BANDGAP ΔW_G

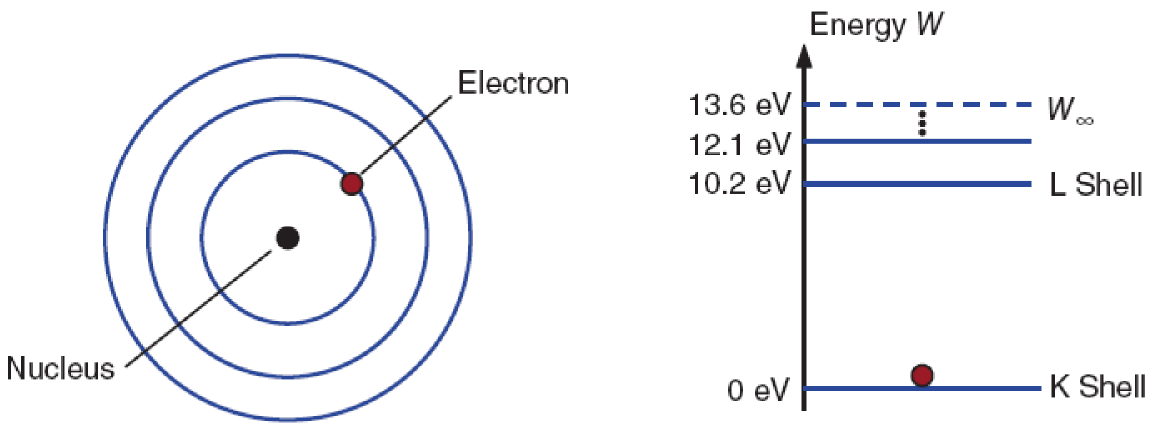

Figure 3.1 Structure and energy model of the hydrogen atom

$$\Delta W = |W_2 - W_1| = h \cdot f \qquad \lambda = \frac{c_0}{f}$$

W_1: energy before the transfer

W_2: energy after the transfer

h: Planck's constant; $h = 6.6 \cdot 10^{-34}\ \mathrm{Ws}^2$

c_0: speed of light in a vacuum, $c_0 = 299.792\ \mathrm{km/s} \approx 3 \cdot 10^8\ \mathrm{m/s}$

Example 3.1 Light emission

An electron of a hydrogen atom falls from the M to the L shell. What will be the wavelength of the radiated light?

Calculation:

$$\Delta W = W_1 - W_2 = 12.1\ \text{eV} - 10.2\ \text{eV} = 1.9\ \text{eV} = h \cdot f$$

$$\Rightarrow f = \frac{1.9\ \text{eV}}{h} = \frac{1.9\ \text{V} \cdot 1.6 \cdot 10^{-19}\text{As}}{6.6 \cdot 10^{-34}\text{Ws}^2} = 0.461 \cdot 10^{15}/\text{s} = 461 \cdot 10^{12}\text{Hz}$$

The wavelength is calculated again by:

$$\lambda = \frac{c_o}{f} = \frac{3 \cdot 10^8\ \text{m/s}}{461 \cdot 10^{12}\ \text{Hz}} = 6.508 \cdot 10^{-7}\ \text{m} = 650.8 \cdot 10^{-9}\ \text{m} \approx 651\ \text{nm}$$

The light radiates at 651 nm and thus in the red region.

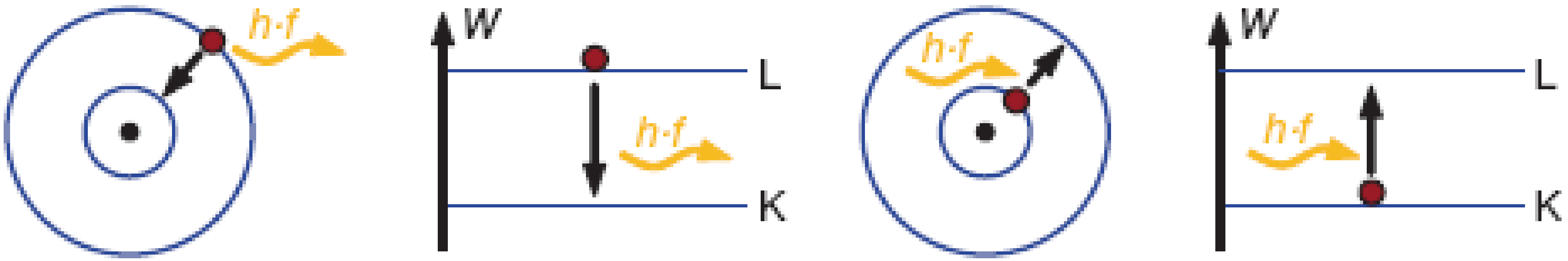

Figure 3.2 Schematic depiction of the emission (left) and absorption (right) of light

Example 3.1 Light emission

An electron of a hydrogen atom falls from the M to the L shell. What will be the wavelength of the radiated light?

Calculation:

$$\Delta W = W_1 - W_2 = 12.1\,\text{eV} - 10.2\,\text{eV} = 1.9\,\text{eV} = h \cdot f$$

$$\Rightarrow f = \frac{1.9\,\text{eV}}{h} = \frac{1.9\,\text{V} \cdot 1.6 \cdot 10^{-19}\,\text{As}}{6.6 \cdot 10^{-34}\,\text{Ws}^2} = 0.461 \cdot 10^{15}/\text{s} = 461 \cdot 10^{12}\,\text{Hz}$$

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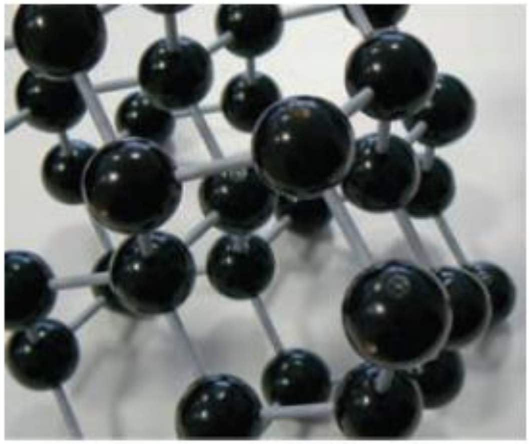
The light radiates at 651 nm and thus in the red region.

TABEL PERIODIK

Table 3.1 Extract from the Periodic Table of Elements. The number under the element name is the atomic number

Main group/valence								Shell
I	II	III	IV	V	VI	VII	VIII	
H Hydrogen 1							He Helium 2	K
Li Lithium 3	Be Beryllium 4	B Boron 5	C Carbon 6	N Nitrogen 7	O Oxygen 8	F Fluorine 9	Ne Neon 10	L
Na Sodium 11	Mg Magnesium 12	Al Aluminum 13	Si Silicon 14	P Phosphorous 15	S Sulfur 16	Cl Chlorine 17	Ar Argon 18	M
K Potassium 19	Ca Calcium 20	Ga Gallium 31	Ge Germanium 32	As Arsenic 33	Se Selenium 34	Br Bromine 35	Kr Krypton 36	N
Rb Rubidium 37	Sr Strontium 38	In Indium 49	Sn Tin 50	Sb Antimony 51	Te Telluride 52	J Iodine 53	Xe Xenon 54	O

STRUKTUR CRISTAL SILIKON



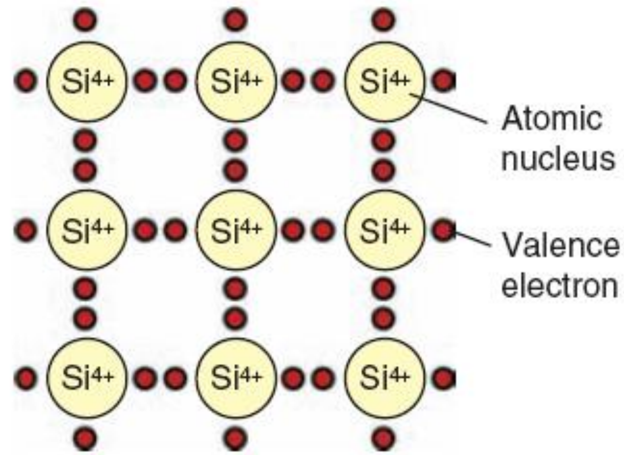


Figure 3.3 Structure of a silicon crystal: The left-hand figure shows the spherical model and the right the two-dimensional depiction

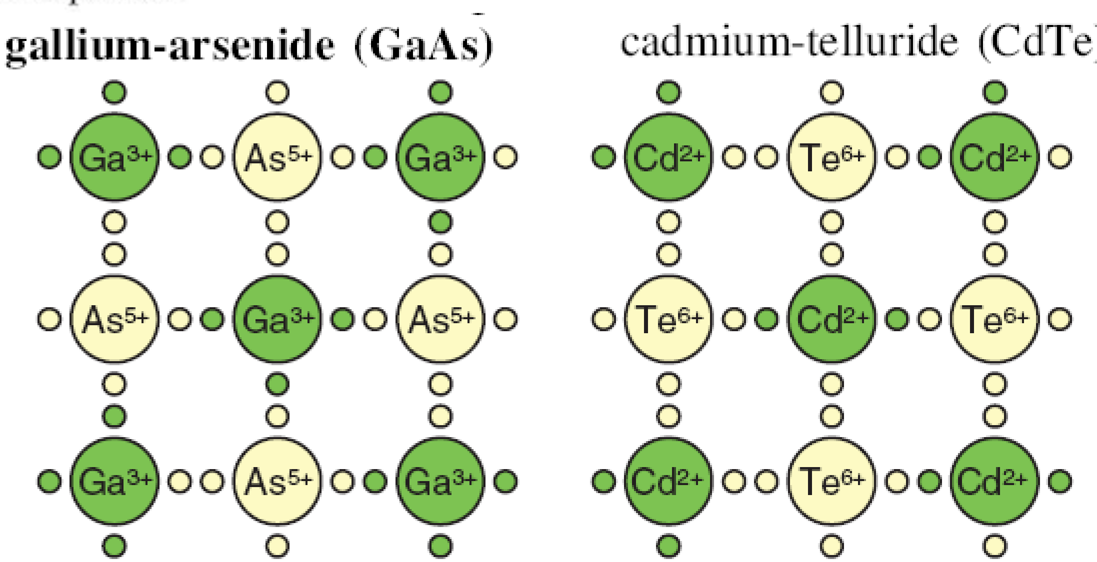


Figure 3.4 Lattice of compound semiconductors of the example GaAs and CdTe

PITA ENERGI

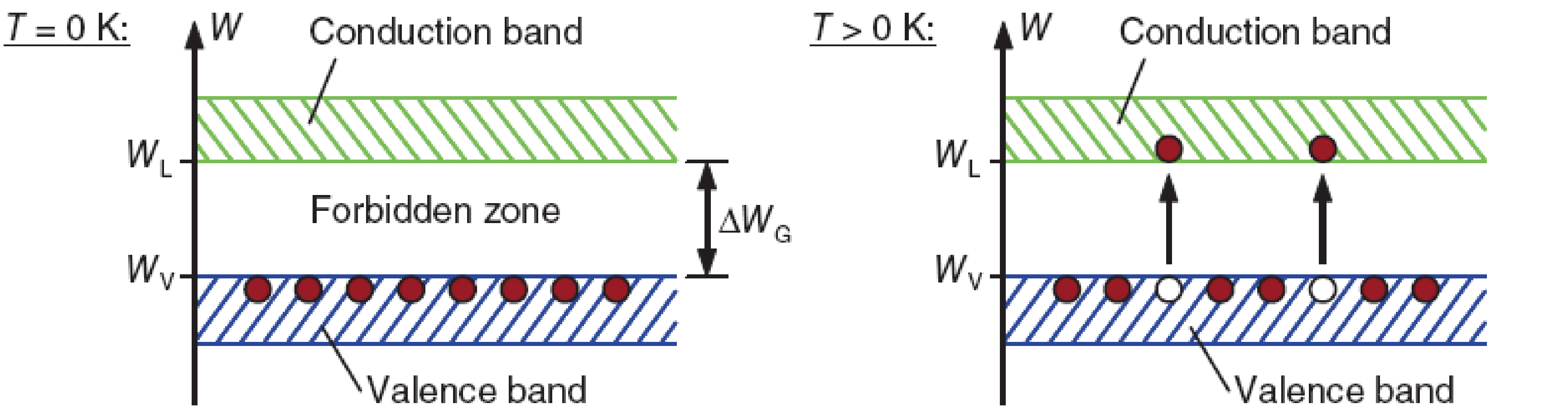


Figure 3.6 Valence and conduction bands for silicon: With rising temperatures individual electrons rise into the conduction band

- Pita yang ditempati oleh elektron valensi disebut Pita Valensi
- Pita yang kosong pertama disebut : Pita Konduksi

ISOLATOR, KONDUKTOR DAN SEMIKONDUKTOR

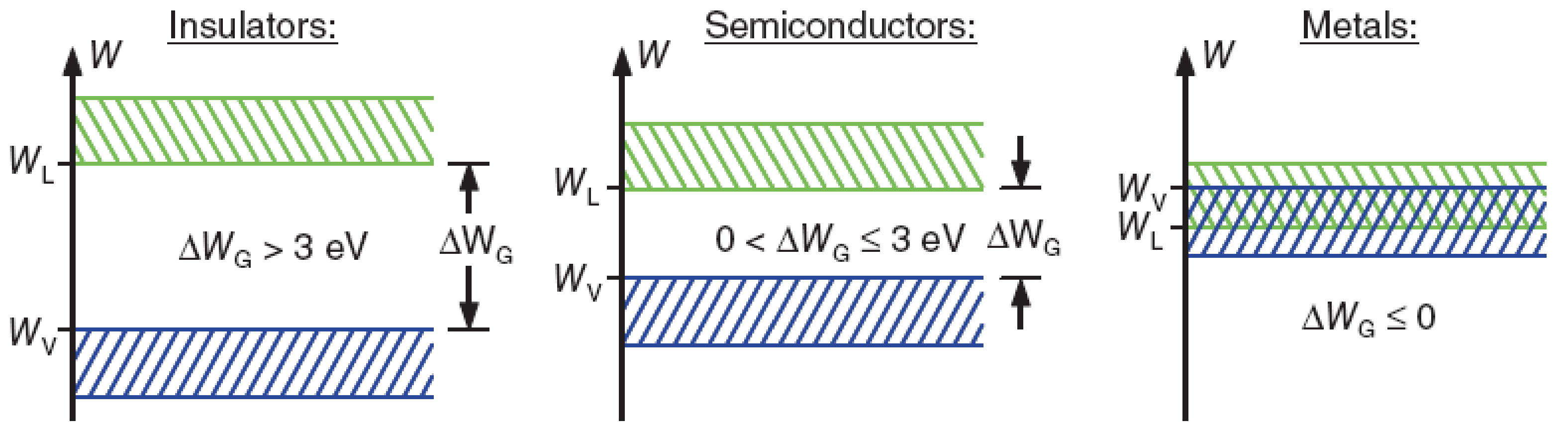


Figure 3.7 Depiction of energy bands of insulators, semiconductors and metals

Table 3.2 Comparison of the bandgaps of various materials

Material	Type of material	Bandgap ΔW_G (eV)
Diamond	Insulator	7.3
Gallium arsenide	Semiconductor	1,42
Silicon	Semiconductor	1.12
Germanium	Semiconductor	0.7

GENERASI DAN REKOMBINASI

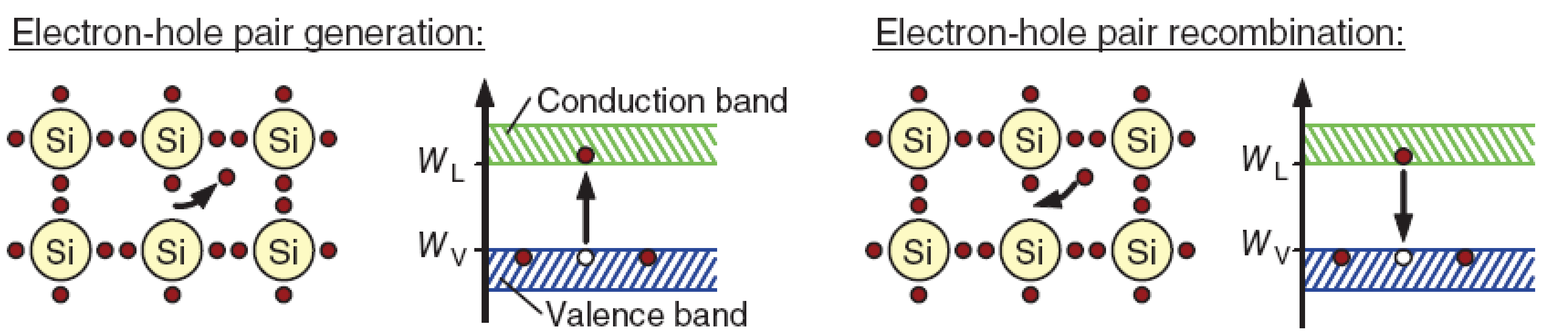


Figure 3.8 Thermal generation and recombination of electron-hole pairs: In a time average there is an average number of free electrons as well as holes, the intrinsic carrier concentration

PERGERAKAN ELEKTRON DALAM

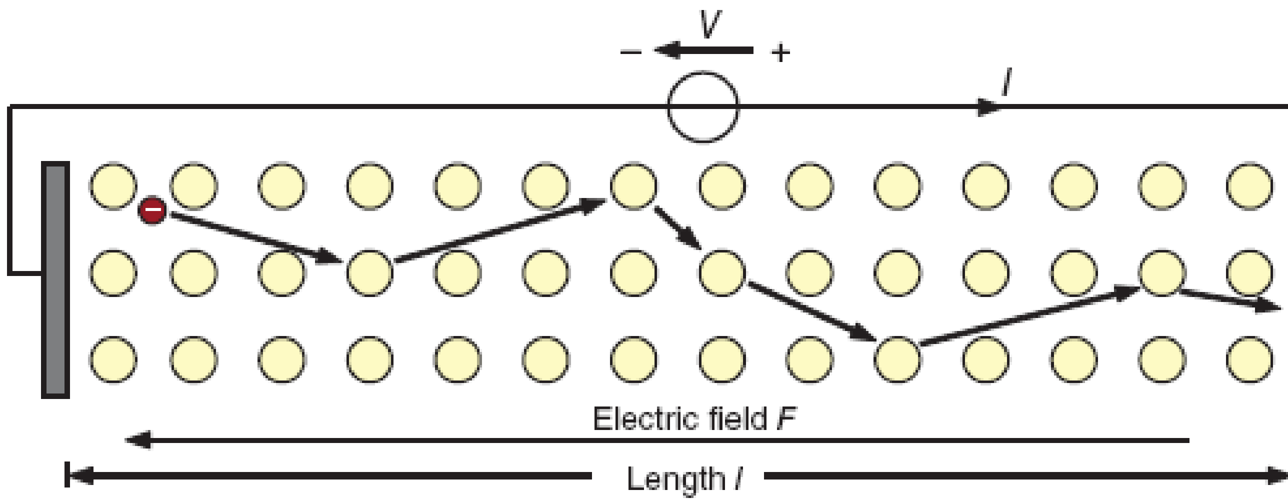
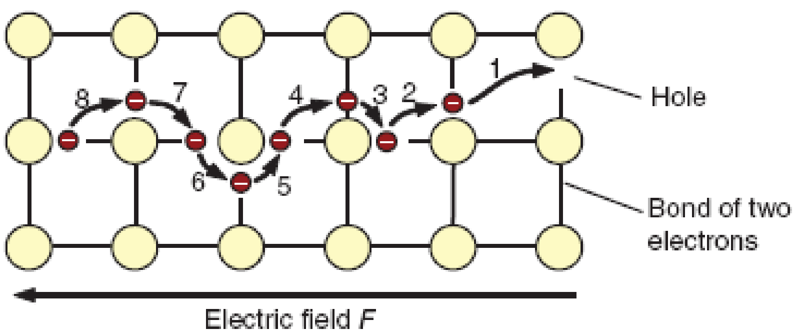


Figure 3.9 Current transport through the silicon crystal: the electrons are repeatedly decelerated by collisions with the atomic nucleus and then accelerated again



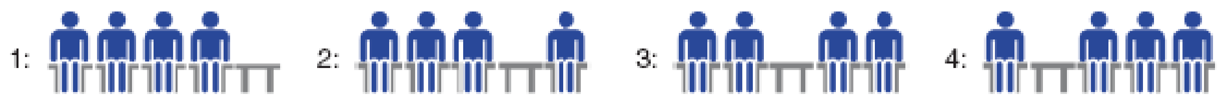


Figure 3.10 Transport of current by means of holes. The electrons move to the right one after the other. Therefore there is a "hole movement" in the opposite direction. The situation is comparable to the movement of people along a row of seats

- Prinsip kerja sel surya adalah karena perpindahan elektron atau hole akibat adanya sinar matahari, perpindahan elektron atau hole ini dibedakan menjadi dua proses yaitu proses drift dan difusi.
- Arus drift adalah arus yang ditimbulkan karena adanya medan listrik akibat adanya pembelokan pada semikonduktor tipe p-n. Arus drift hole bergantung pada seberapa besar medan listrik lokal.

- Arus difusi adalah arus yang terjadi akibat adanya perbedaan konsentrasi muatan dalam semikonduktor. Sehingga tanpa adanya medan listrik pun muatan akan mengalir sesuai dengan prinsip difusi yaitu mengalir dari konsentrasi tinggi ke konsentrasi rendah. Arus difusi hole bergantung kepada perubahan densitas atau konsentrasi muatan.

SEMIKONDUKTOR

- Semikonduktor intrinsik merupakan semikonduktor yang terdiri atas satu unsur saja, misalnya Si saja atau Ge saja. Pada kristal semikonduktor Si, 1 atom Si yang memiliki 4 elektron valensi berikatan dengan 4 atom Si lainnya.
- Semikonduktor yang telah terkotori (tidak murni lagi) oleh atom dari jenis lainnya dinamakan semikonduktor ekstrinsik. Proses penambahan atom pengotor pada semikonduktor murni disebut pengotoran (doping). Dengan menambahkan atom pengotor (impurities), struktur pita dan resistivitasnya akan berubah.

DOPING SEMIKONDUKTOR

n - DOPING

Semikonduktor tipe-n menggunakan semikoduktor intrinsik dengan menambahkan atom donor yang berasal dari kelompok V pada susunan berkala, misalnya Ar (arsenic), Sb (Antimony), phosphorus (P).

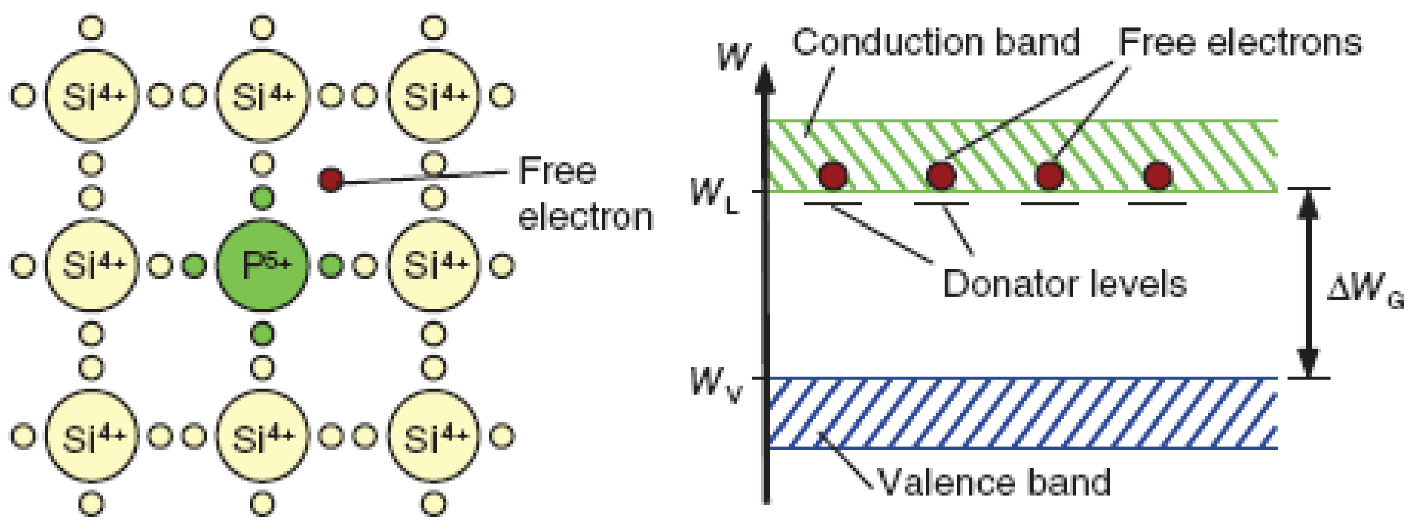


Figure 3.12 n-Doping of semiconductors; one of the five valence electrons of the phosphorous atom is not necessary for the bond and is therefore available as a free electron. Because of the doping there is a new energy level in the band diagram just below the conduction band edge

p - DOPING

Pada Si dan Ge, atomnya aseptor adalah unsur bervalensi tiga (kelompok III pada susunan berkala) misalnya B (boron), Al (alumunium), atau Ga (galium).

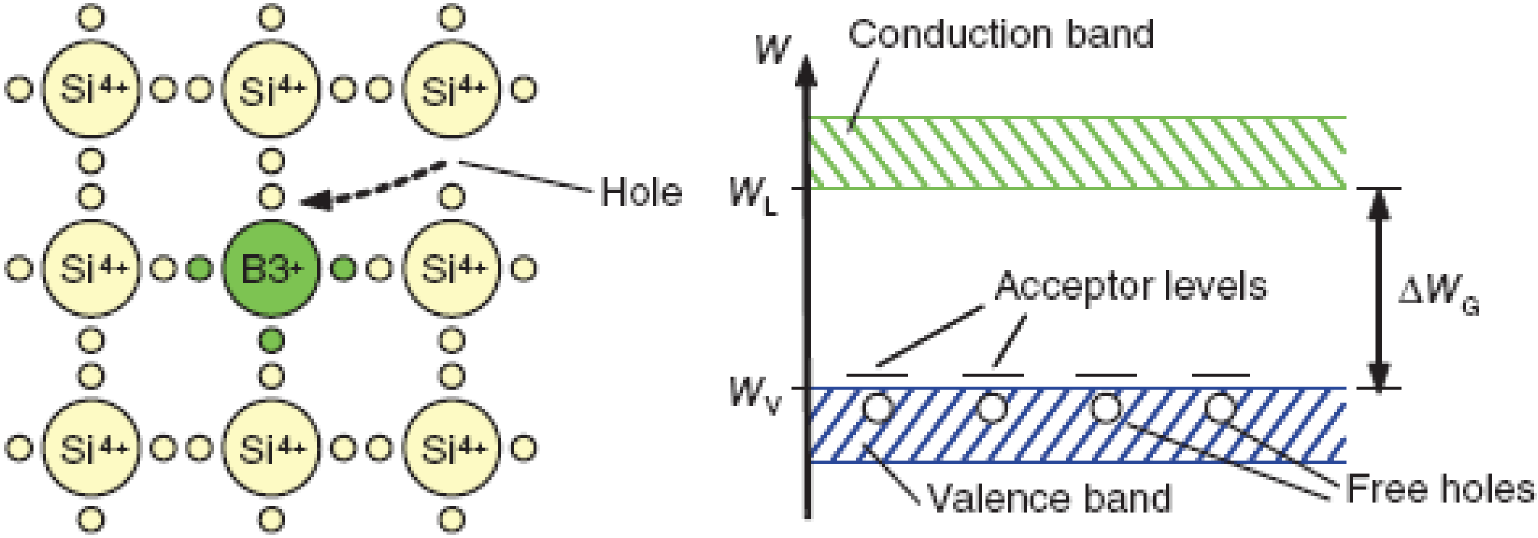


Figure 3.13 Example of p-doping of a silicon crystal with a boron atom: one of the four links remains open as the boron atom can only offer three valence electrons. A neighboring electron moves into this binding and thus "generates" a hole

p-n JUNCTION

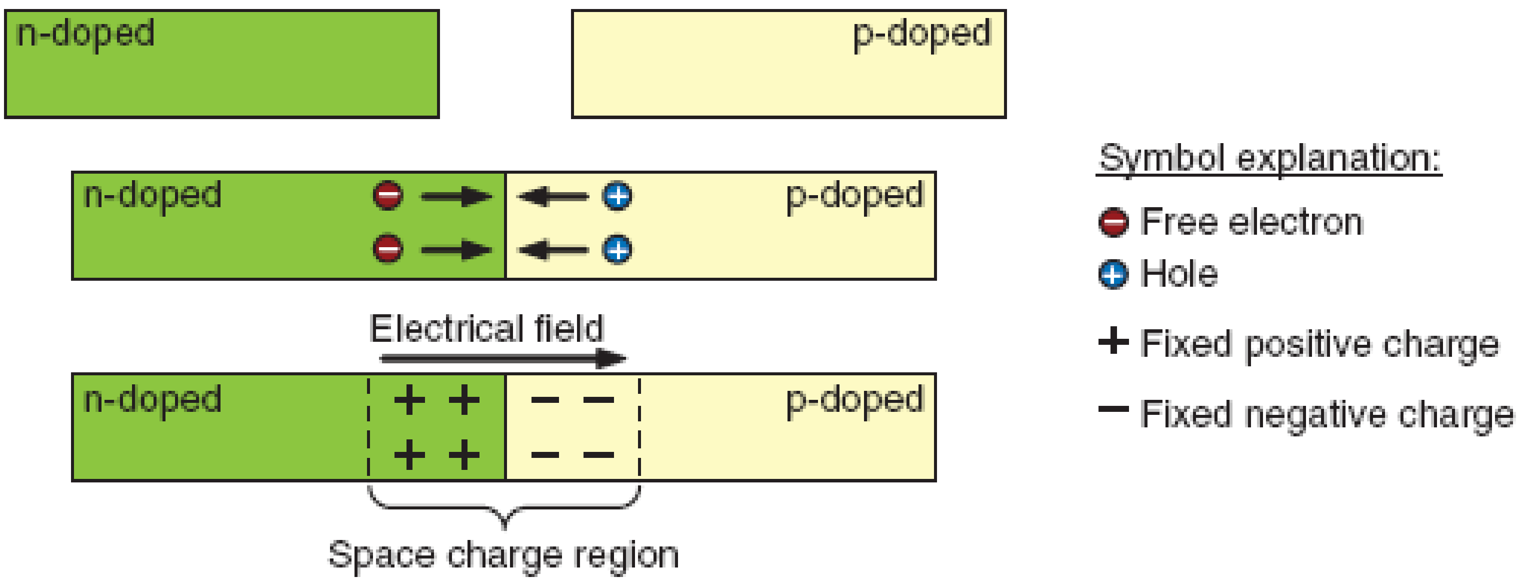


Figure 3.14 The p-n junction: Electrons flow from the n-side to the p-side and there occupy the holes. On the n-side, fixed positive charges remain behind; on the p-side fixed negative charges are generated

DIAGRAM PITA *p-n* JUCNTION

Enrico Fermi (1901–1954).

- Fermi energi W_F secara umum didefinisikan probabilitas untuk mencapai tingkat energi persis 50%.

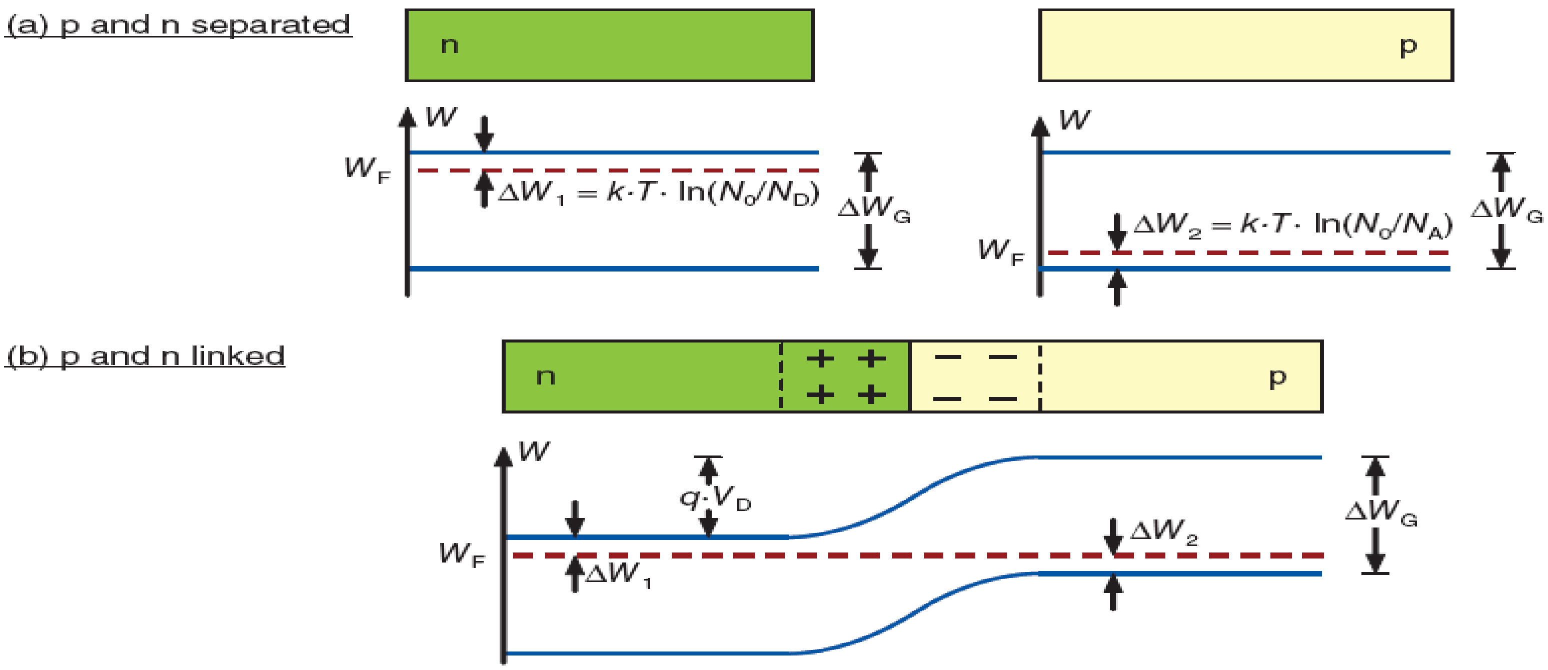


Figure 3.16 Determination of the diffusion voltage V_D of a p-n junction by means of the Fermi energies of n- and p-doped sides [23]

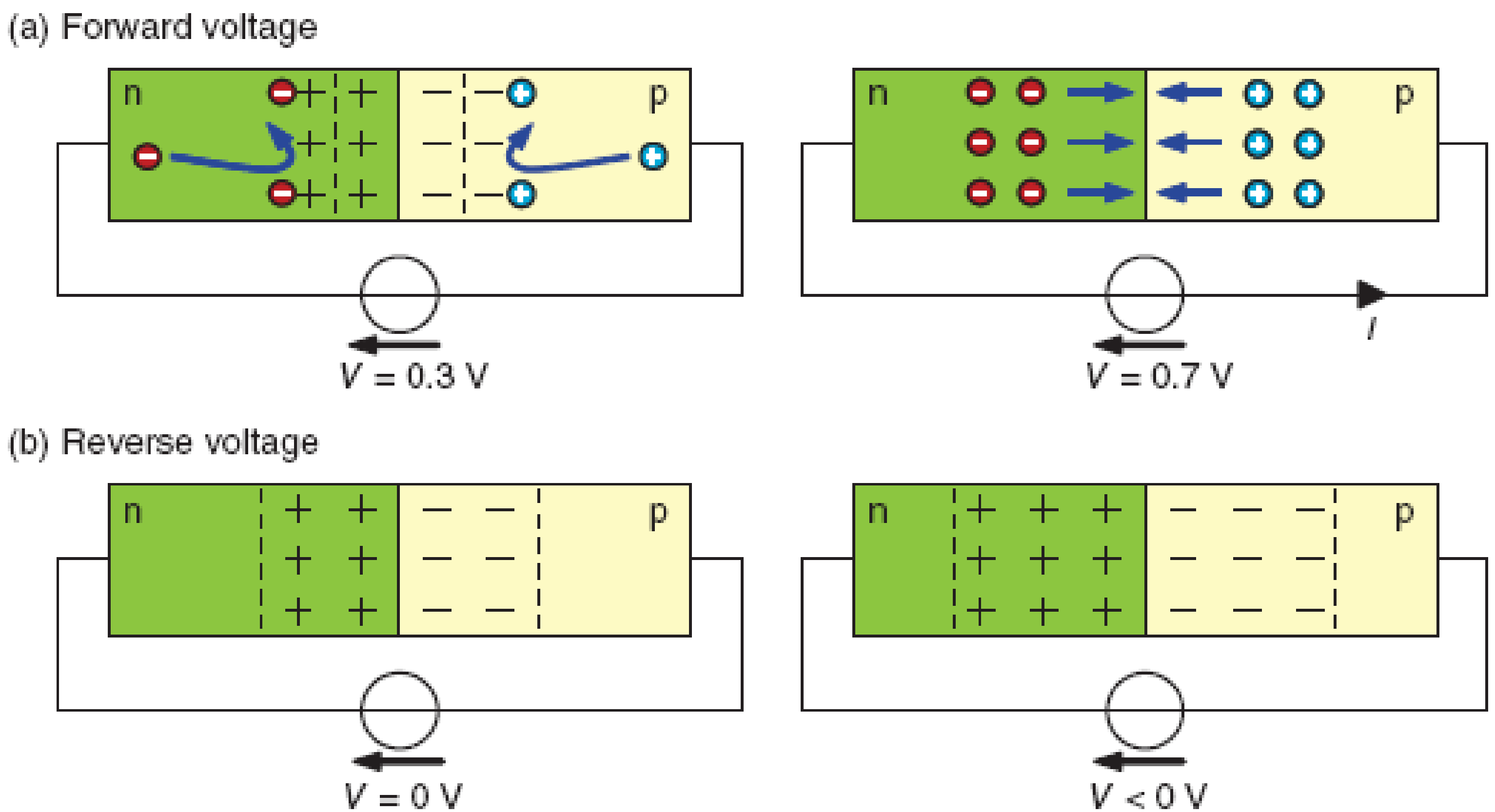


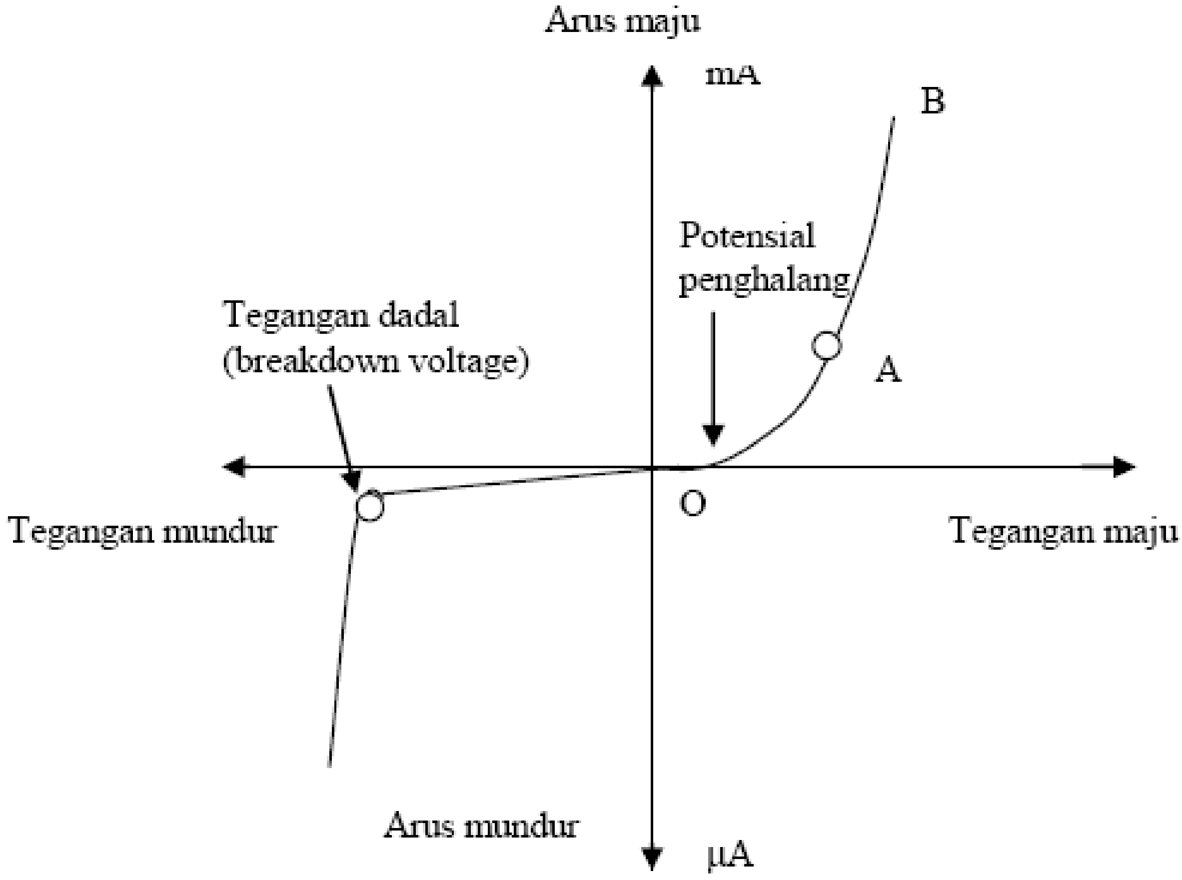
Figure 3.17 Behavior of the p-n junction with applied voltage: when *V* rises the space charge region is reduced until it finally disappears completely and a current can flow. In the case of reverse voltage the diode blocks and the space charge region is enlarged

- Prilaku V-I tersebut dapat dipelajari melalui tiga bagian, sebutlah tegangan luar nol, bias maju, dan bias mundur.

- a. Tegangan luar nol. Ketika tegangan luar nol, yakni rangkaian terbuka pada K, penghalang potensial pada persambungan tidak mengijinkan arus mengalir. Sehingga arus ranglaian nol dan ditunjukkan oleh titik O.

- b. Bias maju. Dengan bias maju pada persambungan pn, yakni tipe p dihubungkan dengan terminal positif dan tipe n dihubungkan dengan terminal negatif, maka potensial penghalang ditiadakan. Pada suatu harga tegangan maju (0,7 volt untuk Si dan 0,3 volt untuk Ge), maka potensial penghalang itu seluruhnya dihilangkan dan arus mulai mengalir di dalam rangkaian. Dari keadaan ini makin maju, maka arus meningkat dengan kenaikan tegangan maju. Kemudian, kenaikan kurva OB diperoleh dengan pemberian bias maju. Dari watak bias maju ini terlihat bahwa yang pertama (daerah OA), arus meningkat dengan sangat lambat dan kurva tidak linier

- c. Bias Mundur. Dengan bias mundur pada sambungan pn, yaitu tipe p dihubungkan dengan terminal negatif dan tipe n dihubungkan dengan terminal positif, penghalang potensial pada persambungan meningkat. Karena itu resistansi persambungan menjadi sangat tinggi dan secara praktis tidak ada arus yang mengalir melalui rangkaian itu.



KARAKTERISTIK DIODE

Figure 3.18 Symbol and *I*/*V* characteristic curve of a p-n diode: in the forward direction the diode only conducts from the threshold voltage V_{Th}, in reverse direction, there are high currents in the case of exceeding the breakthrough voltage V_{Br}

Shockley equation.

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

with

I_S: saturation current of the diode
V_T: thermal voltage

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

Boltzmann constant $k = 1.3807 \cdot 10^{-23}$ J/K $= 8.6174 \cdot 10^{-5}$ eV/K
Elementary charge $q = 1.6022 \cdot 10^{-19}$ As

Example 3.5 **Thermal voltage at room temperature**

The following thermal voltage occurs at room temperature ($T \approx 300\,\mathrm{K}$):

$$V_\mathrm{T} = \frac{k \cdot T}{q} = \frac{8.62 \cdot 10^{-5}\ \mathrm{eV/K} \cdot 300\ \mathrm{K}}{q} = 25.89\ \mathrm{mV} = 26\ \mathrm{mV}$$

At room temperature ($T \approx 300\ \mathrm{K}$) the thermal voltage is approximately $26\,\mathrm{mV}$.

KOEFISIEN PENYERAPAN

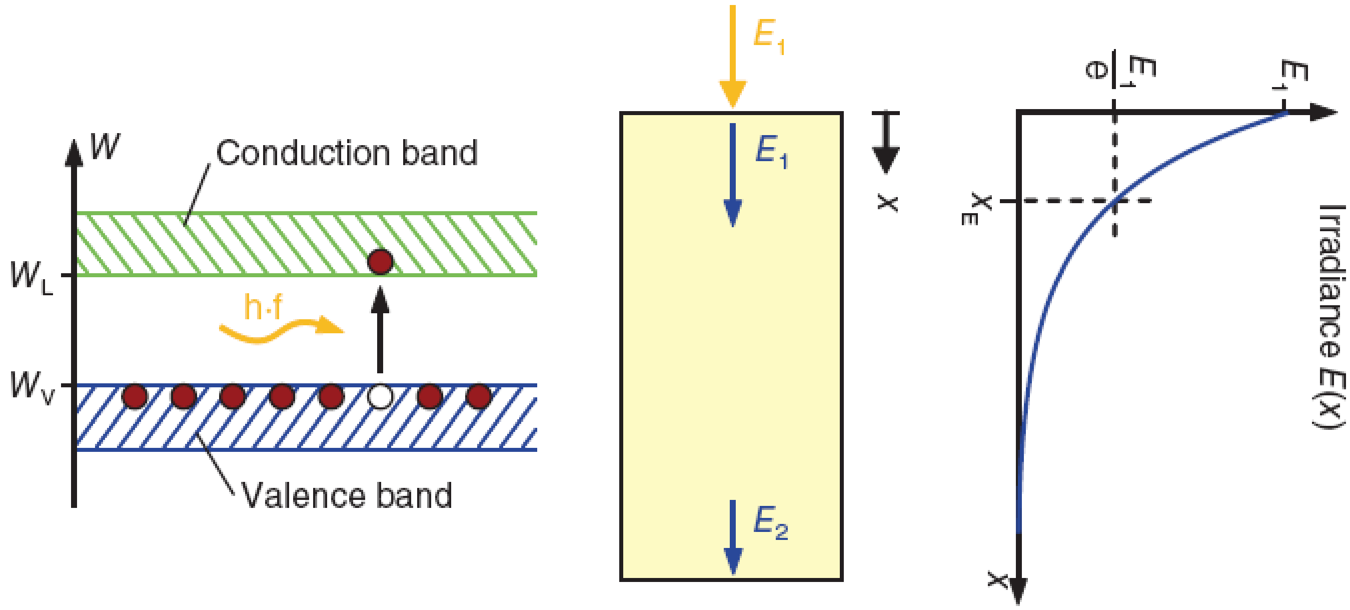


Figure 3.19 Principle of light absorption in the semiconductor. (Left); the photon is absorbed only with sufficient light energy and an electron is raised into the conduction band. (Right); incidental light radiation into a semiconductor crystal: Due to absorption in the material the light intensity sinks with increasing penetration depth

$$E(x) = E_1 \cdot e^{-\alpha \cdot x}$$

E_1: irradiance at $x = 0$

α : absorption coefficient

Table 3.3 Comparison of the absorption coefficients of different materials for light of the wavelength 600 nm [26–28]

Material	Type	Bandgap ΔW_G (eV)	Absorption coefficient α (cm^{-1})	Penetration depth x_p (μm)
c-Si	Indirect	1.12	4000	2.5
a-Si	Direct	1.7	40 000	0.25
CdTe	Direct	1.45	37 000	0.3
GaAs	Direct	1.42	47 000	0.2

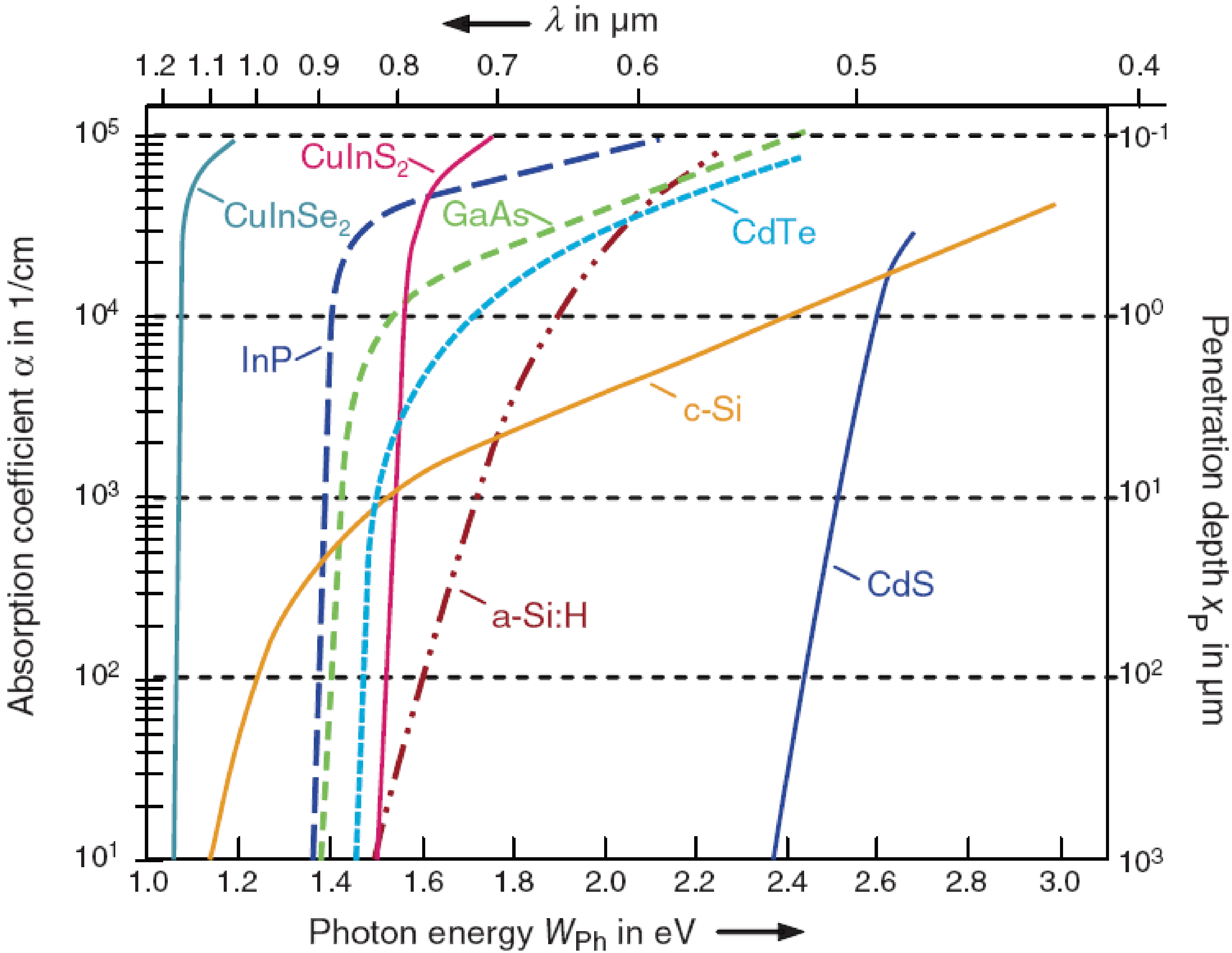


Figure 3.22 Absorption coefficient of different semiconductor materials in dependence of the photon energy: The direct semiconductors show a steep rise in the absorption above the bandgap energy [26–28]

FAKTOR REFLEKSI

$$R = \frac{E_R}{E_0} \tag{3.22}$$

with

E_0: incident irradiance
E_R: reflected irradiance

For vertical incidental radiation the reflection factor is calculated according to the following equation:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \tag{3.23}$$

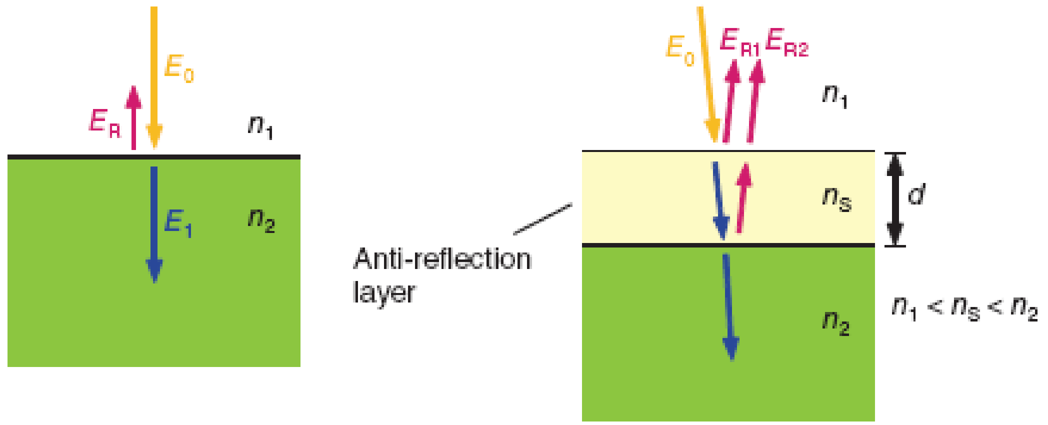


Figure 3.23 Reflection of light on the interface between two media: The reflection can be reduced with the use of an anti-reflection layer (right)

- Refleksi insidental harus dikurangi untuk mencapai tingkat efisiensi yang tinggi dalam sel surya. Sebuah cara standar untuk melakukan hal ini dengan lapisan anti-refleksi.
- Gambar 3.23 bahan ketebalan d disisipkan antara dua media.

Example 3.7 Reflection on a silicon surface

In the case of silicon the refractive index is in the visible spectrum at approximately $n = 3.9$ [30]. If a ray of light ($n = 1$) impinges vertically on the silicon surface, this results in a reflection factor of:

$$R = \left(\frac{1-3.9}{1+3.9}\right)^2 = \left(\frac{-2.9}{4.9}\right)^2 = 0.35 = 35\%$$

The remaining reflection factor can now be calculated according to the **Fresnel equations** [29]:

$$R = \left(\frac{n_S^2 - n_1 \cdot n_2}{n_S^2 + n_1 \cdot n_2} \right)^2 \tag{3.26}$$

From Equation 3.26 can be seen that the reflection factor even reaches to zero, when the refractive index n_S is at the geometric average of the two other indices:

$$n_S = \sqrt{n_1 \cdot n_2} \tag{3.27}$$

Example 3.8 Anti-reflection coating with SiO_2

In the case of silicon the refractive index of $n_S = \sqrt{3.9} = 1.97$ is optimum. The easy-to-use material silicon oxide (SiO_2) has a refractive index of 1.46. With Equation 3.26 this gives a reflection factor of $R = \left(\frac{1.46^2 - 1 \cdot 3.9}{1.46^2 + 1 \cdot 3.9} \right)^2 = 8.6\%$

■

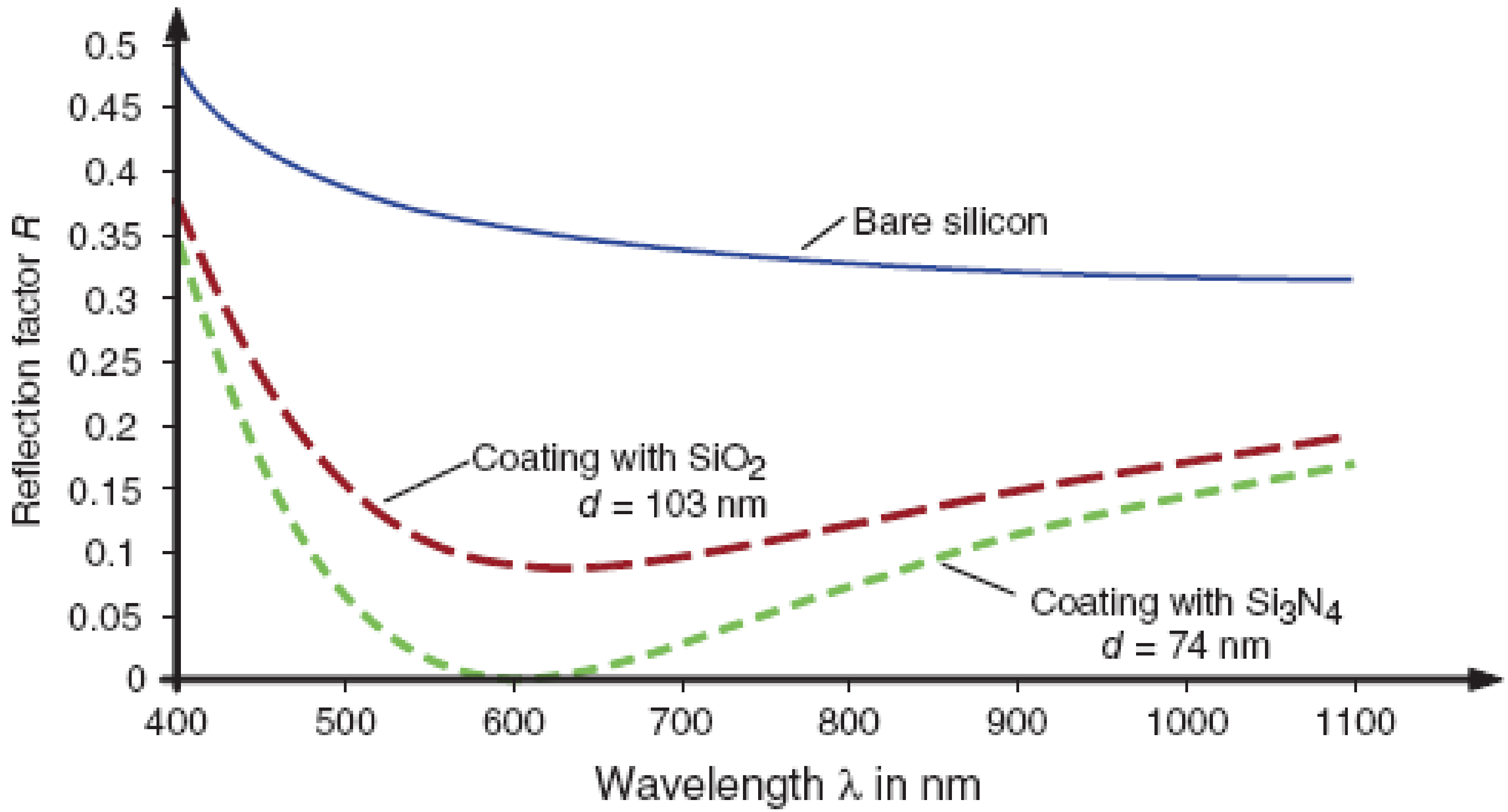


Figure 3.24 Spectral progression of reflection for uncoated and, for silicon oxide or silicon nitride, coated silicon: For both materials the reflection factor can be clearly reduced compared with bare silicon