

UPPSC-AE

2020

Uttar Pradesh Public Service Commission

Combined State Engineering Services Examination
Assistant Engineer

Electrical Engineering

Elements of Electronics (Basic Electronics Engineering)

Well Illustrated **Theory** *with*
Solved Examples and Practice Questions



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Elements of Electronics (Basic Electronics Engineering)

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Semiconductor Physics

1.1 Introduction

A semiconductor is a material that is neither a good conductor nor a good insulator. A material whose conductivity lies between the metal and insulator is a semiconductor. Some common semiconductor materials are Silicon (Si), Germanium (Ge), Gallium-Arsenide (GaAs), etc. Silicon is the most widely used semiconductor material in the electronics industry. Intrinsic semi conductors are semiconductors in their purest form. Extrinsic semiconductors are semiconductors with other atoms (impurity) mixed in. This chapter deals with the basics of semiconductor materials and their characteristics.

1.2 Classification of Materials

A. On the basis of conductivity

On the basis of relative values of electrical conductivity (σ) or resistivity ($\rho = 1/\sigma$), the solids are broadly classified as:

(i) **Metals or conductors:** They possess very low resistivity (or low conductivity)

$$\rho \approx 10^{-2} - 10^{-8} \Omega\text{-m}$$

$$\sigma \approx 10^2 - 10^8 \text{ Sm}^{-1}$$

(ii) **Semiconductors:** They have resistivity or conductivity intermediate to metals and insulators

$$\rho \approx 10^{-5} - 10^6 \Omega\text{-m}$$

$$\sigma \approx 10^5 - 10^{-6} \text{ Sm}^{-1}$$

(iii) **Insulators:** They have high resistivity (or low conductivity)

$$\rho \approx 10^{11} - 10^{19} \Omega\text{-m}$$

$$\sigma \approx 10^{-11} - 10^{-19} \text{ Sm}^{-1}$$

B. On the basis of energy bands

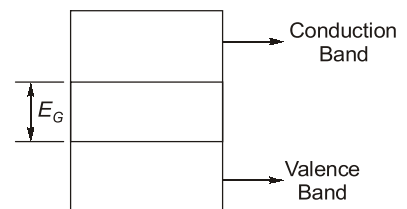
- The minimum energy required to detach an electron from valence band to conduction band is equal to its Energy Gap (E_g).
- Energy band gap E_g is a function of temperature and tends to decrease as the temperature increases.
- At any temperature T ,

$$E_g(T) = E_{g0} - \beta T$$

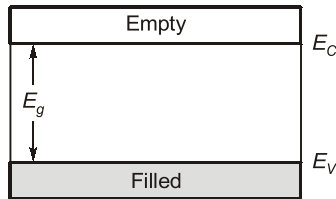
$$E_{g0} = \text{Energy Band Gap at } 0^\circ\text{K}$$

$$\beta = \text{Material constant (Unit : eV/}^\circ\text{K)}$$

- Different energy levels with continuous energy variation form energy bands.
- The energy band which includes the energy levels of valence electrons is called the valence band.



- The energy band above the valence band which can contain conducting electrons is called conduction band.



- Lowest energy level in the conduction band is E_C and highest energy level in the valence band is E_V .

Materials can also be classified on the basis of energy gap:

(i) Metals/Conductors:

- There is no forbidden energy gap between the valence and conduction bands. The two bands actually overlap as shown in figure
- Without supplying any additional energy such as heat or light, a metal already contains a large number of free electrons and that is why it works as a good conductor.
- Example: Al, Cu etc.

(ii) Semiconductors

- At 0°K semiconductor materials have the same structure as insulators except the difference in the size of the band gap E_G , which is much smaller in semiconductors ($E_G \simeq 1$ eV) than in insulators.
- The relatively small band gaps of semiconductors allow for excitation of electrons from the lower (valence) band to the upper (conduction) band by reasonable amount of thermal or optical energy.
- The difference between semiconductors and insulators is that the conductivity of semiconductors can increase greatly by thermal or optical energy.
- Example: Ge and Si.

(iii) Insulators

- It has a very wide forbidden-energy gap ($\simeq 6$ eV) separating the filled valence band from the vacant conduction band. Because of this, it is practically impossible for an electron in the valence band to jump the gap, reach the conduction band.
- At room temperature, an insulator does not conduct. However it may conduct if its temperature is very high or if a high voltage is applied across it. This is termed as the breakdown of the insulator.
- Example: diamond.

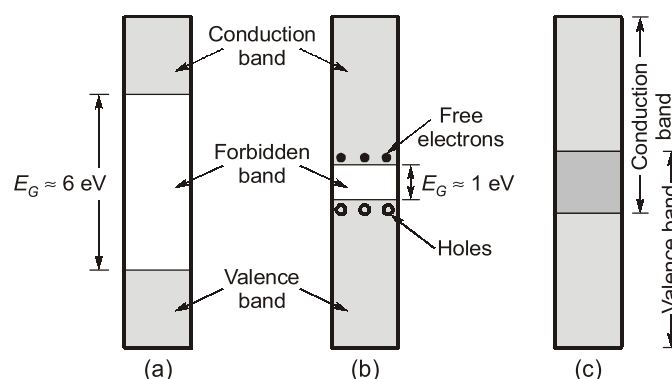


Fig. Simplified energy band diagrams of (a) insulator (b) semiconductor (c) conductor



NOTE

- Conduction band electrons can move along sea of atoms present in the specimen under consideration while the valence band electrons (restrained electrons) are bound to parent atom. These conduction band electrons are known as *free electrons*.

$$E_{G300} = 0.72 \text{ eV for Ge} \quad (\text{at } 300 \text{ K})$$

$$E_{G300} = 1.1 \text{ eV for Si} \quad (\text{at } 300 \text{ K})$$

$$E_G = 0.785 \text{ eV for Ge \& } 1.21 \text{ eV for Si at } 0^\circ \text{ K}$$

- Conduction in semiconductors does not obey ohm's law and will increase rapidly than voltage, i.e. semiconductors are non-linear resistors.

1.3 Types of Semiconductor Materials

A semiconductor material can be either in elemental form or in compound form

- (i) Elemental semiconductor : Si and Ge
- (ii) Compound semiconductors : Examples are
 - Inorganic : GaAs, Cds, GaN, etc.
 - Organic : Anthrance, doped pthalocyanines, etc.

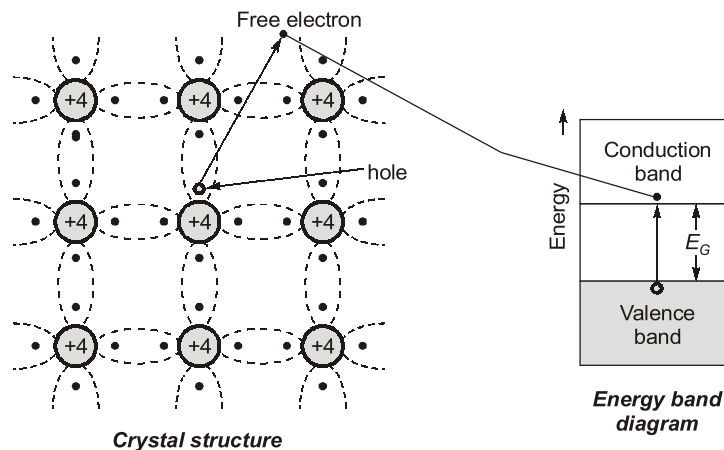
Further on a broad way, they are classified as

- (i) Intrinsic semiconductors
- (ii) Extrinsic semiconductors

1.3.1 Intrinsic Semiconductors

- Semiconductor in its purest form (without any impurity) is known as intrinsic semiconductor.
- An intrinsic semiconductor (such as pure Ge or Si), has only four electrons in the outermost orbit of its atoms. When atoms bond together to form molecules of matter, each atom attempts to acquire eight electrons in its outermost shell. This is done by sharing one electron from each of the four neighboring atoms. This sharing of electrons in semiconductors is known as covalent bonding.
- At absolute zero, all the valence electrons are tightly bound to the parent atoms. No free electrons are available for conduction.
- At room temperature, sufficient thermal energy is supplied to break the covalent bond, thereby, generating electron-hole pairs.
- The concentration of free electrons and holes will always be equal in an intrinsic semiconductor.

$$n = p = n_i \quad (n_i = \text{intrinsic concentration})$$



- At room temperature, some electron-hole pairs are generated. Now, if we raise the temperature further, more electron hole pairs are generated. The higher the temperature, the higher is the concentration of charge carriers. As more charge carriers are made available, the conductivity of intrinsic semiconductor increases with temperature.
- In other words, the resistivity (inverse of conductivity) decreases as the temperature increases. That is; semiconductor have negative temperature coefficient of resistance.

- Intrinsic concentration, $n_i^2 = A_0 T^3 e^{-\left(\frac{E_{G0}}{kT}\right)}$

Where, E_{G0} = Energy gap at 0°K in eVs

k = Boltzman's constant in eV/°K

A_0 = Material constant independent of temperature



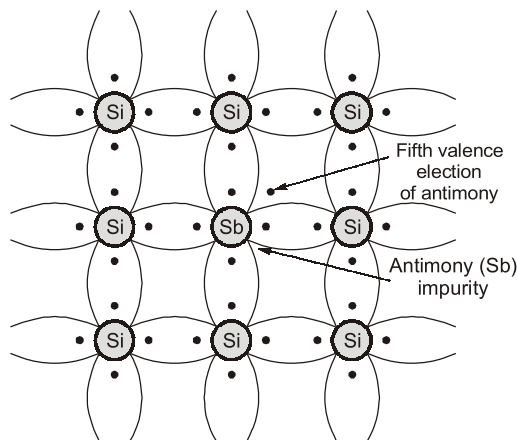
NOTE

- The intrinsic semiconductor behaves as a perfect insulator at absolute zero.
- A hole is not a particle; for all practical purposes we can view it as a positively charged particle capable of conducting current

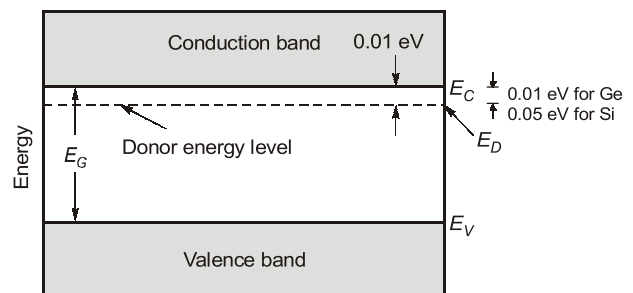
1.3.2 Extrinsic Semiconductors

- In addition to the intrinsic carriers generated thermally, it is possible to create carriers in semiconductors by introducing impurities into the crystal.
- This process, called doping, is the most common technique for varying the conductivity of semiconductors.
- When a crystal is doped such that the equilibrium carrier concentration are different from the intrinsic carrier concentration, the material is said to be extrinsic.
- By doping, a crystal can be altered so that it has a predominance of either electrons or holes. Thus there are two types of doped semiconductors, *n*-type (majority carriers electrons) and *p*-type (majority carries holes).

n-Type Semiconductor



Antimony impurity in n-type material



Energy-band diagram of n-type semiconductor

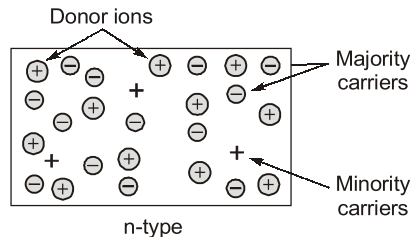
- If suitable pentavalent impurities (antimony, phosphorus and arsenic) are added to intrinsic silicon or Ge, such impurities donate excess (negative) electron carriers, and therefore referred to as donor or *n*-type impurities.
- This excess electron loosely bound to its parent atom, is relatively free to move within the *n*-type material.
- When impurities are introduced in the material, additional levels are created in the energy band structure, usually within the band gap. For *n*-type impurity, it is called "Donor Level".
- In case of Germanium, donor level is only 0.01 eV (0.05 eV in silicon) below the conduction band, and therefore at room temperature almost all the excess electrons of the donor material are raised into the conduction band.
- Donor energy level (E_D) does not depend upon temperature.
- If intrinsic semiconductor is doped with *n* type impurities, not only does the number of electrons increase, but the no. of holes decreases below that which would be available in the intrinsic semiconductor. The reason for the decrease in the no. of holes is that the larger no. of electrons present increases the rate of recombination of electrons with holes.
- In *n*-type semiconductor, majority carriers are electrons and minority carriers are holes.



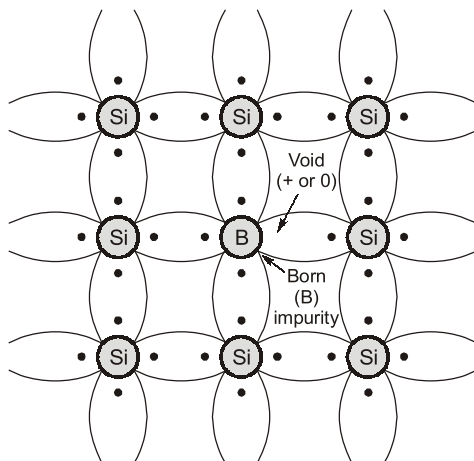
NOTE

- Diffused impurities with five valence electrons are called donor atoms.
- *n*-type material is as a whole electrically neutral since ideally the number of positively charged protons in the nuclei is still equal to the number of free and orbiting negatively charged electrons in the structure.

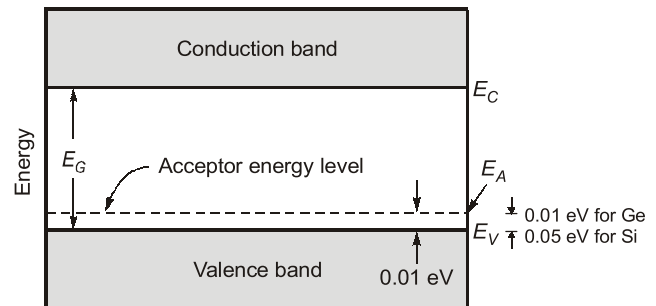
Representation for *n*-type semiconductors:



p-Type Semiconductor



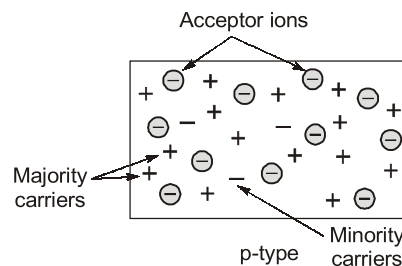
Boron impurity in *p*-type material



Energy-band diagram of *p*-type semiconductor

- If trivalent impurity (Boron, Aluminium, Gallium or Indium) is added to an intrinsic semiconductor, only three of the covalent bonds can be filled and such impurities make available positive carriers because they create holes which can accept electrons. These impurities are referred to as acceptor or p-type impurities.
- A very small amount of energy is required for an electron to leave the valence band and occupy the acceptor energy level, it follows that holes generated in the valence band by these electrons constitute the largest number of carriers in the semiconductor material.
- The acceptor atom introduces an energy level near the valence band known as Acceptor Energy Level (E_A).
- Acceptor Energy level exist just above the valence band. It represents the energy level of all the trivalent impurities.
- At room temperature, enough thermal energy is available to excite electrons from the valence band to acceptor level.
- Acceptor Energy level (E_A) does not depend upon temperature.
- In p-type semiconductor, majority carriers are holes and minority carriers are electrons.

Representation for p-type semiconductors:



NOTE

- The diffused impurities with three valence electrons are called acceptor atoms.
 - Standard Doping Levels
 - Moderate doping : 1 in ($10^6 - 10^8$) : P, N
 - Lightly doped : 1 in 10^{11} : P^-, N^-
 - Highly (heavily) doped : 1 in 10^3 : P^+, N^+
- 1 : 10^6 or 1 in 10^6 or $1/10^6$ is read as “1 impurity atom in 10^6 atoms”.



Example - 1.1 Both donor and acceptor impurities are present in the combination of

- (a) Phosphorous-Arsenic
(c) Boron-Gallium

- (b) Aluminium-Antimony
(d) Arsenic-Antimony

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Solution: (b)

- Pentavalent impurities or donor impurities are Antimony, Phosphorous and Arsenic
- While Boron, Gallium and Aluminium are acceptor impurity atoms.



Example - 1.2 Which of the following band is just above the intrinsic Fermi level for n -type semiconductor?

- (a) Donor band (b) Valence band (c) Acceptor band (d) Conduction band

Solution: (a)

For n -type semiconductors, the donor band is just above the intrinsic Fermi level.



Example - 1.3 Doping in a semiconductor increases which quantity.

- | | |
|----------------|-------------------|
| (a) resistance | (b) conductance |
| (c) inductance | (d) none of these |

Solution: (b)

Doping means adding impurity in semiconductor. It increases the conductivity of the semiconductor since it increases either holes or free electrons in the semiconductor

1.4 Mass-Action Law

- In a semiconductor under thermal equilibrium (constant temperature) the product of electrons and holes concentrations is always a constant and is equal to the square of intrinsic carrier concentration.

$$np = n_i^2$$

- The intrinsic concentration n_i is a function of temperature.
- The law is mainly used to calculate the concentration of minority carriers. In n-type semiconductor, the electrons are called the majority carriers, and the holes are called the minority carriers. In a p-type material, the holes are the majority carriers, and the electrons are the minority carriers.

- For a p-type semiconductor, $p_n = \frac{n_i^2}{n_n}$

- For an n-type semiconductor, $n_n = \frac{n_i^2}{p_n}$

$$\text{Minority carrier concentration} = \frac{n_i^2}{\text{Majority carrier concentration}}$$

but, Majority carrier concentration \propto Doping concentration

so, Minority carrier concentration $\propto \frac{1}{\text{Doping concentration}}$

or, Minority carrier concentration \times Doping concentration $= n_i^2$

- In a semiconductor, if majority carrier concentration increases the minority carrier concentration decreases this is due to the recombinations.



Example - 1.4 In a p-type Si sample, the hole concentration is $2.5 \times 10^{15}/\text{cm}^3$. If the intrinsic carrier concentration is $1.5 \times 10^{10}/\text{cm}^3$, then the electron concentration in p-type Si-sample is

- | | |
|---------------------------------|---------------------------------|
| (a) $10^5/\text{cm}^3$ | (b) zero |
| (c) $9 \times 10^4/\text{cm}^3$ | (d) $9 \times 10^6/\text{cm}^3$ |

Solution: (c)

Given, $p = 2.5 \times 10^{15}/\text{cm}^3$; $n_i = 1.5 \times 10^{10}/\text{cm}^3$

As per mass action law,

$$n \cdot p = n_i^2$$

$$n = \frac{n_i^2}{p} = \frac{(1.5 \times 10^{10})^2}{2.5 \times 10^{15}} = 9 \times 10^4/\text{cm}^3$$

1.5 Charge-Neutrality Equation

- Any part of a semiconductor bar is always electrically neutral.

or

Total positive charge densities = Total negative charge densities.

$$P + N_D = n + N_A$$

- n -type

$$P + N_D = n + N_A$$

$$n > p ; N_A \approx 0 \text{ (} n\text{-type)}$$

$$\Rightarrow \frac{n_i^2}{n} + N_D = n \Rightarrow n^2 - N_D n - n_i^2 = 0$$

$$\Rightarrow n = \frac{N_D}{2} \pm \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2}$$

$$= \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2} \quad (n > 0, \text{ so only +ve sign})$$

$$n = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2}$$

$$N_D \gg n_i$$

So,

$$\boxed{n \approx N_D}$$

- Similarly, for p -type

$$p = \frac{N_A}{2} + \sqrt{\left(\frac{N_A}{2}\right)^2 + n_i^2}$$

$$N_A \gg n_i$$

$$\boxed{p \approx N_A}$$



NOTE

Comparison of Si and Ge:

- $\left. \begin{array}{l} Si \rightarrow I_0 \text{ in nano-ampere} \\ Ge \rightarrow I_0 \text{ in micro-ampere} \end{array} \right\} \text{ Because of gap difference}$

I_0 ideally should be zero but practically, it should be less in value, where I_0 is reverse saturation current.

- Temperature withstand capacity

$$Ge \rightarrow 100^\circ\text{C}$$

$$Si \rightarrow 200^\circ\text{C}$$

- Peak inverse voltage (PIV) rating. It is the maximum reverse biased voltage at which the diode can withstand.

$$Ge \rightarrow 400 \text{ V}$$

$$Si \rightarrow 1000 \text{ V}$$

- Silicon is cheaper as compared to germanium.



Example - 1.5 Silicon is preferred to germanium because

- (a) leakage current due to minority charge carrier is less in silicon
- (b) current sensitivity of silicon with temperature is less
- (c) silicon has higher tolerance to temperature
- (d) All of the above

Solution: (d)

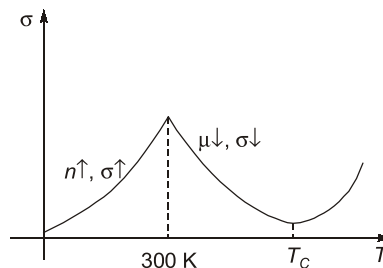
Current sensitivity with temperature, leakage current are lesser in silicon than germanium.

1.6 Temperature and Conductivity Relation

Effect of Temperature on Conductivity of Intrinsic Semiconductor

- For intrinsic semiconductor, $\sigma = n_i q (\mu_n + \mu_p)$
- As temperature increases, $n_i \uparrow \uparrow$ and $\mu \downarrow \Rightarrow \sigma \uparrow$ as $T \uparrow$
- Conductivity of intrinsic semiconductor increases with temperature.

Effect of Temperature on Conductivity of Extrinsic Semiconductor



$0 < T < 300 \text{ K}$: Conductivity increases with the temperature. Because of thermal energy, electrons from valence band gets excited to Acceptor level (in p-type semiconductors) and free electrons from Donor Level gets excited to conduction band (in n-type semiconductors).

$300 \text{ K} < T < T_c$: Majority carrier concentration will remain almost independent of Temperature ($N_D \gg n$ or $N_A \gg P$). As temperature increases, mobility decreases and therefore, conductivity decreases with temperature.

$T > T_c$: At $T = T_c$ (curie temperature) minority carrier concentration will become equal to majority carrier concentration and the extrinsic semiconductor will become intrinsic semiconductor. Above curie temperature, conductivity increases with temperature.



NOTE

- Conductivity of semiconductor is given as

$$\sigma = nq\mu_n + pq\mu_p$$

- For minimum conductivity

$$n = n_i \sqrt{\frac{\mu_p}{\mu_n}} \quad \text{and} \quad P = n_i \sqrt{\frac{\mu_n}{\mu_p}}$$

- $\sigma_{\min} = 2n_i \sqrt{\mu_n \mu_p} \cdot q$