	PbO_2	NiOOH	NiOOH	S
Negative electrode	PbO	Cd	metals	Na
Electrolyte	$H_2SO_4+H_2O$	$KOH+H_2O$	$KOH+H_2O$	β-Al2O3
Energy density (Wh/l)	10–100	80–140	100–160	150–160
Energy density (Wh/kg)	25–35	30–50	50–80	100
Cell voltage (V)	2	1.2	1.2	2.1
Charge/discharge cycles	500–1500	1500–3000	about 1000	about 1500
Operating temperature (°C)	0–55	–20 to 55	–20 to 45	290–350
Self-discharge rate (%/month)	5–15	20–30	20–50	0
Wh efficiency	70–85%	60–70%	60–85%	80–95%
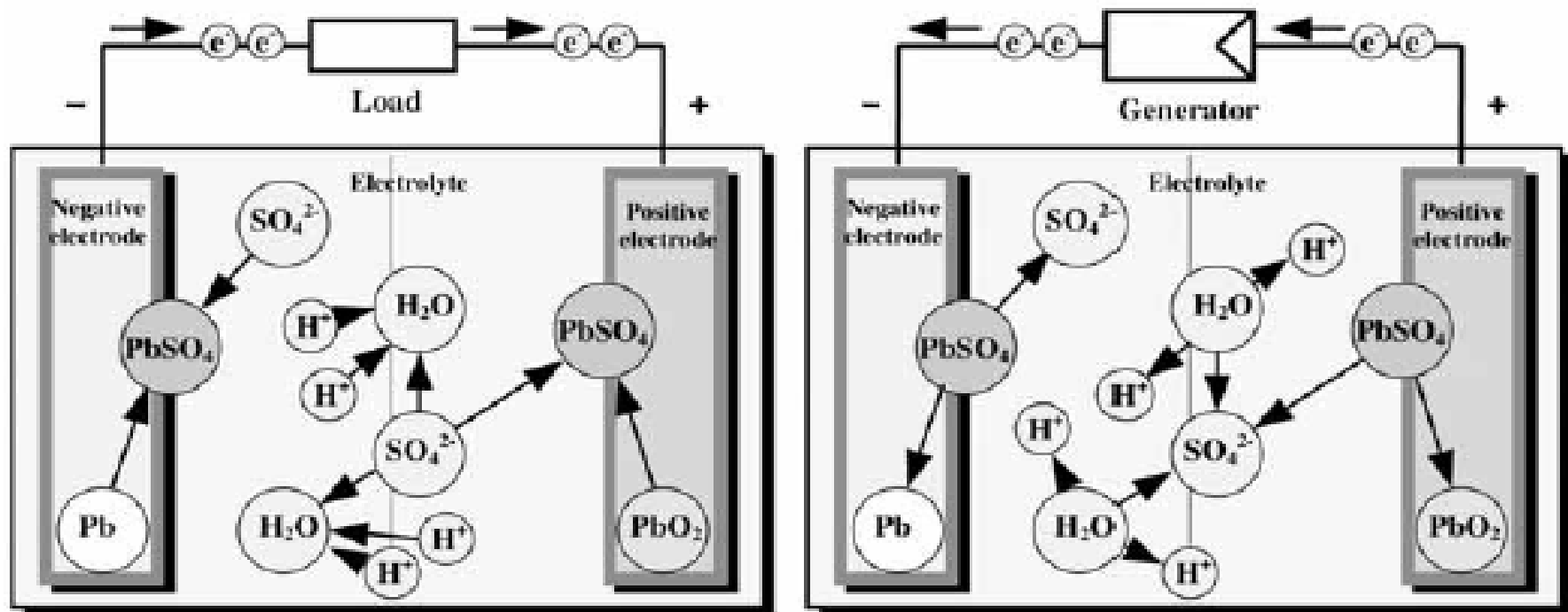
Figure 4.41 *Charging and Discharging a Lead–Acid Battery*

Negative electrode: $\mathrm{Pb} + \mathrm{SO}_4^{2-} \underset{\leftarrow\text{Charge}}{\overset{\text{Discharge}\rightarrow}{\longleftrightarrow}} \mathrm{PbSO}_4 + 2\,\mathrm{e}^-$

$$(4.92)$$

Positive electrode: $\mathrm{PbO}_2 + \mathrm{SO}_4^{2-} + 4\,\mathrm{H}^+ + 2\,\mathrm{e}^- \underset{\leftarrow\text{Charge}}{\overset{\text{Discharge}\rightarrow}{\longleftrightarrow}} \mathrm{PbSO}_4 + 2\,\mathrm{H}_2\mathrm{O}$

$$(4.93)$$

Net reaction: $\mathrm{PbO}_2 + \mathrm{Pb} + 2\,\mathrm{H}_2\mathrm{SO}_4 \underset{\leftarrow\text{Charge}}{\overset{\text{Discharge}\rightarrow}{\longleftrightarrow}} 2\,\mathrm{PbSO}_4 + 2\,\mathrm{H}_2\mathrm{O}$ (4.94)
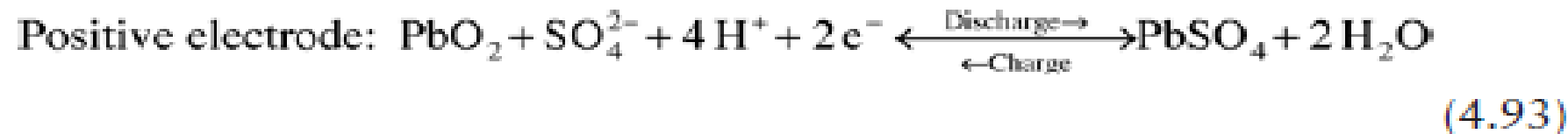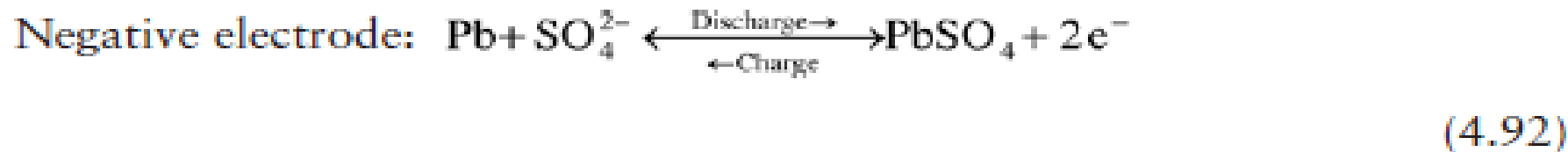
Other storage concepts

- capacitor banks
- storage in superconducting coils
- flywheel storage
- pumped-storage hydroelectric power plants
- compressed air storage.