Renewable Electric Energy Systems EE—546

Semiconductor Physics —Solar Applications

Dr. U. T. Shami

Semiconductors for solar application: Semiconductors as materials for solar cells, Carrier concentration and distribution, generation-recombination processes, Continuity Equations.

Consideration of the Photodiode: Method of Function of the Solar Cell, Photocurrent, Characteristic Curve and Characteristic Dimensions, Electrical Description of Real Solar Cells, Considering Efficiency, High Efficiency Cells.

3.1 Structure of Semiconductors

3.1.1 Bohr's Atomic Model

According to Bohr's atomic model, an atom consists of a nucleus and a shell. The **nucleus** contains **protons and neutrons** whereas the **shell** contains **electrons**, which orbit the nucleus. The **value** of the **elementary charge** is **1.6×10⁻¹⁹ C**. The simplest atom, **hydrogen atom,** has the atomic number 1 and thus has only one proton in the nucleus and one electron in the shell. Bohr recognized that electrons can only circulate in very particular paths (so-called "shells") about the nucleus.

Bohr's First Postulate:
There are only certain discrete shells permitted for an electron.

Each of these shells stands for a respective energy state of the electron. The shells are designated with the letters of K, L, M, and so on.

Initially, the electron is situated on the **K shell**. If the electron is moved to the **L shell then energy of 10.2 eV** (electron volts) is necessary.

In order to separate the electron completely from the the so-called **ionizing energy** W_∞ of **13.6 eV** is required.
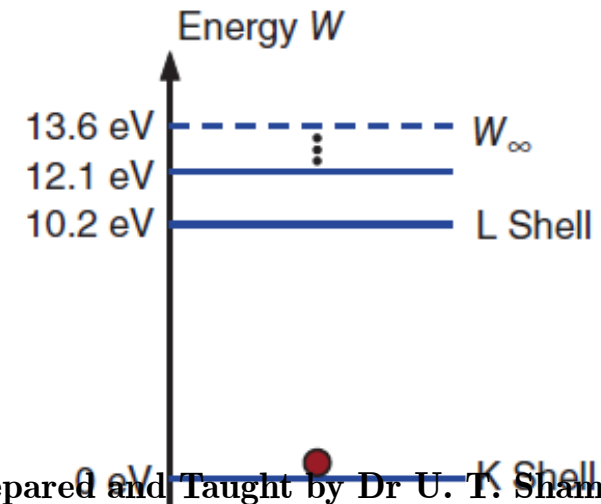
3.1.1 Bohr's Atomic Model

Bohr's Second Postulate:
The transfer of an electron from one shell to another occurs under the emission or absorption of electromagnetic radiation.

The **frequency f** of this radiation is thus determined by the following equation:

$$\Delta W = |W_2 - W_1| = h \cdot f \qquad (3.1)$$

With W_1 : energy before the transfer
       W_2 : energy after the transfer
       h: Planck's constant; $\mathbf{h = 6.62607015 \times 10^{-34}}$ **J·s**

In order to determine the `wavelength` λ from the frequency f the following equation is used:

$$\lambda = \frac{c_0}{f} \ , \ c_0 = 299.792 \,\text{km/s} \approx 3 \cdot 10^8 \,\text{m/s} \qquad (3.2)$$
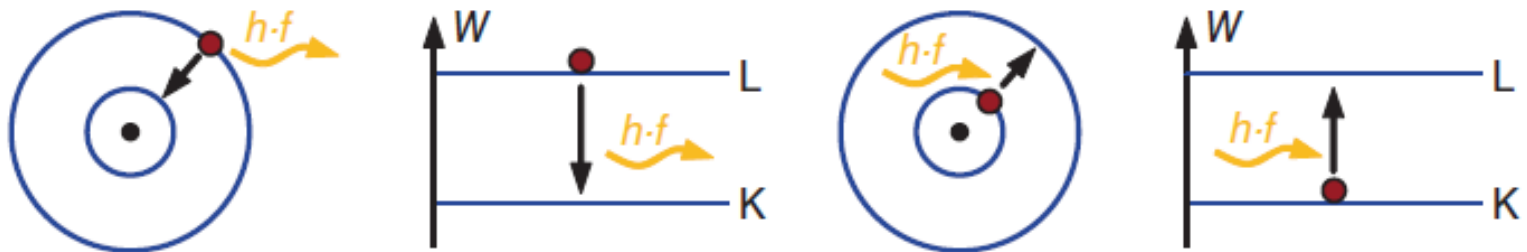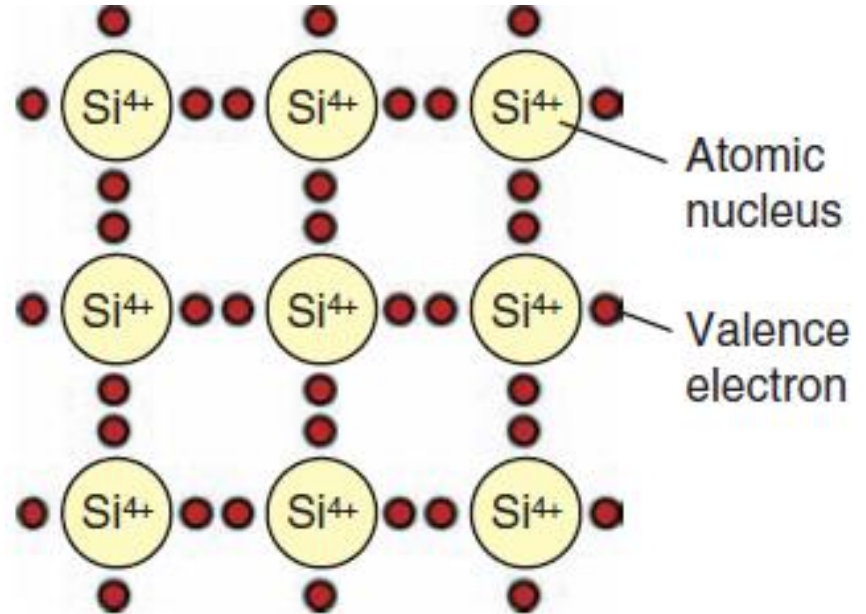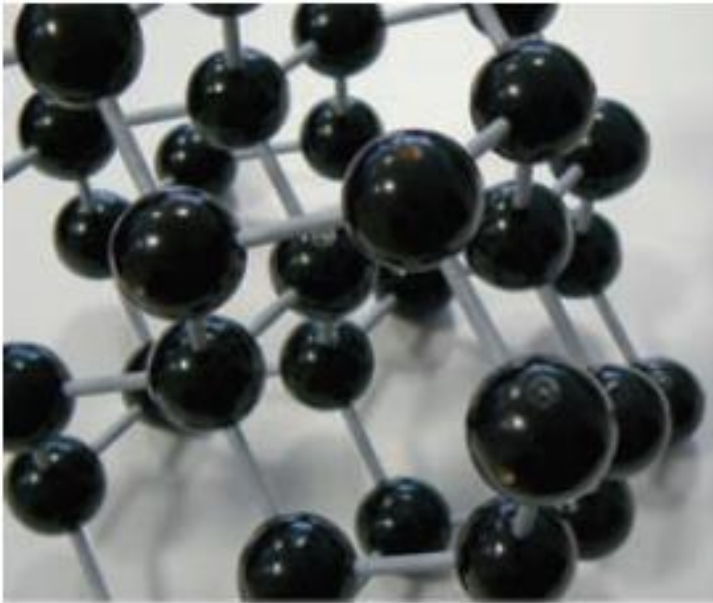

Figure 3.2   Schematic depiction of the emission (left) and absorption (right) of light

3.1.2 Periodic Table of the Elements

3.1.3 Structure of the Silicon Crystal

When the electrons of neighboring atoms make fixed connections, then a regular lattice structure can be formed. Such a structure is called a **crystal**.

3.1.4 Compound Semiconductors

It is possible to combine elements of different main groups. A well-known representative is the compound **gallium-arsenide (GaAs)** that can ensure high efficiencies in solar cells. It consists of trivalent gallium and pentavalent arsenic atoms and is thus called a **III/V-semiconductor**.

Figure 3.4 shows the structure so that the result is again the especially stable noble gas configuration.

Besides the III/V-semiconductor, the **II/VI-semiconductors** are also of possible; Figure 3.4 shows this in the example of cadmium-telluride (CdTe).
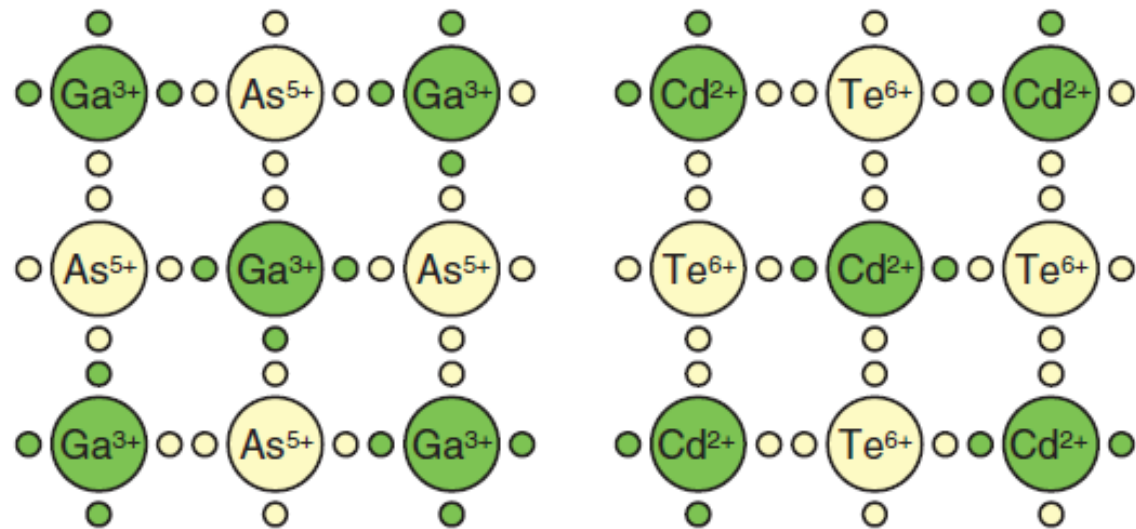

Figure 3.4 Lattice of compound semiconductors of the example GaAs and CdTe
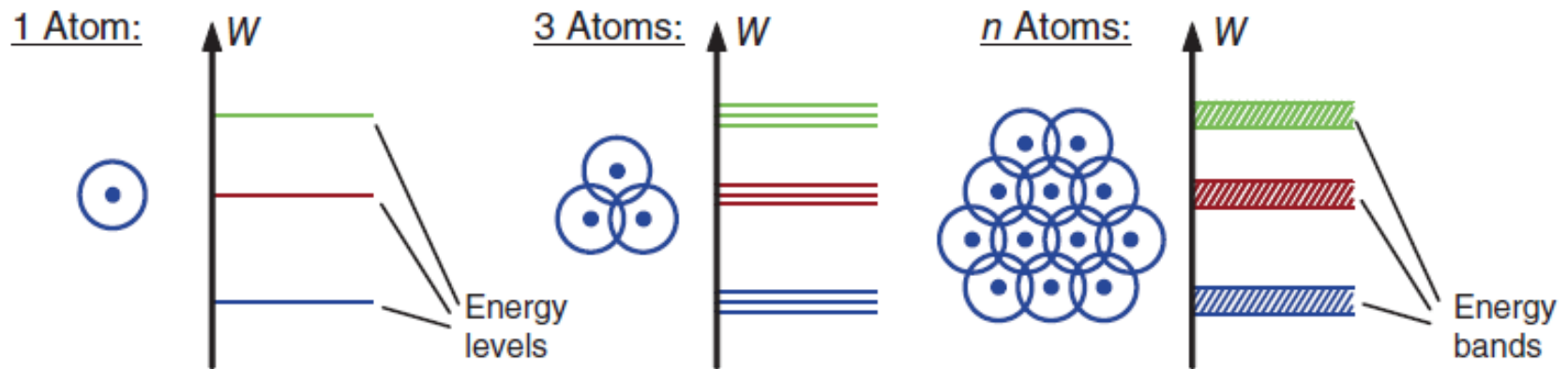
3.2 Band Model of the Semiconductor

Figure 3.5 Origin of the energy bands in a semiconductor crystal: the coupling of the atoms leads to a spreading of the energy levels. For $n \to \infty$ this results in continuous energy bands
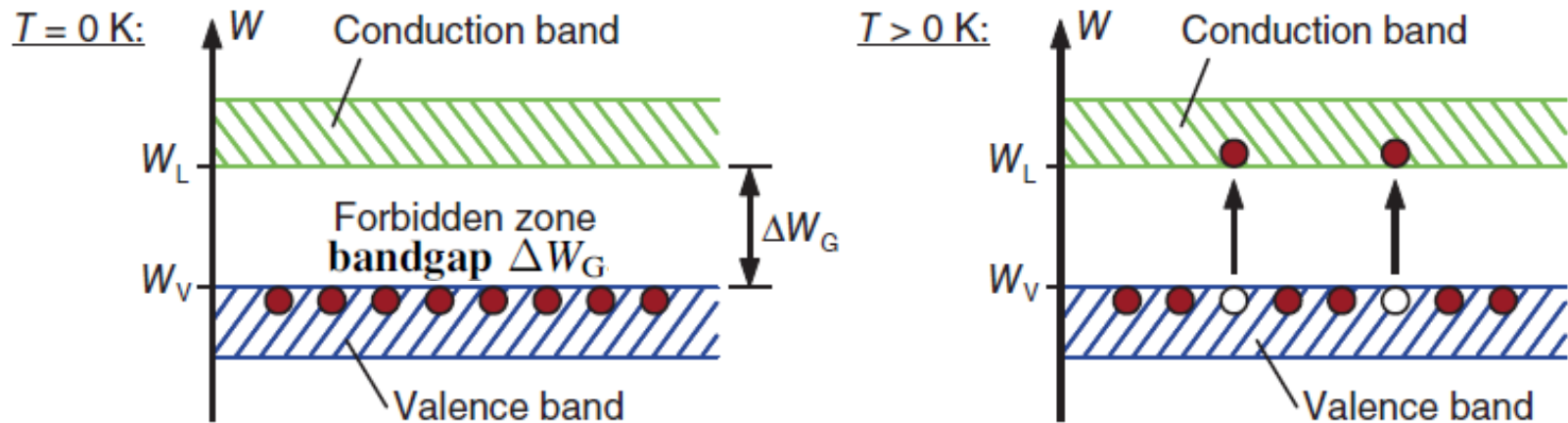

Figure 3.6 Valence and conduction bands for silicon: With rising temperatures individual electrons rise into the conduction band

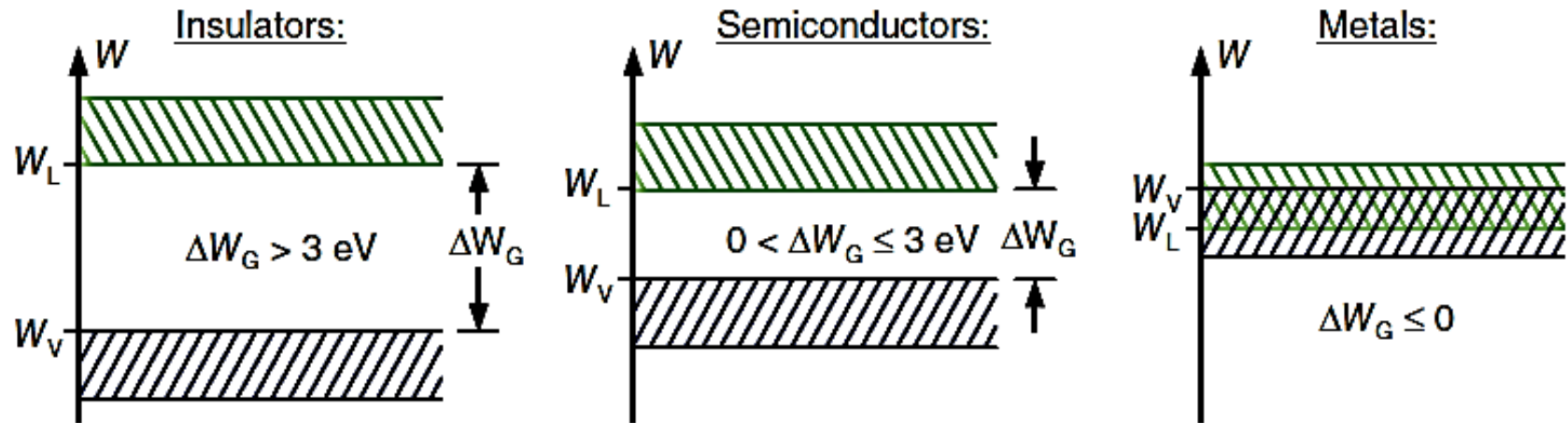# 3.2.2 Differences in Isolators, Semiconductors and Conductors

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

Table 3.2 Comparison of the bandgaps of various materials

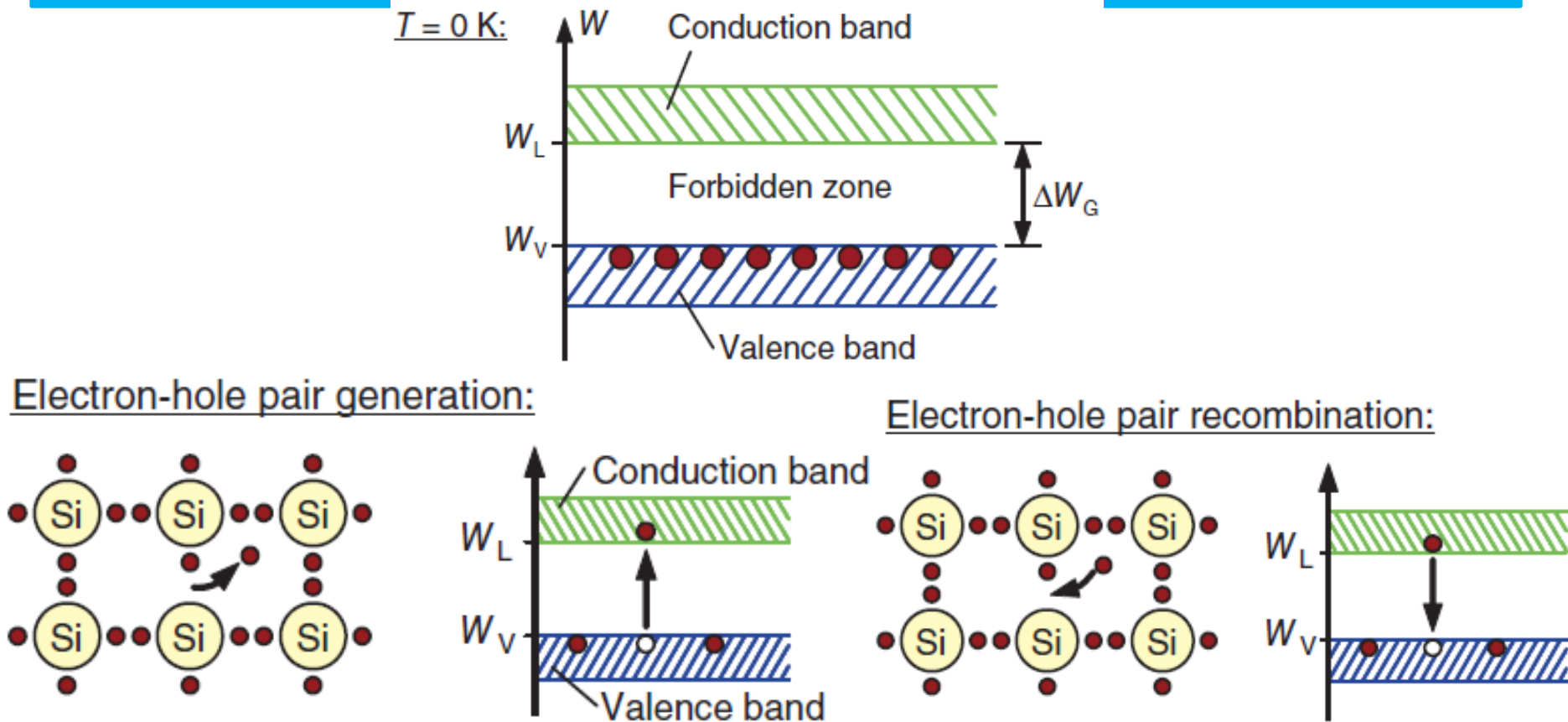| Material	Type of material	Bandgap ΔW_G (eV)
Diamond	Insulator	7.3
Gallium arsenide	Semiconductor	1,42
Silicon	Semiconductor	1.12
Germanium	Semiconductor	0.7

3.2.3 Intrinsic Carrier Concentration

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

The intrinsic carrier concentration can be found as:

$$n_i = N_0 \cdot e^{-\frac{\Delta W_G}{2 \cdot k \cdot T}} \quad (3.3)$$

N_0: effective density of states; for silicon: $N_0 \approx 3 \cdot 10^{19}/\text{cm}^3$

k: Boltzmann constant; $k = 1.38 \cdot 10^{-23}$ Ws/K $= 8.62 \cdot 10^{-5}$ eV/K

3.3 Charge Transport in Semiconductors
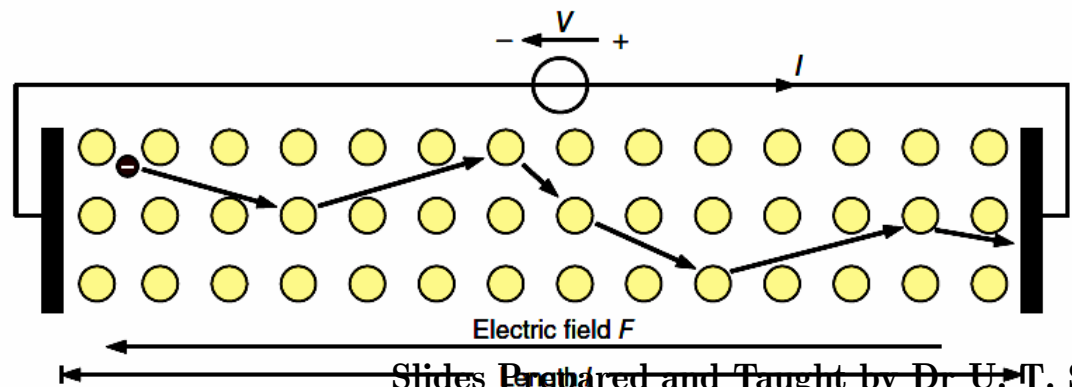
3.3.1 Field Currents

Figure 3.9 shows a crystal of silicon that has an electric voltage V applied to it. As in a plate capacitor this voltage leads to an electrical field F in the crystal:

$$F = \frac{V}{l} \tag{3.4}$$

By means of this field the negatively charged electrons are accelerated in the direction of the positive pole of the voltage source. There is thus a flow of current through the semiconductor, which is called **field current** (sometimes **drift current**). However, the electrons in the crystal repeatedly collide against the atomic nucleus, are decelerated and accelerated again by the field. In a timed average they achieve a certain average **drift velocity** v_D.

These electrons are pushed by the electrical field through the crystal in the time $\Delta t = v_\mathrm{D} \cdot l$, with the Equation 3.5 for the **field current** I_F this results in:

$$I_\mathrm{F} = \frac{\text{Charge}}{\text{Time}} = \frac{q \cdot N}{\Delta t} = q \cdot n \cdot A \cdot \frac{l}{\Delta t} = q \cdot n \cdot A \cdot v_D = q \cdot A \cdot n \cdot \mu_\mathrm{N} \cdot F \tag{3.7}$$
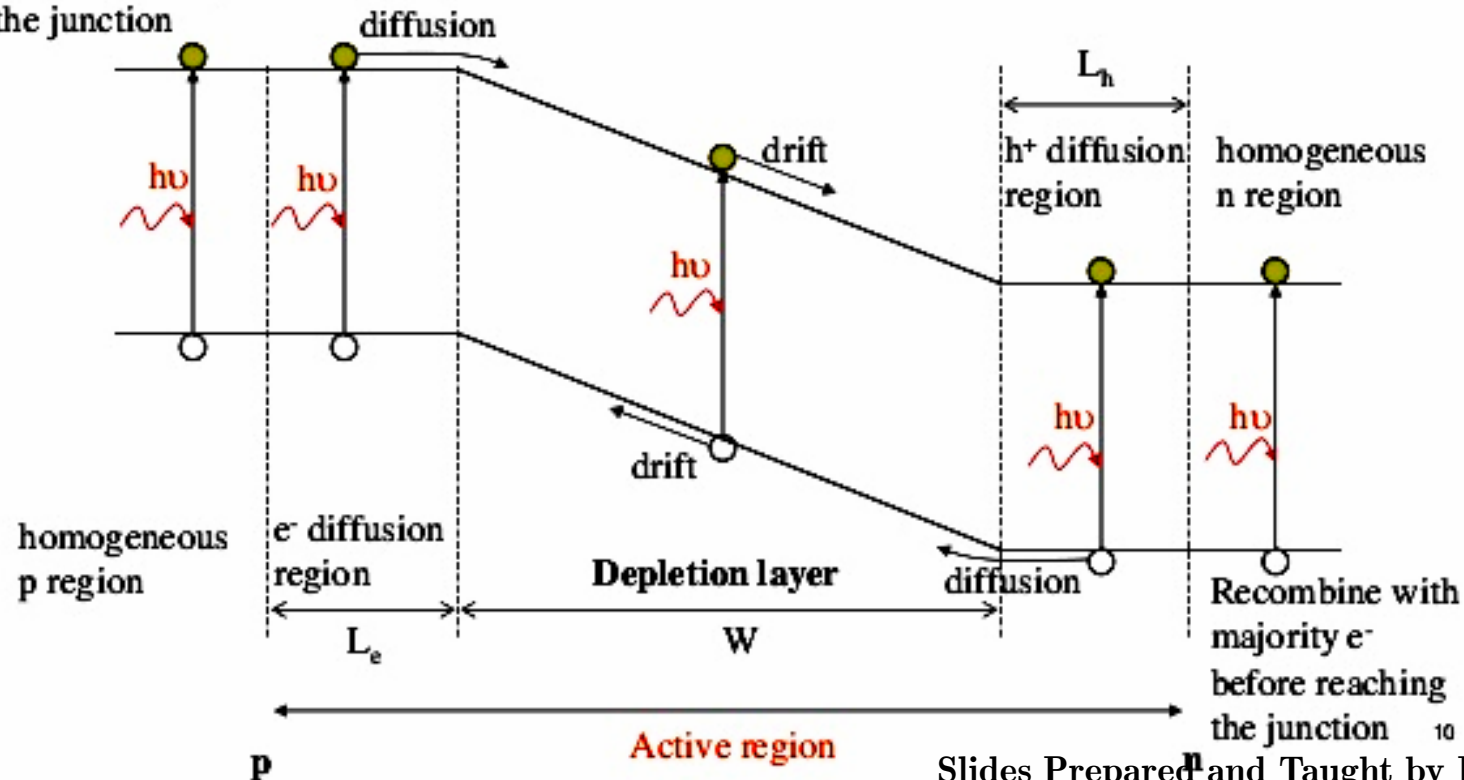

Electric field F

3.3.2 Diffusion Currents

Besides the field current there is also a **second type of current** in semiconductors: the **diffusion current**. This comes from the **differences in concentration.**

Photoexcitation and energy-band diagram of a p-n photodiode

3.4 Doping of Semiconductors

Semiconductors are **poor electrical conductors**. They have achieved their particular importance in that their conductivity can be influenced in a targeted manner. For this purpose one introduces foreign atoms into the semiconductor crystal (**doping**).

Two of the most important materials **Silicon** can be doped with, are **Boron** (3 valence electrons = 3-valent) **(P—Type Material)** and **Phosphorus** (5 valence electrons = 5-valent) **(N—Type Material).**
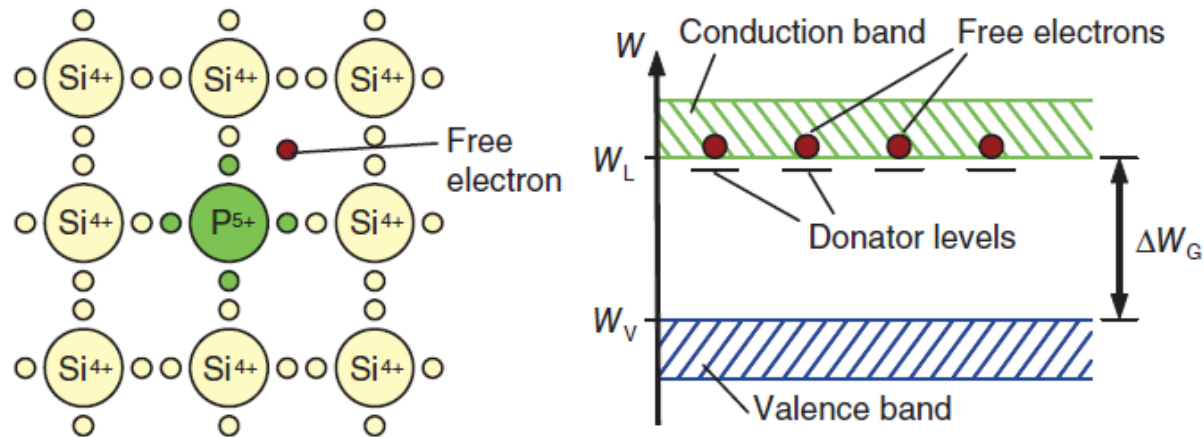
3.4.1 N—Doping   3.4.2 P—Doping

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
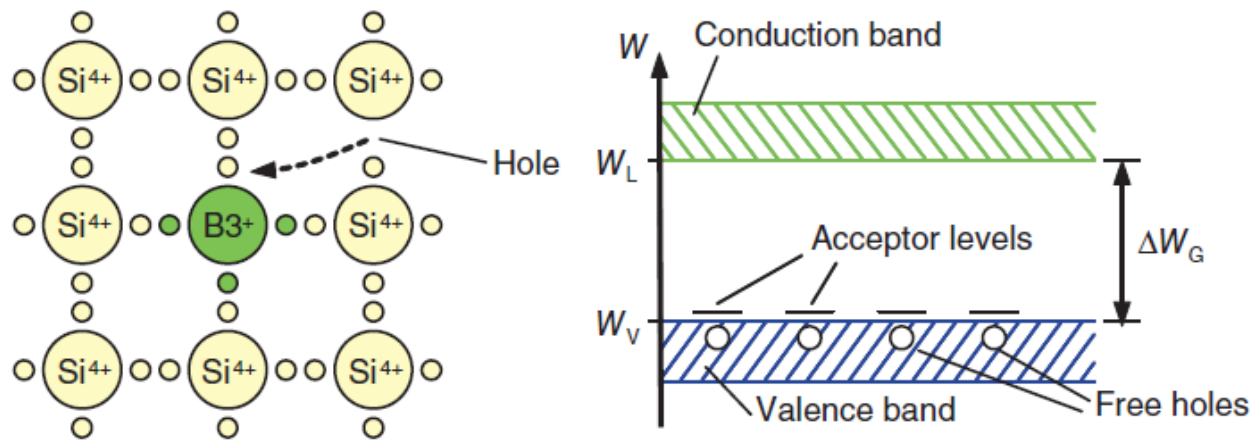

Figure 3.13 Example of p-doping of a silicon crystal with a boron atom: one of the four links remains open as the boron atom can only offer three valence electrons. A neighboring electron moves into this binding and thus "generates" a hole

Slides Prepared and Taught by Dr U. T. Shami

3.5 The P—N Junction

Figure 3.14 shows the principle processes in a P-N junction. Both **regions** are **electrically neutral**. Thus, on the left side, the number of free electrons is equal to the number of fixed positive donor atoms. Let us now assume that both regions have just been combined. On the n-side there is a surplus of free electrons. These diffuse due to the **concentration gradient** from the **diffusion current** to the right into the p-doped region, and there they re-combine with the holes. A new balance is built up in which **diffusion and field current cancel each other** and a **space charge region** exists at the p-n junction. (also known as depletion region)

Symbol explanation:
- ⊖ Free electron
- ⊕ Hole
- + Fixed positive charge
- – Fixed negative charge
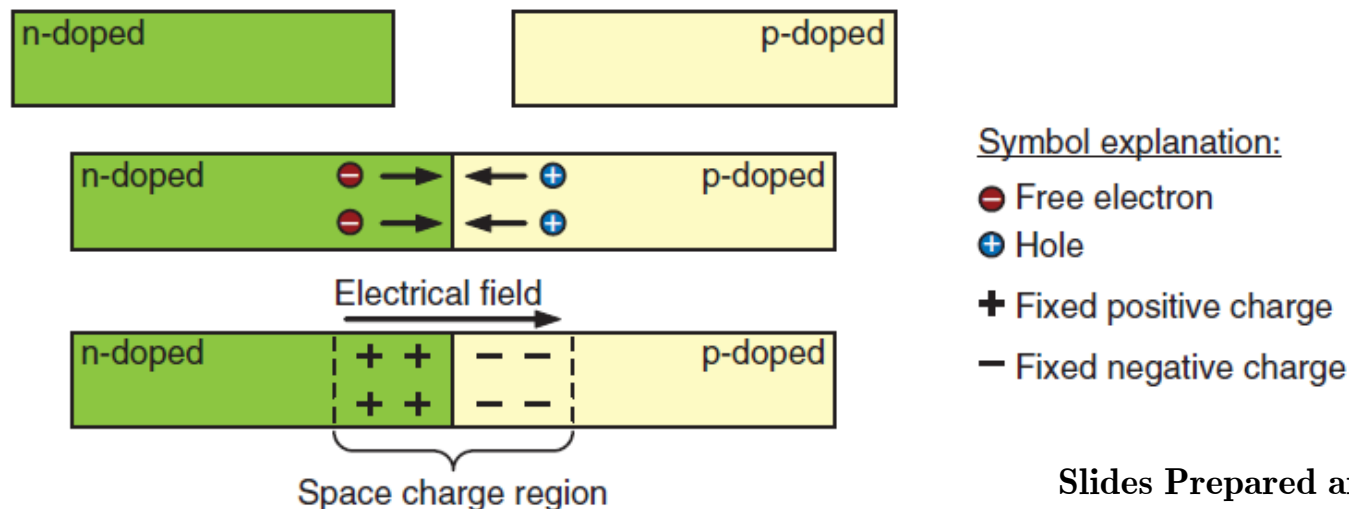
3.5.1 Principle of Method of Operation

As done in class or read book

3.5.2 Band Diagram of the p-n Junction

As done in class or read book

3.5.3 Behavior with Applied Voltage

As done in class or read book

3.5.4 Diode Characteristics

As done in class or read book

3.6 Interaction of Light and Semiconductors

3.6.1 Phenomenon of Light Absorption

We learned of the effect of light absorption on individual atoms when discussing the Bohr's atomic model (see Section 3.1.1). The behavior of the semiconductor is similar. In place of the individual energy levels, however, the bandgap ΔW_G is decisive here for the absorption behavior.

3.6.1 Phenomenon of Light Absorption

Incident light photons lift individual electrons from the valence into the conduction band. In order to trigger this effect, the energy W_{Ph} of the photons must be greater than the bandgap:

$$W_{\text{Ph}} = h \cdot f = \Delta W_{\text{G}}$$

The path **of the irradiance (light rays)** in the absorbing material can be described as,

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

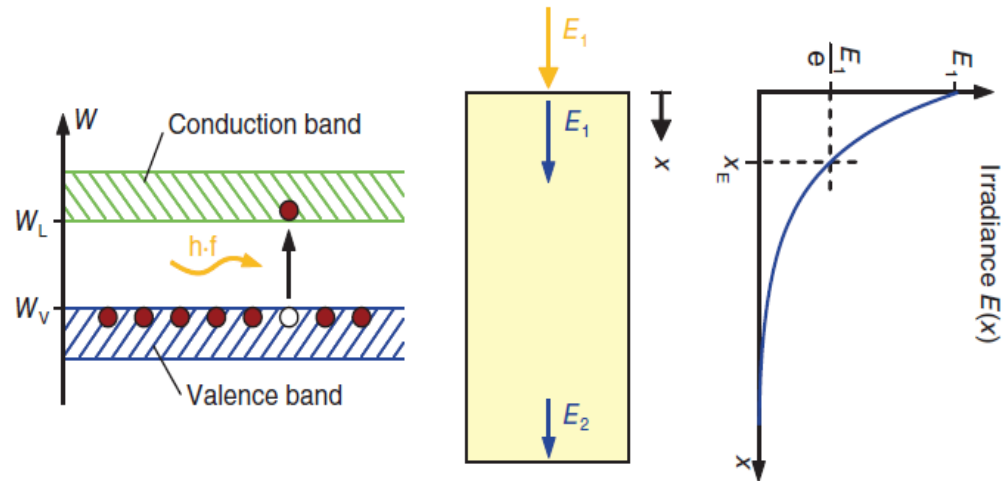E_1: irradiance at $x = 0$
α: absorption coefficient

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

The **absorption coefficient** α indicates the absorption "ability" of the material. Another term, the **penetration depth x_P,** describes the light path the intensity has decayed by the 1/e times (thus approx. 37%).

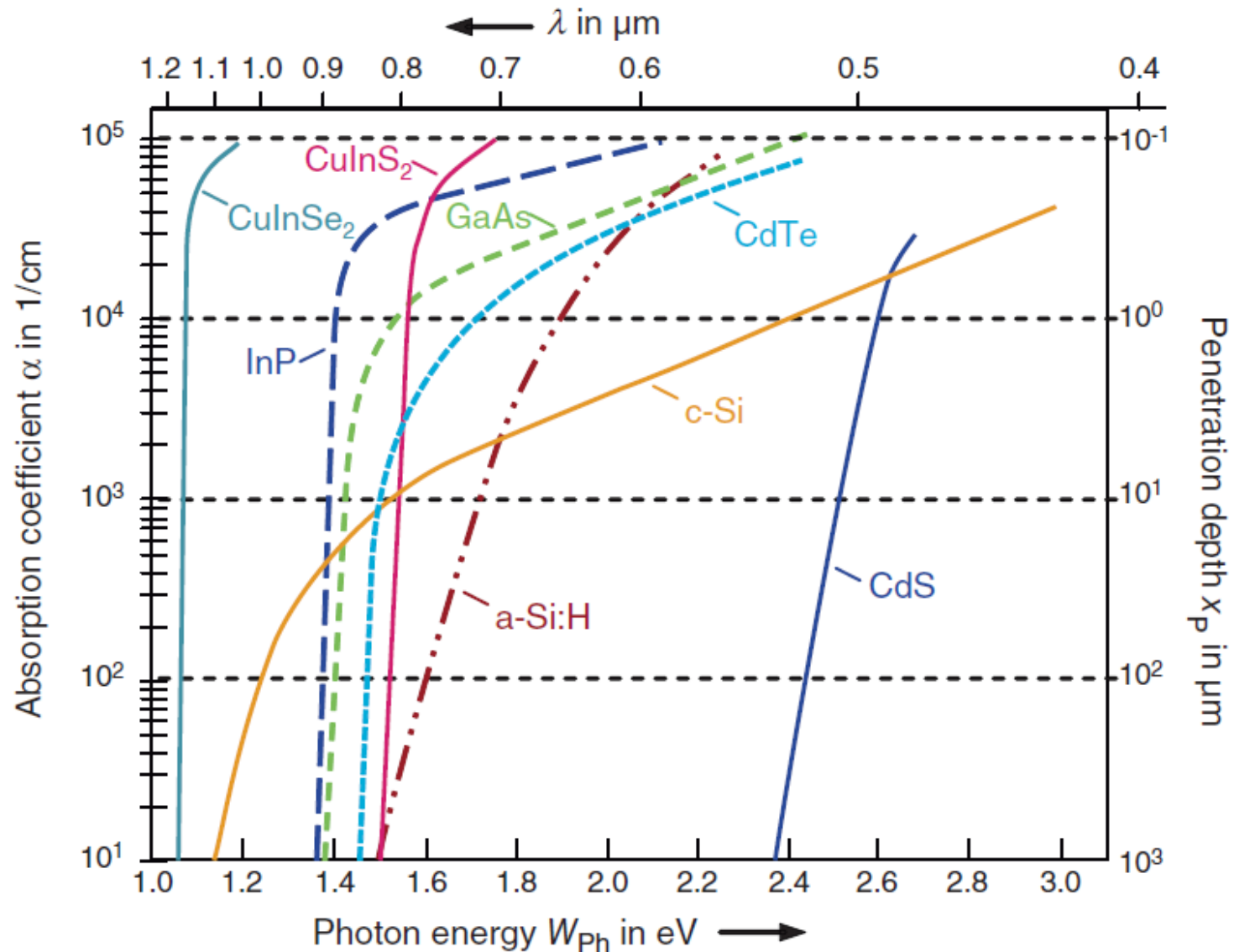$$x_P = \frac{1}{\alpha}$$

3.6.1 Phenomenon of Light Absorption

Figure 3.22 Absorption coefficient of different semiconductor materials in dependence of the photon

3.6.2 Light Reflection on Surfaces

3.6.2.1 Reflection Factor

Consider two materials with different *refractive indices* n_1 and n_2. The **refractive index n** of a material indicates by which factor the speed of light is reduced compared to its speed in a vacuum: $n = c_0/c$. If the ray of light falls on an interface between two materials then *reflection* is the result. The strength of the reflection is given by the **reflection factor R.**
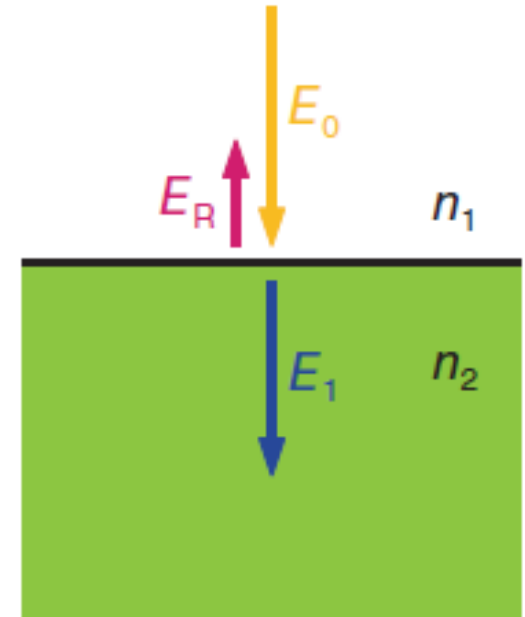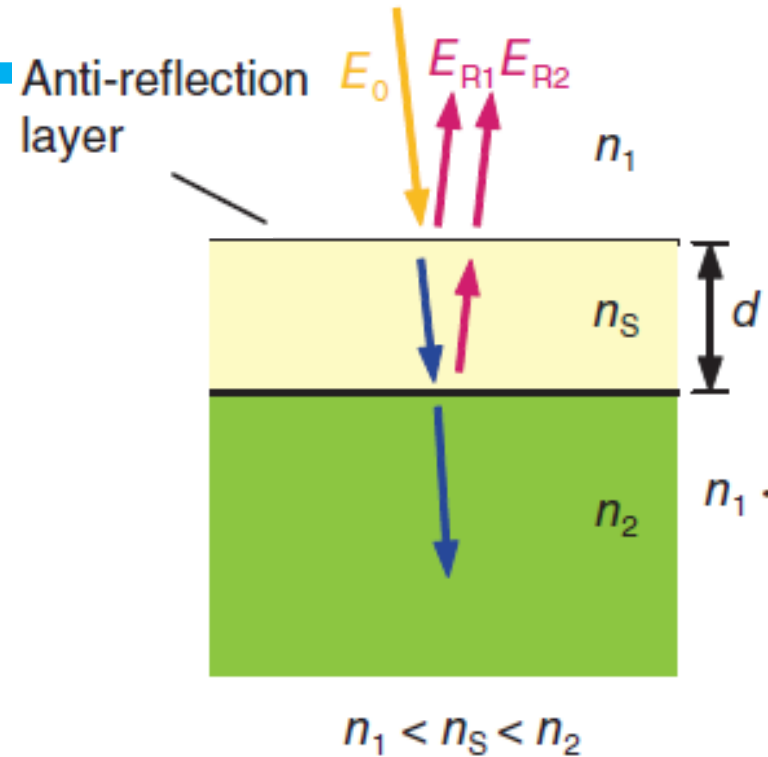
$$R = \frac{E_R}{E_0}$$

E_0 : incident irradiance
E_R : reflected irradiance

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

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

3.6.2.2 Anti-Reflection Coating

The incidental reflection must be reduced in order to achieve a high degree of efficiency in a solar cell. A standard means of doing this is **anti-reflection coating**.

$n_1 < n_S < n_2$

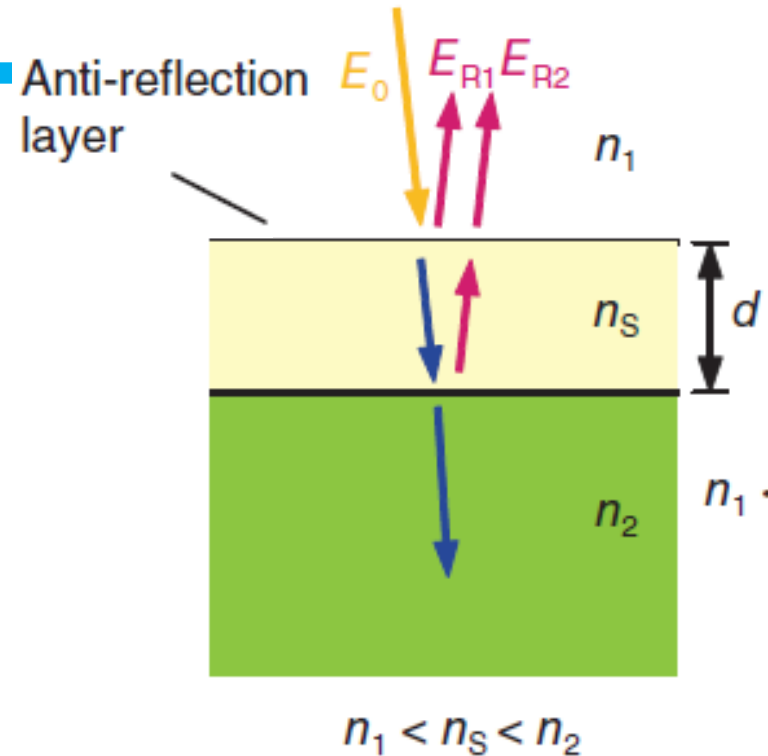# 3.6.2.2 Anti-Reflection Coating

The incidental reflection must be reduced in order to achieve a high degree of efficiency in a solar cell. A standard means of doing this is **anti-reflection coating**.

Figure shows the principle in the right-hand picture: a material of thickness d is inserted between the two media.

At the interface there is a reflective ray $\mathbf{R_1}$. There is also a reflection at the transition from $\mathbf{n_S}$ to $\mathbf{n_2}$ that appears at the surface with the strength $\mathbf{R_2}$. If the layer d is made so thick that the **ray 2** is displaced by **180°** phase compared to **ray 1** so that the reflective radiations cancel each other out due to interference.

$$d = \lambda/4$$

3.6.2.2 Anti-Reflection Coating

The incidental reflection must be reduced in order to achieve a high degree of efficiency in a
solar cell. A standard means of doing this is **anti-reflection coating**.

Figure shows the principle in the right-hand picture: a material of thickness **d** is inserted between the two media.
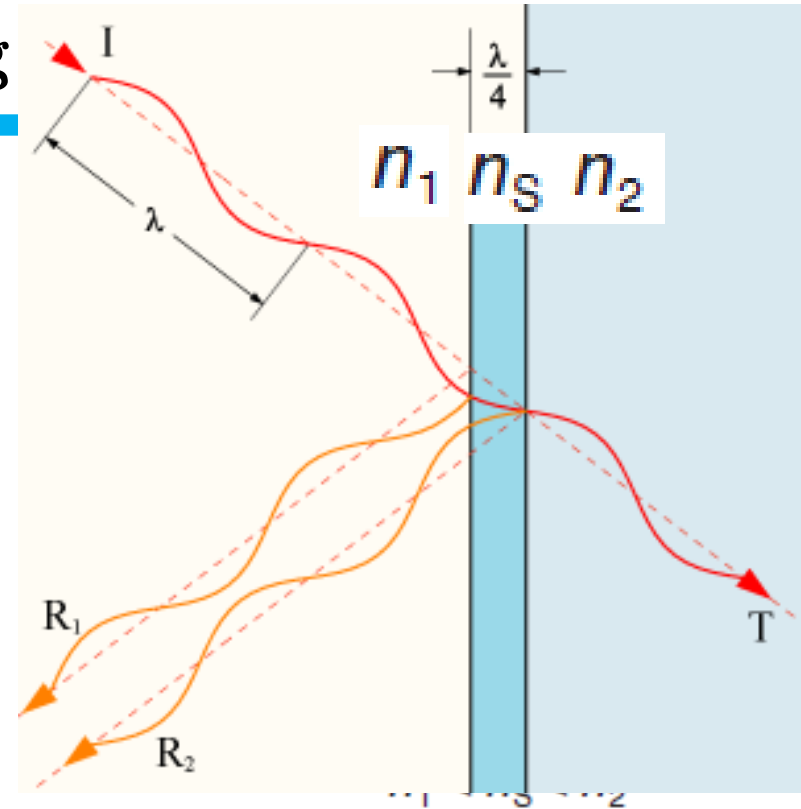
At the interface there is a reflective ray **R₁**. There is also a reflection at the transition from n_S to n_2 that appears at the surface with the strength **R₂**. If the layer **d** is made so thick that the **ray 2** is displaced by **180°** phase compared to **ray 1** so that the reflective radiations cancel each other out due to interference.

$$d = \lambda / 4$$

End of Solar Energy—Semiconductor Part 2 Course Work