Semiconductor Physics

Semiconductor Physics

- On the basis of electrical conductivity of solid, solid may be classified into following types

- Conductor
- Insulator
- Semiconductor

Semiconductor Physics

- Conductor:

  A material which contain free electrons to conduct electricity.

- Insulator:

  A material which do not contain free electrons to conduct electricity.

- Semiconductor:

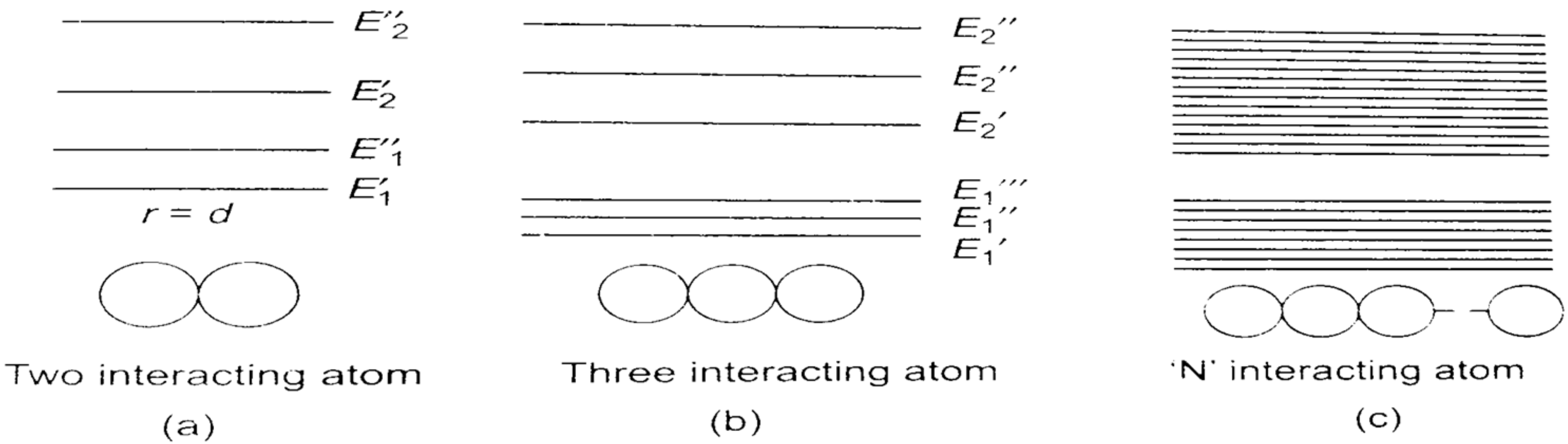
  Electrical conductivity of the material is lies between conductors and insulators.

Semiconductor Physics

Band Theory of solid

- The transformation of a single energy level into two or more separate energy levels is known as energy level splitting.
- When two atoms come close, one energy level split into two energy levels.
- When three atoms approach each other closely, original level split into three energy levels.
- Four atoms produces four levels, and so on.
- The group of energy levels resulting from splitting is so closely spaced that they form a virtual continuum, which is called an Energy band.

Semiconductor Physics



- The large number of energy levels resulting from splitting of an energy level will be very closely spaced and form an energy continuum , which is called as energy band structure.
- Each of energy level splits into many distinct levels and form energy bands.

Semiconductor Physics

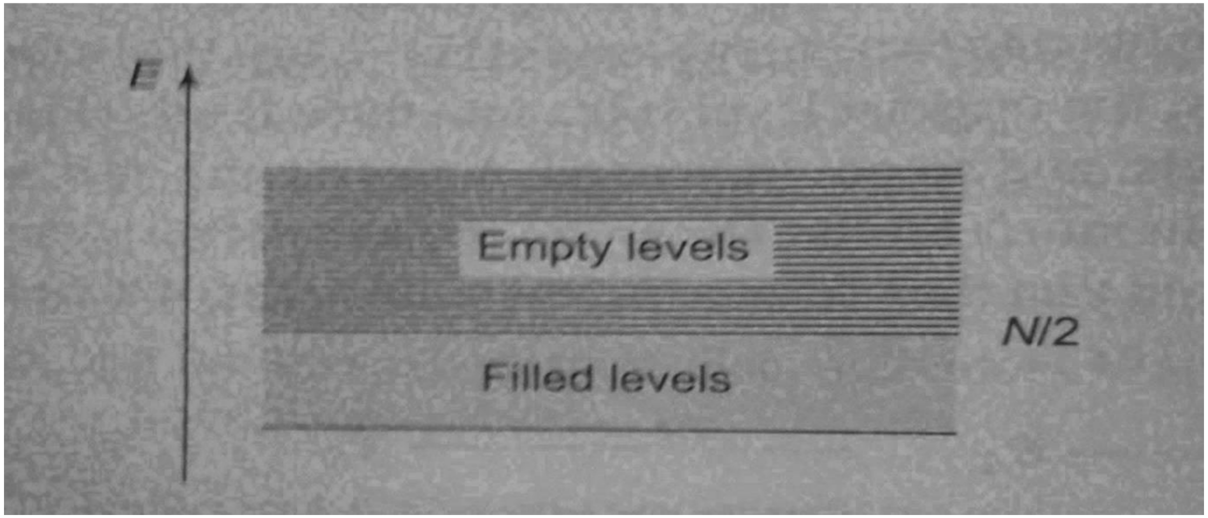
- At absolute zero temperature highest filled energy band by valence electrons is known as Valence Band (VB).
- Below valence band all energy levels are completely filled by an electron.
- Above Valence band all energy levels are empty such band is known as Conduction Band (CB).
- The gap between conduction and valence band is known as Forbidden gap. It is more popularly called as Band gap and is denoted by the symbol E_g

Classification of solids based on energy bands

- According to the band theory, a solid is characterized by the energy gap Eg, separating conduction and valence band.

- **Conductor:**

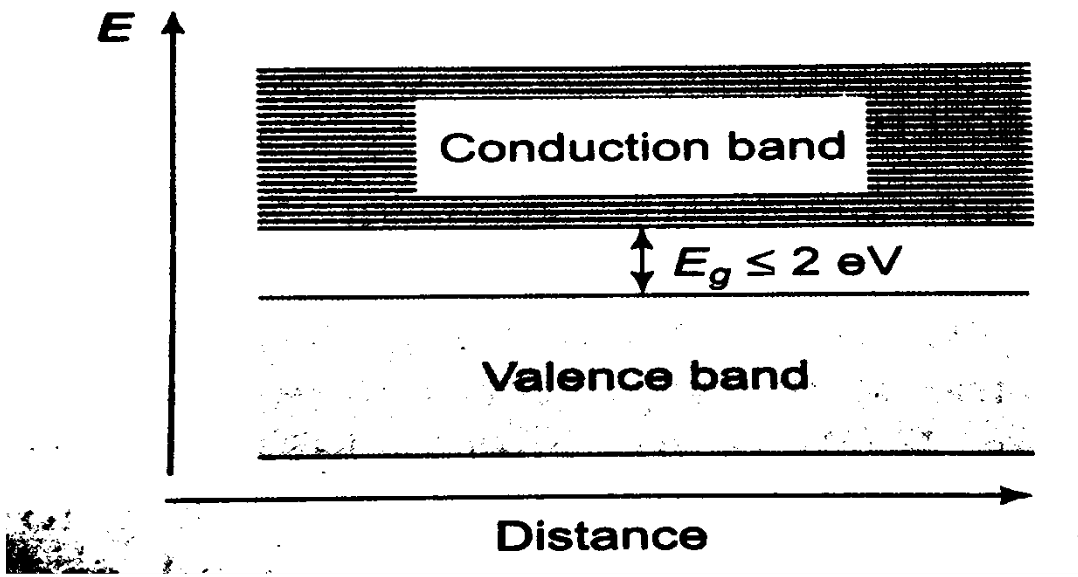
- In some solids an lower vacant levels of conduction band overlaps with upper energy levels of valence band
- So electrons in the valence band have easy access to conduction band
- Very large number of electron are available for conduction
- These solids exhibit good electrical conductivity are known as Conductors.



Classification of solids based on energy bands

➢ Semiconductor:

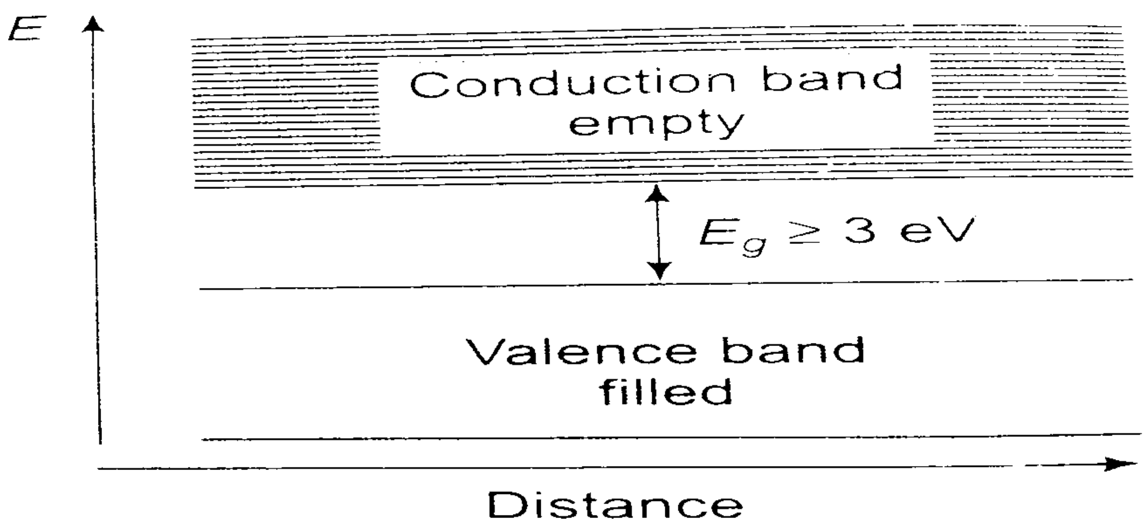
- In some solid band gap is narrow and is of the order of 2eV or less
- If potential is applied across the material, it causes the electron in the conduction band to move in the upper levels.
- Such solids are called as Semiconductors.



Classification of solids based on energy bands

Insulators:

- Some solids have very wide band gaps
- It would required very large amount of energy to jump electron from valence band to conduction band
- Very few electrons can get such large amount of energy
- When a voltage is applied across the solid, negligible current flows and solid exhibits very low electrical conductivity.
- These solids are known as Insulators.



Fermi Dirac distribution function

$$f(E) = \frac{1}{1 + e^{(E-E_f)/KT}}$$

Where ,

f(E) = probability that a particular energy level E is occupied by an electron

E_f = fermi energy level

K = Boltzman constant

T = Temperature

Fermi Energy and Fermi level

- The highest occupied energy level at absolute zero temperature is known as Fermi level.

- The Energy corresponding to Fermi level is known as Fermi Energy

Fermi level in conductor

- At T = 0K level above E_f , E> E_f

$$f(E) = \frac{1}{1+\mathrm{e}^{(\mathrm{E}-\mathrm{E_f})/\mathrm{KT}}} = \frac{1}{1+e^{\infty}} = 0$$

f(E) = 0

It shows that all the energy levels above E_F are vacant.

Fermi level in conductor

- At T = 0K for energy level E , E = E_f

$$f(E) = \frac{1}{1+e^{(E-E_f)/KT}} = \frac{1}{1+e^{0/0}}$$

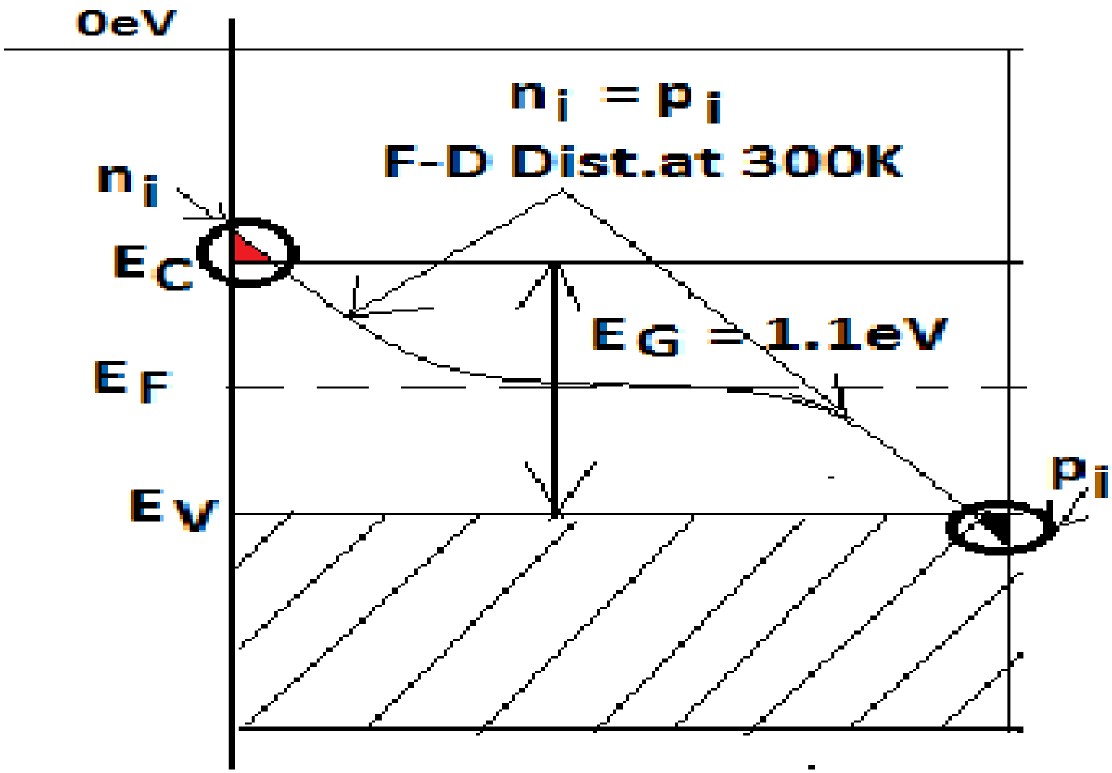
f(E) is inderminable

Fermi level in conductor

- At T > 0K for the energy level E, $E = E_f$

$$f(E) = \frac{1}{1+e^{(E-E_f)/KT}} = \frac{1}{1+e^0} = 0.5$$

f(E) = 0.5



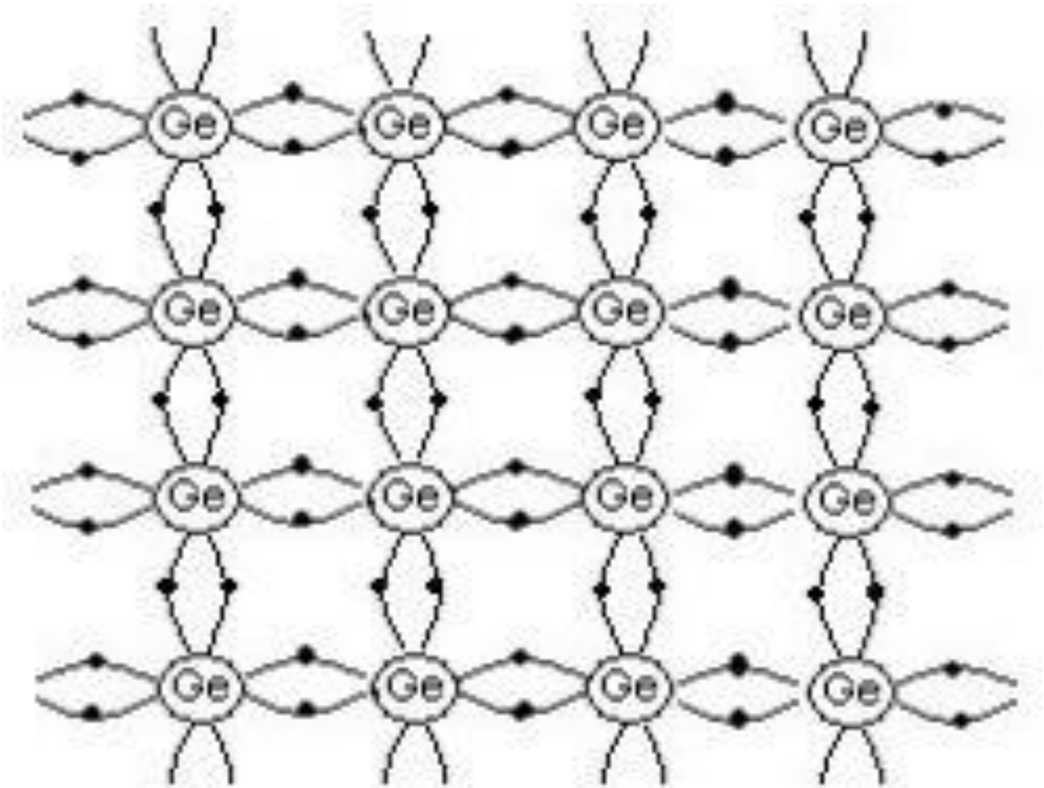
Semiconductors

- Types of Semiconductors

1. Intrinsic semiconductors
   Pure semiconductors are known as Intrinsic semiconductors.
2. Extrinsic semiconductors
   Impure semiconductors are known as Extrinsic semiconductor. It is also called as doped semiconductors

Intrinsic Semiconductors

- Pure semiconductors are known as Intrinsic semiconductors.
- Intrinsic semiconductors behaves as an insulators at absolute zero temperature.



Fermi level in Intrinsic Semiconductor

- At any temperature $T > 0K$

  n_e = Number of electrons in the conduction band at temperature $T > 0K$.

  n_h = Number of holes in the valence band at temperature $T > 0K$.

We have,

$$n_e = N_c \, e^{-(E_c - E_f)/KT} \quad \text{-----------} \ 1$$

$$n_h = N_v \, e^{-(E_f - E_v)/KT} \quad \text{-----------} \ 2$$

Fermi level in Intrinsic Semiconductor

Where,

N_c = Effective density of state in conduction band

$$N_c = 2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}$$

N_v = Effective density of state in valence band

$$N_v = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}$$

Fermi level in Intrinsic Semiconductor

For Intrinsic semiconductor,

$n_e = n_h$ ---------------- 3

$$N_c\, e^{-(E_c - E_f)/KT} = N_v\, e^{-(E_f - E_v)/KT}$$

$$\frac{e^{-(E_c - E_f)/KT}}{e^{-(E_f - E_v)/KT}} = \frac{N_v}{N_c} \quad \text{------------ 4}$$

As effective mass of electron and hole is same.

$m_e^* = m_h^*$

$N_c = N_v$

Fermi level in Intrinsic Semiconductor

then equation 4 becomes,

$$\therefore \frac{e^{-(E_c - E_f)/KT}}{e^{-(E_f - E_v)/KT}} = 1$$

$$\therefore e^{-(E_c - E_f - E_f + E_v)/KT} = 1$$

$$\therefore e^{-(E_c + E_v - 2E_f)/KT} = 1$$

Taking log on both sides,

$$\therefore \frac{-(E_c + E_v - 2E_f)}{KT} = 0$$

Fermi level in Intrinsic Semiconductor

$$\therefore \frac{(E_c + E_v - 2E_f)}{KT} = 0$$

$E_c + E_v - 2E_f = 0$

$2E_f = E_c + E_v$.

$$\therefore E_f = \frac{(E_c + E_v)}{2}$$

In Intrinsic semiconductor Fermi level lies exactly mid way between conduction and valence band.

Extrinsic Semiconductor

- Intrinsic Semiconductors have low conductivity.
- The conductivity of intrinsic semiconductor can be increased by adding impurities from other groups.
- The process of adding impurities in intrinsic semiconductors is known as doping process.
- The impurity added is known as dopant.
- The doped semiconductors are known as Extrinsic semiconductors.
- The impurities to be used as a dopant are selected from 3rd group and 5th group.

Extrinsic Semiconductor

- **Types of Extrinsic Semiconductor**

1. n-type semiconductor

2. p-type semiconductor

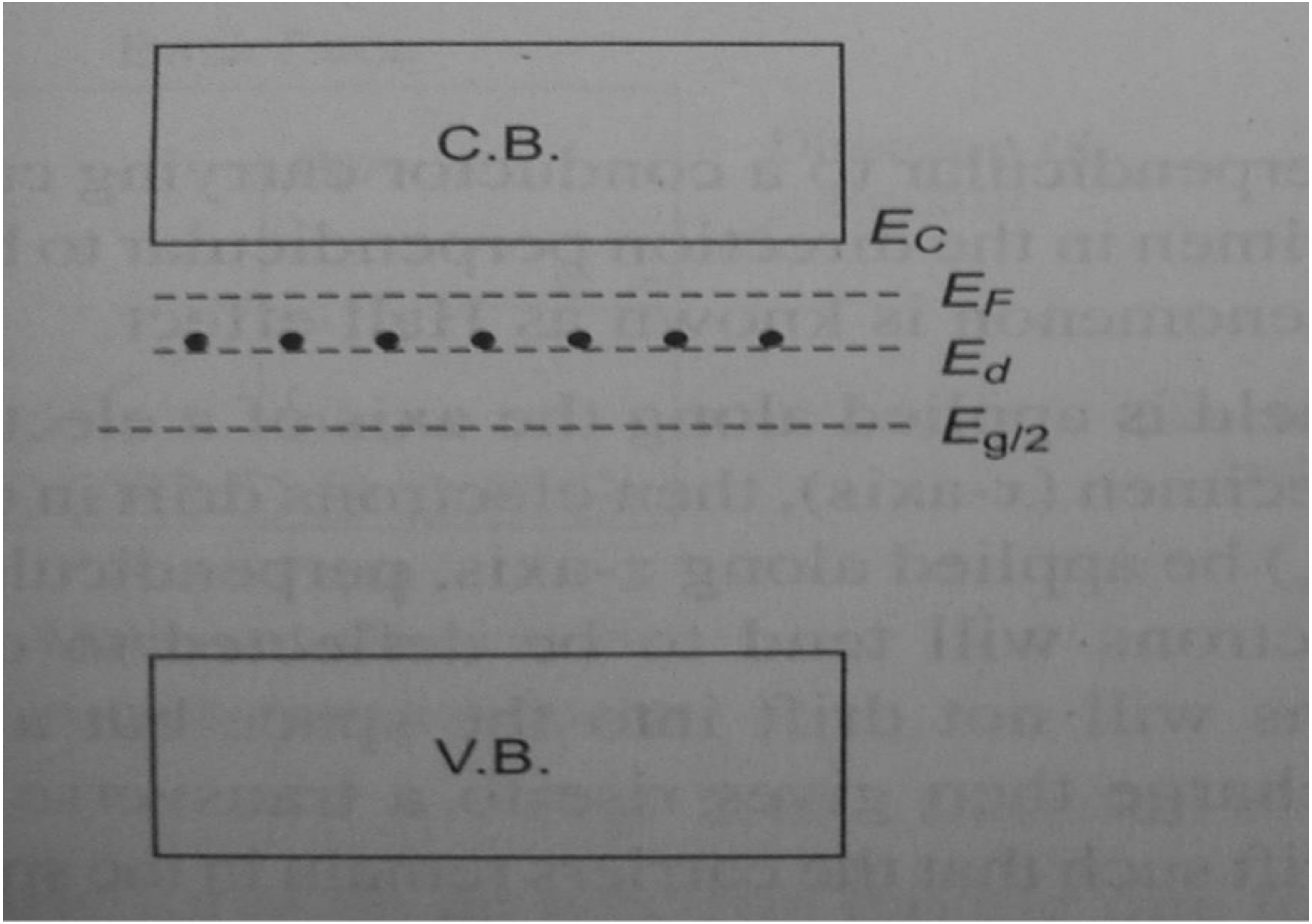
n-type semiconductor

- When atoms of the fifth group add as an impurity in fourth group then resultant semiconductor is known as n-type semiconductor.
- Added impurity from fifth group is known as pentavalent impurity.
- In this case, four valence electrons of the pure semiconductor form covalent bond with four valence electrons of pentavalent impurity.
- One free electron remains due to single atom of pentavalent impurity.
- Resultant charge on the n-type semiconductor is negative.

n-type semiconductor

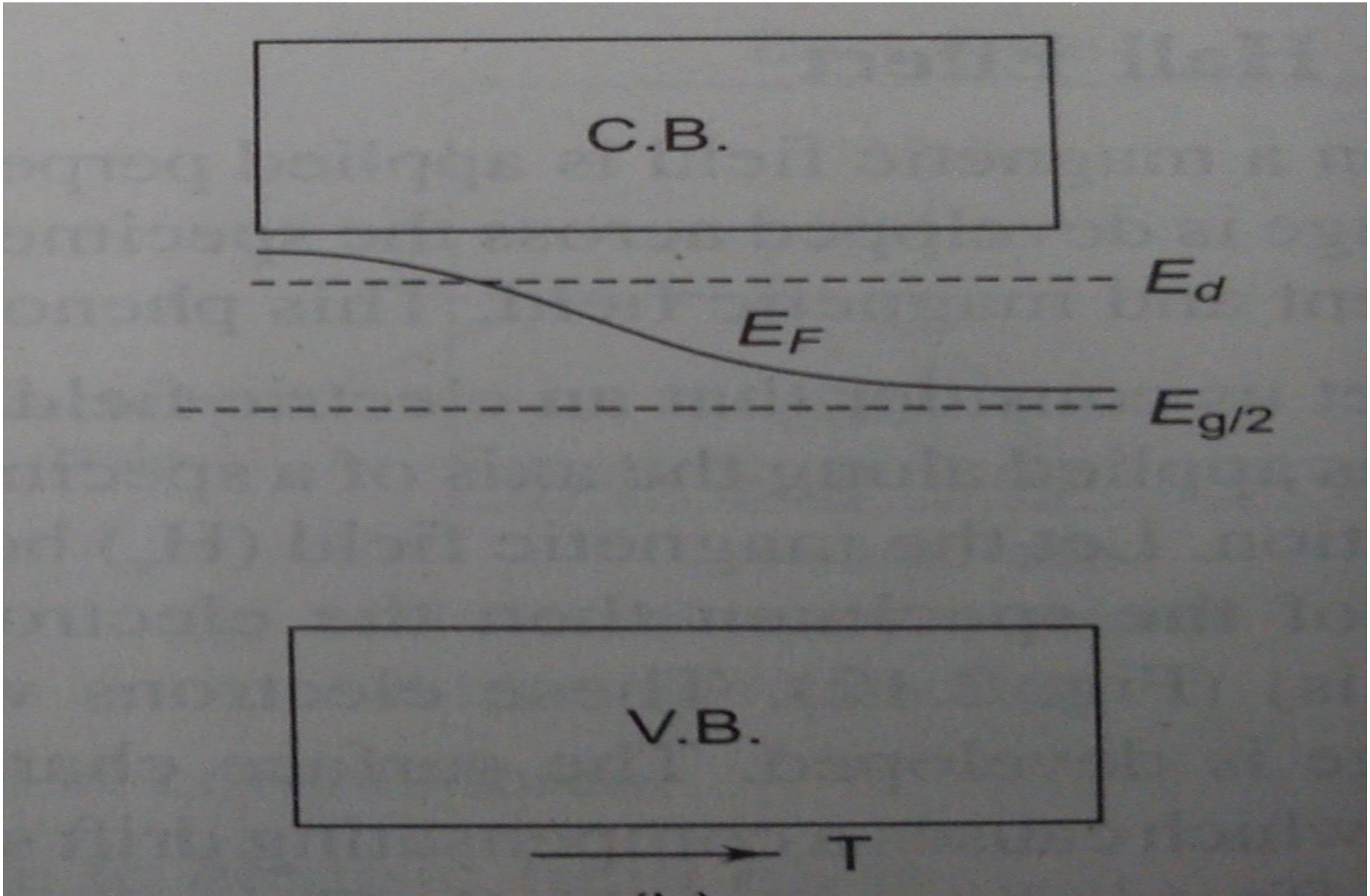
- Majority carriers are electrons and minority carriers are holes.
- So, pentavalent impurity is also known as donor impurity.
- Current flows through the n-type semiconductor is due to flow of the electrons.
- Impurity atoms introduce discrete energy levels for such electron just below the conduction band. These are called donor impurity levels.
- At 0^0 K, Fermi level lies between bottom of conduction band and donor energy level.

n-type semiconductor



n-type semiconductor

- Variation in fermi level with temperature.



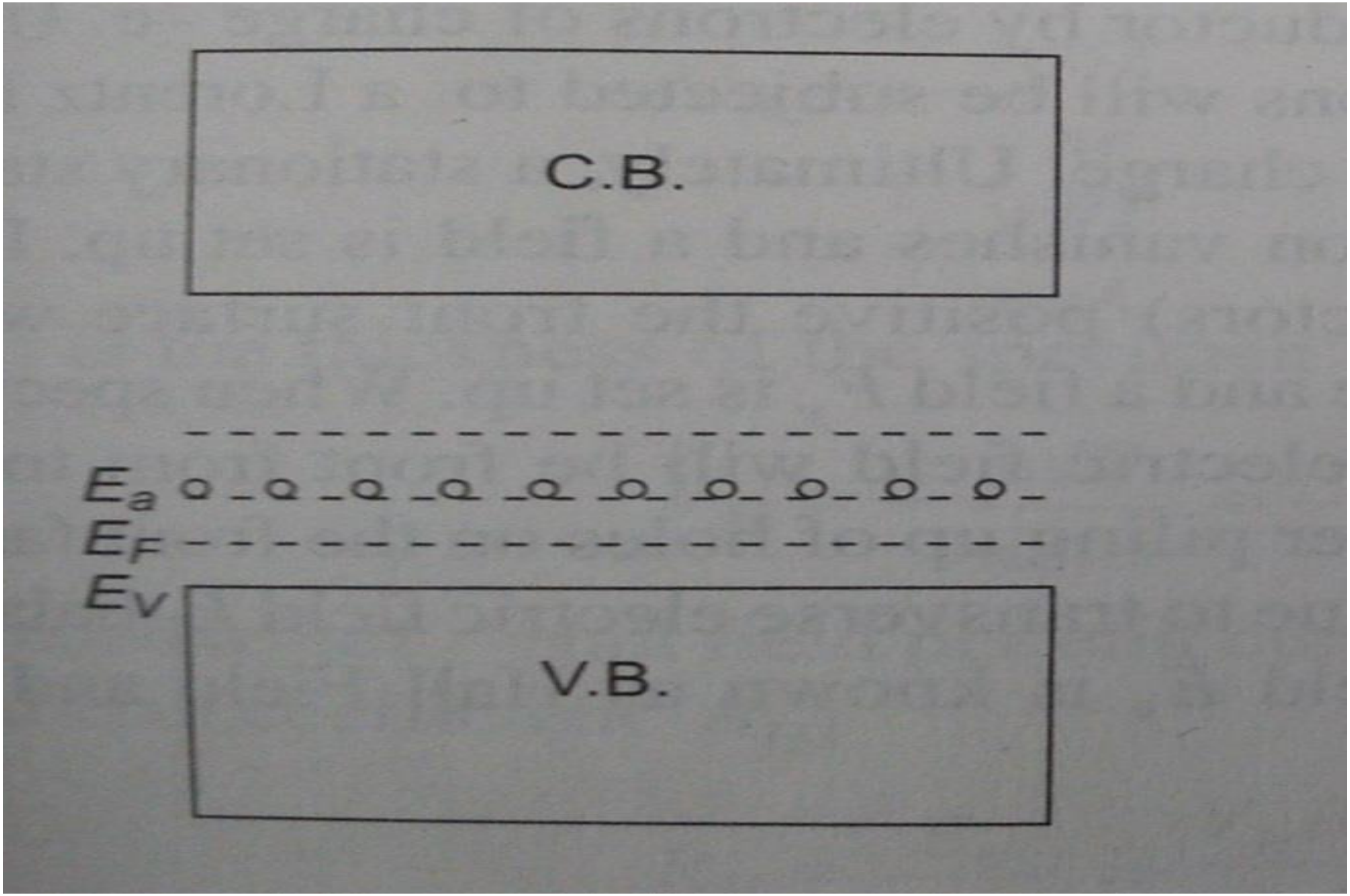
p-type semiconductor

- When atoms of the third group add as an impurity in fourth group then resultant semiconductor is known as p-type semiconductor.
- Added impurity from third group is known as trivalent impurity.
- In this case, three valence electrons of the pure semiconductor form covalent bond with three valence electrons of trivalent impurity.
- One vacancy for electron due to single atom of trivalent impurity.
- When external energy is applied this vacancy is filled by electron from adjacent covalent bond, leaving behind positive charged space is known as hole.
- Resultant charge on the p-type semiconductor is positive.

p-type semiconductor

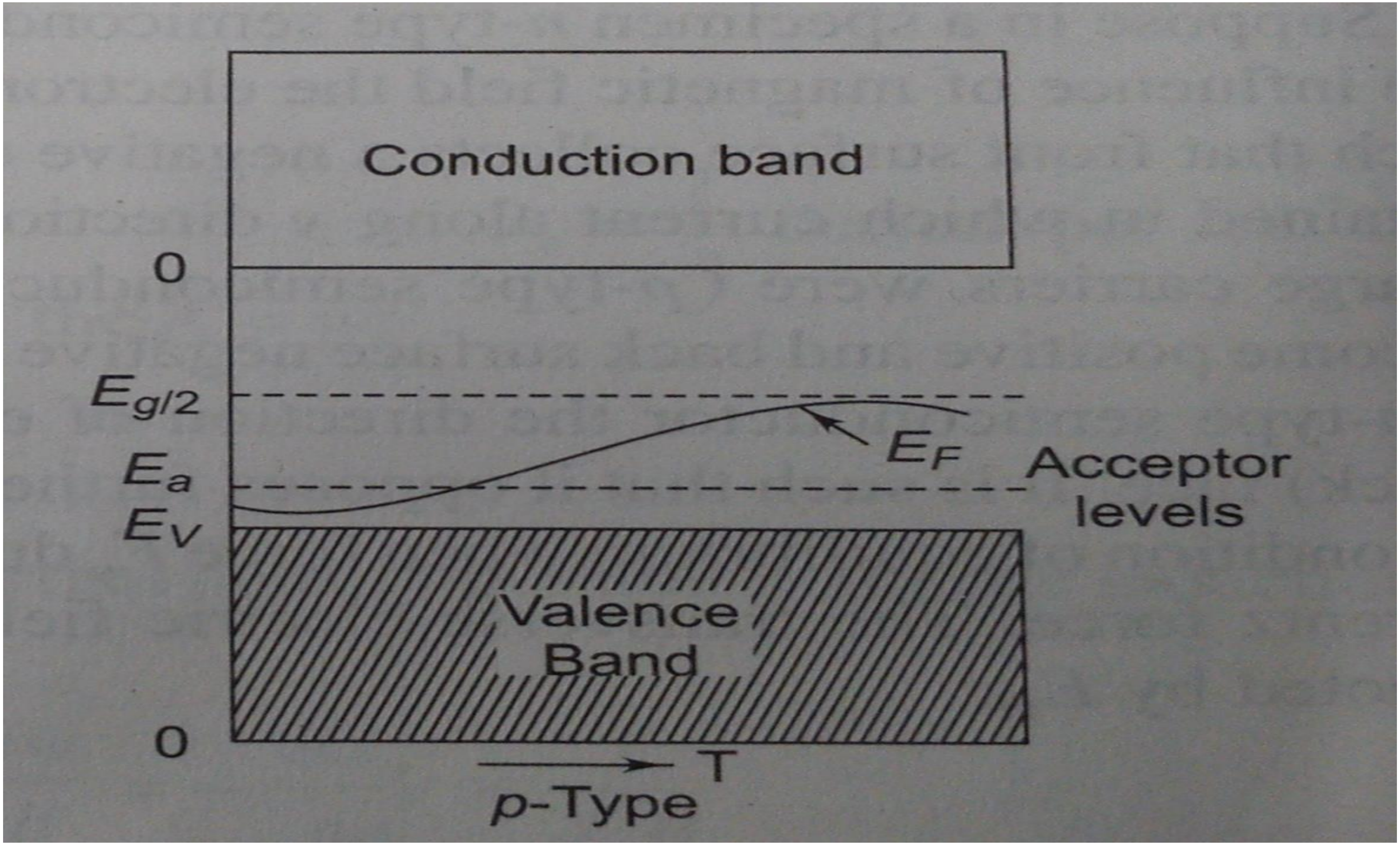
- Majority carriers are holes and minority carriers are electrons.
- So, trivalent impurity is also known as acceptor impurity.
- Current flows through the p-type semiconductor is due to flow of the holes.
- Impurity atoms introduce discrete energy levels for such holes just above the valence band. These are called acceptor impurity levels.
- At 0^0 K, Fermi level lies between top of valence band and acceptor energy level.

p-type semiconductor



p-type semiconductor

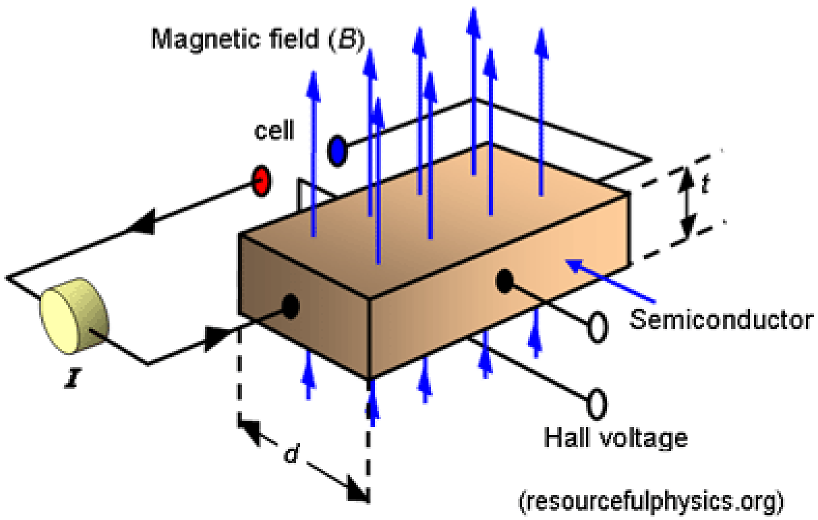
- Variation of fermi level with temperature.



n-type semiconductor

- Variation in fermi level with increase in impurity concentration

Hall Effect



- When magnetic field is applied perpendicular to a conductor carrying current, a voltage is developed across the specimen in the direction perpendicular to both the current and magnetic field. This phenomenon is known as Hall effect.
- Consider an electric field is applied along the axis of specimen(x-axis), then electron drift in opposite direction.
- Let magnetic field is applied along z-axis, perpendicular to the axis of specimen then electron will tends to deflected to one side (y-axis).

Hall Effect

- If a specimen is n-type semiconductor then front surface charged with negative charge and back surface charged with positive charge.
- If a specimen is p-type semiconductor then front surface charged with positive charge and back surface charged with negative charge.
- Voltage developed due to surface charges is known as Hall voltage(V_H).
- Electric force on charge carrier due to electric field E_H .

$$F_E = - eE_H \qquad \text{------------------(1)}$$

- Magnetic force on charge carrier due to magnetic field B

$$F_B = BeV_d \qquad \text{------------------(2)}$$

$$= BeJ_x / ne$$

$$= BJ_x / n \qquad \text{------------------(3)}$$

from eq. (1)

$$F_E = -eV_H / d \qquad \text{----} \{ E_H = V_H / d, \quad E = v/ l \} \quad \text{-------------(4)}$$

Hall Effect

- from eq. (3) and (4)

$$\therefore -\frac{eV_H}{d} = \frac{BJ_x}{n}$$

$$\therefore V_H = -\frac{BJ_x d}{ne}$$ ------------ $\{J_x = I/A\}$

$$\therefore V_H = -\frac{Bd}{ne} \text{ x } \frac{I}{A}$$ ------------- $\{A = dt\}$

$$\therefore V_H = -\frac{Bd}{ne} \text{ x } \frac{I}{dt}$$

$$\therefore V_H = -\frac{BI}{net}$$ --------------------- (5)

- Equation no. (5) is known as Hall voltage.

Hall Effect

- Hall coefficient:

Hall field per unit current density per unit magnetic induction is known as Hall coefficient. It is denoted by R_H.

$$\therefore R_H = \frac{E_H}{J_x B}$$

$$\therefore R_H = \frac{V_H / d}{J_x B}$$

$$\therefore R_H = -\frac{BI}{net} \text{ x } \frac{1}{d} \text{ x } \frac{1}{J_x B}$$

$$\therefore R_H = -\frac{BI}{neA} \text{ x } \frac{1}{J_x B}$$

For n-type $\boxed{\therefore R_H = -\frac{1}{ne}}$ For p-type $\boxed{\therefore R_H = \frac{1}{pe}}$

- Hall coefficient is inversely proportional to number of carriers per unit volume. Then equation (5) becomes

$$\boxed{\therefore V_H = R_H \frac{BI}{t}}$$

$$\boxed{\therefore R_H = \frac{V_H t}{BI}}$$