1. Light absorption in materials and excess carrier generation

Photon energy $h\nu = hc/\lambda$ (h is the Planck constant)

photon momentum ≈ 0

Light is absorbed in the material.

$\Phi(x)$ is the light intensity $\qquad \Phi(x) = \Phi_0 \exp(-\alpha x) = \Phi_0 \exp\left(-\dfrac{x}{x_L}\right)$

$\alpha = \alpha(\lambda)$ is the absorption coefficient

$x_L = \dfrac{1}{\alpha}$ is the so-called **absorption length** $\qquad \int\limits_0^{x_L} \Phi(x)dx = 0.68\int\limits_0^{\infty} \Phi(x)dx$

Absorption is due to interactions with material particles (electrons and nucleus).

If particle energy before interaction was W_1, after photon absorption is $W_1 + h\nu$

- **interactions with the lattice –results in an increase of temperature**

- **interactions with free electrons - results also in temperature increase**

- **interactions with bonded electrons- the incident light may generate some excess carriers (electron/hole pairs)**
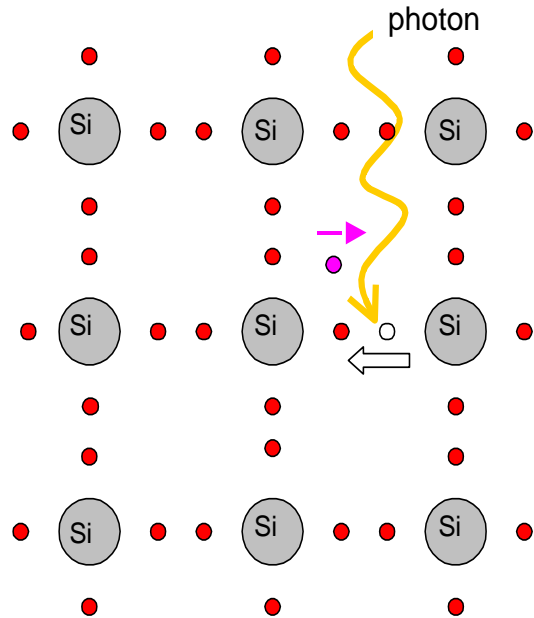
Photovoltaic Quantum generator
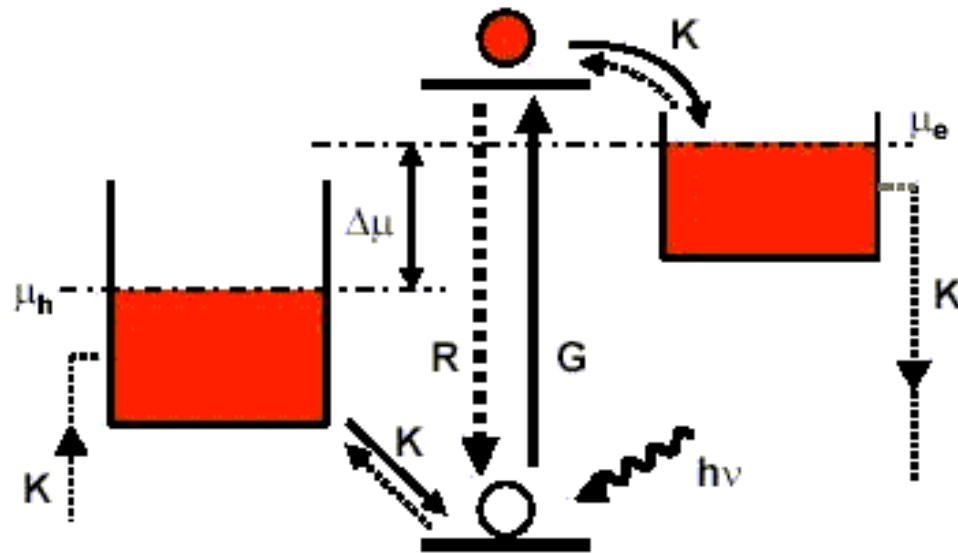
This process can be realised in different materials

Semiconductors

Before interaction with photon
(in thermodynamic equilibrium)

$$n_0 = N_c \exp\left(\frac{W_F}{kT}\right)$$

$$n_0 p_0 = n_i^2 = BT^3 \exp\left(\frac{-W_g}{kT}\right) = N_c N_v \exp\left(\frac{-W_g}{kT}\right)$$

photon

●   bonded electron
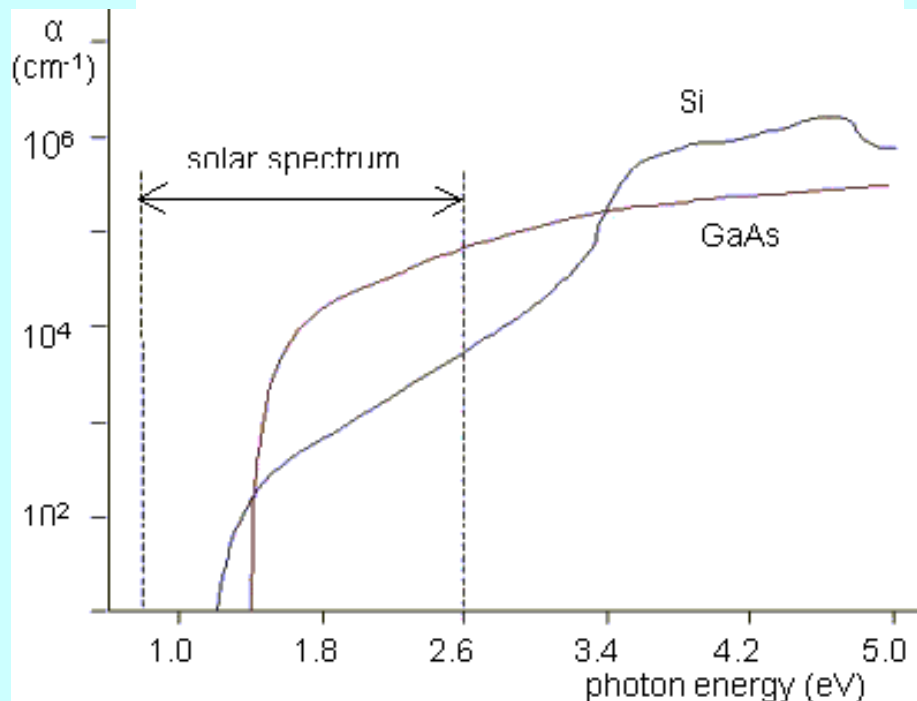
●   free electron

○   hole
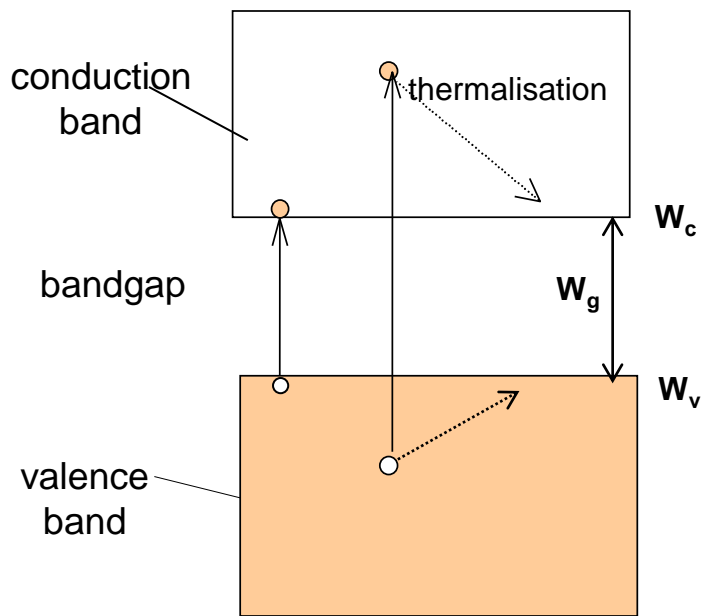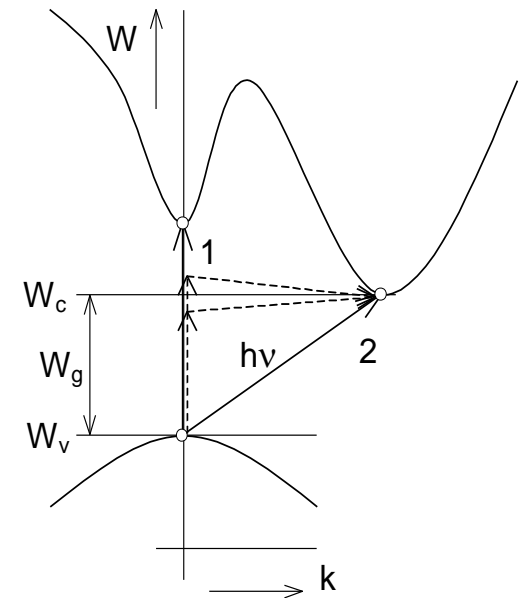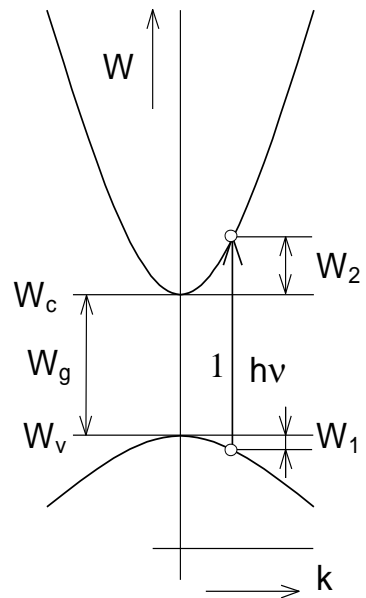
Si Si Si
Si Si Si
Si Si Si

After interaction with photons $h\nu > W_g$

$$n = n_0 + \Delta n, \quad p = p_0 + \Delta p \quad np > n_i^2$$

$\Delta n, \Delta p$ *excess carrier concentration*
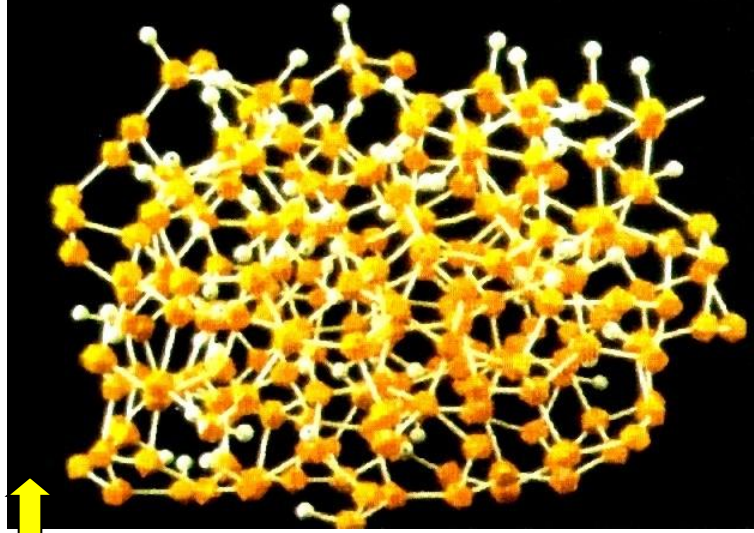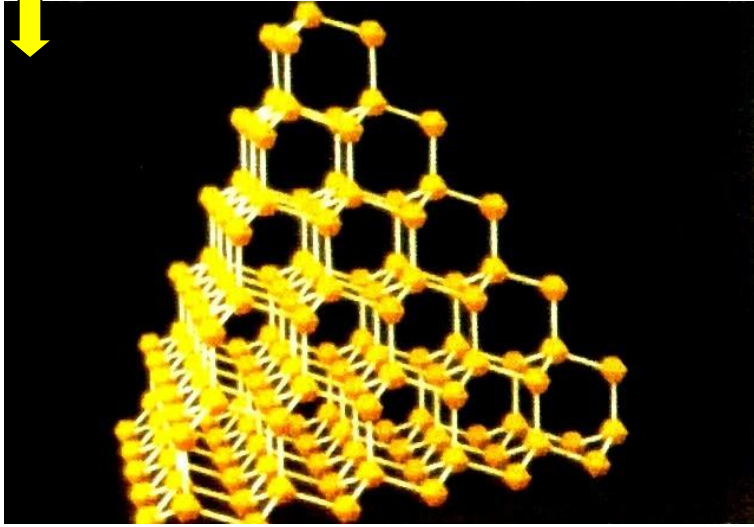*(no thermodynamic equilibrium)*

(*$\Delta n = \Delta p$*, because electron-hole pairs are generated)
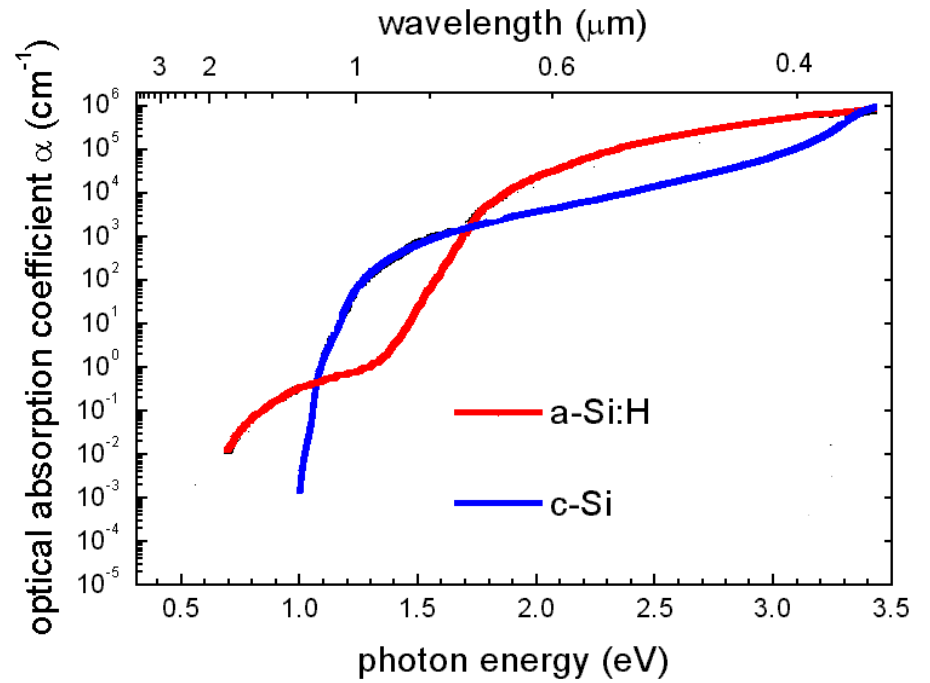
Excess carrier generation $h\nu \geq W_g$

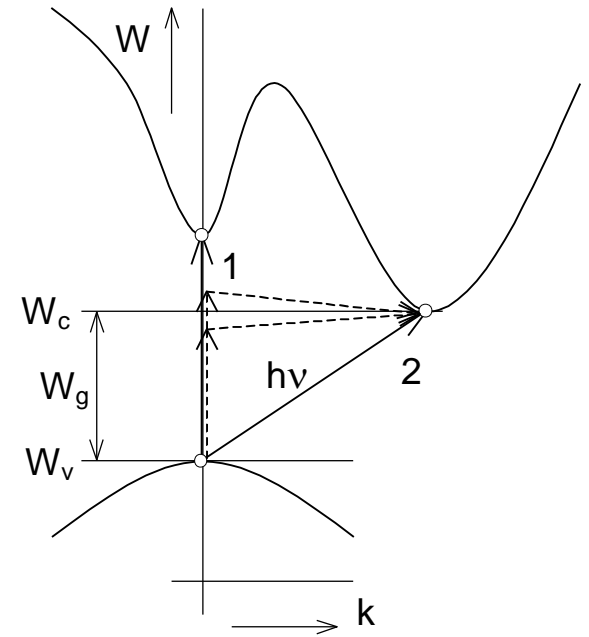conduction band

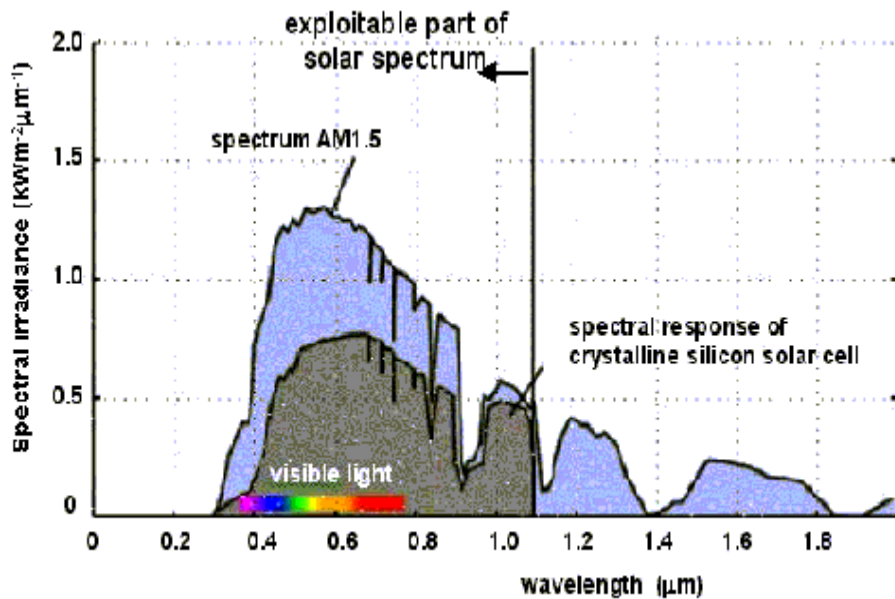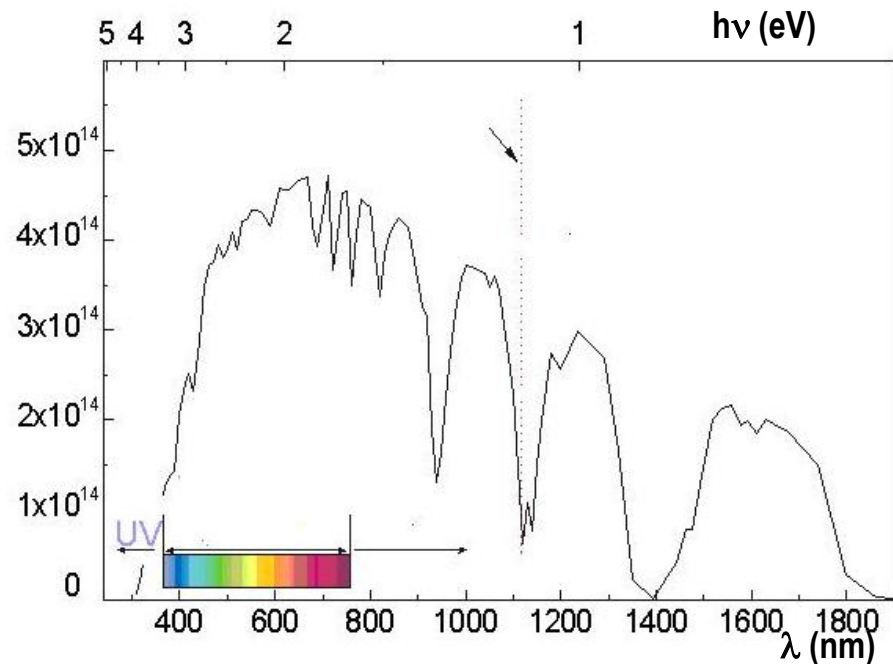thermalisation

bandgap

valence band

W_c

W_g

W_v

Silicon

crystalline

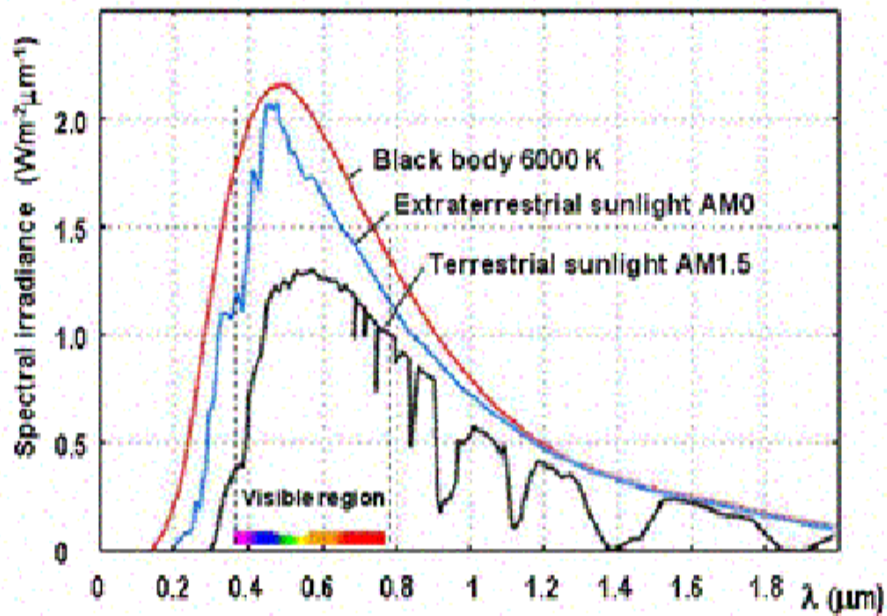
amorphous

Carrier generation with respect to solar spectrum

$$G(\lambda; x) = \left(\frac{d\Delta n}{dt}\right)_{gen} = \alpha(\lambda)\beta(\lambda)\Phi(\lambda; x) =$$

$$= \alpha(\lambda)\beta(\lambda)\Phi_0(\lambda)\exp(-\alpha(\lambda)x)$$

Total generation

$$G_{tot}(x) = \int_0^\infty G(\lambda; x)d\lambda = \int_0^\infty \alpha(\lambda)\beta(\lambda)\Phi(\lambda; x)d\lambda$$

Efficiency of excess carrier generation by solar
energy depens on the semiconductor band gap

Suitable materials
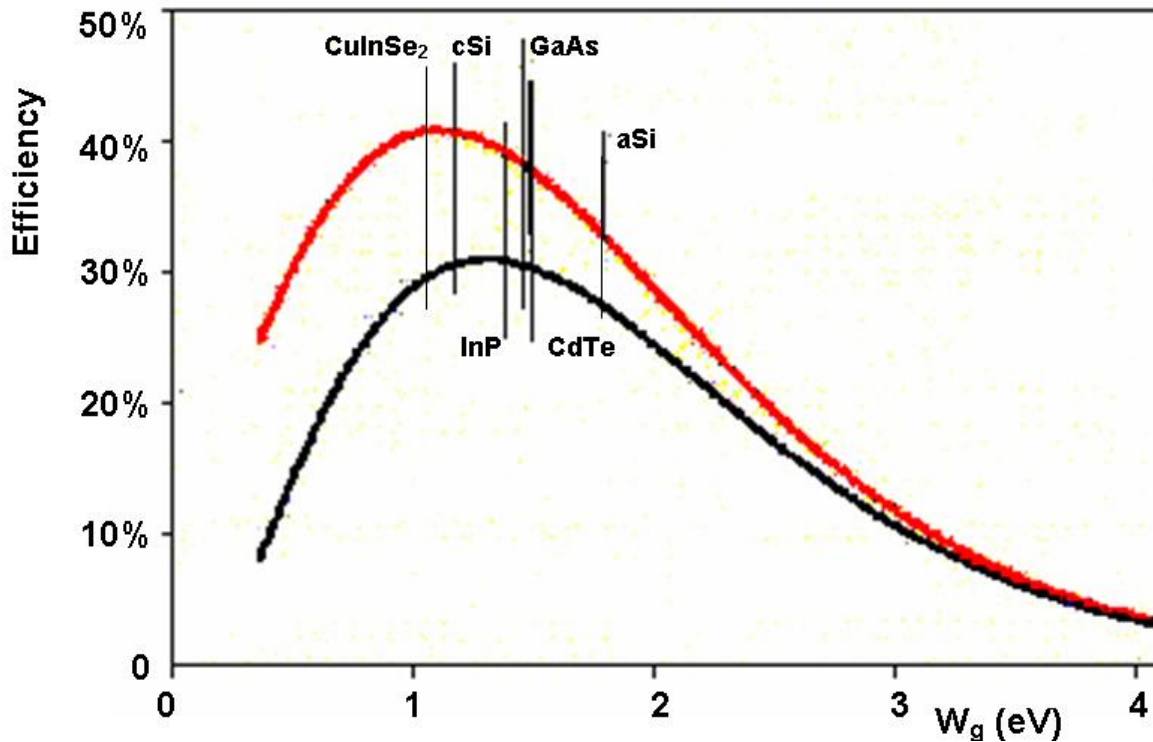
Silicon

GaAs

$CuInSe_2$
amorphous SiGe
CdTe/CdS

Carrier recombination
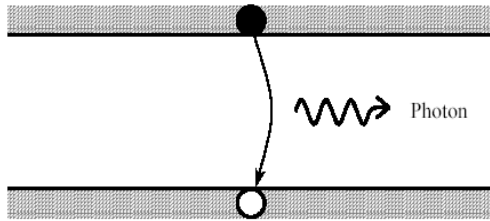
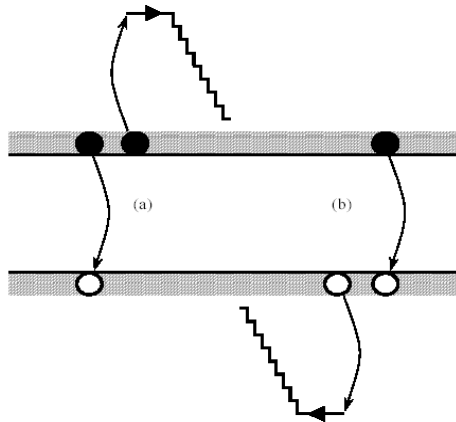$$\left(\frac{d\Delta n}{dt}\right)_{rec} = -\frac{\Delta n}{\tau}$$
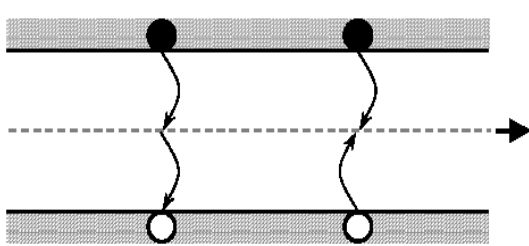
τ is carrier lifetime

irradiative recombination

$$\tau_r = \frac{1}{C_r N}$$

Auger recombination

$$\tau_A = \frac{1}{C_{An} N_D^2}$$

recombination via local centres

$$\tau_t = \frac{1}{C_t N_t}$$

Resulting carrier lifetime

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_A} + \frac{1}{\tau_t}$$

Excess carrier concentration

Diffusion current is connected with carrier concentration gradient

$$J_{ndif} = qD_n \frac{dn}{dx} \qquad D_n = kT\mu_n/q \qquad\qquad J_{pdif} = -qD_p \frac{dp}{dx} \qquad D_p = kT\mu_p/q$$

Continuity equations

$$\frac{\partial n}{\partial t} = G_n - \frac{\Delta n}{\tau_n} + \frac{1}{q}\frac{d}{dx}J_n \qquad\qquad\qquad \frac{\partial p}{\partial t} = G_p - \frac{\Delta p}{\tau_p} - \frac{1}{q}\frac{d}{dx}J_p$$

usually $\tau_n = \tau_p = \tau$

In the dynamic equilibrium $\quad \dfrac{\partial n}{\partial t} = 0$

$$\frac{d^2\Delta n}{dx^2} = \frac{\Delta n}{L_n^{\,2}} - \frac{G(\lambda; x)}{D_n} \qquad\qquad\qquad \frac{d^2\Delta p}{dx^2} = \frac{\Delta p}{L_p^{\,2}} - \frac{G(\lambda; x)}{D_p}$$

$L_n = \sqrt{D_n\tau}$ electron diffusion length $\qquad\qquad L_p = \sqrt{D_p\tau}$ hole diffusion length

Excess carrier concentration can be found solving continuity equations
under proper boundary conditions

Electrical neutrality is in homogeneous semiconductor $\Delta n = \Delta p \Rightarrow$ no potencial difference

To separate excess carrier generated, an **inhomogeneity with a strong internal electric field** must be created
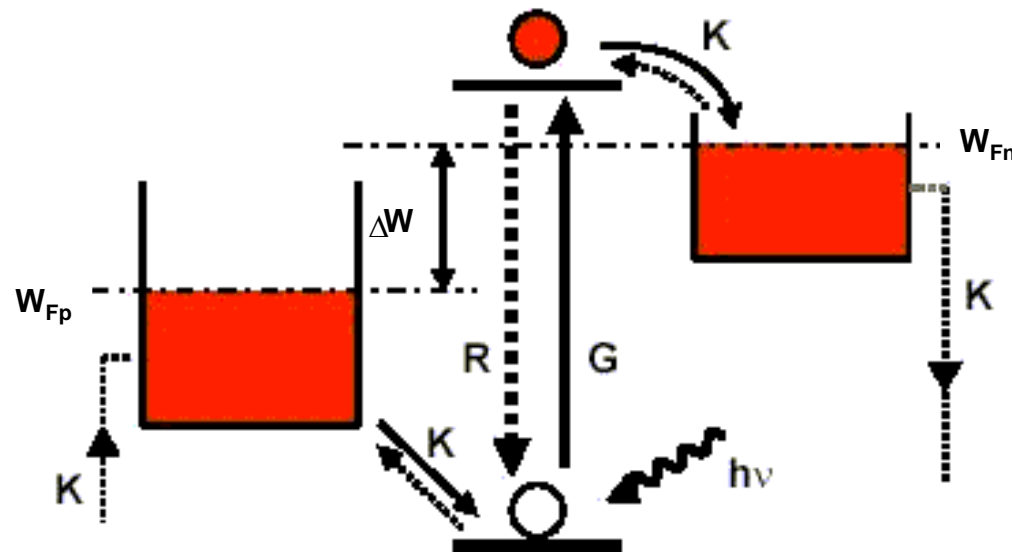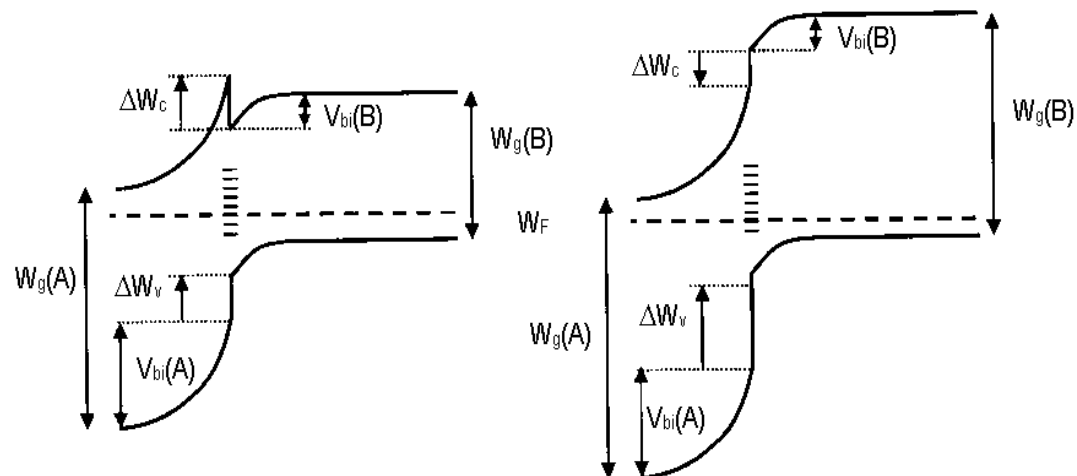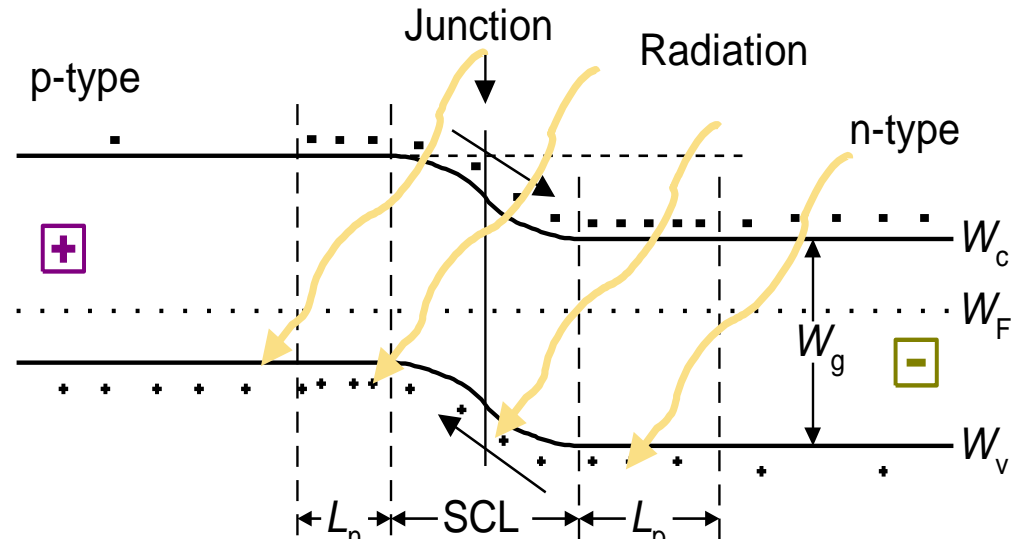
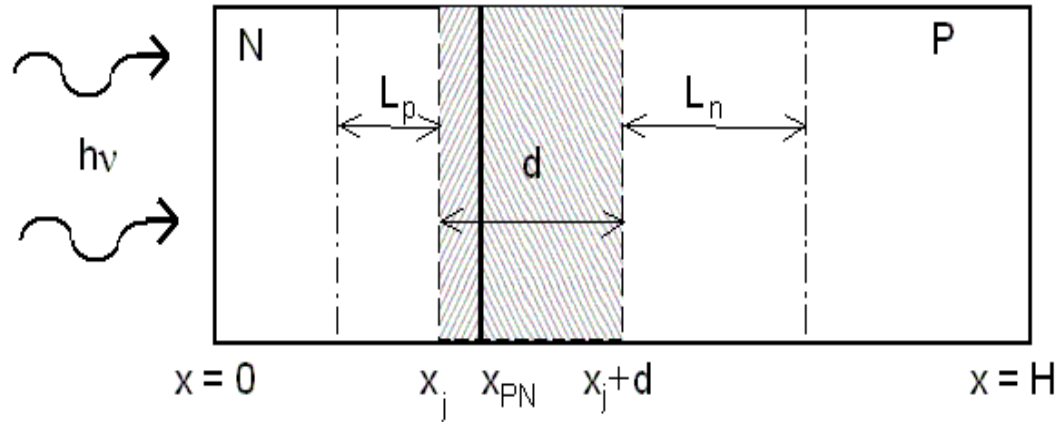# Photovoltaic effect and basic solar cell parameters

To obtain a potential difference that may be used as a source of electrical energy, an inhomogeneous structure with internal electric field is necessary.

Suitable structures may be:
• PN junction
• heterojunction (contact of different materials).
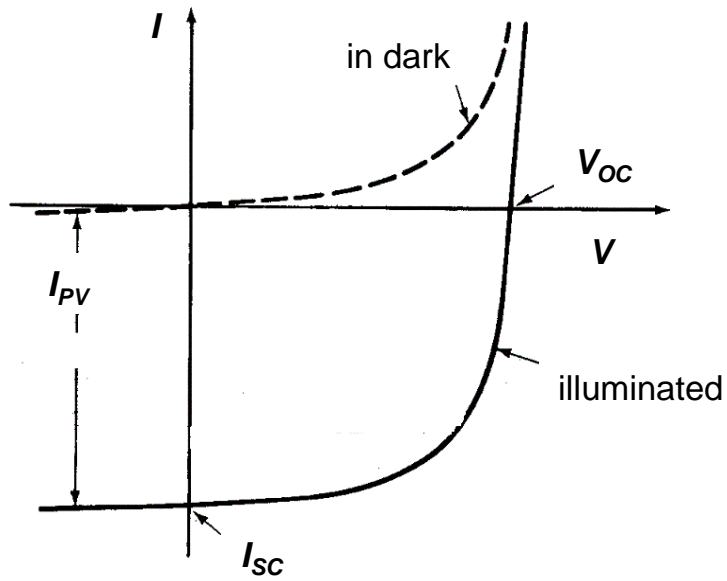
Principles of solar cell function

In the illuminated area generated excess carriers diffuse towards the PN junction. The density J_{FV} is created by carriers collected by the junction space charge region
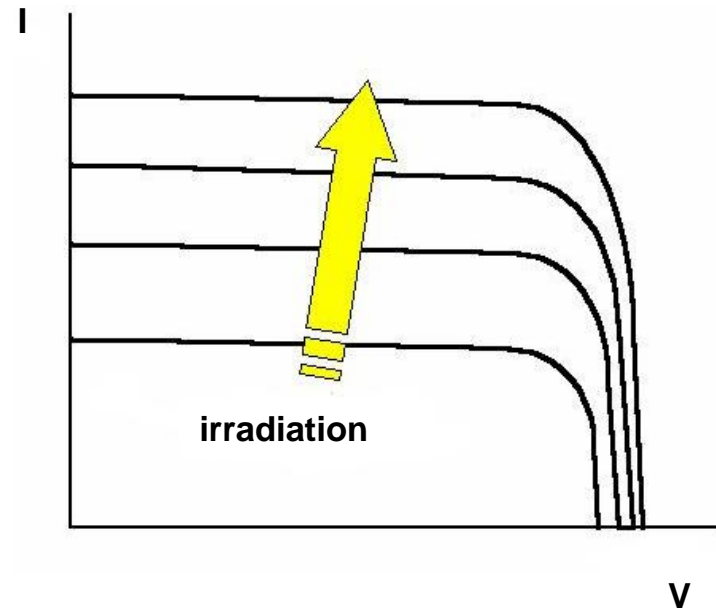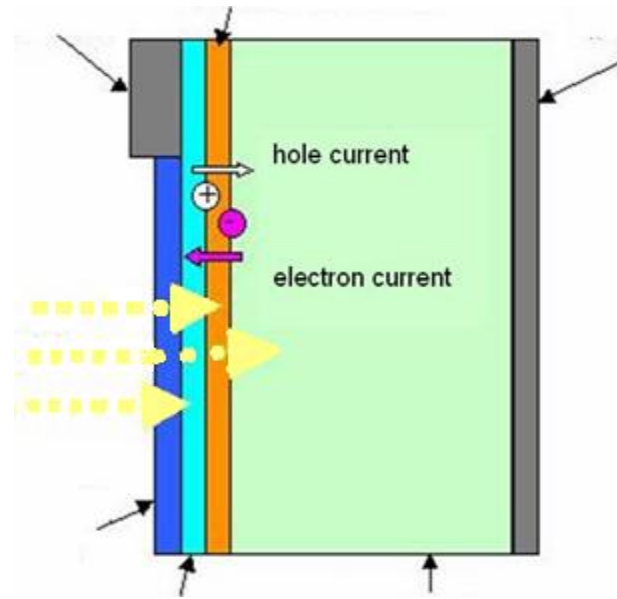
$$J_{PV}(\lambda) = J_{PVN}(\lambda) + J_{PVP}(\lambda) + J_{OPN}(\lambda)$$

- in the N-type region
$$J_{PVN}(\lambda) = q\int_0^{x_j} G(\lambda)dx - q\int_0^{x_j} \frac{\Delta p}{\tau_p}dx - J_{sr}(0)$$

- in the P-type region
$$J_{PVP}(\lambda) = q\int_{x_j+d}^{H} G(\lambda)dx - q\int_{x_j+d}^{H} \frac{\Delta n}{\tau_n}dx - J_{sr}(H)$$

- in the PN junction space charge region
$$J_{OPN}(\lambda) \approx q\int_{x_j}^{x_j+d_j} G(\lambda)dx - q\int_{x_j}^{x_j+d_j} \frac{\Delta n}{\tau_{OPN}}dx$$

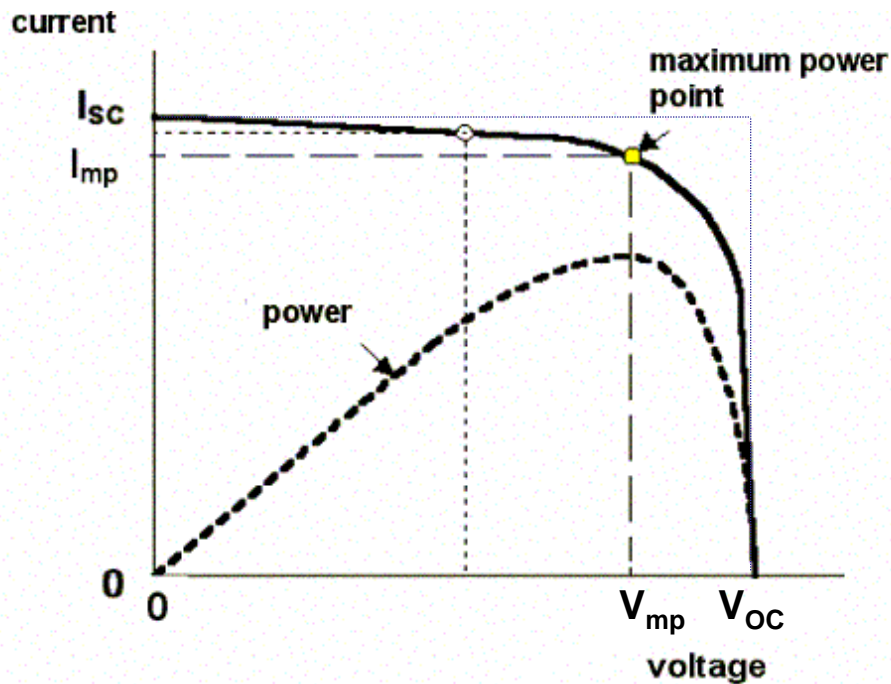**Illuminated PN junction:** **A supperposition of photo-generated current andPN junction (dark) I-V characteristic**

hole current

electron current

I

in dark

V_{OC}

V

I_{PV}

illuminated

I_{SC}

I

irradiation

V

Important solar cell electrical parameters

- open circuit voltage V_{OC},

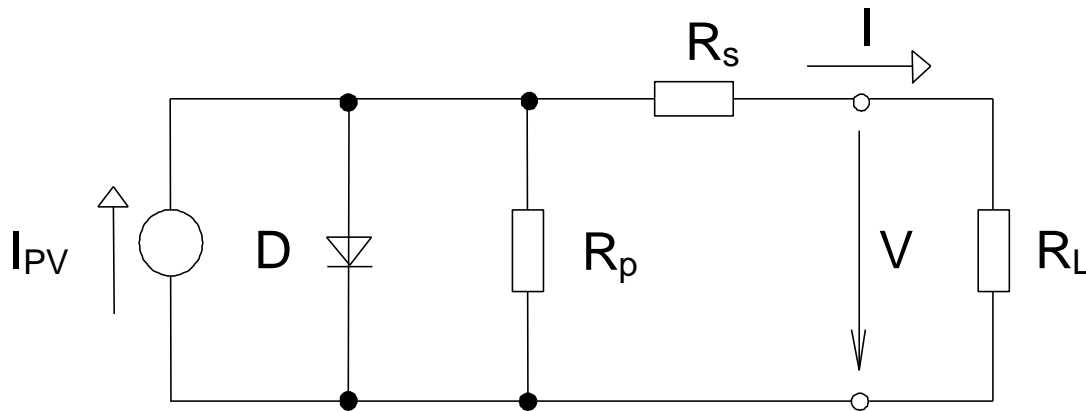- short circuit current I_{SC}

- maximum output power $V_{mp}I_{mp}$

- fill factor $\quad FF = \dfrac{V_{mp}I_{mp}}{V_{OC}I_{SC}}$

- efficiency $\quad \eta = \dfrac{V_{mp}I_{mp}}{P_{in}} = \dfrac{V_{OC}I_{SC}FF}{P_{in}}$

Parameters V_{OC}, I_{SC}, FF and η are usually given for standard conditions:

- **spectrum AM 1.5**

- **radiation power 1000 W/m²**

- **cell temperature 25°C.**

Modelling I-V characteristics of a solar cell

Parallel resistance R_p

Series resistance R_S

PN junction I-V characteristics

$$J = J_{01}\left[\exp\left(\frac{qV_j}{kT}\right) - 1\right] + J_{02}\left[\exp\left(\frac{qV_j}{2kT}\right) - 1\right]$$

$$J_{01} = n_i^2 q\left(\frac{D_n}{L_n}\frac{1}{p_{p0}} + \frac{D_p}{L_p}\frac{1}{n_{n0}}\right) \qquad J_{02} = \frac{qn_i d}{\tau_{sc}}$$

Output cell voltage $V = V_j - R_s I$

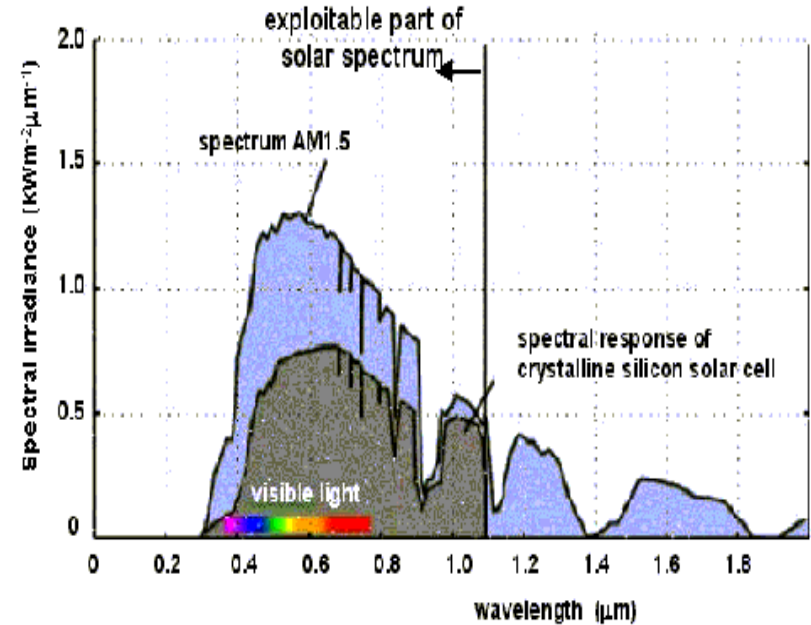A - total cell area A_{ill} – illuminated cell area

$$I = A_{ill}J_{PV} - AJ_{01}\left[\exp\left(q\frac{V + R_s I}{kT}\right) - 1\right] - AJ_{02}\left[\exp\left(q\frac{V + R_s I}{2kT}\right) - 1\right] - \frac{V + R_s I}{R_p}$$
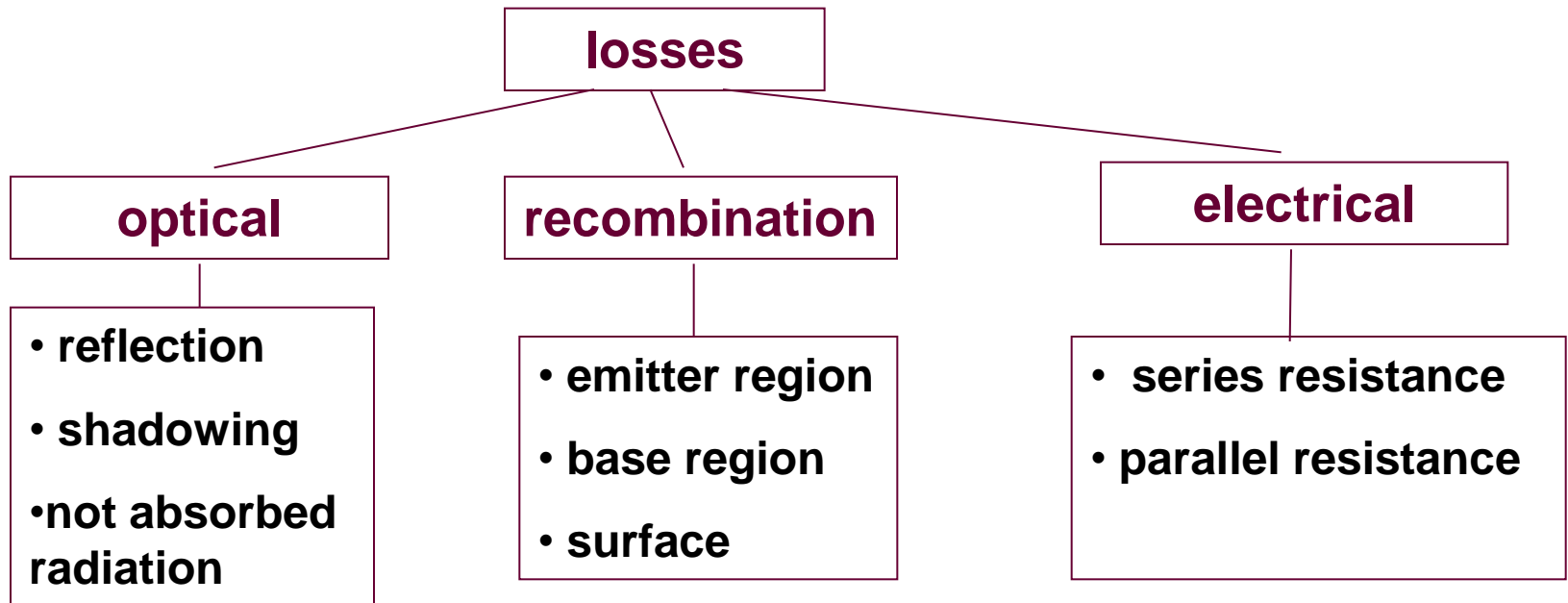
To maximise current density J_{PV} it is necessary

• **maximise generation rate G**

$$G(\lambda; x) = \left(\frac{d\Delta n}{dt}\right)_{gen} = \alpha(\lambda)\beta(\lambda)\Phi_0(\lambda)\exp\left(-\alpha(\lambda)x\right)$$

$$\Phi_0 = \Phi_{in}(1 - \mathcal{R})$$

• **minimise losses**

```
                    losses
          /           |            \
     optical    recombination    electrical
```

| optical	recombination	electrical
• reflection • shadowing •not absorbed radiation	• emitter region • base region • surface	• series resistance • parallel resistance

Optimising PN junction depth

The photo-current density J_{PV} consists from carriers collected by the electric field in the space charge region of the PN junction, i.e. from carriers generated in a distance of about diffusion length from the PN junction.
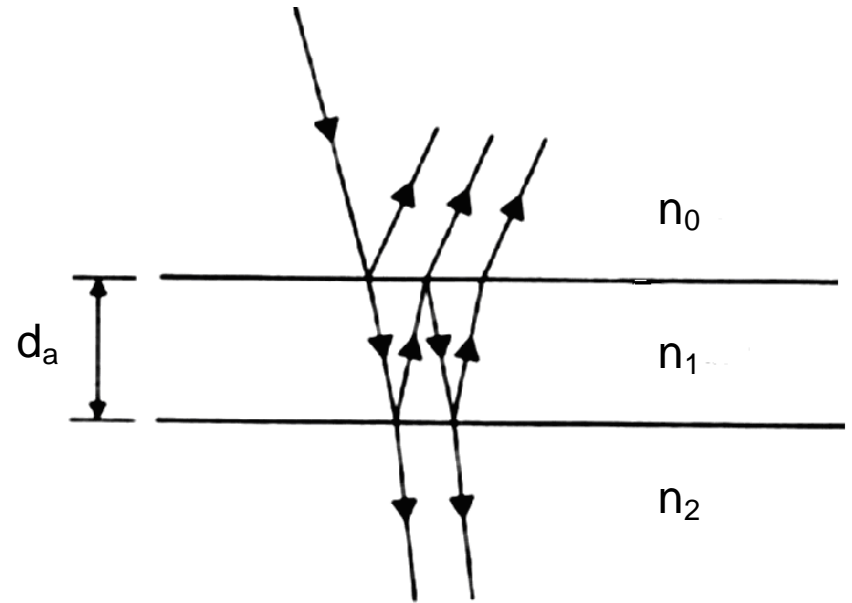
The PN junction depth x_j should be less than 0.5 μm (0.2 μm is desirable).
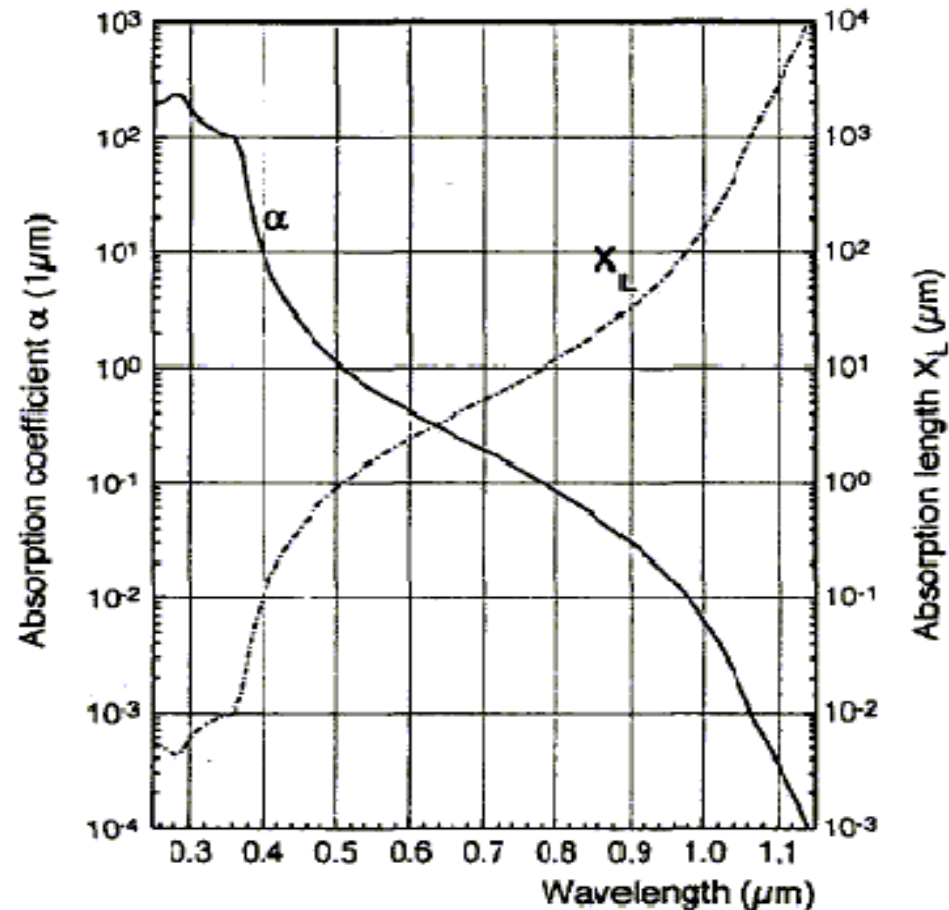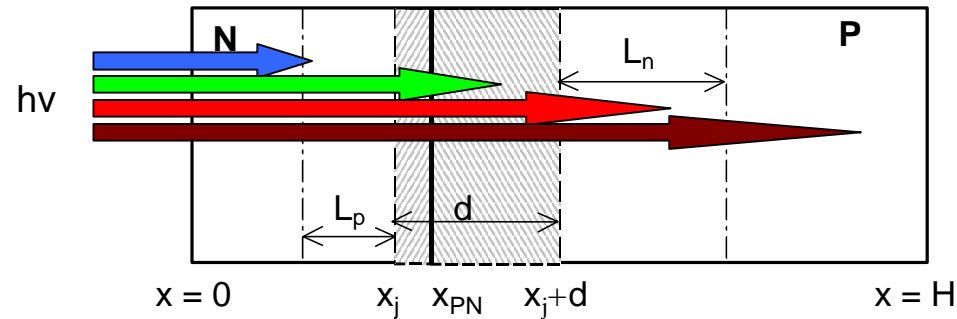
Antireflection coating

For a monochromatic light, the minimum reflexivity $\mathcal{R}_{min}$ occurs when the optical path is equal to a quarter of wavelength, i.e. the layer thickness is
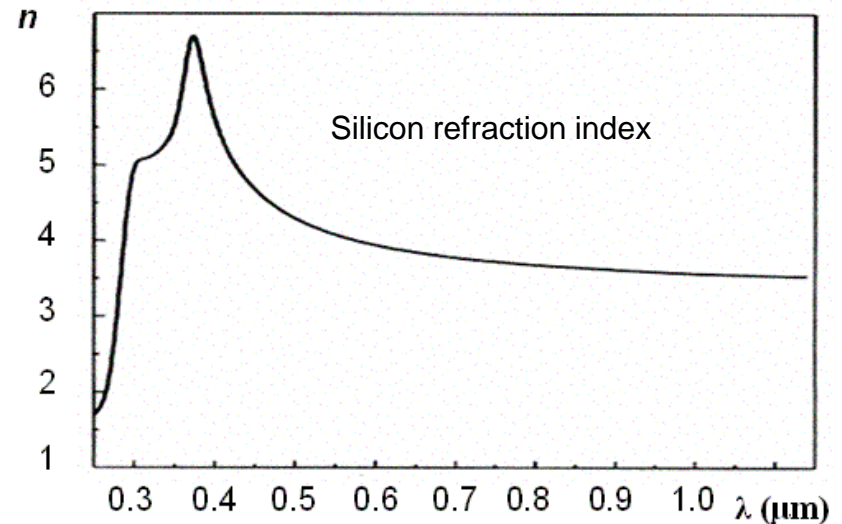
$$d_a = \frac{\lambda}{4n_1}$$

.

$$(n_1^2 + n_0 n_2)^2 \, \mathcal{R}_{min} = (n_1^2 - n_0 n_2)^2$$
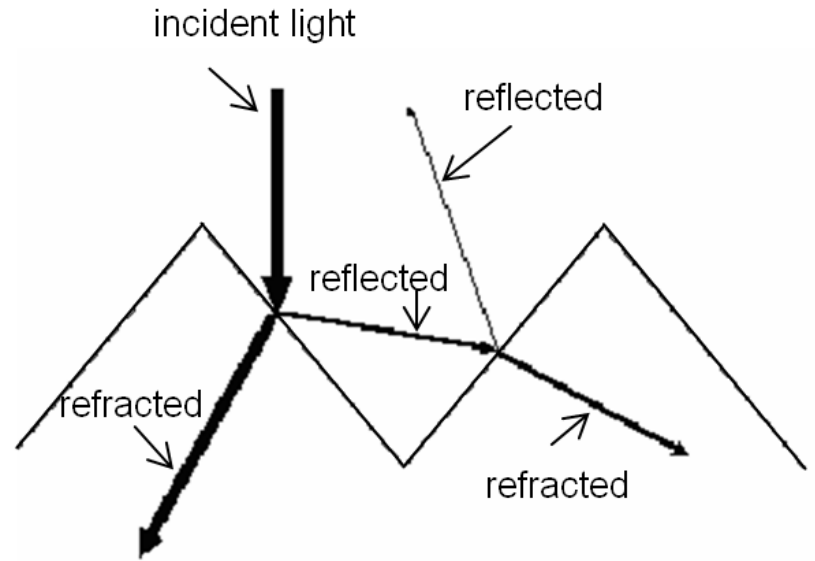
From that follows for $\mathcal{R}_{min} = 0$

$$n_1 = \sqrt{n_0 n_2}$$

Thin film material of $n_2 \cong 2$ is desirable for silicon solar cells (Si_3N_4 or TiO_2 layers of d $\cong$ 75 nm are usually used for antireflection coating).
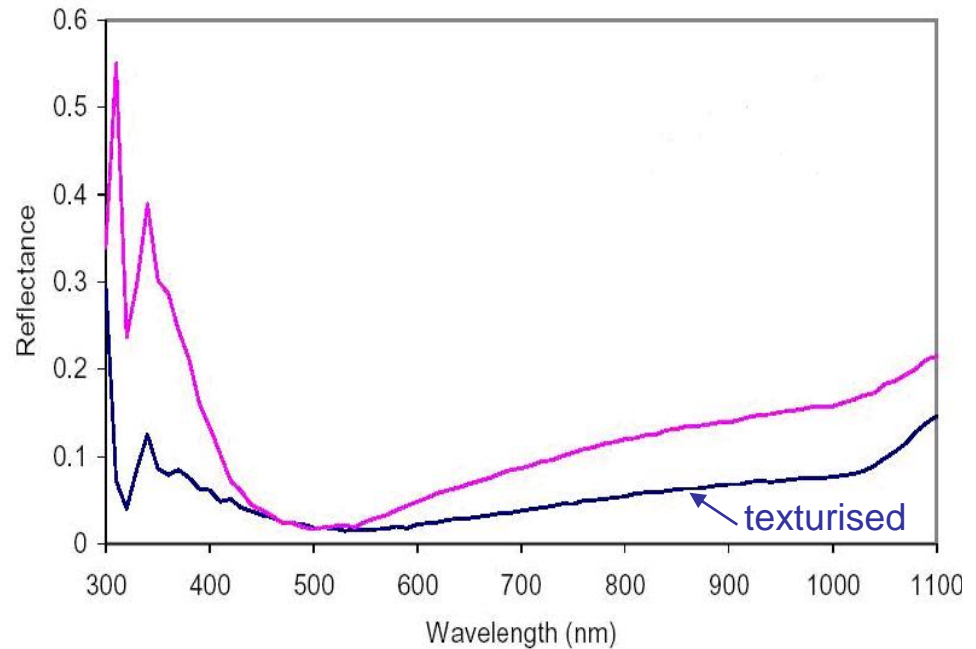

Silicon refraction index

Surface texturing

If the surface has a pyramidal structure it is possible to decrease reflection on about one third of that on a plane surface.
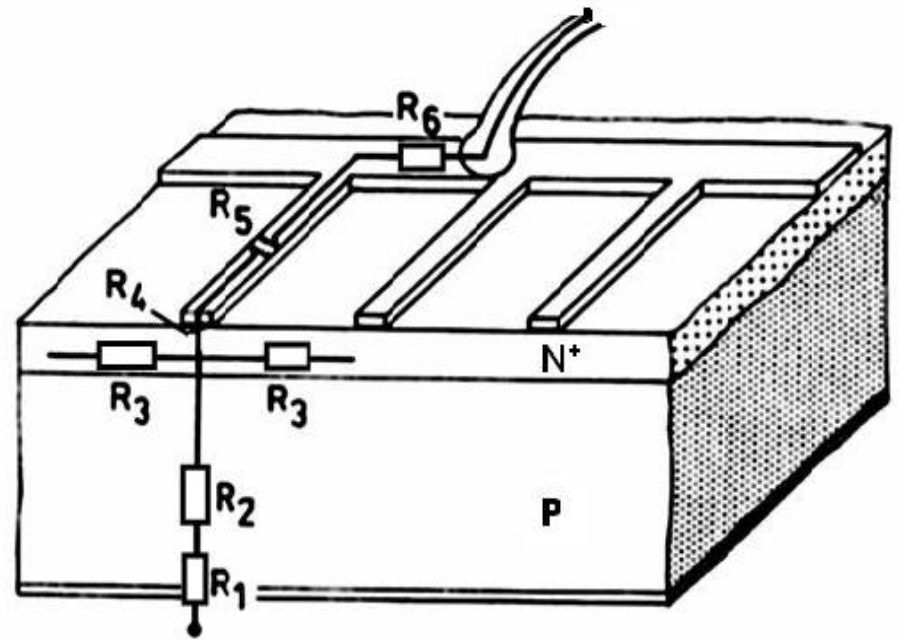

Both principles (surface texturing and antireflection coating) can be combined to minimise losses by surface reflection

Electrical losses

Series resistance R_s influences strongly solar cells efficiency

Series resistance R_s consists of:

·R_1 – contact metal-semiconductor on the back surface

·R_2 – base semiconductor material

·R_3 – lateral emitter resistance between two contact grid fingers

· R_4 – contact metal-semiconductor on the grid fingers

·R_5 – resistance of the grid finger

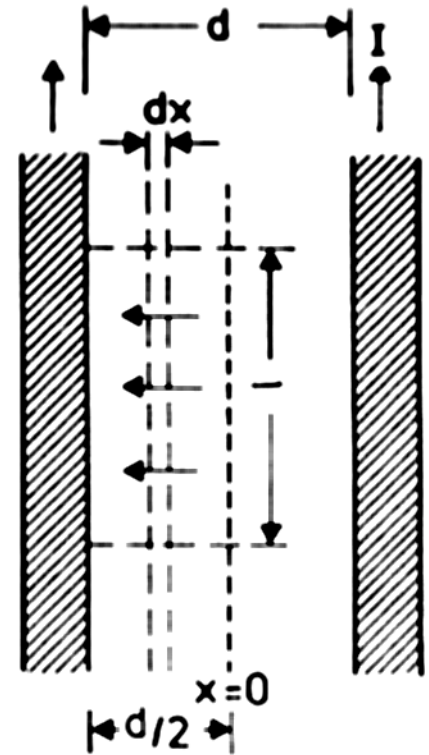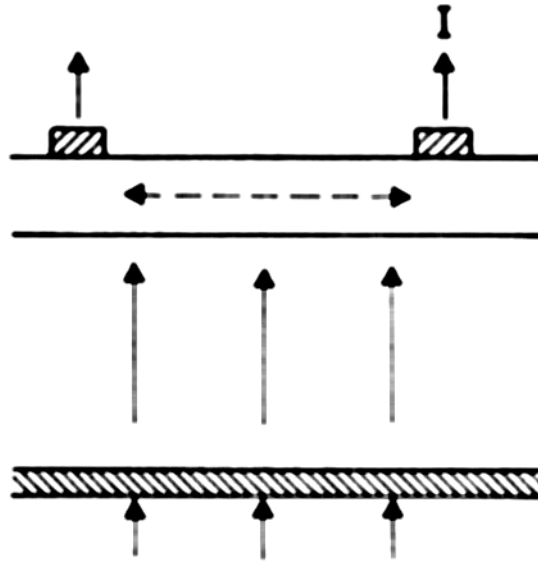·R_6 – resistance of the collector bus

$$R_2 = \rho_{Si} H / A$$

$$R_3 \sim \frac{\rho_N d}{x_j}$$

$$R_5 = \frac{\rho_M l}{3bh}$$

$$R_6 \sim \frac{\rho_M l_B}{h b_B}$$

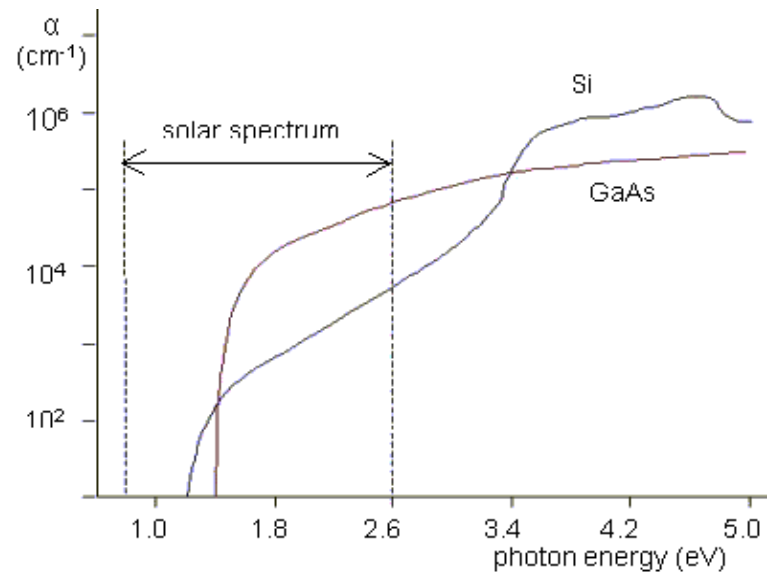R_3 – lateral emitter resistance between two contact grid fingers

$$R_3 \sim \frac{\rho_N d}{x_j}$$

Decrease of ρ_N is connected with increasing N_D $\Rightarrow$ Auger recombination rate increases

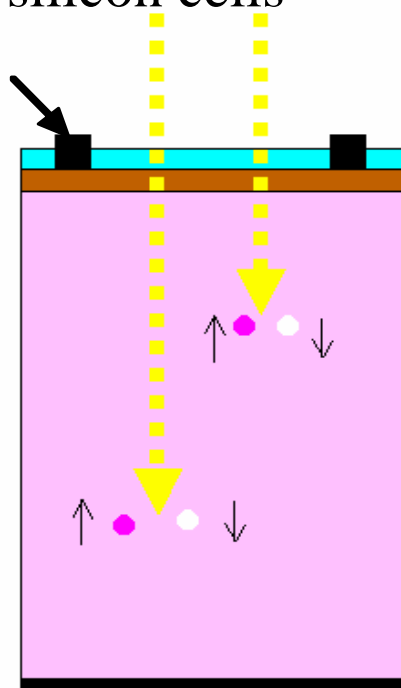Decrease of the finger distance d results in a decrease of illuminated area *Aill*

It is very important to optimise x_j

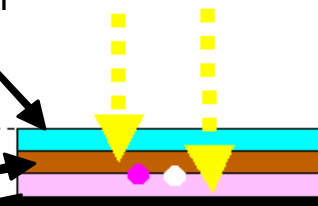**Basic types of solar cells:**

Crystalline silicon cells

Thin film cells

α
(cm⁻¹)

solar spectrum

Si

GaAs

10⁶

10⁴

10²

1.0   1.8   2.6   3.4   4.2   5.0
photon energy (eV)

contact

antireflection coating

N-type

P-type

Suitable materials

CuInSe₂

amorphous silicon

amorphous SiGe

CdTe/CdS