Electronic Devices

Lecture 5

14-08-2018

Charge Carriers in Semiconductors

innovate achieve lead

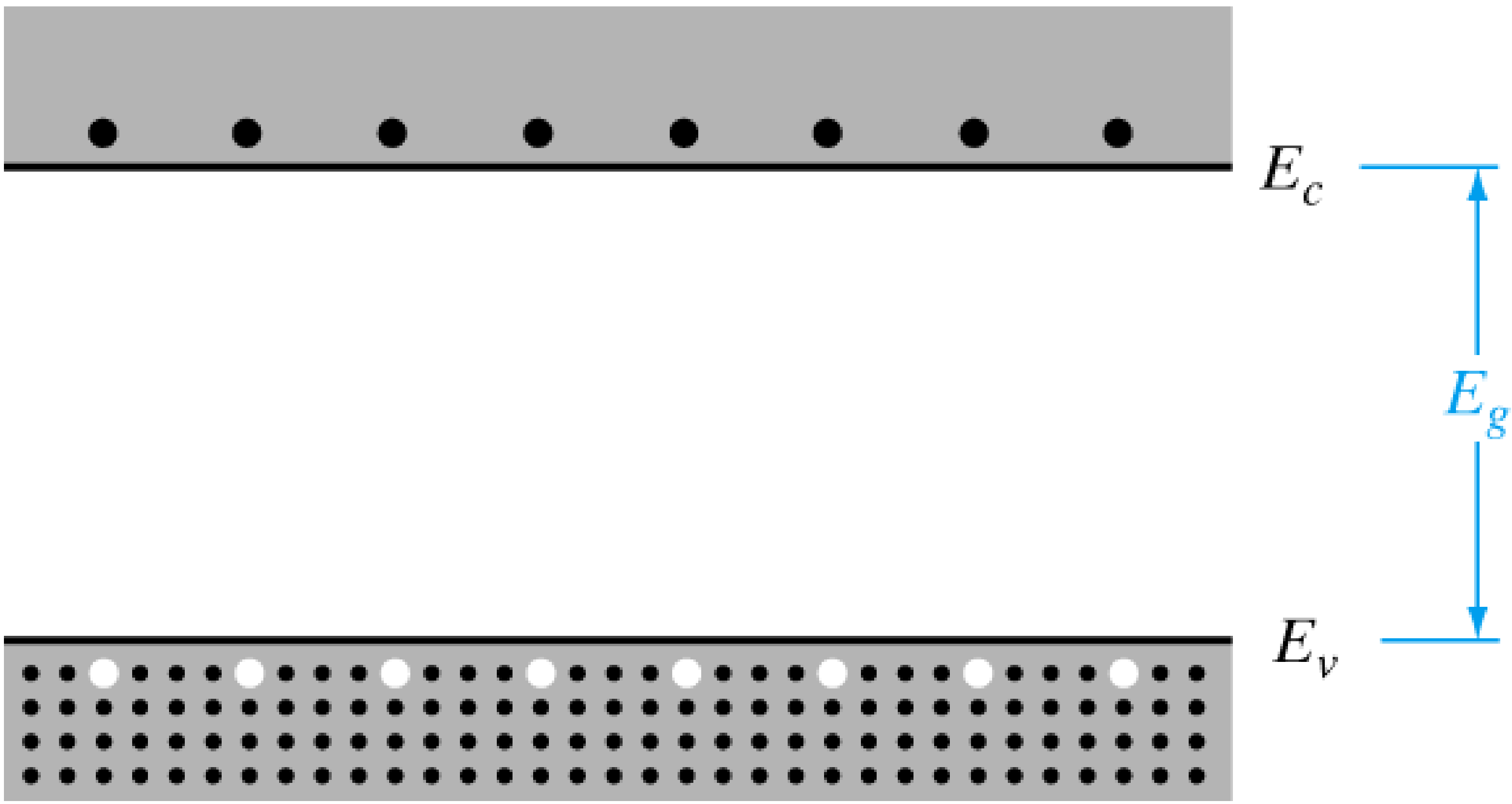
- **Consideration of Current Conductions** :

- **Metals** : Metal atoms are imbedded in a "sea" of free electrons, and these electrons can move as a group under the influence of an electric field.

- **Semiconductors** : Since the semiconductors has a filled valence band and an empty conduction band at **0K**, the increase of electrons in conduction band by thermal excitations across the band gap must be considered as the temp. is raised. In addition, after electrons are excited to the conduction band, the empty states left in the valence band can contribute to the conduction process. Also, the introduction of impurities is considered to have an important effect on the energy band structure and on the availability of charge carriers.

- **Electrons & Holes** : As the temp. is raised from 0K, some electrons in the V.B. receive enough thermal energy to be excited across the band gap to the C.B., and this results in a semiconductor with ***some electrons in an otherwise empty C.B.*** and ***some unoccupied states (called holes) in an otherwise filled V.B.***

Electron-hole pairs in a semiconductor.



Electron-Hole Pair (EHP)

- **EHP = A pair of conduction band electron and valence band hole** created by the excitation of a valence band electron to the conduction band.

- Equilibrium number of EHPs in pure Si at RT = **1.5×10^{10} EHP/cm^3**

- Si atom density = **5×10^{22} atoms/cm^3**

→ Very few electrons are free to move about via the many available empty states

In the filled valence band, all available energy states are occupied. For every electron moving with a given velocity, there is an equal and opposite electron motion elsewhere in the band. If we apply an electric field, the net current is zero because for every electron **j** moving with velocity $\mathbf{v_j}$, there is a corresponding electron **j´** with velocity $\mathbf{-v_j}$.

With **N** electrons/cm^3 in the band, the current density **J** :

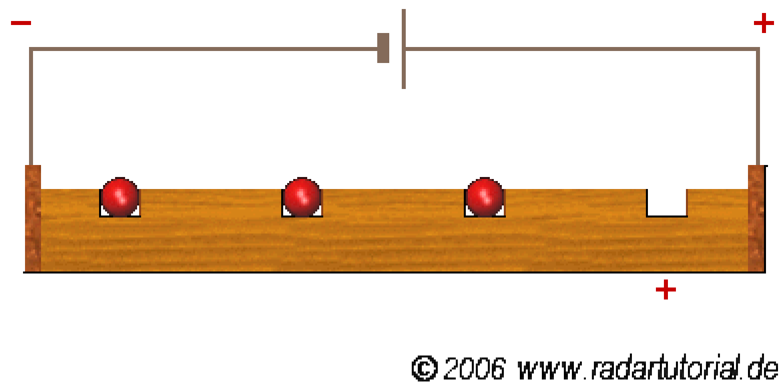
$$J = (-q)\sum_i^N V_i = 0$$

(filled band),

If we create a hole by removing the **j-th** electron, the net current J in V.B. will be,

$$J = (-q)\sum_i^N V_i - (-q)V_j = qV_j \quad \textbf{(j-th electron missing)}$$

Hole movement in a Semiconductor



http://www.radartutorial.eu/21.semiconductors/hl06.en.html

Intrinsic Semiconductor Materials

When a Si valence electron is broken away from its position in the bonding structure and it becomes free to move around in the lattice, a conduction electron is created, leaving behind a broken bond (as a hole). In this case, **the band gap energy (E_g) is just the energy required to break the bond.**

At steady state, since the carrier concentration should be maintained steady, there must be recombination of EHPs **at the same rate at which** they are generated. In equilibrium state, $r_i = g_i$ (EHPs/cm^3-s) and

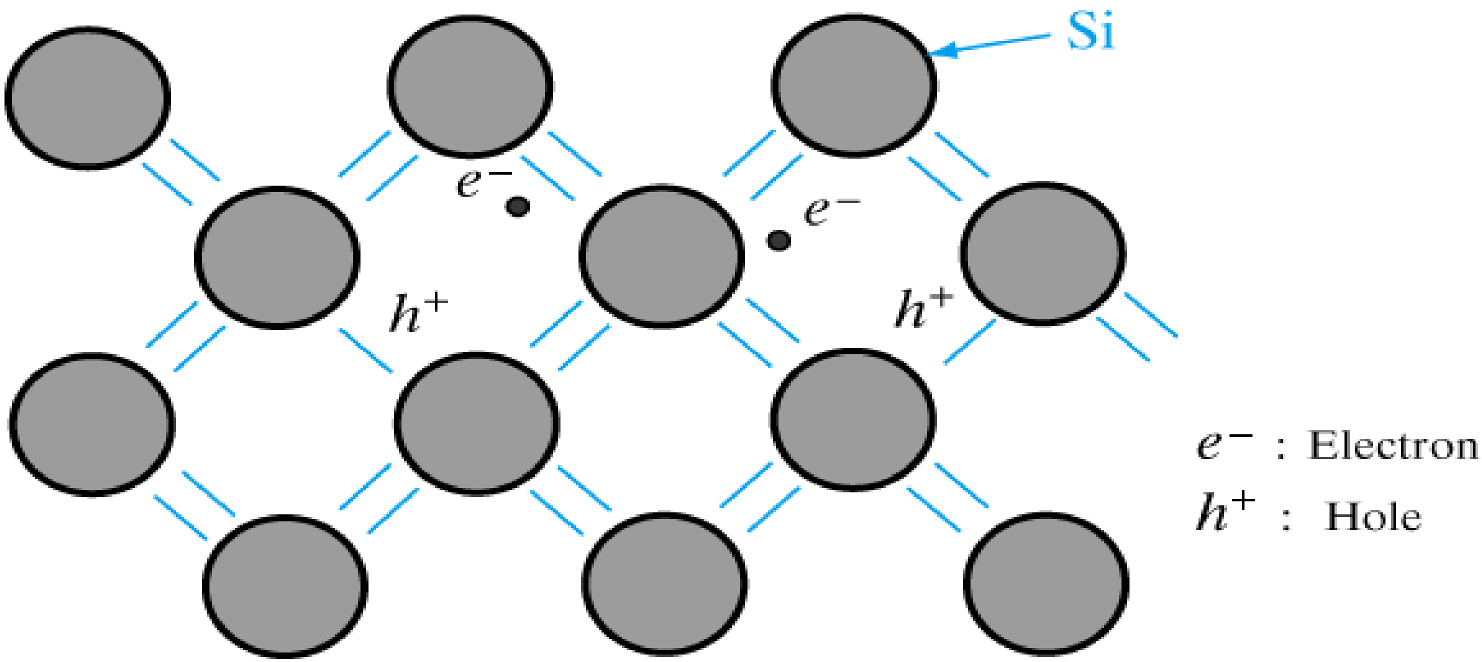
if n_0 = ***equilibrium conc. of electrons and*** p_0 = ***equilibrium conc. of holes,*** then

$$r_i = \alpha_r n_0 p_0 = \alpha_r n_i^2 = g_i$$

(α_r = recombination constant)

Bonding Model of Si : Qualitatively

$$n = p = n_i$$



Extrinsic Semiconductor Material

Extrinsic Material: the semiconductor crystal where the equilibrium carrier concentrations $\mathbf{n_0}$ and $\mathbf{p_0}$ are different from the intrinsic carrier concentration $\mathbf{n_i}$ (**due to impurity doping**).

Impurities or lattice defects are introduced into otherwise perfect crystal, which in turn, create additional levels in the energy band structure usually within the band gap.

Extrinsic Semiconductor Material

- Column V elements (donor impurities: P, As, Sb):
- A "**donor**" energy level formation near conduction band (C.B.) → **n-type** material $\mathbf{n_0} >> (\ \mathbf{p_0}\ ,\ \mathbf{n_i})$

* The material doped with donor impurities can have a considerable conc. of electrons in C.B. (**due to the donor energy level**), <u>even when</u> the temperature is too low to generate an appreciable intrinsic EHP concentration. This donor energy level is filled with electrons at 0K, and very small thermal energy can cause these electrons to excite to C.B. At 50-100K, almost all electrons in the donor impurity level are donated to C.B.

Energy Band diagram of a n-type Semiconductor

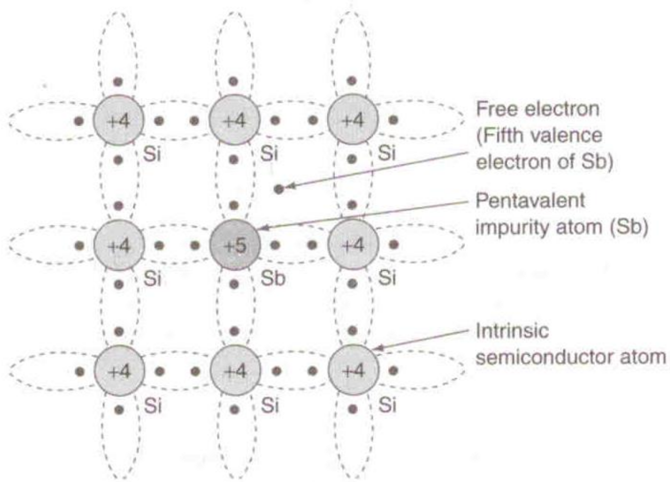


Figure 1.8 | Crystal structure of an N-type semiconductor.

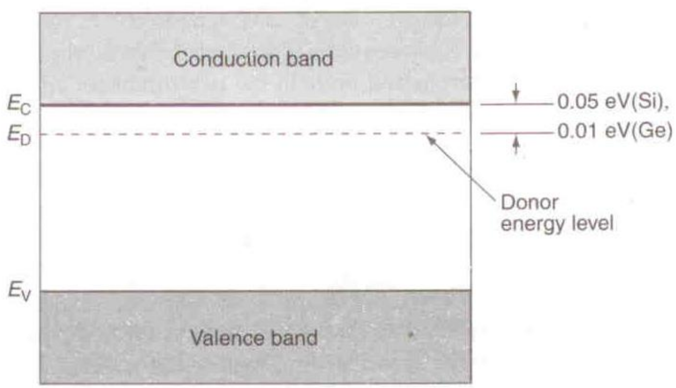
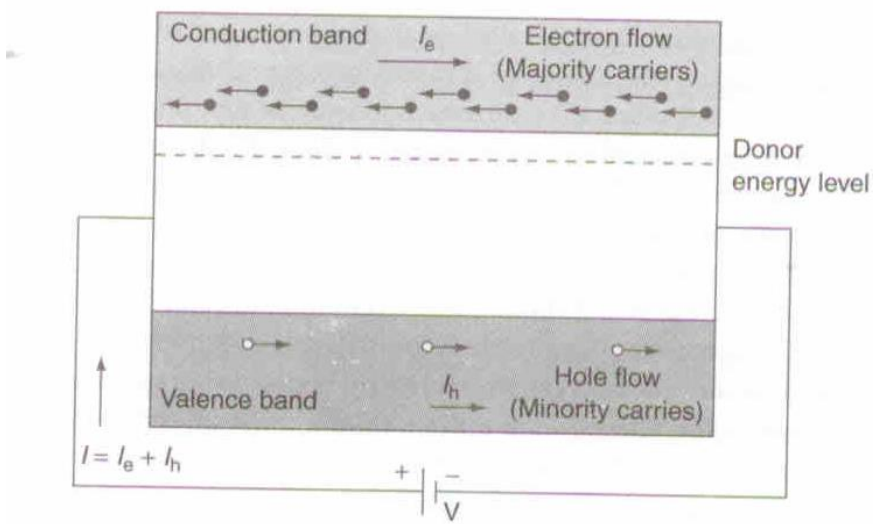


Figure 1.9 | Energy band diagram of an N-type semiconductor.



Group V Impurity Atom

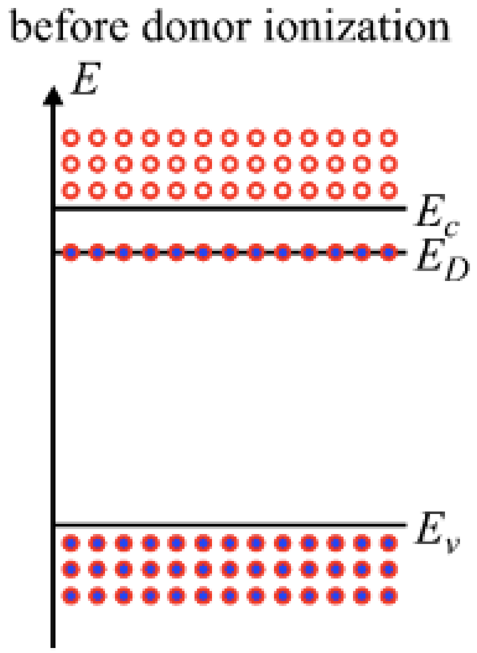
- An atom from group V of the periodic table has one more nuclear proton and valence electron than silicon

II	III	IV	V	VI
	B 5	C 6	N 7	O 8
	Al 13	Si 14	P 15	S 16
Zn 30	Ga 31	Ge 32	As 33	Se 34
Cd 48	In 49	Sn 50	Sb 51	Te 52

- If the atom replaces a silicon atom in the lattice, the extra electron can move into the conduction band (ionization)
- A group V atom is a donor since it donates an electron to the silicon lattice
- Density of donor dopant atoms given symbol N_D (cm^{-3})

Donor Ionization - Energy Band Diagram

- Extra electrons in donor atoms are at a donor energy level E_D just below the silicon conduction band (E_C-E_D $\approx$ 0.05 eV)
- Small energy will move extra electrons into conduction band
- Therefore, at room temperature virtually all donors are ionized



Donor Doping -Electron and Hole Densities

- Since virtually all donors are ionized at room temperature (complete ionization), and N_D is normally much larger than n_i, the electron density n is essentially just the density of donors, with p given by the mass action law

$$n = N_D \qquad p = \frac{n_i^2}{n} = \frac{n_i^2}{N_D}$$

- Since $n >> p$ for donor doping, the material is termed n-type, electrons are called the majority carriers and holes the minority carriers
- Donor doping allows direct control of n

A sample of silicon is doped with 10^{16} /cm^3 of Arsenic (As), a group V atom. What are the concentrations of electrons and holes?

- Since Arsenic is a group V atom, it functions as a donor, and the doped material is therefore *n*-type. The density of electrons is essentially equal to the density of donors, so

$$n = N_D = 10^{16} \ /\text{cm}^3$$

- The density of holes is given by the mass-action law as

$$p = \frac{n_i^{\,2}}{n} = \frac{n_i^{\,2}}{N_D} = \frac{(1.45\times 10^{10})^2}{10^{16}} = 2.1\times 10^4 \ /\text{cm}^3$$

Extrinsic Semiconductor Material

- Column III elements (acceptor impurities: **B, Al, Ga, In**):

- An "**acceptor**" energy level formation near valence band (V.B.) → **p-type** material ($\mathbf{p_0} >> \mathbf{n_0}$, $\mathbf{n_i}$)

- These acceptor levels are empty of electrons at 0K. The material doped with acceptor impurities can have a considerable conc. of holes in V.B. due to the acceptor level, even when the temperature is too low to generate an appreciable intrinsic EHP conc.

- This acceptor level is empty of electrons at 0K, and very small thermal energy can excite the electrons from V.B. to acceptor level. At 50-100K, almost all empty sites in the acceptor impurity level are filled with the electrons, leaving behind holes in V.B.

Energy Band diagram of a p-type Semiconductor

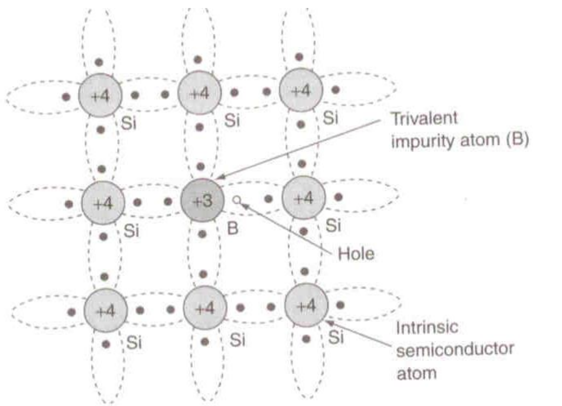


Figure 1.12 | Crystal structure of a P-type semiconductor.

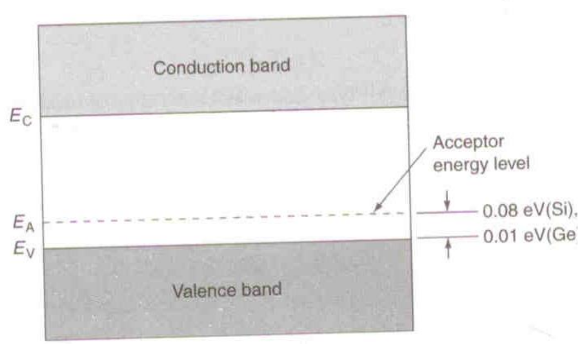
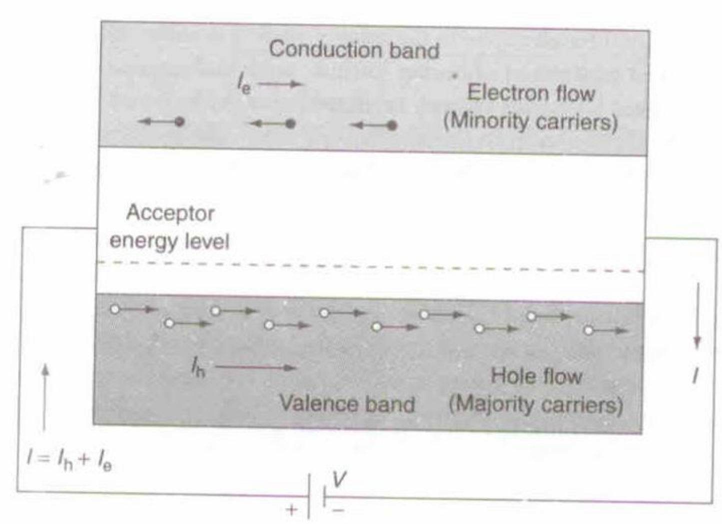


Figure 1.13 | Energy band diagram of a P-type semiconducto



Group III Impurity Atom

- An atom from group III of the periodic table has one less nuclear proton and valence electron than silicon

II	III	IV	V	VI
	B 5	C 6	N 7	O 8
	Al 13	Si 14	P 15	S 16
Zn 30	Ga 31	Ge 32	As 33	Se 34
Cd 48	In 49	Sn 50	Sb 51	Te 52

- If the atom replaces a silicon atom in the lattice, the empty valence orbital can be filled by an electron (ionization)
- A group III atom is an acceptor since it accepts an electron from the silicon lattice
- Density of acceptor dopant atoms given symbol N_A (cm^{-3})

Acceptor Doping - Electron and Hole Densities

- Virtually all acceptors are ionized at room temperature (complete ionization), and N_A is normally much larger than n_i - the valence band hole density p is essentially just the density of acceptors, with n given by the mass action law

$$p = N_A \qquad n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A}$$

- Since $p >> n$ for acceptor doping, the material is termed p-type, holes are called the majority carriers and electrons the minority carriers
- Acceptor doping allows direct control of p

A sample of silicon is doped with $4 \times 10^{16}/cm^3$ of Gallium (Ga), a group III atom. What are the concentrations of electrons and holes?

- As a group III atom Gallium functions as an acceptor, so the doped material is therefore p-type. The density of holes is essentially equal to the density of acceptors, so

$$p = N_A = 4 \times 10^{16} \ / \ \mathrm{cm}^3$$

- The density of electrons is given by the mass-action law as

$$n = \frac{n_i^{\ 2}}{p} = \frac{n_i^{\ 2}}{N_A} = \frac{\left(1.45 \times 10^{10}\right)^2}{4 \times 10^{16}} = 5.3 \times 10^3 \ / \ \mathrm{cm}^3$$