Semiconductors

I. Definition

Semiconductors are materials whose conductivity is intermediate between that of conductors and that of insulators.

Materials	Conductivité (S/cm)
Conductors	$10^2 \sim 10^6$
Semiconductor	$10^{-6} \sim 10^2$
Insulator	$10^{-16} \sim 10^{-6}$

Unlike that of conductors and insulators, conductivity of semiconductors is highly dependent on their purity, organization and irregularities of the molecular structure, on the temperature and other physical and chemicals qualities.

This property represents their main advantage since it allows the construction of most electronic components with very diverse characteristics.

Materials can be classified as conductive, semiconductor and insulating by the width of their prohibited area. It is known that the electrons circulate around the nucleus of any atom in a layer. The farther a layer is from the nucleus, the higher the energy of the electrons in that layer. The movement of an electron from one layer to another to the outside is done discreetly (by jumping) if it is provided with additional energy (warm-up for example). Going back is possible and it is accompanied by a release of energy.

The conductivity of materials is determined by the electrons of the 2 zones furthest from the nucleus, called Valence Zone and Conduction Zone. The electrons that are in the Valence Zone don't have enough energy to detach from the nucleus, but can start circulating around 2 nuclei close together creating a covalence bond.

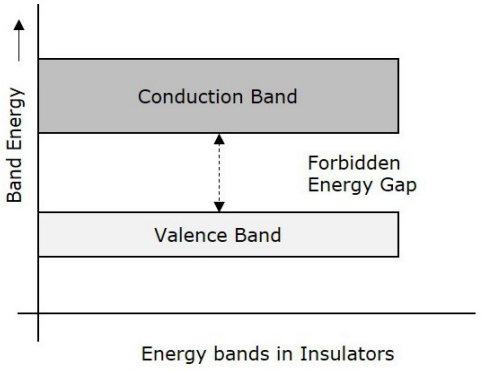
Electrons in the Conduction Zone have quite a high energy, which allows them to detach from their nucleus. They circulate chaotically among all the atom nuclei of the material. They are called free electrons. They move easily in an electric field by constituting a current whose value depends on their quantity.

✓ <u>Insulator case:</u>

- Conduction Zone : almost empty
- Forbidden Zone : ΔW (width) of 3 to 15 eV

⇒ Very few Valence electrons receive enough energy to jump the forbidden zone. Conductivity is low.

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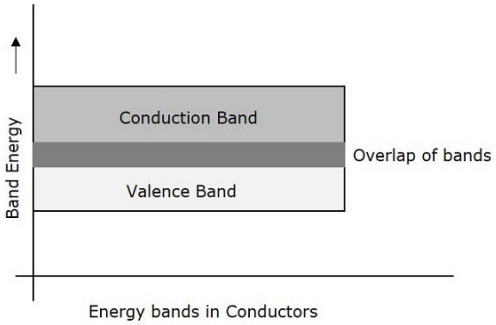


Energy bands in Insulators

✓ <u>Conductor case</u>:

The Conduction Zone coincides with the Valence Zone (ΔW = 0). In other words, all the valence electrons of conductors are free.

⇒High Conductivity

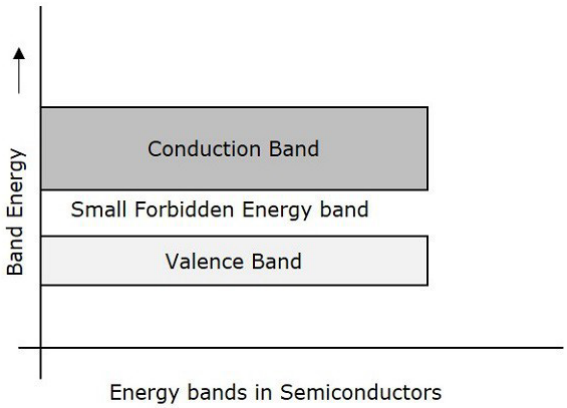


Energy bands in Conductors

✓ <u>Semiconductor case:</u>

The conduction zone is separated from the valence zone by a ΔW very weak but not zero. Basically $\Delta W = 0{,}7eV$ for Germanium and about $1{,}1eV$ for Silicium.

At $T = 0K$ (soit $-273{,}15°C$), the valence electrons do not have enough energy to jump the forbidden zone and the conduction band is empty. But when the temperature is higher (and it is still is) a thermal vibration appears and the energy of some valence electrons become quite high for them to turn into free electrons.

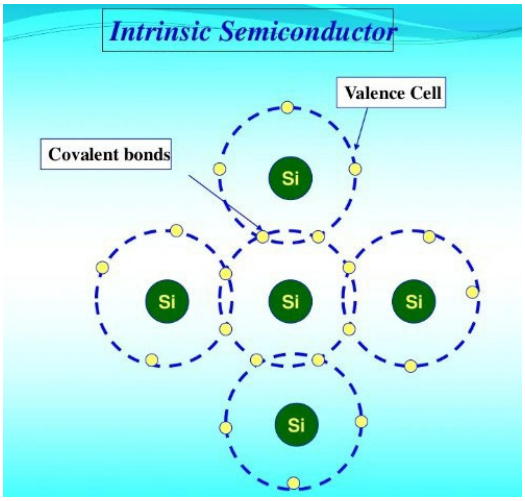


Energy bands in Semiconductors

II. Intrinsic conductivity of a semiconductor

There are several types of semiconductors used in electronics (Silicon, Germanium, etc.). We will limit our study to the case of Silicon (easy generalization for other semiconductors because same behavior). At first, we consider the «pure» component.

At T = 0K, each cristal atom is bound to the neighboring atoms by 4 covalent bonds.



For T ≠ 0 K, some electrons from the valence band pass into conduction band, causing some covalent bonds to be interrupted. The absence of a valence electron in a covalent bond ids equivalent to the existence of a hole that has in absolute value the same charge as the electron but counted positively. The number of free electrons is always equal to the number of holes. This number is all the more important the higher the temperature.

The process of creating electron/hole pair in a semiconductor is called thermogeneration. It is accompanied by the reverse process called recombination. Indeed, during its chaotic movement, a free electron can encounter a hole and thus reconstitute an interrupted covalent bond. The electron is said to recombine with the hole. During this transition from the conduction zone to the valence zone, the energy of the electron decreases, so recombination releases energy.

For each temperature, there is a dynamic equilibrium between the number of pairs of thermogenerated and recombinant electron-holes. This means that at a given temperature, the concentration of free electrons n and the concentration of holes p is constant. This concentration is called intrinsic concentration n_i.

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

A hole can attract an electron from a neighboring covalent bond that will give way to a hole. We can also say that it is the hole that moved in the opposite direction of the displacement of the electron. This process is not accompanied by a change in the energy of the electron.

It is chaotic like the movement of free electrons in the crystal.

If an electric field (voltage) is applied to the crystal, the chaotic movements of the electrons and the holes become ordered and oriented. The current that will then through the semiconductor is composed of 2 types of carriers, free electrons and holes that move in opposite directions.

Conductivity depends on the number and speed of the movement of electrons and holes. For the silicon, $\sigma = 4.58*10^{-6}$ S/cm.

It is shown that the resistance of a piece of silicon of length 3mm and rectangular section of 50x100µm 2 (dimensions of the same order of magnitude as those of electronic components) has a resistance of 1.31GΩ, which is huge.

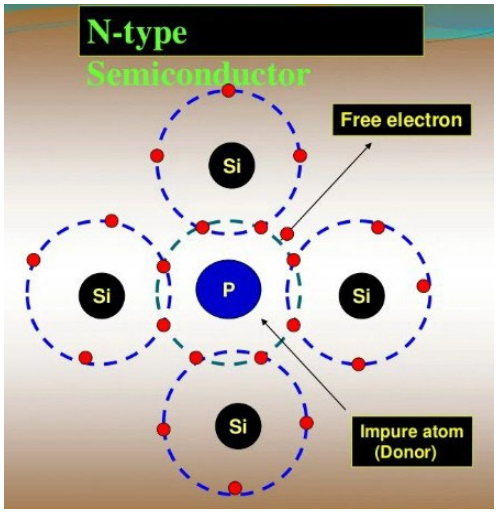
Conclusion: Pure silicon is not suitable for building electronic components because its conductivity is too low.

III. Conductivity of a doped semiconductor

To increase the conductivity of silicon and thus make it usable in electronics, the number of mobile load carriers is increased by introducing into its structure a certain number of impurities. This process is called doping. Impurities are elements with one electron more or less than silicon in their valence band.

- ✓ N Doping Type:

  Atoms with one more electron are introduced into the valence layer, such as silicon or germanium, phosphorus P, arsenic As or antimony Sb. These atoms, inserted into the crystal lattice, will form four covalent bonds with four silicon atoms, the fifth electron of the valence layer remaining free. This electron, which is only weakly bound to the atom, will be placed on an energy level closer to the conduction band. It will be enough to acquire a low additional energy ($\Delta E \approx 0.01\ eV$) to access this band. As a result, the material has better electrical conductivity.
  These free electrons do not create holes in the network, so the total number of electrons is greater than the number of holes. **Electrons** are **the majority carriers** and **holes are the minority carriers**. Dopant atoms are called donor atoms.



✓ <u>Dopage Type P :</u>

Atoms with one electron less are introduced into the valence layer such as, in the case of silicon or germanium, gallium Ga, boron B, aluminum Al or indium In. They lack an electron to complete the four covalent bonds with the neighbouring silicon atoms. A hole is created in the structure. This hole creates a new energy level close to the valence band (ΔE 0.05 eV), more easily accessible to electrons. It can be filled by an electron from another silicon atom, which in turn releases a hole and so on (figure below). The material thus becomes conductor of electricity.

As the number of holes eventually exceeds the number of electrons, the holes are the majority carriers and the electrons the minority carriers. Dopant atoms are called acceptor or receiver atoms.

