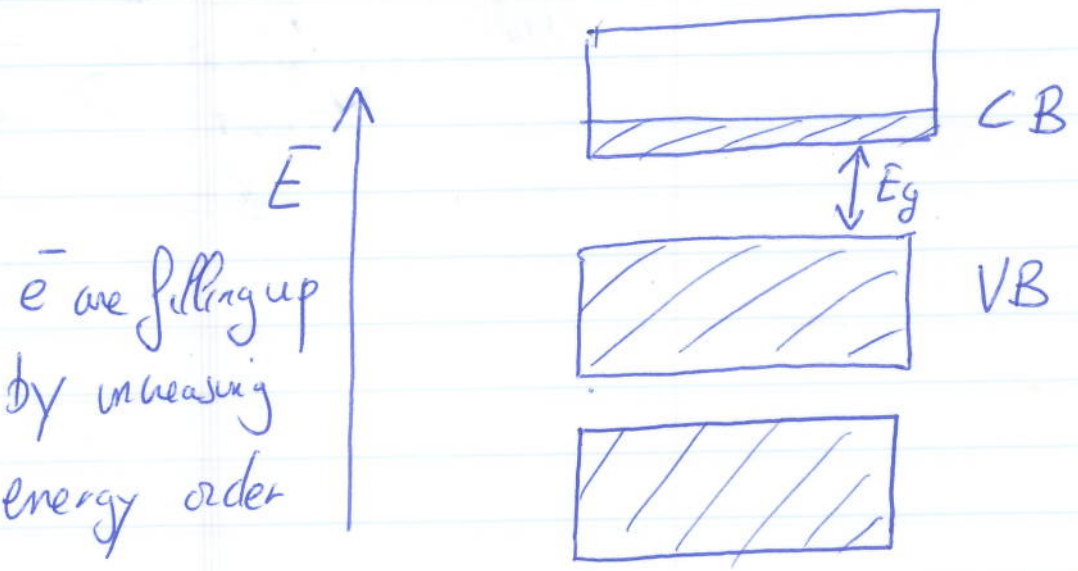


② Energy band model

① Valence band and conduction band

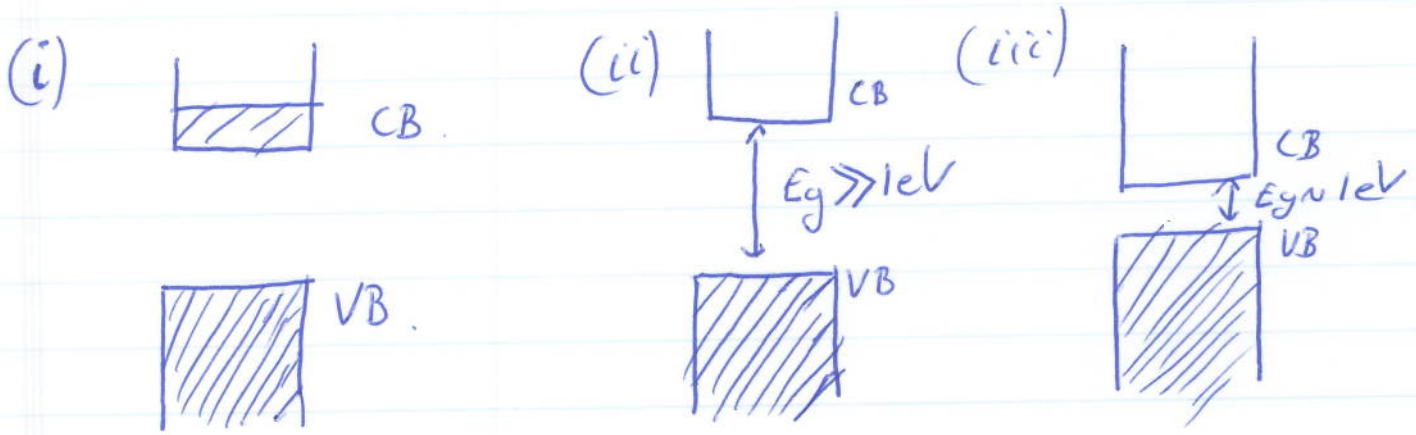


- * The last completely filled band is called the valence band (VB)
- * The energy band directly above the valence band is called the conduction band (CB)
- * the energy bandgap between VB and CB is called E_g .

* The e^- that are contained in the VB and the CB, dominate the behavior of the solid.

[2.2A] (D) Insulator, Metal or Semiconductor?

Let us consider 3 possible configurations. (materials configurations)



~~(i) VB is completely filled, CB is partially filled.~~

at temperature equal to zero ($T=0$), there is no thermal excitation, e^- will stay in the energy state.

What happens with thermal excitation ($T > 0$) for the above three cases?

(L) VB is completely filled and CB is partially filled.

~~at finite temperature~~

Therefore there is "no space left" for the e^- in the VB to be able to change energy states.

However, there exists unfilled space in the CB close to the highest energy level (Fermi-level).

\Rightarrow at $T > 0$ ~~the~~ e^- close to E_F can travel in all directions and with many different velocities.

\Rightarrow If an electric field is applied to the solid, these e^- can be accelerated and it appears an e^- flow \Rightarrow the conduction is then possible.

These solids (materials) are good conductors

\Rightarrow we call them Metal

(ii) VB is completely filled, and the energy gap is very very large (much larger than energy coming from thermal excitation).

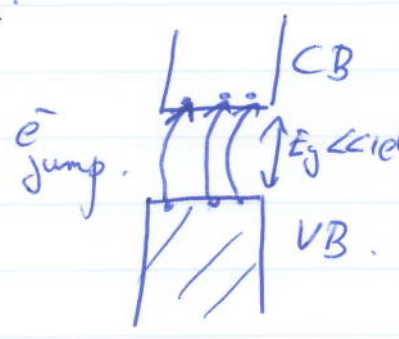
VB cannot carry a current since no empty state is available. These materials are called

Insulators.

(iii) VB is completely filled but the energy gap is very small. at $T > 0$; ~~the~~ ^{some} e^- have enough energy to jump from the VB to the CB!

These materials are then very bad insulators and very bad conductors!

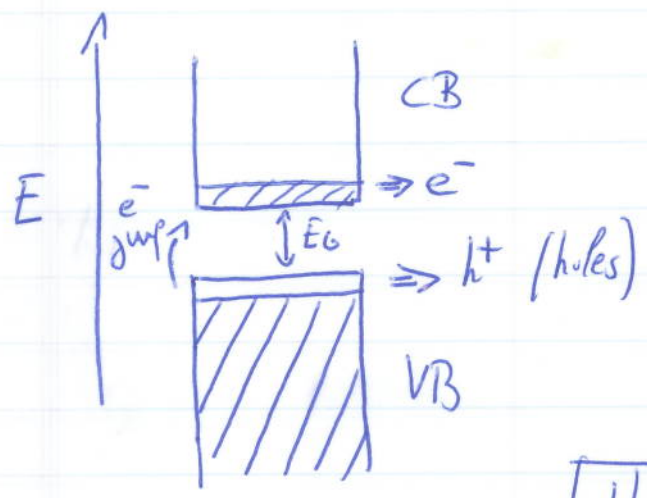
we call them semiconductors



[2.2-3] (c) Electrons (e^-) and holes (h^+) in semiconductors.

Since with $T > 0$ few e^- can jump from the VB to the CB.

- the CB is then an "almost empty band"
- the VB is then an "almost full band"



the concept of hole is introduced to keep track of the missing e^- in the VB.

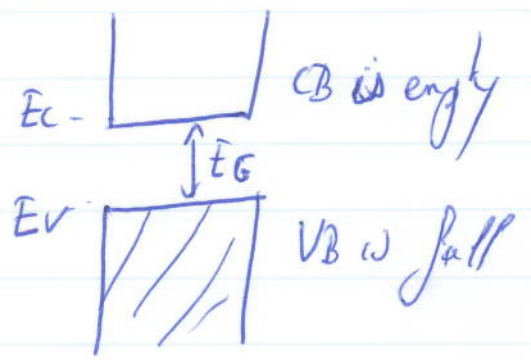
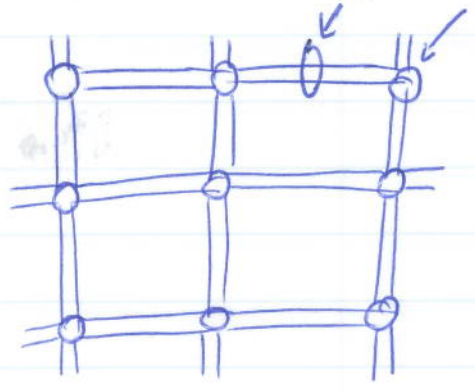
Holes are missing e^-

~~Example~~ Example = Silicon 14 valence $e^- \Rightarrow 4$ neighbors in Si crystal

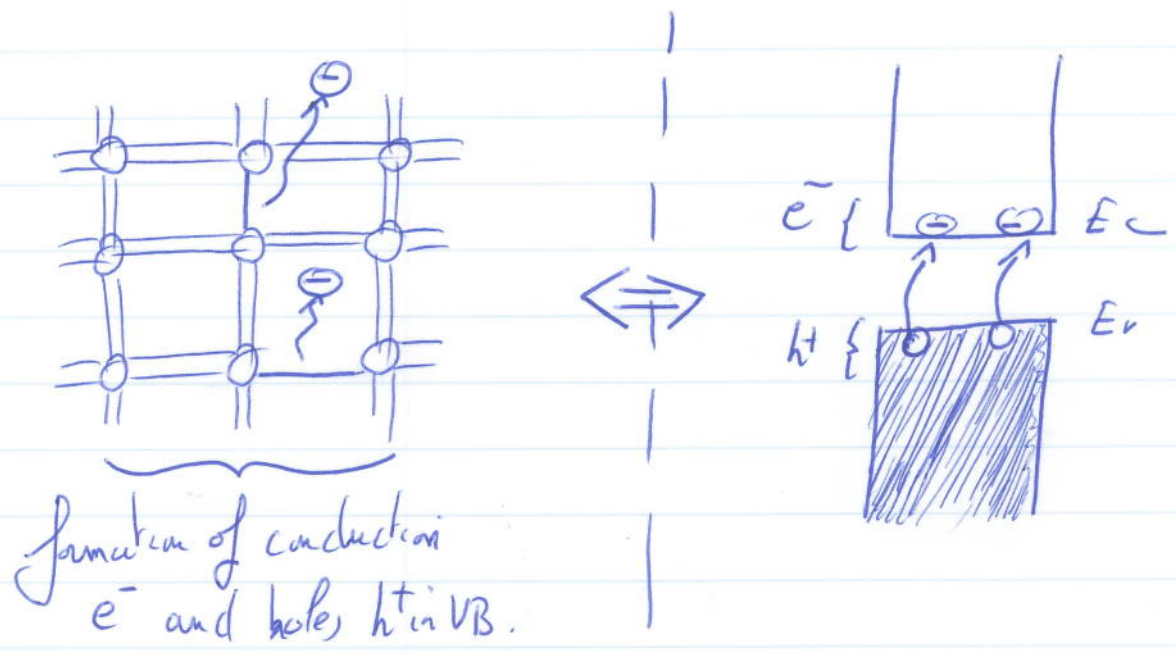
Banding model $2e^-$ si atom

Energy Spectrum

T=0

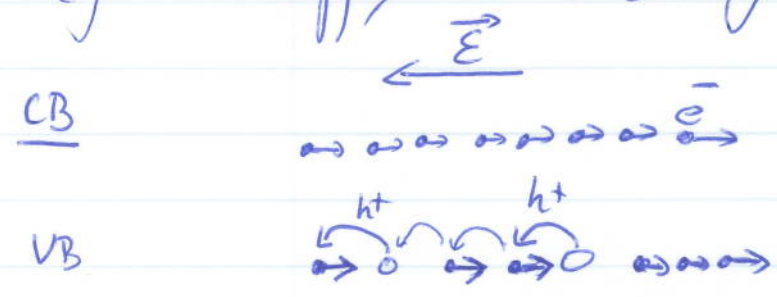


at $T > 0$
[Fig 2.7]



Consequences one will need to consider two types of charge carriers in semiconductors e^- and holes h^+ . e^- has a negative charge, while holes behave like positively charged particles (they can move inside the VB).

Example if we apply an electric field



holes are not real particles! they account for the combined behavior of all the e^- in the VB.

[2.3.3] (d) Intrinsic Semiconductors

It is a ("hypothetical") semiconductor without any impurity and defect.

(The number of e^- per unit of volume is called electron density or electron concentration.)

The electron density in the CB, n , is equal to the hole density in the VB, p .

[2.4] $n = p = n_i$ where n_i is the intrinsic carrier density

\Rightarrow electrical neutrality

Example at room temperature $T = 300\text{K}$

	E_g	$n_i \text{ (cm}^{-3}\text{)}$
GaAs	1.42 eV	2×10^6
Si	1.12 eV	1×10^{10}
Ge	0.66 eV	2×10^{13}

[2.3.4] (e) Extrinsic Semiconductor

These are semiconductors that are doped with impurities (foreign atoms incorporated into the crystal).
These impurities:

- can be unintentional, due to the lack of control during the growth of the semiconductors.
- can be added on purpose to provide free carriers.

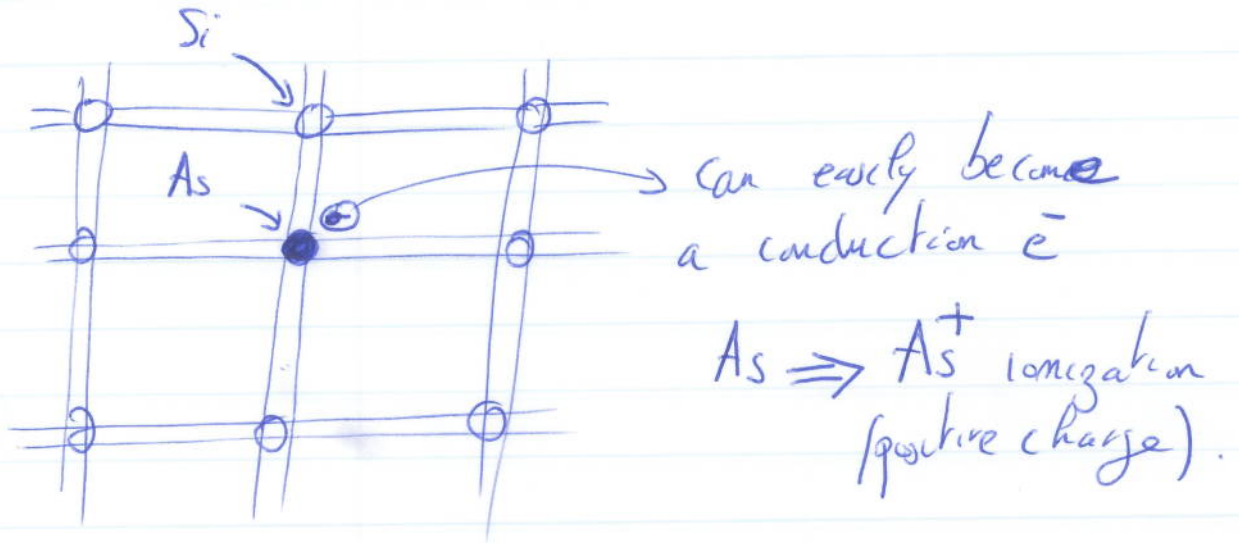
2 types of impurities

- (i) Donor impurities are introduced to increase the e^- density in the CB.
- (ii) Acceptor impurities are introduced to increase the h^+ density in the VB.

(i) Donor (Silicon with As atoms)

{ Si has 4 valence e^-
As (Arsenic) has 5 valence e^-

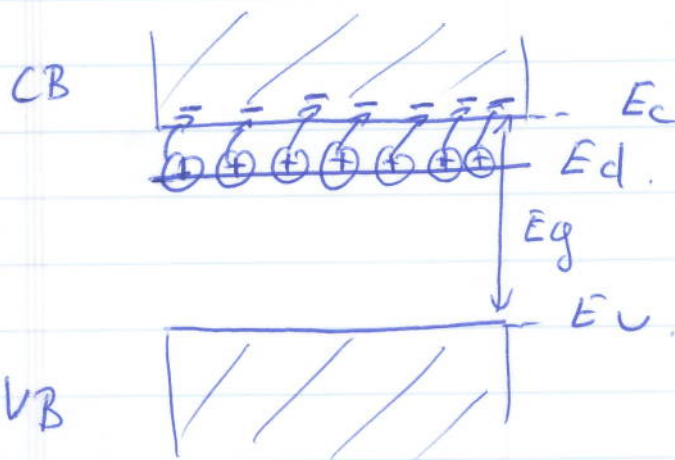
Bonding representation



As has 5 valence e^- , but only 4 are there necessary to make the bonding with the Silicon atoms. With very small temperature, the unused e^- becomes a conduction e^- .

Energy band Representation

Donor atoms give rise to permitted energy levels in the bandgap. The energy level for donors, E_d , is only few meV below the CB.



e^- can jump from E_d to the CB, increasing the e^- density in the CB.

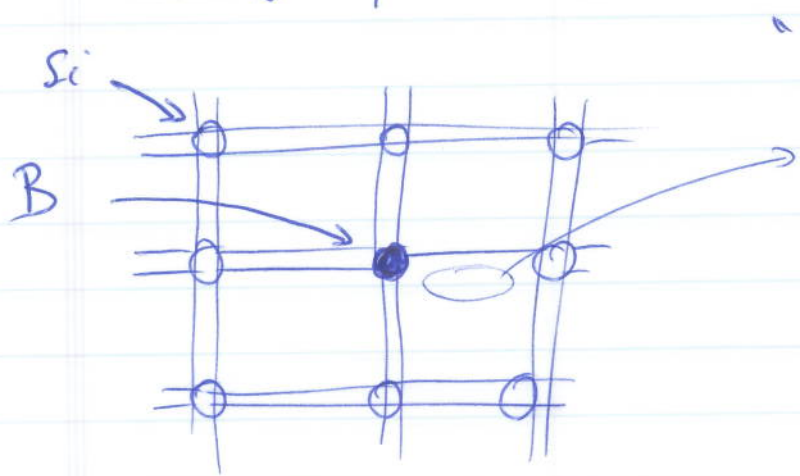
neutrality equation

$$n = p + \underbrace{N_D^+}_{\text{concentration of donors}}$$

(ii) Acceptors (Silicon with B atoms)

- { Silicon has 4 valence e^-
- { B (Boron) has 3 valence e^-

Bonding representation

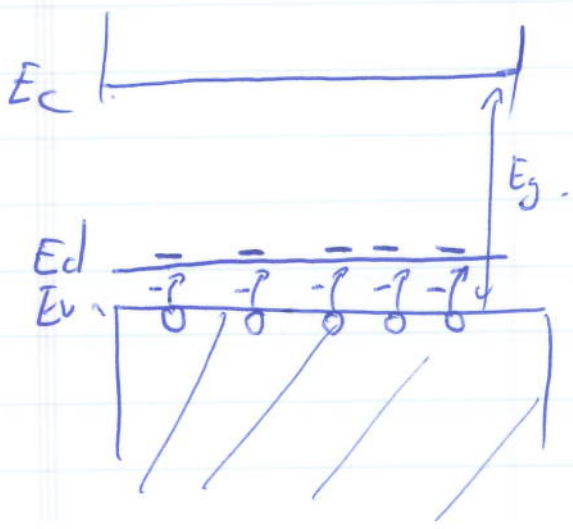


"conduction" hole with temperature.
 $B \Rightarrow B^-$ ionization
 (negative charge).

[B has 3 valence e^- and can then accept e^- to make the Bonding with Silicon.

Energy band representation

Acceptor atoms give rise to permitted energy levels in the bandgap. The energy level for acceptors, E_A , is few meV above the VB.



At room temperature e^- have jumped from VB to ~~EA~~ EA.
 \Leftrightarrow holes jump from EA to VB.

$$n + N_A^- = p$$

density of acceptors

③ Bandstructure. (Notion of)

[1.1.3] ① Crystal Structure

Solid materials are classified by the way the atoms are arranged within the solid;

3 type of materials:

Fig 1.1

- amorphous = atoms are placed at random \Rightarrow no order.
- poly-crystalline = order by segment, no long range order.
- crystalline = order are placed in highly ordered structure. (crystal)

Fig 1.3
1.4

we will study crystalline semiconductors where an unit cell can be repeated periodically to form a solid.

⑤ Effective mass approximation

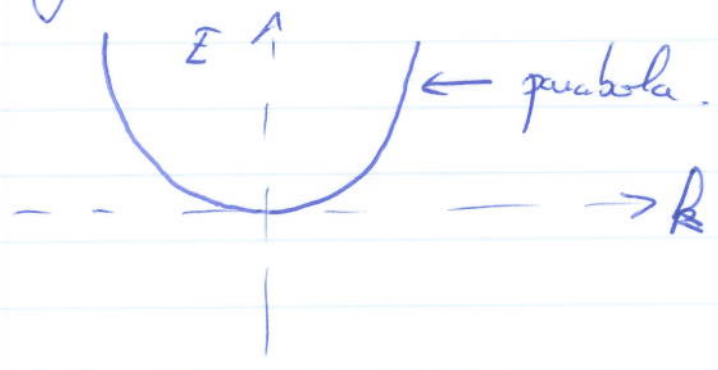
In crystal, bandstructure calculations (i.e. solving the Schrödinger equation by taking advantage of the periodicity of the unit cell) can be performed to obtain the dispersion relation, $E(k)$.

~~So for a given wave vector k~~

[So for a given \bar{e} or \hbar^+ with a wave vector \vec{k} , we can get its energy.

For example for a free e^- on vacuum, we saw

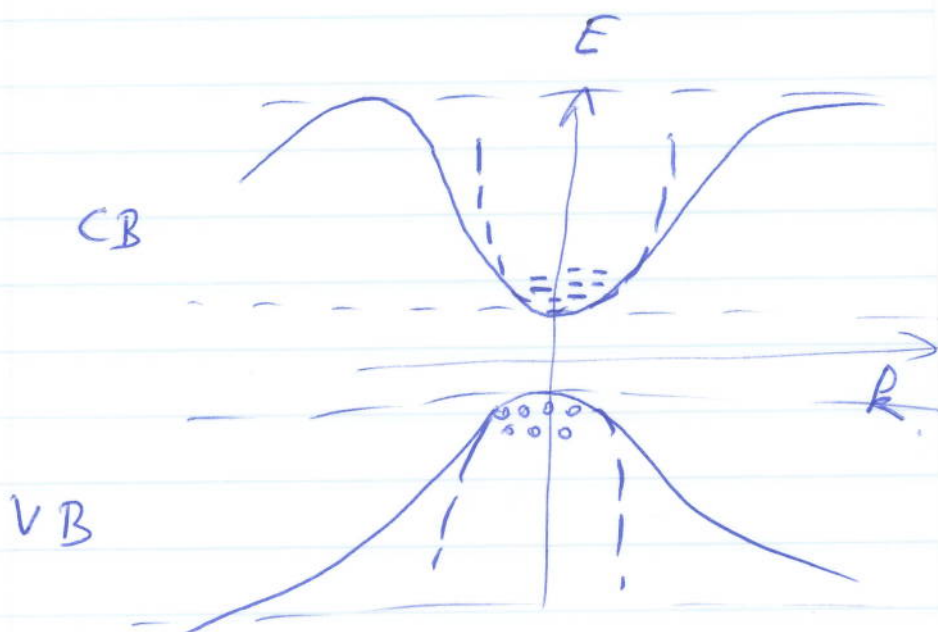
$$E = \frac{\hbar^2 k^2}{2m}$$



The situation in crystal is far more complex.

~~As~~

Example GaAs.



however, physics of semiconductors usually deals with e^- located near the minimum of the CB, and holes h^+ near the maximum of the VB.

\Rightarrow These extrema in the dispersion relation can be approximated by a quadratic curve (parabola)

\Rightarrow within the parabolic band approximation, the e^- (h^+) behaves like free e^- (h^+) in the vacuum.

[However, they have now an effective mass m^* that accounts for the crystal structure.

e⁻ in crystal

$$E = \frac{\hbar^2 p^2}{2m_n^*} + E_c$$

m_n^* = effective mass of electron.

h⁺ in crystal

$$E = -\frac{\hbar^2 k^2}{2m_p^*} + E_v$$

m_p^* = effective mass of h.k.

Table 2.1

	m_n^*/m_0	m_p^*/m_0
GaAs	0.066	0.52
Si	1.18	0.81
Ge	0.55	0.36

m_0 = mass of electron.