SOME BASIC FACTS ABOUT SEMICONDUCTORS

FACT 1) We first introduce the concept of potential barrier. Given a charge q in a point where the potential is V, its potential energy is:

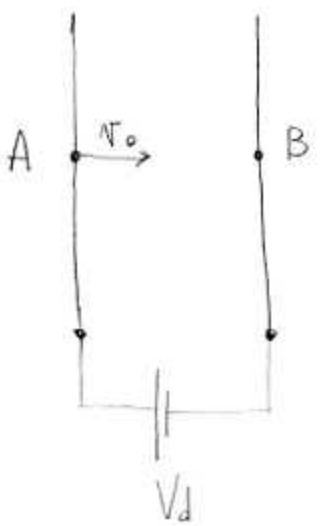
$$U = qV$$

To understand better, we can make the following analogy. If an object of mass m is in a point whose height is h, then its potential energy is

$$U = mgh$$

h is defined with respect to a reference point (the sea level for instance). The same applies to V.

Consider two plates connected to a voltage source:

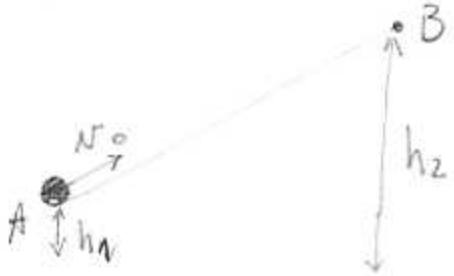


an electron in q has an initial velocity v_0. Its total energy in A is

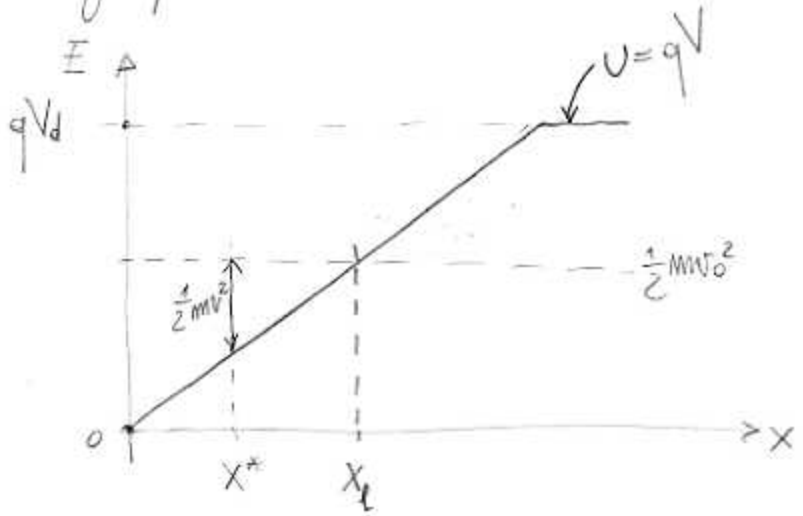
$$W = U + \underbrace{\frac{1}{2} m v_0^2}_{\text{Kinetic energy}}$$

Intuitively, the electron has to move against an electric field (or a potential difference). During its motion it looses energy so at some point its velocity will be 0.

To continue the analogy, consider a ball going uphill. It has an initial velocity v_0. If v_0 is too small the ball will never be able to reach point B.



We can plot the energy versus position on a graph



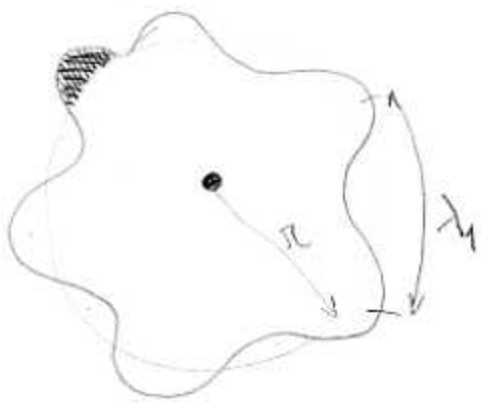
W is a constant so if we consider $V(x=0)=0$ then $W=\frac{1}{2}mv_0^2$.

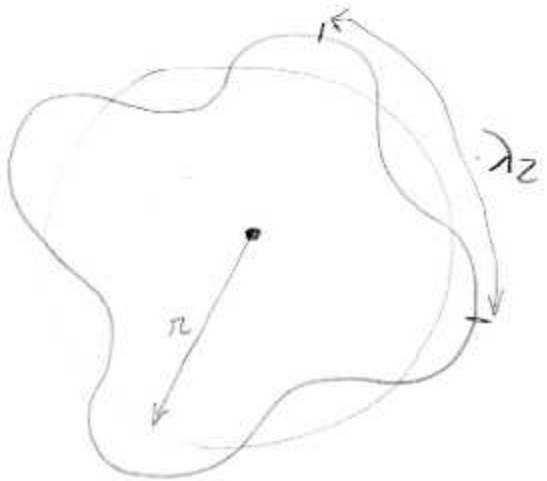
The kinetic energy is $W-qV-\frac{1}{2}mv^2$ so it is the difference between the horizontal line and the graph representing U (like in position x^*). In x_1, $\frac{1}{2}mv^2=0 \Rightarrow v=0$ so the electron is not moving anymore. <u>The potential difference represents a barrier for electrons.</u>

FACT 2) The Bhor atom

Bhor built a theory for the structure of an atom following the idea that an atom is like a planetary system. Protons are concentrated in the center of the atom and attract electrons that circle in orbits around the protons. The centripetal force will oppose the protons attraction.

Now Bhor introduced also the analogy between electrons an wave. If you consider an electron orbiting around the protons as a were Then there are only certain wave lenght that are admissible depending on the orbit radius. To understand this look at the following two cases:





Consider the total energy of the wave to be something proportional to the integral of the wave along the circle (this is not precise and it is just for you to understand the concept).

For a wavelength equal to λ_1 the integral is not zero (it is the shaded area in the figure to the left).

In this case an electron would lose or gain energy at every turn. At the equilibrium this does not happen so an electron on an orbit of radius r cannot be represented by a wave of wavelength λ_1.

For λ_2 instead, the integral is zero so λ_2 is a good candidate for the electron wave length.

λ then has to be a multiple of $2\pi r$.

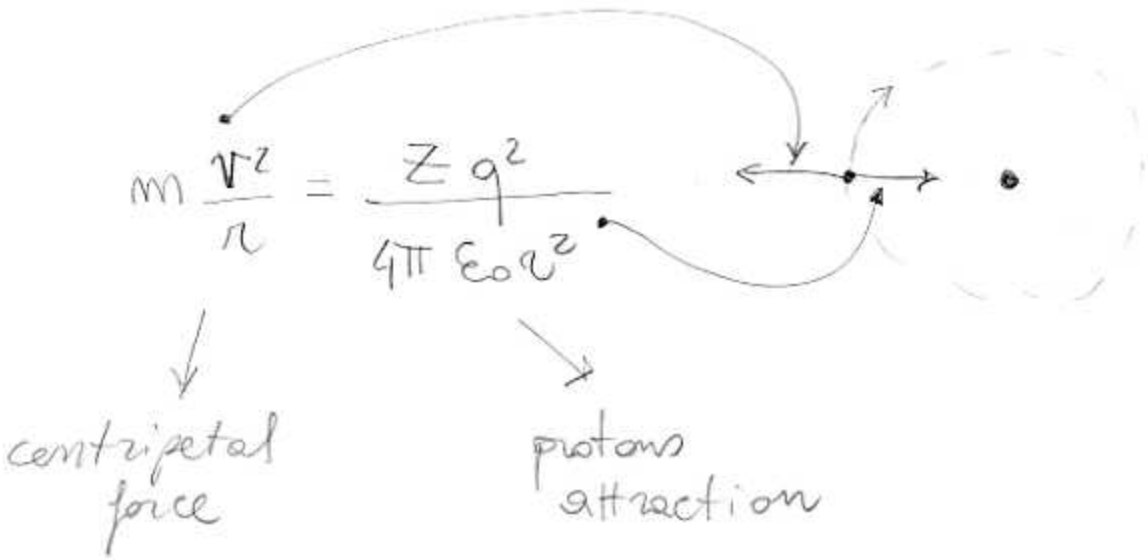
This was what Bohr came up with. Keep this in mind!

Protons generate an electric field, so the energy of an electron, which is the sum of kinetic + potential, depends on the distance

of the electron to the center of the atom.
So we have the constraint that

$$2\pi r = n\lambda$$

(r: radius; n: integer)



$$m\frac{v^2}{r} = \frac{Zq^2}{4\pi\varepsilon_0 r^2}$$

centripetal force — protons attraction

and finally another relation that comes from the de Broglie theory which relates momentum an wavelenght:

$$\lambda = \frac{h}{mv}$$

(h is the Plank constant)

Putting everything together:

$$E = -\frac{1}{2}\frac{Z^2 e^4 m}{(4\pi\varepsilon_0\hbar)^2}\frac{1}{n^2}$$

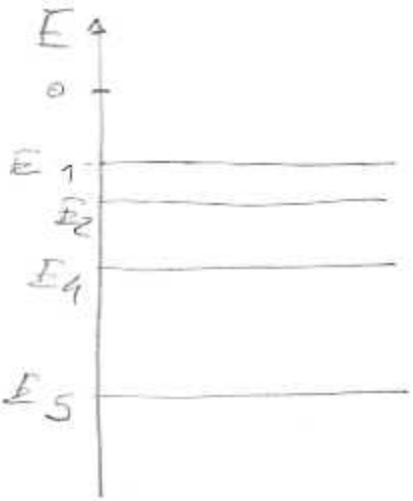
!!!

electron energy in the Hydrogen atom

E is quantized by an integer number n

The previous formula says that the energy on an electron of an Hydrogen atom can be $E_1, E_2 \ldots$ depending on the values of n (E_1 for $n=1$, E_2 for $n=2$ ---).

So we can plot the possible energy levels in a vertical graph:



Notice that the energy is negative.

The Bhor theory helps in understanding the basic concept that the energy of an electron is quantized. The theory - though is not correct.

SCHRÖDINGER MODEL

I'm not going to give the details of this theory but just the result.

Schrödinger came up with an equation describing the probability that an atom

in a certain position has an energy W. The solution to the equation for an atom requires the introduction of integers numbers n, l, m_l:

$n = 1, 2, 3 \cdots$

$l = 0, 1, 2 \cdots (n-1)$

$m_l = 0, \pm 1, \pm 2, \cdots, \pm l$

also m_s (which is called spin) can be $1/2$ or $-1/2$.

Each electron in an atom is characterized by these numbers, that, when plugged in the energy equation, give the electron energy. Each electron is characterized by a unique set of numbers, in other words, no two electrons have the same values of n, l, m_l, m_s, n represent the orbit meaning the distance from the nucleus.

So, for instance, for an atom with 14 electrons (like silicon) the first orbit is occupied by only two electrons with numbers

$n=1,\ l=0,\ m_l=0,\ m_s=1/2$ $\quad$ $n=1,\ l=0,\ m_l=0,\ m_s=-\frac{1}{2}$

The second orbit by 8 electrons with numbers:

n	2	2	2	2	2	2	2	2
l	0	0	1	1	1	1	1	1
m_l	0	0	0	0	1	1	-1	-1
m_s	1/2	-1/2	1/2	-1/2	1/2	-1/2	1/2	-1/2

s lever p lever

The orbit is denoted by $n=2$. l denotes a sub-orbit that gets the name s, for $l=0$, an p, for $l=1$.

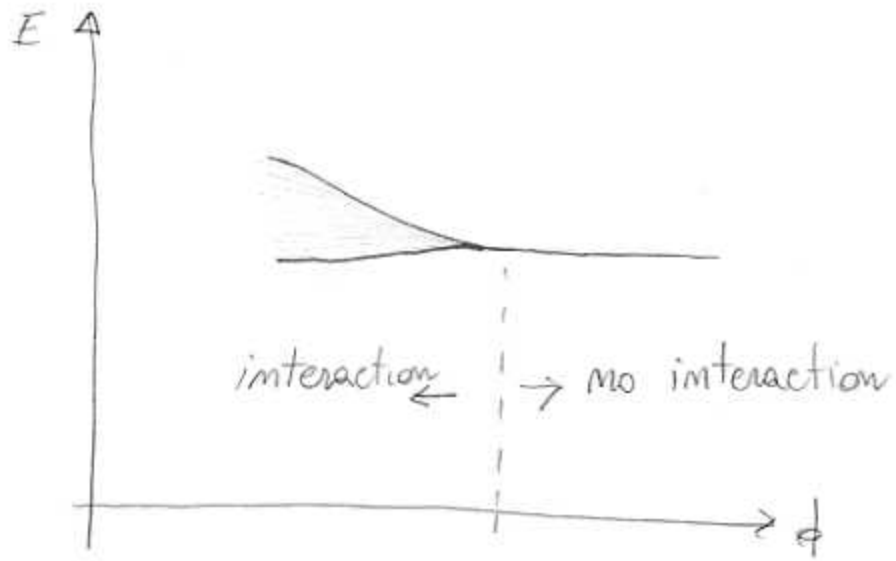
So now the 4 electrons left will sit on the orbit number 3. They are pretty far from the nucleus, plus the electric field generated by the protons is shield by the electrons on the inner orbits. The last 4 electrons are then loosly attached to the atoms and a little energy would be sufficient to make them move away.

FACT 3) BAND MODEL OF SOLIDS

We have described an atom in isolation. What happens when a certain number of atoms are put together to form a solid? Define d to be the minimum distance between the centers of a set of atoms. If $d \to \infty$ then it is like the atoms are isolated, they don't interact. So the analysis that we have done in FACT2 holds. If d decreases, then the atoms start interacting. The interaction causes the electrons energy to change. This phenomenon can be seen as if the solid was a big atom. Since not two electrons can have the same numbers in the solution of the Schrödinger equation, their energy has to change a little bit.

The electrons that are really affected by the interaction are the ones with the highest n, in other words the ones that occupy the last orbit. For the atom of Silicon they are the last four electrons with $n=3$.

If we look at the entire solid then, and we plot the energy of the more external electrons as a function of d we expect something like this:



When the atoms start interacting, their energy have to differentiate. The result is that the electrons of the entire solid, instead of occupying a specific energy level, occupy an energy band.

This is true for all energy levels, even for levels that are not occupied by any electrons (like n=4 for silicon).

If we put together N electrons whose outermost shell contains k electrons each, the total number of electrons in the band representing the outermost

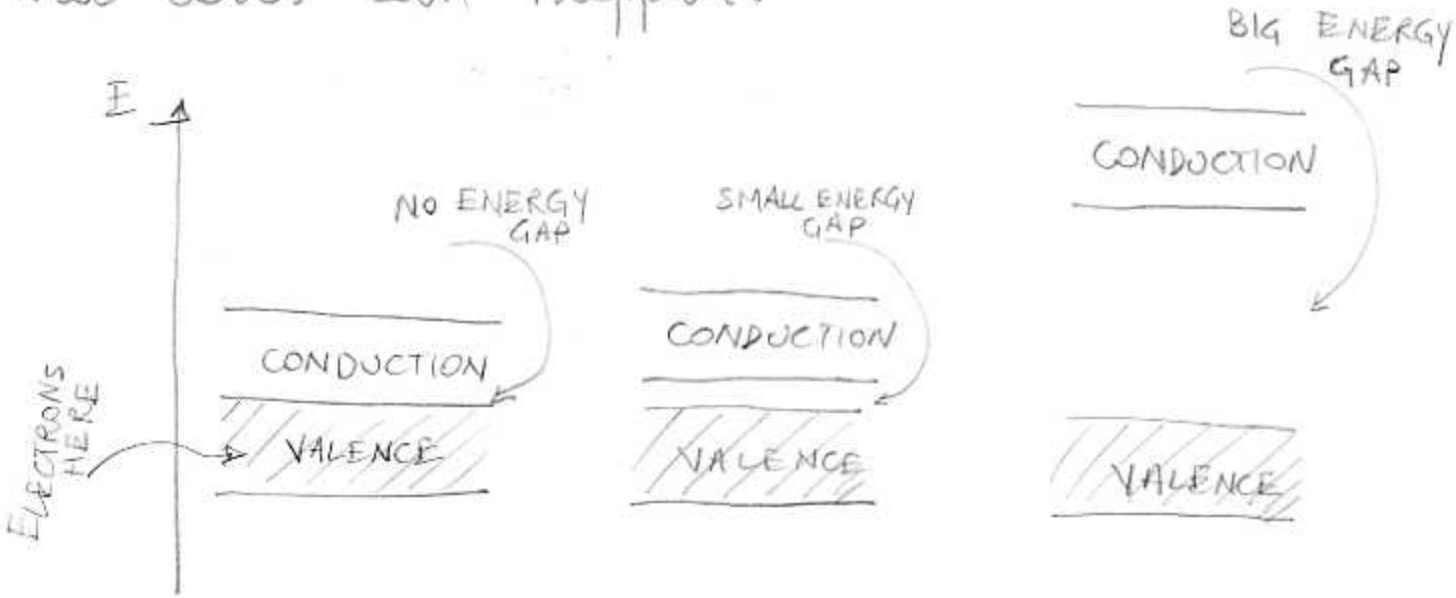
level is N*K.

The number of levels in the band that are occupied by electrons is called <u>valence band</u>. In our example, the valence band contains N*K electrons.

The energy level right above the last level in the band which is occupied by an electron, marks the separation between the valence band and another band which we call <u>conduction band</u>.

(Given a solid, d is know so we only draw the energy bands for that d)

Three cases can happen:



For instance, for silicon the outermost level has $n=3$ where ther are 4 electrons.

If $n=3 \Rightarrow l=0,1,2 \Rightarrow m_l = 0, \pm 1, \pm 2$

$n=3$ can then contain up to 18 electrons but only 4 are present.

If N atoms of silicon form a solid then the band corresponding to the original $n=3$ level contains $4N$ electrons (valence band) and $(18-4)N = 12N$ empty states (or energy levels:

The energy gap is measured in electron Volt(s)

$eV = 1.6 \cdot 10^{-19}$ Joule.

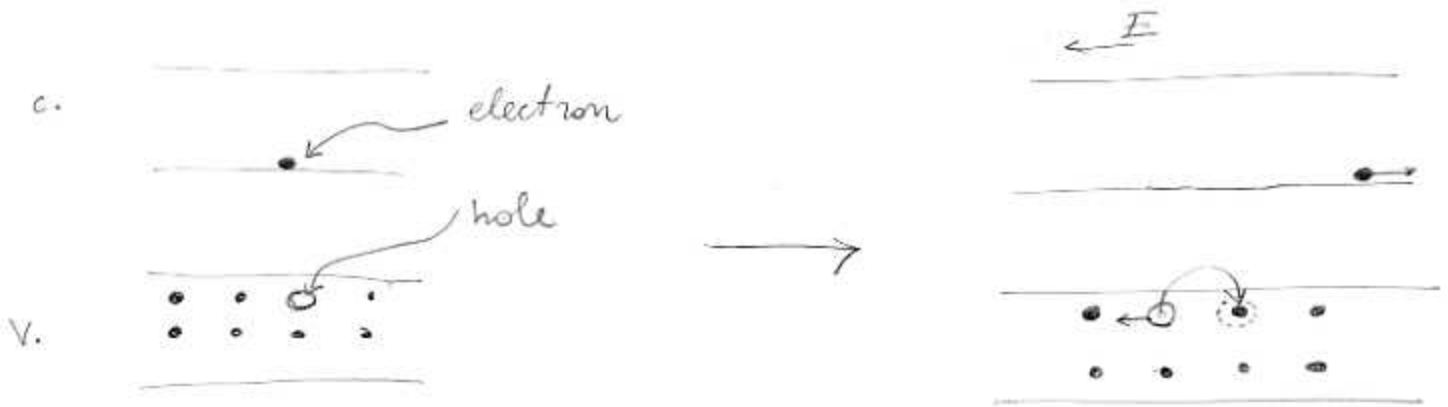
If there is no gap than an electron can easily increase its energy and reach the conduction band where the attraction from the nucleus is so small that the electron is basically free to move in the solid.

This is <u>a conductor</u>

If the energy gap is big then there are no hopes for an electron to move in the conduction band and all the electrons are constreined to their positions.
We have an <u>insulator</u>
This happens when the outermost shell is completely occupied by electrons, like Neon for instance. In fact, Neon is one of the inert gas (inert comes from the latin "inertem" which means inactive. When W. Ramsay discovered this gas, his son suggested to call it "Novum" which means new, young. Ramsay called it Neon to give it the suffix -on like Argon, another gas he previously discovered).

If the gap is small then we have somthing in between : a <u>semiconductor</u>.
A small energy, an electric field or light for instance is sufficient to move some electrons in the conduction band and increase the conductivity of the solid.

If in a semiconductor an electron gains enough energy to jump in the conduction band, an energy state remains empty in the valence band. This state is called hole



If a state is left available an we apply a small electric field to the semiconductor, then another electron in the valence band can move to the available state. It will leave another state, a hole, available.

If is like holes will move in the direction of the electric field an electron in the other directions. Since holes are + charge and electrons are − charge their currents sum up.

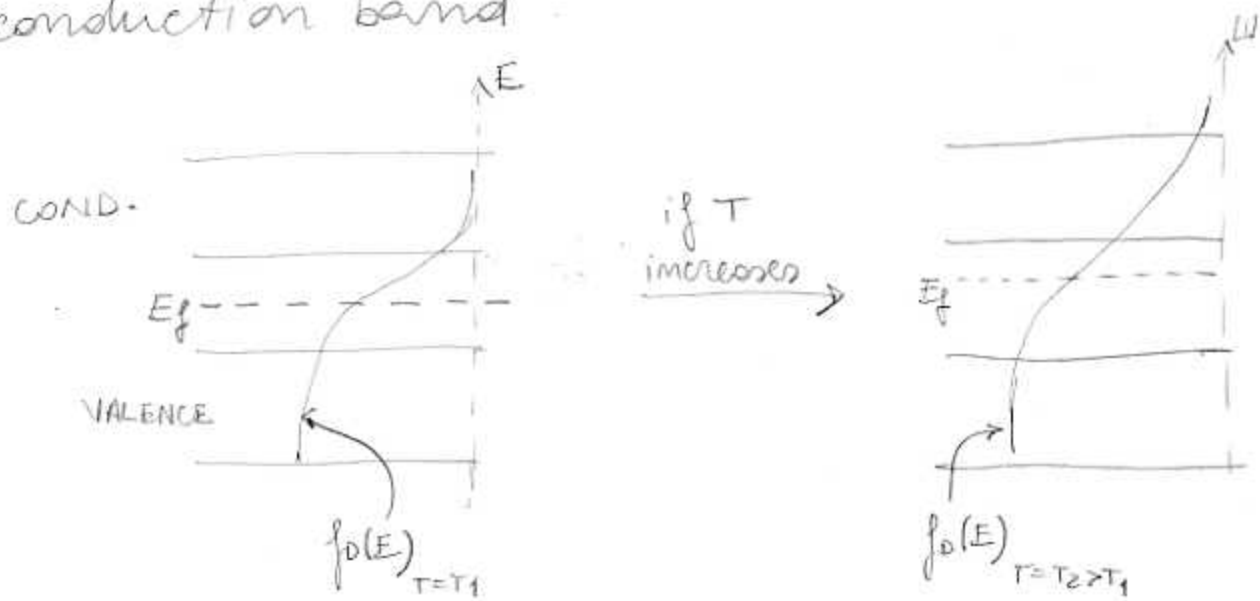
Current in a semiconductor is due to two types of charges. It is a bipolar current

LAST FACT) FERMI LEVEL

Given a system of electrons, the probability that an electron occupies an energy level E is given by the Fermi-Dirac distribution function:

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

E_f is called the "Fermi Level". For a semicond. the probability is very high if E is in the valence band and very low if E is in the conduction band

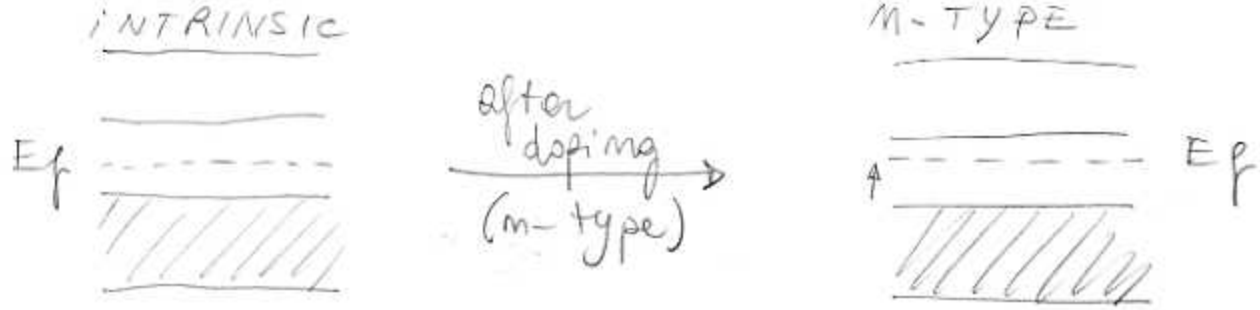


If temperature increases, then electrons have more energy to jump in te conduction band so the 'Fermi' lever increases.

In a system <u>at equilibrium E_f is constant throughout the system</u>

(Here I'm assuming that you know about doping. Read pag. 1-82 of the Reader first)

In an n-type semiconductor there are electrons in the conduction band due to doping. The probability to find an electron with energy E in the conduction band is then higher than an intrinsic semiconductor. Doping has the effect of rising the Fermi level:



For p-type semiconductor, E_f is decreased instead:

JUNCTIONS

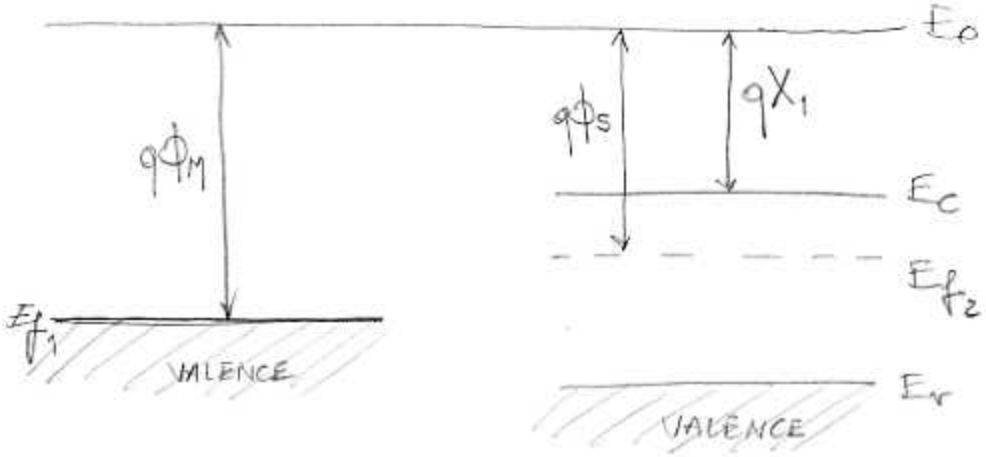
Read pag. 1-82 of the reader

Here I will give an explanation of the behaviour of a junction. Doping, current etc. are in the reader.

- ## METAL - SEMICONDUCTOR

Define E_0 the energy of a free electron or the vacuum energy. It is the energy of an electron which is not under the influence of the given material. Given a material, the distance between E_0 and the lower bound of the conduction band E_c is called electron affinity and is a constant for that material. Let's denote $(E_0 - E_c) = qX$.
Also The difference $(E_0 - E_f)$ is called work function.

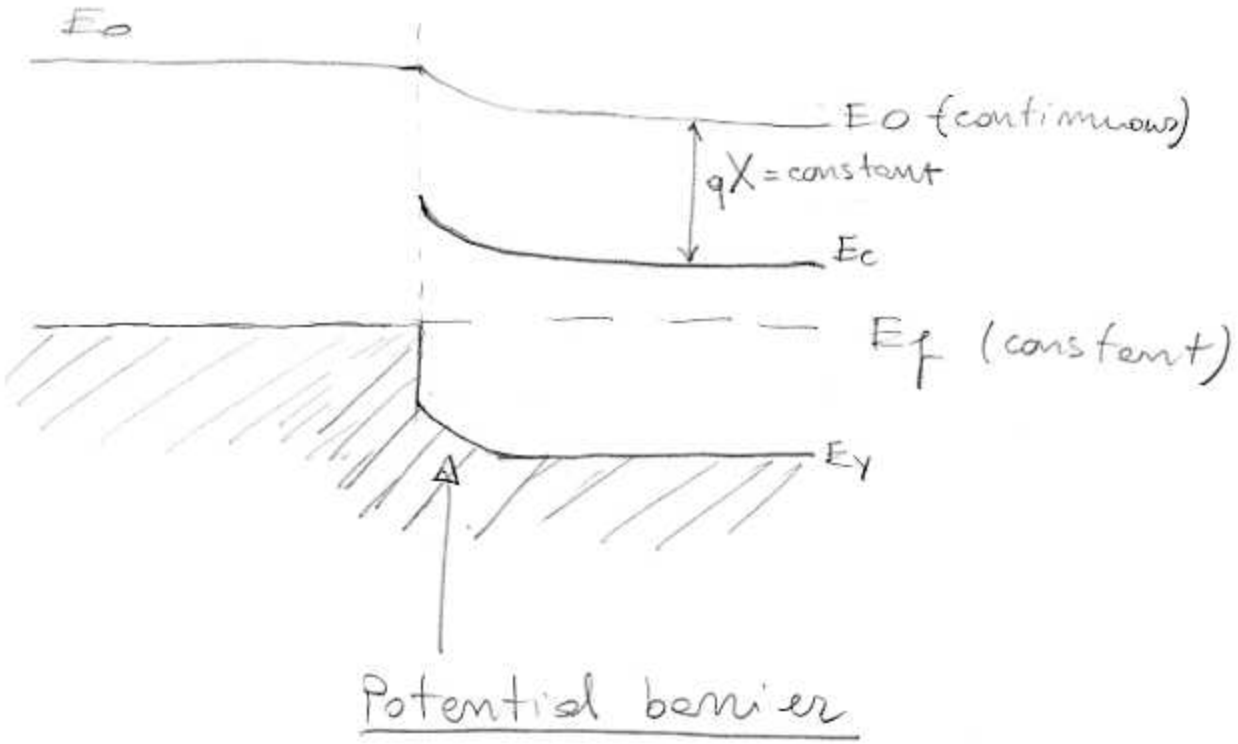
Consider a metal and a semiconductor in isolation:



For the metal the Fermi level is at the border of the only band that is available. If the two materials are in isolation than E_{f_1} could be different from E_{f_2}. When we build a junction of the two materials we have to consider the following things:

- E_0 must be a continuos function otherwise an electron moving of a quantity $dx \to 0$ (spending an energy $E \to 0$) could generate an energy $\neq 0$
- E_f is constant at equilibrium
- qX is constant and depends on the material only.

So we have the following Energy diagram for the junction:



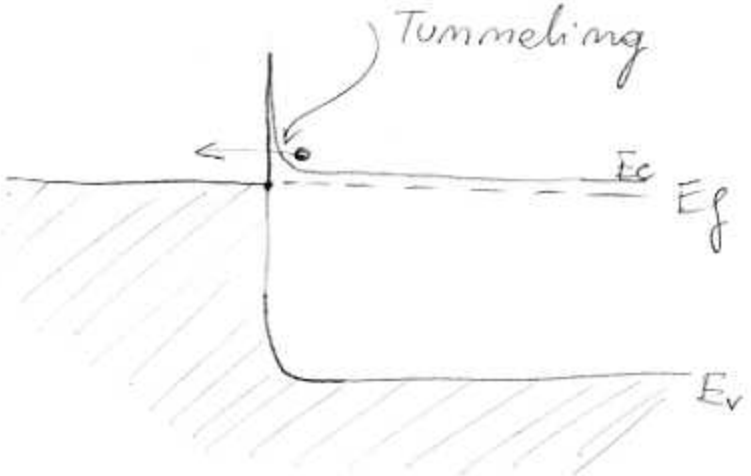
The diagram show that the electrons that want to move from the semiconductor to the metal have to gain energy, or they must have enough kinetic energy to cross the potential barrier.

Electrons can instead move from the metal to the semiconductor easily.

This is a rectifying metal-semiconductor junctions.

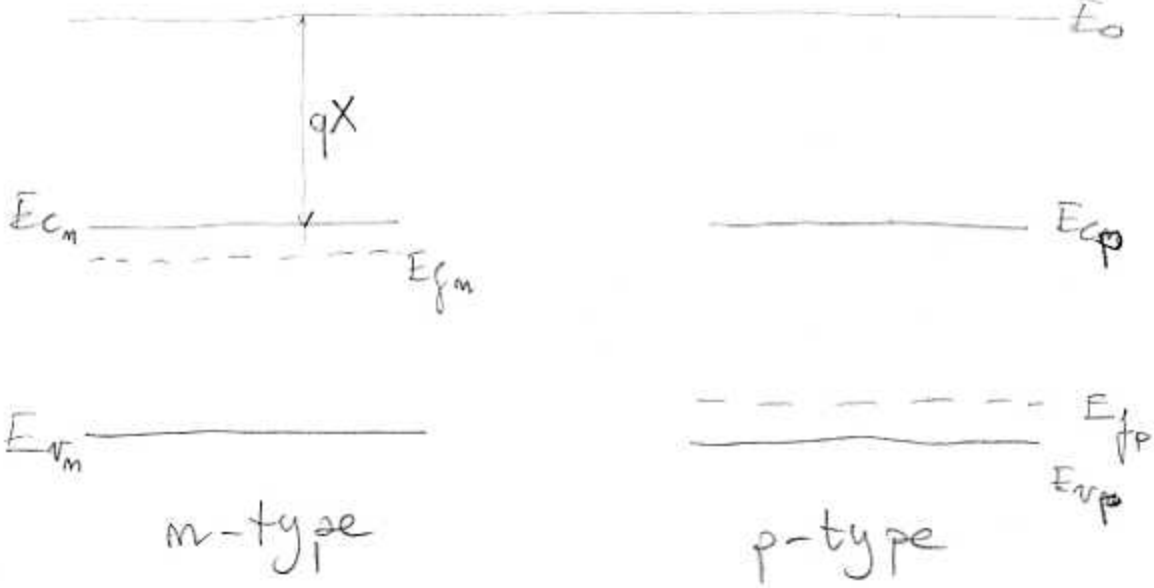
How can we make a non-rectifying contact?

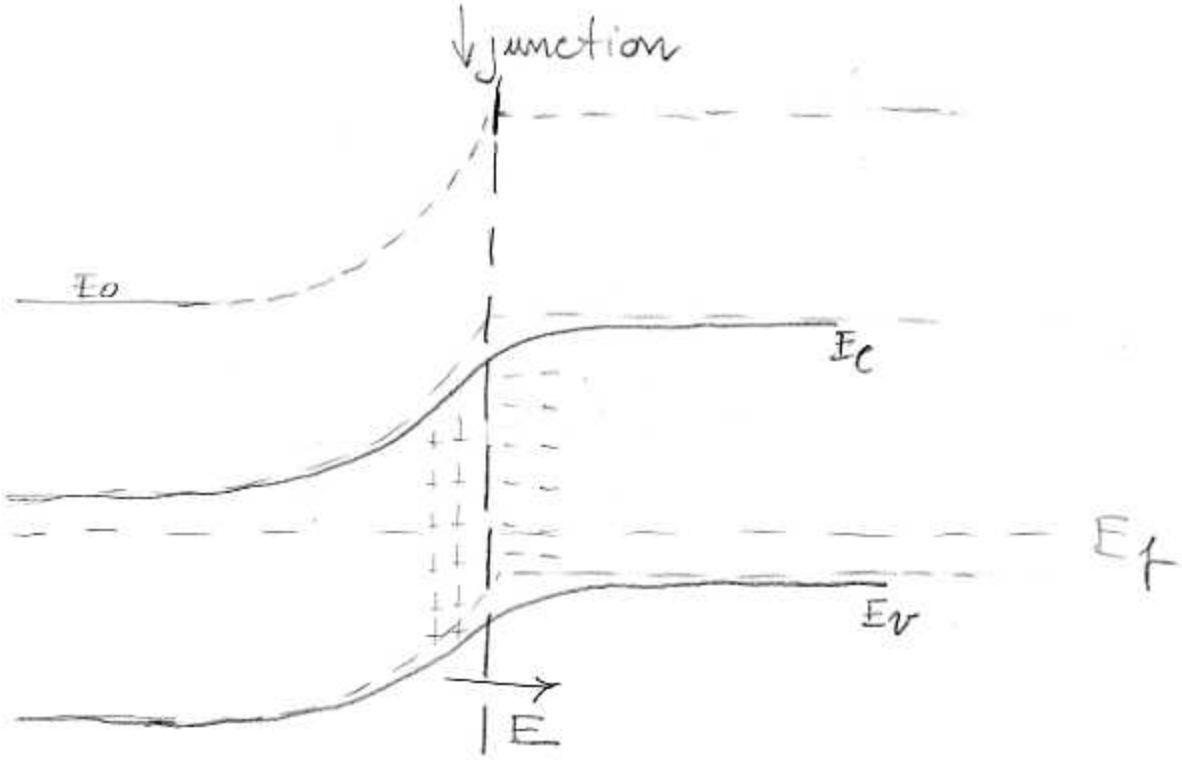
One method it to have a semiconductor heavily doped in such a way that the E_f for the semiconductor is very close to the conduction band:



If the potential barrier is very thin then the electrons can tunnel through it. The phenomenon is called tunnelling and happens when the barrier approches few nanometer.

For a p-n junction we can use the band model to explain its behaviour.





What happens is that holes will move from p to n and electrons from n to p. So there will be an induced electric field and hence a potential difference ΔV that is called built-in voltage (Read the Reader).