Electrotechnical Materials

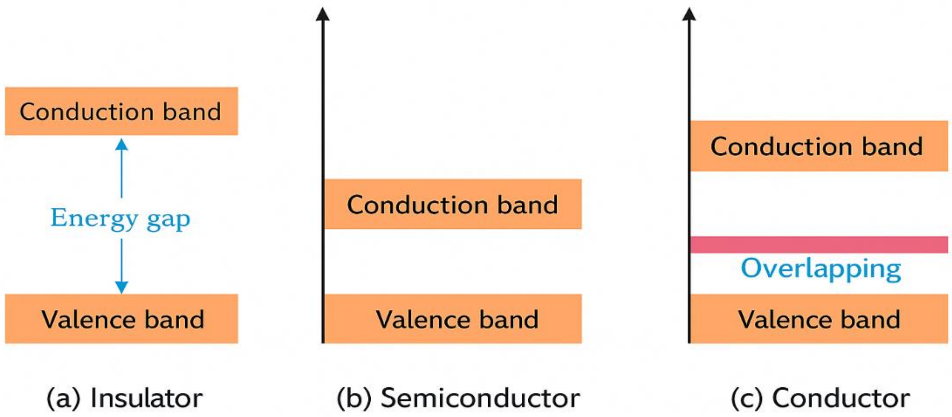
Chapter 5

Semiconductor Materials

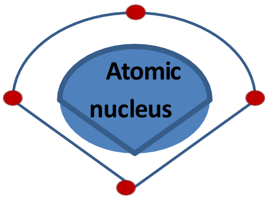
I. Introduction

Semiconductor materials constitute a foundational class of solids whose electrical behavior places them between conductors and insulators. Their distinctive property lies in the sensitivity of their conductivity to external factors such as temperature, illumination, and the controlled introduction of impurities. These characteristics arise from the electronic band structure of crystalline solids, in which the energy gap separating the valence and conduction bands governs the mobility and generation of charge carriers. A rigorous understanding of semiconductors therefore requires an examination of their atomic arrangements, intrinsic electronic properties, and the physical mechanisms that enable electron–hole pair formation and transport.

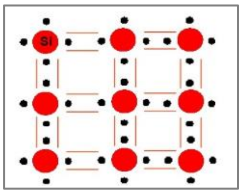
This chapter provides a systematic analysis of semiconductor materials, beginning with intrinsic semiconductors and progressing to extrinsic (doped) materials. The discussion then extends to the operation of fundamental semiconductor devices—including the PN junction diode and bipolar junction transistors—which form the basis of modern electronic and microelectronic technologies.

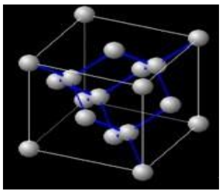


I.2. Pure or intrinsic semiconductors

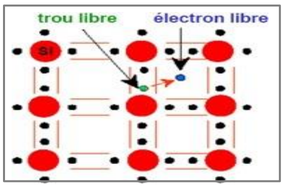


As mentioned above, a semiconductor is a material that lies between a conductor and an insulator. A pure (intrinsic) semiconductor is neither a good conductor nor a good insulator. Semiconductors are materials whose atoms contain four electrons in the valence band.





Generally, the atomic structure of a semiconductor is cubic (the same as that of diamond). Each atom is bonded to four neighbors at the vertices of a tetrahedron by a covalent bond.



Based on the periodic table, the most commonly used semiconductor elements are: silicon (Si, E_g= *1.12 eV*), germanium (*Ge*, E_g= *0.66 eV*), and carbon (*C*, E_g= *5.47 eV*).

In a pure semiconductor, the gap is small enough to allow a small number of electrons to pass from the valence band (VB) to the conduction band (CB) at room temperature. The electron in the CB becomes free. It leaves an excess of positive charge in the VB, the "hole," which in turn will be filled by a neighboring electron. Each electron (positive mass, negative charge) corresponds to a hole (negative mass, positive charge). Generation of electron-hole pairs.

The neutrality of the material requires that the holes (p) and electrons (n) be in equal numbers, which depends on the temperature and the gap (Si or Ge). The movement of electrons in one direction corresponds to the opposite movement of holes.

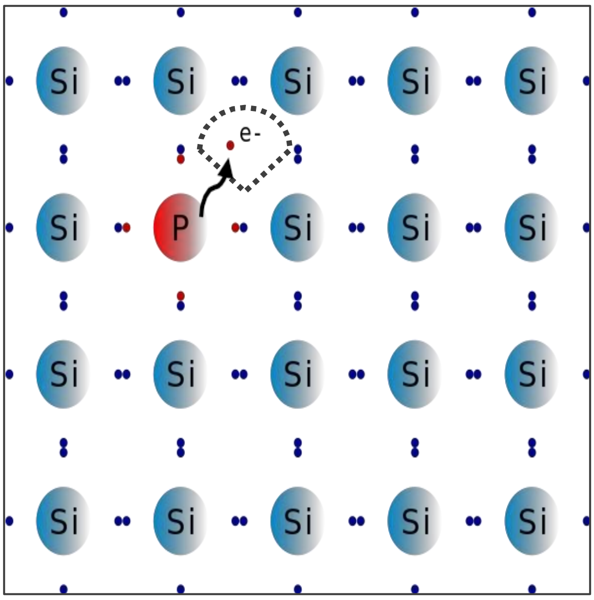
I.3. Doped or extrinsic semiconductors

Doping involves introducing impurities to increase the number of free electrons or holes. This results in extrinsic conduction. There are two types of doped semiconductors:

- N-type semiconductor: Increase in the number of electrons
- P-type semiconductor: Increase in the number of holes

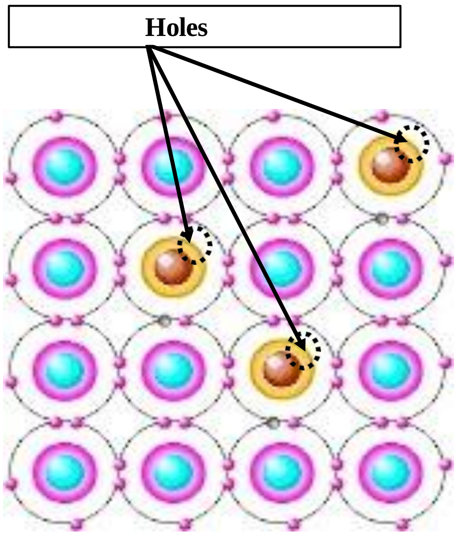
I.3.1. N-type semiconductors

To obtain this type of semiconductor, pentavalent impurity atoms (5 electrons in the valence layer) such as phosphorus (P), arsenic (AS), and antimony (Sb) are introduced into the pure silicon crystal. Each impurity atom brings a valence electron (the valence orbit can only accept 8e). This electron, which is weakly bound to the nuclei (E~0.01eV), quickly becomes free in the BC. Each pentavalent or donor atom thus generates a free electron. Electrons are the majority carriers, while holes are the minority carriers. Conduction is ensured.



Therefore, based on electrons: the semiconductor is N-type (N comes from the negative charge of the electron).

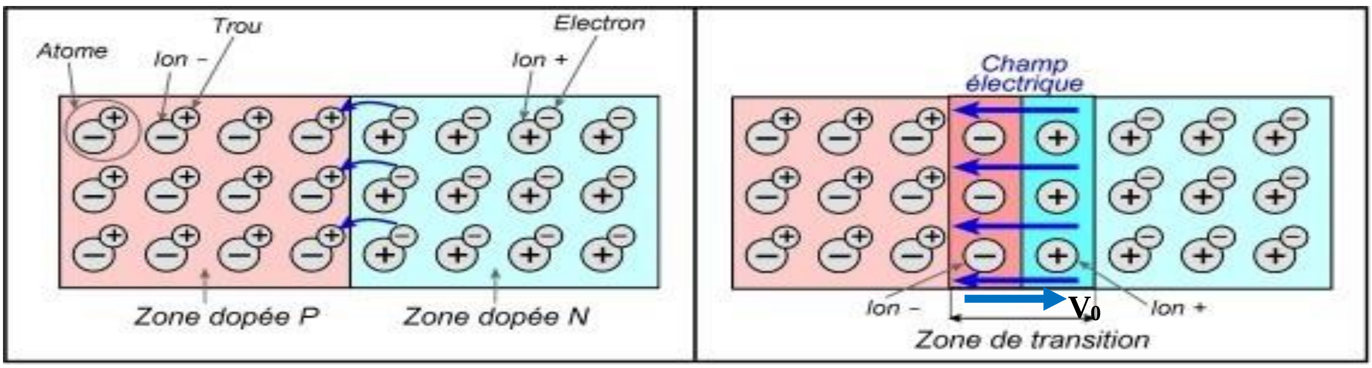
I.3.2. P-type semiconductors:



For this type of semiconductor, trivalent impurity atoms (3 electrons in the valence shell) such as boron (B), aluminum (Al), gallium (Ga), or indium (In) are introduced into the pure silicon lattice. Since the valence orbit can only accept eight electrons, each impurity atom creates an excess hole. This location or hole is quickly filled by a neighboring electron (E~0.05eV) and moves easily in the BV. Each trivalent atom or acceptor thus generates a mobile hole. In this case, the holes are the majority carriers and the electrons are the minority carriers. Conduction is therefore provided by the holes: The semiconductor is P-type (P comes from the positive charge of the holes).

I.3.3. PN junction diode

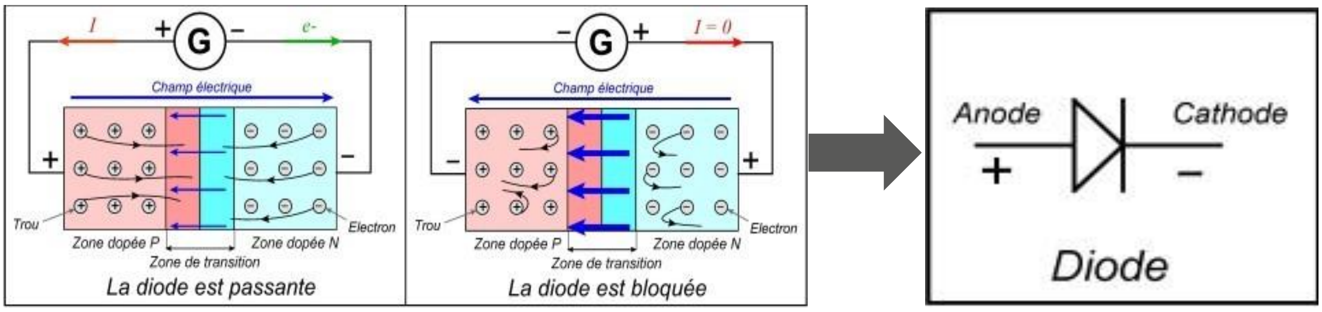
When a P-doped semiconductor is brought into contact with an N-doped semiconductor, a PN junction is created. Some electrons from the N region migrate to the P region to combine with the holes. When the electron leaves its atom, the atom becomes positively ionized. When the electron combines with a hole, the hole-carrying atom becomes a negative ion. This creates a transition layer with a thickness $\boldsymbol{\varepsilon}$ $(\varepsilon < 1\mu)$ at the interface between the P and N zones. In this layer, the ions produce a potential difference (V_0≈0.6~0.7V) and an electric field (K_0). Under normal conditions, this field opposes the passage of majority carriers and only favors the passage of minority carriers. Therefore, without external excitation, the transition layer only allows the passage of a very weak current (practically negligible).



The behavior of a PN junction can only be seen if it is biased by connecting it to a DC voltage source (battery), in which case:

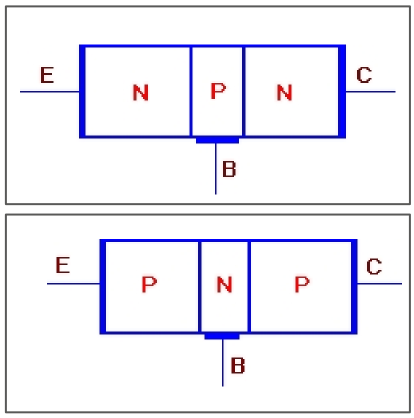
* If the junction is biased in the forward direction (positive terminal (+) on the P-doped side and negative terminal (-) on the N-doped side) with a voltage greater than V_0, the electric field imposed by the generator opposes the internal electric field, allowing charge carriers to cross the junction: the junction is conductive, allowing electric current to pass through.
* If the junction is reverse biased, the electric field due to the generator is added to the internal field, preventing the charge carriers from passing: the junction is blocked, and no current flows.

The polarized junction expresses the behavior of one of the most widely used electronic components, the ***diode***.



I.3.4. Transistor - NPN/PNP junction:

A transistor is a device consisting of three semiconductor regions arranged side by side in such a way that two consecutive regions are of different types. With this system, only two types of transistor can be obtained:

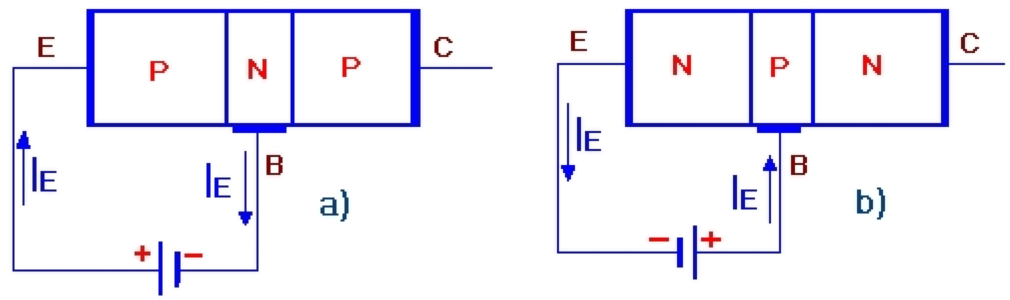


- An NPN transistor: A P semiconductor region is inserted between two N semiconductor regions.
- A PNP transistor: An N semiconductor region is inserted between two P semiconductor regions.

In both structures, the terminals are labeled with three letters: Emitter (E), Collector (C), and Base (B).

- For a transistor to function normally, whether it is PNP or NPN type, the ***emitter-base*** junction must be forward biased while the collector-base junction must be reverse biased.

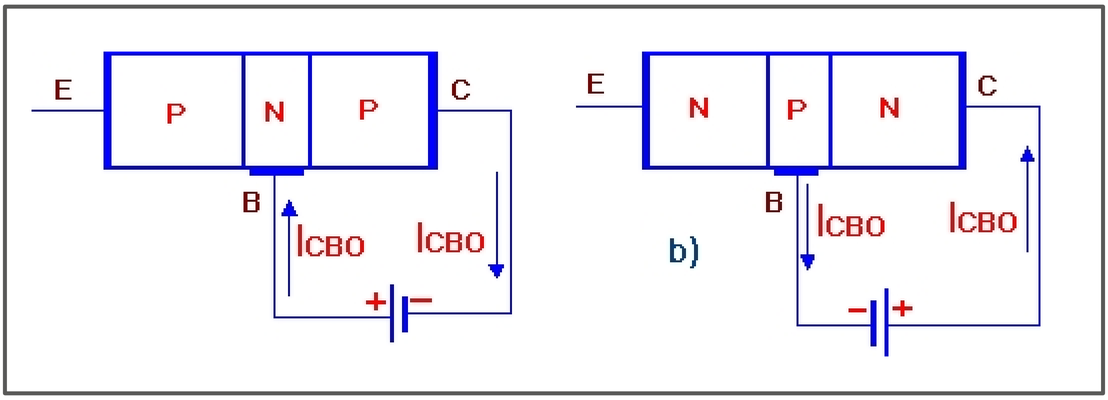
  Similar to what happens in a diode, a forward current called the emitter current and designated IE flows.



Forward biasing of the emitter–base junction

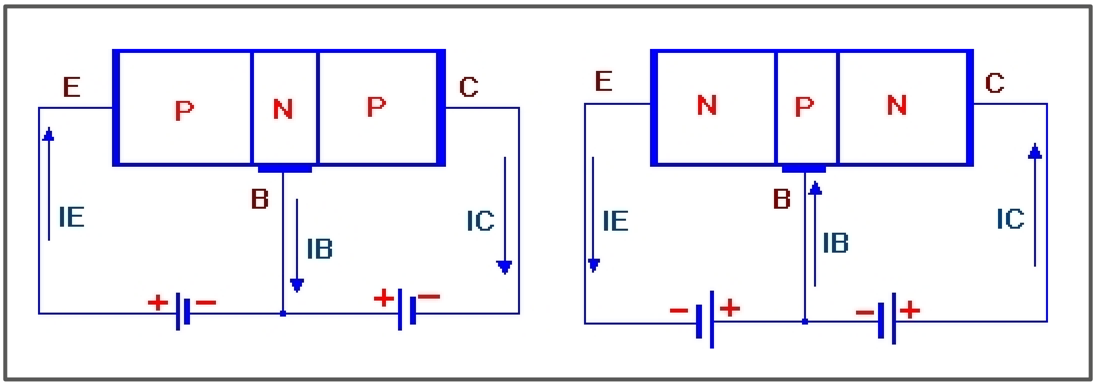
- For reverse bias, the ***collector-base*** junction must be reverse biased. A very weak reverse current called residual current, denoted by ICB0, flows. This symbol

  indicates that this is the current flowing through the collector-base junction when the emitter-base junction is not biased (IE = 0).



- Normal operation of a transistor: If the two junctions of a transistor are biased separately, each one behaves like a perfect diode. In practice, they are

  When both are polarized simultaneously, the transistor behaves differently. In this case, the emitter current can influence the collector current ICB0, causing the latter to be almost equal to the current IE.



I.4. Applications of semiconductors

It is not difficult to imagine what life would be like without semiconductors. Several components, the best known of which are transistors and diodes, function thanks to the special properties of semiconductors. These components are found in televisions, radios, calculators, telephones, computers, industrial control devices, aircraft autopilot instruments, rockets, spacecraft, satellites, etc.