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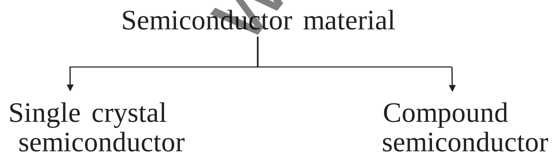
Electronic Devices and Circuits

Semiconductor Physics

Semiconductor	Certain substances such as germanium, silicon, carbon etc are neither good conductors as copper nor insulators like glass. In other words, the resistivity of these materials lies in between conductors and insulators. Such substances are classified as semiconductors. Semiconductors have some useful properties and are being extensively used in electronic circuits. The semiconductor device is fast replacing bulky vacuum tubes in almost all applications. Transistors are only one of the family of semiconductor devices : many other semiconductor devices are becoming increasing popular.

Semiconductor Materials

Semiconductor is a special class of elements having conductivity between that of a good conductor and that of an insulator.



Single Crystal Semiconductors

Such as germanium (Ge) and silicon (Si) have a repetitive crystal structure,

$$\text{Ge} : 32 = 2, 8, 18, 4$$

$$\text{Si} : 14 = 2, 8, 4$$

Both Ge (32) and Si (14) are tetravalent atoms and they form covalent bonding as shown in figure.

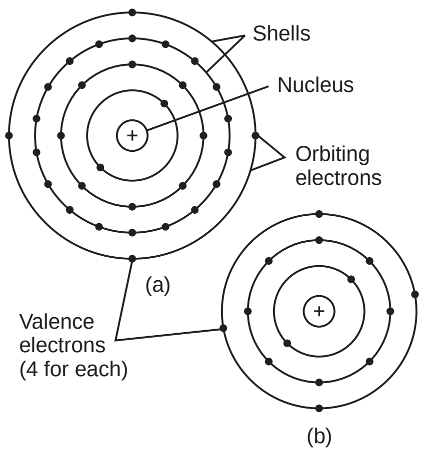


Fig. 1. **Atomic structure (a) Germanium, (b) Silicon**

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Compound Semiconductors

Such as gallium arsenide (GaAs), cadmium sulphide (CdS), gallium arsenide phosphide (GaAsP), gallium nitride (GaN) are constructed by two or more semiconductor materials of different atomic structures.

> **Do You Know?**
> The three semiconductors used most frequently in the construction of electronic devices are Ge, Si and GaAs.

General Properties of Gallium Arsenide (GaAs)

1. It is a compound with Ga from 3rd group and As from 5th group.
2. During the recombination, energy is released in the form of light.
3. It is the best example for direct band gap semiconductor.
4. It is a microwave material with very smaller switching time.
5. $\mu_n/\mu_p = 14.5:1$ for GaAs.

General Properties of Ge and Si

S. No.	Property	Ge	Si
1.	**Atomic number**	**32**	**14**
2.	**Total number of atoms per** cm^3 **or density of atoms**	**4.421** $\times 10^{22}$	5×10^{22}
3.	**Intrinsic concentration at 300 K (atom/**cm^3**)**	**2.5** $\times 10^{13}$	**1.5** $\times 10^{10}$
4.	**Intrinsic resistivity** (Ω**-cm)**	**45**	**230000**
5.	**Electron mobility** (μ_n) (cm^2/ V-s)	**3800**	**1300**
6.	**Hole mobility** (μ_p) (cm^2/ V-s)	**1800**	**500**
7.	E_{go} (eV)	**0.785**	**1.21**
8.	$E_{go(300)}$ (eV)	**0.72**	**1.1**
9.	**Leakage current at 300 K**	μA	**nA**
10.	**Maximum operating temperature**	**75°C**	**175°C**
11.	**Power handling capacity**	**Low power**	**High power**
12.	D_n **at 300 K** (cm^2/s)	**99**	**34**
13.	D_p **at 300 K** (cm^2/s)	**47**	**13**
14.	μ_n/μ_p	**2.1 : 1**	**2.6 : 1**

> **Do You Know?**
> $\frac{\mu_n}{\mu_p}$ ratio decides switching operation. So, Si has better switching operation compared to Ge.

Negative Temperature Coefficient

Any parameter decreasing with the temperature has negative temperature coefficient, *e.g.*, energy gap (E_g)

$$E_g T = E_{g_0} - \beta_0 T$$

$$\beta_0 = 2.2 \times 10^{-4} \qquad \text{(for Ge)}$$

$$\beta_0 = 3.6 \times 10^{-4} \qquad \text{(for Si)}$$

Mobility (μ),

$$\mu \propto T^{-m}$$

	Si	Ge
m :	2.5 for electrons	1.66 for electrons
m :	2.7 for holes	2.33 for holes

Semiconductor materials such as Ge and Si that show a reduction in resistance with increase in temperature are said to have a negative temperature coefficient.

Positive Temperature Coefficient

Any parameter increasing with temperature has positive temperature coefficient *e.g.*, leakage current I_0.

Leakage Current

1. Leakage current never depends upon applied voltage.
2. Leakage current is due to minority charge carriers so it depends upon temperature.
3. It is also known as reverse saturation current because it is saturated for voltage.
4. For better device this current should be very low.
5. Leakage current doubles for every 10°C rise in temperature.

$$I_0(T_2) = I_0(T_1)\,(2)^{\left(\frac{T_2 - T_1}{10}\right)}$$

Intrinsic Semiconductor

An intrinsic semiconductor is also called as pure semiconductor or non-degenerative semiconductor. For germanium and silicon, there are four electrons in the outermost shell, which are referred to as valence electrons. Gallium has three valence electrons and arsenic has five valence electrons. Atoms that have four valence electrons are called tetravalent, those with three are called trivalent and those with five are called pentavalent. The term valence is used to indicate that the potential (ionization potential) required to remove any one of these electrons from the atomic structure is significantly lower than that required for any other electron in the structure. The condition for intrinsic semiconductor is

$$n = p = n_i$$

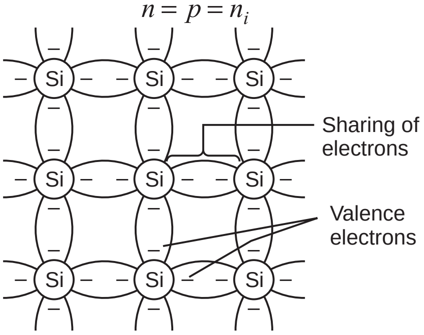

Fig. 2. **Covalent bonding of the silicon atom.**

The conductivity of intrinsic semiconductor is

$$\sigma_i = e(n_e\mu_e + n_n + \mu_n) = e(n\mu_n + p\mu_p)$$

or $$\sigma_i = qn_i(\mu_n + \mu_p)$$

$$\sigma_i \propto n_i \quad \text{but} \quad n_i \propto T^{3/2}$$

So, $$\sigma_i \propto T^{3/2}$$

This bonding of atoms, strengthened by the sharing of electrons is called covalent bonding. At room temperature there are approximately 1.5×10^{10} free carriers in 1 cm^3 of intrinsic silicon material, that is 15000000000 (15 billion) electrons in space smaller than a small sugar cube, an enormous number.

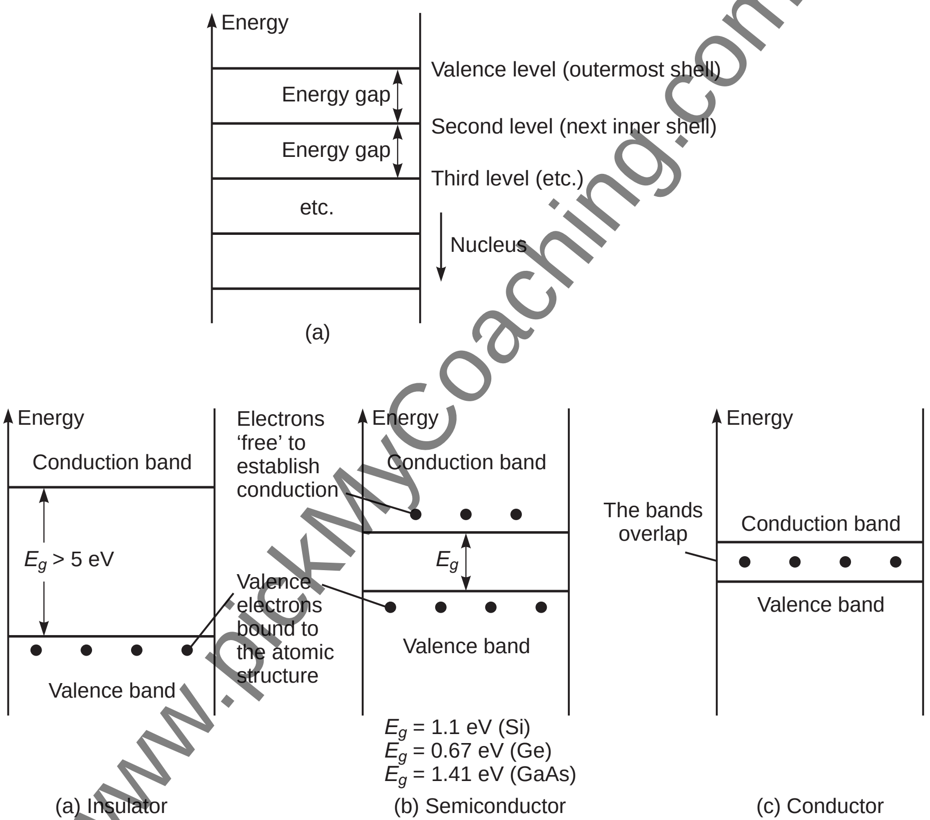

Fig. 3. **Energy levels (a) Discrete levels in isolated atomic structures; (b) Conduction and valence bands of an insulator, semiconductor and conductor.**

The more distant the electron from the nucleus, the higher energy state and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.

Extrinsic Materials

The characteristics of a semiconductor material can be altered significantly by the addition of specific impurity atoms to the relatively pure semiconductor material (intrinsic semiconductor). These impurities, although only added at 1 part in 10 million, can alter the band structure sufficiently to totally change the electrical properties of the material. A semiconductor material that has been subjected to the doping process is called an extrinsic material.

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n-type Materials

- Due to pentavalent impurity added in a pure or intrinsic semiconductor, a new discrete energy level is created just below the conduction band.
- In n -type semiconductor, majority carriers are electrons while minority carriers are holes.
- Majority carrier current will contribute more current than minority carrier current.
- Minority carrier noise is called as thermal noise or white noise or Johnson noise while majority carrier will contribute less noise.

Condition for n-type semiconductor

$$n > n_i$$
$$p < n_i$$

According to the law of electrical neutrality,

Number of positive charges = Number of negative charges

$$N_D + p = N_A + n$$

or $$N_D - N_A = n - p$$

In n-type semiconductor,

$$N_A = 0$$

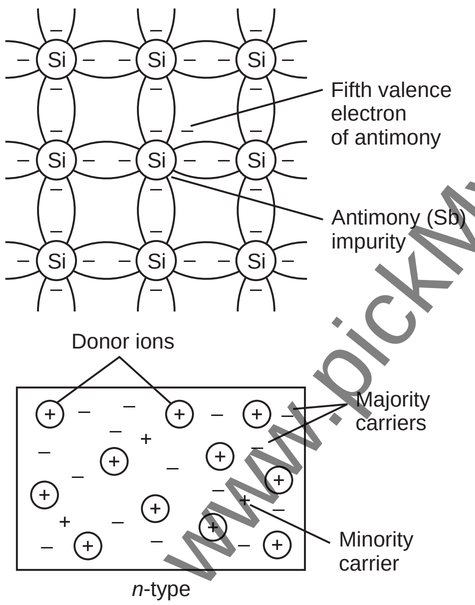

Fig. 4 **Antimony impurity in *n*-type material**

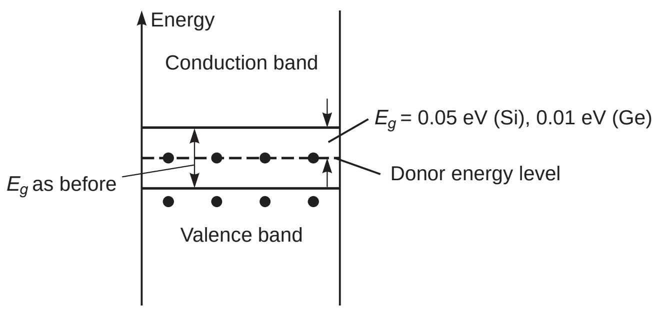

Fig. 5 **Effect of donor impurities on the energy band**

$$n = N_D + p$$
$$n \cong N_D$$

The conductivity of n-type semiconductor is

$$\sigma_n \cong nq\mu_n \text{ mho/cm}$$

Example 1. 4n-type semiconductor is
(a) negatively charged
(b) positively charged
(c) no charge at all
(d) electrically neutral

Sol. (d) n-type semiconductor as a whole is electrically neutral.

p-type Materials

- Due to trivalent impurity added in a pure or intrinsic semiconductor, a new discrete level is created just above the valence band.

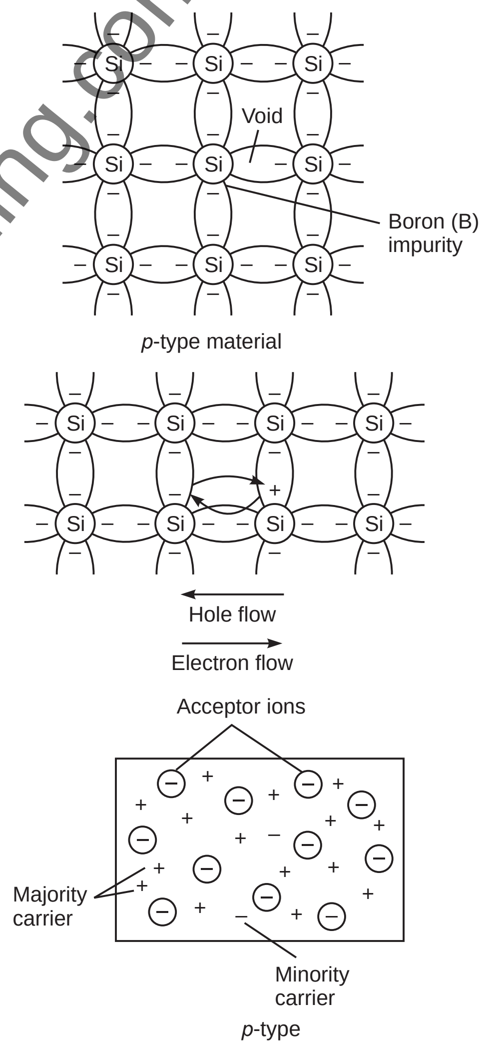

Fig. 6

- In p-type semiconductor majority carriers are holes while minority carriers are electrons.

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- Current is dominated by the flow of holes.

The condition of p-type semiconductor is

$$p > n_i$$
$$n < n_i$$

According to the law of neutrality,

$$N_D + p = N_A + n$$

For p-type semiconductor,

$$N_D = 0$$
$$p = N_A + n$$
$$p \cong N_A$$

where, N_A = acceptor concentration

N_A = Total number of atoms $\times$ Impurity ratio

Unit of N_A = atom/cm^3

The conductivity of p-type semiconductor is

$$\text{mho}_p = N_A q \mu_p$$

Example 2. Choose the correct answer.

(a) $\mu_n = \mu_p$ (b) $\mu_n > \mu_p$
(c) $\mu_p < \mu_n$ (d) None of these

Sol. (b) $\mu_n > \mu_p$

Mobility of electrons is greater than mobility of holes.

Current Density (J)

Current passing per unit area is called as current density.

$$J = \frac{I}{A} \Rightarrow \text{A/m}^2$$

$$J = \sigma E \text{ A/m}^2 \quad \left[\frac{\mho}{\text{m}} \cdot \frac{\text{V}}{\text{m}} = \text{A/m}^2\right]$$

For metals, $J = nq\mu_n E = ne\mu_n E$

For semiconductor,

$$J = nq\mu_n E + pq\mu_p E$$
$$J = (ne\mu_n + pe\mu_p)\, E$$
$$J = e\,(n\mu_n + p\mu_p)\, E \text{ A/m}^2$$

Carrier Flow in a Semiconductor

The total carrier flow in a semiconductor is the sum of three flow phenomena, *i.e.*,

(a) Drift current
(b) Diffusion
(c) Recombination

(a) Drift Current

In free space, an electric field will accelerate electrons in a straight line from the negative terminal to the positive terminal of the applied voltage. In a conductor or semiconductor at 25°C, a free electron under the influence of an electric field will move toward the positive terminal of the applied voltage but will continually collide with atoms along the way. The presence of the electric field does not stop the collisions and random motion, but it does cause the electrons to drift in the direction of the positive terminal. Consequently, current produced in this way is termed as drift current.

$$v_d = \mu E$$

Here, μ is the constant of proportionality.

(b) Diffusion and Diffusion Current

Diffusion is defined as the migration of charge carriers from higher concentration to lower concentration or from higher density to lower density. Diffusion current flows only in semiconductor due to unequal distribution of charge carriers in the semiconductor.

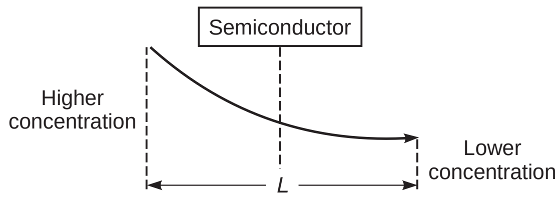


Fig. 7

$\frac{dn}{dx}$ = electron concentration gradient

$\frac{dp}{dx}$ = hole concentration gradient

L = diffusion length

$$L = \sqrt{D\tau}$$

D = diffusion constant

τ = carrier life time

$L_n = \sqrt{D_n \tau}$ cm and $L_p = \sqrt{D_p \tau}$ cm

Electron diffusion current density (J_n)

$$J_n = qD_n \frac{dn}{dx} \text{ A/cm}^2$$

Hole diffusion current density (J_p)

$$J_p = -qD_p \frac{dp}{dx} \text{ A/cm}^2$$

Combined drift and diffusion current is

$$J_n = e\mu_n nE + eD_n \frac{dn}{dx}$$

$$J_p = e\mu_p pE - eD_p \frac{dp}{dx}$$

Einstein's Equation

In a semiconductor,

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

It gives the relationship between diffusion constant, mobility and thermal voltage.

$$V_T = \frac{KT}{q} = \frac{T}{11600} \text{ V}$$

$$\frac{\mu_n}{D_n} = \frac{\mu_p}{D_p} = \frac{1}{V_T}$$

D_n and D_p are the diffusion constants.

Example 3. What is the unit of D/μ?

Sol. Volt

Example 4. What is the unit of μ/D?

[GATE 2009]

Sol. V^{-1}.

Mass-Action Law

This law states that in a semiconductor (intrinsic or extrinsic) under thermal equilibrium, the product of electrons and holes is always a constant and is equal to the square of intrinsic concentration. This law is widely used to calculate the concentration of minority carrier.

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

For p-type semiconductor Electrons are minority carriers.

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

For n-type semiconductor Holes are minority carriers.

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

Minority carrier concentration

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

Hall Effect

Hall effect states that if specimen (metal or semiconductor) carry the current I, is placed in a transverse magnetic field B, an electric field intensity E induced in a direction perpendicular to both I and B.

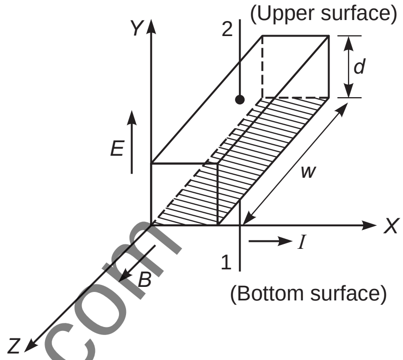


Fig. 8

- Force due to B is towards downward, so all majority charge carriers will come and deposit to bottom.

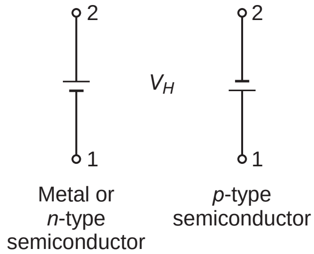


Fig. 9

- It is used to find out concentration of charge carriers and mobility of charge carriers.
- According to Hall experiment, the mobility of charge carriers is

$$\mu = \frac{8}{3\pi} \sigma R_H \quad \cong \quad \mu \cong \sigma R_H$$

σ = conductivity of the specimen

R_H = Hall coefficient

$$E = \frac{V_H}{d} \text{ V/m}$$

d = thickness or distance between surfaces 1 and 2

$$V_H = \frac{BI}{\rho w}$$

w = width of given specimen

Hall coefficient

$$R_H = \frac{1}{\rho}$$

$$\therefore \quad V_H = \frac{BR_H I}{w} \Rightarrow V_H \propto R_H$$

Hall voltage $V_H \propto$ Hall coefficient R_H

$$\propto \frac{1}{\text{Carrier concentration}}$$

$R_H \propto$ temperature coefficient of R

When semiconductor is simultaneously doped with donor and acceptor impurity

- If $N_D > N_A$
  Semiconductor turns into n-type
  $$\sigma_n = (N_D - N_A)\, q\, \mu_n \text{ mho/cm}$$
- If $N_A > N_D$
  Semiconductor turns into p-type
  $$\sigma_p = (N_A - N_D)\, q\, \mu_P \text{ mho/cm}$$
- If $N_D \equiv N_A$
  Semiconductor remains intrinsic
  $$\sigma_i = n_i q(\mu_n + \mu_p) \text{ mho/cm}$$

Example 5. In which case, there is not an effect of doping?

(a) $N_D > N_A$ (b) $N_A > N_D$ (c) $N_A = N_D$

Sol. (c) $N_A = N_D$

Concentration of Electrons in Conduction Band

- E_C is minimum energy of conduction band.
- E_V is maximum energy of the valence band.

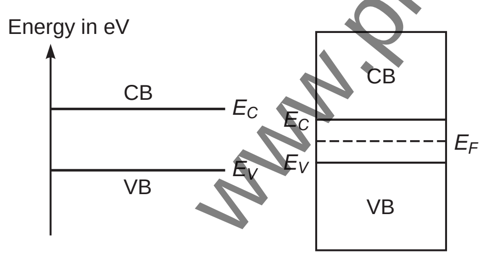


Fig. 10

- The concentration of electron in the conduction band is given by
  $$n \cong N_C\, e^{-\frac{(E_C - E_F)}{kT}}$$
  N_C is the material constant and is a function of temperature
  $$N_C = 2\left[\frac{2\pi \bar{k}\, Tm_n}{h^2}\right]^{3/2}$$

$$\bar{k} = 1.381 \times 10^{-23} \text{ J/K}$$

$m =$ rest mass of electrons $= 9.1 \times 10^{-31}$ kg

$m_n =$ effective mass of the electrons

$E_F =$ Fermi energy in eV

- The electron in the conduction band has energy in the range of E_C to positive infinite.

Concentration of Holes in Valence Band

- The concentration of holes in the valence band is given by
  $$p \cong N_V\, e^{-\left[\frac{E_F - E_V}{kT}\right]}$$
  where, N_V is a material constant and is a function of temperature
  $$N_V = 2\left[\frac{2\pi - \bar{k}\, Tm_p}{h^2}\right]^{3/2}$$
  $m_p =$ effective mass of the holes
  $$m_p > m_n$$
- Effective mass of the holes is always greater than effective mass of electrons. So mobility of holes is less than electrons.
  $h =$ Planck constant in J-s $= 6.625 \times 10^{-34}$ J-s
  $\bar{k} =$ Boltzmann constant in J/K
  $= 1.602 \times 10^{-19} \times 8.62 \times 10^{-5} = 1.38 \times 10^{-23}$ J/K
- The energy of the holes in the valence band is extended from $-\infty$ to E_V.

Fermi Level

- Fermi energy also called characteristic energy and it is expressed in eV.
- Fermi energy is defined as 'the maximum energy possessed by the electron at 0 K'.
- Fermi energy is also defined as the energy possessed by fastest moving electron at 0 K'.

Fermi-Dirac Function

It is also called Fermi-Dirac probability function. The Fermi-Dirac function of a metal or semiconductor is given by

$$F(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

$E =$ energy possessed by electron in eV

If $\quad E = E_F \Rightarrow F(E) = \dfrac{1}{1+e^0} = \dfrac{1}{2} = 50\%$

If $\quad E < E_F \Rightarrow F(E) = 0$

If $\quad E > E_F \Rightarrow F(E) = 1 \quad \Rightarrow \quad 100\%$

- '$F(E)$ specifies the fraction of all the states at energy E in eV occupied under thermal equilibrium'.
- 'Fermi level is the energy level with 50% probability of being filled, if no forbidden band exists'.

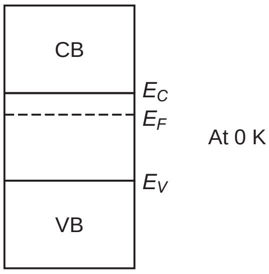


Fig. 12

Fermi Level in Intrinsic Semiconductor

In intrinsic semiconductor, $n = p = n_i$

$$N_C\, e^{-\frac{[E_C - E_F]}{kT}} = N_V\, e^{-\frac{[E_F - E_V]}{kT}}$$

$$\Rightarrow \quad \frac{N_C}{N_V} = e^{\frac{-E_F + E_V + E_C - E_F}{kT}}$$

Taking natural log on both sides,

$$\log_e \frac{N_C}{N_V} = \frac{E_C + E_V - 2E_F}{kT}$$

$$E_F = \left(\frac{E_C + E_V}{2}\right) - \frac{kT}{2} \log_e \frac{N_C}{N_V}$$

In intrinsic semiconductor, Fermi level is a function of temperature.

If $\quad m_n = m_p$

Then $\quad N_C = N_V$

$$E_F = \left(\frac{E_C + E_V}{2}\right)$$

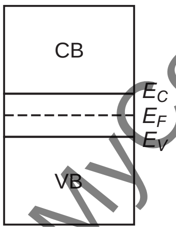


Fig. 11

In intrinsic semiconductor, Fermi level will be passed to the centre of forbidden energy gap.

If $\quad T = 0\,\text{K} \quad \Rightarrow \quad E_F = \dfrac{E_C + E_V}{2}$

In intrinsic semiconductor, as temperature increases, the Fermi level will move away from the centre upto the energy gap. Therefore, conductivity will increase.

Do You Know?

- E_F at the centre of energy gap $E_g (\sigma = 0)$
- E_F moves away from centre of E_g (σ increases)
- E_F moves towards the centre of E_g (σ decreases)

Fermi Level in *n*-type Semiconductor

In *n*-type semiconductor, $n \cong N_D$

$$\Rightarrow \quad N_C\, e^{-\frac{[E_C - E_F]}{kT}} = N_D$$

$$\Rightarrow \quad E_F = E_C - kT \log_e \frac{N_C}{N_D}$$

$$\Rightarrow \quad E_C - E_F = kT \log_e \frac{N_C}{N_D}$$

In the *n*-type semiconductor, Fermi level exists just below the donor energy level or just below the conduction band. (At room temperature)

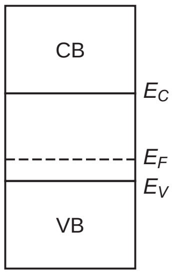


Fig. 13

Fermi Level in *p*-type Semiconductor

In *p*-type semiconductor,

$$p \cong N_A$$

$$N_V\, e^{-\frac{[E_F - E_V]}{kT}} \cong N_A$$

$$E_F - E_V = kT \log_e \frac{N_V}{N_A}$$

$$E_F = E_V + kT \log_e \frac{N_V}{N_A}$$

In the *p*-type semiconductor, Fermi level exists just above the acceptor energy level.

	Doping (increases)	Temperature (increases)
-type	**Upward shift in E_F**	**E_F moves towards centre**
type	**Downward shift in E_F**	**E_F moves towards centre**
Result	**Conductivity increases**	**Conductivity decreases**

Example 6. In an *n*-type semiconductor the Fermi level lies 0.3 eV below the conduction band at 300 K. If the temperature is increased to 330 K. Find the new position of Fermi level?

Sol. $E_C - E_F = kT \log_e \dfrac{N_C}{N_D}$

$$\Rightarrow \quad 0.3 = k \times 300 \log_e \frac{N_C}{N_D} \qquad \ldots\text{(i)}$$

At $\quad T = 330\,\text{K}$

$$\Rightarrow \quad (E_C - E_F)_2 = k \times 330 \log_e \frac{N_C}{N_D} \qquad \ldots\text{(ii)}$$

Dividing Eq. (i) by Eq. (ii),

$$\frac{0.3}{(E_C - E_F)_2} = \frac{300}{330}$$

$$(E_C - E_F)_2 = 0.33\,\text{eV}$$

Intro Exercise - 1

1. The drift velocity of electrons, in silicon
   (a) is proportional to the electric field for all values of electric field
   (b) is independent of the electric field
   (c) increases at low values of electric field and decreases as high values of electric field exhibiting negative differential resistance
   (d) increases linearly with electric field at low values of electric field and gradually saturates at higher values of electric field

2. The electron and hole concentrations in a intrinsic semiconductor are n_i and p_i respectively. When doped with a p-type material, they change to n and p respectively. Then
   (a) $n + p = n_i + p_i$
   (b) $n + n_i = p + p_i$
   (c) $np_i = n_i p$
   (d) $np = n_i p_i$

3. n-type silicon is obtained by doping silicon with
   (a) germanium
   (b) aluminium
   (c) boron
   (d) phosphorus

4. The resistivity of a uniformly doped n-type silicon sample is 0.5 Ω-cm. If the electron mobility (μ_n) is 1250 cm^2/V-s and the charge of an electron is 1.6×10^{-19}, the donor impurity concentration (N_D) in the sample is
   (a) 2×10^{16} cm^{-2}
   (b) 1×10^{16} cm^{-3}
   (c) 2.5×10^{15} cm^{-3}
   (d) 2×10^{15} cm^{-3}

5. If an intrinsic semiconductor is doped with a very small amount of aluminium, then in the extrinsic semiconductor so formed, the number of electrons and holes will
   (a) decrease
   (b) increase and decrease respectively
   (c) increase
   (d) decrease and increase respectively

6. The concentration of minority carriers in an extrinsic semiconductor under equilibrium is
   (a) directly proportional to the doping concentration
   (b) inversely proportional to the doping concentration
   (c) directly proportional to the intrinsic concentration
   (d) inversely proportional to the intrinsic concentration

7. For a particular semiconductor material following parameters are observed :
   $$\mu_n = 1000 \text{ cm}^2/\text{V-s}$$
   $$\mu_p = 600 \text{ cm}^2/\text{V-s}$$
   $$N_c = N_v = 10^{19} \text{ cm}^{-3}$$
   These parameters are independent of temperature. The measured conductivity of the intrinsic material is
   $$\sigma = 10^{-6} (\Omega\text{-cm})^{-1} \text{ at } T = 300 \text{ K}$$
   The conductivity at $T = 500$ K is
   (a) 2×10^{-4} (Ω-cm)$^{-1}$
   (b) 4×10^{-5} (Ω-cm)$^{-1}$
   (c) 2×10^{-5} (Ω-cm)$^{-1}$
   (d) 6×10^{-3}(Ω-cm)$^{-1}$

8. Under low level injection assumption, the injected minority carrier current for an extrinsic semiconductor is essentially the
   (a) diffusion current
   (b) drift current
   (c) recombination current
   (d) induced current

9. Silicon is doped with germanium to a concentration of 4×10^{17} atoms/cm^3. Assume the intrinsic carrier concentration of silicon to be 1.5×10^{10} cm^{-3} and the value of kT/q to be 25 mV at 300 K. Compared to undoped silicon, the Fermi level of doped silicon
   (a) goes down by 0.13 eV
   (b) goes up by 0.13 eV
   (c) goes down by 0.427 eV
   (d) goes up by 0.427 eV

10. In an n-type silicon crystal at room temperature, which of the following can have a concentration of 3×10^{19} cm^{-3}?
    (a) Silicon atoms
    (b) Dopant atoms
    (c) Holes
    (d) Valence electrons

11. A sample of silicon at $T = 300$ K is doped with aluminium at a concentration of 2.5×10^3 cm^{-3} and with arsenic at a concentration of 1×10^{13} cm^{-3}. The material is
    (a) p-type with $p_0 = 1.5 \times 10^8$ cm^{-3}
    (b) p-type with $p_0 = 1.5 \times 10^{13}$ cm^{-3}
    (c) n-type with $n_0 = 1.5 \times 10^{13}$cm^{-3}
    (d) n-type with $n_0 = 1.5 \times 10^7$ cm^{-3}

12. In a particular semiconductor, the donor impurity concentration is $N_D = 10^{14}\ \text{cm}^{-3}$. Assume the following parameters :

$$\mu_n = 1000\ \text{cm}^2/\text{V-s}$$

$$N_V = 1\times 10^{13}\left(\frac{T}{300}\right)^{3/2}\ \text{cm}^{-3}$$

$$N_C = 2\times 10^{19}\left(\frac{T}{300}\right)^{3/2}\ \text{cm}^{-3}$$

$$E_g = 1.1\ \text{eV}$$

If an electric field of $E = 10$ V/cm is applied, then electric current density at 300 K is

(a) 2.3 A/cm^2 (b) 1.6 A/cm^2

(c) 9.6 A/cm^2 (d) 3.4 A/cm^2

13. At room temperature, a possible value for the mobility of electrons in the inversion layer of a silicon *n*-channel MOSFET is

(a) 850 cm^2/V-s (b) 1350 cm^2/V-s

(c) 1750 cm^2/V-s (d) 3650 cm^2/V-s

14. A Hall effect transducer can be used to measure

(a) displacement, temperature and magnetic flux

(b) displacement, position and velocity

(c) position, magnetic flux and pressure

(d) displacement, position and magnetic flux

15. The majority carriers in an *n*-type semiconductor have an average drift velocity v_d in a direction perpendicular to a uniform magnetic field B. The electric field E induced due to hall effect acts in the direction

(a) $v_d \times B$ (b) $B \times v_d$

(c) along v_d (d) opposite to v_d

16. The electron and hole concentrations in an intrinsic semiconductor are n_i per cm^3 at 300 K. Now, if acceptor impurities are introduced with a concentration of N_A per cm^3 (where, $N_A >> n_i$) the electron concentration per cm^3 at 300 K will be

(a) n_i (b) $n_i + N_A$

(c) $N_A - n_i$ (d) $\dfrac{n_i^2}{N_A}$

17. The longest wavelength that can be absorbed by silicon which has the bandgap of 1.12 eV, is 1.1 μm. If the longest wavelength that can be absorbed by another material is 0.87 μm, then the bandgap of this material is

(a) 1.416 eV (b) 0.886 eV

(c) 0.854 eV (d) 0.706 eV

18. The electron concentration in a sample of uniformly doped *n*-type silicon at 300 K varies linearly from $10^{17}/\text{cm}^3$ at $x = 0$ to $6\times 10^{16}/\text{cm}^3$ at $x = 2\,\mu\text{m}$. Assume a situation that electrons are supplied to keep this concentration gradient constant with time. If electronic charge is 1.6×10^{-19} C and the diffusion constant $D_n = 35\ \text{cm}^2/\text{s}$, the current density in the silicon, if no electric field is present, is

(a) zero (b) −1120 A/cm^2

(c) − 660 A/cm^2 (d) +1120 A/cm^2

19. In a sample of gallium arsenide at $T = 200$ K, $n_0 = 5p_0$ and $N_a = 0$. The value of n_0 is

(a) $9.86\times 10^9\ \text{cm}^{-3}$ (b) 7 cm^{-3}

(c) $4.86\times 10^3\ \text{cm}^{-3}$ (d) 3.3 cm^{-3}

20. A GaAs device is doped with a donor concentration of $3\times 10^{15}\ \text{cm}^{-3}$. For the device to operate properly, the intrinsic carrier concentration must remain less than 5% of the total concentration. The maximum temperature on which the device may operate is

(a) 763 K (b) 769 K

(c) 486 K (d) 243 K

Answers with Solutions

1. (d) We know that, $v_d = \mu E$

where, E = applied electric field

μ = electron mobility

However, when applied field is large, then number of electrons in conduction band becomes very large and due to collisions, the motion becomes erratic and linear relationship becomes invalid. For $E > 10^4$ V/cm, μ is inversely proportional to E and so V_n.

2. (b) We know that extrinsic semiconductor is electrically neutral. So,

$$n + n_i = p + p_i$$

3. (d) To get *n*-type semiconductor from intrinsic semiconductors, we add pentavalent impurity and phosphorus is Vth group element contains five electrons in its outermost shell.

4. (b) $$p = \frac{1}{nq\mu_n}$$

$$n = N_D$$

$$N_D = \frac{1}{q\mu_n p} = \frac{1}{1.6\times10^{-19}\times1250\times0.5} = 10^{16}\text{cm}^{-3}$$

5. (d) Due to doping with small amount of aluminium, number of holes will increase.

But $n_n \times n_p = n_i^2$

Therefore, n_n will decrease.

6. (b) $np = n_i^2$

n_i = constant

For n-type, p is minority carrier concentration.

$$p = \frac{n_i^2}{n};\ p \propto \frac{1}{n}$$

7. (d) We know that

$$\sigma_i = en_i(\mu_n + \mu_p)$$

$$\therefore\ 10^{-6} = (1.6\times10^{-19})(1000+600)\,n_i$$

Now, $n_i^2 = N_C N_V\, e^{-\left(\frac{E_g}{kT}\right)}$

$$\Rightarrow\quad E_g = kT\ \ln\frac{N_C N_V}{n_i^2}$$

$$\Rightarrow\quad E_g = 2(0.0259)\ \ln\left(\frac{10^{19}}{3.91\times10^{9}}\right)$$

$$\Rightarrow\quad E_g = 1.122\ \text{eV}$$

At $T = 500$ K,

$$kT = 0.0259\left(\frac{500}{300}\right) = 0.0432\ \text{eV}$$

$$\therefore\quad n_i^2 = (10^{19})^2 e^{-\left(\frac{1.122}{0.0432}\right)}\ \text{cm}^{-3}$$

$$\Rightarrow\quad n_i = 2.29\times10^{13}\ \text{cm}^{-3}$$

$$\sigma_i = (1.6\times10^{-19})(2.29\times10^{13})(1000+600)$$

$$\sigma_i = 5.86\times10^{-3}\ (\Omega\text{-cm})^{-1}$$

8. (a) Under low level injection assumption, the injected minority carrier for an extrinsic semiconductor is essentially the diffusion current.

9. (c) Since, germanium is p-type impurity therefore, Fermi level goes down.

$$E_i - E_f = kT\ \ln\frac{N_A}{N_i}$$

$$= 25\times10^{-3}\ln\frac{4\times10^{17}}{1.5\times10^{10}}$$

$$= 0.427\ \text{eV}$$

10. (b) In an n-type silicon crystal at room temperature, dopant atoms have a concentration of $3\times10^{19}\ \text{cm}^{-3}$.

11. (b) Since, $N_A > N_D$, thus material is p-type.

$$p_0 = N_A - N_D$$

$$= 2.5\times10^{3} - 1\times10^{3}$$

$$= 1.5\times10^{13}\ \text{cm}^{-3}$$

12. (b) We know that

$$n_i^2 = N_C N_V\, e^{-\left(+\frac{E_g}{kT}\right)}$$

$$= (2\times10^{19})(1\times10^{19})\, e^{-\left(\frac{11}{0.0259}\right)}$$

$$= 7.18\times10^{19}$$

$$\therefore\quad n_i = 8.47\times10^{9}\ \text{cm}^{-3}$$

Now $N_D >> n_i$

$\Rightarrow$ $N_D = n_0$

$\therefore$ $J = \sigma E = e\mu_n n_0 E$

$$J = (1.6\times10^{-19})(1000)(10^{14})(100)$$

$$J = 1.6\ \text{A/cm}^2$$

13. (b) At room temperature a possible value for the mobility of electrons in the inversion layer of a silicon n-channel MOSFET is 1350 cm^2/V-s.

14. (a) It can be used to measure displacement temperature and magnetic flux.

15. (b) Hall effect—

Electric force + Magnetic force = 0

$$qE + q\nu\times B = 0$$

$$E = -\nu\times B$$

$$E = B\times\nu$$

16. (d) By the law of electrical neutrality,

$$p + N_D = n + N_A$$

As $N_D = 0,\ N_A >> n_i \cong 0,\ p = N_A$

Using mass action law,

$$np = n_i^2$$

So, $n = \dfrac{n_i^2}{p} = \dfrac{n_i^2}{N_A}$

17. (a) $E_g = \dfrac{1.24}{\lambda} = \dfrac{1.24}{0.87} = 1.425$ eV

18. (b) $J_n = nq\mu_e E + D_n q\dfrac{dn}{dx}$ (Here, $E = 0$)

$$= qD_n\frac{dn}{dx}\qquad\left(\frac{dn}{dx} = \frac{6\times10^{16}-10^{17}}{2\times10^{-4}} = -2\times10^{20}\right)$$

$$= 1.6\times10^{-19}\times35\times(-2\times10^{20})$$

$$= -1120\ \text{A/cm}^2$$

19. (d) $kT = 0.0259\left(\dfrac{200}{300}\right) = 0.0173$ eV

For GaAs at 300 K,

$N_C = 4.7\times10^{17}\,\text{cm}^{-3},\ H_V = 7.0\times10^{18},\ E_g = 1.42$ eV

$$\therefore\quad n_i^2 = 4.7\times10^{17}\,\text{cm}^{-3}\times7.0\times10^{18}\left(\frac{200}{300}\right)^3 e^{-\left(\frac{1.42}{0.0173}\right)}$$

$$\Rightarrow\quad n_i = 1.48\ \text{cm}^{-3}$$

Now, $n_i^2 = n_0 p_0 = 5p_0^2 = \dfrac{n_0^2}{5}$

$$n_0 = \sqrt{5}\ n_i = 3.3\ \text{cm}^{-3}$$

20. (a) We know that

$$n_0 = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2}$$

$$n_i = 0.05\, n_0$$

$$\therefore \quad n_0 = 1.5 \times 10^{15} + \sqrt{(1.5 \times 10^{15})^2 + (0.05 n_0)^2}$$

$$n_0 = 3.0075 \times 10^{15} \text{ cm}^{-3}$$

$$\therefore \quad n_i = 1.504 \times 10^{14} \text{ cm}^{-3}$$

Now, $n_i^2 = N_C N_V e^{\left(-\frac{E_g}{kT}\right)}$

For GaAs at $T = 300$ K,

$N_C = 4.7 \times 10^{17}$, $N_V = 7 \times 10^{18}$, $E_g = 1.42$ eV

$$\therefore (1.504)^2 = 4.7 \times 10^{17} \times 7 \times 10^{18} \left(\frac{T}{300}\right)^3 e^{-\left(\frac{1.42 \times 300}{0.0259\, T}\right)}$$

By trial and error, $T = 763$ K

The *p-n* Junction

p-n Junction	When *p*-type and *n*-type materials are placed in contact with each other, the junction behaves very differently than the either type of material alone. A *p-n* junction conducts current easily when forward biased and practically no current flows when it is reverse biased. This unilateral conduction characteristic of *p-n* junction (*i.e.,* semiconductor diode) is similar to that of a vacuum tube.

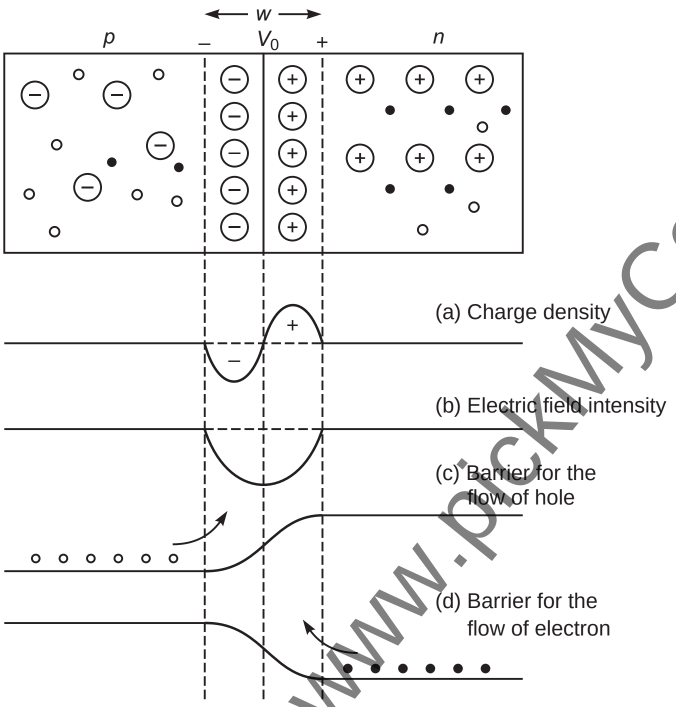


Fig. 1

A *p-n* junction is said to be form only when a bonding force is created between *p*-type and *n*-type semiconductors.

Ideal Diode

The ideal diode may be considered the most fundamental non-linear circuit element. It is a two-terminal device having the circuit symbol of figure and the *I-V* characteristics shown in figure.

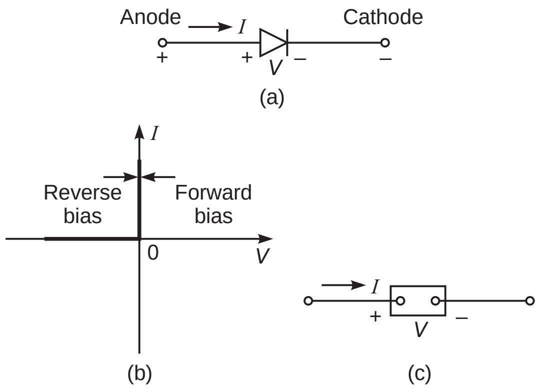


Fig. 2

Semiconductor Diode

The semiconductor diode, with application also numerous to mention, is created by simply joining an *n*-type and *p*-type materials together, nothing more, just the joining of one material with a majority carrier of electrons to one with a majority carrier of holes.

$$V < 0 \quad \Rightarrow \quad I = 0$$

(behave as a open circuit)

Value of reverse bias resistance

$$R_R = \frac{V_R}{I_R}$$

When $V < 0$ or $V_R \Rightarrow I_R = 0$

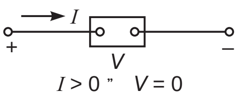
$$R_R = \infty$$

Value of forward bias resistance

$$R_F = \frac{V_F}{I_F}$$

$$V_F = 0$$

$$R_F = 0$$



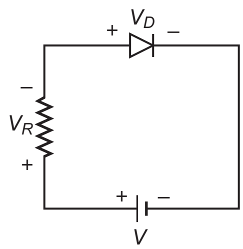


Fig. 5. **Forward bias voltage**

Biasing of a Diode

(a) No Bias (V – 0 V)

This region of uncovered positive and negative ions is called the depletion region due to the 'depletion' of free carriers in the region.

$$\text{Width of depletion region} \propto \frac{1}{\sqrt{\text{Doping}}}$$

In the absence of any applied bias across a semiconductor diode, the net flow of charge in one direction is zero.

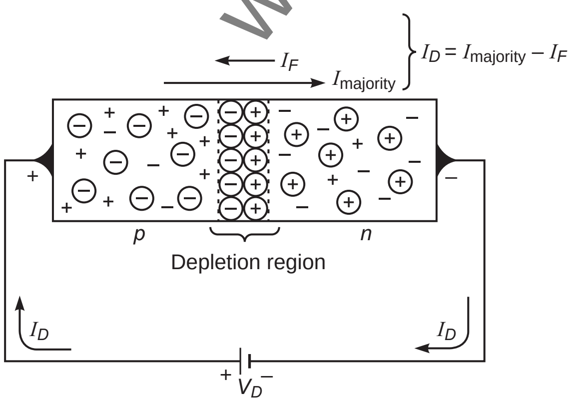


Fig. 4 **Forward biased** p-n **junction**

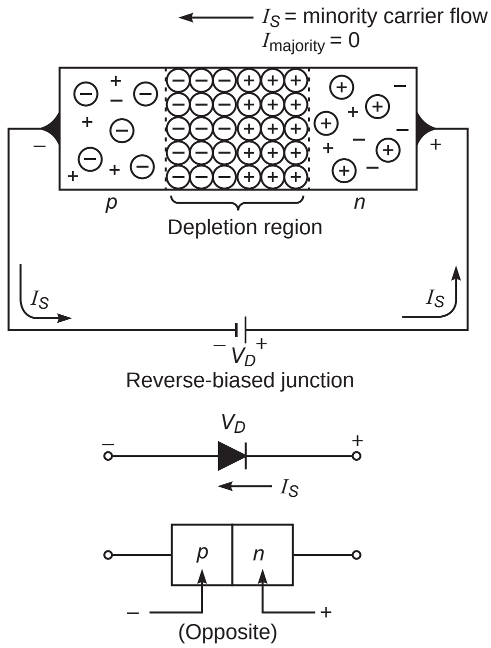


Fig. 6 **Reverse bias condition for a semiconductor**

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(b) Forward Bias Condition

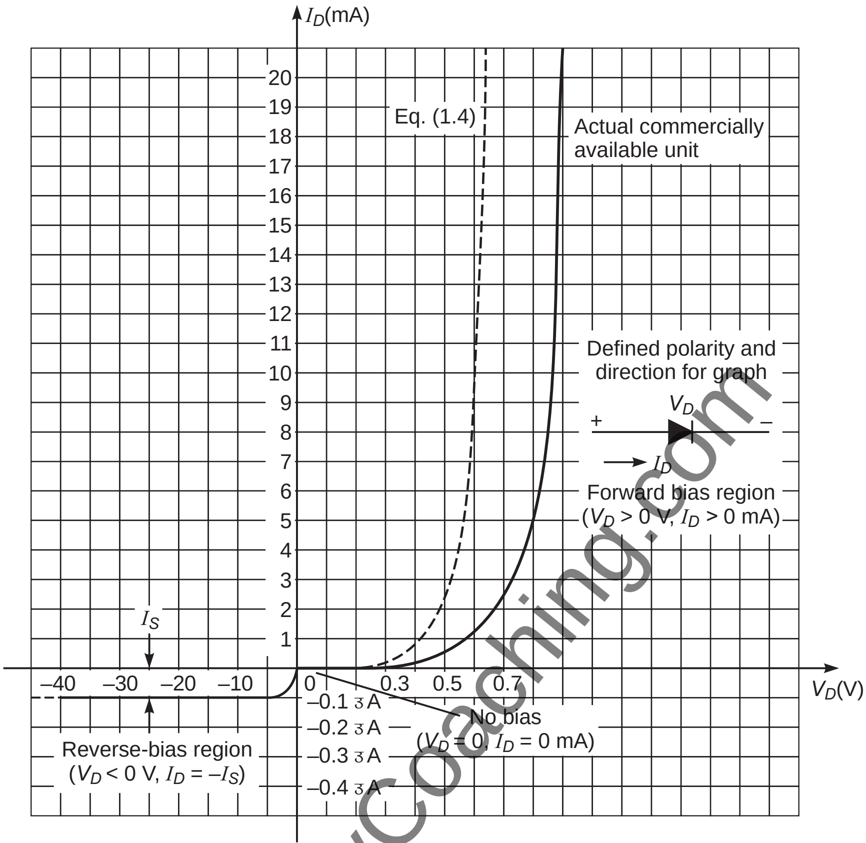

Fig. 7 **Silicon semiconductor diode characteristics**

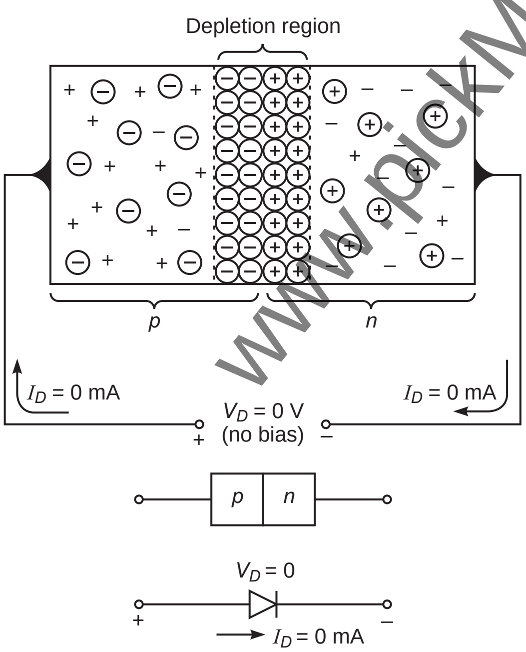

Fig. 3 *p-n* **junction with no external bias**

(V_D > 0 V)

A forward bias or on condition is established by applying the positive potential to the *p*-type material and the negative potential to the *n*-type material.

When a *p-n* junction is forward biased, the width of depletion layer reduces. The forward current is only due to majority carriers and the value of forward current

$$I_F = I_0\,[e^{V_D/nV_T} - 1]$$

$$I_F \cong I_0 e^{V_D/nV_T}$$

where, V_T = thermal voltage (26 mV for room temperature)

n = recombination factor or utility factor

$n = 1$ for Ge

$n = 2$ for Si

I_0 = reverse saturation current

$$V = V_R + V_D$$

Forward bias voltage

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(c) Reverse-Bias Condition ($V_D < 0$V)

If an external potential of V volt is applied across the p-n junction such that the positive terminal is connected to the n-type material and the negative terminal is connected to the p-type material.

The current that exists under reverse-bias condition is called the reverse saturation current and is represented by I_S.

$$I_D = I_0[e^{V/nV_T} - 1]$$

$$I_S \cong -I_0$$

I_0 doubles for every 10°C rise in temperature and it is independent of applied voltage.

$$\text{Width of depletion region} \propto \sqrt{\text{Reverse-bias voltage}}$$

I_0 for Ge is in μA and for Si is nA.

V-I Characteristics of a Diode

When $V > 0$ (forward bias)

$$I_F = I_0 e^{V/nV_T}$$

And $V < 0$ (reverse bias)

$$I_S = -I_0$$

Zener Region

As the voltage across the diode increases in the reverse-bias region, the velocity of the minority carriers responsible for the reverse saturation current I_S will also increase. Eventually, their velocity and associated kinetic energy $(W_K = \frac{1}{2}mv^2)$ will be sufficient to release additional carriers through collisions with otherwise stable atomic structures. That is, an ionization process will result whereby valence electrons absorb sufficient energy to leave the parent atom. These additional carriers can then aid the ionization process to the point where a high avalanche current is established and the avalanche breakdown region determined.

The avalanche region (V_Z) can be brought closer to the vertical axis by increasing the doping levels in the p and n-type materials. However, as V_Z decreases to very low levels, such as −5 V, another mechanism called Zener breakdown, will contribute to the sharp change in the characteristic. It occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and generate carriers. Although the Zener breakdown mechanism is a significant contributor only at lower levels of V_Z, this sharp change in the characteristic at any level is called the Zener region and diodes employing this unique portion of the characteristic of a p-n junction are called Zener diodes.

The Zener region of the semiconductor diode described must be avoided, if the response of a system is not to be completely altered by the sharp change in characteristic in this reverse voltage region.

The maximum reverse-bias potential that can be applied before entering the Zener region is called the peak inverse voltage (referred to simply as the PIV rating) or the peak reverse voltage (denoted by PRV rating).

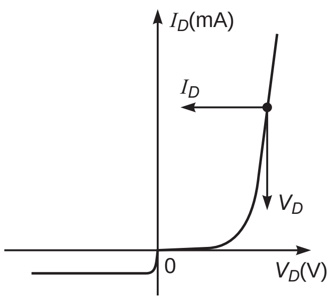

Fig. 10. **Determining the DC resistance of a diode a particular operating point**

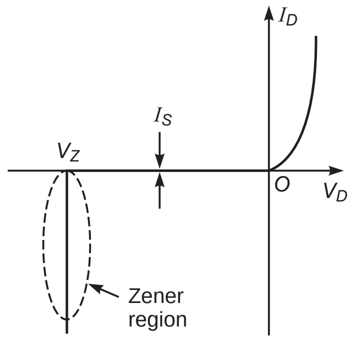

Fig. 8 **Zener region**

Variation in Diode Characteristics with Temperature Change

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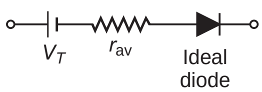
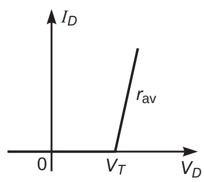
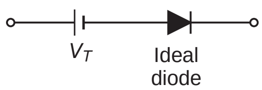
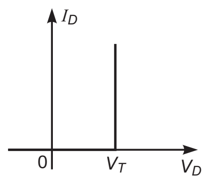
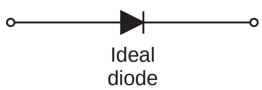
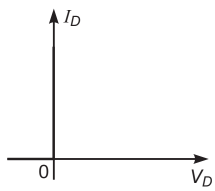
चपमबमू पेम सपदमं तउ वकमस			
" फ्ड चसपपिमकउ वकमस	ृ दमजूवत झ तअ		
प्कमं सकमअपबम	ृ दमजूवत झ तअ ृ दमजूवत झ तु		

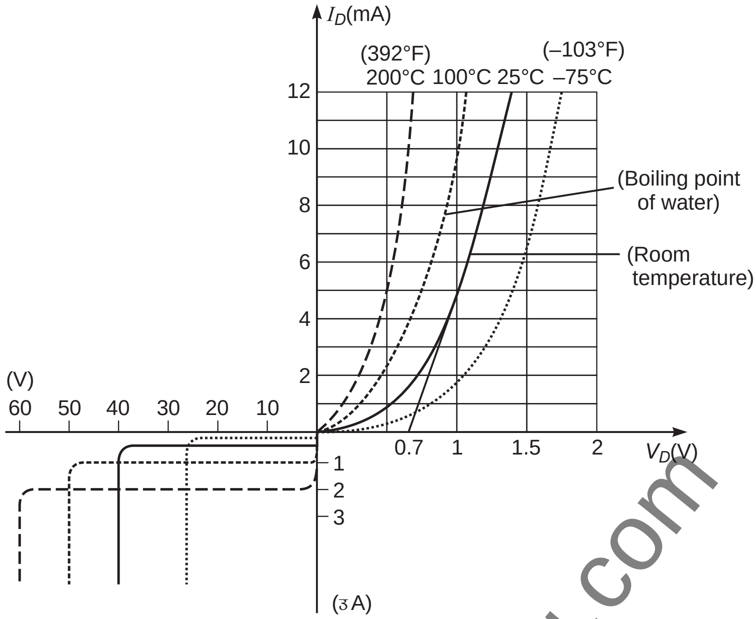


Fig. 9 **Variation in diode characteristics with temperature change**

Diode resistance

- Forward resistance (10 to 100)
  - DC resistance or static resistance
  - AC resistance or dynamic resistance
- Reverse resistance (R > 1 M)

$$R_D = \frac{V_D}{I_D}$$

DC resistance is always greater than AC or dynamic resistance. Dynamic resistance is more in Si diode in compare to Ge diode.

AC or Dynamic Resistance

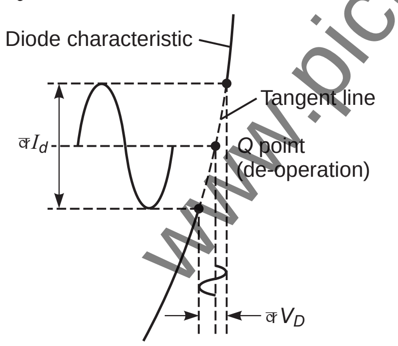


Fig. 11 **Defining the dynamic or AC resistance**

$$r_d = \frac{\Delta V_D}{\Delta I_D}$$

$$r_d = \frac{nV_T}{IF}\ \Omega$$

r_d = dynamic resistance

Average AC Resistance

$$r_{av} = \left.\frac{\Delta V_D}{\Delta I_D}\right|_{\text{point to point}}$$

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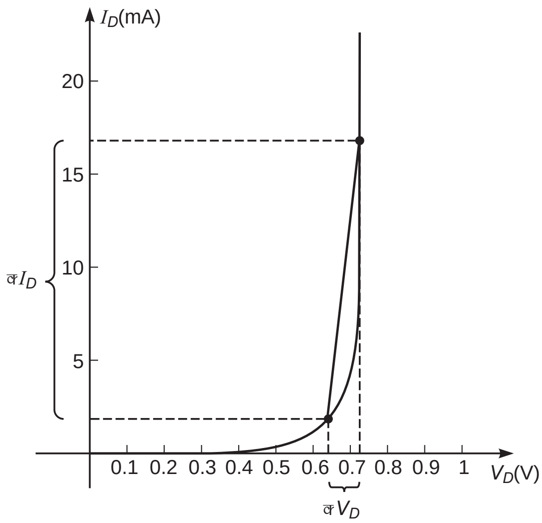

Fig. 12 **Determining the average ac resistance between indicated limits**

$$r_{av} = \frac{\Delta V_D}{\Delta I_D}\bigg|_{\text{point to point}}$$

For the situation indicated by above figure,

$$\Delta I_D = 17 - 2 = 15 \text{ mA}$$

and $\Delta V_D = 0.725 - 0.65 = 0.075$ V

with $r_{av} = \dfrac{\Delta V_D}{\Delta I_D} = \dfrac{0.075}{15} = 5\,\Omega$

Zener Diode

A Zener diode is also called a voltage reference, voltage regulator or breakdown diode. Like a rectifier diode, it is of utmost importance in several power applications.

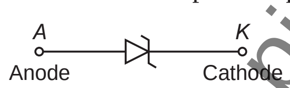

Fig. 13 **(a) Symbol**

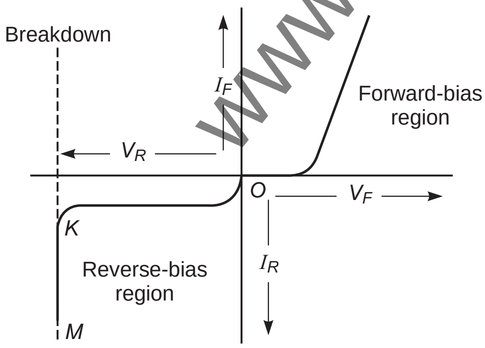

Fig.13 **(b)** *V-I* **characteristics**

The Zener diode is a silicon *p-n* junction device which differs from a rectifier diode, in the sense, that it is operated in the reverse breakdown region. Also, the breakdown voltage of a Zener diode is set by carefully controlling the doping level during manufacturing process. We know that when a reverse voltage across a diode is increased, a critical voltage called breakdown voltage is reached at which the reverse current increases sharply.

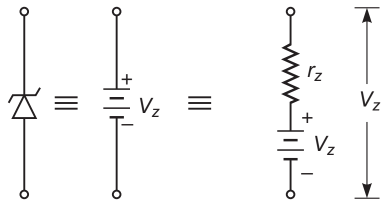

Fig. 14 (a) Ideal Zener diode equivalent diode circuit (b) Practical Zener diode equivalent circuit

Tunnel Diode

The *p-n* junction diode has an impurity concentration of about 1 part in 10^8. This amount of doping results in the width of depletion region of the order of 5 micron (5×10^{-4} cm). If the impurity concentration is increased to a great extent, say 1 part in 10^3, then the device characteristics are completely changed. This new diode is called as tunnel diode. The operation of a tunnel diode is based on a special characteristic known as the negative resistance.

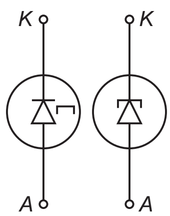

Fig. 15 (a) Circuit symbol of tunnel diode

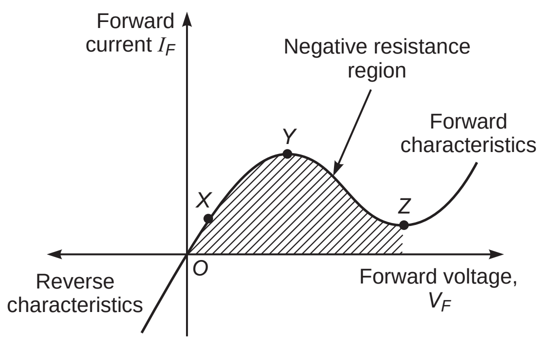

Fig. 15 (b) *V-I* characteristics of a tunnel diode

Do You Know?
The semiconductor materials used for constructing the tunnel diodes are germanium or gallium arsenide.

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Equivalent Circuit of a Tunnel Diode

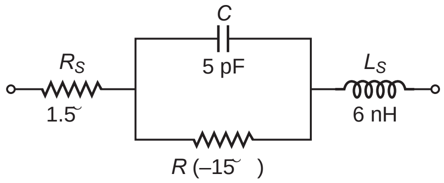


Fig. 16 **Tunnel diode is used as an oscillator**

Varactor (varicap) Diode

A varactor diode is basically, a reverse-biased *p-n* junction, which utilizes the inherent capacitance of the depletion layer. It is also known as varicap, voltcap or tunning diode. It is used as a voltage variable capacitor.

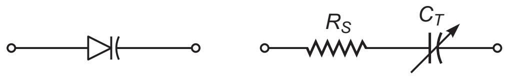


Fig. 17 (a) Circuit symbol (b) Equivalent circuit

Schottky Diode

The Schottky barrier diode is a two-terminal device which is being increasingly used in applications such as AC to DC converters, radar systems, mixers and detectors in communication equipment, instrumentation and *A* to *D* converter. The Schottky barrier diode is also called as surface barrier diode or hot carrier diode.

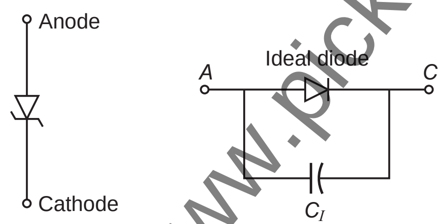


Fig. 18 (a) Circuit symbol of a Schottky diode (b) Approximate equivalent circuit of a Schottky diode

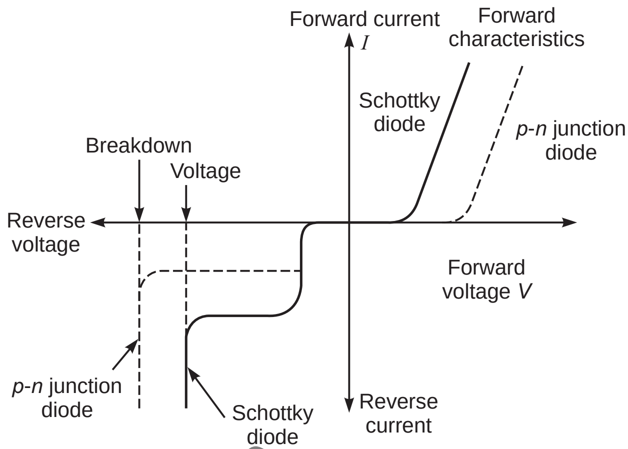
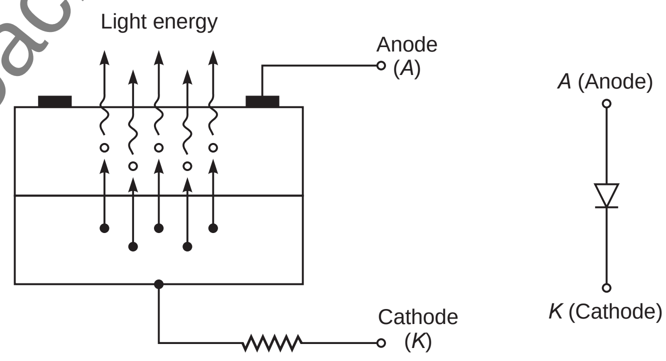


Fig. 19

Light Emitting Diode (LED)

A *p-n* junction diode, which emits light when forward biased, is known as a light emitting diode. The emitted light may be visible or invisible. The amount of light output is directly proportional to forward current. Hence, higher the forward current higher is the light output.



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Intro Exercise - 2

1. The depletion layer across a p^+-*n* junction lies
   (a) mostly in the p^+-region
   (b) mostly in the *n*-region
   (c) equally in both the p^+ and *n*-regions
   (d) entirely in the p^+-regions

2. In an abrupt *p-n* junction, the doping concentrations on the *p*-side and *n*-side are $N_A = 9 \times 10^{16}$ /cm^3 and $N_D = 1 \times 10^{16}$ /cm^3 respectively. The *p-n* junction is reverse-biased and the total depletion width is 3 μm. The depletion width on the *p*-side is
   (a) 2.7 μm (b) 0.3 μm

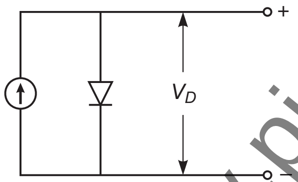
(c) 2.25 μm (d) 0.75 μm

3. At 300 K, for a diode current of 1 mA, a certain germanium diode requires a forward bias of 0.1435 V, whereas a certain silicon diode requires a forward-bias of 0.718 V. Under the conditions stated above, the closest approximation of the ratio of reverse saturation current in germanium diode to that in silicon diode is **[GATE 2003]**
(a) 1 (b) 5
(c) 4×10^3 (d) 8×10^3

4. A *p-n* junction in series with a 100 Ω resistor is forward biased so that a current of 100 mA flows. If voltage across this combination is instantaneously reversed to 10 V at $t = 0$, then reverse current that flows through the diode at $t = 0$ is approximately given by
(a) Zero (b) 100 mA
(c) 200 mA (d) 50 mA

5. An abrupt silicon in thermal equilibrium at $T = 300$ K is doped such that $E_C - E_F = 0.21$ eV in the *n*-region and $E_F - E_V = 0.18$ eV in the *p*-region the built-in potential barrier V_{bi} is
(a) 0.69 V (b) 0.83 V
(c) 0.61 V (d) 0.88 V

6. In the figure, silicon diode is carrying a constant current of 1 mA. When the temperature of the diode is 20°C, V_D is found to be 700 mV. If the temperature rises to 40°C, V_D becomes approximately equal to **[GATE 2002]**



(a) 740 mV (b) 660 mV
(c) 680 mV (d) 700 mV

7. A *p-n* junction diode's dynamic conductance is directly proportional to
(a) the applied voltage (b) the temperature
(c) its current (d) the thermal voltage

8. Consider an abrupt *p*-junction. Let V_{bi} be the built-in potential of this junction and V_R be the applied reverse bias. If the junction capacitance (C_j) is 1 pF for $V_{bi} + V_R = 1$ V, then for $V_{bi} + V_R = 4$ V, C_j will be
(a) 4 pF (b) 2 pF
(c) 0.25 pF (d) 0.5 pF

9. A silicon *p-n* junction at a temperature of 20°C has a reverse saturation current of 10 pA. The reveres saturation current at 40°C for the same bias is approximately
(a) 30 pA (b) 40 pA
(c) 50 pA (d) 60 pA

10. The diffusion capacitance of a *p-n* junction diode
(a) increases exponentially with forward-bias voltage
(b) decreases exponentially with forward-bias voltage
(c) decreases linearly with forward-bias voltage
(d) increases linearly with forward-bias voltage

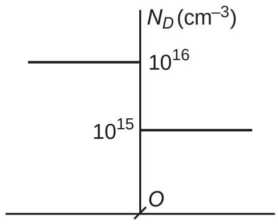
11. Depletion capacitance in a diode depends on which of the following?
1. Applied junction voltage
2. Junction built-in potential
3. Current through junction
4. Doping profile across the junction
(a) 1 and 2 (b) 1 and 3
(c) 1, 2 and 4 (d) 2, 3 and 4

12. Which of the following is not associated with *p-n* junction?
(a) Junction capacitance
(b) Charge storage capacitance
(c) Depletion capacitance
(d) Channel length modulation

13. The static characteristic of an adequately forward-biased *p-n* junction is a straight line, if the plot is of
(a) log *I* vs log *V* (b) log *I* vs *V*
(c) *I* vs log *V* (d) *I* vs *V*

14. Avalanche breakdown diodes have breakdown voltage
(a) having positive temperature coefficient
(b) having negative temperature coefficient
(c) independent of temperature
(d) None of the above

15. An *n-n* isotype doping profile is shown in figure. The built-in potential barrier is



(a) 0.66 V (b) 0.06 V
(c) 0.03 V (d) 0.33 V

16. A silicon *p-n* junction diode has doping profile $N_A = N_D = 5\times10^{19}\,\text{cm}^{-3}$. The space charge width at a forward-bias voltage of $V_A = 0.4$ V, is

(a) 102 Å (b) 44 Å
(c) 153 Å (d) 62 Å

17. A *p-n* junction biased at $V_A = 0.72$ V has DC bias current $I_{DQ} = 2$ mA. The minority carrier life time is $1\,\mu$s in both the *n* and *p*-regions. The diffusion capacitance is

(a) 4.9×10^{-8} F (b) 3.86×10^{-8} F
(c) 7.74×10^{-3} F (d) 9.86×10^{-8} F

18. A diode has reverse saturation current $I_s = 10^{-18}$ A and non-ideality factor $n = 1.05$. If diode has current of 70 µA, then diode voltage is

(a) 0.63 V (b) 0.87 V
(c) 0.54 V (d) 0.93 V

19. Silicon diode is less suited for low voltage rectifier operation, because

(a) it can withstand high temperature
(b) its reverse saturation current is low
(c) its cut-in voltage is high
(d) its breakdown voltage is high

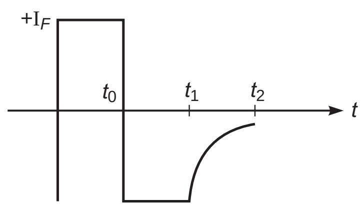
20. A p^+-n silicon diode is forward biased at a current of 1 mA. The hole life time in the *n*-region is 0.1 µs. Neglecting depletion capacitance, the diode impedance at 1 MHz is

(a) 38.7 + *j* 12.1 Ω (b) 23.5 + *j* 7.5 Ω
(c) 38.7 − *j* 12.1 Ω (d) 23.5 − *j* 7.5 Ω

Answers with Solutions

1. (b) When we increase doping level, depletion layer will decrease. Hence, the depletion layer across a p^+-n junction lies mostly in the *n*-region.

2. (b)
$$\frac{w_n}{w_p} = \frac{N_A}{N_D}$$
$$w \cong w_n \qquad (\because w_n > w_p)$$
$$w_p = \frac{w_n \times N_D}{N_A}$$
$$w_p = \frac{3\times10^{16}}{9\times10^{16}} = 0.3\,\mu\text{m}$$



Negative sign is indicating reversal of current and voltages.

$$\therefore \qquad I_R = \frac{10}{100} = 100\text{ mA}$$

BJT A Bipolar Junction Transistor (BJT) is a three-terminal device that acts like a current-controlled switch in most logic circuits. If we put a small current into one of the terminals, called the 'base', then the switch is On and current may flow between the other two terminals, called the 'emitter' and the 'collector'. If no current is put into the base, then the switch is Off and no current flows between the emitter and the collector.

3. (c) $n = 1$ for germanium

$n = 2$ for silicon at low value of current

$$I = I_{0_{\text{Si}}}\,(e^{V_{D_1}/nV_T} - 1) \qquad \ldots\text{(i)}$$
$$I = I_{0_{\text{Ge}}}\,(e^{V_{D_2}/nV_T} - 1) \qquad \ldots\text{(ii)}$$

LHS of (i) = Eq. (ii)

$$\Rightarrow \quad I_{0_{\text{Si}}}\left(e^{V_{D_1}/nV_T} - 1\right) = I_{0_{\text{Ge}}}\,(e^{V_{D_2}/nV_T} - 1)$$

$$\frac{I_{0_{\text{Ge}}}}{I_{0_{\text{Si}}}} = \frac{e^{V_{D_1}/nV_T} - 1}{e^{V_{D_2}/nV_T} - 1} = \frac{\left(e^{\frac{0.718}{2\times26\times10^{-3}}}\right) - 1}{\left(e^{\frac{0.1435}{26\times10^{-3}}}\right) - 1} = 4\times10^3$$

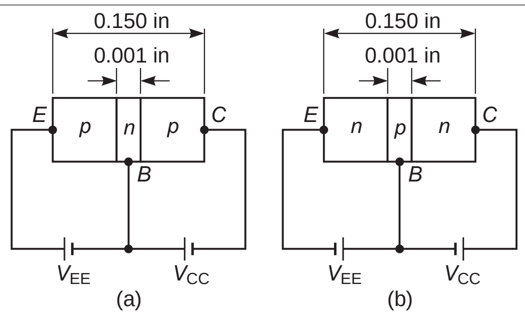


Fig. 1 **Types of transistors : (a)** *p-n-p*; **(b)** *n-p-n*

4. (b) Reverse current at $t = 0$ when the voltage is instantaneously reversed to $-V_R = -10$ V is $-I_R = -\dfrac{V_R}{R_L}$

5. (a) $n_0 = N_C\, e^{\frac{(\varepsilon_C - \varepsilon_F)}{kT}}$

For Si, $N_C = 2.8\times10^{19}$ cm^{-3}

$$n_0 = 2.8\times10^{19}\, e^{-\frac{0.21}{0.0259}} = 8.43\times10^{15}\,\text{cm}^{-3}$$
$$n_0 = N_D = 8.43\times10^{15}\ \text{cm}^{-3} \qquad \text{(Since, } n\text{-region)}$$