Semiconductors

I. Definition

Semiconductors are materials whose conductivity depends on their purity, their molecular structure, their temperature and on other physical and chemical properties.

Materials can be sorted in conductors, semiconductors and insulators according to the width of their forbidden band or band gap. It is indeed well known that the electronic structure of atoms can be described as bands. The further the band is from nucleus, the higher is the electron energy of this band. Any shift of an electron from a band to another one which is further from nucleus occur by discrete transition if one supplies enough additional energy (heat for example). The reverse process is possible and it corresponds to an energy release.

Material conductivity is determined by the electrons of the two furthest bands, the valence and the conduction bands. Electrons in valence band don't have enough energy for leaving nucleus but they can freely move around two neighbouring atoms and form a covalent bond.
Electrons in conduction band have enough energy for leaving nucleus. They move freely but in a chaotic, disordered way amongst all atom nuclei of the material. They are called free electrons. They move easily in an electric field and they create a current whose intensity depends on their amount.

i. Insulators:

- Conduction band: Empty
- Forbidden band: ΔW from 3 to 15 eV

$\Longrightarrow$Infrequent electron in valence band receive enough energy to cross the band gap. Thus conductivity is low.

ii. Conductors:

Conduction band coincides with valence band ($\Delta W = 0$). So all valence electrons in conductors are free charges.

$\Longrightarrow$High conductivity

iii. Semiconductors:

An energy gap ΔW from 0.5 to 3 eV separates the conduction band and the valence band.

$\Longrightarrow$At T = 0K (i.e. -273.15°C) valence electrons don't have enough energy to cross the forbidden band and the conduction band is empty. But, as temperature is always higher in real conditions, a thermal vibration occurs and the energy of some electrons is high enough so that they can freely move.

II. Intrinsic conductivity of some semiconductor

In electronics the following semiconductors are often used:
- Silicium (Si)
- Germanium (Ge)

- Selenium (Se)
- Gallium Arsenide (AsGa)
- ...

In this course we will only study Silicium (similar properties for other semiconductors). And first let's consider the pure cristal.

At T = 0K any atom is bound to neighbouring atoms by 4 covalent bounds.

At T $\neq$ 0K some electrons in valence band flow into conduction band and thus some covalent bounds disappear. Absence of a valence band electron in a covalent bound is equivalent to existence of a hole whose charge has the same absolute value than the electron one but the hole charge is positive. The number of free electrons is always equal to the number of holes. The higher the temperature is, the larger this number is.

Creation process of electron/hole pairs in a semiconductor is the so-called thermal generation. The reverse process is the recombination. Indeed, during its chaotic motion a free electron can encounter a hole and so create a former covalent bound. This electron is said to recombine with the hole. While flowing back from conduction band to valence band the electron energy decreases. The recombination thus releases energy.

For any temperature a dynamical equilibrium exists between the number of pairs electrons/holes which are thermally generated and recombined. It means that at a given temperature the concentration of free electrons n or the hole concentration p is constant. This constant is called the intrinsic concentration n_i.

Ex: At T = 300K, $n_i = 1{,}45.10^{10} cm^{-3}$

Any hole can attract an electron from a neighbouring covalent bound and it will create another hole. One can describe this process by saying that the hole has moved in the opposite direction of the electron one. This process doesn't correspond to any change of the electron energy. It is chaotic process as the free electron motion in cristal.

If now an electric field is generated in cristal (voltage) chaotic motions of electrons and holes are ordered and oriented. The electric current which flows through the semiconductor is made of two kinds of charge carriers, free electrons and holes, which move in opposite direction.

The conductivity depends on number and motion speed of electrons and holes. For Silicium $\sigma = 4{,}58.10^{-6} S.cm^{-1}$.

The resistance of some Silicium piece of length 3mm and of rectangular section $50 * 100 \mu m^2$ (size of electronic components) is huge: $1{,}31 G\Omega$!

<u>Conclusion</u>: <u>Pure Silicium is not appropriate for electronic devices</u> as its conductivity is too low.

III. <u>Conductivity of a doped semiconductor</u>

In order to increase Silicium conductivity and thus to use this element in electronics one increases the number of mobile charge carriers by introducing some impurities in its structure. This process is called doping. Impurities are elements which have either one extra electron or lack of one electron in comparison with Silicium electronic structure (valence band).

i) <u>N-Doping:</u>

Atoms with one extra (still if compared with Si) electron in valence band are introduced. These atoms are called donors.

The 4 valence electrons of the donor form 4 covalent bounds with its neighbouring Silicium atoms. The fifth electron is free and the donor is now a positive atom. Thus there will be more electrons than holes as some amount of holes will recombine with donor electrons.

ii) <u>P-Doping:</u>

One introduces atoms with one missing atom in their valence band. These atoms are called acceptors.
The 3 valence electrons of the acceptor will form covalent bounds with 3 neighbouring Silicium atoms. So the covalent bound with the fourth atom is still missing. Hole of this bound can be seen as mobile and the acceptor becomes a negative ion. So there will be more holes than electrons because a lot of electrons will recombine with acceptors holes.