IRE 105 ELECTRONICS DEVICES AND APPLICATIONS

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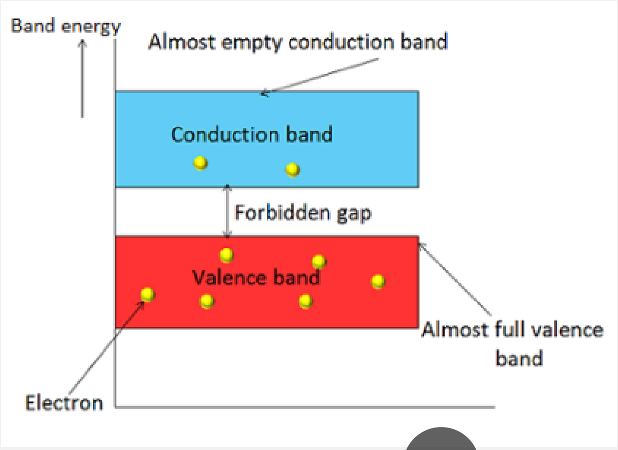
BDU

SEMICONDUCTOR

- A semiconductor material has an electrical conductivity value that falls in between that of conductor such as metallic cu and insulator such as rubber.
- Its resistivity falls as the temperature rises; metals are the opposite.
- Semiconductors are the foundation of modern electronics, including transistors, Light-Emitting diodes, solar cells etc.
- In semiconductors, the forbidden gap between valence band and conduction band is very small. It has a forbidden gap of about 1 electron volt (eV).



SEMICONDUCTOR (CONTD.)

- At low temperature, the valence band is completely occupied with electrons and conduction band is empty because the electrons in the valence band does not have enough energy to move in to conduction band. Therefore, semiconductor behaves as an insulator at low temperature.

- However, at room temperature some of the electrons in valence band gains enough energy in the form of heat and moves in to conduction band. When the valance electron moves in to conduction band they becomes free electrons. These electrons are not attached to the nucleus of a atom, So they moves freely.

The conduction band electrons are responsible for electrical conductivity. The measure of ability to conduct electric current is called as electrical conductivity.

SEMICONDUCTOR (CONTD.)

- When the temperature is goes on increasing, the number of valence band electrons moving in to conduction band is also increases. This shows that electrical conductivity of the semiconductor increases with increase in temperature. i.e. a semiconductor has negative temperature co-efficient of resistance. The resistance of semiconductor decreases with increase in temperature.
- In semiconductors, electric current is carried by two types of charge carriers they are electrons and holes.

TYPES OF SEMICONDUCTOR

- # Intrinsic Semiconductor

  ## Extrinsic Semiconductor

- Extrinsic semiconductors can further be classified as

  # P-type semiconductor

  ## N-type semiconductor

INTRINSIC SEMICONDUCTOR

- Pure semiconductors are called intrinsic semiconductors. Silicon and germanium are the most common examples of intrinsic semiconductors. Both these semiconductors are most frequently used in the manufacturing of transistors, diodes and other electronic components.
- Intrinsic semiconductor is also called as undoped semiconductor or I-type semiconductor. In intrinsic semiconductor the number of electrons in the conduction band is equal to the number of holes in the valence band. Therefore the overall electric charge of a atom is neutral.

Intrinsic semiconductor energy band diagram

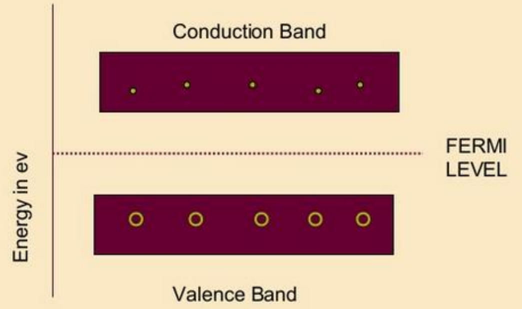


Fig 2.
Fermi level lies in the middle

FERMI LEVEL IN INTRINSIC SEMICONDUCTOR

- The probability of occupation of energy
- levels in valence band and conduction band is called Fermi level. At absolute zero temperature intrinsic semiconductor acts as perfect insulator. However as the temperature increases free electrons and holes gets generated.
- In intrinsic or pure semiconductor, the number of holes in valence band is equal to the number of electrons in the conduction band. Hence, the probability of occupation of energy levels in conduction band and valence band are equal. Therefore, the Fermi level for the intrinsic semiconductor lies in the middle of forbidden band.
- ** At 0 K all states below the **Fermi level** are filled, and all above are empty.**

INTRINSIC CARRIER CONCENTRATION

- In intrinsic semiconductor, when the valance electrons broke the covalent bond and jumps into the conduction band, two types of charge carriers gets generated. They are free electrons and holes.
- The number of electrons per unit volume in the conduction band or the number of holes per unit volume in the valence band is called intrinsic carrier concentration. The number of electrons per unit volume in the conduction band is called electron-carrier concentration and the number of holes per unit volume in the valence band is called as hole-carrier concentration.
- In an intrinsic semiconductor, the number of electrons generated in the conduction band is equal to the number of holes generated in the valence band. Hence the electron-carrier concentration is equal to the hole-carrier concentration.

INTRINSIC CARRIER CONCENTRATION

- It can be written as,

$$ni = n = p$$

Where, $n = electron - carrier\ concentration$

$P = hole - carrier\ concentratio$

and $ni = intrinsic\ carrier\ concentration$

- The hole concentration in the valence band is given as $p = N_V e^{\frac{-(E_F - E_V)}{K_B T}}$

The electron concentration in the conduction band is given as $\mathrm{n} = N_c e^{\frac{-(E_C - E_F)}{K_B T}}$

Where K_B is the Boltzmann constant = 8.625 * 10^-5 eV / K

T is the absolute temperature of intrinsic semiconductor

N_c is the effective density of states in conduction band.

N_v is the effective density of states in valence band.

EXTRINSIC SEMICONDUCTOR

- The semiconductor in which impurities are added is called extrinsic semiconductor. When the impurities are added to the intrinsic semiconductor, it becomes an extrinsic semiconductor. The process of adding impurities to the semiconductor is called doping. Doping increases the electrical conductivity of semiconductor.
- Extrinsic semiconductor has high electrical conductivity than intrinsic semiconductor. Hence the extrinsic semiconductors are used for the manufacturing of electronic devices such as diodes, transistors etc. The number of free electrons and holes in extrinsic semiconductor are not equal.
- Two types of impurities are added to the semiconductor. They are pentavalent and trivalent impurities.

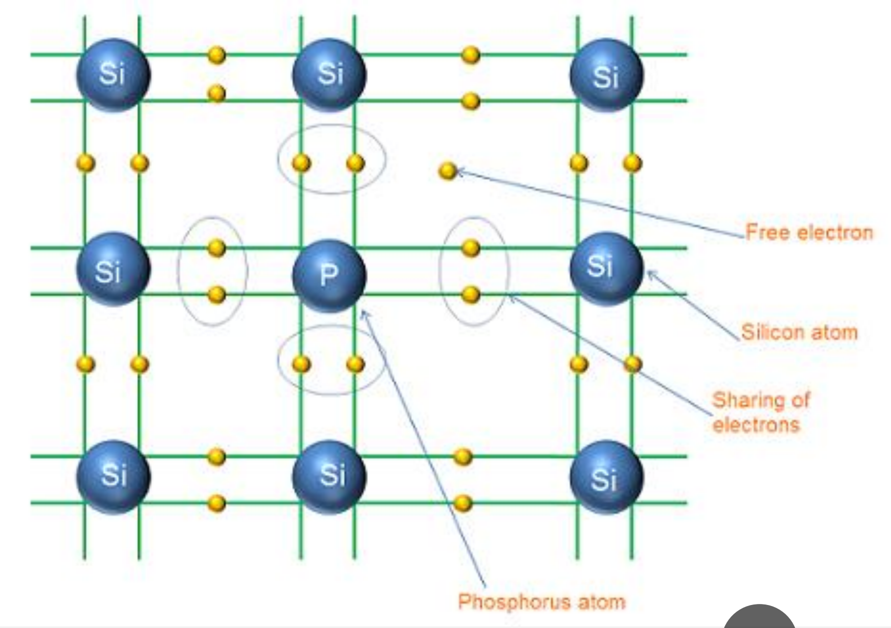
- **Pentavalent impurity** atoms have 5 valance electrons. The various examples of pentavalent impurity atoms include Phosphorus (P), Arsenic (As), Antimony (Sb), etc.
- **Trivalent impurities** Trivalent impurity atoms have 3 valence electrons. The various examples of trivalent impurities include Boron (B), Gallium (G), Indium(In), Aluminium(Al).

N TYPE SEMICONDUCTOR

- When pentavalent impurity is added to an intrinsic or pure semiconductor (silicon or germanium), then it is said to be an n-type semiconductor. Pentavalent impurities such as phosphorus, arsenic, antimony etc are called donor impurity.
- Let us consider, pentavalent impurity phosphorus is added to silicon as shown in below figure. Phosphorus atom has 5 valence electrons and silicon has 4 valence electrons. Phosphorus atom has one excess valence electron than silicon. The four valence electrons of each phosphorus atom form 4 covalent bonds with the 4 neighboring silicon atoms. The fifth valence electron of the phosphorus atom cannot able to form the covalent bond with the silicon atom because silicon atom does not have the fifth valence electron to form the covalent bond.
- Thus, fifth valence electron of phosphorus atom does not involve in the formation of covalent bonds. Hence, it is free to move and not attached to the parent atom.

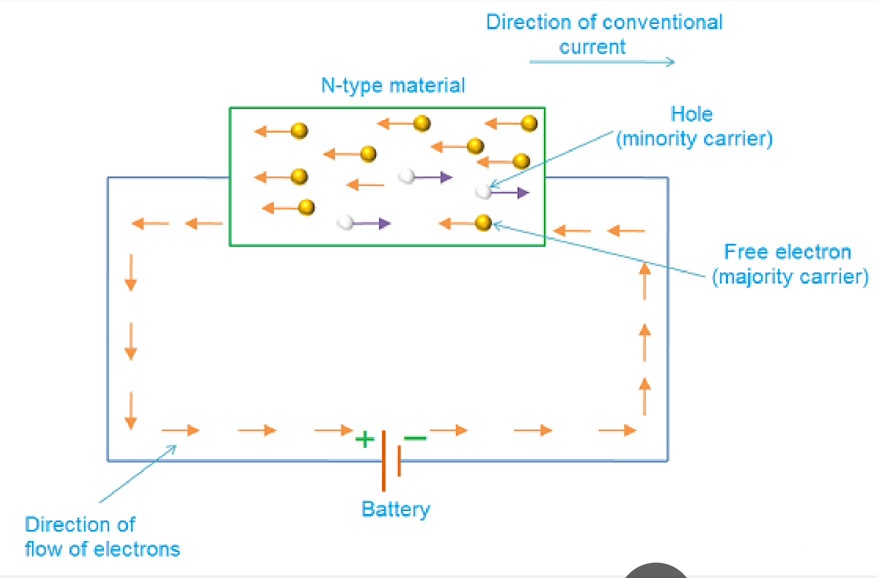
N TYPE SEMICONDUCTOR

This shows that each phosphorus atom donates one free electron. Therefore, all the pentavalent impurities are called donors. The number of free electrons are depends on the amount of impurity (phosphorus) added to the silicon. A small addition of impurity (phosphorus) generates millions of free electrons.



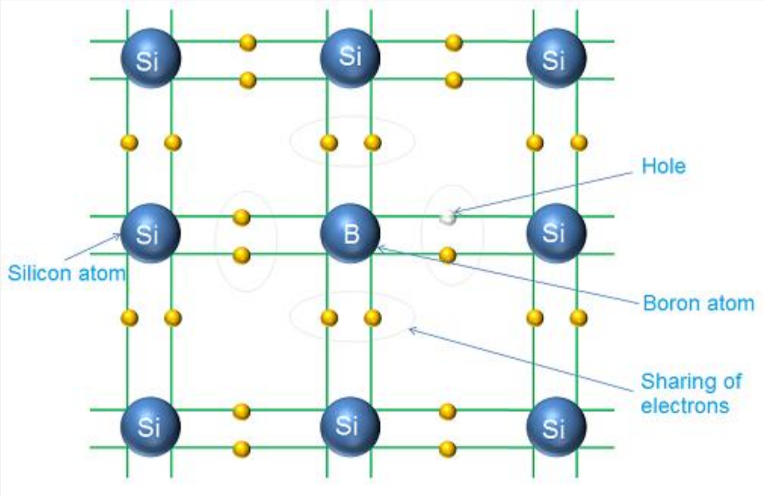
CONDUCTION IN N-TYPE SEMICONDUCTOR

- Let us consider an n-type semiconductor as shown in below figure. When voltage is applied to n-type semiconductor; the free electrons moves towards positive terminal of applied voltage. Similarly holes moves towards negative terminal of applied voltage.
- In n-type semiconductor, the population of free electrons is more whereas the population of holes is less. Hence in n-type semiconductor free electrons are called majority carriers and holes are called minority carriers. Therefore, in a n-type semiconductor conduction is mainly because of motion of free electrons.



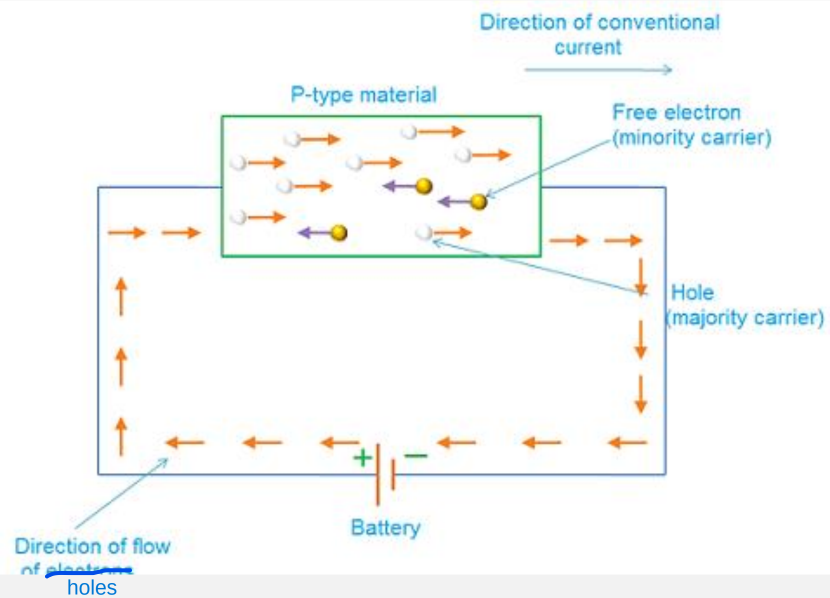
P-TYPE SEMICONDUCTOR

- When the trivalent impurity is added to an intrinsic or pure semiconductor (silicon or germanium), then it is said to be an p-type semiconductor. Trivalent impurities such as Boron (B), Gallium (G), Indium(In), Aluminium(Al) etc are called acceptor impurity.
- Let us consider, trivalent impurity boron is added to silicon as shown in below figure. Boron atom has three valence electrons and silicon has four valence electrons. The three valence electrons of each boron atom form 3 covalent bonds with the 3 neighboring silicon atoms.
- In the fourth covalent bond, only silicon atom contributes one valence electron, while the boron atom has no valence electron to contribute. Thus, the fourth covalent bond is incomplete with shortage of one electron. This missing electron is called hole.
- This shows each boron atom accept one electron to fill the hole. Therefore, all the trivalent impurities are called acceptors. A small addition of impurity (boron) provides millions of holes.



CONDUCTION IN P-TYPE SEMICONDUCTOR

- Let us consider a p-type semiconductor as shown in below figure. When voltage is applied to p-type semiconductor; the holes in valence band moves towards negative terminal of applied voltage. Similarly free electrons move towards positive terminal of applied voltage.
- In p-type semiconductor, the population of holes in valence band is more, whereas the population of free electrons in conduction band is less. So, current conduction is mainly because of holes in valence band. Free electrons in conduction band constitute little current. Hence in p-type semiconductor, holes are called majority carriers and free electrons are called minority carriers.

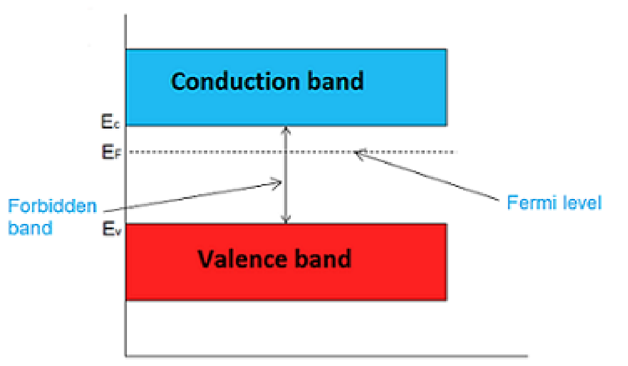


FERMI LEVEL IN EXTRINSIC SEMICONDUCTOR

- In extrinsic semiconductor, the number of electrons in the conduction band and the number of holes in the valence band are not equal. Hence, the probability of occupation of energy levels in conduction band and valence band are not equal. Therefore, the Fermi level for the extrinsic semiconductor lies close to the conduction or valence band.

FERMI LEVEL IN N-TYPE SEMICONDUCTOR

- In n-type semiconductor pentavalent impurity is added. Each pentavalent impurity donates a free electron. The addition of pentavalent impurity creates large number of free electrons in the conduction band.
- At room temperature, the number of electrons in the conduction band is greater than the number of holes in the valence band. Hence, the probability of occupation of energy levels by the electrons in the conduction band is greater than the probability of occupation of energy levels by the holes in the valence band. This probability of occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the n-type semiconductor lies close to the conduction band.



FERMI LEVEL IN N-TYPE SEMICONDUCTOR

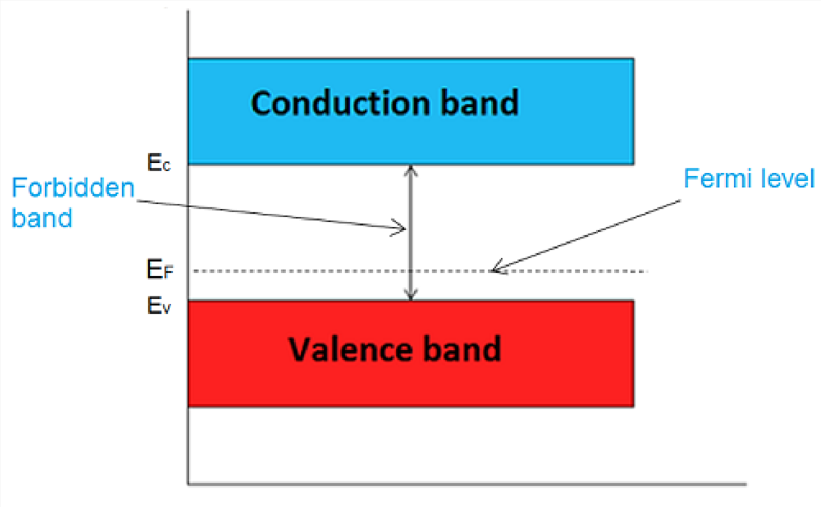
- The Fermi level for n-type semiconductor is given as

$$E_F = E_C - K_B T \log \frac{N_C}{N_D}$$

Where E_F is the fermi level.
E_C is the conduction band.
K_B is the Boltzmann constant.
T is the absolute temperature.
N_C is the effective density of states in the conduction band.
N_D is the concentration of donar atoms.

FERMI LEVEL IN P-TYPE SEMICONDUCTOR

- In p-type semiconductor trivalent impurity is added. Each trivalent impurity creates a hole in the valence band and ready to accept an electron. The addition of trivalent impurity creates large number of holes in the valence band.
- room temperature, the number of holes in the valence band is greater than the number of electrons in the conduction band. Hence, the probability of occupation of energy levels by the holes in the valence band is greater than the probability of occupation of energy levels by the electrons in the conduction band. This probability of occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the p-type semiconductor lies close to the valence band.



- The Fermi level for p-type semiconductor is given as $E_F = E_V + K_B T \log \frac{N_V}{N_A}$

Where N_V is the effective density of states in the valence band.

N_A is the concentration of acceptor atoms.

FERMI LEVEL IN INTRINSIC SEMICONDUCTOR AT THE MIDDLE OF THE FORBIDDEN GAP PROOF

The electron concentration in conduction band of semiconductor at temperature T is given by -

$$\boxed{n = N_C e^{-(E_C - E_F)/kT}} \quad (1)$$

N_C is the effective density of states in conduction band

The hole concentration in valence band of semiconductor at temperature T is given by -

$$\boxed{p = N_V e^{-(E_F - E_V)/kT}} \quad (2)$$

N_V is the effective density of states in valence band

For intrinsic semiconductor,

$$\mathbf{n = p}$$

$$\therefore N_C\, e^{-(E_C - E_F)/kT} = N_V e^{-(E_F - E_V)/kT}$$

$$\therefore \frac{e^{-(E_C - E_F)/kT}}{e^{-(E_F - E_V)/kT}} = \frac{N_C}{N_V}$$

$$\boxed{\text{At equilibrium, } N_C = N_V} \quad (3)$$

$$\therefore \frac{e^{-(E_C - E_F)/kT}}{e^{-(E_F - E_V)/kT}} = 1$$

FERMI LEVEL IN INTRINSIC SEMICONDUCTOR AT THE MIDDLE OF THE FORBIDDEN GAP PROOF

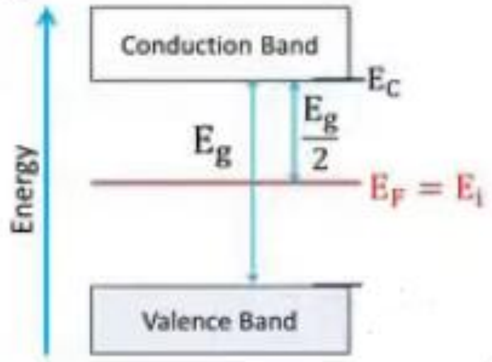
$$\therefore \frac{e^{-(E_C - E_F)/kT}}{e^{-(E_F - E_V)/kT}} = 1$$

$$\therefore e^{\frac{-(E_C - E_F - E_F + E_V)}{kT}} = 1 = e^0$$

$$\therefore \frac{E_C - E_F - E_F + E_V}{kT} = 0$$

$$\therefore E_C + E_V = 2E_F$$

$$\boxed{\therefore\ E_F = \frac{E_C + E_V}{2}}$$



NUMERICAL PROBLEMS BASED ON FERMI LEVEL IN SEMICONDUCTORS

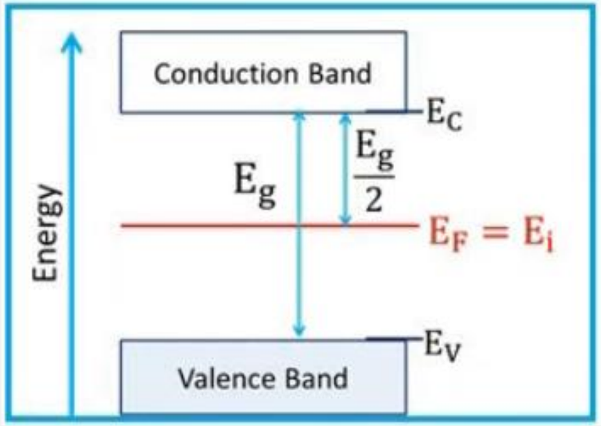
- 1.What is the probability of an electron being thermally excited to conduction band in intrinsic silicon at 27 deg Celsius. The band gap energy of Si is 1.12 eV.

Solution:

Given : T = 27 ^{0}C = 300 ^{0}K, $k = 8.625 \times 10^{-5}\,\frac{eV}{^0K}$, $E_g = 1.12$ eV

For intrinsic semiconductor $E_F = \frac{E_C + E_V}{2}$

$$\therefore E_C - E_F = \frac{E_g}{2} = \frac{1.12}{2} = 0.56 \text{ eV}$$



$$\therefore \text{Probability of occupancy} = f(E_C) = \frac{1}{1+e^{\left(\frac{E_C - E_F}{kT}\right)}}$$

$$= \frac{1}{1+e^{\left(\frac{0.56}{8.625\times10^{-5}\times300}\right)}}$$

$$= 3.99 \times 10^{-10}$$