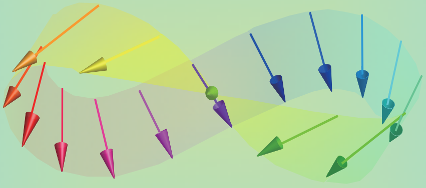
Semiconductor Devices

22



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Department of Electronics

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11:00 Monday, 24/November/2014 (P/L 005)

Exercise 1

Find the probability of occupation of a level of 0.05 eV above the conduction band edge of a Silicon device if the Fermi level is 0.7 eV above the valence band edge.

Assume the bandgap (E_g) of Silicon is 1.1 eV and the effective mass of electron in Silicon is

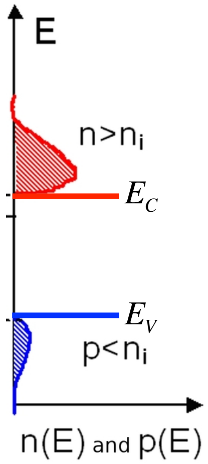
$0.40 \times (0.91 \times 10^{-30}$ kg).

The Boltzmann constant (k_B) is 1.4×10^{-23} J/K,

the Planck constant is 6.6×10^{-34} J·s and

the temperature is 300K.

Use the conversion ratio: 1 eV = 1.6×10^{-19} J.



Answer to Exercise 1

Carrier density can be defined by

$$n =$$

Here, the effective density of states at the conduction band is defined as

$$N_C =$$

where m_e is the effective mass of electron.

$$n = 2\left(\frac{2\pi\cdot 0.40\times 0.91\times 10^{-30}\left[\mathrm{kg}\right]\cdot 1.4\times 10^{-23}\left[\mathrm{J/K}\right]\cdot 300\left[\mathrm{K}\right]}{\left(6.6\times 10^{-34}\left[\mathrm{J\cdot s}\right]\right)^2}\right)^{3/2}$$

$$\times\exp\left(\frac{\left\{0.7-\left(1.1+0.05\right)\right\}\left[\mathrm{eV}\right]\cdot 1.6\times 10^{-19}\left[\mathrm{J}\right]}{1.4\times 10^{-23}\left[\mathrm{J/K}\right]\cdot 300\left[\mathrm{K}\right]}\right)$$

$$= 2\left(2.21\cdots\times 10^{16}\left[\mathrm{kg/J\cdot s^2}\right]\right)^{3/2}\cdot\exp\left(-17.1\right)$$

$$= 2\left(2.21\cdots\times 10^{16}\left[\mathrm{m^{-2}}\right]\right)^{3/2}\cdot\exp\left(-17.1\right)\quad [\mathrm{J}]=[\mathrm{kg\cdot m^2/s^2}]$$

$$= 6.55\cdots\times 10^{24}\cdot 3.74\cdots\times 10^{-8} = 2.44\cdots\times 10^{17}\left[\mathrm{m^{-3}}\right]$$

$$\approx$$

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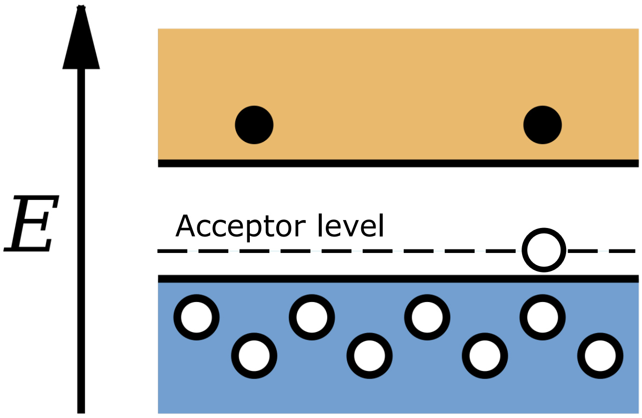
22 Extrinsic Semiconductor

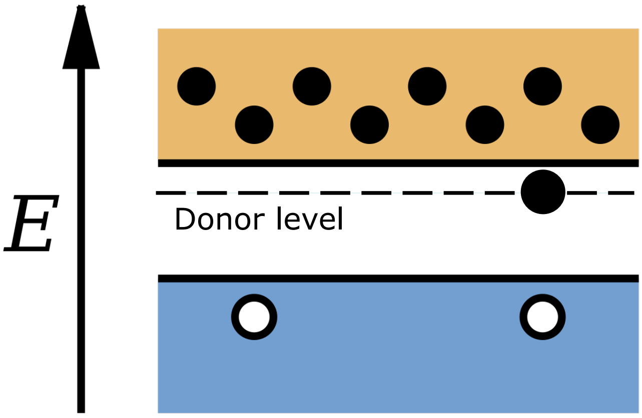
- Doping
- Donor / acceptor
- Carrier density

Extrinsic Semiconductors

p-type band structures :



n-type band structures :



Group IV semiconductors:

( )

( )

Group III-V semiconductors:

GaAs and GaN

( ): Be, Zn, Cd and Ge

Group IV semiconductors:

( )

( )

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( ): Se, Te, Si and Ge

* http://www.wikipedia.org/

Atomic Structure of *p*-Type Semiconductors

p-type semiconductor structures :

Group IV semiconductors:

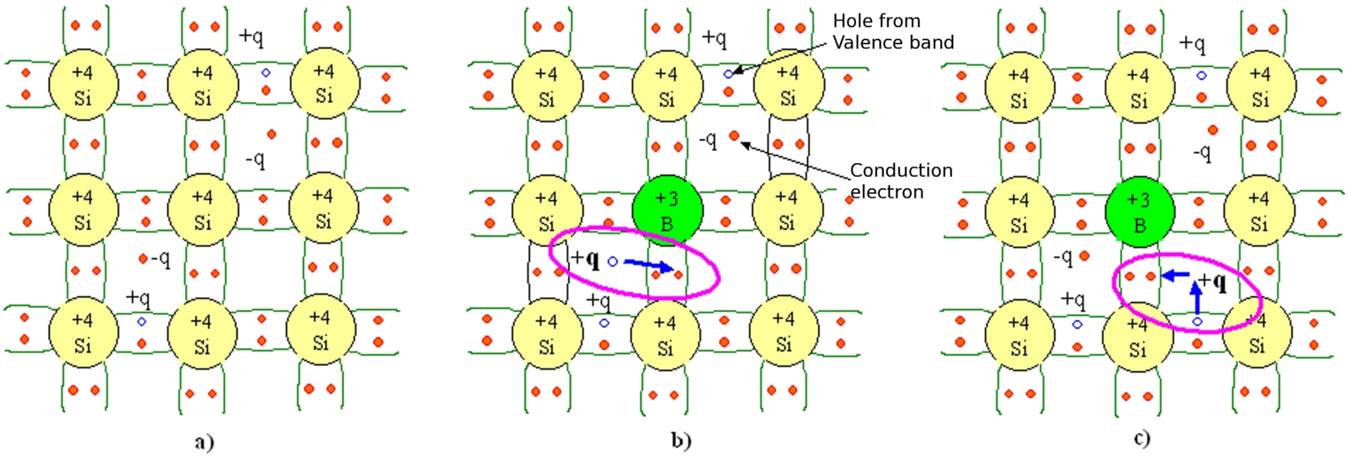
Si and Ge

Acceptors: B and Al

Group III-V semiconductors:

GaAs and GaN

Acceptors: Be, Zn, Cd and Ge

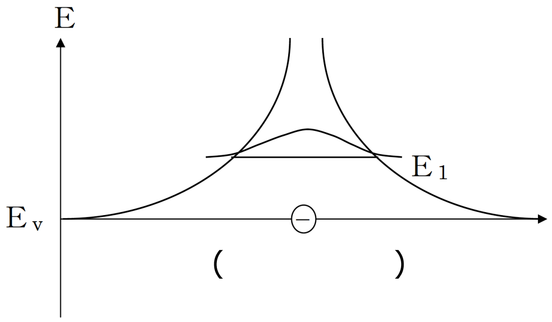


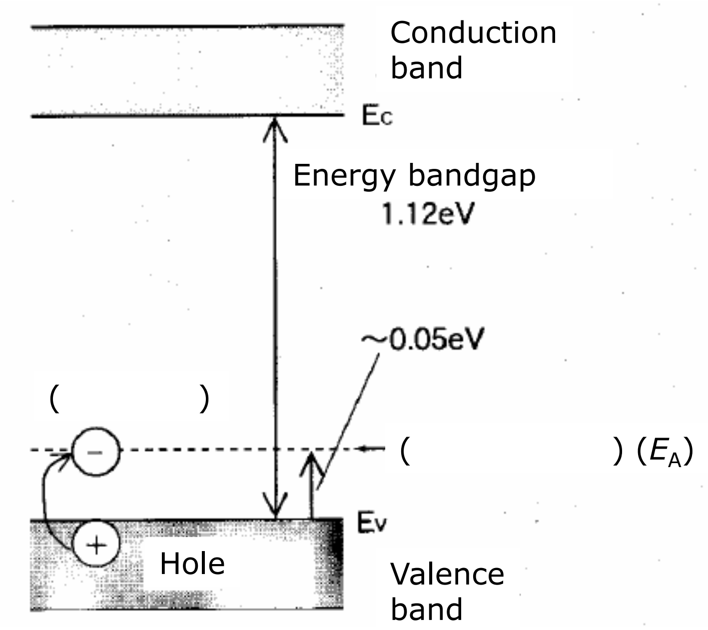
a) b) c)

* http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C02/co/Contenu_04.html

p-Type Acceptors

Energy potential created by an acceptor ion :





* http://www.phys.chuo-u.ac.jp/labs/wakabaya/lecture/applphys/2C_$4.3.pdf

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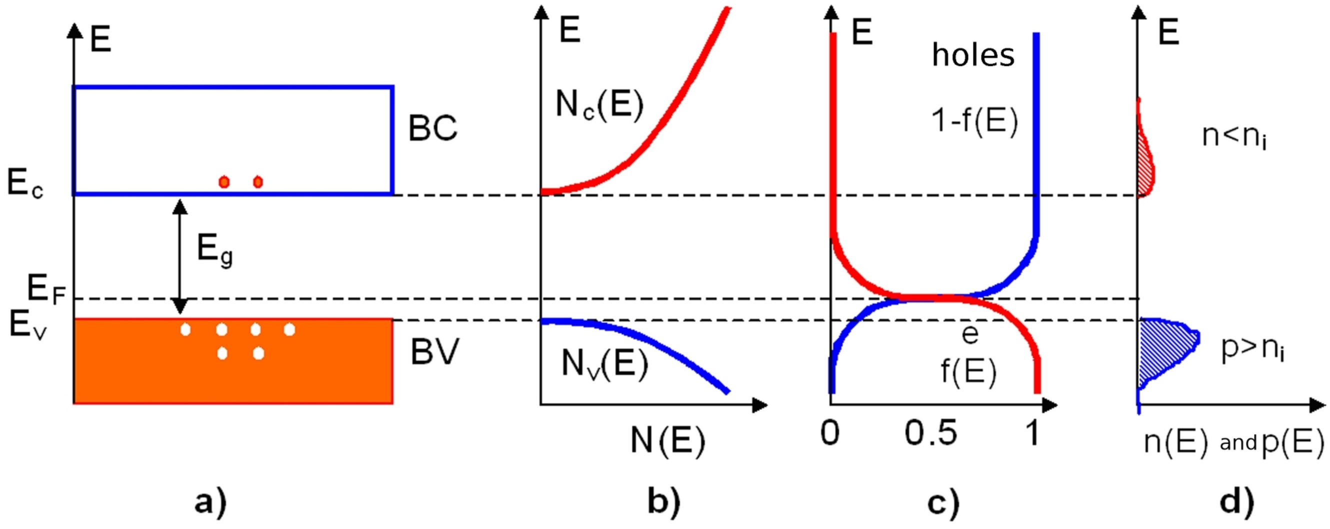
Atomic Structure of *p*-Type Semiconductors

p-type band structures :



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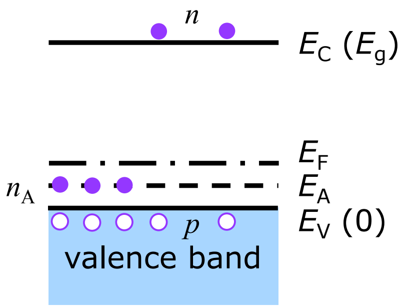
Carrier Number Density

Numbers of holes in the valence band E_V should equal to

the sum of those of electrons in the conduction band E_C and in the acceptor level E_A :

$p =$



Similar to the intrinsic case,

$$p = N_V f_p(0) \approx N_V \exp\left(-\frac{E_F}{k_B T}\right)$$

$$n = N_C f_e(E_g) \approx N_C \exp\left(-\frac{E_g - E_F}{k_B T}\right)$$

Assuming numbers of neutral acceptors are N_A,

$$n_A = \frac{N_A}{1 + 2\exp\left(\frac{E_A - E_F}{k_B T}\right)}$$

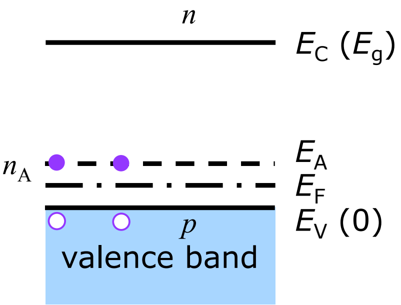
For E_A - E_F > $k_B T$, $n_A \approx N_A$

$$\therefore N_V \exp\left(-\frac{E_F}{k_B T}\right) \approx N_C \exp\left(-\frac{E_g - E_F}{k_B T}\right) + N_A$$

Carrier Number Density (Cont'd)

At low temperature, one can assume $p >> n$, $p \approx n_A$

As n_A is very small, E_A > E_F



$$n_A = \frac{N_A}{2} \exp\left(-\frac{E_A - E_F}{k_B T}\right)$$

$$\therefore N_V \exp\left(-\frac{E_F}{k_B T}\right) \approx \frac{N_A}{2} \exp\left(-\frac{E_A - E_F}{k_B T}\right)$$

$$\therefore \exp\left(-\frac{E_F}{k_B T}\right) \approx \sqrt{\frac{N_A}{2N_V}} \exp\left(-\frac{E_A}{2k_B T}\right)$$

$$\therefore E_F \approx \frac{k_B T}{2} \ln \frac{2N_V}{N_A} + \frac{E_A}{2}$$

By substituting $N_V \equiv N_{Vp} T^{3/2}$

$$\therefore E_F \approx \frac{k_B T}{2} \ln\left(\frac{2N_{Vp}}{N_A} T^{3/2}\right) + \frac{E_A}{2}$$

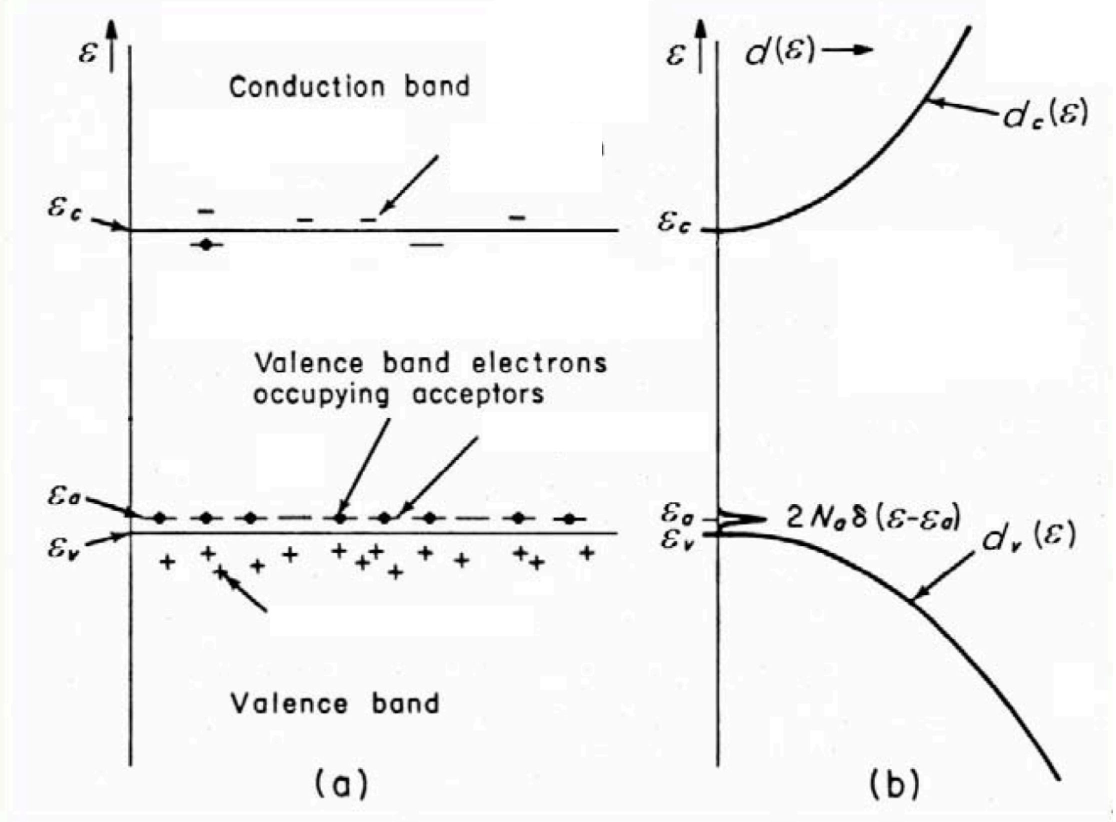
For T ~ ,

At high temperature, one can assume $n >> n_A$, $p \approx n$

Similar to the intrinsic case, for $m_e^* = m_p^*$,

Typical Band Structures

Acceptor level near the valence bands :



* http://www.phys.chuo-u.ac.jp/labs/wakabaya/lecture/applphys/2C_$4.3.pdf

Atomic Structure of *n*-Type Semiconductors

n-type semiconductor structures :

Group IV semiconductors:

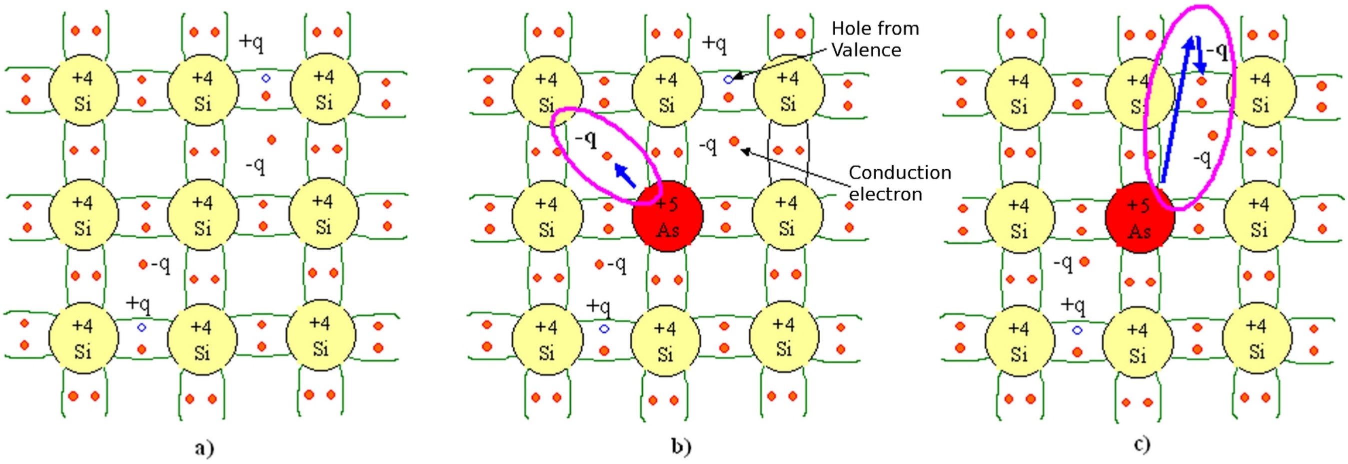
Si and Ge

Donors: P and As

Group III-V semiconductors:

GaAs and GaN

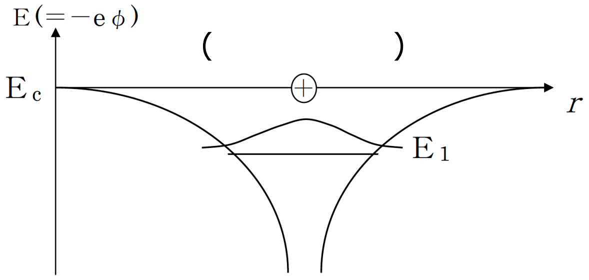
Donors: Se, Te, Si and Ge

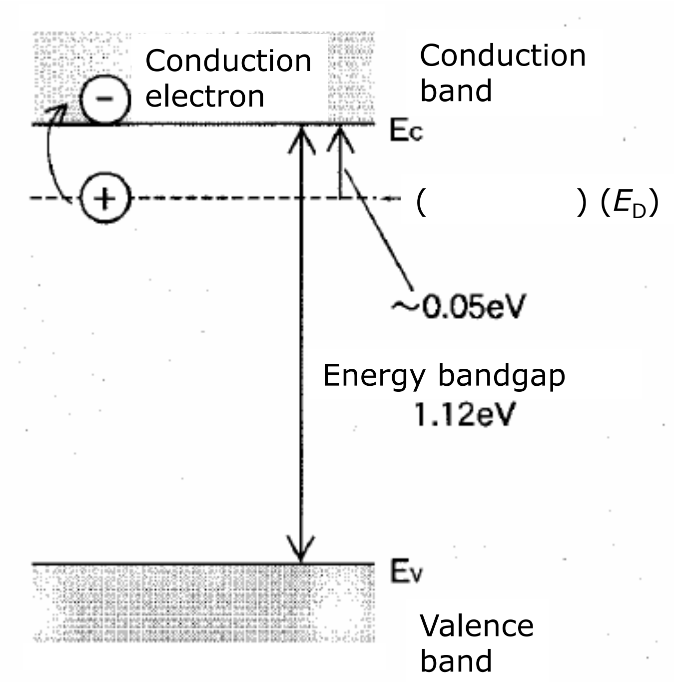


* http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C02/co/Contenu_04.html

n-Type Donors

Energy potential created by a donor ion :





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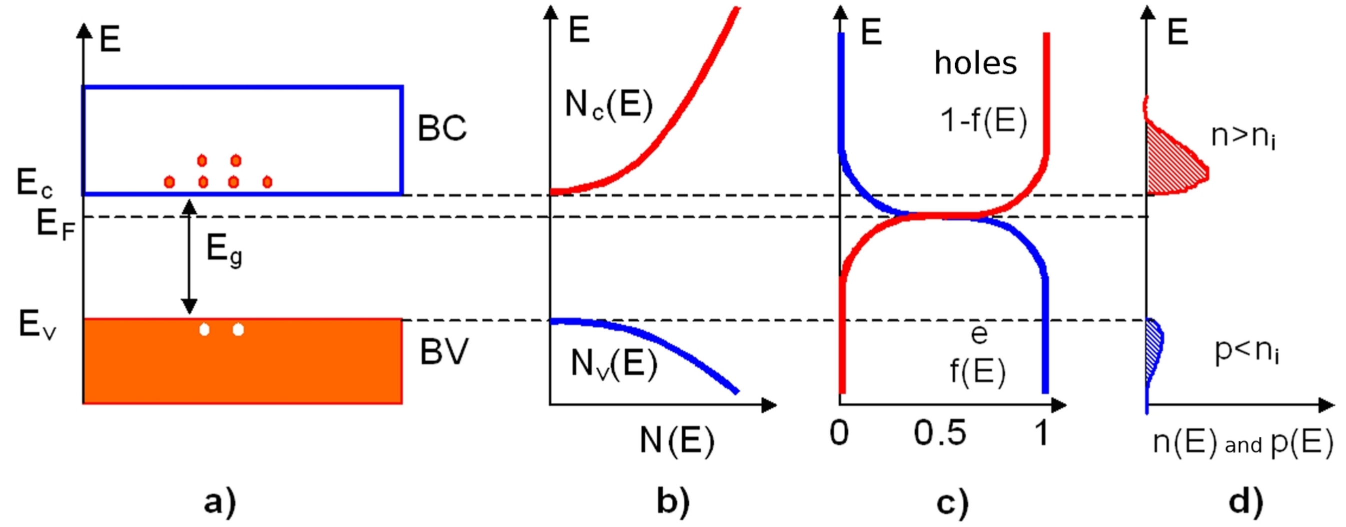
Atomic Structure of *n*-Type Semiconductors

n-type band structures :



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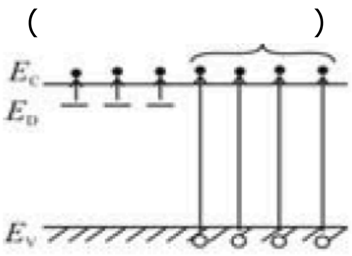
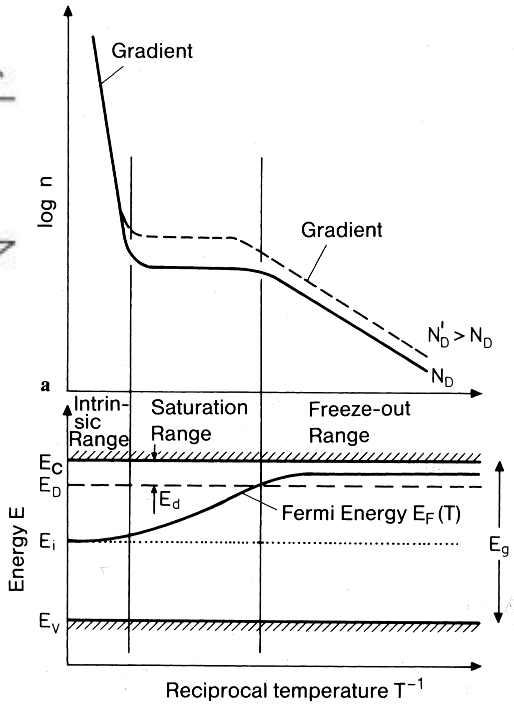
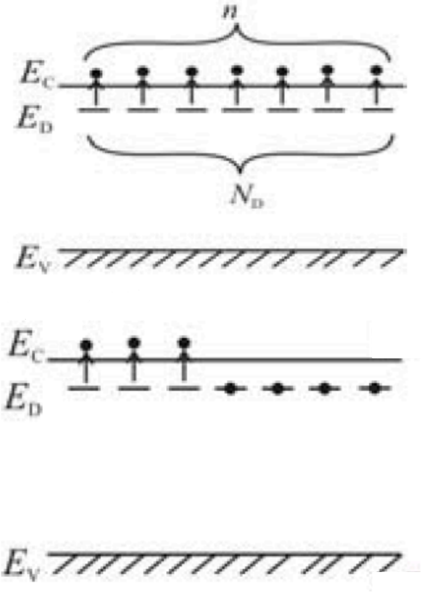
Temperature Dependence of an Extrinsic Semiconductor







* H. Ibach and H. Lüth, *Solid-State Physics* (Springer, Berlin, 2003);
** http://akita-nct.jp/tanaka/kougi/2007nen/3e/3-4hujunbutu.pdf

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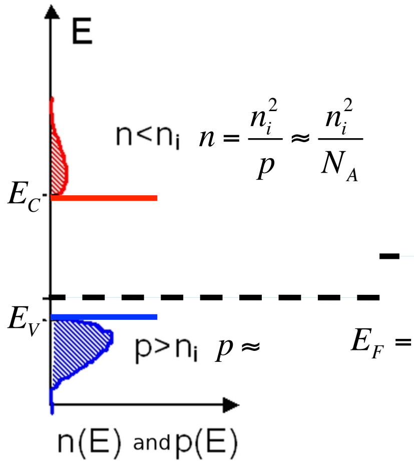
Carrier Densities of Extrinsic Semiconductors

p-type band structure :

n-type band structure :



n<n$_i$ $n = \frac{n_i^2}{p} \approx \frac{n_i^2}{N_A}$

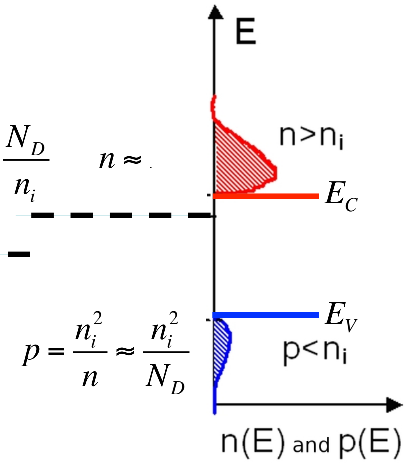
p>n$_i$ $p \approx$

$$E_F = E_i - k_B T \ln \frac{N_A}{n_i}$$

$$E_i = \frac{E_C + E_V}{2} + \frac{1}{2} k_B T \ln \frac{N_V}{N_C}$$

$$E_F = E_i + k_B T \ln \frac{N_D}{n_i}$$

$n \approx$



n>n$_i$

$p = \frac{n_i^2}{n} \approx \frac{n_i^2}{N_D}$ p<n$_i$

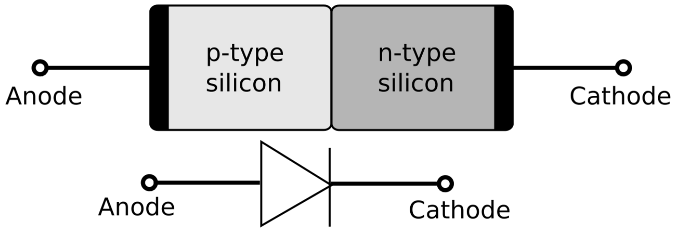
* http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C02/co/Contenu_04.html

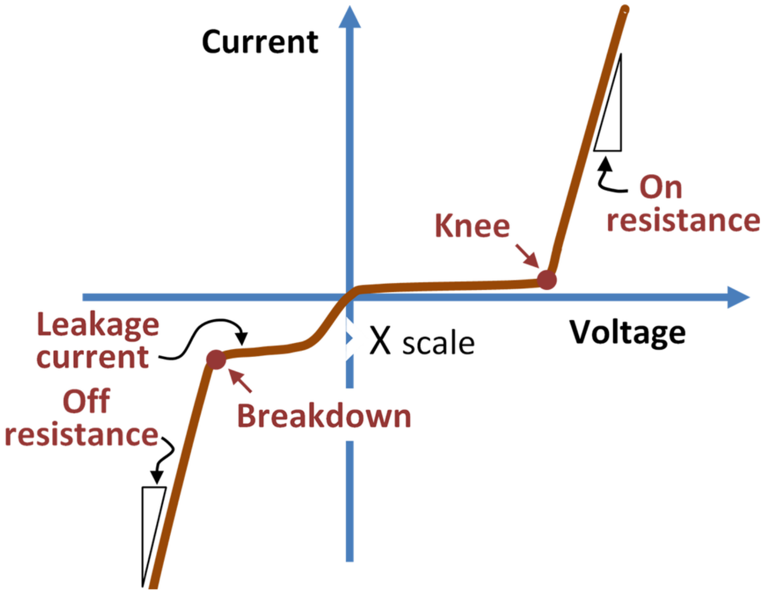
p-n Diode

A junction made by attaching *p*- and *n*-doped semiconductors :

Widely used to insulate transistors.

Common circuit to convert ac to dc in a battery charger.

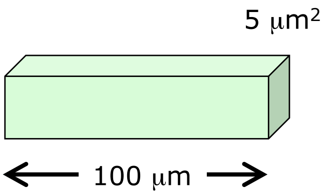




* http://www.wikipedia.org/

Exercise 2

For the Silicon material with doping, estimate the dopant concentration (N_D) needed to manufacture a 1 MΩ resister measuring 100 μm in length and 5 μm^2 in cross section.



Assume that the transport of current will be carried out by majority carriers and that for Silicon,
intrinsic carrier density: $n_i = 10^{16}$ m^{-3},
mobility of electrons: $\mu_e = 0.135$ m^2/V·s
and mobility of holes: $\mu_h = 0.05$ m^2/V·s.