Chapter III : Undoped and Doped Semiconductor

III.1. Introduction

Semiconductors are materials whose electrical conductivity lies between that of conductors and insulators. Their unique electrical behavior is primarily determined by their electronic structure and can be significantly modified through doping. Based on the presence or absence of impurities, semiconductors are classified into **intrinsic** and **extrinsic** types.

III.2. Intrinsic semiconductor

A semiconductor is referred to as **intrinsic** when its crystal is pure, meaning it is not contaminated by impurities that could alter the concentration of free charge carriers. At temperatures above absolute zero (0 K), some electrons can gain enough energy to transition from the **valence band (VB)** to the **conduction band (CB)**. These excited electrons are considered free carriers and have a concentration denoted by **n**. Their absence in the VB creates **holes** with a concentration **p**, which are also mobile. In an intrinsic semiconductor, the number of electrons and holes is equal, and both are referred to as the **intrinsic carrier concentration**, denoted by $\mathbf{n_i}$ (in cm^3), and given by the expression:

$$n = p = n_i(T) = A.T^{\frac{3}{2}}.\exp(-\frac{E_g}{2K.T})$$

Where :

A is a material-dependent constant;

Eg is the energy bandgap;

K is Boltzmann's constant $=8.62.10^{-5}$ $eV.K^{-1}$;

Note: To express Boltzmann's constant in **J /K** , multiply it by the elementary charge q= $1,60 \times 10^{-19}$ C.

K $=8.62.10^{-5} \times 1,60 \times 10^{-19} = 1.380649 \times 10^{-23}$ $J \cdot K^{-1}$).

Example :

At **300 K**, the intrinsic carrier concentration of **silicon** is 1.45×10^{10} cm^{-3}, and the energy gap **Eg = 1.12 eV**. Calculating the constant A gives:

$$A = 1.49 \times 10^{16} cm^{-3}.K^{-3/2}$$

According to statistical mechanics, the populations of free carriers (electrons **n** in the CB and holes **p** in the VB) follow:

$$n = N_c \exp\left(-\frac{\Delta E_n}{KT}\right)$$

$$p = N_v \exp(-\frac{\Delta E_p}{KT})$$

$$n_i = n = p$$

With :

- Nc and Nv : Effective density of states in the CB and VB respectively (Silicon at 300K : Nc = 2.82×10^{19} cm^{-3} , Nv = 1.83×10^{19} cm^{-3}).
- $\Delta E_n = E_c - E_{Fi}$ *and* $\Delta E_n = E_{Fi} - E_v$ are energy differences relative to the intrinsic Fermi level E_{Fi}

Hence :

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_v)}{KT}\right] = N_c N_v \exp\left[\frac{-E_g}{KT}\right]$$

- **k** is Boltzmann's constant.
- T is the absolute temperature in Kelvin.

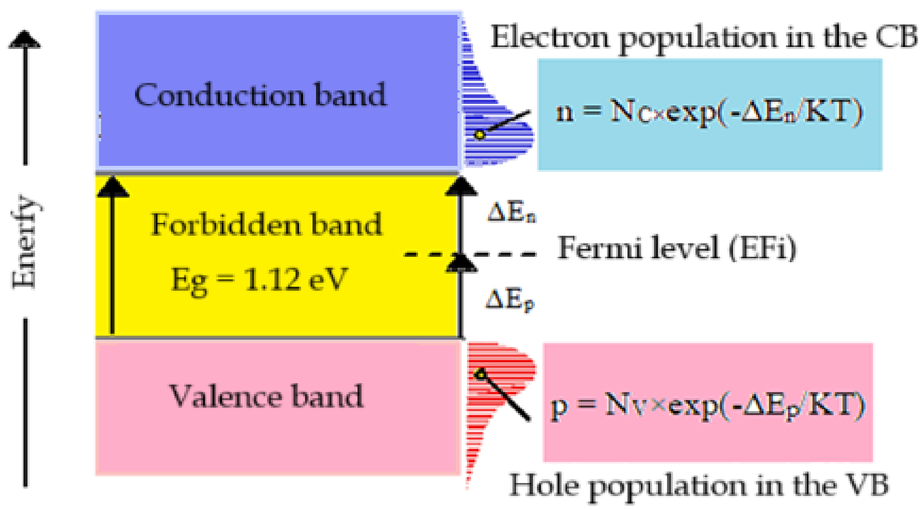


Figure III.1: Electron and hole populations in intrinsic silicon and position of the Fermi level

E_{Fi}

- **Law of mass action :**

For any semiconductor:

$n.p = n_i^2$

This relationship always holds at equilibrium.

Intrinsic conductivity $\sigma_i(T)$:

$$\sigma_i(T) = q.n_i(T).(\mu_n + \mu_p)$$

Where :

$q = 1.6\times 10^{-19}$C (elementary charge);

$n_i(T)$: intrinsic carrier concentration [m^{-3}] ;

μ_n and μ_p : mobilities of electrons and holes [$m^2\ V^{-1}S^{-1}$].

II.3. Extrinsic semiconductor - Doping :

Pure intrinsic semiconductors have limited practical application. Most electronic components use **doped** semiconductors, called **extrinsic semiconductors**.

Doping involves introducing a very small amount of foreign atoms, called **dopants**, into the intrinsic crystal. For common semiconductors like **Silicon (Si)** and **Germanium (Ge)**, typical dopants include:

- **Pentavalent elements** (five valence electrons): Examples: Arsenic (As), Antimony (Sb), Phosphorus (P)
- **Trivalent elements** (three valence electrons): Examples: Boron (B), Gallium (Ga), Indium (In)

These dopants are introduced in extremely low concentrations (about one dopant atom per 10^6 semiconductor atoms).

II.3.1. N- Type semiconductor

Consider a crystal made of a group-IV element like **Silicon**. When a **pentavalent dopant** is introduced, it forms bonds with four neighboring atoms, but one extra electron remains unbonded. This excess electron becomes **free** and contributes to conduction..

Such a dopant is called a **donor (N)** because it **donates electrons** (negatively charged carriers). Once the electron is released, the dopant atom becomes a **positively charged fixed ion**, increasing the material's conductivity. The electrons are the **majority carriers** in n-type materials. Pentavalent dopants are often referred to as **donor atoms**.

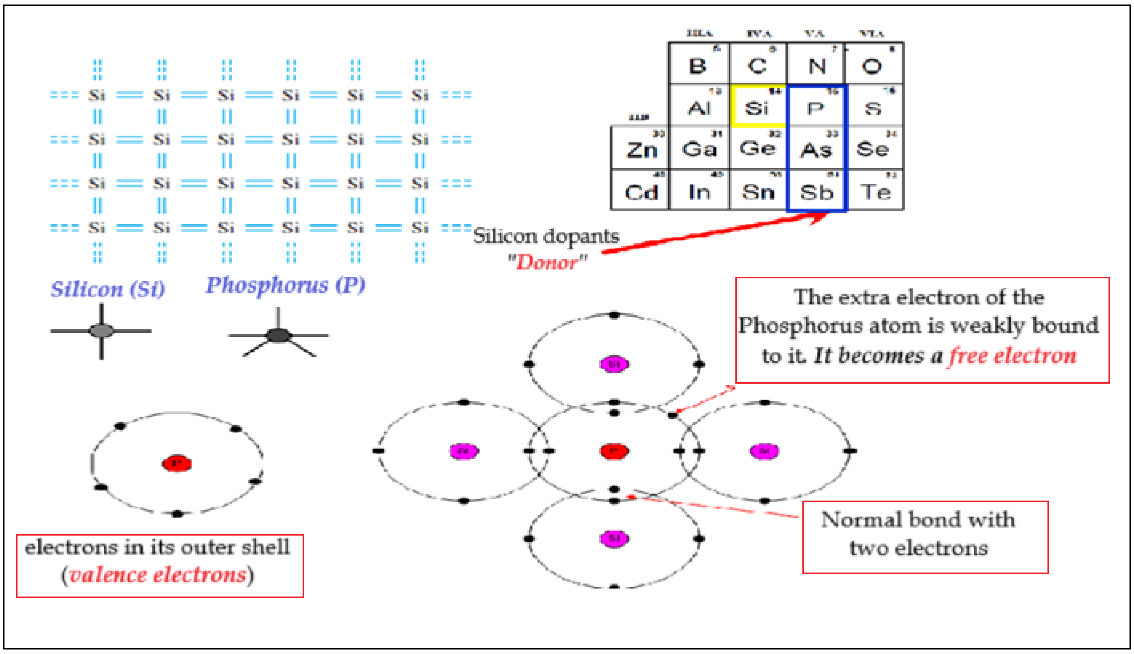


Figure III.2: A phosphorus atom incorporated into a semiconductor crystal

- **Donor Energy Level Definition** (E_d)

The presence of impurities significantly alters the electrical properties of the semiconductor. When a group-V atom like **phosphorus** replaces a **silicon** atom, it forms bonds with four neighbors and has **nine electrons** in total—eight form bonds and one is loosely bound.

This extra electron occupies a more delocalized orbital due to the positive charge of the P^+ ion. The **donor energy level** is given:

$$E_D = E_C - E_d.$$

Where: *E*D is the energy level of the donor impurity.

At room temperature, this electron is easily thermally excited into the conduction band, leaving behind a **P^+ ion**. Phosphorus is called a **donor** because it donates a conduction electron to the crystal.

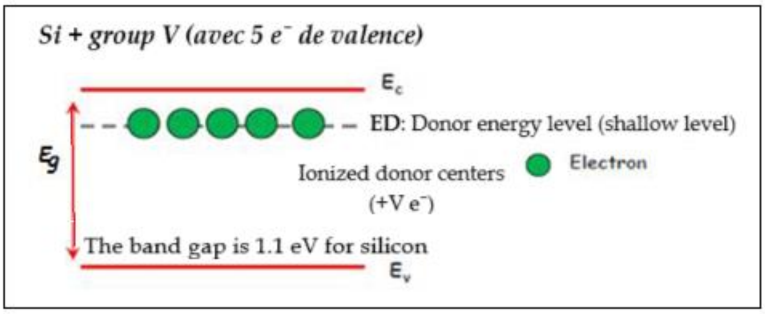


Figure III.3: N-type semiconductor

II.3.2. P-Type semiconductor:

In this case, the dopant is a **trivalent element**. When integrated into the crystal, the dopant can only form **three bonds**—one bond is left **incomplete**, creating a **hole** that can accept an electron.

A nearby electron may fill this hole, making the dopant an **electron acceptor (P)**. As a result, **holes** become the **majority carriers** and conductivity increases. These trivalent dopants are referred to as **acceptor atoms** because each hole they generate can later **accept an electron** during recombination.

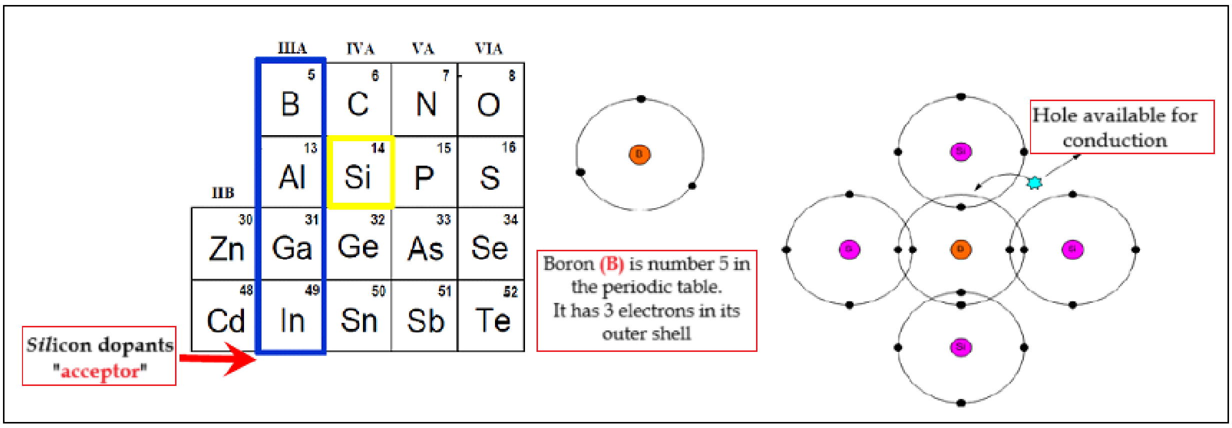


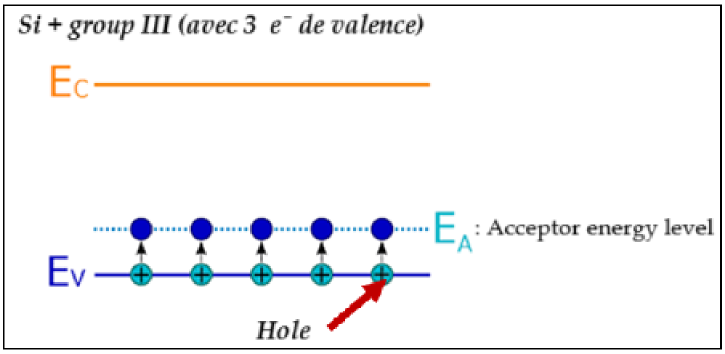
Figure III.4: A boron atom incorporated into the semiconductor crystal.

- **Acceptor Energy Level Definition (E_a)**

When a group-III atom like **Boron** replaces a silicon atom, it lacks one electron to complete the four required bonds. An electron from a neighboring bond may fill the missing spot, creating a **hole** in the valence band, and a **negatively charged ion B^-**

This process defines the **acceptor energy level**, given by: $E_A = E_a - E_V$

Where **E_A** is the energy level of the acceptor impurity. The **binding energy** of the hole to the acceptor is typically in the range of a few tens of meV.



FigureIII.5: P-type semiconductor