Renewable Electric Energy Systems EE—546

Consideration of the Photodiode

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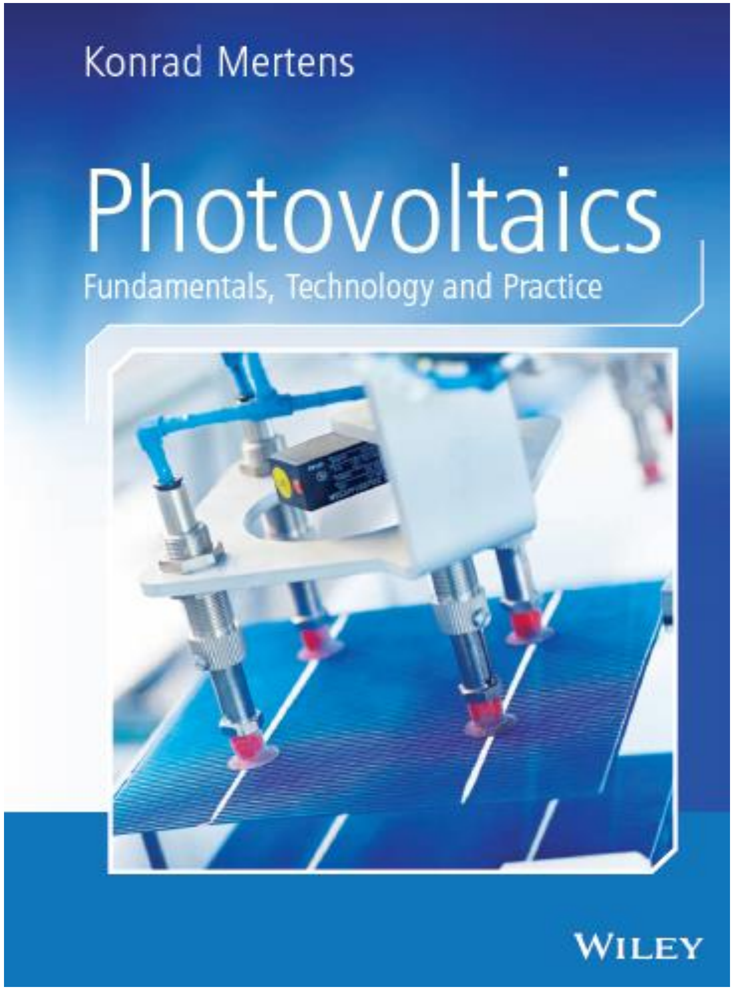
Slides are prepared from:—Chapter 4



Konrad Mertens—Photovoltaics Fundamentals Technology and Practice

4.1 Consideration of the Photodiode

A good foundation for understanding the solar cell is the photo diode.

Penetrating photons are absorbed and generate free electron-hole pairs. The current generated by photons, it is called **photocurrent** $I_{ph.}$ The **photocurrent** I_{Ph} **is proportional to the irradiance** E:

$$I_{Ph} = \text{const} \cdot E$$

(constant current source)

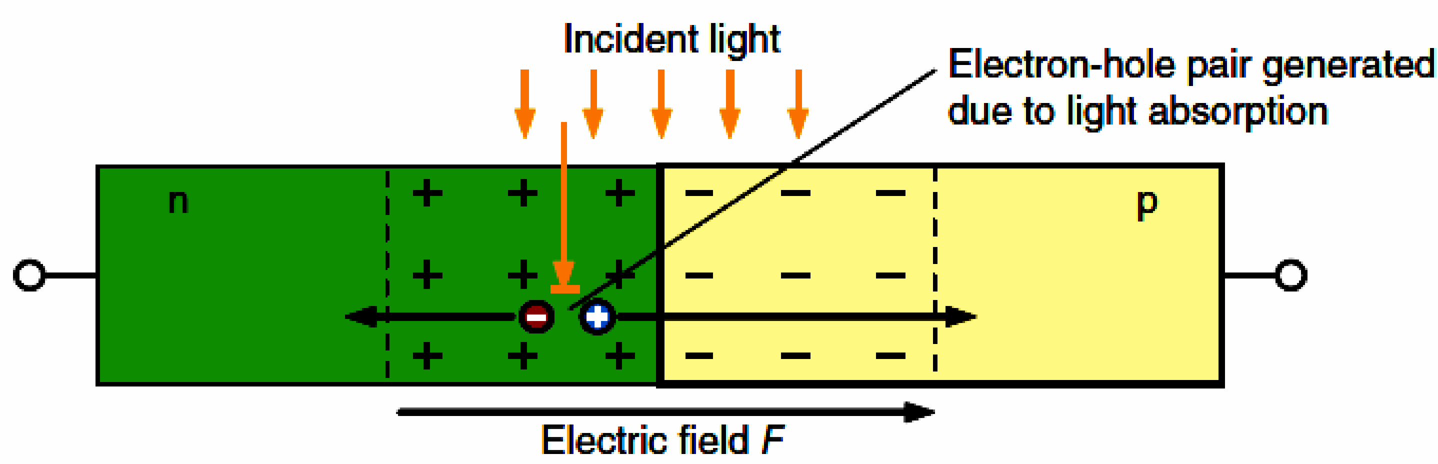
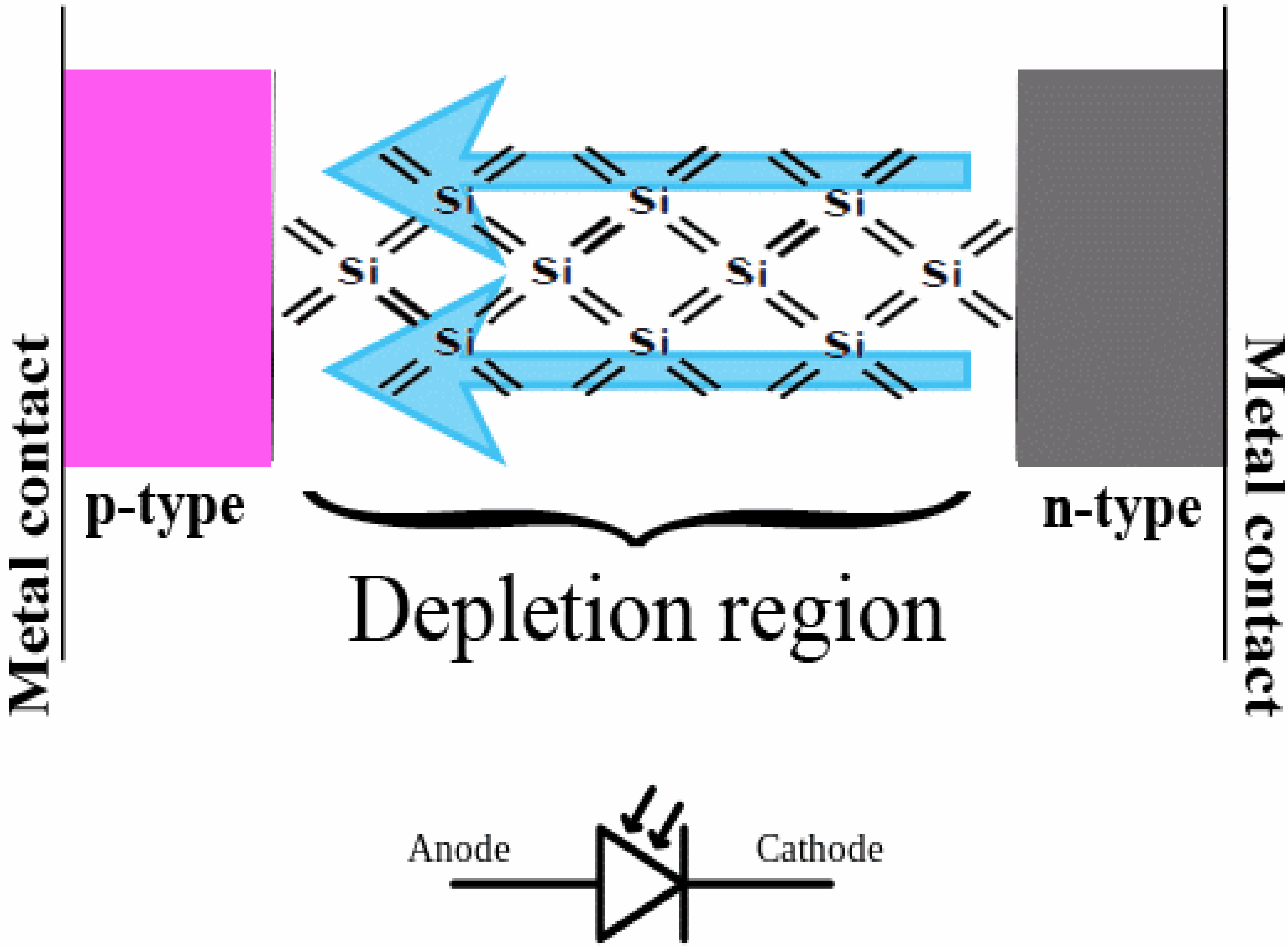
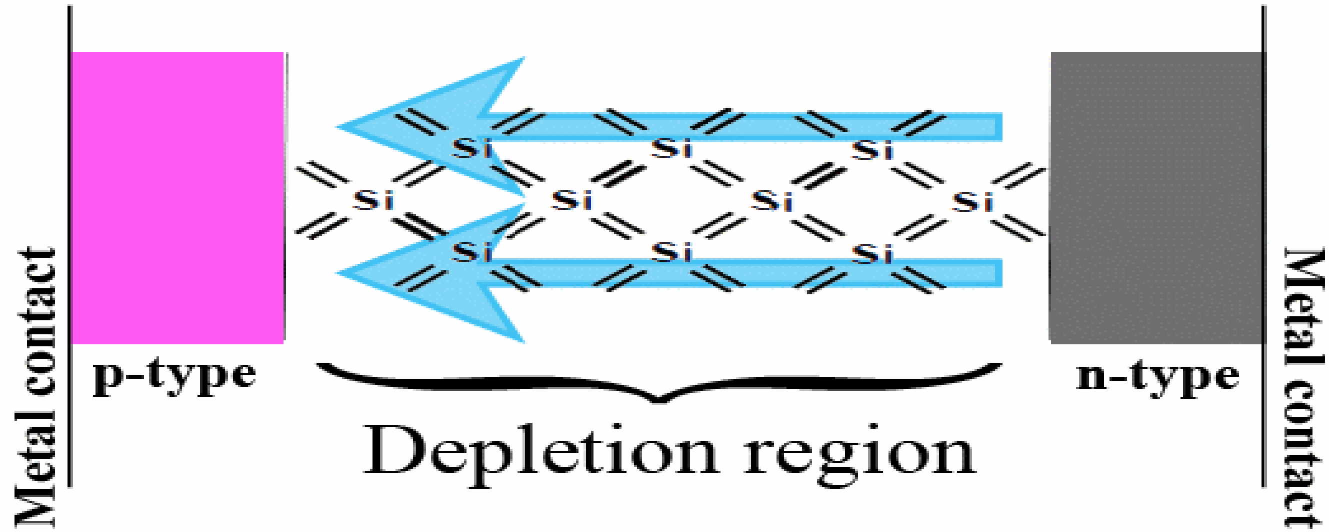
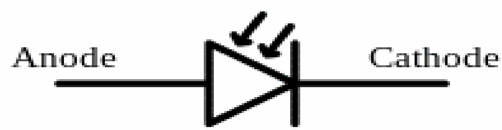


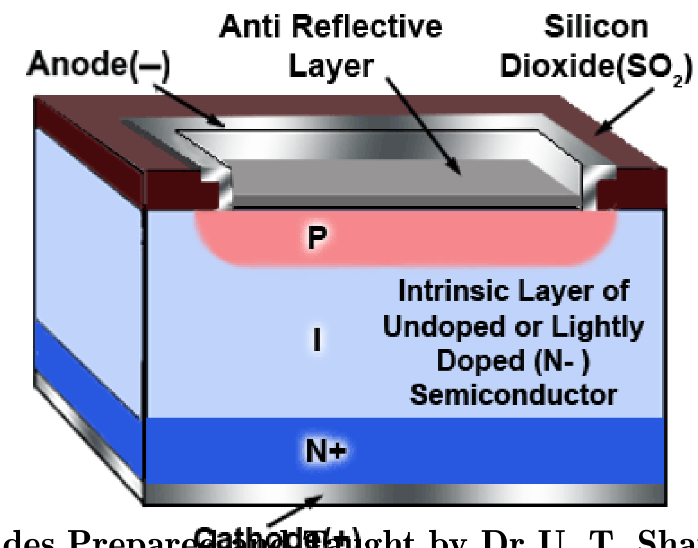
Figure 4.1 Lighted p-n junction: The free electrons and holes generated by light absorption are separated from the field of the space charge region and "brought home"


Metal contact
p-type
Si
Si
Si
Si
Si
Si
Si
Si
Si
Si
n-type
Metal contact
Depletion region
Anode
Cathode





The electron-hole pair thus created needs to be separated to avoid recombination of the free electron and the hole. This can be achieved by employing a P–N junction.



Characteristic Curve

Study the graph axis carefully.

Meaning that there is no light

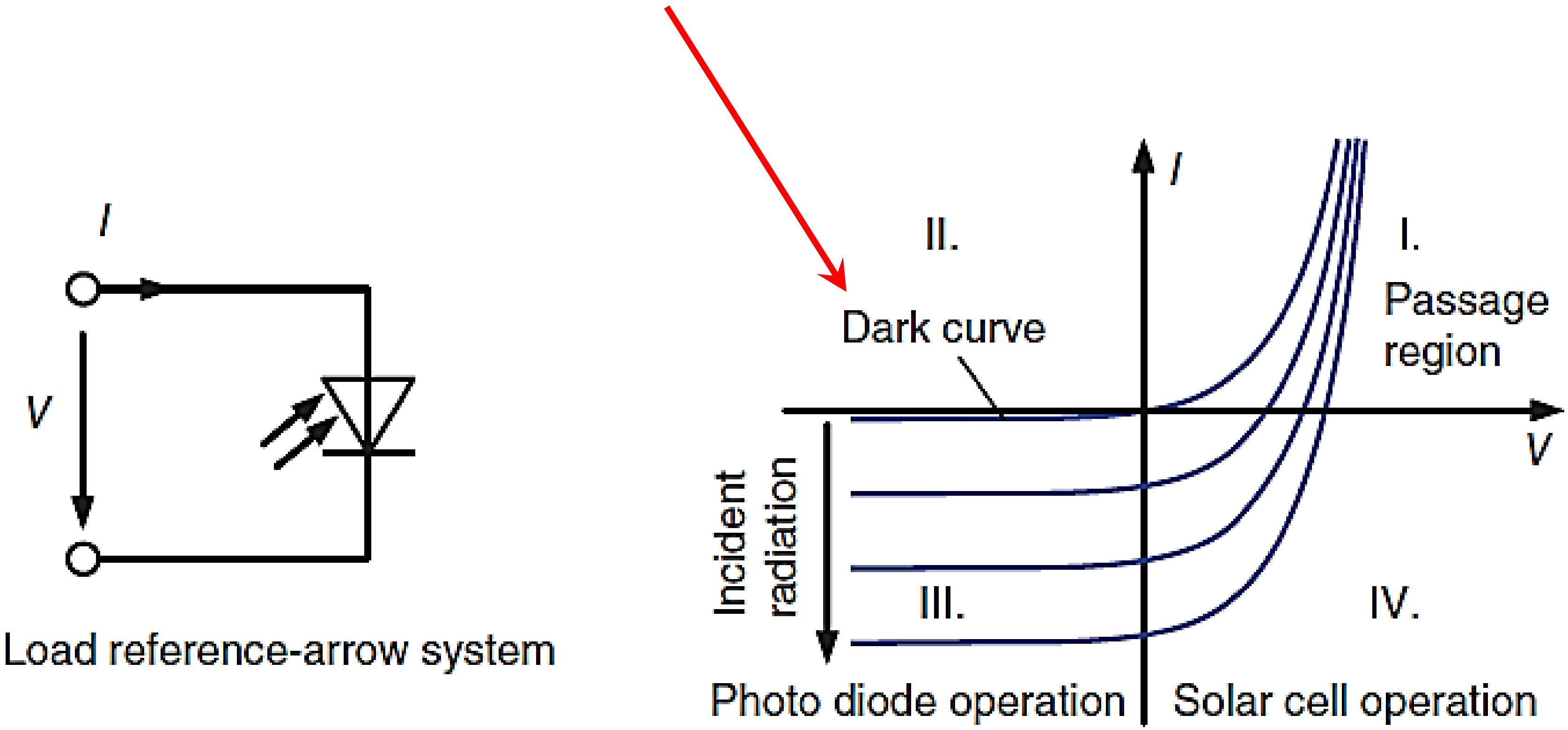
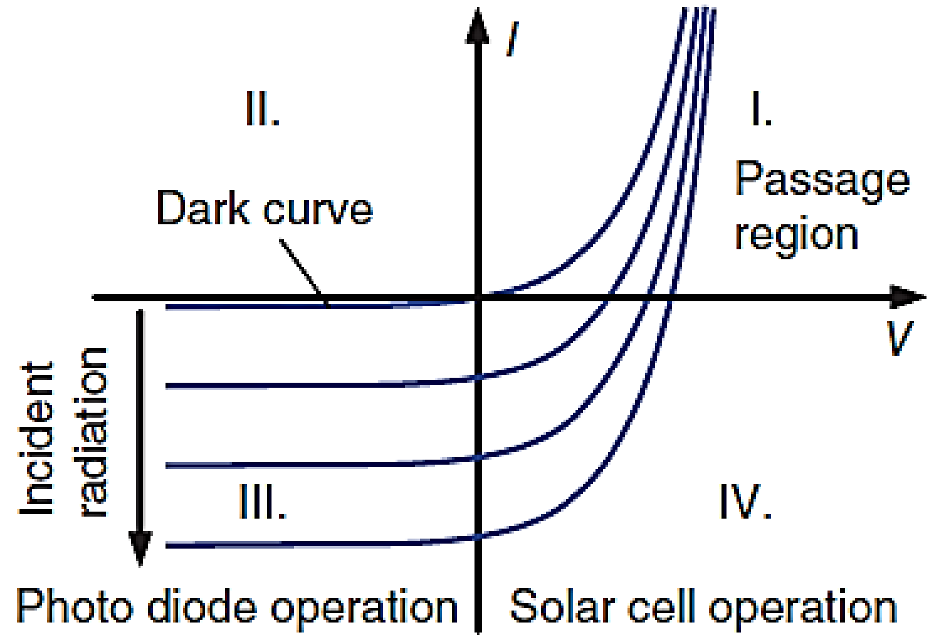


Figure 4.2 Symbol and curves of a photodiode

Characteristic Curve

As long as no photons fall on the photodiode **(quadrant I & II)** it behaves like a normal **P-N** junction. With a reverse voltage only a small reverse current flows, which is called **dark current**.

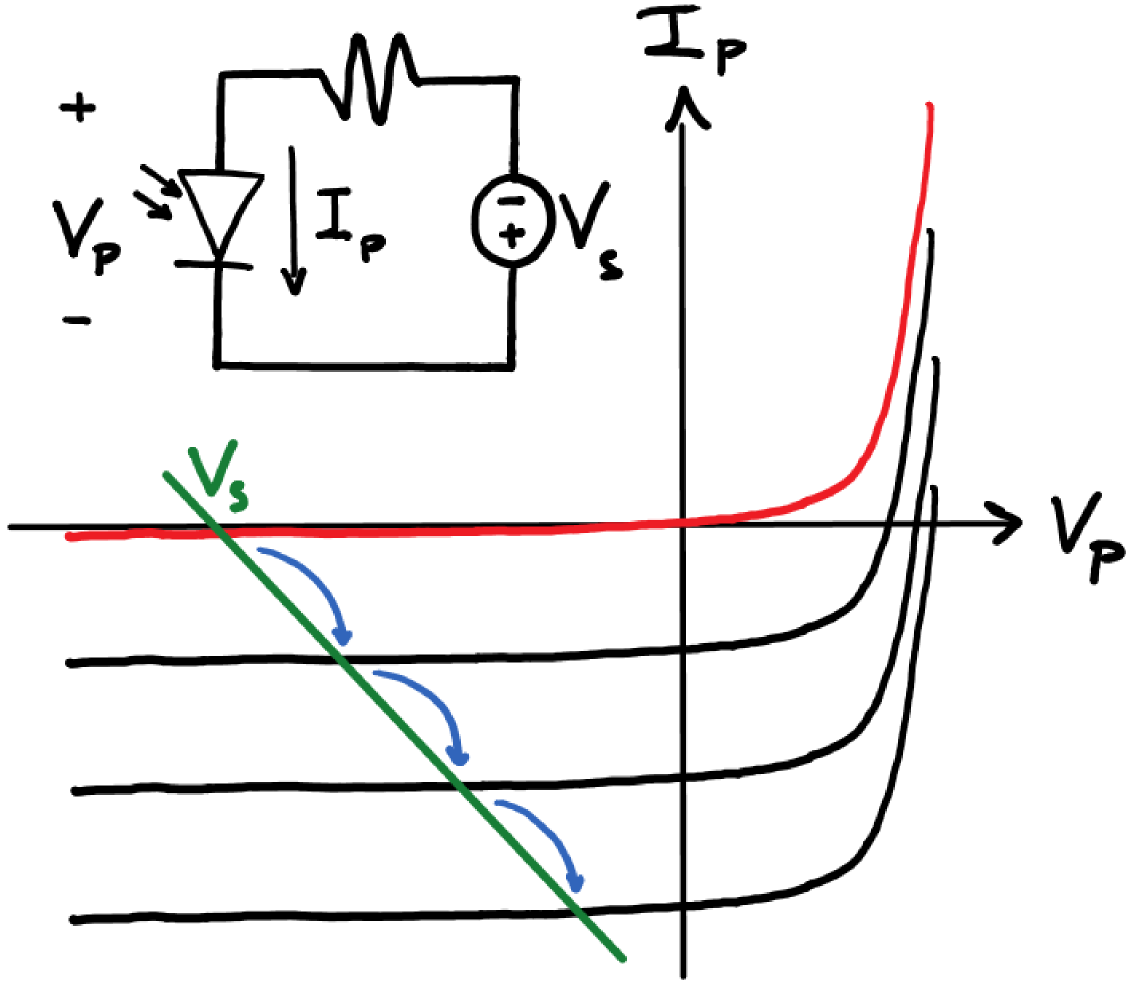


As photons fall on the diode **(quadrant III)**, a photocurrent that is independent of the voltage, flows in the reverse direction. The use of the photodiode in quadrant III is called p**hotodiode operation** as photodiodes are operated with applied reverse voltage in order, e.g., to serve as detectors for optical data receivers.

In **quadrant IV** the photodiode is operated as a **solar cell**: with positively applied voltage the result is a negative current.

What is negative current ?

Characteristic Curve



4.1.2 Equivalent Circuit

The electrical behavior of the photodiode can be expressed by the Shockley equation

$$I = I_D - I_{Ph} = I_S \cdot \left(e^{\frac{V}{V_T}} - 1\right) - I_{Ph} \tag{4.2}$$

I_D is the **Diode current,** expressed as

$$I_D = I_S \cdot \left(e^{\frac{V}{V_T}} - 1\right)$$

4.1.2 Equivalent Circuit

The electrical behavior of the photodiode can be expressed by the Shockley equation

$$I = I_D - I_{Ph} = I_S \cdot \left(e^{\frac{V}{V_T}} - 1 \right) - I_{Ph} \tag{4.2}$$

I_S is the **saturation current,** expressed as

$$I_S = A \cdot q \cdot n_i^2 \cdot \left(\frac{D_N}{L_N \cdot N_A} + \frac{D_P}{L_P \cdot N_D} \right) \tag{4.3}$$

A: cross sectional area of the crystal
q: is elementary charge
n_i is the intrinsic carrier concentration in the semiconductor material
D: diffusion constant of N or P type material,
L_N, L_P: diffusion lengths of the electrons or holes,
N_D and N_A: donor density N_D and acceptor density N_A

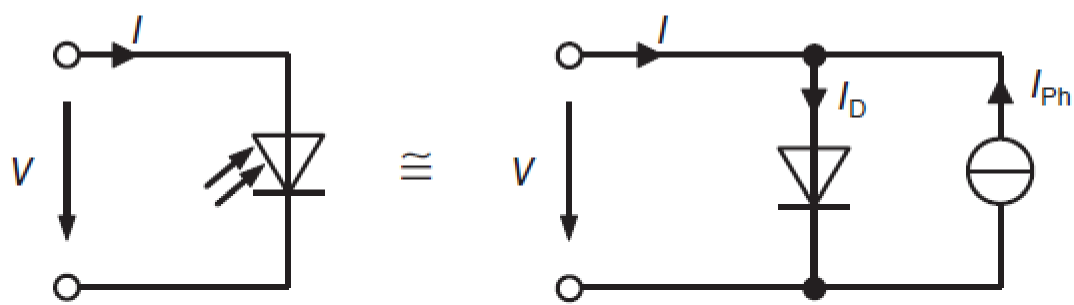
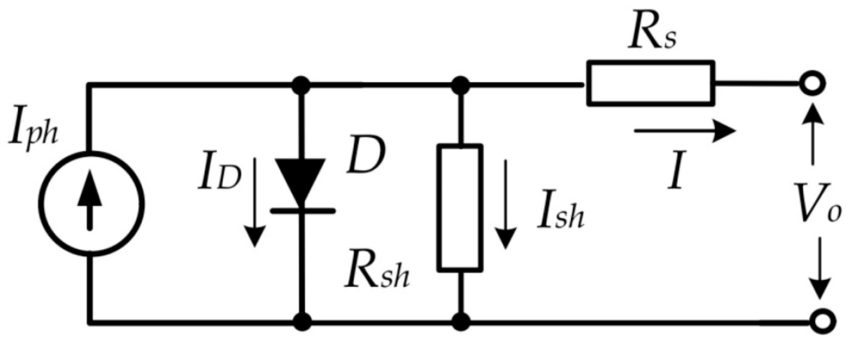
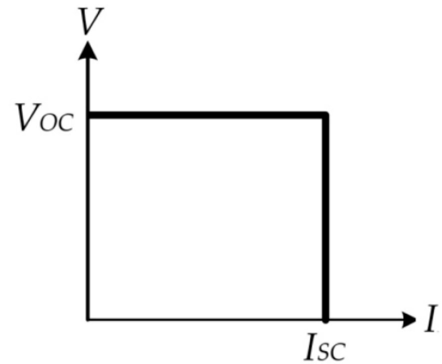


Figure 4.3 Equivalent circuit of the photodiode



(a)



(b)

4.2 Method of Function of the Solar Cell

These are small metal strips that transport the generated electrons to the **current collector rail (busbar)**. When a load is connected to the two poles of the solar cell then this load can consume the generated electrical energy.

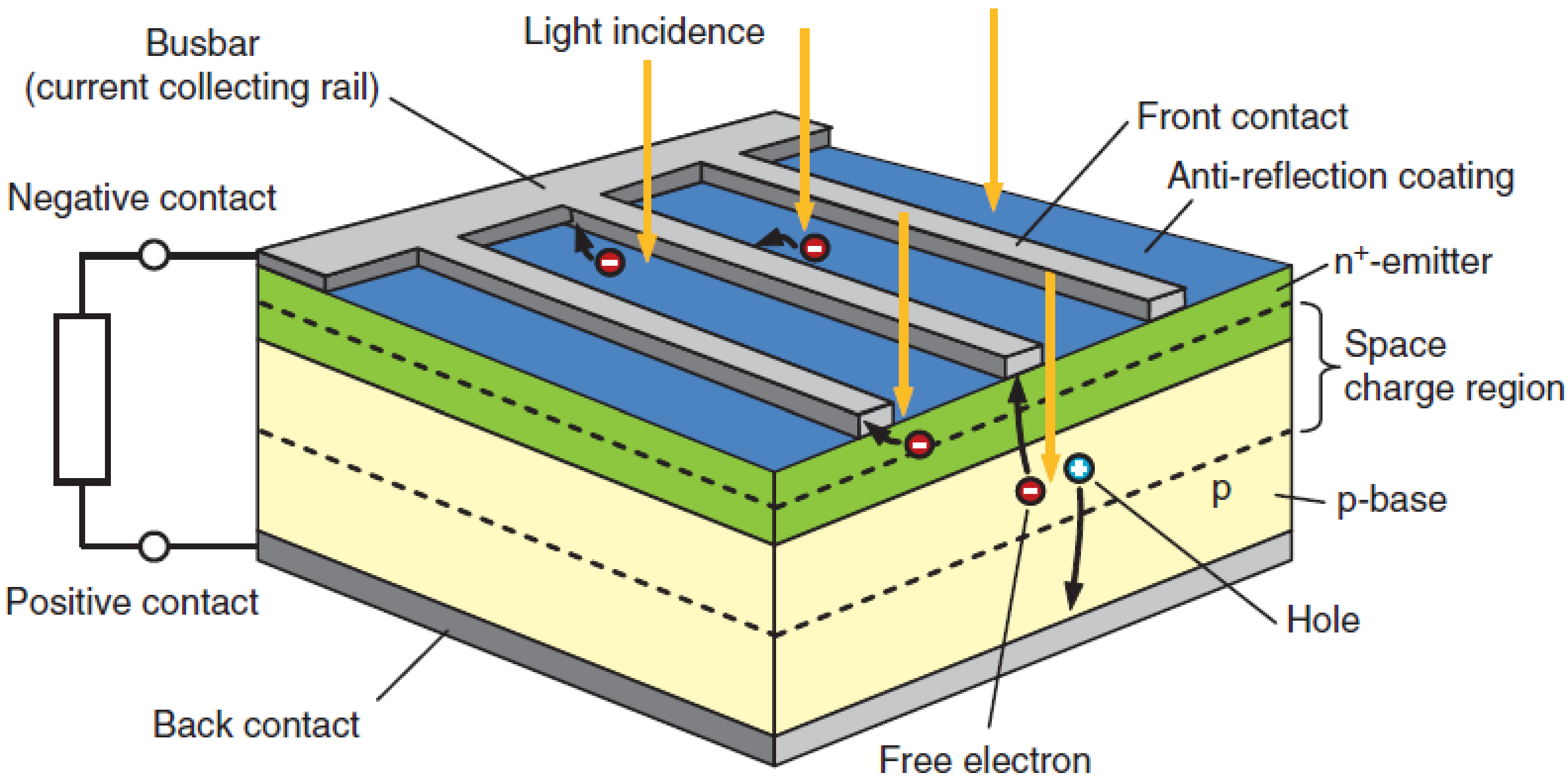


Figure 4.4 Typical silicon solar cell

4.2.2 Recombination and Diffusion Length

Self-Study

4.2.3 What Happens in the Individual Cell Regions?

Light is absorbed differently for different wavelengths.

Blue light has the highest absorption coefficient with penetration depths of less than **1 μm**.

Infrared, in comparison, has penetration depths of more than **100 μm**.

For this reason we will look more closely at the situation of the photocurrent generation at the different depths of the cell.

4.2.3 What Happens in the Individual Cell Regions?

Photocurrent and Responsivity Depend on the Wavelength

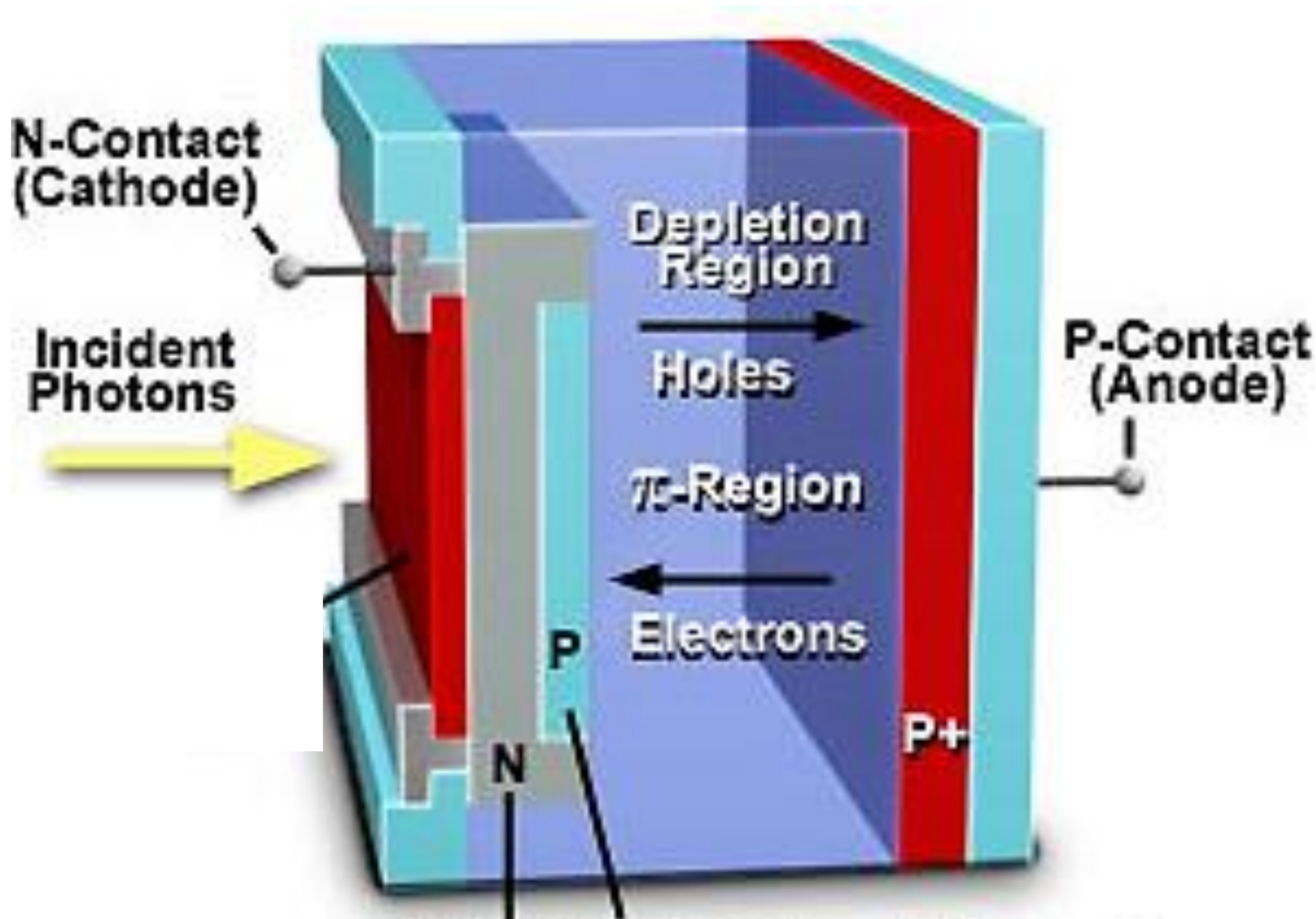
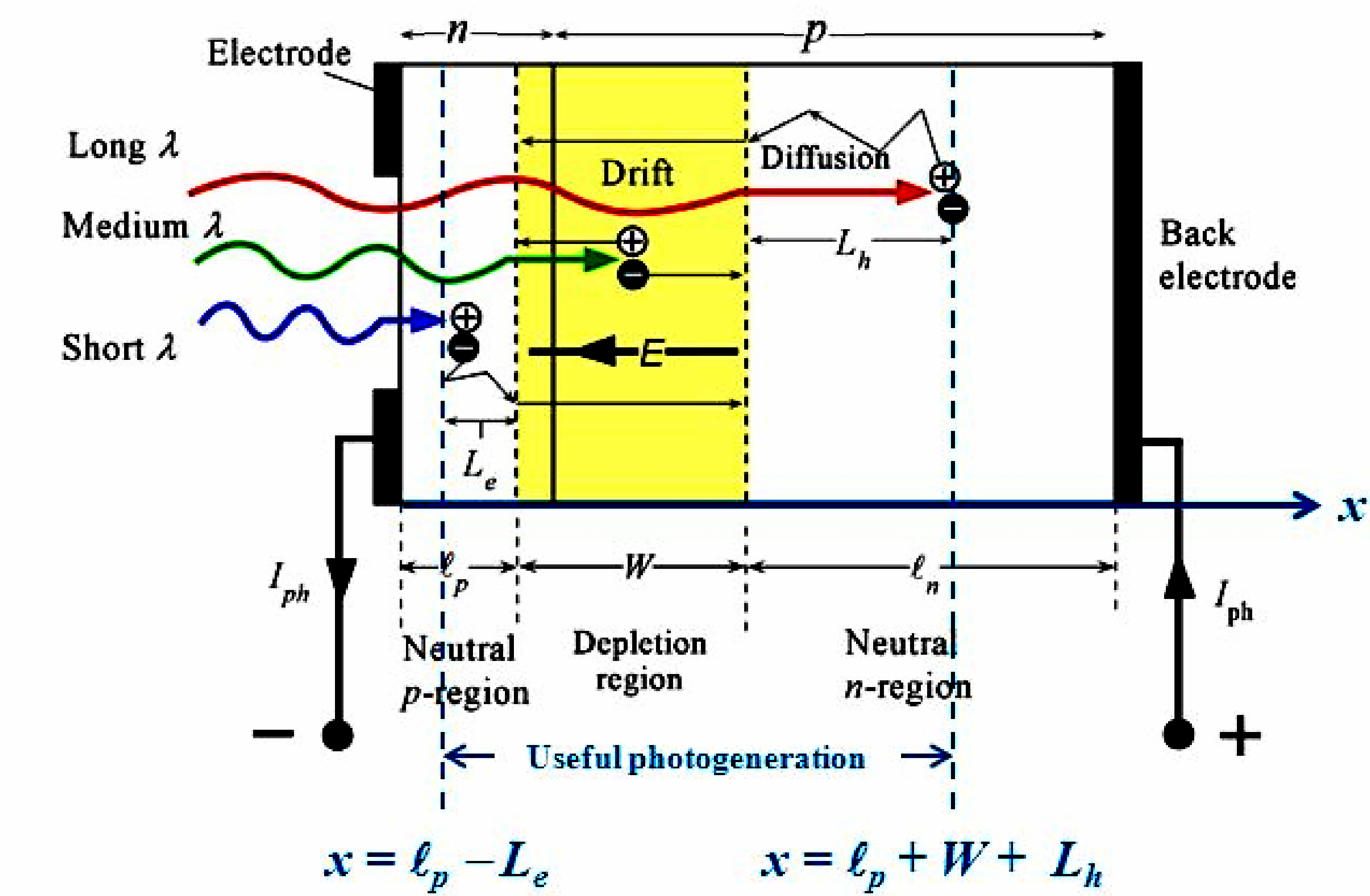


Figure 1

4.2.3 What Happens in the Individual Cell Regions?

Photocurrent and Responsivity Depend on the Wavelength



Different contributions to the photocurrent I_{ph}. Photogeneration profiles corresponding to short, medium and long wavelengths are also shown.

Spectrum of the Sun

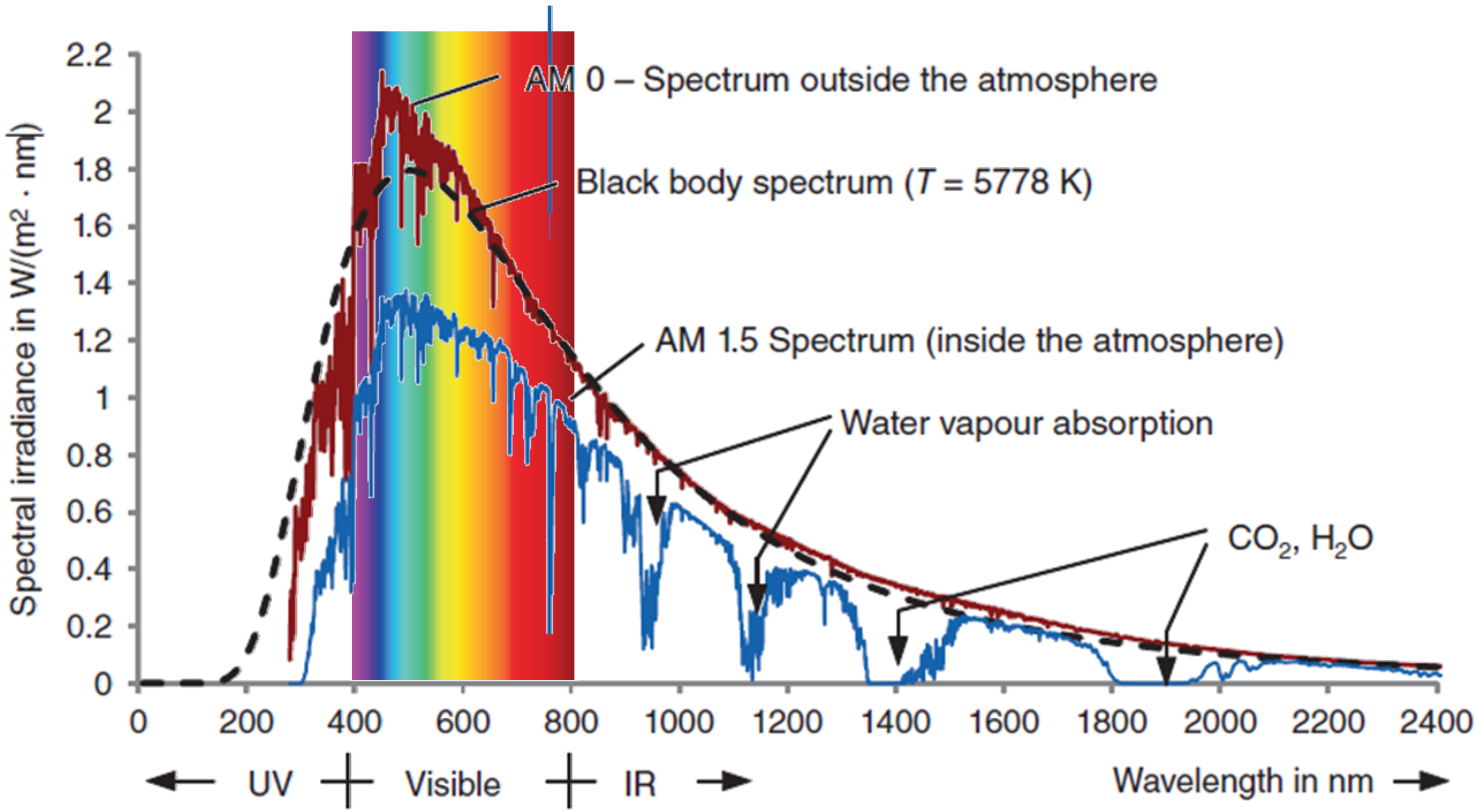
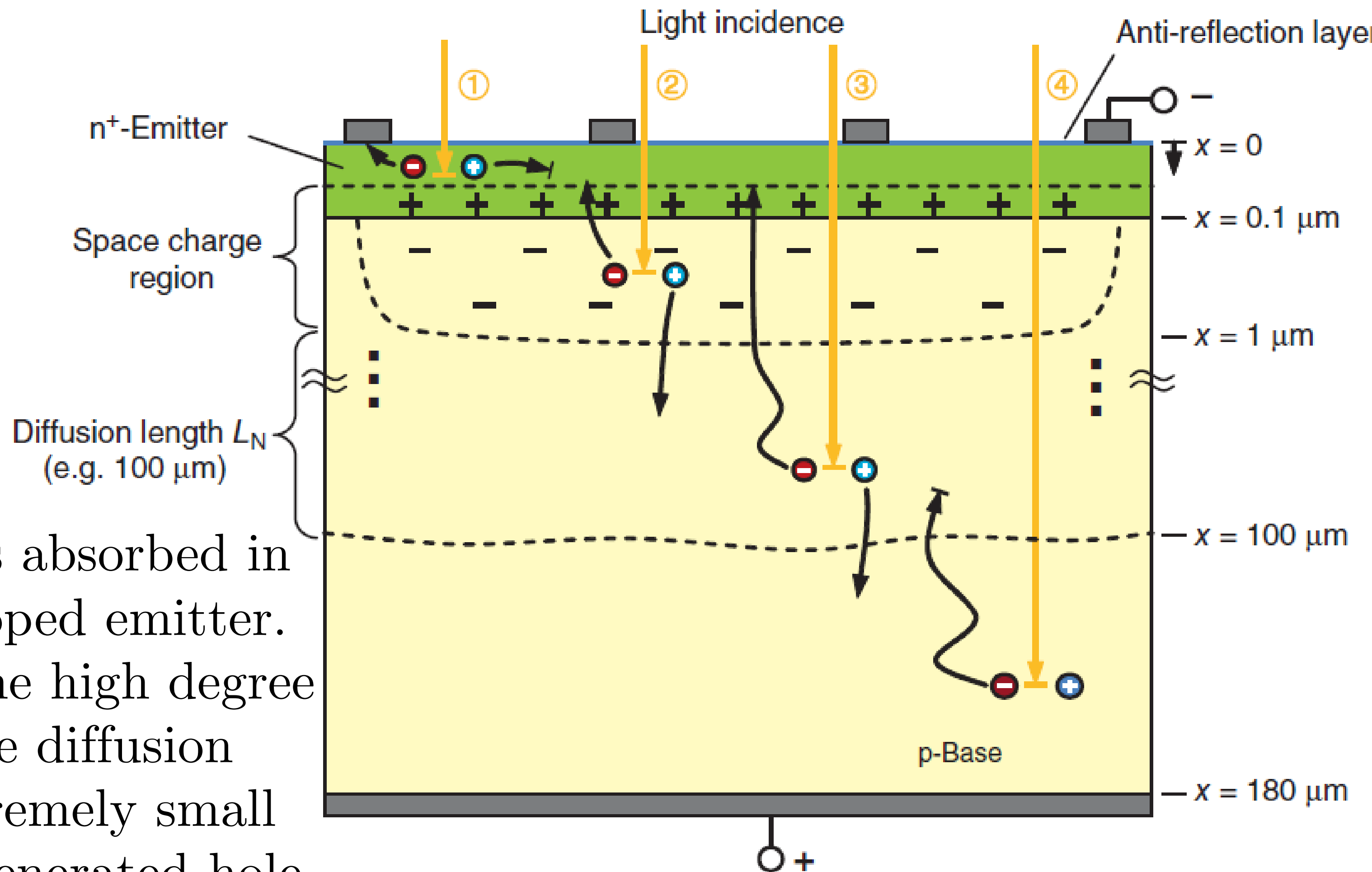


Figure 2.2 Spectrum outside and inside the atmosphere

4.2.3 What Happens in the Individual Cell Regions?

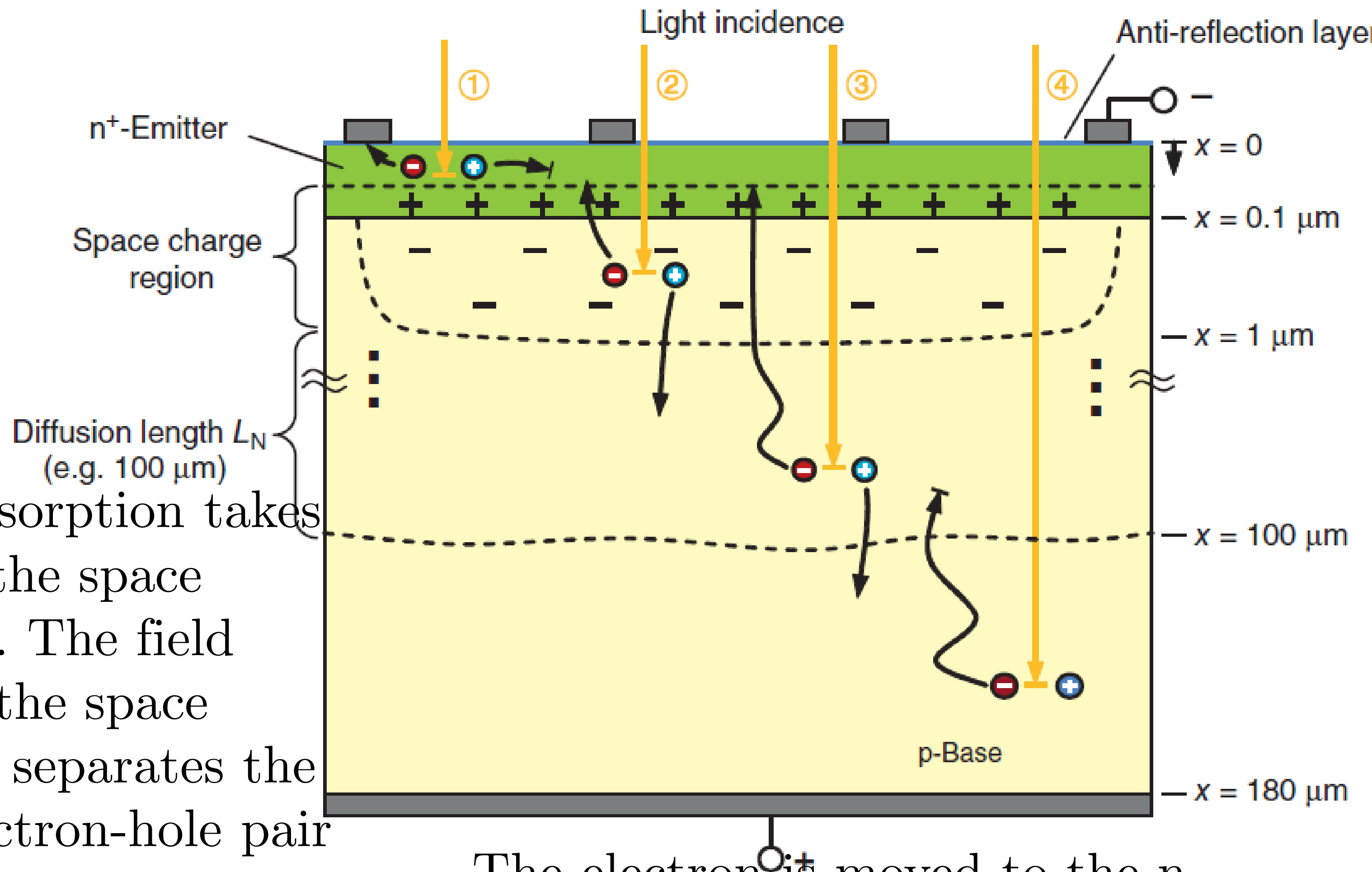
4.2.3.1 Absorption in the Emitter



Photon (1) is absorbed in the highly doped emitter. Because of the high degree of doping, the diffusion length is extremely small so that the generated hole recombines before reaching the space charge region.

4.2.3 What Happens in the Individual Cell Regions?

4.2.3.2 Absorption in the Space Charge Region

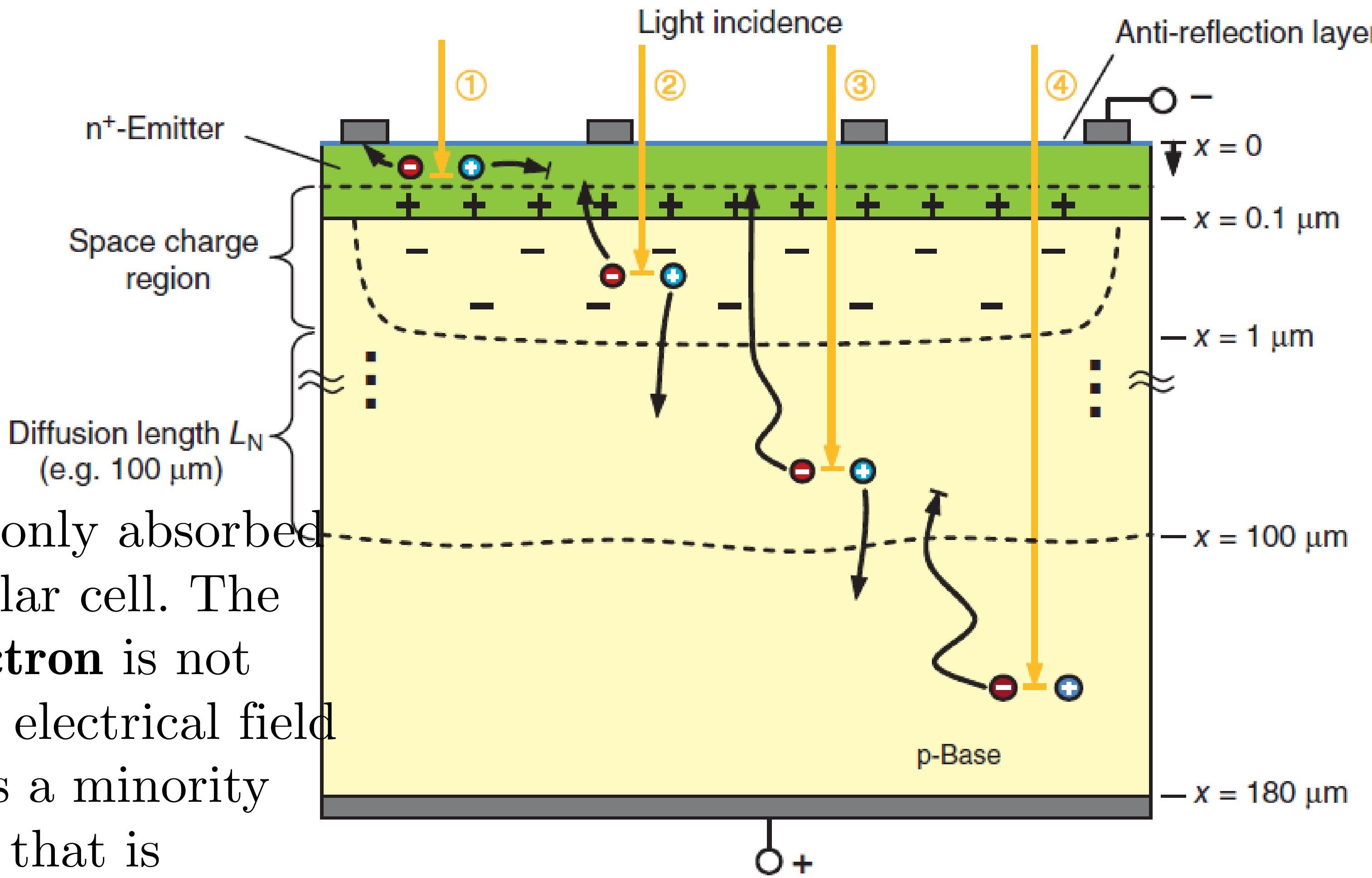


Photon(2) absorption takes place within the space charge region. The field prevailing in the space charge region separates the generated electron-hole pair and drives the two charge carriers in different directions.

The electron is moved to the n-region and hole is moved in the opposite direction.

4.2.3 What Happens in the Individual Cell Regions?

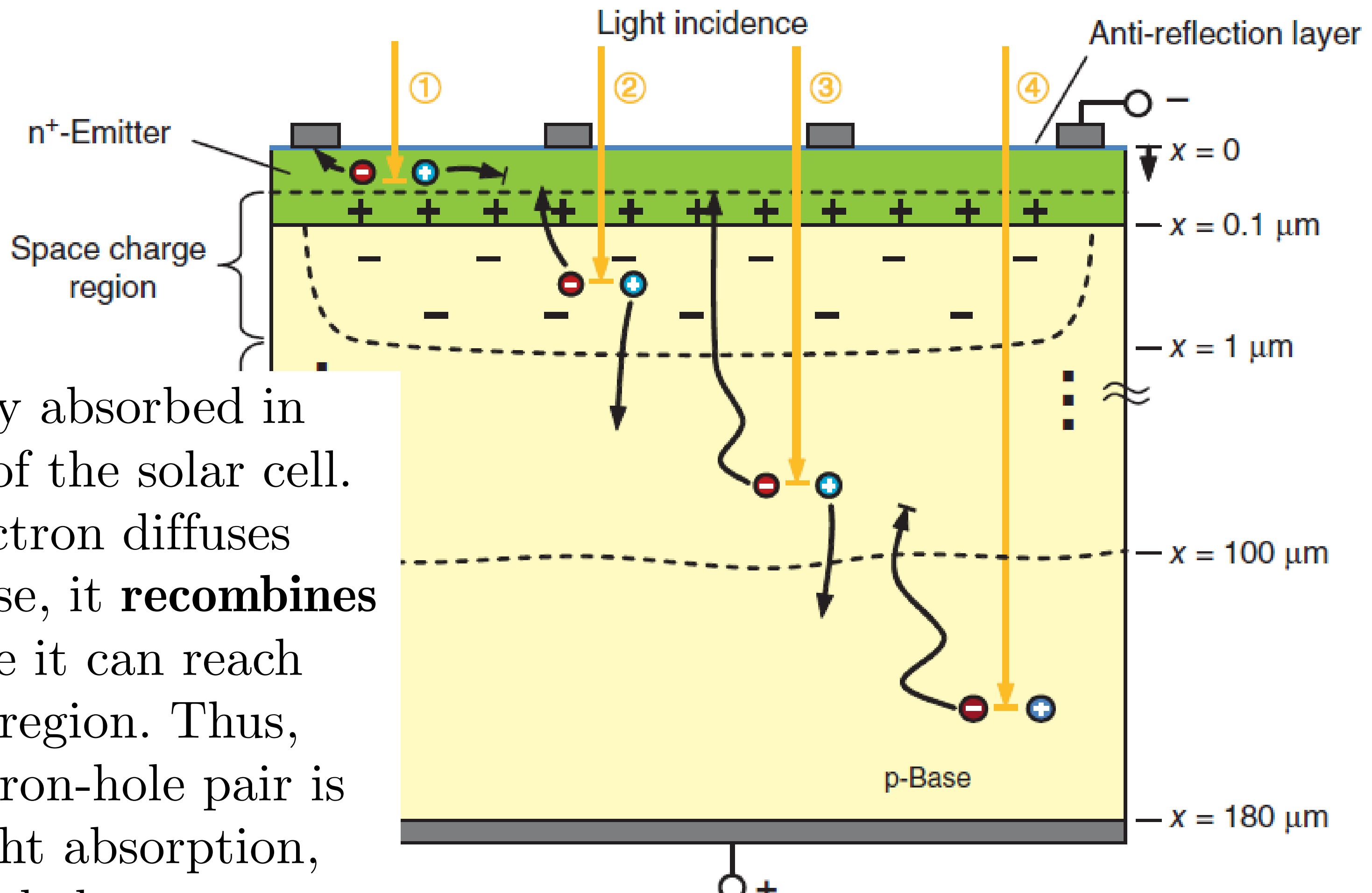
4.2.3.3 Absorption within the Diffusion Length of the Electrons



Photon (3) is only absorbed deep in the solar cell. The generated **electron** is not situated in an electrical field but **diffuses** as a minority charge carrier that is somewhat motivation-less throughout the crystal.

4.2.3 What Happens in the Individual Cell Regions?

4.2.3.4 Absorption outside the Diffusion Length of the Electrons



Photon (4) is only absorbed in the lower region of the solar cell. Although the electron diffuses through the p-base, it **recombines** with a hole before it can reach the space charge region. Thus, although an electron-hole pair is formed due to light absorption, an electron and a hole are "eliminated."

This has contributed nothing to the photocurrent and only become slightly warmer.

4.3 Photocurrent

On the one hand, the amount of the photocurrent depends on the number of incident photons that are absorbed by the solar cell. On the other hand, the electron-hole pairs generated by light absorption must be separated.

4.3.1 Absorption Efficiency

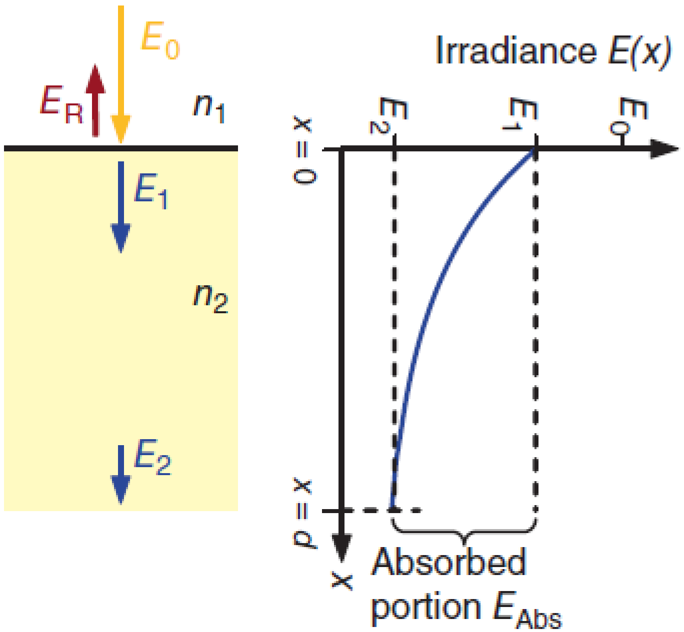


Figure 4.8 Light absorption in the solar cell

4.3.1 Absorption Efficiency

Figure 4.8 shows the light absorption of a solar cell similar to Figure 3.19. One part E_R of the overall irradiance E_0 is reflected at the surface (see Section 3.6.2). Thus the portion $E_1 = (1 - R) \cdot E_0$ penetrates into the cell. The intensity of the light is now weakened by absorption by passing through the cell according to Equation 3.20. At the bottom end $E_2 = E(x = d) = E_1 e^{-\alpha \cdot d}$ still remains. The difference $E_{Abs} = E_1 - E_2$ gives the portion of the light absorbed in the cell.

We define the **absorption efficiency** η_{Abs} as the relationship between the number of absorbed photons and the number of photons incident from outside.

$$\eta_{Abs} = \frac{\text{Number of absorbed photons}}{\text{Number of incident photons}}$$

$$= \frac{N_{Ph\_Abs}}{N_{Ph}} = \frac{E_{Abs}}{E_0} = \frac{E_1 - E_2}{E_0} \tag{4.5}$$

$$\eta_{Abs} = (1 - R) \cdot (1 - e^{-\alpha \cdot d}) \tag{4.6}$$

R: reflection factor

α: absorption coefficient

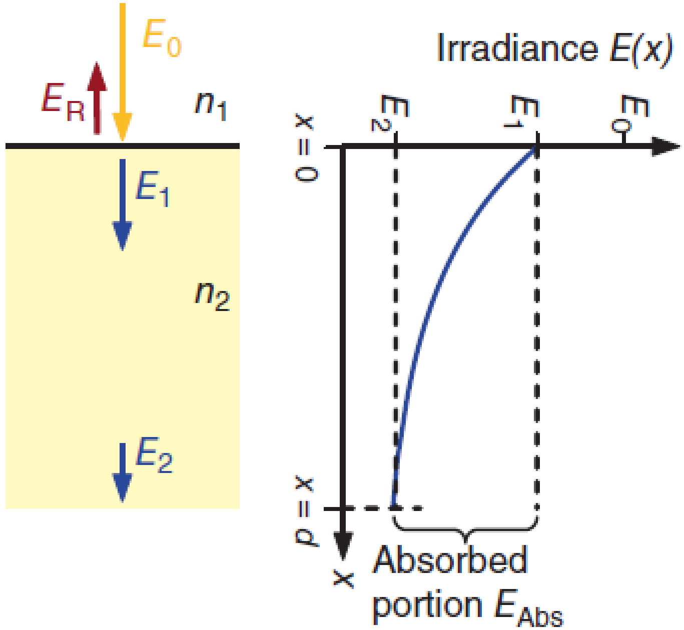


Figure 4.8 Light absorption in the solar cell

4.3.2 Quantum Efficiency

Even if it is successful in driving the absorption efficiency up to 100%, not all electron-hole pairs generated would contribute to the photocurrent. For this reason one defines the **external quantum efficiency** $\eta_{\mathbf{Ext}}$ as the relationship between the electron-hole pairs usable for the photocurrent and the overall incident photons:

$$\eta = \frac{\textit{Number of usable electron-hole pairs}}{\textit{Number of impinging photons}} = \frac{N_{\text{EHP}}}{N_{\text{Ph}}} \tag{4.7}$$

In addition to the external, we also define the **internal quantum efficiency** $\eta_{\mathbf{Int}}$, where the losses caused by reflections are not considered:

$$\eta_{\text{Int}} = \frac{\eta_{\text{Ext}}}{1 - R} \tag{4.8}$$

Naturally, its value is always greater than the external quantum efficiency.

4.3.3 Spectral Sensitivity

The **spectral sensitivity** $S(\lambda)$ shows which photocurrent is generated with the incidence of a particular optical power:

$$S(\lambda) = \frac{I_{Ph}}{P_{Opt}} \tag{4.9}$$

The connection between the two quantities can be easily found when the current is interpreted as a charge Q per time and the optical power as optical energy W_{Opt} per time:

$$S(\lambda) = \frac{I_{Ph}}{P_{Opt}} = \frac{\frac{Q}{\Delta t}}{\frac{W_{Opt}}{\Delta t}} = \frac{N_{EHP} \cdot q}{N_{Ph} \cdot (h \cdot f)} = \frac{N_{EHP}}{N_{Ph}} \cdot \frac{q}{\frac{h \cdot c}{\lambda}} = \frac{q}{h \cdot c} \cdot \lambda \cdot \eta_{Ext}(\lambda) \tag{4.10}$$

The pre-factor $q/(h \cdot c)$ consists only of natural constants and can be combined to:

$$\frac{q}{h \cdot c} = \frac{1.6 \cdot 10^{-19}\,\text{As}}{3.6 \cdot 10^{-34}\,\text{Ws} \cdot 3 \cdot 10^{8}\,\text{m/s}} = 0.808 \cdot \frac{\text{A}}{\text{W} \cdot \mu\text{m}} = \frac{1}{1.24\,\mu\text{m}} \cdot \frac{\text{A}}{\text{W}} \tag{4.11}$$

Thus, finally for spectral sensitivity:

$$S(\lambda) = \frac{\lambda}{1.24\,\mu\text{m}} \cdot \frac{\text{A}}{\text{W}} \cdot \eta_{Ext}(\lambda) \tag{4.12}$$

4.4 Characteristic Curve and Char. Dimensions

The characteristic curve equation of photodiode is:

$$I = I_{\mathrm{Ph}} - I_{\mathrm{D}} = I_{\mathrm{Ph}} - I_{\mathrm{S}} \cdot \left(e^{\frac{V}{m \cdot V_{\mathrm{T}}}} - 1 \right) \tag{4.13}$$

We introduce an **ideality factor** m into the exponent that permits a better model of real solar cell curves. The ideality factor is usually between 1 and 2.

The generation of energy now takes place in the first quadrant

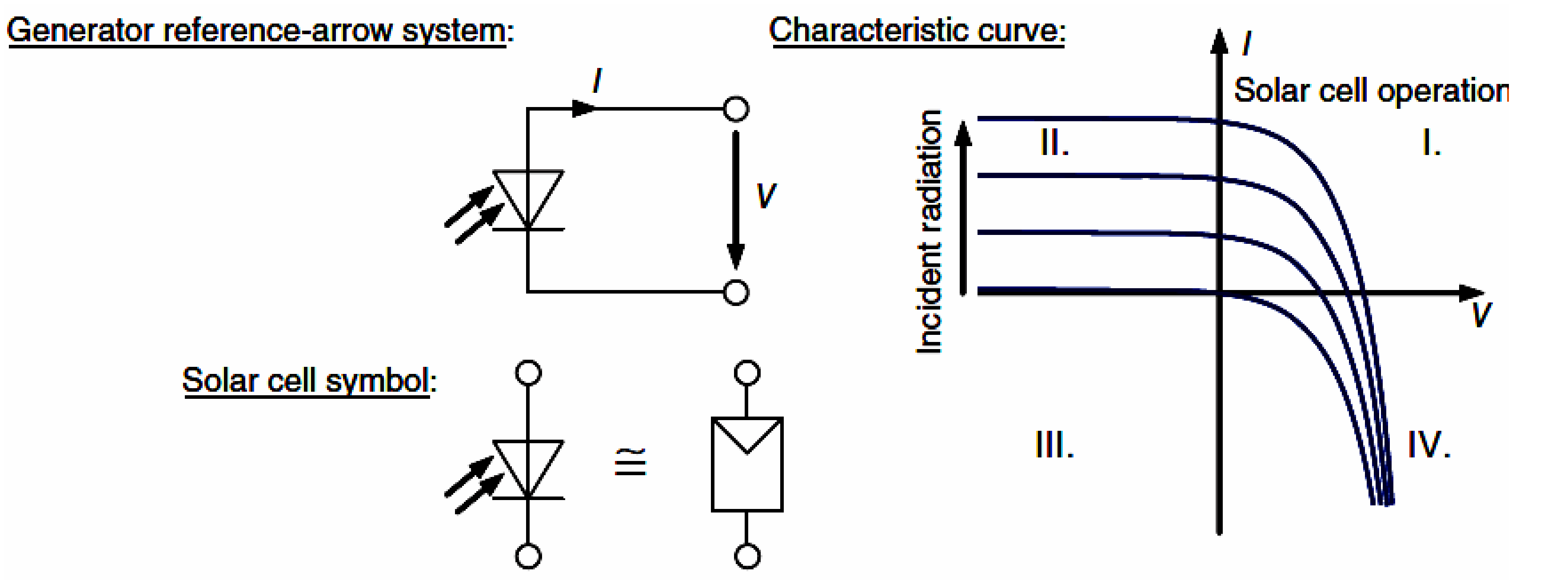


Figure 4.10 Characteristic curves of a solar cell in the generator reference-arrow system

4.4 Characteristic Curve and Char. Dimensions

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$$I = I_{\mathrm{Ph}} - I_{\mathrm{D}} = I_{\mathrm{Ph}} - I_{\mathrm{S}} \cdot \left(e^{\frac{V}{m \cdot V_{\mathrm{T}}}} - 1 \right) \tag{4.13}$$

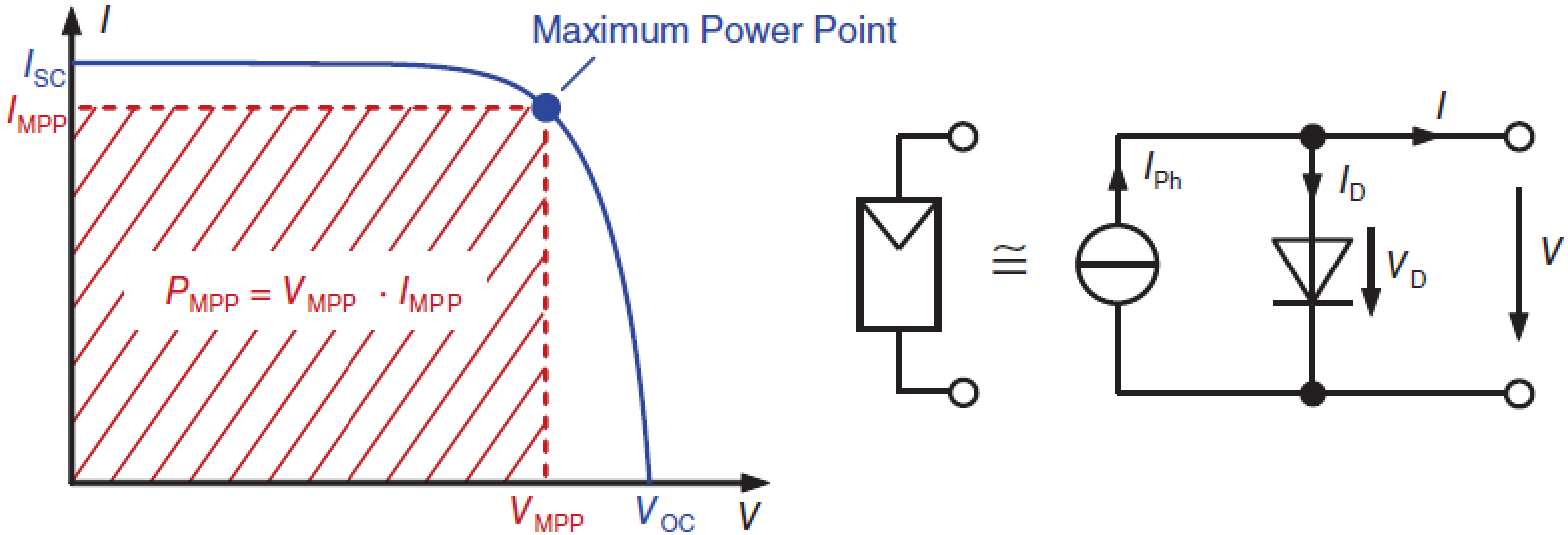


Figure 4.11 Characteristic curve of a solar cell and its associated simplified equivalent circuit

4.4.1 Short Circuit Current I_{SC}

The **short circuit current** I_{SC} is delivered by the solar cells when it is short circuited at its connections; the voltage V is thus 0.

$$I_{SC} = I(V=0) = I_{Ph} - I_S \cdot \left(e^0 - 1\right) = I_{Ph} \tag{4.14}$$

The short circuit current I_{SC} is equal to the photocurrent I_{Ph}.

The short circuit current I_{SC} of a solar cell is proportional to the irradiance E.

4.4.2 Open Circuit Voltage V_{OC}

Open Circuit Voltage V_{OC} occurs when the current becomes zero. Rearrange eq. 4.13 to get V, as

$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot \left(e^{\frac{V}{m \cdot V_T}} - 1 \right) \tag{4.13}$$

$$V_{OC} = V(I = 0) = m \cdot V_T \cdot ln\left(\frac{I_{SC}}{I_S} + 1 \right) \tag{4.15}$$

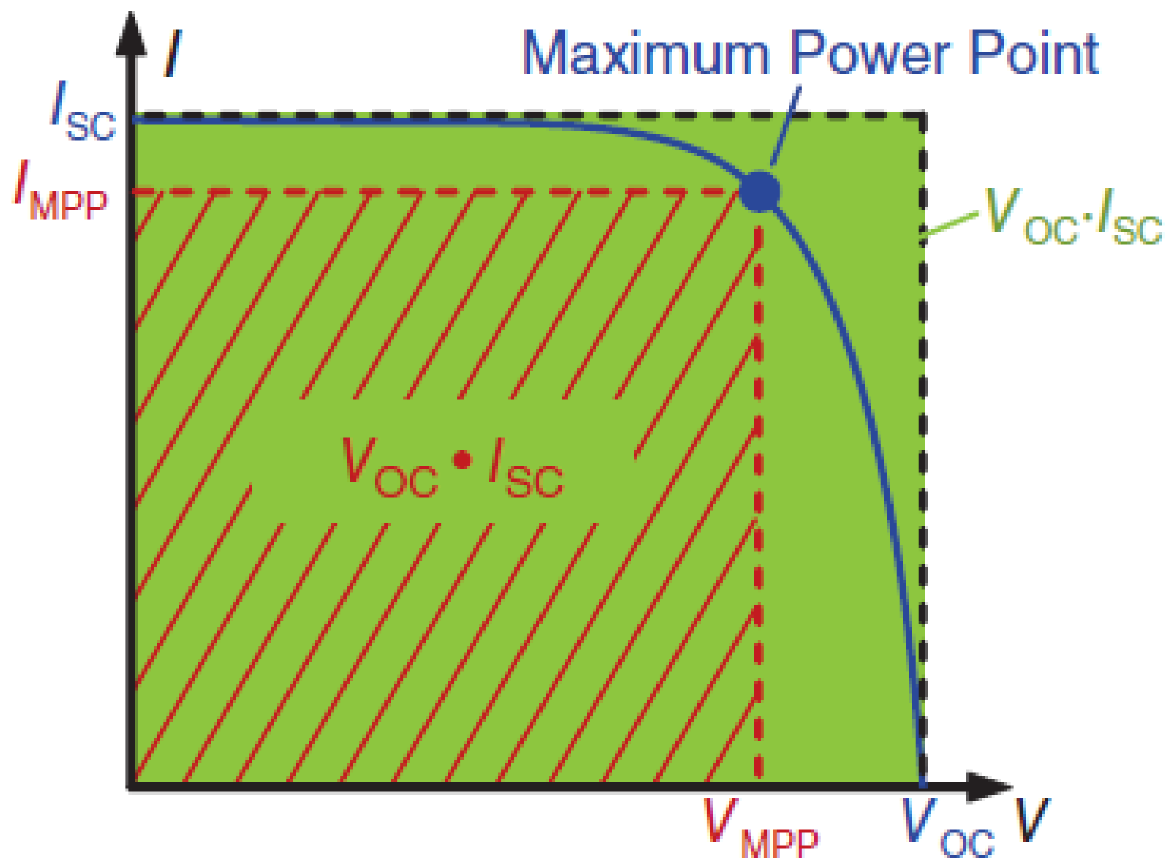
ln(1) can be ignored so that

$$V_{OC} = m \cdot V_T \cdot ln\left(\frac{I_{SC}}{I_S} \right) \tag{4.16}$$

The open circuit voltage V_{OC} of a solar cell only changes with the natural logarithm of the irradiance E.

4.4.3 Maximum Power Point (MPP)

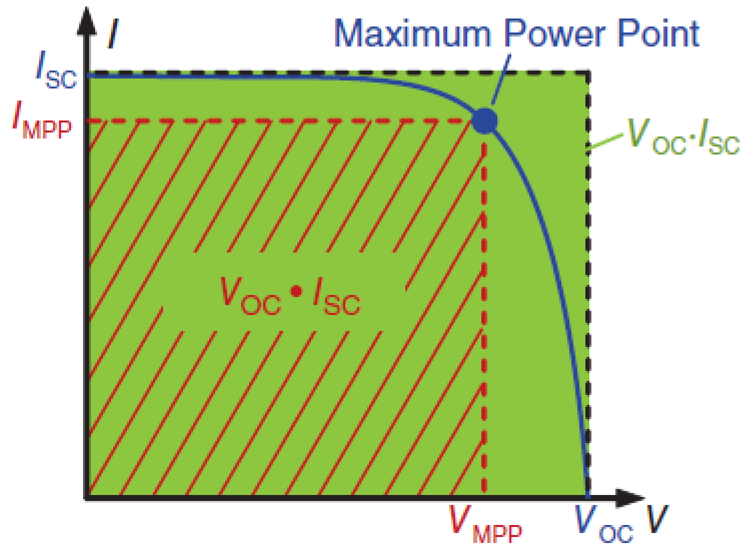
The operating point at which the maximum power is provided is called the ***Maximum Power Point*** (**MPP**). As the power of a working point always corresponds to the surface $\boldsymbol{V \times I}$, this **area** must be the **maximum** in the case of the MPP.



4.4.4 Fill Factor FF

The ***fill factor FF***, describes the relationship of MPP power and the product from open circuit voltage and short circuit current

$$FF = \frac{V_{\mathrm{MPP}} \cdot I_{\mathrm{MPP}}}{V_{\mathrm{OC}} \cdot I_{\mathrm{SC}}} = \frac{P_{\mathrm{MPP}}}{V_{\mathrm{OC}} \cdot I_{\mathrm{SC}}} \tag{4.17}$$



The fill factor is a measure for the quality of a cell; typical values for silicon cells are between 0.75–0.85 and in the region of thin film materials they are between 0.6–0.75.

4.4.5 Efficiency —η

The efficiency of a solar cell describes what portion of the optical power $\boldsymbol{P}_{\mathbf{Opt}}$ incident on the cell is output as electrical energy $\boldsymbol{P}_{\mathbf{MPP}}$ again.

Recall from chap-2

$$P_{\mathrm{Opt}} = E_{\mathrm{Direct\_H}} \cdot A_{\mathrm{H}} \tag{2.13}$$

$$\eta = \frac{P_{\mathrm{MPP}}}{P_{\mathrm{Opt}}} = \frac{P_{\mathrm{MPP}}}{E \cdot A} = \frac{FF \cdot V_{\mathrm{OC}} \cdot I_{\mathrm{SC}}}{E \cdot A} \tag{4.19}$$

Typical efficiencies of crystalline silicon cells are **between 15 and 22%**.

4.4.6 Temperature Dependency of Solar Cells

A rise in temperature of a semiconductor brings an increase in thermal movement of the electrons built into the crystal lattice. Electrons are separated from their bonds and move into the conduction band and that therefore the **intrinsic carrier concentration** n_i rises

Higher intrinsic carrier concentration leads to an **increase in saturation current** I_S.

But increase in temperature is not good for PV panels.

According to Equation 4.16 the increased saturation current leads to a **reduction in open circuit voltage**.

$$V_{OC} = m \cdot V_T \cdot ln\left(\frac{I_{SC}}{I_S}\right) \tag{4.16}$$

$$V_{OC} = m \cdot V_T \cdot ln\left(\frac{I_{SC}}{I_S}\right) = m \cdot V_T \cdot ln\left(\frac{I_{SC}}{B}\right) + m \cdot \frac{\Delta W_G}{q} \tag{4.20}$$

The constant B collates the following expression:

$$B = A \cdot q \cdot N_0^2 \cdot \left(\frac{D_N}{L_N \cdot N_A} + \frac{D_P}{L_P \cdot N_D}\right) \tag{4.21}$$

$$I_S = A \cdot q \cdot n_i^2 \cdot \left(\frac{D_N}{L_N \cdot N_A} + \frac{D_P}{L_P \cdot N_D}\right) \tag{4.3}$$

If the Equation 4.20 is differentiated to T, then, applying Equation 4.20 again, the result is:

$$\frac{V_{OC}}{\mathrm{d}T} = \frac{m \cdot k}{q} \cdot ln\left(\frac{I_{SC}}{B}\right) = \frac{V_{OC} - m \cdot \Delta W_G / q}{T} \tag{4.22}$$

For a typical solar cell we obtain ($m = 1$):

$$\frac{\Delta V_{OC}}{\Delta \vartheta} = \frac{0.6\ \mathrm{V} - 1.12\ \mathrm{V}}{300\ \mathrm{K}} = 1.7\ \mathrm{mV/K} \tag{4.23}$$

In this derivation we have not yet taken into account that the **bandgap** and the intrinsic carrier concentration of the semiconductor are also **temperature dependent**. A more accurate consideration gives [36]:

$$\frac{\Delta V_{\mathrm{OC}}}{\Delta \vartheta} = \frac{V_{\mathrm{OC}} - \Delta W_{\mathrm{G0}}/q - \gamma \cdot V_{\mathrm{T}}}{T} \tag{4.24}$$

with:

ΔW_{G0}: Bandgap at $T = 0$; for silicon: $\Delta W_{\mathrm{G0}} = 1.2$ eV
γ: Temperature parameter, typically $\gamma = 1 \ldots 4$

Thus, for the Si cell we obtain ($\gamma = 3$):

$$\frac{\Delta V_{\mathrm{OC}}}{\Delta \vartheta} = -2.3\ \mathrm{mV/K} \tag{4.25}$$

For a typical open circuit voltage of 600 mV there is thus a temperature coefficient $TC(V_{\mathrm{OC}})$ of approx. 0.4%/K.

The Temperature Dependence of the Energy Bandgap

The temperature dependence of the energy bandgap has been experimentally determined yielding the following expression for E_g as a function of the temperature T:

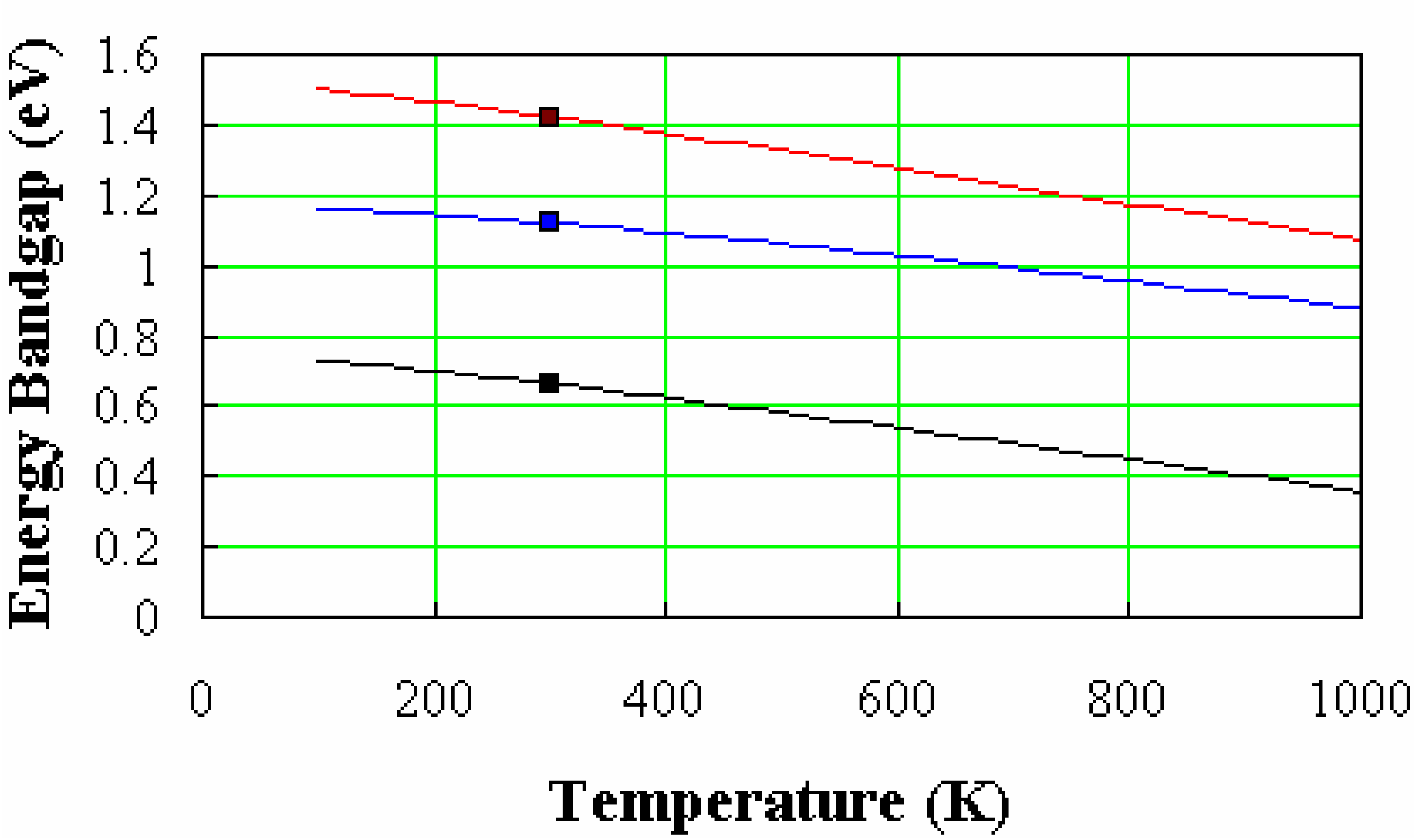
$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$

where $E_g(0)$, α and β are the fitting parameters. These fitting parameters are listed for germanium, silicon and gallium arsenide in the table below:

	Germanium	Silicon	GaAs
$E_g(0)$ [eV]	0.7437	1.166	1.519
α [eV/K]	4.77×10^{-4}	4.73×10^{-4}	5.41×10^{-4}
β [K]	235	636	204

The Temperature Dependence of the Energy Bandgap

A plot of the resulting bandgap versus temperature is shown in the figure below for **Germanium**, **Silicon** and **Gallium Arsenide**.



The Temperature Dependence of the Energy Bandgap

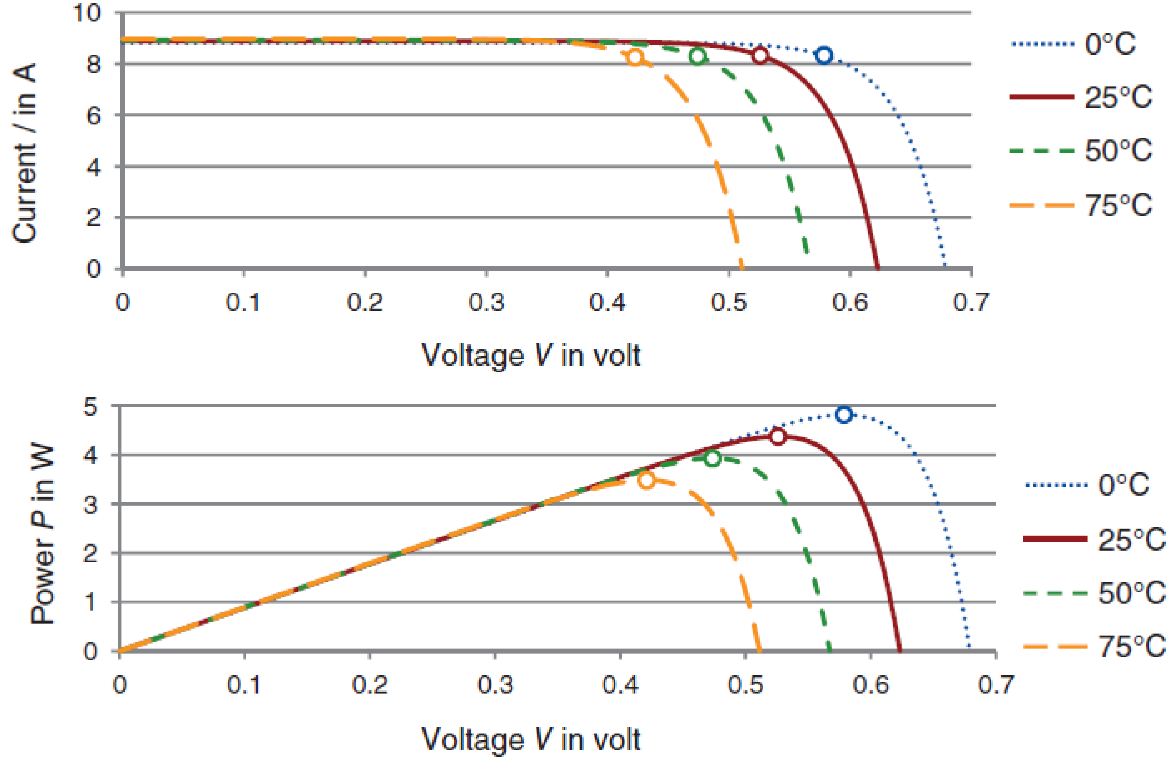


Figure 4.13 Temperature-dependency of a Si solar cell as an example of the Bosch Solar Cell M-3BB: The circles indicate the position of the MPP [37]

The power of a Si solar cell DECREASES by 0.4 to 0.5% per Kelvin.

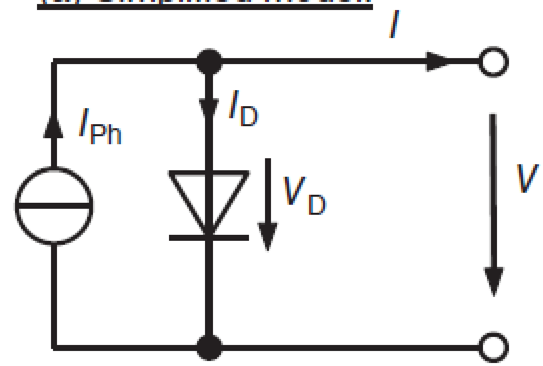
4.5 Electrical Description of Real Solar Cells

4.5.1 Simplified Model

This model is already known from Equation 4.13:

$$I = I_{\mathrm{Ph}} - I_{\mathrm{D}} = I_{\mathrm{Ph}} - I_{\mathrm{S}} \cdot \left(e^{\frac{V}{m \cdot V_{\mathrm{T}}}} - 1 \right) \tag{4.27}$$

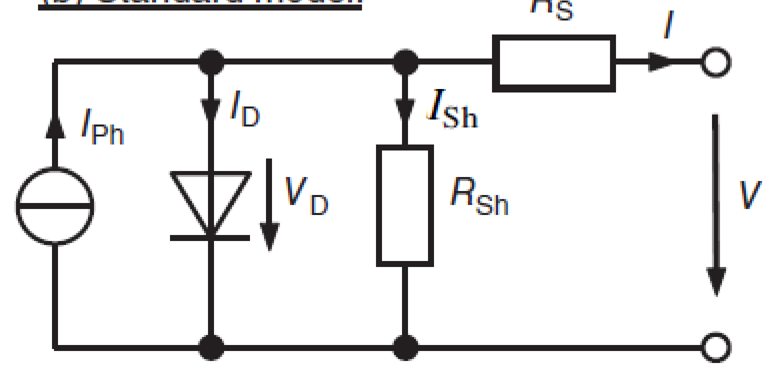
(a) Simplified model:



4.5.2 Standard Model (Single—Diode Model)

The **standard model** , also called the **single-diode mode l includes e**lectrical losses in the solar cell. The **series resistance R_S** describes the ohmic losses at the contacts of the solar cell and at the metal—semiconductor interface. In contrast, leak currents with-in solar cell as well as any point short circuits of the p-n junction are modeled by the **shunt resistance R_{Sh}**.

(b) Standard model:

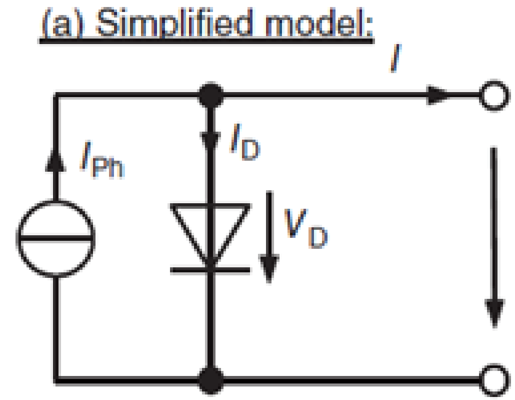


$$I = I_{\mathrm{Ph}} - I_{\mathrm{D}} - I_{\mathrm{Sh}}$$

4.5 Electrical Description of Real Solar Cells

4.5.1 Simplified Model

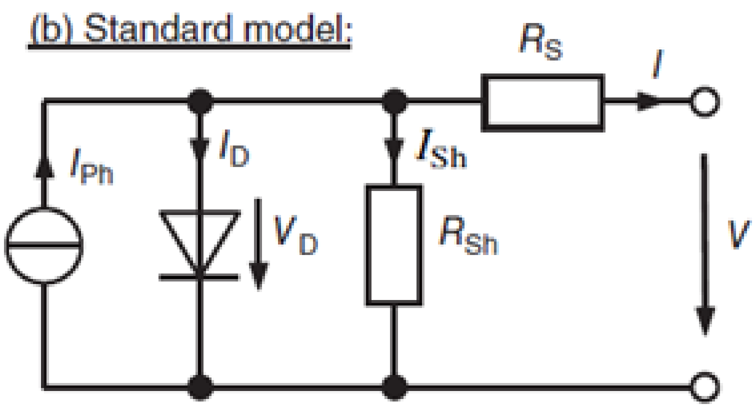
This model is already known from Equation 4.13:



$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot \left(e^{\frac{V}{m \cdot V_T}} - 1\right) \qquad (4.27)$$

4.5.2 Standard Model (Single—Diode Model)

The **standard model** , also called the **single-diode mode l includes** electrical losses in the solar cell. The **series resistance R_S** describes the ohmic losses at the contacts of the solar cell and at the metal—semiconductor interface. In contrast, leak currents with-in solar cell as well as any point short circuits of the p-n junction are modeled by the **shunt resistance R_{Sh}**.



$$I = I_{Ph} - I_D - I_{Sh}$$

Slides Prepared and Taught by Dr U. T. Shami

4.5 Electrical Description of Real Solar Cells

4.5.1 Simplified Model

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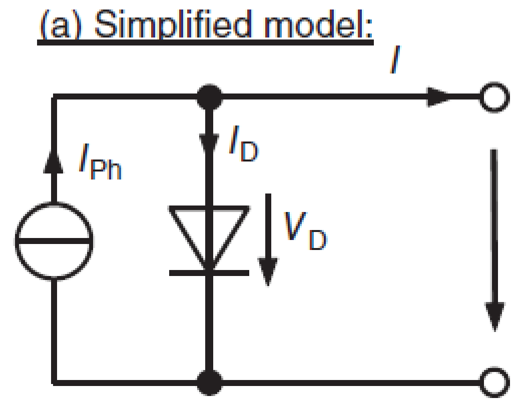

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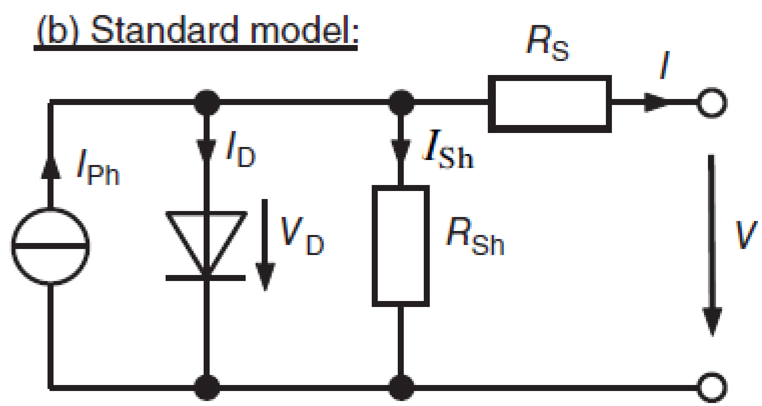

$$I = I_{\mathrm{Ph}} - I_{\mathrm{D}} - I_{\mathrm{Sh}}$$

4.5 Electrical Description of Real Solar Cells

4.5.2 Standard Model (Single—Diode Model)

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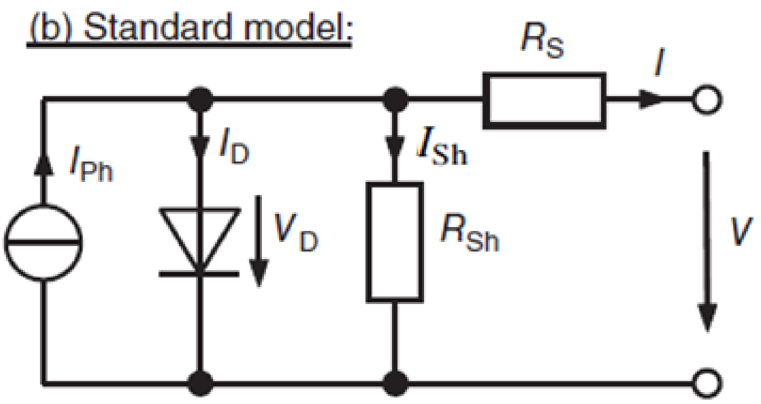


$$I = I_{Ph} - I_D - I_{Sh}$$

$$I_{Sh} = \frac{V_D}{R_{Sh}} = \frac{V + I \cdot R_S}{R_{Sh}} \tag{4.28}$$

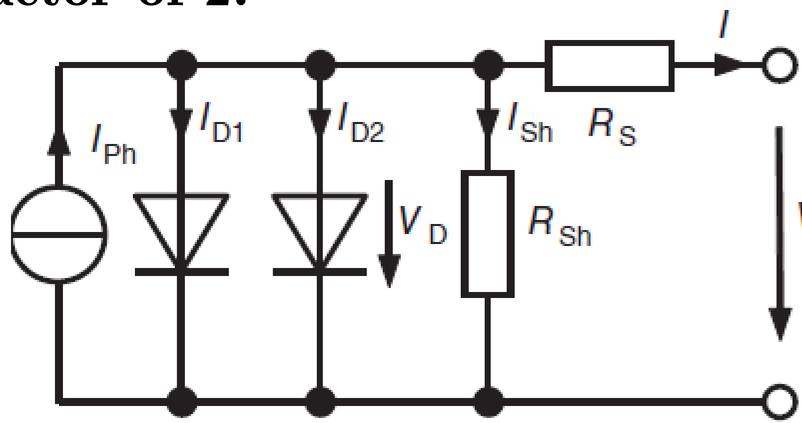
This gives the **characteristic curve equation of the standard model**:

$$I = I_{Ph} - I_S \cdot \left(e^{\frac{V + I \cdot R_S}{m \cdot V_T}} - 1 \right) - \frac{V + I \cdot R_S}{R_{Sh}} \tag{4.29}$$

This equation can only be solved numerically as the current I appears on both sides

4.5.3 Two-Diode Model

In this case, one makes use of the **two-diode model** in which the **diffusion current** is modeled by means of a diode with an **ideality factor of 1** and a **recombination current** through an additional diode with an **ideality factor of 2.**



The characteristic curve equation can be determined in a similar manner to Equation 4.29:

$$I = I_{\mathrm{Ph}} - I_{\mathrm{S1}} \cdot \left(e^{\frac{V + I \cdot R_{\mathrm{S}}}{V_{\mathrm{T}}}} - 1 \right) - I_{\mathrm{S2}} \cdot \left(e^{\frac{V + I \cdot R_{\mathrm{S}}}{2 \cdot V_{\mathrm{T}}}} - 1 \right) - \frac{V + I \cdot R_{\mathrm{S}}}{R_{\mathrm{Sh}}} \qquad (4.30)$$

4.5.4 Determining the Parameters of the Equivalent Circuit

Determining R_{Sh}

If the measured I/V characteristic curve of a solar cell is available, then the parameters of the simplified equivalent circuit can be derived from it.

The saturation current I_S can then be determined

$$I_S = I_{SC} \cdot e^{-V_{OC}/V_T}$$

Values for the two resistances R_S and R_{Sh} are obtained from the **curve gradient in the short circuit and open circuit points**

The current I_D in the diode can therefore be ignored. So that,

$$I = I_{Ph} - \frac{V + I \cdot R_S}{R_{Sh}} \tag{4.32}$$

The slope of the curve is found from the derivation:

$$\frac{\mathrm{d}I}{\mathrm{d}V} = 0 - \frac{1}{R_{\mathrm{Sh}}} - \frac{R_{\mathrm{S}}}{R_{\mathrm{Sh}}} \cdot \frac{\mathrm{d}I}{\mathrm{d}V} \tag{4.33}$$

Resolving the equation according to $\mathrm{d}I/\mathrm{d}V$ gives:

$$\frac{\mathrm{d}I}{\mathrm{d}V} = \frac{1}{R_{\mathrm{S}} + R_{\mathrm{Sh}}} \tag{4.34}$$

In general applies $R_{\mathrm{S}} \ll R_{\mathrm{Sh}}$ so that we finally write:

$$R_{\mathrm{Sh}} = -\left.\frac{\mathrm{d}V}{\mathrm{d}I}\right|_{V=0} \tag{4.35}$$

Thus the **shunt resistance R_{Sh}** can be determined **directly from the slope of the tangent in the short circuit point** (Figure 4.18).

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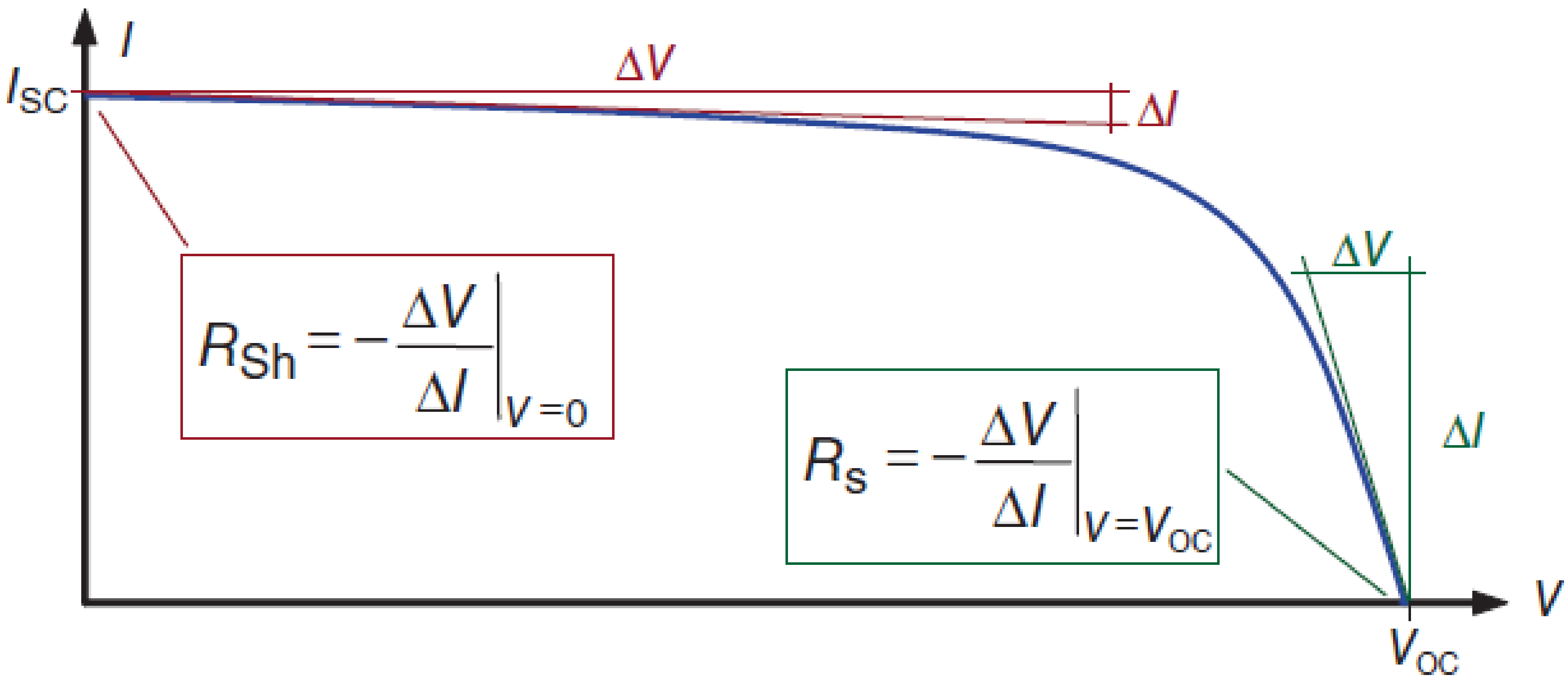
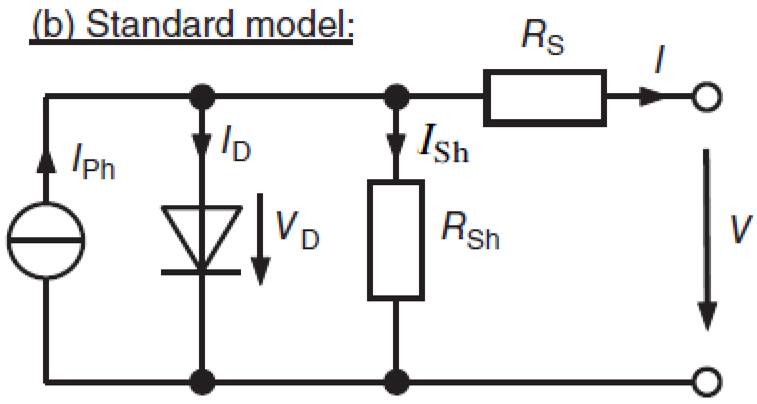


Determining R_S

A similar consideration is made for the **open circuit case**: here the voltage $\boldsymbol{V_D}$ is quite large but the diode becomes very low resistant, so that in Figure 4.14(b) the current $\boldsymbol{I_D}$ can be ignored compared to $\boldsymbol{I_{Sh}}$. The remaining equation from Equation 4.29 is now:

$$I = I_{Ph} - I_S \cdot \left(e^{\frac{V + I \cdot R_S}{m \cdot V_T}} - 1\right) \qquad (4.36)$$



We differentiate this with respect to the current and rearrange it for dV/dI. In this we take into account that V is dependent on the current I:

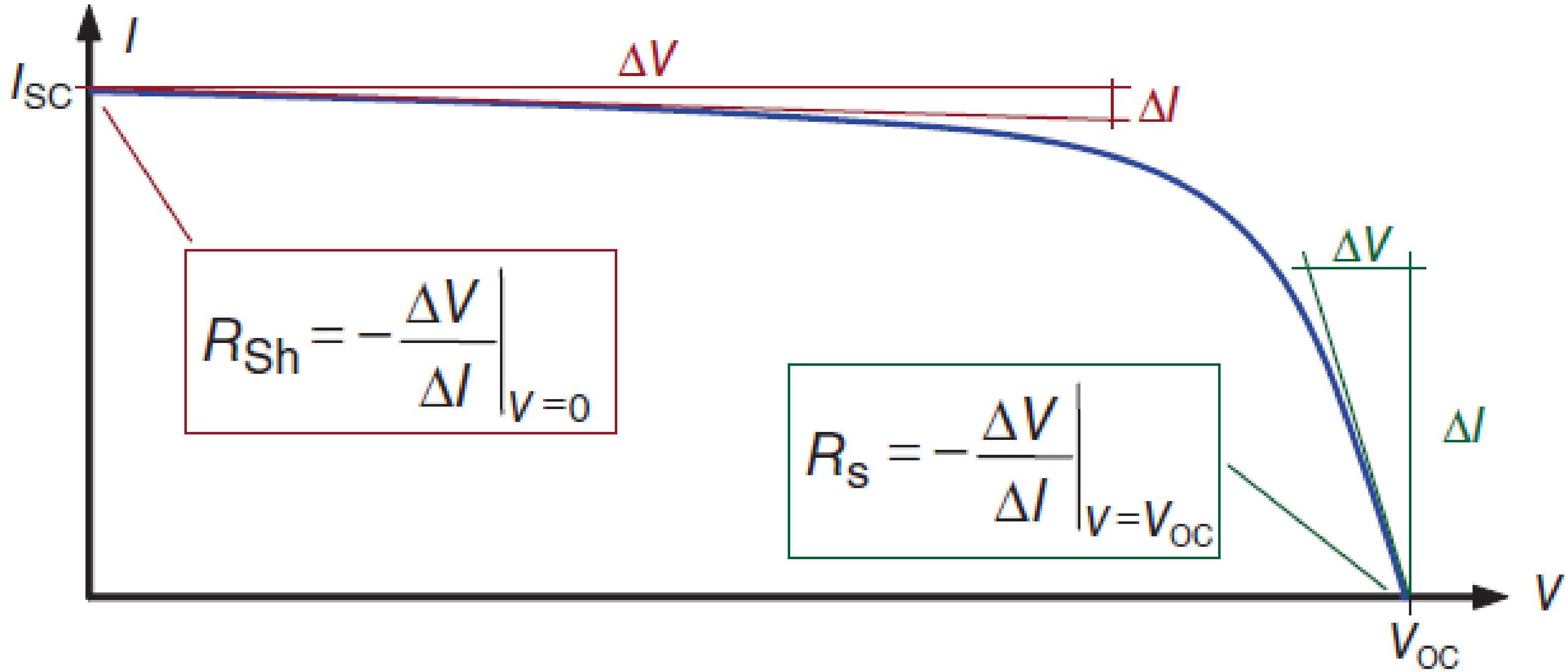
$$\frac{\mathrm{d}(I)}{\mathrm{d}I} = 1 = 0 - I_S \cdot e^{\frac{V + I \cdot R_S}{m \cdot V_T}} \cdot \frac{1}{m \cdot V_T} \cdot \left(\frac{\mathrm{d}V}{\mathrm{d}I} + R_S\right) \qquad (4.37)$$

Determining R_S

$$\frac{dV}{dI} = -R_S - \frac{m \cdot V_T}{I_S} \cdot e^{-\frac{V + I \cdot R_S}{m \cdot V_T}} \tag{4.38}$$

In the open circuit point there applies $V = V_{OC}$ and $I = 0$, thus the equation simplifies to:

$$\left.\frac{dV}{dI}\right|_{V=V_{OC}} = R_S + \frac{m \cdot V_T}{I_S} \cdot e^{-\frac{V_{OC}}{m \cdot V_T}} \approx R_S \tag{4.39}$$



4.6.2 Theoretical Efficiency

conditions we define the **theoretical efficiency** η_{T} [40]:

$$\eta_{\mathrm{T}} = \frac{P_{\mathrm{MPP}}}{E \cdot A} \tag{4.47}$$

With Equation 4.17 this results in:

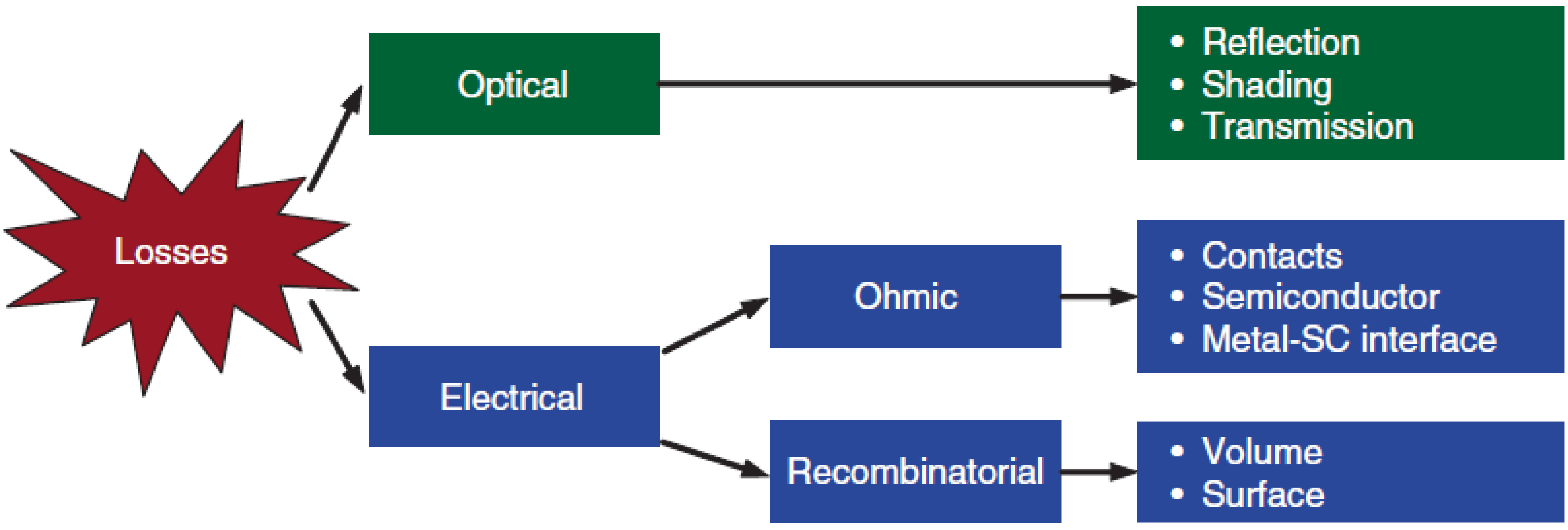
$$\eta_{\mathrm{T}} = \frac{FF \cdot V_{\mathrm{OC}} \cdot I_{\mathrm{SC}}}{E \cdot A} = FF \cdot \frac{V_{\mathrm{OC}}}{V_{\mathrm{Max}}} \cdot \frac{V_{\mathrm{Max}}}{E} \cdot \frac{I_{\mathrm{SC}}}{A} = FF \cdot \frac{V_{\mathrm{OC}}}{V_{\mathrm{Max}}} \cdot \frac{V_{\mathrm{Max}}}{E} \cdot j_{\mathrm{Max}} \tag{4.48}$$

With the use of Equation 4.45 we can directly determine a connection with the already calculated spectral efficiency η_{S}.

$$\eta_T = FF \cdot \frac{V_{\mathrm{OC}}}{V_{\mathrm{Max}}} \cdot \eta_{\mathrm{s}} \tag{4.49}$$

The theoretical efficiency of 28.6% is the upper limit of the achievable efficiency of a cell of crystalline silicon (assumption: only one p-n junction).

4.6.3 Losses in Real Solar Cells



4.6.3.1 Optical Losses, Reflection on the Surface

As we have already seen in Chapter 3, the refractive index step of air on silicon causes a reflection of approximately 35%. **Anti-reflective coating** that lowers the average reflection of an AM 1.5 spectrum to around 10%.

A further measure is **texturing** the cell surface. The surface is etched with an acid in order to roughen it up. The results are pyramids with an angle at the top of 70.5° (Figure 4.26).

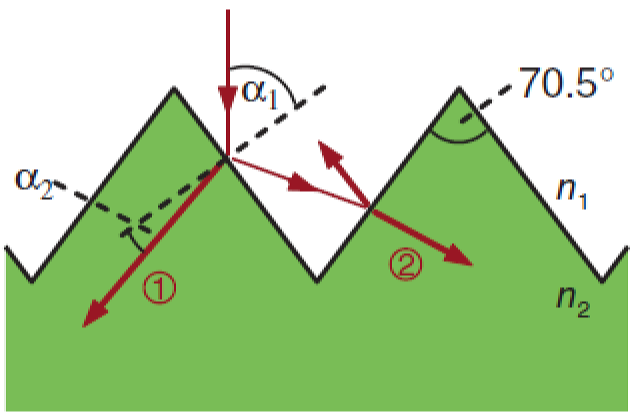


Figure 4.26 Reduction of overall reflection by means of texturing: giving light "a second chance"

4.6.3.1 Optical Losses, Reflection on the Surface

What does this texturization yield? Figure 4.26 shows how incident rays partly penetrate the cell and are partly reflected. According to the **Fresnel equations** the strength of the reflection factor R can be determined from the **angle of incidence** $\boldsymbol{\alpha_1}$ [29]:

$$R(\alpha) = \left(\frac{\sin(\alpha_1 - \alpha_2)}{\sin(\alpha_1 + \alpha_2)}\right)^2 \tag{4.51}$$

In this, the **exit angle** $\boldsymbol{\alpha_2}$ can be determined by the ***law of refraction:***

$$n_1 \cdot sin\ \alpha_1 = n_2 \cdot sin\ \alpha_2 \tag{4.52}$$

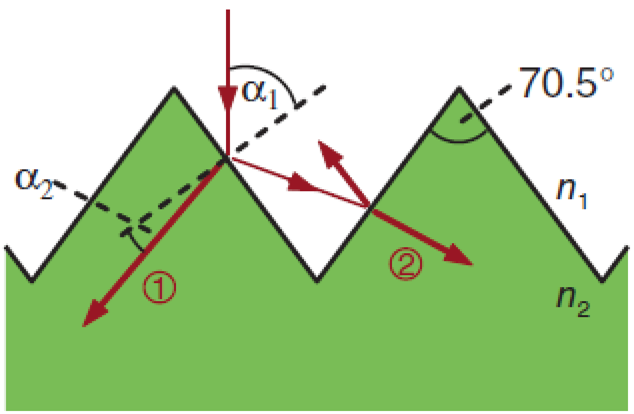


Figure 4.26 Reduction of overall reflection by means of texturing: giving light "a second chance"

4.6.3.2 Electrical Losses and Ohmic Losses

There are electrical losses in the **contact fingers** on the top side of the cell. Narrow and high contacts (in the optimum case as buried contacts) help in this. In addition, ohmic losses can occur in the **semiconductor material** as the conductivity of the doping material is limited.

Recombination Losses

The various reasons for recombination of generated charge carriers in the **semiconductor volume** have already been discussed in Section 4.2.2. Added to this in real cells are recombinations at surfaces that are created by the open bonds at the **border** of the crystal lattice.

4.7 High Efficiency Cells

4.7.1 Buried-Contact Cells

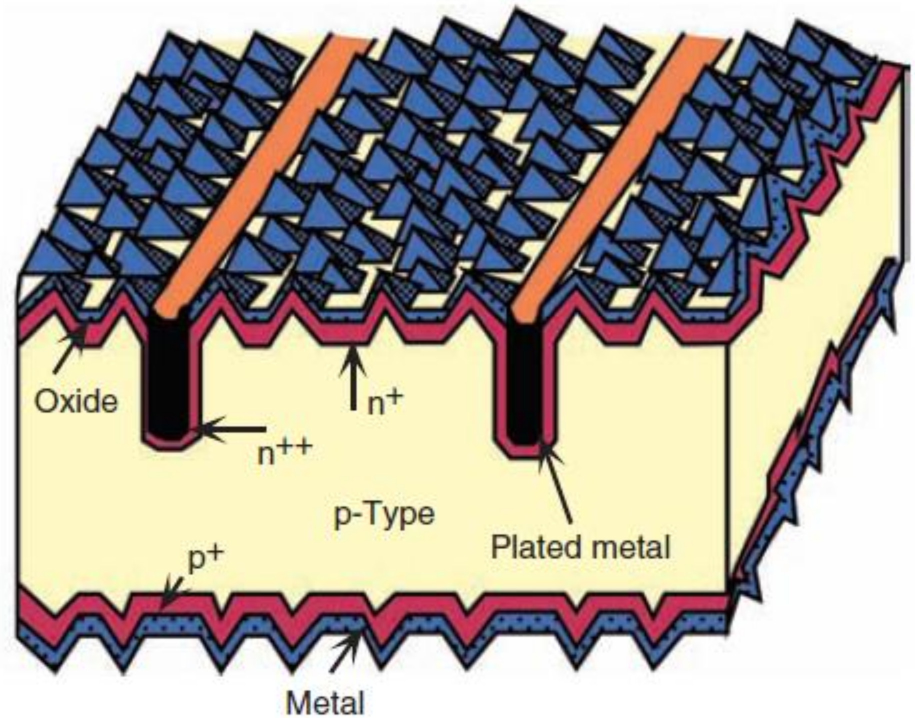


Figure 4.31 Buried contact cell (more accurately: Laser Grooved Buried Contact: LGBC cell) (reprinted with the kind permission of Martin Green)

4.7.2 Point-Contact Cell

A noticeable feature is that both the negative as well as the positive **contacts** are positioned **on the rear side of the cell** and that therefore **no shading** occurs.

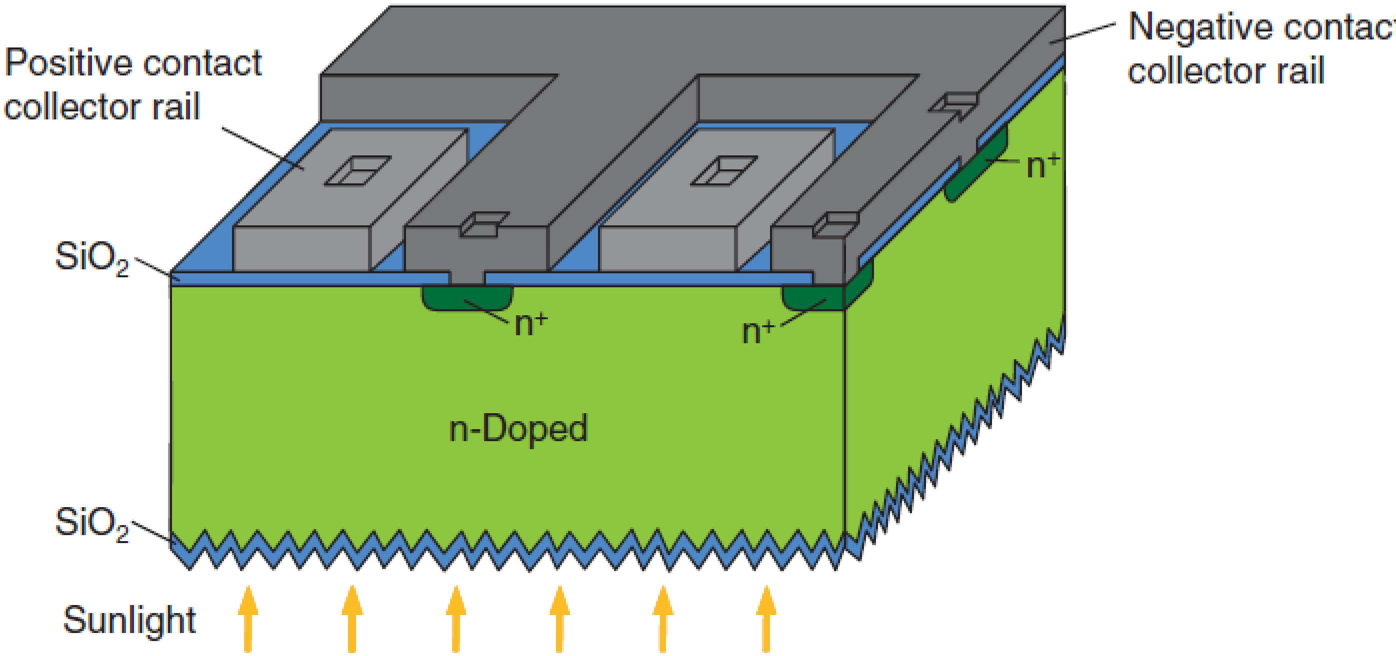


Figure 4.32 View of the point-contact cell: all contacts are positioned on the rear side of the cell and can thus be made as thick as desired [44]

4.7.3 PERL Cell (Passivated Emitter Rear Locally diffused)

The cell achieves a short circuit current of 42mA/cm2 and an open circuit voltage of 714 mV.
With the fill factor of 83% this results in a **record efficiency of 25%** [45,46].

Approximately 100 process steps were required for the manufacture of the record cell, which is an unacceptable effort for industrial production.

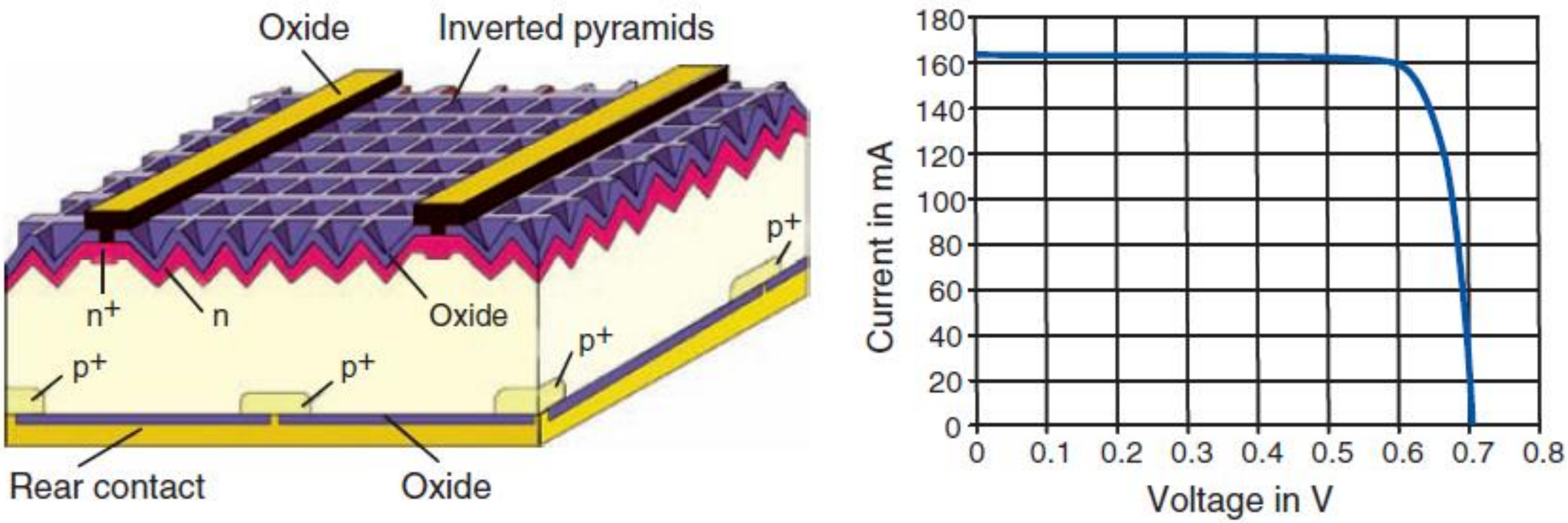


Figure 4.33 PERL cell together with *I/V* characteristic curve, characteristic curve to [35] (reprinted with the kind permission of Martin Green)

End of Solar Energy—Semiconductor Part 3
Course Work