Solar cell operating principles

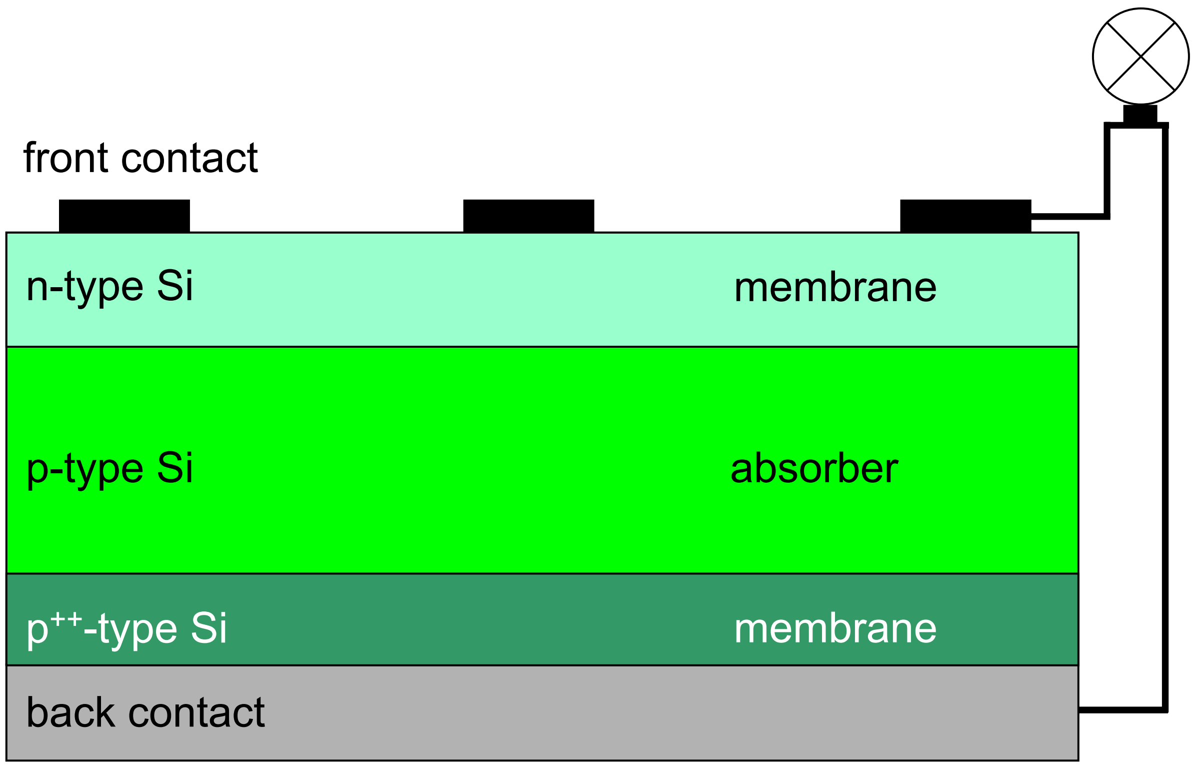
Solar cell operation is based on the photovoltaic effect:

The generation of a voltage difference at the junction of two different materials in response to visible or other radiation.

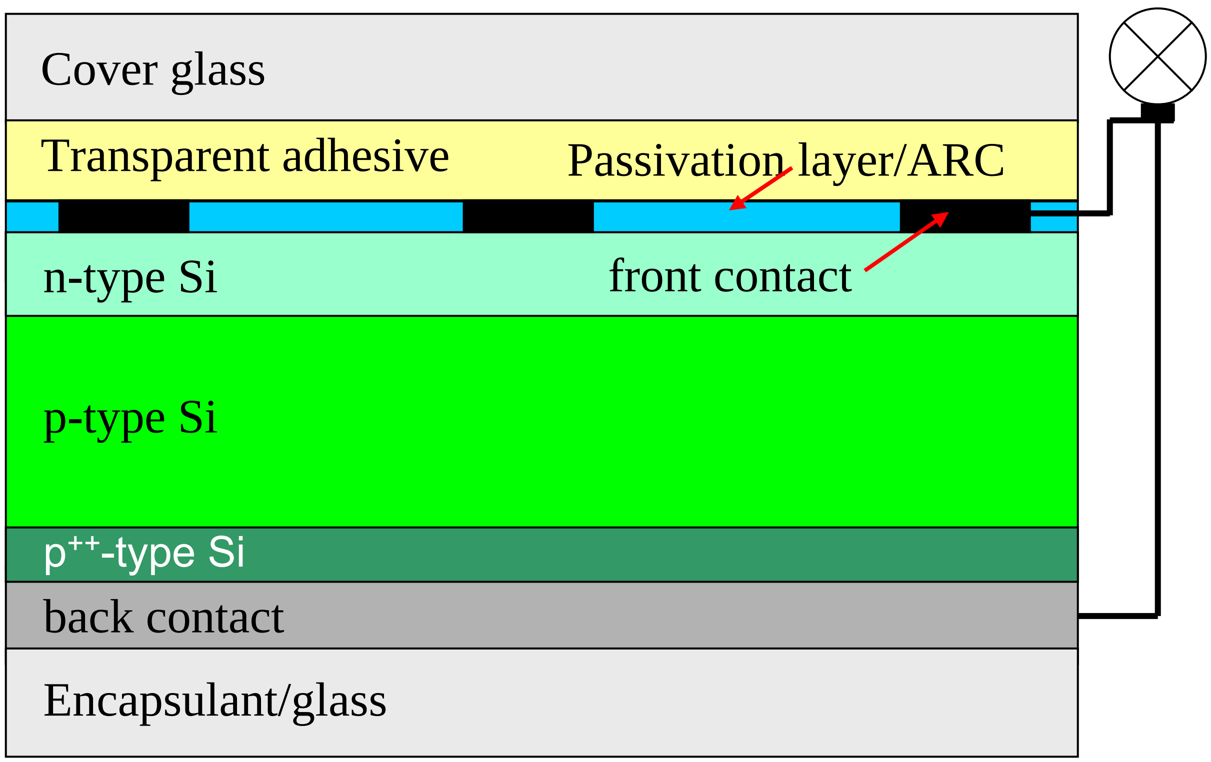
1. **Absorption** of light - **Generation** of charge carriers
2. **Separation** of charge carriers
3. **Collection** of the carriers at the electrodes

Semiconductor based solar cells

p-n junction



Solar cell materials



Semiconductors

General properties

Solid materials

- crystalline (regular atomic structure: long range order)
- amorphous (amorphous network: short range order)

Electrical conductivity based upon mobile electrons

- conductors ($\sigma > 10^4\ \Omega^{-1}\ cm^{-1}$)
- semiconductors ($10^4\ \Omega^{-1}\ cm^{-1} > \sigma > 10^{-8}\ \Omega^{-1}\ cm^{-1}$)
- insulators ($\sigma < 10^{-8}\ \Omega^{-1}\ cm^{-1}$)

Thermal behavior of electrical conductivity

Control of electrical conductivity by doping

Semiconductors

Important properties for a solar cell:

Optical properties

- band gap
- absorption coefficient
- index of refraction

Carriers concentration

- Concentration of dopant atoms

Transport properties

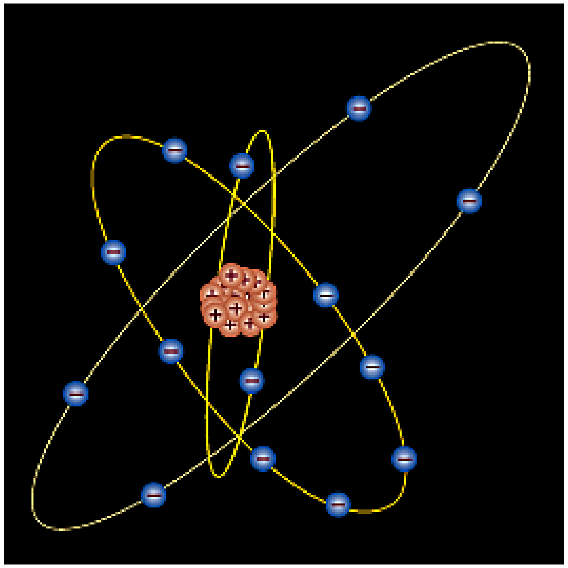
- mobility of carriers (drift)
- diffusion coefficient (diffusion)

Recombination

- lifetime of minority carriers and diffusion length
- distribution of density of energy states

Silicon

Atom



Atomic number: 14

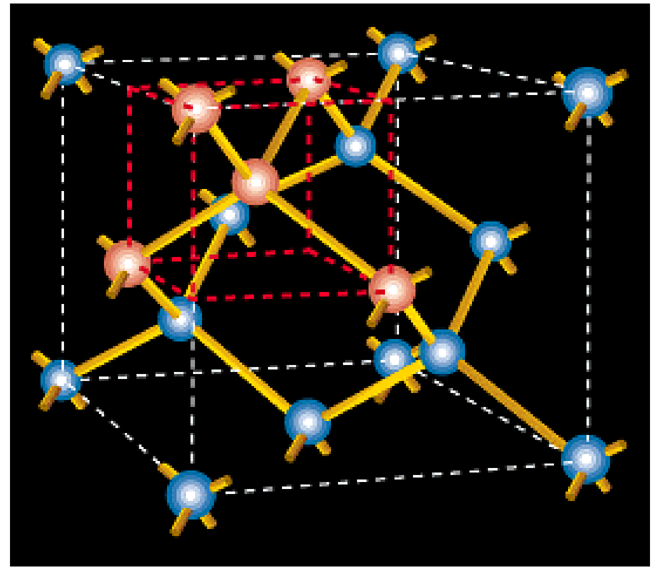
Atomic weight: 28.08

Ground state

electron configuration:

4 valence electrons

Crystal



Covalent bond

Basic unit: 5 Si atoms

Crystal lattice:

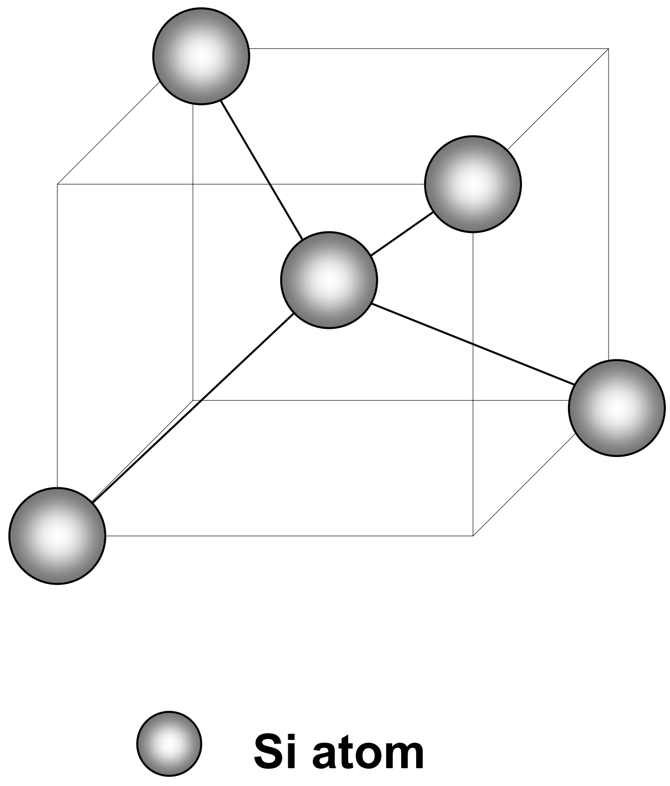
- diamond lattice unit
- **lattice constant 5.4 Å**

DIMES Delft Institute of Microsystems and Nanoelectronics

TU Delft Delft University of Technology

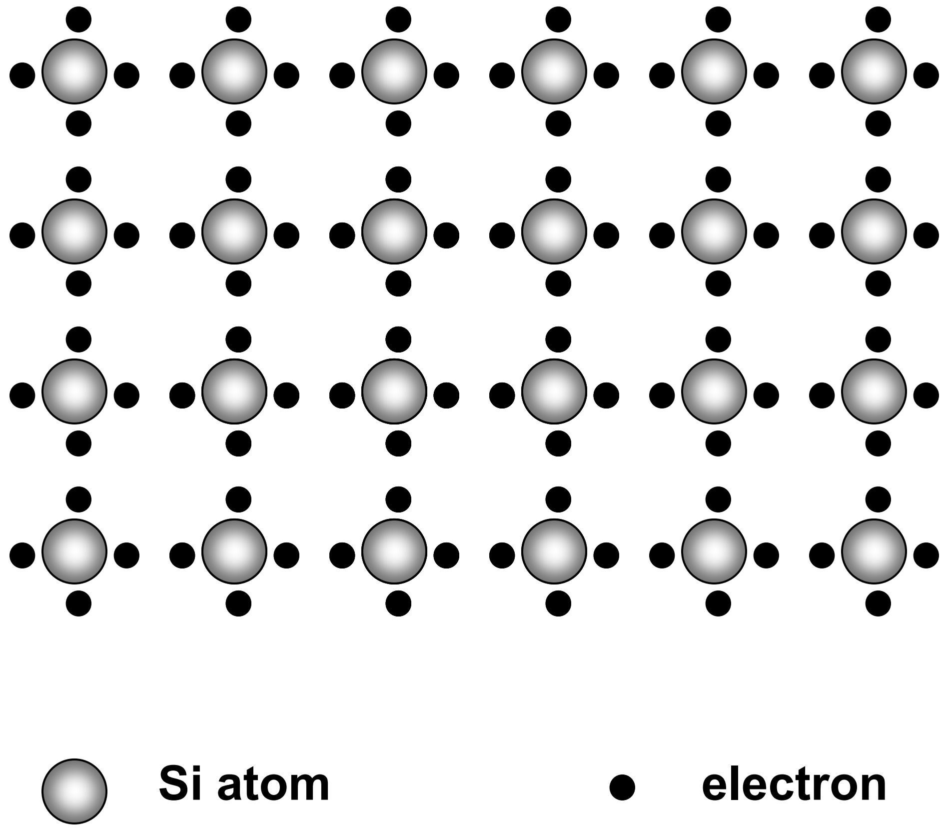
Silicon

Unit cell



Silicon

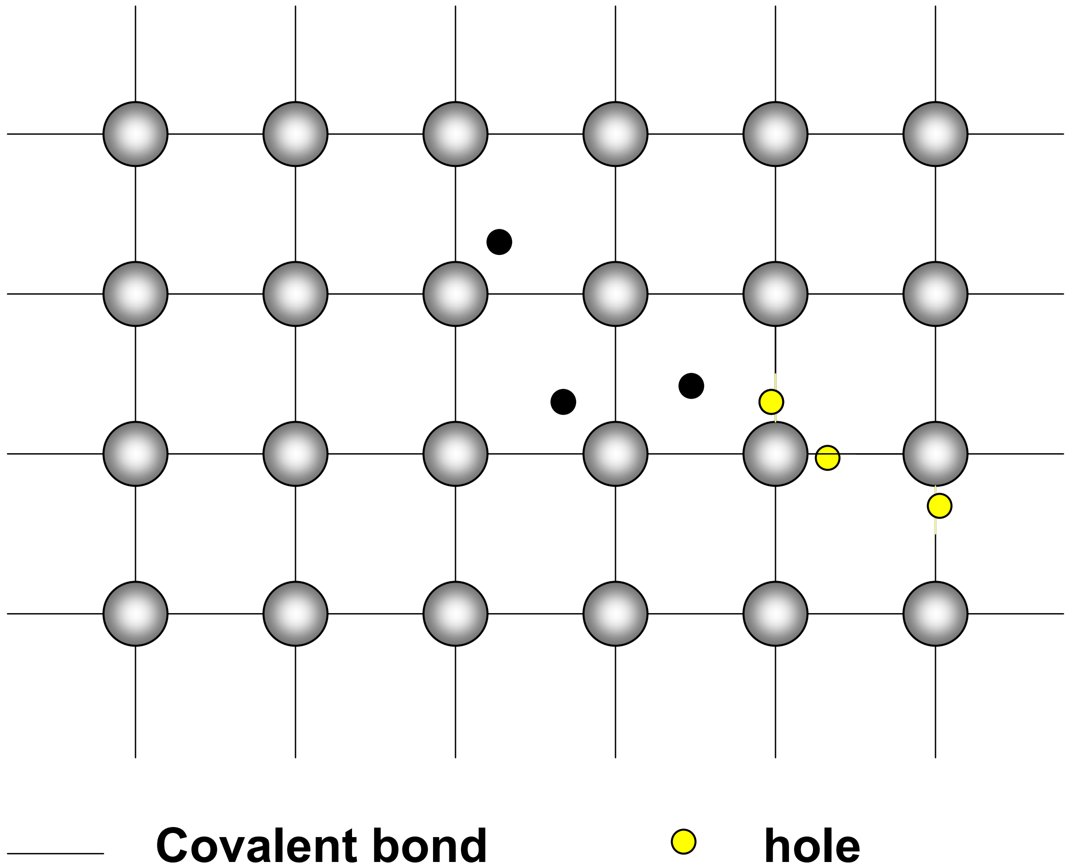
Bonding model



Silicon

Bonding model

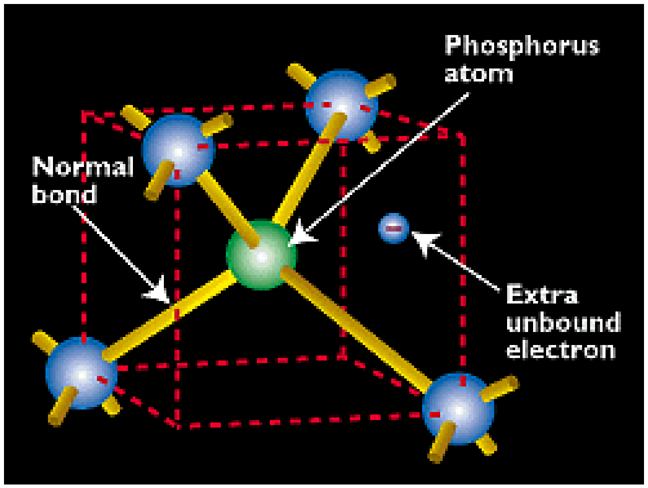
n = p



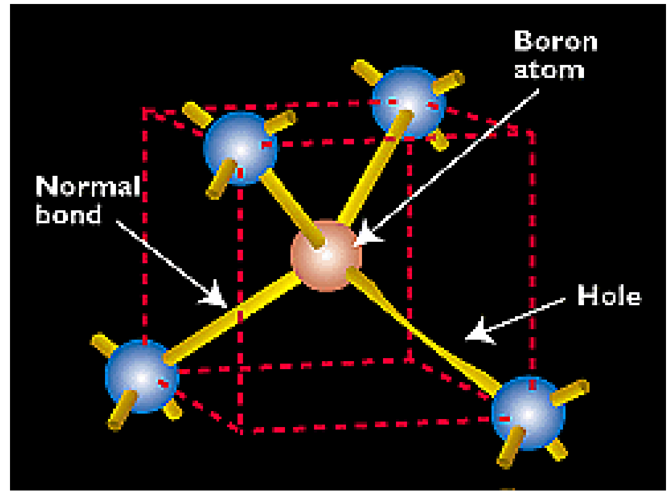
Covalent bond   hole

Silicon

Doping



n-type



p-type

Introducing Phosphorus

Phosphorus atom:

5 valence electrons

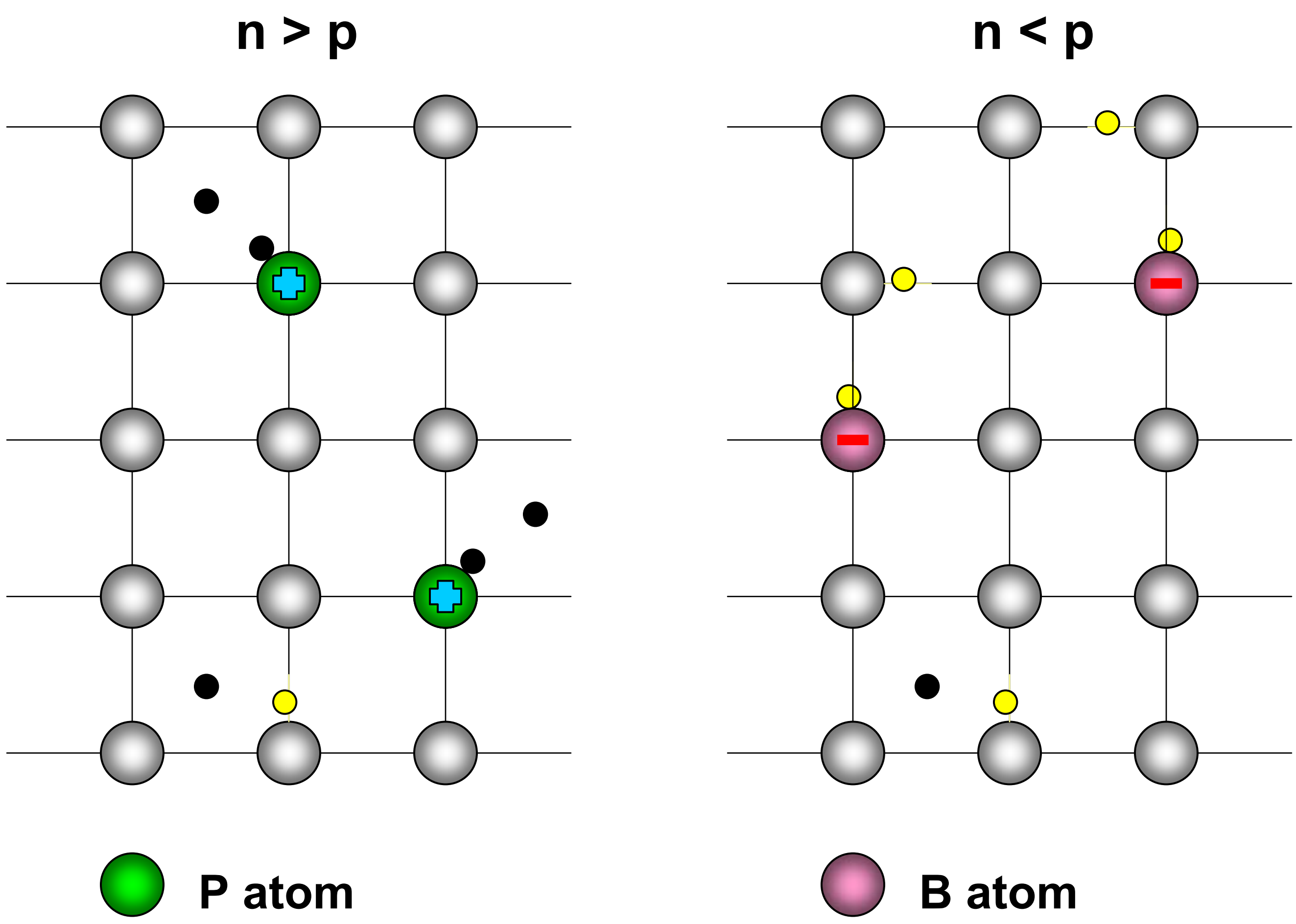
Introducing Boron

Boron atom:

3 valence electrons

Silicon

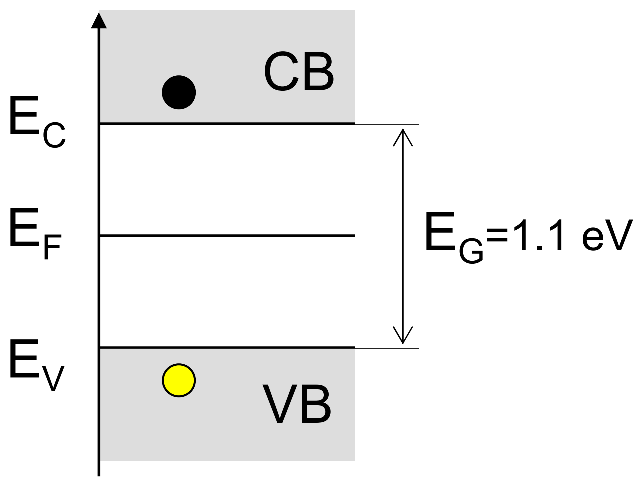
Bonding model



Silicon

Energy band diagram

A plot of the allowed electron energy states in a material as a function of position along pre-selected direction.



$$n = p = n_i$$

n_i = 1.5 ×10^{10} cm^{-3}

Fermi-Dirac distribution function

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

Concetrantion of electrons and holes

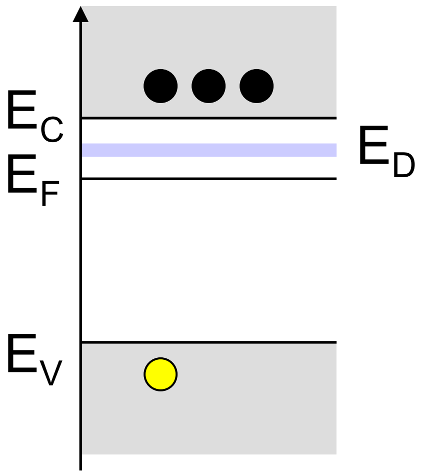
$$n = N_C \exp\left(-\frac{E_C - E_F}{kT}\right) \qquad N_C = 3.2\times10^{19}\ cm^{-3}$$

$$p = N_V \exp\left(-\frac{E_F - E_V}{kT}\right) \qquad N_V = 1.8\times10^{19}\ cm^{-3}$$

Silicon

n-type Si

$n > p \quad n \times p = n_i^2$



$n \approx N_D$ (T=300 K)

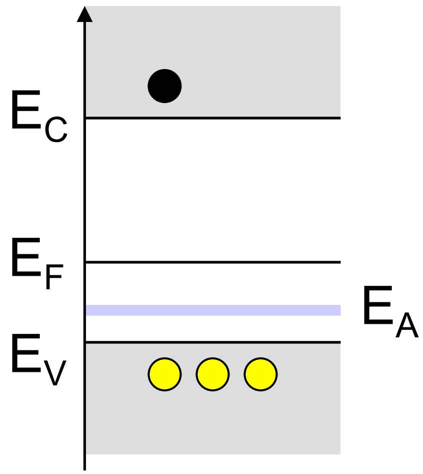
$N_D = n = 1.0 \times 10^{17}\ cm^{-3}$

$p = n_i^2/n = 2.25 \times 10^3\ cm^{-3}$

$E_C - E_F = 0.14\ eV$

p-type Si

$n < p \quad n \times p = n_i^2$



$p \approx N_A$ (T=300 K)

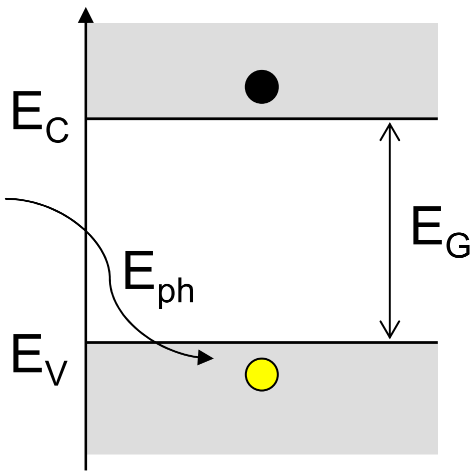
$N_A = p = 1.0 \times 10^{20}\ cm^{-3}$

$n = n_i^2/p = 2.25\ cm^{-3}$

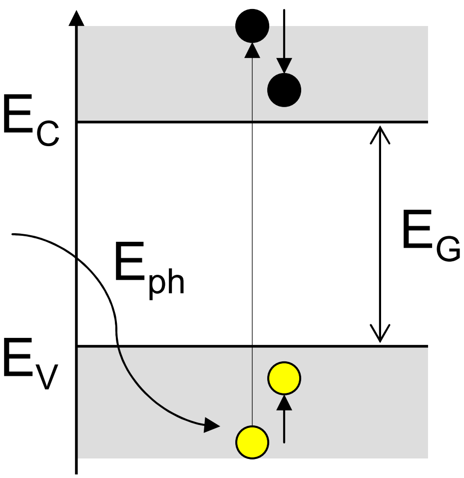
$E_F - E_V = 0.04\ eV$

Semiconductors

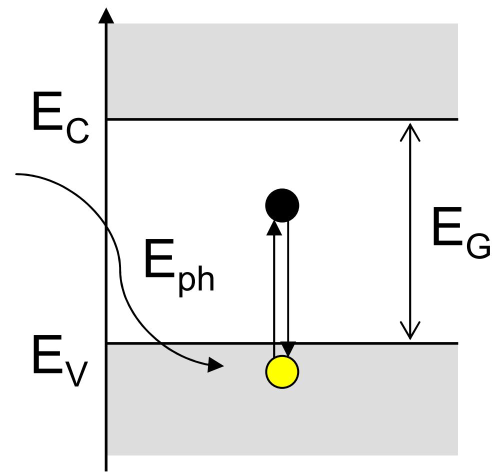
Band gap (E_G)



Creation of an electron-hole pair



Thermalization $E_{ph}>E_G$

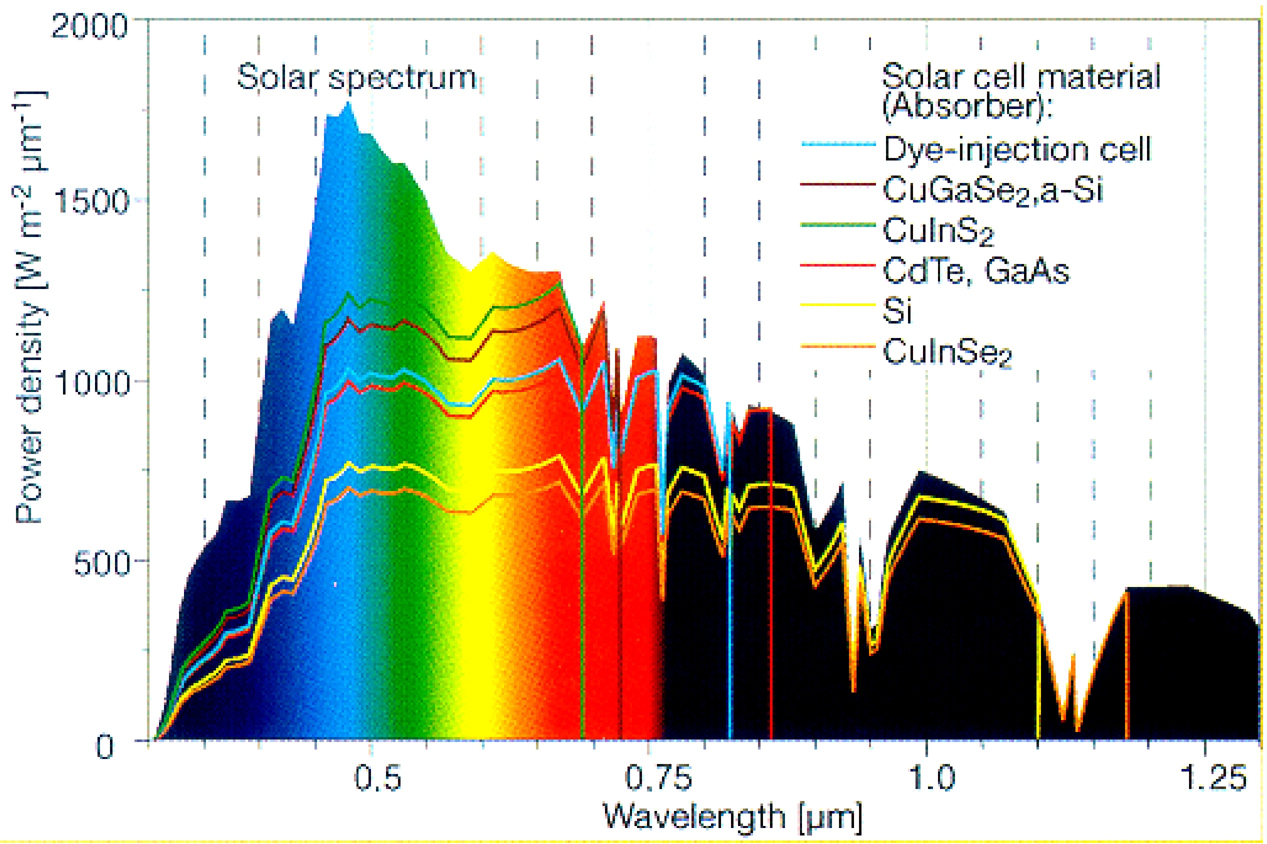


Non absorption $E_{ph}<E_G$

About 55% of solar energy is not usable by PV cells

Semiconductors

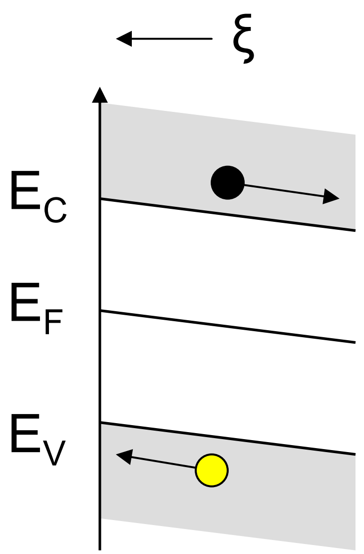
Band gap (E_G)



Semiconductors

Transport

Drift: Charged-particle motion in response to electric field



Drift current:

$$J_{N/drift} = q\, n\, \mu_n\, \xi \qquad J_{P/drift} = q\, p\, \mu_p\, \xi$$

Mobility:

- Phonon scattering
- Ionized impurity scattering

$$\mu \propto T^{-3/2} / \left(N_D^+ + N_A^-\right)$$

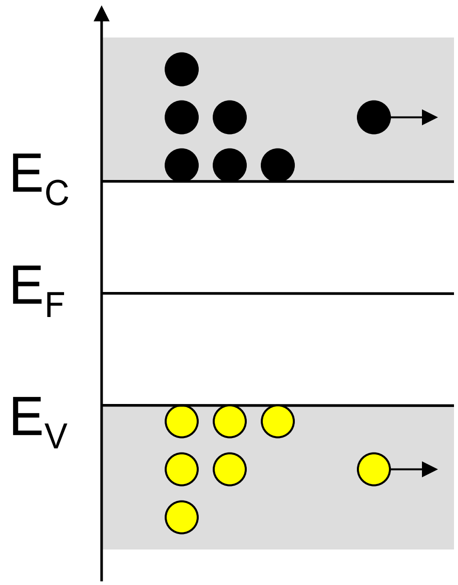
Electrical conductivity:

$$\sigma = q\mu_n\, n + q\mu_p\, p$$

Semiconductors

Transport

Diffusion: A process whereby particles tend to spread out from regions of high particle concentration into regions of low particle concentration as a result of random thermal motion.



Diffusion current:

$$J_{N/diff} = q D_n \frac{dn}{dx}$$

$$J_{P/diff} = -q D_p \frac{dp}{dx}$$

Diffusion coefficient:

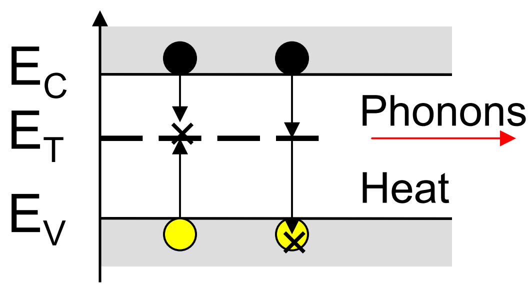
$$D_n = \frac{kT}{q} \mu_n \qquad D_p = \frac{kT}{q} \mu_p$$

Semiconductors

Recombination: A process whereby electrons and holes (carriers) are annihilated or destroyed.

Generation: A process whereby electrons and holes are created.

R-G Center recombination



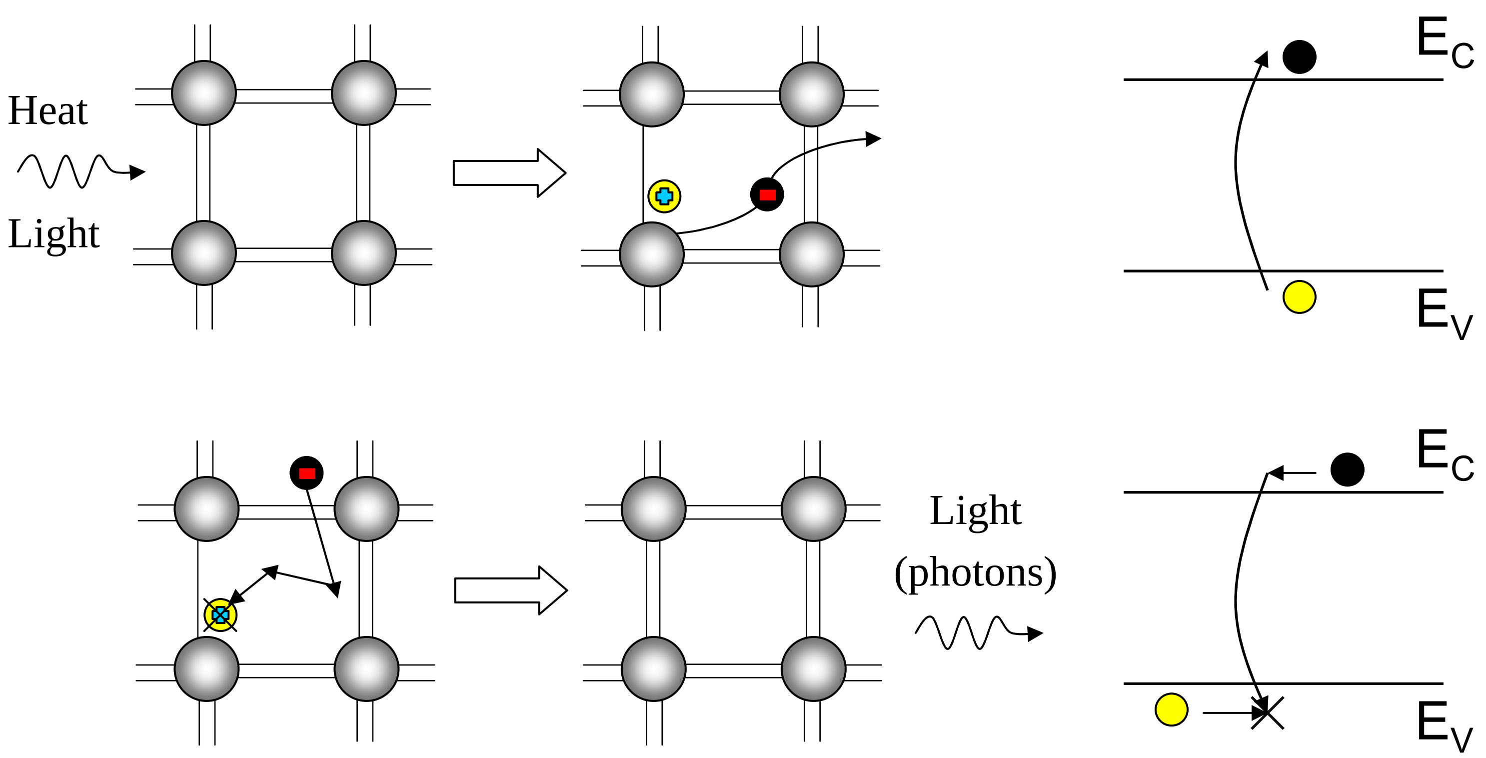
Minority carrier lifetime:

$$\tau_n = \frac{1}{C_n N_T} \qquad \tau_p = \frac{1}{C_p N_T}$$

Diffusion length:

$$L_n = \sqrt{D_n \tau_n} \qquad L_p = \sqrt{D_p \tau_p}$$

Band-to-band recombination



R-G center

- dominant recombination-generation mechanism