CHAPTER 3
CARRIER CONCENTRATIONS IN SEMICONDUCTORS

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CARRIER CONCENTRATIONS IN SEMICONDUCTORS

- **Donors and Acceptors**
- **Fermi level , E_f**
- **Carrier concentration equations**
- **Donors and acceptors both present**

Donors and Acceptors

- The conductivity of a pure (intrinsic) s/c is low due to the low number of free carriers.
- The number of carriers are generated by thermally or electromagnetic radiation for a pure s/c.

- For an intrinsic semiconductor

$$n = p = n_i$$

n = concentration of electrons per unit volume

p = concentration of holes per unit volume

n_i = the intrinsic carrier concentration of the semiconductor under consideration.

$n.p = n_i^2$

$n = p$

number of e^-'s in CB = number of holes in VB

- This is due to the fact that when an e^- makes a transition to the CB, it leaves a hole behind in VB. We have a bipolar (two carrier) conduction and the number of holes and e^- 's are equal.

$$n.p = n_i^2$$

This equation is called as mass-action law.

$n.p = n_i^2$

The intrinsic carrier concentration n_i depends on;

- the semiconductor material, and
- the temperature.

- For silicon at 300 K, n_i has a value of $1.4 \times 10^{10}\ cm^{-3}$.
- Clearly , equation ($n = p = n_i$) can be written as

$$n.p = n_i^2$$

- This equation is valid for extrinsic as well as intrinsic material.

What is doping and dopants impurities ?

- To increase the conductivity, one can dope pure s/c with atoms from column III or V of periodic table. This process is called as doping and the added atoms are called as dopants impurities.

There are two types of doped or extrinsic s/c's;

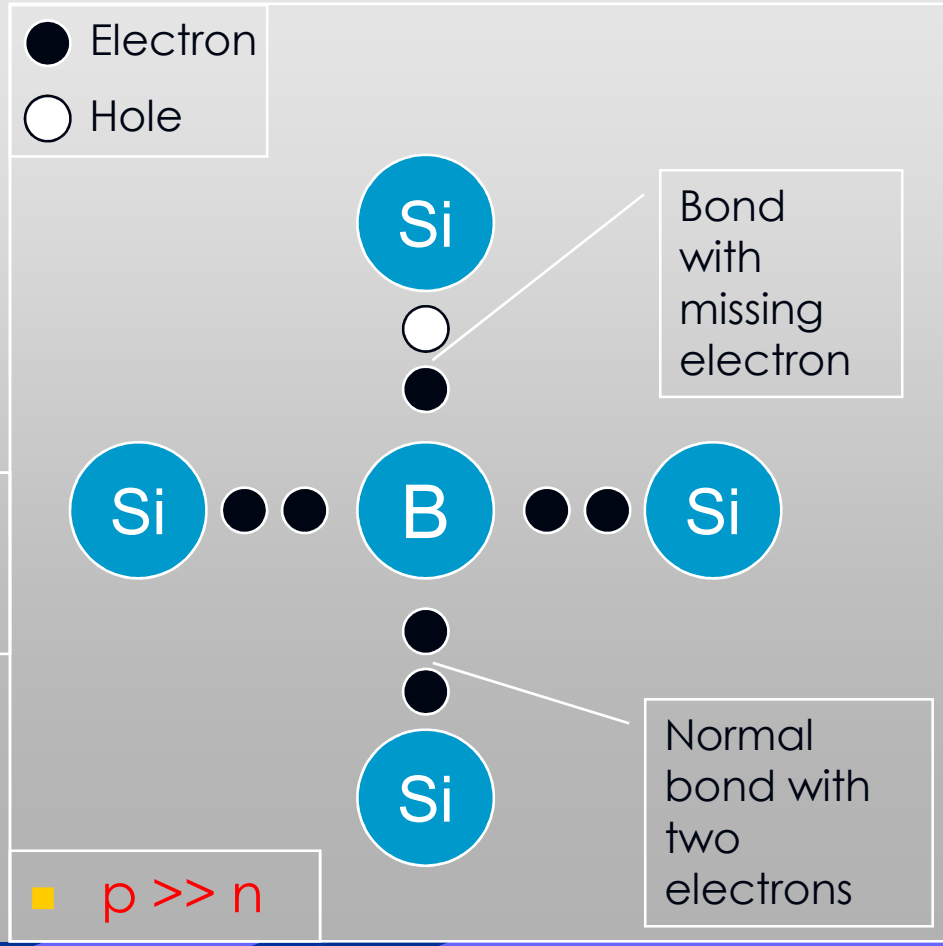
- n-type
- p-type

Addition of different atoms modify the conductivity of the intrinsic semiconductor.

p-type doped semiconductor

- Si + Column III impurity atoms
  - Have four valance e⁻'s
  - Boron (B) has three valance e⁻' s

- Boron bonding in Silicon
- Boron sits on a lattice side



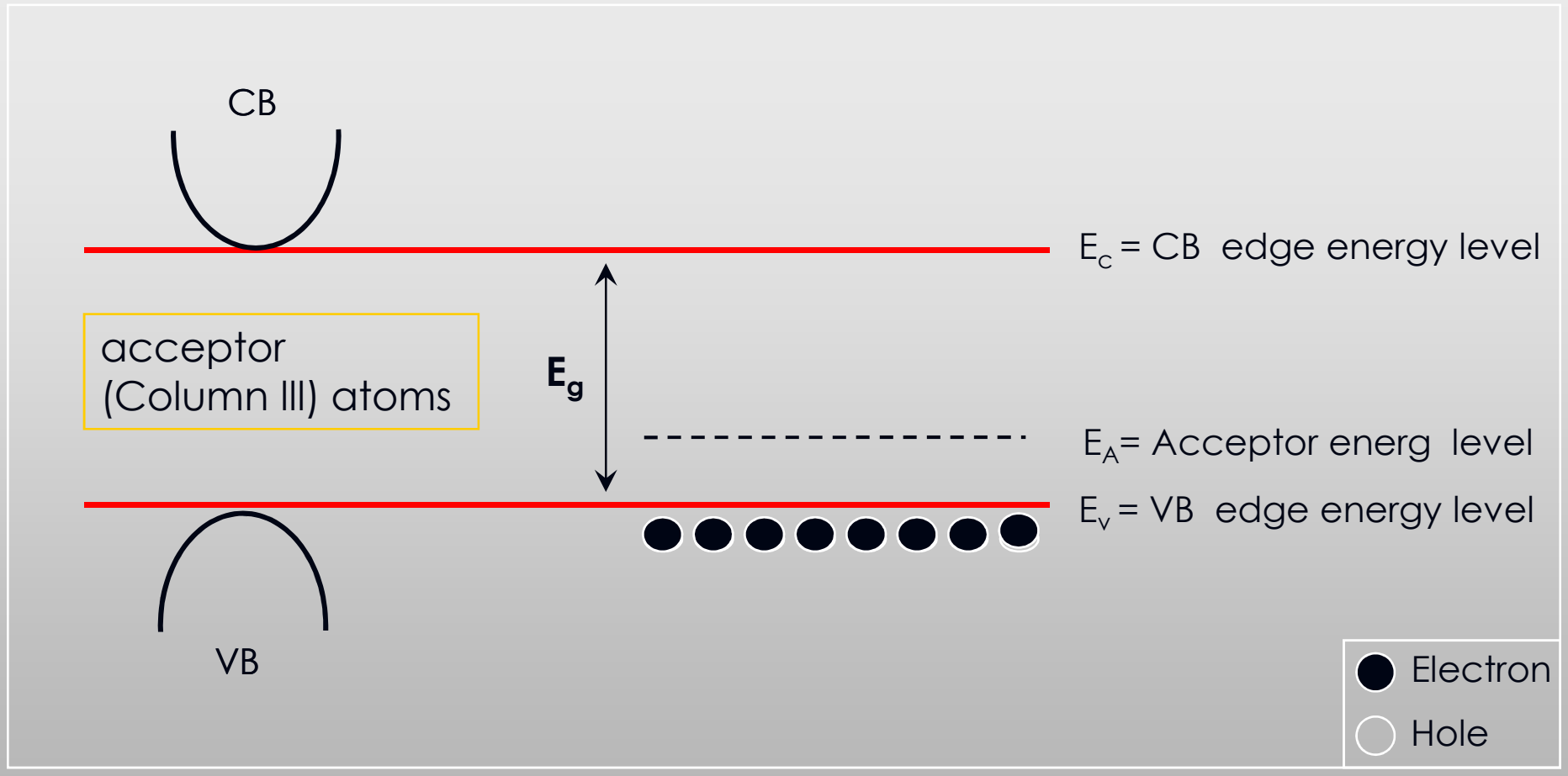
- p >> n

- Boron(column III) atoms have three valance electrons, there is a deficiency of electron or missing electron to complete the outer shell.
- This means that each added or doped boron atom introduces a single hole in the crystal.

- There are two ways of producing hole

1) Promote e^-'s from VB to CB,
2) Add column III impurities to the s/c.

Energy Diagram for a p-type s/c



The energy gap is forbidden only for pure material, i.e. Intrinsic material.

p-type semiconductor

- ***The impurity atoms from column III occupy at an energy level within E_g. These levels can be***

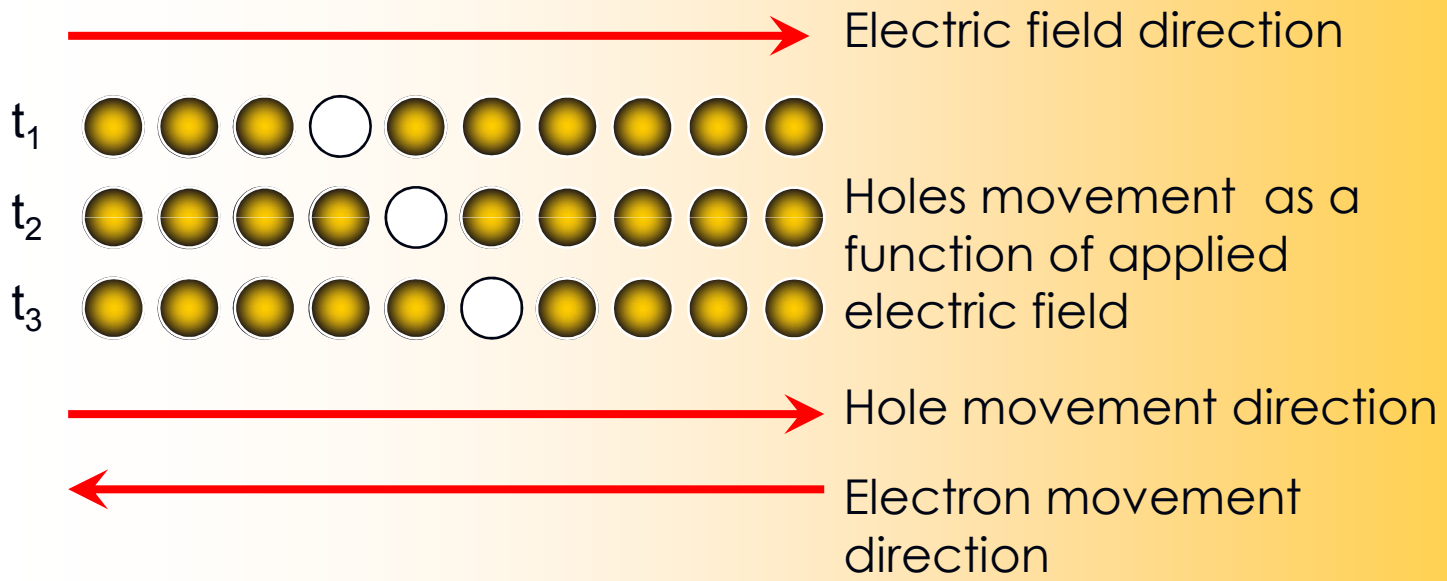
1. Shallow levels which is close to the band edge,
2. Deep levels which lies almost at the mid of the band gap.

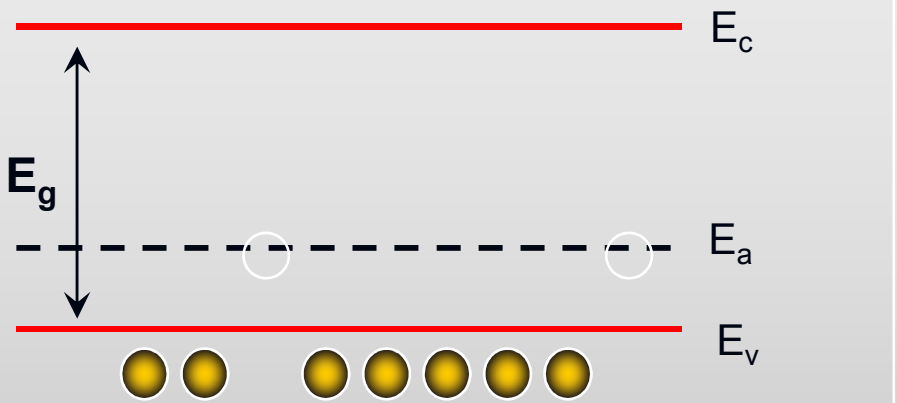
- If the E_A level is shallow i.e. close to the VB edge, each added boron atom accepts an e^- from VB and have a full configuration of e^-'s at the outer shell.
- These atoms are called as acceptor atoms since they accept an e^- from VB to complete its bonding. So each acceptor atom gives rise a hole in VB.
- The current is mostly due to holes since the number of holes are made greater than e^-'s.

Majority and minority carriers in a p-type semiconductor

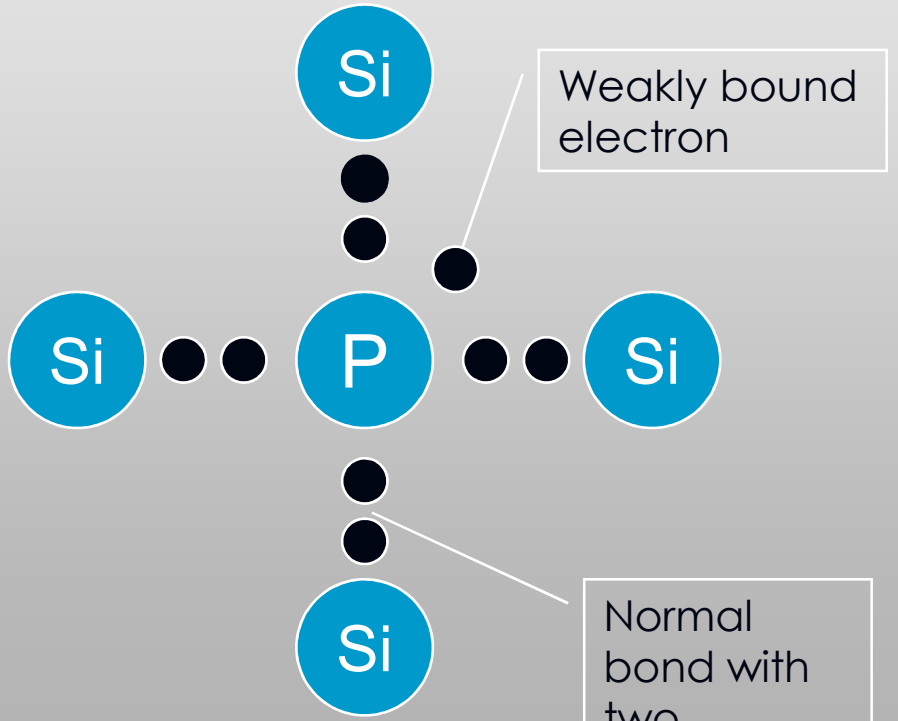
Holes = p = majority carriers

Electrons = n = minority carriers

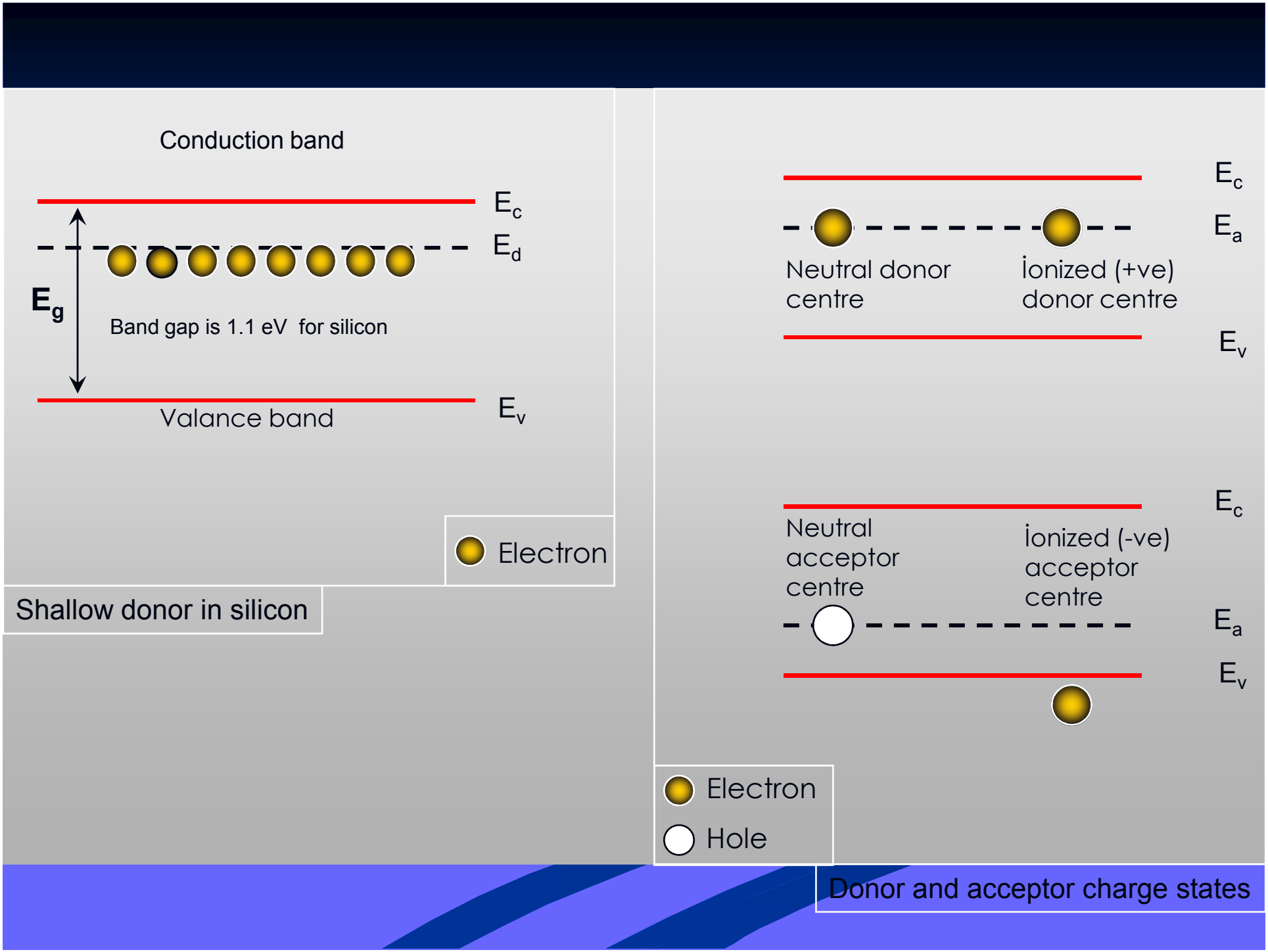




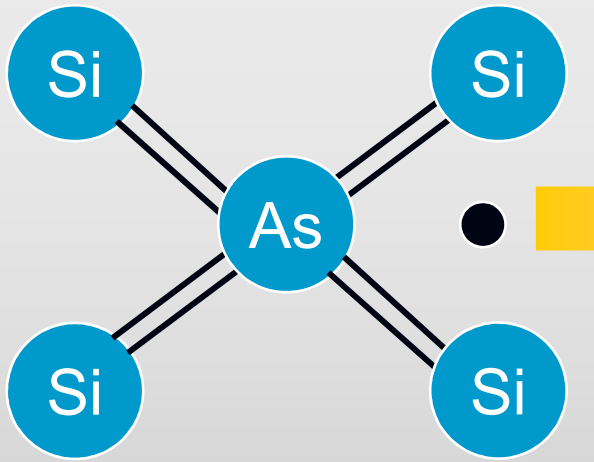
Shallow acceptor in silicon



Phosporus bonding in silicon

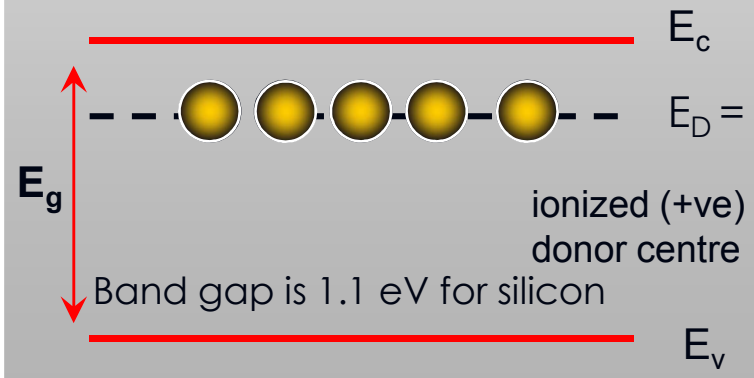

Conduction band
E_c
E_d
E_g
Band gap is 1.1 eV for silicon
E_v
Valance band
Electron
Shallow donor in silicon
E_c
E_a
Neutral donor centre
İonized (+ve) donor centre
E_v
E_c
Neutral acceptor centre
İonized (-ve) acceptor centre
E_a
E_v
Electron
Hole
Donor and acceptor charge states

n-type semiconductor



Extra e^- of column V atom is weakly attached to its host atom

Si + column V (with five valance e^-)

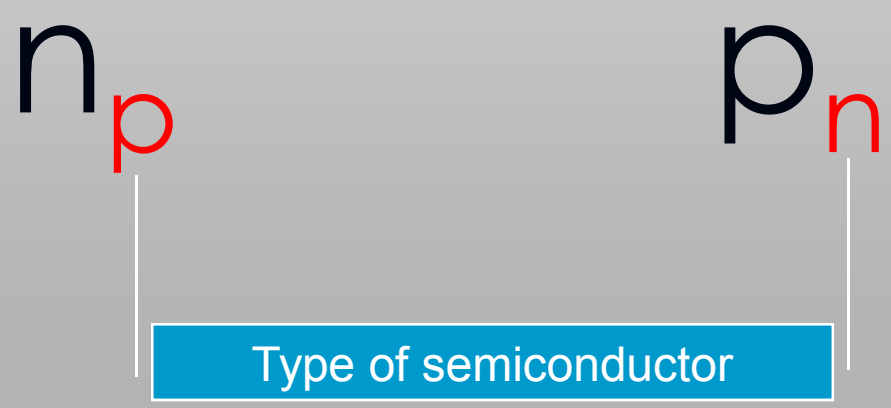


Electron
Hole

n - type semiconductor

n_p , p_n

- n-type , $n >> p$; n is the majority carrier concentration n_n
  p is the minority carrier concentration p_n
- p-type , $p >> n$; p is the majority carrier concentration p_p
  n is the minority carrier concentration n_p



calculation

- Calculate the hole and electron densities in a piece of p-type silicon that has been doped with 5×10^{16} acceptor atoms per cm^3.

  $n_i = 1.4 \times 10^{10}\ cm^{-3}$ (at room temperature)

  Undoped

  $n = p = n_i$

  p-type ; $p >> n$

  $n.p = n_i^2$ $N_A = 5 \times 10^{16}$ $p = N_A = 5 \times 10^{16}\ cm^{-3}$

$$n = \frac{n_i^2}{p} = \frac{(1.4x10^{10} cm^{-3})^2}{5x10^{16} cm^{-3}} = 3.9x10^3$$ electrons per cm^3

$p >> n_i$ and $n << n_i$ in a p-type material. The more holes you put in the less e^-'s you have and vice versa.

Fermi level , E_F

- This is a reference energy level at which the probability of occupation by an electron is ½.
- Since E_f is a reference level therefore it can appear anywhere in the energy level diagram of a S/C .
- Fermi energy level is not fixed.
- Occupation probability of an electron and hole can be determined by Fermi-Dirac distribution function, F_{FD} ;

$$F_{FD} = \frac{1}{1 + \exp(\frac{E - E_F}{k_B T})}$$

E_F = Fermi energy level
k_B = Boltzman constant
T = Temperature

Fermi level , E_F

$$F_{FD} = \frac{1}{1 + \exp(\frac{E - E_F}{k_B T})}$$

- E is the energy level under investigation.
- F_{FD} determines the probability of the energy level E being occupied by electron.

$$if\ E = E_F \longrightarrow f_{FD} = \frac{1}{1 + \exp 0} = \frac{1}{2}$$

- $1 - f_{FD}$ determines the probability of not finding an electron at an energy level E; the probability of finding a hole .

Carrier concentration equations

The number density, i.e., the number of electrons available for conduction in CB is

$$n = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \exp-(\frac{E_C - E_F}{kT})$$

$$n = N_C \exp-(\frac{E_C - E_F}{kT}) \qquad n = n_i \exp(\frac{E_F - E_i}{kT})$$

The number density, i.e., the number of holes available for conduction in VB is

$$p = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \exp-(\frac{E_F - E_V}{kT})$$

$$p = N_V \exp-(\frac{E_F - E_V}{kT}) \qquad p = n_i \exp(\frac{E_i - E_F}{kT})$$

Donors and acceptors both present

- Both donors and acceptors present in a s/c in general. However one will outnumber the other one.
- In an n-type material the number of donor concentration is significantly greater than that of the acceptor concentration.
- Similarly, in a p-type material the number of acceptor concentration is significantly greater than that of the donor concentration.
- A p-type material can be converted to an n-type material or vice versa by means of adding proper type of dopant atoms. This is in fact how p-n junction diodes are actually fabricated.

Worked example

- How does the position of the Fermi Level change with

(a) increasing donor concentration, and

(b) increasing acceptor concentration ?

(a) We shall use equation

$$n = N_C \exp -\left(\frac{E_C - E_F}{kT}\right)$$

İf n is increasing then the quantity E_C-E_F must be decreasing **i.e.** as the donor concentration goes up the Fermi level moves towards the conduction band edge E_c.

Worked example

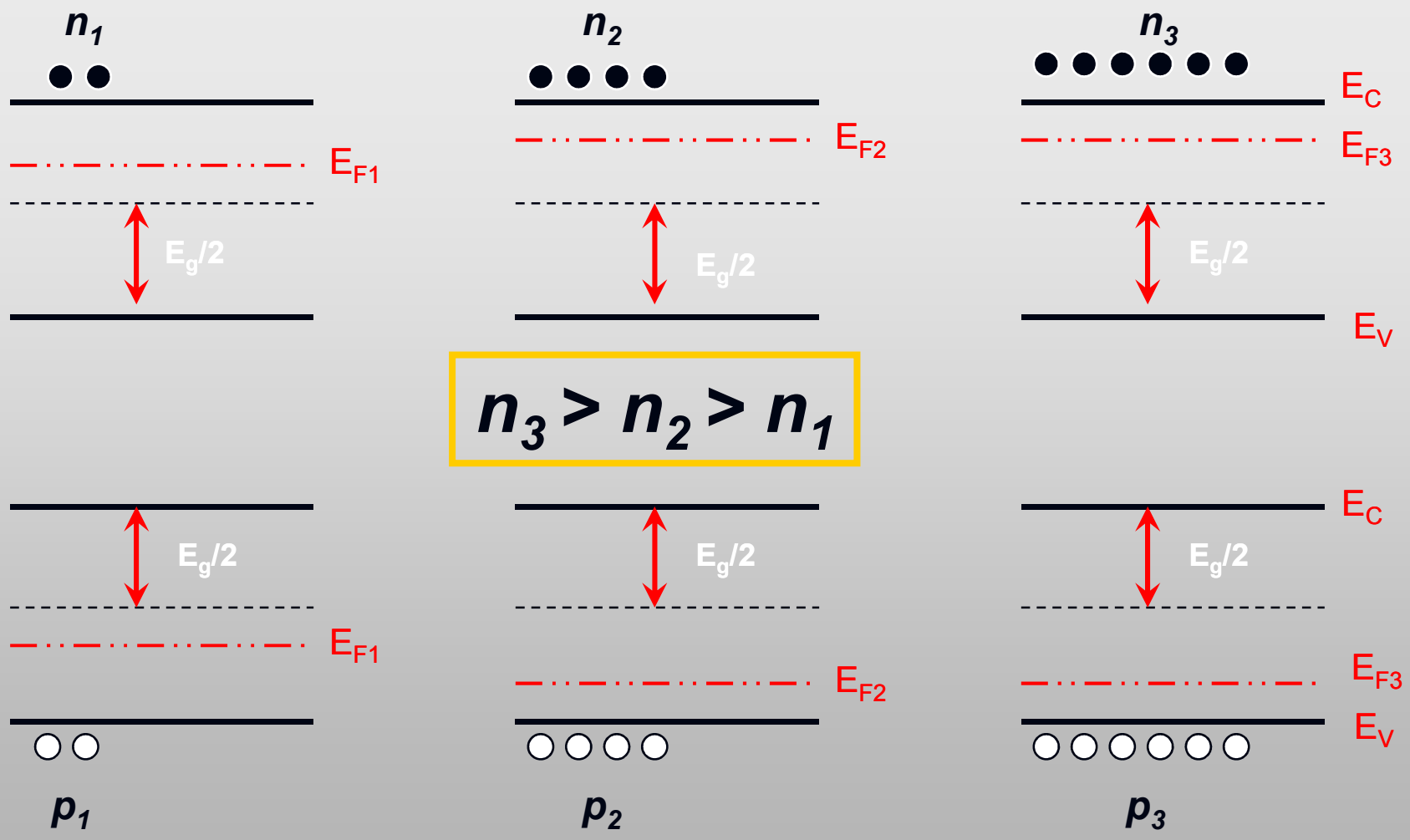
But the carrier density equations such as;

$$n = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left(-\frac{E_c - E_F}{kT}\right) \quad and$$

$$p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

aren't valid for all doping concentrations! As the fermi-level comes to within about 3kT of either band edge the equations are no longer valid, because they were derived by assuming the simpler Maxwell Boltzmann statics rather than the proper Fermi-Dirac statistic.

Worked example



Worked example

(b) Considering the density of holes in valence band;

$$p = N_v \exp -\left(\frac{E_F - E_V}{kT} \right)$$

It is seen that as the acceptor concentration increases, Fermi-level moves towards the *valance band edge*. These results will be used in the construction of device (energy) band diagrams.

Donors and acceptor both present

- In general, both donors and acceptors are present in a piece of a semiconductor although one will outnumber the other one.
- The impurities are incorporated unintentionally during the growth of the semiconductor crystal causing both types of impurities being present in a piece of a semiconductor.
- How do we handle such a piece of s/c?

1) Assume that the shallow donor concentration is significantly greater than that of the shallow acceptor concentration. In this case the material behaves as an n-type material and

$$n_n = N_D - N_A$$

2) Similarly, when the number of shallow acceptor concentration is signicantly greater than the shallow donor concentration in a piece of a s/c, it can be considered as a p-type s/c and

$$p_p = N_A - N_D$$

Donors and acceptor both present

- For the case $\mathbf{N_A > N_D}$, **i.e.** for p-type material

$$n_p . p_p = n_i^2$$

$$n_p + N_A^- = N_D^+ + p_P \Rightarrow p_p + N_D - n_p - N_A = 0$$

$$p_p \cdot \left[p_p + N_D - \frac{n_i^2}{p_p} - N_A = 0 \right] \Rightarrow p_p^2 + (N_D - N_A) p_p - n_i^2 = 0$$

Donors and acceptor both present

$$p_p^2 + (N_D - N_A)p_p - n_i^2 = 0, \quad \text{solving for } p_p; x_{1,2} = \frac{-b \mp \sqrt{b^2 - 4ac}}{2a}$$

$$p_p = \frac{1}{2}\left(N_A - N_D + \left[(N_A - N_D)^2 + 4n_i^2 \right]^{1/2} \right)$$

majority

$$n_p = \frac{n_i^2}{p_p}$$

minority

Donors and acceptor both present

- For the case $N_D > N_A$, i.e. n-type material

$$n_n . p_n = n_i^2 \Rightarrow p_n = \frac{n_i^2}{n_n}$$

$$n_n + N_A = N_D + P_n \Rightarrow n_n + N_A - p_n - N_D = 0$$

$$n_n \cdot \left[n_n + N_A - \frac{n_i^2}{n_n} - N_D = 0 \right] \Rightarrow n_n^2 + (N_A - N_D) n_n - n_i^2 = 0$$

$$\text{solving for } n_n \text{ ; } x_{1,2} = \frac{-b \mp \sqrt{b^2 - 4ac}}{2a}$$

$$n_n = \frac{1}{2}\left(N_D - N_A + \left[(N_D - N_A)^2 + 4 n_i^2 \right]^{1/2} \right)$$

$$p_n = \frac{n_i^2}{n_n}$$