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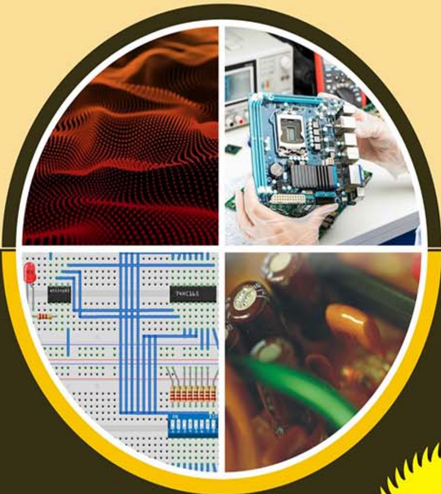

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Electronic Devices

By

Ankit Tyagi **Ishita Singhal**

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Delhi Office : 1/6590, East Rohtas Nagar, Sahadara, Delhi-110032

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1 UNIT

Introduction to Semiconductor Physics

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PART-1

Introduction to Semiconductor Physics : Review of Quantum Mechanics.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.1. What is semiconductor and also explain its properties ?

Answer

A. Semiconductor : A semiconductor is a substance which has resistivity (10^{-4} to 0.5 Ωm) in between conductors and insulators *e.g.*, germanium, silicon, etc.

B. Properties of semiconductors :

1. The resistivity of a semiconductor is less than an insulator but more than a conductor.
2. Semiconductors have negative temperature co-efficient of resistance *i.e.*, the resistance of a semiconductor decreases with the increase in temperature and vice-versa. For example, germanium is actually an insulator at low temperatures but it becomes a good conductor at high temperatures.
3. When a suitable metallic impurity (e.g. arsenic, gallium etc.) is added to a semiconductor, its current conducting properties change appreciably.

Que 1.2. Explain Heisenberg's uncertainty principle.

Answer

1. According to this principle, "It is impossible to determine the exact position and momentum of a particle simultaneously".
2. If Δx and Δp are the uncertain position and momentum of particle then according to this principle

$$\Delta x \, \Delta p \geq \frac{h}{2\pi}$$

or $$\Delta x \, \Delta p \geq \hbar$$

where $$\hbar = \frac{h}{2\pi}$$

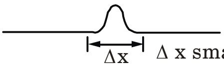
The product of uncertainty position and uncertainty momentum of particle is greater than or equal to $h/2\pi$.

3. Relation between uncertainty energy ΔE and uncertainty time Δt is

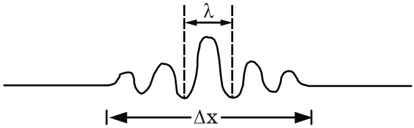
$$\Delta E\ \Delta t \geq \frac{h}{2\pi}$$

4. If $\Delta\theta$ and ΔJ are uncertainty angular position and angular momentum then

$$\Delta\theta\ \Delta J \geq \frac{h}{2\pi}$$



Narrow wave packet
(a)



Wide wave packet
(b)

Fig. 1.2.1.

Que 1.3. **Apply uncertainty principle to calculate the radius of the Bohr's first orbit.**

Answer

1. The energy of electron in a hydrogen atom is given by

$$E = KE + PE = \frac{p^2}{2m_0} + \frac{(-e^2)}{4\pi\varepsilon_0 x} \quad \text{... (1.3.1)}$$

where x is the distance between the electron and the centre of the nucleus.

2. Eq. (1.3.1) in terms of uncertainty can be expressed as

$$\Delta E = \frac{(\Delta p)^2}{2m_0} - \frac{e^2}{4\pi\varepsilon_0 \Delta x} \quad \text{... (1.3.2)}$$

3. Using the Heisenberg's uncertainty principle

$$\Delta p \Delta x \approx \hbar \quad \text{... (1.3.3)}$$

4. Putting equation (1.3.3) in equation (1.3.2)

$$\Delta E = \frac{(\hbar)^2}{2m_0(\Delta x)^2} - \frac{e^2}{4\pi\varepsilon_0 \Delta x} \quad \text{... (1.3.4)}$$

5. For minimum energy (*i.e.*, for ground state) of electron,

$$\frac{\partial(\Delta E)}{\partial(\Delta x)} = 0$$

$$\frac{\partial}{\partial(\Delta x)}\left[\frac{\hbar^2}{2m_0(\Delta x)^2} - \frac{e^2}{4\pi\varepsilon_0 \Delta x}\right] = 0$$

$$\frac{\partial}{\partial(\Delta x)}\left[\frac{\hbar^2}{2m_0}(\Delta x)^{-2} - \frac{e^2}{4\pi\varepsilon_0}(\Delta x)^{-1}\right] = 0$$

$$-2\frac{\hbar^2}{2m_0}(\Delta x)^{-3} + \frac{e^2}{4\pi\varepsilon_0}(\Delta x)^{-2} = 0$$

$$-\frac{\hbar^2}{m_0(\Delta x)^3} + \frac{e^2}{4\pi\varepsilon_0(\Delta x)^2} = 0$$

$$\frac{\hbar^2}{m_0(\Delta x)^3} = \frac{e^2}{4\pi\varepsilon_0(\Delta x)^2}$$

$$\Delta x = \frac{4\pi\varepsilon_0\hbar^2}{m_0 e^2}$$

6. For this value of Δx,

$$\frac{\partial^2(\Delta E)}{(\partial(\Delta x))^2} > 0$$

7. Hence for the given value of Δx the value of ΔE will give the minimum or ground state energy of an electron, *i.e.*,

$$E_{\min} = [\Delta E]_{\Delta x = \frac{4\pi\varepsilon_0\hbar^2}{m_0 e^2}} = \left[\frac{(\hbar)^2}{2m_0(\Delta x)^2} - \frac{e^2}{4\pi\varepsilon_0\Delta x}\right]_{\Delta x = \frac{4\pi\varepsilon_0\hbar^2}{m_0 e^2}}$$

i.e.,

$$E_{\min} = \left[\frac{(\hbar)^2}{2m_0\left(\frac{4\pi\varepsilon_0\hbar^2}{m_0 e^2}\right)^2} - \frac{e^2}{4\pi\varepsilon_0\left(\frac{4\pi\varepsilon_0\hbar^2}{m_0 e^2}\right)}\right]$$

$$E_{\min} = \left[\frac{m_0 e^4}{32\pi^2\,\varepsilon_0^2\,\hbar^2} - \frac{m_0 e^4}{16\pi^2\,\varepsilon_0^2\,\hbar^2}\right]$$

$$E_{\min} = \frac{-m_0 e^4}{32\pi^2\,\varepsilon_0^2\,\hbar^2}$$

8. This is the required expression for the minimum or ground state energy of an electron in the hydrogen atom.
9. Also, the value of Δx for which the ground state energy of an electron is obtained gives the value of radius for the first Bohr's orbit.
10. This value is known as Bohr's radius and it is denoted by r_0.
11. Thus the Bohr's radius is given by

$$r_0 = \Delta x = \frac{4\pi\varepsilon_0 \hbar^2}{m_0 e^2}$$

12. Using the values of m, e and $\hbar$, we get

$$r_0 = \frac{4 \times 3.14 \times (8.85 \times 10^{-12}) \times (1.054 \times 10^{-34})^2}{(9.1 \times 10^{-31}) \times (1.6 \times 10^{-19})^2}$$

$$= 0.53 \text{ Å}$$

Que 1.4. **Discuss some important application of uncertainty principle.**

Answer

a. Non-existence of Electrons in the Nucleus :

1. We know that the radius of nucleus is the order of 10^{-14} m.
2. If an electron is confined within nucleus the uncertainty position of electron is

$$\Delta x = 2 \times 10^{-14} \text{ m}$$

3. Now according to uncertainty principle,

$$\Delta x \, \Delta p \geq \frac{h}{2\pi}$$

and $$\Delta p = \frac{h}{2\pi \Delta x} = \frac{6.63 \times 10^{-34}}{2 \times \pi \times 2 \times 10^{-14}} = 5.276 \times 10^{-21} \text{ kg m/s}$$

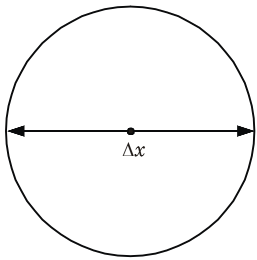


Fig. 1.4.1.

4. Using relativistic formula for the energy of the electron

$$E^2 = p^2 c^2 + m_o^2 c^4$$

As the rest energy $m_o c^2$ of an electron is of the order of 0.511 MeV, which is much smaller than the value of first term.

5. Hence the second term is neglected therefore,

$$E^2 = p^2 c^2$$

$$E = pc = (5.276 \times 10^{-21}) \times (3 \times 10^8) \text{ J}$$

$$E = \frac{5.276 \times 10^{-21} \times 3 \times 10^{8}}{1.6 \times 10^{-19}} \text{ eV} \approx 9.9 \text{ MeV}$$

6. Thus, if an electron exists inside the nucleus then its energy should be of the order of 9.9 MeV. But the experiment shows that no electron in the atom possesses kinetic energy greater than 4 MeV.
7. Hence, no electron can exist inside the nucleus.

b. Binding Energy of an Electron in Atom :

1. The uncertainty in position Δx of an electron is of order of $2R$, where R is radius of orbit.
2. The corresponding uncertainty in its momentum is

$$\Delta p \geq \frac{h}{2\pi.2R}$$

$$R = 10^{-10} \text{ m}$$

then $$\Delta p \approx 0.527 \times 10^{-24} \text{ kg-m/s}$$

3. Kinetic energy of electron is

$$E_k = \frac{p^2}{2m_0} = \left(\frac{h}{4\pi R}\right)^2 \frac{1}{2m_o} = \frac{h^2}{32\pi^2 m_o R^2}$$

4. Potential energy of electron in electrostatic field of the nucleus is

$$V = \frac{-Ze^2}{4\pi \in_o R}$$

5. So the total energy of its orbit will be

$$E = E_k + V$$

$$= \frac{h^2}{32\pi^2 m_o R^2} - \frac{Ze^2}{4\pi \in_o R}$$

$$= \frac{(6.63 \times 10^{-34})^2}{32 \times (3.14)^2 \times 9.1 \times 10^{-31} \times R^2} - \frac{Z(1.6 \times 10^{-19})^2}{4 \times 3.14 \times 8.85 \times 10^{-12} R}$$

$$E = \frac{10^{-20}}{R^2} - \frac{15 \times 10^{-10} Z}{R} \text{ eV}$$

Taking $R = 10^{-10}$ m

$$E = (1 - 15Z) \text{ eV}$$

6. Now the binding energy of outermost electron in H is – 13.6 eV
7. For H atom

$$E = (1 - 15) = -14 \text{ eV} \qquad (\because \text{ for } H \text{ atom, } Z = 1)$$

It is very near to – 13.6 eV.

8. Hence, binding energy of an electron can be calculated.

c. Radius of Bohr's First Orbit : Refer Q. 1.3, Page 1–3A, Unit-1.

Que 1.5. **The speed of an electron is measured to be 5.0×10^3 m/s to an accuracy of 0.003 %. Find the uncertainty in determining the**

position of this electron (mass of electron is 9.1×10^{-31} kg and Planck's constant is 6.62×10^{-34} Js).

Answer

Given : $m_e = 9.1 \times 10^{-31}$ kg, $h = 6.62 \times 10^{-34}$ J s
To Find : Uncertainty in the position of electron, Δx

1. Uncertainty in velocity $= \dfrac{0.003}{100} \times 5.0 \times 10^3 = 0.15$ m/s

2. $$\Delta x \, \Delta p = \frac{h}{2\pi} \quad \Rightarrow \quad \Delta x = \frac{h}{2\pi \times \Delta p}$$

3. $$\Delta x = \frac{h}{2\pi m(\Delta v)} = \frac{6.62 \times 10^{-34}}{2 \times 3.14 \times 9.1 \times 10^{-31} \times 0.15}$$

$$\Delta x = 7.72 \times 10^{-4} \text{ m.}$$

Que 1.6. **Calculate the uncertainty in the position of a dust particle with mass equal to 1 mg if uncertainty in its velocity is 5.5×10^{-20} m/s.**

Answer

Given : $m = 1$ mg $= 10^{-6}$ kg, $\Delta v = 5.5 \times 10^{-20}$ m/s
To Find : Uncertainty in the position of a dust particle, Δx

1. From the uncertainty principle, we have

$$\Delta x . \Delta p \geq \frac{h}{2\pi}$$

$$\Delta v = 5.5 \times 10^{-20} \text{ m/s}$$

2. So,

$$\Delta x = \frac{h}{2\pi \times m\Delta v} = \frac{6.63 \times 10^{-34}}{2 \times 3.14 \times 10^{-6} \times 5.5 \times 10^{-20}}$$

$$= \frac{6.63 \times 10^{-34}}{34.54 \times 10^{-26}}$$

$$\Delta x = 19.2 \text{ Å}$$

Que 1.7. **Write the postulates of quantum mechanics.**

Answer

Postulates of quantum mechanics :

1. Wave function $\Psi(x, t)$ gives information about each particle of a physical system.

2. Quantum mechanical operators are used to obtain measurable information about system. The operators corresponding to the various dynamic variables are as follows :

Dynamic variable	Quantum operator
Position, x	x
Momentum, P_x	$\frac{\hbar}{j}\frac{\partial}{\partial x}$
Total energy, E	$-\frac{\hbar}{j}\frac{\partial}{\partial t}$
Potential energy, $V(x)$	$V(x)$

3. The wave function $\Psi(x, t)$ and its space derivative $\frac{\partial \Psi}{\partial x}$ must be continuous, finite and single valued for all values of x.
4. The function Ψ must be normalised

$$\int_{-\infty}^{\infty} \psi \psi^* dx = 1$$

where Ψ^* is the complex conjugate of Ψ.

Que 1.8. **What is wave function ? Write its physical significance.**

Answer

1. The quantity in quantum mechanics undergoes periodic changes and gives information about the particle within the wave packet. It is called wave function ψ.
2. The wave function ψ itself has no physical significance but the square of its absolute magnitude $|\psi|^2$ gives the probability of finding the particle at that time.

a. Normalization of Wave Function :

1. If the wave function ψ of any system is such that it gives the value of given integral a finite quantity say N.

$$\int_{-\infty}^{\infty} \psi \psi^* dx = \int_{-\infty}^{\infty} |\psi|^2 dx$$

$$= N \text{ (Integral)} \quad (\psi^* \text{ is complex conjugate.})$$

then ψ is called normalization of wave function.

b. Orthogonal Wave Function :

1. When the value of the integral is equal to zero ($N = 0$), the wave function ψ is known as orthogonal wave function.

$$\int_{-\infty}^{\infty} |\psi|^2 \, dx = 0$$

Que 1.9. What is Schrodinger wave equation ? Derive time independent Schrodinger wave equations.

Answer

Schrodinger's equation :

Schrodinger's equation which is the fundamental equation of quantum mechanics is a wave equation in the variable ψ.

A. Time Independent Schrodinger Wave Equation :

1. Consider a system of stationary wave to be associated with particle and the position coordinate of the particle (x, y, z) and ψ is the periodic displacement of any instant time 't'.
2. The general wave equation in 3-D in differential form is :

$$\nabla^2 \psi = \frac{1}{\mathrm{v}^2} \frac{\partial^2 \psi}{\partial t^2} \quad \text{...(1.9.1)}$$

where, v = velocity of wave, and

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} = \text{Laplacian operator.}$$

3. The wave function may be written as

$$\psi = \psi_o e^{-i\omega t} \quad \text{...(1.9.2)}$$

4. Differentiate eq. (1.9.2) with respect to time, we get

$$\frac{\partial \psi}{\partial t} = -i \, \omega \, \psi_o e^{-i\omega t} \quad \text{...(1.9.3)}$$

5. Again differentiating eq. (1.9.3)

$$\frac{\partial^2 \psi}{\partial t^2} = + i^2 \, \omega^2 \, \psi_o e^{-i\omega t}$$

$$\frac{\partial^2 \psi}{\partial t^2} = - \omega^2 \psi \quad \text{...(1.9.4)}$$

6. Putting these value in eq. (1.9.1),

$$\nabla^2 \psi = \frac{-\omega^2}{\mathrm{v}^2} \psi \quad \text{...(1.9.5)}$$

7. But $\quad \omega = 2\pi\nu = \dfrac{2\pi \mathrm{v}}{\lambda} \Rightarrow \dfrac{\omega}{\mathrm{v}} = \dfrac{2\pi}{\lambda}$

8. Eq. (1.9.5) becomes

$$\nabla^2 \psi = -\frac{4\pi^2}{\lambda^2}\psi \quad ...(1.9.6)$$

9. From de-Broglie's wavelength, $\lambda = \frac{h}{mv}$

then $$\nabla^2 \psi = \frac{-4\pi^2 m^2 v^2}{h^2}\psi \quad ...(1.9.7)$$

10. If E and V are the total and potential energies of a particle and E_k is kinetic energy, then

$$E_k = E - V \text{ or } \frac{1}{2}mv^2 = E - V \quad \text{or} \quad m^2v^2 = 2m(E-V)$$

11. Now eq. (1.9.7) becomes

$$\nabla^2\psi = \frac{-4\pi^2 2m[E-V]\psi}{h^2} \qquad \left[\text{Since } \hbar = \frac{h}{2\pi}\right]$$

$$\therefore \quad \nabla^2\psi + \frac{2m[E-V]\psi}{\hbar^2} = 0 \quad ...(1.9.8)$$

This is required time-independent Schrodinger wave equation.

12. For free particle ($V = 0$)

$$\therefore \quad \nabla^2\psi + \frac{2m}{\hbar^2}E\psi = 0$$

Que 1.10. **Derive time dependent Schrodinger wave equation.**

Answer

1. We know that wave function is $\psi = \psi_o e^{-i\omega t}$ ...(1.10.1)
2. On differentiating with respect to time, we get

$$\frac{\partial\psi}{\partial t} = -i\omega\,\psi_o e^{-i\omega t}$$

or $$\frac{\partial\psi}{\partial t} = -i\,(2\pi\nu)\,\psi \quad ...(1.10.2)$$

3. But $$E = h\nu \Rightarrow \nu = \frac{E}{h}$$

4. Eq. (1.10.2) becomes

$$\frac{\partial\psi}{\partial t} = -i2\pi\left(\frac{E}{h}\right)\psi \qquad \left[\text{Since } \hbar = \frac{h}{2\pi}\right]$$

5. $$\frac{\partial\psi}{\partial t} = -\frac{i}{\hbar}E\psi$$

and $$E\psi = -\frac{\hbar}{i}\frac{\partial\psi}{\partial t}$$

or $$E\psi = i\hbar \frac{\partial \psi}{\partial t} \qquad ...(1.10.3)$$

6. Now time independent Schrodinger wave equation is

$$\nabla^2 \psi + \frac{2m}{\hbar^2} (E - V) \psi = 0$$

or $$\nabla^2 \psi + \frac{2m}{\hbar^2} [E\psi - V\psi] = 0$$

7. Using eq. (1.10.3), we get

$$\nabla^2 \psi + \frac{2m}{\hbar^2} \left[i\hbar \frac{\partial \psi}{\partial t} - V\psi \right] = 0$$

$$\nabla^2\psi - \frac{2m}{\hbar^2} V\psi = -\frac{2m}{\hbar^2} i\hbar \, . \, \frac{\partial \psi}{\partial t}$$

$$\left(\nabla^2 - \frac{2m}{\hbar^2} V \right) \psi = -\frac{2m}{\hbar^2} i\hbar \frac{\partial \psi}{\partial t}$$

or $$\left(-\frac{\hbar^2}{2m} \nabla^2 + V \right) \psi = i\hbar \frac{\partial \psi}{\partial t}$$

8. This is required time dependent Schrodinger wave equation.

$$-\frac{\hbar^2}{2m} \nabla^2 + V = H \rightarrow \text{is known as Hamiltonian operator.}$$

$$i\hbar \frac{\partial \psi}{\partial t} = E \rightarrow \text{energy operator.}$$

Then, $$H\psi = E\psi$$

Que 1.11. **A particle is in motion along a line between $x = 0$ and $x = L$ with zero potential energy. At points for which $x < 0$ and $x > L$, the potential energy is infinite. The wave function for the particle in n^{th} state is given by :**

$$\psi_n = A \sin \frac{n\pi x}{L}$$

Find the expression for the normalized wave function.

Answer

1. The eigen function is

$$\psi_n (x) = A \sin \frac{n\pi x}{L} \qquad ...(1.11.1)$$

2. Now applying normalization condition.

$$\int_0^L | \psi_n(x) |^2 \, dx = 1$$

$$\int_0^L A^2 \sin^2\left(\frac{n\pi x}{L}\right) dx = 1$$

$$\frac{A^2}{2}\int_0^L \left(1-\cos\frac{2n\pi}{L}x\right) dx = 1$$

$$\frac{A^2}{2}\left[x - \frac{\sin\frac{2n\pi x}{L}}{\frac{2n\pi}{L}}\right]_0^L = 1$$

$$\frac{A^2}{2} L = 1$$

$$A = \sqrt{\frac{2}{L}}$$

3. Equation (1.11.1) becomes

$$\psi_n(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right)$$

this is normalization function.

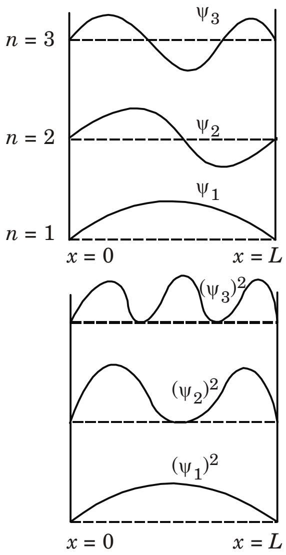


Fig. 1.11.1.

Que 1.12. **Discuss quantum mechanical tunneling in brief.**

Answer

1. The quantum mechanical tunneling of an electron through a barrier of finite height and thickness
2. Let us consider the potential barrier of Fig. 1.12.1. If the barrier is not infinite, the boundary conditions do not force ψ to zero at the barrier.

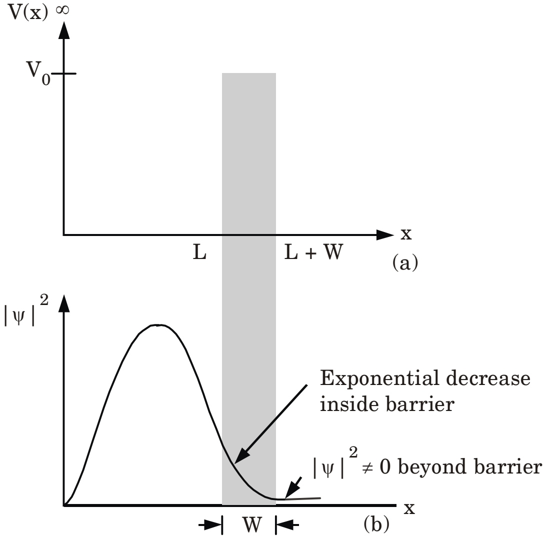


Fig. 1.12.1. (a). Potential barrier of height V_0 and thickness W; (b). Probability density for an electron with energy $E < V_0$, indicating a non-zero value of the wave function beyond the barrier.

3. Instead, we use the condition that ψ and its slope $d\psi/dx$ are continuous at each boundary of the barrier.
4. Thus ψ must have a non-zero value within the barrier and also on the other side.
5. Since ψ has a value to the right of the barrier, $\psi^*\psi$ exists there also, implying that there is some probability of finding the particle beyond the barrier.
6. The particle does not go over the barrier because its total energy is less than barrier height V_0. The mechanism by which the particle penetrates the barrier is called tunneling.
7. Quantum mechanical is intimately bound to the uncertainty principle. If the barrier is sufficiently thin, that means the particle exists only on one side.

8. However, the wave function amplitude for the particle is reduced by the barrier as shown in Fig. 1.12.1, so that by making the thickness W greater, we can reduce ψ on the right-hand side to the point the negligible tunneling occurs.

Que 1.13. **State wave particle duality.**

Answer

1. In the photoelectric effect, light waves behave as particles. The Compton Effect explains the particle like behaviour of EM wave.
2. In this effect, an x-ray beam was incident on a solid. A portion of the x-ray beam was deflected and the frequency of the deflected wave had shifted compared with the incident wave.
3. The observed change in frequency and the deflected angle corresponded exactly to the expected results of a billiard ball collision between x-ray quanta, or photon, and an electron in which both energy and momentum are conserved.
4. De Broglie postulated the existence of matter waves which exhibit particle-like behavior. The hypothesis of de Broglie was the existence of a principle wave particle duality.
5. The momentum of a photon is given by

$$p = \frac{h}{\lambda}$$

where λ is the wavelength of the light wave.

6. Then, de Broglie hypothesized that the wavelength of a particle can be expressed as

$$\lambda = \frac{h}{p}$$

where p is the momentum of the particle and λ is known as the de Broglie wavelength of the matter wave.

Que 1.14. **What is the de Broglie wavelength (in Å) of an electron at 100 eV ? What is the wavelength for electron at 12 *k*eV ?**

Answer

1. We have,

$$\text{v} = \sqrt{2E/m}\ ,\ \lambda = \frac{h}{m\text{v}} = \frac{h}{\sqrt{2Em}} = \frac{6.63\times10^{-34}}{[2\times9.1\times10^{-31}]^{1/2}}E^{-1/2} \quad ...(1.14.1)$$

i. For 100 eV :

From eq. (1.14.1),

$$\lambda = \frac{4.9 \times 10^{-19}}{(1.6 \times 10^{-19})^{1/2}}[100]^{-1/2} = 1.23 \times 10^{-9}[100]^{-1/2}$$

$$= 1.23 \times 10^{-10} \text{ m} = 1.23 \text{ Å}$$

ii. For 12 *k*eV :

From eq. (1.14.1),

$$\lambda = \frac{4.9 \times 10^{-19}}{(1.6 \times 10^{-19})^{1/2}}[1.2 \times 10^4]^{-1/2} = 1.23 \times 10^{-9}[1.2 \times 10^4]^{-1/2}$$

$$= 1.12 \times 10^{-11} \text{ m} = 0.112 \text{ Å}$$

Que 1.15. Describe Davisson-Germer experiment to demonstrate the wave-character of electrons.

Answer

Construction :

1. A collimated beam of electrons is produced using an electron gun. This beam is incident on a target of nickel crystal.
2. The electrons are scattered in all directions by the atoms of the target.
3. The intensity of the scattered electrons in a given direction is measured by allowing it to enter in a collector, which can be moved along a circular scale.

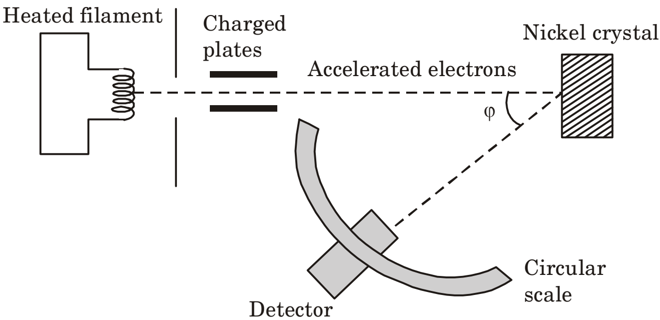


Fig. 1.15.1.

Principle :

1. If the material particles have a wave character, they are expected to show the interference and diffraction phenomena.
2. Davisson and Germer experimentally demonstrated the diffraction of electron beam.

Working :

1. Let an electron of rest mass m_0 be accelerated by potential V, then its kinetic energy is given by

$$K = \frac{1}{2} m_0 \nu^2 = eV \quad \text{...(1.15.1)}$$

where ν is the velocity of the accelerated electron.

2. From equation (1.15.1),

$$\nu = \sqrt{\frac{2eV}{m_0}} \quad \text{...(1.15.2)}$$

3. The wavelength of the de-Broglie wave associated with this electron is expressed as

$$\lambda = \frac{h}{m_0 \nu} \quad \text{...(1.15.3)}$$

4. Using eq. (1.15.2) in eq. (1.15.3),

$$\lambda = \frac{h}{m_0 \sqrt{\frac{2eV}{m_0}}}$$

i.e.,
$$\lambda = \frac{h}{\sqrt{2em_0V}} \quad \text{...(1.15.4)}$$

5. Substituting $m_0 = 9.1 \times 10^{-31}$ kg, $e = 1.6 \times 10^{-19}$ C and $h = 6.62 \times 10^{-34}$ J-s in equation (1.15.4)

$$\lambda = \frac{h}{\sqrt{2em_0V}} = \frac{6.62 \times 10^{-34}}{\sqrt{2 \times 1.6 \times 10^{-19} \times 9.1 \times 10^{-31} \times V}}$$

or
$$\lambda = \frac{12.24}{\sqrt{V}} \text{ Å}$$

6. Davisson and Germer calculated the de-Broglie wavelength using two different approaches.
7. In the first approach, Davisson and Germer used de-Broglie's hypothesis.
8. They plotted the variation in the intensity of electron beam against scattering angle for different accelerating voltages to study the effect of increasing electron energy on the scattering angle φ.
9. They found that a bump begins to appear in the curve for $V = 44$ volts.
10. With increasing potential, the bump moves upward, and becomes more prominent in the curve for $V = 54$ volts at $\varphi = 50°$, thereby indicating the maximum suffering in electron beam for $V = 54$ volts as shown in Fig. 1.15.2.

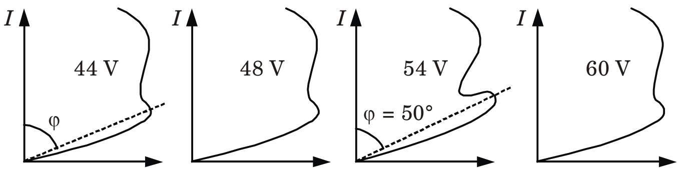


Fig. 1.15.2. Plots of intensity of electron beam against scattering angle for different values of accelerating voltage.

11. Thus, for $V = 54$ V, the de-Broglie wavelength of the electrons is

$$\lambda = \frac{12.24}{\sqrt{V}} = \frac{12.24}{\sqrt{54}} = 1.66 \text{ Å} \quad \text{... (1.15.5)}$$

12. In the second approach, Davisson and Germer calculated the de-Broglie wavelength by treating the electron beam as a wave.
13. They used Bragg's equation, $n\lambda = 2d \sin \theta$.
14. For nickel crystal, $d = 0.91$ Å. Also, $\theta = 65°$.
15. Hence for the first order ($n = 1$) reflection, we have

$$\lambda = 2d \sin \theta = 2 \times 0.91 \times \sin 65° = 1.65 \text{ Å} \quad \text{... (1.15.6)}$$

16. Eq. (1.15.5) and eq. (1.15.6) show an excellent agreement between the two approaches.
17. Thus, the Davisson–Germer experiment provides a direct verification of wave nature of electrons and hence it also verifies the de Broglie's hypothesis.

PART-2

Electrons in Periodic Lattices.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.16. **Write a short note on periodic lattice potential.**

Answer

1. An electron in a crystal moves in a perfectly periodic potential with a periodicity equal to the lattice spacing. The potential has strong negative peaks at the lattice sites.
2. A one dimensional representation of a periodic crystal potential, is shown in Fig. 1.16.1.
3. The crystal periodicity extends to infinity in all direction. But at the surface of any actual crystal, the periodicity is interrupted, because within a few atomic spacing of the surface, the lattice spacing is not uniform.
4. The solution of Schrodinger equation for a typical single electron in such potential provides a set of 'one electron' states (orbitals) which the single electron may occupy.
5. It should be noted that the one electron treatment is an approximation in which the electron-electron interaction is ignored.

6. One electron wave function has certain properties closely related to the lattice periodicity. Hence, the allowed electronic energies occur in bands of allowed states separated by forbidden energy regions.
7. In these allowed bands, the dynamic behaviour of electrons will be found to be almost similar to that of a free electron.

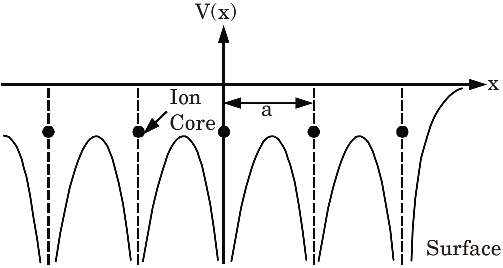


Fig. 1.16.1. Variation of potential energy of a valence electron in the periodic field of the ion cores of a one dimensional lattice.

Que 1.17. **State and proof Bloch theorem.**

Answer

Statement :

The Bloch theorem states that the eigen functions of the wave equation for a periodic potential are of the form of product of a plane wave and a function with the periodicity of the potential.

Proof :

1. Let in a crystal lattice of constant a, an electron has a periodic potential,
$$V(x) = V(x + a)$$
2. Then, the eigen functions of the electron obtained from the Schrodinger equation,
$$\frac{d^2\psi}{\partial x^2} + \frac{2m}{\hbar^2}[E - V(x)]\psi = 0 \qquad ...(1.17.1)$$
have the form
$$\psi(x) = e^{\pm ikx} u_k(x) \qquad ...(1.17.2)$$
3. The function $\psi(x)$ is a plane wave $e^{\pm ikx}$ modulated by a periodic function,
$$u_k(x) = u_k(x + a)$$
4. Since eq. (1.17.1) is a linear second order differential equation, its general solution should be of the form.
$$\psi(x) = Af(x) + Bg(x) \qquad ...(1.17.3)$$
where A and B are constants and $f(x)$ and $g(x)$ are two independent solution of eq. (1.17.1).
5. Since the potential is periodic with period a, not only $f(x)$ and $g(x)$ but $f(x + a)$ and $g(x + a)$ also should satisfy eq. (1.17.1), and expressible as a linear combination of $f(x)$ and $g(x)$.

i.e.,
$$f(x + a) = \alpha_1 f(x) + \alpha_2\, g(x)$$
$$g(x + a) = \beta_1 f(x) + \beta_2\, g(x) \quad ...(1.17.4)$$

where α_1, α_2, β_1, β_2 are constants.

6. Then from eq. (1.17.3)
$$\psi(x + a) = Af(x + a) + Bg(x + a)$$

7. Substituting from eq. (1.17.4), we have
$$\psi(x + a) = (\alpha_1 A + \beta_1 B)f(x) + (\alpha_2 A + \beta_2 B)g(x) \quad ...(1.17.5)$$

8. But, by definition, the function
$$\psi(x + a) = e^{ik(x+a)} = e^{ika}\, e^{ikx} = \lambda\psi(x) \quad ...(1.17.6)$$
where $\lambda = e^{ika}$ is constant,

9. Substituting from eq. (1.17.3) and (1.17.5) in eq. (1.17.6), we have
$$(\alpha_1 A + \beta_1 B)\, f(x) + (\alpha_2 A + \beta_2 B)\, g(x) = \lambda A\, f(x) + \lambda B\, g(x) \quad ...(1.17.7)$$

10. Comparing the co-efficients of $f(x)$ and $g(x)$ on both sides of the eq. (1.17.7), we have
$$(\alpha_1 - \lambda)\, A + \beta_1 B = 0,\ \alpha_2 A + (\beta_2 - \lambda)\, B = 0 \quad ...(1.17.8)$$

11. This set of equations will have non-zero solution only if
$$\begin{vmatrix} \alpha_1 - \lambda & \beta_1 \\ \alpha_2 & \beta_2 - \lambda \end{vmatrix} = 0$$
$$\lambda^2 - (\alpha_1 + \beta_2)\, \lambda + (\alpha_1\beta_2 - \alpha_2\beta_1) = 0 \quad ...(1.17.9)$$

12. The two solutions λ_1 and λ_2 of this quadratic equation give, from eq. (1.17.6)
$$\psi(x + a) = \lambda_1\, \psi(x) = \lambda_2\, \psi(x) \quad ...(1.17.10)$$
which define two wave vectors k_1 and k_2 such that
$$\lambda_1 = e^{ik_1 a},\ \lambda_2 = e^{ik_2 a} \quad ...(1.17.11)$$
and also define two functions
$$u_{k_1}(x) = e^{-ik_1 x}\, \psi(x)$$
$$u_{k_2}(x) = e^{-ik_2 x}\, \psi(x) \quad ...(1.17.12)$$

13. From the last three sets of relations, we have
$$u_{k_1}(x + a) = e^{-ik_1(x+a)}\, \psi(x + a) = e^{-ik_1(x+a)}\, \lambda_1\, \psi(x)$$
$$= e^{-ik_1(x+a)}\, e^{ik_1 a}\, \psi(x) = e^{-ik_1 x}\, \psi(x)$$
$$= u_{k_1}(x)$$

14. Similarly, we have
$$u_{k_2}(x + a) = u_{k_2}(x)$$

15. Thus the function $u_k(x)$ is periodic with period a, according to eq. (1.17.1), then we can write
$$\psi_k(x) = e^{ikx}\, u_k(x)$$
This is Bloch theorem.

PART-3

E-k Diagrams.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.18. **Classify semiconductors on the basis of energy band gap with the help of suitable diagram.**

Answer

1. **Direct band gap semiconductors :** In direct band gap semiconductors, an electron in conduction band falls directly to valence band, giving off the energy difference E_g as a photon of light. It cannot undergo change in energy and momentum.

   Example : GaAs, GaN etc.

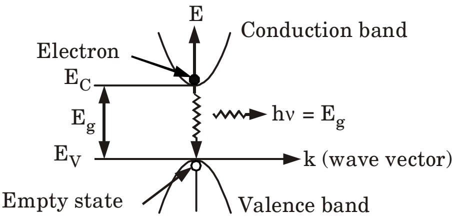


Fig. 1.18.1.

2. **Indirect band gap semiconductors :** In indirect band gap semiconductors, an electron in conduction band fall indirectly to valence band giving a part of energy to the lattice in the form of heat. It undergoes a change in momentum as well as energy.

   Example : Si, Ge etc.

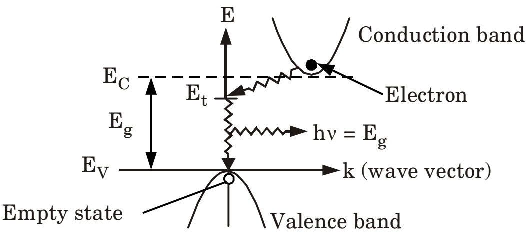


Fig. 1.18.2.

Que 1.19. **Describe briefly the band structure of Si with suitable sketch.**

AKTU 2013-14, Marks 05

Answer

1. Fig. 1.19.1(*a*) shows the ideal band structure of Si, while Fig. 1.19.1(*b*) shows the actual band structure of Si. In Fig. 1.19.1(*b*), we observe that the lowest energy gap between the bottom of conduction band and top of valence band is 1.08 eV.
2. Here the bottom of conduction band does not lie directly above the valence band and indicates a difference in momentum between the two points. Such energy band structure is called indirect semiconductor energy band.
3. Fig. 1.19.1(*c*) shows the indirect transition via of defect level (E_t).
4. An electron in the conduction band minimum of Si cannot fall directly to the valence band maximum but must undergo a momentum as well as energy change as the transition is not occurring at the same value of k.
5. A photon by itself cannot excite an electron from the top of the valence band of an indirect semiconductor to the bottom of the conduction band.
6. This is because the photon has sufficient energy to cause the transition but does not possess the necessary momentum for this transition.
7. An electron moving between the valence band and the conduction band of an indirect semiconductor can occur through a defect in the semiconductor or by the action of phonons. Phonons can provide sufficient momentum to assist indirect transitions.

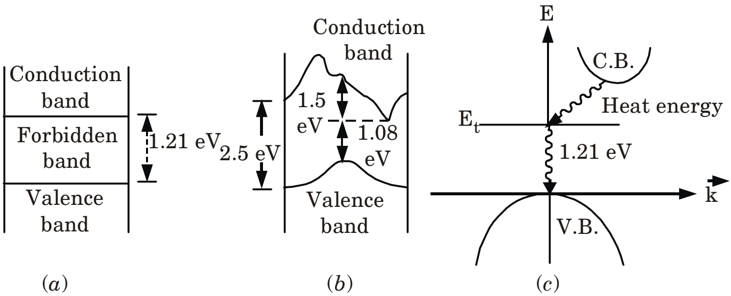


Fig. 1.19.1.

Que 1.20. **Derive the expression for the effective mass of an electron in an energy band in terms of wave vector.**

AKTU 2013-14, Marks 05

Answer

1. Effective mass of electrons within a crystal is a function of the semiconductor material and is different from the mass of electrons within the vacuum.

2. $(E, \vec{k})$ relationship for the free electron and to the electron mass is established as electron momentum $p = mv = \hbar \vec{k}$ $\left(\text{where } \hbar = \dfrac{h}{2\pi}\right)$

$\therefore$
$$E = \frac{1}{2}mv^2 = \frac{1}{2}\frac{p^2}{m} = \frac{\hbar^2}{2m}k^2$$

$\therefore$ The electron energy is parabolic with wave vector $\vec{k}$.

3. As, the electron mass is inversely related to the curvature (second derivative), of the $(E, \vec{k})$ relationship,

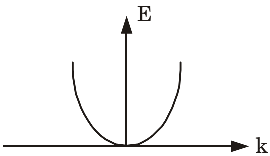


Fig. 1.20.1.

so,
$$\frac{d^2E}{d\vec{k}^2} = \frac{\hbar^2}{m}$$

4. The effective mass of an electron in a band with a given $(E, \vec{k})$ relationship is formed as

$$m^* = \frac{\hbar^2}{d^2E / d\vec{k}^2}$$

5. Therefore, the curvature of the band determines the electron effective mass. The electrons near the top of the valence band have negative effective mass.

6. The electron effective mass is denoted by m_n^* and hole effective mass is denoted by m_p^*. The n subscript indicates the electron as negative charge carrier and p subscript indicates the hole as positive charge carrier.

7. For holes, the top of the valence band corresponds to zero kinetic energy.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Explain Heisenberg's uncertainty principle.

Ans. Refer Q. 1.2.

Q. 2. Apply uncertainty principle to calculate the radius of the Bohr's first orbit.

Ans. Refer Q. 1.3.

Q. 3. What is Schrodinger wave equation ? Derive time independent Schrodinger wave equations.

Ans. Refer Q. 1.9.

Q. 4. State and proof Bloch theorem.

Ans. Refer Q. 1.17.

Q. 5. Classify semiconductors on the basis of energy band gap with the help of suitable diagram.

Ans. Refer Q. 1.18.

Q. 6. Describe briefly the band structure of Si with suitable sketch.

Ans. Refer Q. 1.19.

Q. 7. Derive the expression for the effective mass of an electron in an energy band in terms of wave vector.

Ans. Refer Q. 1.20.

☺☺☺

2
UNIT

Energy Bands of Semiconductor

CONTENTS

PART-1

Energy Bands in intrinsic and Extrinsic Semiconductor.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.1. Explain intrinsic semiconductor and also draw its energy band diagram.

Answer

1. A semiconductor in an extremely pure form is known as intrinsic semiconductor or a semiconductor in which electrons and holes are solely created by thermal excitation is called a pure or intrinsic semiconductor.

   For example : Pure crystals (like germanium, silicon) which provide electron-hole pairs are called intrinsic semiconductors.
2. Therefore, electron-hole pairs are the only charge carriers in an intrinsic material.
3. The generation of electron-hole pairs (EHPs) can be explained by considering the breaking of covalent bonds in the crystal lattice.
4. When a covalent bond of Ge crystal is broken, an electron becomes free to move about in the lattice and a hole is left behind. The energy required to break the bond is known as band gap energy E_g.
5. The energy band diagram of intrinsic semiconductor is shown in Fig. 2.1.1.

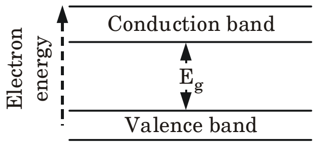


Fig. 2.1.1. Energy band diagram of intrinsic semiconductor.

6. At 0 K, the valence band is completely filled and the conduction band has no electrons. So, the material is an insulator.
7. At a finite temperature, thermal vibrations of lattice atoms produce a certain concentration of electrons (say n) in conduction band and an equal number of holes (say p) in valence band. For intrinsic material,

$$n = p = n_i \quad \text{...(2.1.1)}$$

   where n_i is known as intrinsic carrier concentration.
8. If the steady state carrier concentration is maintained, then the generation rate (g_i) should be equal to recombination rate (r_i),

i.e., $r_i = g_i$ ...(2.1.2)

Both are temperature dependent.

9. At any temperature, the recombination rate is proportional to equilibrium concentration of electrons n_0 and concentration of holes p_0, *i.e.*,

$$r_i = \alpha_r p_0 n_0 = \alpha_r n_i^2 = g_i$$

where α_r is constant of proportionality.

Que 2.2. **Discuss extrinsic semiconductor with energy band diagram.**

Answer

1. When a small amount of pentavalent impurity added to a pure semiconductor crystal during the crystal growth, the resulting crystal as *n*-type extrinsic semiconductor.

   Example : Pentavalent arsenic is added to pure germanium crystal as shown in Fig. 2.2.1.

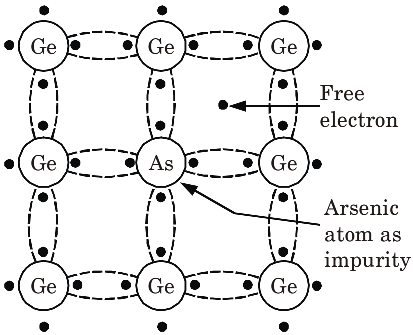


Fig. 2.2.1. Crystal lattice with germanium atom displaced by arsenic atom.

2. The energy band as shown in Fig. 2.2.2. As seen, in addition to the electrons and holes available in pure germanium, the addition of arsenic greatly increases the number of conduction electrons.

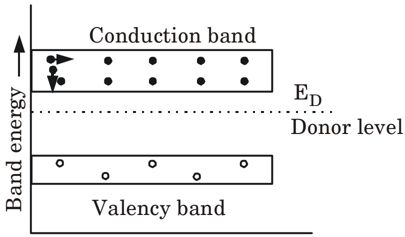


Fig. 2.2.2. Energy band description of *n*-type semiconductor.

3. Thus, the concentration of electrons in conduction band is increased and exceeds the concentration of holes in the valence band.
4. When a small amount of trivalent impurity is added to a pure crystal during the crystal growth, the resulting crystal is called a *p*-type extrinsic semiconductor.

   Example : Trivalent boron is added to pure germanium crystal as shown in Fig. 2.2.3.

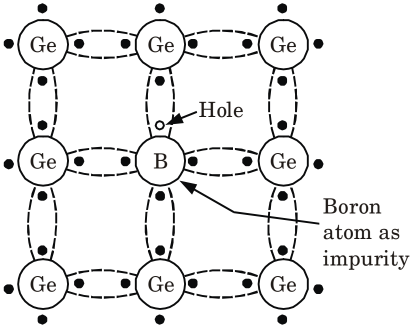


Fig. 2.2.3. Crystal lattice with one germanium atom displaced by trivalent impurity atom(boron).

5. The energy band description of *p*-type is shown in Fig. 2.2.4. The addition of trivalent impurity produces a large number of holes in the valence band.

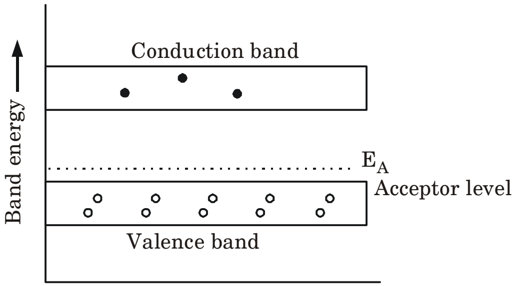


Fig. 2.2.4. Energy band description of p-type semiconductor.

6. However, there are few conduction band electrons due to thermal energy associated with room temperature.

Que 2.3. **Differentiate between direct and indirect band gap semiconductor. Also discuss the variation of energy band with alloy composition.**

AKTU 2017-18, Marks 07

Answer

Difference :

S. No.	Direct band gap semiconductor	Indirect band gap semiconductor
1.	A direct band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band aligns with the minimum energy level of the conduction band with respect to momentum.	An indirect band-gap (IBG) semiconductor is one in which the maximum energy level of the valence band are misaligned with the minimum energy level of the conduction band with respect to momentum.
2.	In a DBG semiconductor, a direct recombination takes place with the release of the energy equal to the energy difference between the recombining particles.	Due to a relative difference in the momentum, first the momentum is conserved by release of energy and only after both the momentum aligns themselves, a recombination occurs accompanied with the release of energy.
3.	The efficiency factor of a DBG semiconductor is more.	The probability of a radiative recombination is less.
4.	Example of DBG semiconductor is gallium arsenide (GaAs)	Examples of IBG semiconductors are silicon and Germanium.
5.	DBG semiconductors emit light.	IBG semiconductors emit heat.

Variation of energy bands with alloy composition :

1. The energy band gap E_g is a very important parameter of a semiconductor. The wavelength (colour) of the light emitted by a direct semiconductor depends on this gap.
2. This means that we can only get certain limited wavelengths from the semiconductors. But that is not true. We can get number of wavelengths using alloy semiconductor.
3. Alloy semiconductors provide a class of semiconductor materials where the band gap can be varied continuously by having proper percentage of alloying.
4. A particular alloy semiconductor may behave as direct semiconductor for certain of its alloying range and starts behaving as an indirect semiconductor for the remaining range.

5. Let consider a particular case of Al_xGa_{1-x} As. GaAs is a column III-V compound semiconductor. Ga and Al both belong to column III, so they can easily replace each other.

6. In this alloy, let x % of Ga are replaced by Al in GaAs and one gets Al_xGa_{1-x} As. The band gap variation with alloy composition is shown in Fig. 2.3.1.

7. This alloy has three energy bands in conduction band variation of x (*i.e.*, x in Al_x). The energy of these bands change, therefore band gap will change. Further the alloy behaves as a direct semiconductor up to $x = 0.38$.

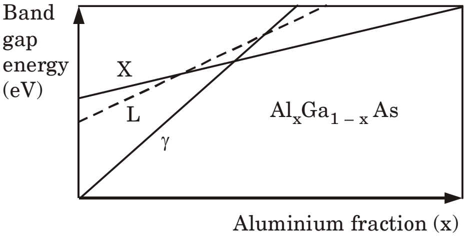


Fig. 2.3.1. Band gap variation with alloy composition.

Que 2.4. **Define Fermi level and plot the Fermi function at 0 °C. Calculate the probabilities of finding electrons and holes at the energy level of 0.1 eV above and below the Fermi level at temperature 0 K and 300 K.**

Answer

Fermi level : It is the energy state having probability of half of being occupied by an electron.

Fermi-Dirac distribution function $f(E)$:

1. It gives the probability that an available energy state at E will be occupied by an electron at absolute temperature T.

$$f(E) = \frac{1}{1+e^{(E-E_F)/kT}} \qquad ...(2.4.1)$$

where E_F = Fermi energy level
k = Boltzmann constant
T = absolute temperature in Kelvin.

2. The probability that energy state E will be occupied by hole is given by $[1 - f(E)]$.

3. If the energy E is equal to the Fermi level E_F, then occupying probability is $f(E_F) = \dfrac{1}{(1+e^0)} = \dfrac{1}{2}$

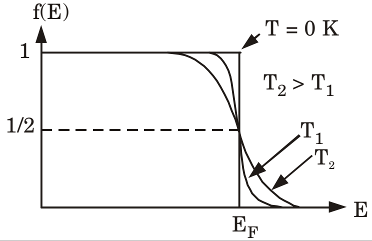


Fig. 2.4.1. The Fermi-Dirac distribution function.

4. From the given Fig. 2.4.1, it indicates that at 0 K, the distribution takes the simple rectangular form.
5. With $T = 0$ in the denominator of the exponent $f(E)$ is $1/(1 + 0) = 1$ when the exponent is negative ($E < E_F$), and is $1/(1+ \infty) = 0$ when the exponent is positive ($E > E_F$).
6. Therefore, this rectangular distribution implies that at 0 K every available energy state up to E_F is filled with electrons and all states above E_F are empty.
7. At temperatures higher than 0 K, some probability exists for states above the Fermi level to be filled.
8. For example, at $T = T_1$ in Fig. 2.4.1 there is some probability $f(E)$ that states above E_F are filled, and there is a corresponding probability $[1 - f(E)]$ that states below E_F are empty.
9. The Fermi function is symmetrical about E_F for all temperatures; that is, the probability $f(E_F + \Delta E)$ that a state ΔE above E_F is filled is the same as the probability $[1 - f(E_F - \Delta E)]$ that a state ΔE below E_F is empty.
10. Calculation of probabilities at energy level 0.1 eV at $T = 0$ K :

Case 1 : When $E - E_F = 0.1$ eV

i. For electrons $f(E) = \dfrac{1}{1+e^{\left(\frac{0.1}{0}\right)}} = 0$

ii. For holes $[1 - f(E)] = 1 - 0 = 1$

Case 2 : When $E - E_F = -0.1$ eV

i. For electrons $f(E) = \dfrac{1}{1+e^{(-0.1/0)}} = 1$

ii. For holes $[1 - f(E)] = 1 - 1 = 0$

11. Calculation of probabilities at energy level 0.1 eV at $T = 300$ K :

Case I : When $E - E_F = 0.1$ eV

i. For electrons $f(E) = \dfrac{1}{1+e^{(0.1/0.0259)}} = 0.02061$

ii. For holes $[1 - f(E)] = 1 - 0.02061 = 0.97939$

Case II : When $E - E_F = -0.1$ eV

i. For electrons $f(E) = \dfrac{1}{1 + e^{(-0.1/0.0259)}} = 0.9793$

ii. For holes $[1 - f(E)] = 1 - 0.9793 = 0.0207$

Que 2.5. **Discuss the temperature dependence of Fermi-Dirac distribution function for semiconductor materials. Derive the thermal equilibrium concentration of electron.**

AKTU 2015-16, Marks 10

OR

Derive the expression for the equilibrium carrier concentrations for holes using Fermi-Dirac distribution function.

AKTU 2016-17, Marks 7.5

Answer

1. The Fermi-Dirac distribution function can be used to calculate the concentrations of electrons and holes in a semiconductor, if the densities of available states in the valence and conduction bands are known.
2. The concentration of electrons in the conduction band is

$$n_0 = \int_{E_C}^{\infty} f(E) N(E) dE \qquad ...(2.5.1)$$

where $N(E)\, dE$ is the density of states (cm^{-3}) in the energy range dE. The electron and hole concentration symbol (n_0, p_0) indicates equilibrium conditions.
3. The number of electrons per unit volume in the energy range dE is the product of the density of states and the probability of occupancy $f(E)$.
4. Thus the total electron concentration is the integral over the entire conduction band, as in eq. (2.5.1).
5. $N(E)$ is proportional to $E^{1/2}$, so the density of states in the conduction band increases with electron energy.
6. On the other hand, the fermi function becomes extremely small for large energies. This result that the product $f(E)\, N(E)$ decreases rapidly above E_C, and very few electrons occupy energy states far above the conduction band edge.
7. Similarly, the probability of finding an empty state (hole) in the valence band $[1 - f(E)]$ decreases rapidly below E, and most holes occupy states near the top of the valence band.
8. This effect is demonstrated in Fig. 2.5.1, which shows the fermi function, and the resulting number of electrons and holes occupying available energy states in the conduction and valence bands at thermal equilibrium.

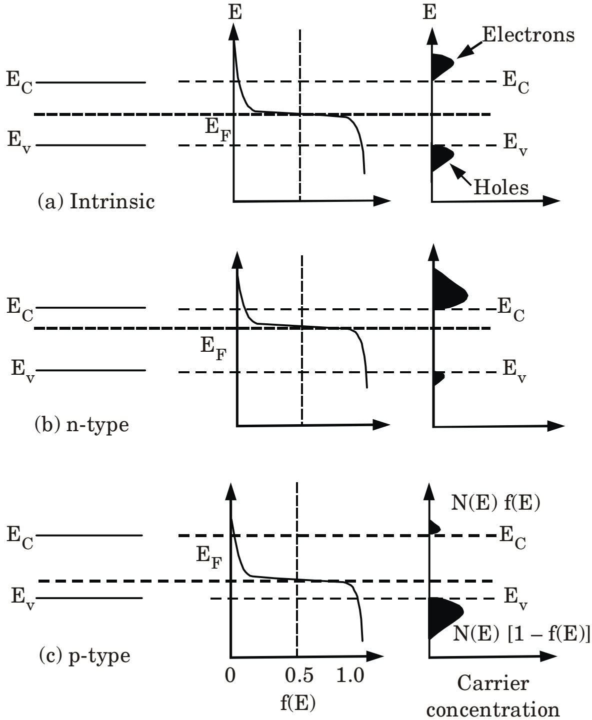


Fig. 2.5.1. Schematic band diagram, Fermi-Dirac distribution, and the carrier concentration for (a) intrinsic, (b) n-type (c) p-type at thermal equilibrium.

9. The conduction band electron concentration is the effective density of state (N_C) at E_C times the probability of occupancy at E_C.

$$n_0 = N_c f(E_c) \quad ...(2.5.2)$$

10. In this expression we assume the fermi level E_F lies at least several kT below the conduction band. Then the exponential term is large compared with unity, and the fermi function $f(E_C)$ can be simplified as

$$f(E_C) = \frac{1}{1 + e^{(E_C - E_F)/kT}} \simeq e^{-[(E_C - E_F)/kT]} \quad ...(2.5.3)$$

Since kT at room temperature is only 0.026 eV.

11. For this condition the concentration of electrons in the conduction band is,

$$n_0 = N_C e^{-(E_C - E_F)/kT} \quad ...(2.5.4)$$

Here, the effective density of states N_C is,

$$N_C = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

m^*_n is the density-of-states effective mass for electrons.

12. The concentration of holes in the valence band is

$$p_0 = N_v[1 - f(E_v)] \quad ...(2.5.5)$$

where N_v is the effective density of states in the valence band.

13. The probability of finding an empty state at E_v is

$$1 - f(E_v) = 1 - \frac{1}{1 + e^{(E_v - E_F)/kT}} \simeq e^{-(E_F - E_V)/kT} \quad ...(2.5.6)$$

for E_F larger than E_v by several kT.

14. So, the concentration of holes in the valence band is

$$p_0 = N_v e^{-(E_F - E_v)/kT} \quad ...(2.5.7)$$

15. The effective density of states in the valence band reduced to the band edge is

$$N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

Que 2.6. The energy distribution function ρ(E) is given by product of two factor [ρ(E) = N(E). f(E)]. What is the interpretation to be given to each of these factors ? **AKTU 2018-19, Marks 07**

Answer

1. The energy distribution function of the electrons can be interpreted as a product of two factors.

i. The first is called the degeneracy, or the density of states per unit energy. This factor is independent of the statistical nature of the particles.

ii. The second is the average number of electrons with energy.

Que 2.7. What do you mean by intrinsic concentration of charge carriers ?

Answer

1. The intrinsic electron and hole concentrations are

$$n_i = N_C\, e^{-(E_C - E_i)/kT}, p_i = N_V\, e^{-(E_i - E_V)/kT}$$

2. The product of n_0 and p_0 at equilibrium is constant for a particular material and temperature, even if the doping is varied :

$$n_0 p_0 = (N_C\, e^{-(E_C - E_F)/kT})(N_V e^{-(E_F - E_V)/kT})$$

$$= N_C N_V e^{-(E_C - E_V)/kT} = N_C N_V e^{-E_g/kT}$$

$$n_i p_i = (N_C e^{-(E_C - E_i)/kT})\,(N_V e^{-(E_i - E_V)/kT}) = N_C N_V e^{-E_g/kT}$$

3. The intrinsic electron and hole concentrations are equal, $n_i = p_i$; thus the intrinsic concentration is

$$n_i = \sqrt{N_C N_V}\; e^{-E_g/2kT}$$

4. The constant product of electron and hole concentrations can be written as

$$n_0 p_0 = n_i^2$$

For Si at room temperature, $n_i = 1.5 \times 10^{10}$ cm^{-3}

5. Equilibrium carrier concentration can also be written as

$$n_0 = n_i e^{(E_F - E_i)/kT}$$

$$p_0 = n_i e^{(E_i - E_F)/kT}$$

Que 2.8. **Si sample is doped with 10^{20} As atoms/cm^3. What is equilibrium concentration of holes at 300 K ? Where is E_F (*i.e.*, Fermi level) ? Draw the energy band diagram to show the position of E_i and E_F. Take n_i = 1.5 × 10^{10} cc.** **AKTU 2014-15, Marks 05**

Answer

Given : $N_d = 10^{20}$ atoms / cm^3, T = 300 K, $n_i = 1.5 \times 10^{10}$ c.c.

To Find : p_0, $E_F - E_i$

1. Since, $N_d > n_i$, we can approximate $n_0 = N_d$ and

$$p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{20}} = 2.25 \text{ cc}$$

2. Fermi level, $E_F - E_i = kT \ln \dfrac{n_0}{n_i} = 0.0259 \ln \dfrac{10^{20}}{1.5 \times 10^{10}} = 0.59$ eV

3. The resulting band diagram is as shown in Fig. 2.8.1.

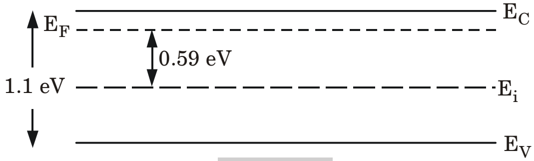


Fig. 2.8.1.

Que 2.9. **A Si sample is doped with 10^{16} boron atoms/ cm^3. What is the equilibrium concentration n_0 at 300 K ? Where E_F is relative to E_i. Assume for Si at 300 K. n_i = 1.5 × 10^{10} cm^{-3} and E_g = 1.12 eV**

Answer

Given : $N_a = 10^{16}$ cm^{-3}, T = 300 K, $n_i = 1.5 \times 10^{10}$ cm^{-3}, E_g = 1.12 eV

To Find : $E_i - E_F$

1. Since boron is a *p*-type dopant in Si, hence the material will be *p*-type. Since $N_A >> n_i$, we can approximate

$$p_0 = N_A = 10^{16}\ \text{cm}^{-3}$$

$$n_0 = \frac{n_i^2}{p_0} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4\ \text{cm}^{-3}$$

2. $$E_i - E_F = kT \ln \frac{p_0}{n_i}$$

$$E_i - E_F = 0.0259 \ln \frac{10^{16}}{1.5 \times 10^{10}} = 0.347\ \text{eV}$$

3. The resulting band diagram is as shown in Fig. 2.9.1.

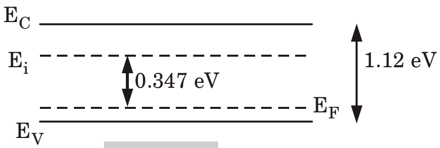


Fig. 2.9.1.

PART-2

Carrier Transport : Mobility, Resistivity, Diffusion Current and Drift Current.

Questions-Answers
Long Answer Type and Medium Answer Type Questions

Que 2.10. **What do you mean by mobility of a carrier ? How does it depend on temperature, doping concentrations and high field ? Explain.**

Answer

Mobility : The mobility of a carrier is a measure of its ease of motion, and is defined as the drift velocity per unit electric field,

i.e., $$\mu = \frac{v_d}{E}$$

where, v_d = drift velocity, and E = applied electric field . It is a positive quantity and has a unit of cm^2/ V-sec.

Effect of temperature on mobility :

The mobility is determined by scattering of the carriers. Scattering mechanism influence electron and hole mobility.

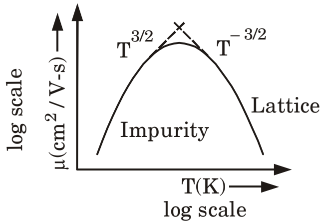


Fig. 2.10.1.

i. Lattice scattering :

1. If scattering occurs due to vibrations of lattice atom then it is called lattice scattering.
2. As the temperature increases, the frequency of lattice vibration increases. As a result, the mobility decreases.
3. The approximate temperature dependency is given by $T^{-3/2}$ as shown in Fig. 2.10.1.

ii. Impurity scattering :

1. If scattering occurs under the influence of interaction with impurity atoms, it is called impurity scattering.
2. Such scattering dominates at low temperature. At low temperature the thermal motion of carriers is slow. So, there is an increase in mobility (μ) as the temperature increases. The dependency is expressed by $T^{3/2}$ as shown in Fig. 2.10.1.

Effect of doping on mobility :

1. As the dopant concentration in a semiconductor increases, the carrier mobility at a given temperature decreases. The reason is the increased scattering by the impurity ions.

Effect of high field on mobility :

1. Since, $\mu = \dfrac{v_d}{E}$, this shows that mobility decreases at high fields which leads to velocity saturation.

Que 2.11. What do you mean by Fermi level ? Discuss the effect of temperature and doping on mobility. A Si sample is doped with 10^{17} As atoms/cm³. What is the equilibrium hole concentration on p_0 at 300 K ? Where is E_F relative to E_i.

AKTU 2017-18, Marks 07

Answer

Fermi level : Refer Q. 2.4, Page 2–6A, Unit-2.

Effect of temperature and doping on mobility : Refer Q. 2.10, Page 2–12A, Unit-2.

Numerical :

Given : $N_d = 10^{17}$ atoms/cm^3, T = 300 K.
To Find : p_0, $E_F - E_i$

1. Since, $N_d > n_i$ we can approximate $n_0 = N_d$ and $n_i = 1.5 \times 10^{10}$ cm^{-3} (For Si)

$$p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{17}}$$

$$p_0 = 2250 \text{ atoms/cm}^3$$

2. Fermi level, $$E_F - E_i = kT \ln\left(\frac{n_0}{n_i}\right) = 0.0259 \ln\left(\frac{10^{17}}{1.5 \times 10^{10}}\right) = 0.406 \text{ eV}$$

3. The resulting band diagram is shown in Fig. 2.11.1.

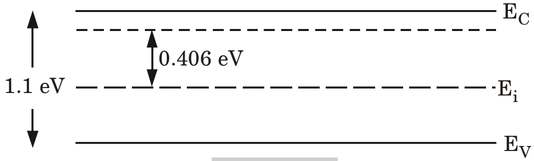


Fig. 2.11.1.

Que 2.12. **Explain high field effect.** **AKTU 2014-15, Marks 05**

Answer

1. Large electric fields ($E > 10^3$ V/cm) can cause the drift velocity and therefore the current $J = -qnv_d$ to exhibit a sublinear dependence on the electric field.
2. This dependence of σ upon E is an example of a hot carrier effect, which implies that the carrier drift velocity v_d is comparable to the thermal velocity v_{th}.
3. In many cases, an upper limit is reached for the carrier drift velocity in a high field as shown in Fig. 2.12.1.

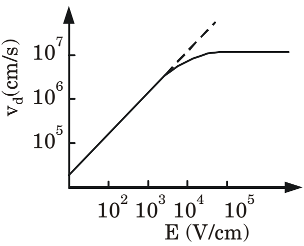


Fig. 2.12.1. Saturation of electron drift velocity at high electric fields for Si.

4. This limit occurs near the mean thermal velocity ($\simeq 10^7$ cm/s) and represents the point at which added energy imparted by the field is transferred to the lattice rather than increasing the carrier velocity.

5. The result of this scattering limited velocity is a fairly constant current at high field. This behaviour is typical of Si, Ge and some other semiconductors.

Que 2.13. **Derive the expression for resistivity.**

Answer

Consider a semiconductor sample shown in Fig. 2.13.1 which has a cross-sectional area A, a length L, and a carrier concentration of n electrons/cm^3. Suppose we now apply an electric field E to the sample.

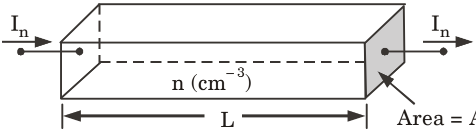


Fig. 2.13.1. Current conduction in a uniformly doped semiconductor bar with length L and cross-sectional area A.

1. The electron current density J_n flowing in the sample can be found by summing the product of the charge $(-q)$ on each electron times the electron's velocity over all electrons per unit volume n :

$$J_n = \frac{I_n}{A} = \sum_{i=1}^{n}(-qv_i) = -qnv_n = qn\mu_n E \qquad ...(2.13.1)$$

where I_n is the electron current.

2. A similar process applies to holes. By taking the charge on the hole to be positive, we have

$$J_p = qpv_p = qp\mu_p E. \qquad ...(2.13.2)$$

3. The total current flowing in the semiconductor sample due to the applied field E can be written as the sum of the electron and hole current components :

$$J = J_n + J_p = (qn\mu_n + qp\mu_p)E. \qquad ...(2.13.3)$$

4. The quantity in parentheses is known as conductivity :

$$\sigma = q(n\mu_n + p\mu_p) \qquad ...(2.13.4)$$

5. The electron and hole contributions to conductivity are simply additive. The corresponding resistivity of the semiconductor, which is the reciprocal of σ, is given by

$$\rho = \frac{1}{\sigma} = \frac{1}{q(n\mu_n + p\mu_p)}$$

Que 2.14. **In a semiconductor at room temperature, the intrinsic carrier concentration and intrinsic resistivity are 1.5×10^{16} m^{-3} and 2×10^3 Ω-m respectively. It is converted into an extrinsic semiconductor with a doping concentration of 10^{20}/m^3 for the extrinsic semiconductor. Calculate for the extrinsic minority carrier concentration, mobility and resistivity of doped**

semiconductor, minority carrier concentration when temperature is increased to a value at which intrinsic carrier concentration n is doubled $\mu_n = \mu_p$.

Answer

Given : $n_i = 1.5 \times 10^{16}\ m^{-3}$, $\rho = 2 \times 10^3\ \Omega m$

Doping concentration = $10^{20}\ /m^3$

To Find : μ_n, σ, minority carrier concentration

1. **Assumptions :**
   i. Mobility of majority and minority carrier to be the same.
   ii. $kT = 26$ mV at room temperature.
2. **Minority carrier concentration :**

$$= \frac{n_i^2}{\text{Doping concentration}}$$

$$= \frac{(1.5 \times 10^{16})^2}{10^{20}} = 2.25 \times 10^{12} \text{ atoms/m}^3$$

3. **Electron mobility :**

$$(\mu_n + \mu_p) = \frac{1}{\rho q n} = \frac{1}{2 \times 10^3 \times 1.6 \times 10^{-19} \times 1.5 \times 10^{16}}$$

$$2\mu_n = \frac{1}{4.8}$$

$$\mu_n = \frac{1}{9.6} = 0.1042 \text{ m}^2\text{/volt-sec}$$

4. **Resistivity :**

$$\sigma = qn(\mu_n)$$

As doping concentration >> minority concentration

$$\sigma = 1.6 \times 10^{-19} \times 10^{20} \times 0.1042 = 1.6672\ \Omega^{-1}\, m^{-1}$$

$$\text{Resistivity} = \frac{1}{\sigma} = 0.5998\ \Omega\text{-m}$$

5. **Minority carrier concentration when n is doubled :**

$$= \frac{(1.5 \times 2 \times 10^{16})^2}{10^{20}} = \frac{9 \times 10^{32}}{10^{20}}$$

$$= 9 \times 10^{12} \text{ atoms/m}^3$$

Que 2.15. Mobilities of electrons and holes in a sample of intrinsic Germanium at room temperature are 3900 cm²/ V-sec and 1900 cm²/ V-sec respectively. If the electrons and hole densities are each equal to 2.5 × 10¹³ per cm³, calculate Germanium resistivity and conductivity.

Answer

Given : μ_n = 3900 cm^2/ V-sec, μ_p = 1900 cm^2/ V-sec
$n_0 = p_0 = 2.5 \times 10^{13}$ per cm^3
To Find : σ, ρ

1. Conductivity of Germanium is given by

$$\sigma = e\,(\mu_n n_0 + \mu_p p_0)$$
$$= 1.6 \times 10^{-19} \times 2.5 \times 10^{13}\,(3900 + 1900)$$
$$= 0.0232\,(\Omega\text{-cm})^{-1}$$

2. Resistivity of Germanium is given by

$$\rho = \frac{1}{\sigma} = \frac{1}{0.0232} \approx 43\ \Omega\text{-cm}$$

Que 2.16. **Calculate the conductivity of specimen if a donor impurity is added to an extent of one part in 10^8 Ge atoms at room temperature.**
Avogadro number = 6.02×10^{23} atoms/mole
At. weight of Ge = 72.6 gm
Density of Ge = 5.32 gm/cc
Mobility μ = 3800 cm^2 / V-s

Answer

Given : Avogadro number = 6.02×10^{23} atoms/mole, At. weight of Ge = 72.6 gm, Density of Ge = 5.32 gm/cc,
Mobility μ = 3800 cm^2 /V-s.
To Find : Conductivity, σ.

1. Concentration of Ge atoms $= \dfrac{\text{Avogadro number}}{\text{Atomic weight of Ge}} \times \text{Density of Ge}$

$$= \frac{6.02 \times 10^{23}}{72.6} \times 5.32 = 4.41 \times 10^{22} / \text{cm}^3$$

2. As there is one donor atom per 10^8 atom of Ge.

Hence, $$n_d = \frac{4.41 \times 10^{22}}{10^8} = 4.41 \times 10^{14} \text{ per cc}$$

3. Now conductivity, $\sigma = n_d \mu e$

$$= (4.41 \times 10^{14}) \times (3800 \times (1.6 \times 10^{-19})) = 0.268 \text{ mho/cm}$$

Que 2.17. **A specimen of pure germanium at 300 K has a density of charge carriers of 2.5×10^{19}/m^3. It is doped with donor impurity at the rate of one impurity atom for every 10^6 atoms of Ge. All impurity atoms may be supposed to be ionized. The density of Ge atoms is 4.2×10^{28} atoms/m^3. Find the resistivity of doped germanium if the electron mobility is 0.36 m^2/V-s.**

Answer

Given : Density of charge carrier = $2.5 \times 10^{19}/m^3$, Density of Ge atoms = 4.2×10^{28} atoms/m^3, $\mu_n = 0.36$ m^2/V-s.
To Find : Resistivity, ρ_n

1. Intrinsic carrier concentration = $2.5 \times 10^{19} / m^3$
2. Density of added impurity atoms N_d is given by

$$N_d = \frac{\text{Density of Ge atom}}{\text{Rate of one impurity atoms}} = \frac{4.2 \times 10^{28}}{10^6}$$
$$= 4.2 \times 10^{22} \text{ atoms} / m^3$$

3. Here, donor concentration is very large as compared to intrinsic carrier concentration. Hence, the intrinsic concentration may be neglected.
4. The conductivity of doped material is

$$\sigma_n = N_d e \mu_n$$
$$= (4.2 \times 10^{22}) \times (1.6 \times 10^{-19}) \times 0.36$$
$$= 2.492 \times 10^3 \text{ mho / m}$$

5. Therefore, resistivity, $\rho_n = \dfrac{1}{\sigma_n} = \dfrac{1}{(2.492 \times 10^3) \text{ mho / m}}$

or $\rho_n = 0.4133 \times 10^{-3}\ \Omega$ m

Que 2.18. Calculate minimum conductivity of Si at 300 K. Derive the expression used, if any.

OR

Show that the minimum conductivity of a semiconductor sample occurs when $n_0 = n_i \sqrt{\dfrac{\mu_p}{\mu_n}}$. What is the expression for minimum conductivity ?

Answer

Derivation :

1. As $\sigma = q(n\mu_n + p\mu_p)$
   we know that,

$$n_i^2 = np$$

$$\therefore \quad p = \frac{n_i^2}{n}$$

so, $$\sigma = q\left(n\mu_n + \frac{n_i^2}{n}\mu_p\right)$$

2. $$\frac{\partial \sigma}{\partial n} = q\left(\mu_n - \frac{n_i^2}{n_{min}^2}\mu_p\right) = 0 \text{ (for minimum conductivity)}$$

$$\mu_n = \frac{n_i^2}{n_{min}^2}\mu_p$$

$$n_{\min}^2 = n_i^2 \frac{\mu_p}{\mu_n}$$

$$n_{\min} = n_i \sqrt{\frac{\mu_p}{\mu_n}}$$

3. $$\sigma_{\min} = q\left[n_{\min}.\mu_n + \frac{n_i^2}{n_{\min}}.\mu_p\right]$$

as $$n_{\min} = n_i \sqrt{\frac{\mu_p}{\mu_n}}$$

$\therefore$ $$\sigma_{\min} = q\left[n_i \sqrt{\frac{\mu_p}{\mu_n}}.\mu_n + \frac{n_i^2}{n_i.\sqrt{\frac{\mu_p}{\mu_n}}}.\mu_p\right]$$

$$\sigma_{\min} = 2qn_i\sqrt{\mu_n.\mu_p}$$

Numerical :

Given : $q = 1.6 \times 10^{-19}$ C
$n_i = 1.5 \times 10^{10}$ cm^{-3}, $\mu_n = 1350$ cm^2/ V-s, $\mu_p = 480$ cm^2/ V-s
To Find : $\sigma_{\min}$.

$$\sigma_{\min} = 2 \times 1.6 \times 10^{-19} \times 1.5 \times 10^{10} \sqrt{1350 \times 480}$$
$$= 3.9 \times 10^{-6} \ (\Omega\text{-cm})^{-1}$$

Que 2.19. **What is Hall effect ? Derive the relation between Hall voltage and carrier concentration.**

Answer

Hall effect :

According to Hall effect, if a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field, then an electric field is induced in the direction perpendicular to both I and B. This phenomenon is known as Hall effect.

Derivation :

1. Consider, an n-type semiconductor bar carrying a current I in positive x-direction and placed in a magnetic field B. A force is exerted in negative y-direction.
2. If the semiconductor is of n-type, current will be carried by electrons and these electrons will be forced downward side 1 and side 1 becomes negatively charged thus, a potential difference V_H called Hall voltage is developed between surfaces 1 and 2.
3. The polarity of Hall voltage enables to determine whether semiconductor is of n-type or p-type.

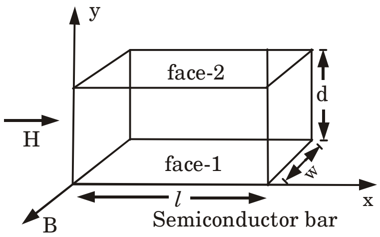


Fig. 2.19.1.

4. In equilibrium state,

$$qE = Bqv$$

or $$E = Bv \quad \text{...(2.19.1)}$$

where, v = Drift speed

q = Electric charge

5. As, $$E = \frac{V_H}{d} \text{ and } J = \rho v = \frac{I}{wd}$$

$\therefore$ $$V_H = Ed = Bvd = \frac{BJd}{\rho} = \frac{BI}{\rho w}$$

$\therefore$ $$V_H = BI/\rho w \quad \text{...(2.19.2)}$$

where, w = Width of specimen and ρ = Charge density

6. Now, Hall co-efficient

$$R_H = \frac{1}{\rho} \quad \text{...(2.19.3)}$$

hence, $$R_H = \frac{V_H w}{BI} \quad \text{...(2.19.4)}$$

7. If carriers are electrons then $\rho = -nq$ and if carriers are holes then $\rho = pq$

$\therefore$ Hall coefficient for n-type semiconductor, $R_H = -\dfrac{1}{nq}$

and for p-type semiconductor, $R_H = +\dfrac{1}{pq}$

8. If both σ and R_H are measured the mobility may be determined by the following relation

$$\mu = \sigma R_H.$$

Que 2.20. **What is Hall angle ? Show that $\theta_H = \tan^{-1}(\mu B)$ where symbols have their usual meaning.**

Answer

1. The net electric field E in the specimen is a vector sum of electric field component in the x-direction because of flow of current, E_x and electric field due to Hall effect, *i.e.*, E_H.

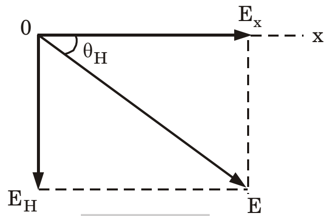


Fig. 2.20.1.

2. So, resultant electric field E acts at an angle of θ_H to the x-axis and this angle is called Hall angle.

Thus, Hall angle, $\theta_H = \tan^{-1} \dfrac{E_H}{E_x}$ ...(2.20.1)

3. We have $E_H = \dfrac{V_H}{d}$

and $E_x = \dfrac{\text{Voltage drop along the length}}{\text{Length of specimen}}$

$$= \frac{IR}{l} = \frac{I \times \text{resistivity} \times l}{l \times a}$$

$$= \frac{I}{a} \times \text{resistivity} = J \times \frac{1}{\sigma} = \frac{J}{\sigma}$$

4. Substituting the value of E_H and E_x in eq. (2.20.1)

$$\theta_H = \tan^{-1} \frac{E_H}{E_x} = \tan^{-1} \frac{V_H / d}{J / \sigma} = \tan^{-1} \frac{BI / \rho w d}{J / \sigma}$$

$\because$ $J = \dfrac{I}{wd}$

$$\theta_H = \tan^{-1} \frac{B\sigma}{\rho} = \tan^{-1} \sigma B R_H$$

$\theta_H = \tan^{-1} \mu B$ $(\because \mu = \sigma R_H)$

Que 2.21. **An electric field of 100 V/m is applied to a specimen of n-type semiconductor for which the Hall co-efficient is 0.0145 m³/C. Determine the current density in the specimen. Given that μ_n = 0.36 m²/volt-sec.**

Answer

Given : E = 100 V/m, R_H = 0.0145 m³/C, μ_n = 0.36 m²/ V-sec

To Find : J

1. Current density, $J = \sigma E$

$J = nq\mu_n E$ ...(2.21.1)

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

$$n = \frac{1}{qR_H} = \frac{1}{1.6 \times 10^{-19} \times 0.0145} = 4.31 \times 10^{20}/\text{m}^3$$

2. Putting the value of n in eq. (2.21.1)

$$J = nq\mu_n E = 4.31 \times 10^{20} \times 1.6 \times 10^{-19} \times 0.36 \times 100$$

$$J = 2482 \text{ A} / \text{m}^2$$

Que 2.22. The resistivity of a sample semiconductor is 9 milli ohm-meter. Its holes have mobility of 0.03 m²/V-s. Calculate hall coefficient.

Answer

Given : Resistivity = 9×10^{-3} ohm-meter, Mobility (μ) = 0.03 m²/V-s.
To Find : Hall coefficient.

1. We know that

Conductivity, $$\sigma = \frac{1}{\text{resistivity}} = \frac{1}{9 \times 10^{-3}} = 111.11/\Omega\text{-m}$$

2. Now, Hall coefficient, $$R_H = \frac{\mu}{\sigma} = \frac{0.03}{111.11} = 2.7 \times 10^{-4} \text{ m}^3/\text{C}$$

Que 2.23. The resistivity of semiconductor material was known to 0.00912 Ω-m at room temperature. The flux density in the hall model was 0.48 Wb/m². Calculate hall angle for a hall coefficient of 3.55 × 10⁻⁴ m³/ coulomb.

Answer

Given : Resistivity = 0.00912 Ω-m, Flux density (B) = 0.48 Wb/m²,
Hall coefficient (R_H) = 3.55×10^{-4} m³/c
To Find : Hall angle θ_H

1. Conductivity, $$\sigma = \frac{1}{\text{resistivity}}$$

$$\therefore \quad \sigma = \frac{1}{0.00912} = 109.65\ (\Omega\text{-m})^{-1}$$

2. Hall angle, $$\theta_H = \tan^{-1}(\sigma B R_H)$$
$$= \tan^{-1}(109.65 \times 0.48 \times 3.55 \times 10^{-4})$$
$$= \tan^{-1}(0.01868) = 1.0704°$$

Que 2.24. What is diffusion of carriers ? Derive the expression for the diffusion current crossing a unit area.

Answer

1. Diffusion is the natural result of the random motion of the individual molecules when excess carriers are created non-uniformly in a semiconductor, the electron and hole concentrations vary with position in the sample.
2. Any such spatial variation in n and p calls for a net high carrier concentration to region of low carrier concentration. This type of phenomenon is called diffusion of carrier.
3. Let us consider an arbitrary distribution $n(x)$ as shown in Fig. 2.24.1.
4. Since the mean free path $\bar{l}$ between collisions is a small incremental distance, we can divide x into segments $\bar{l}$ wide, with $n(x)$ evaluated at the center of each segment.

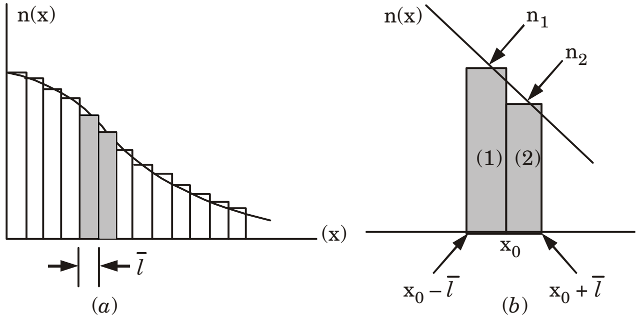


Fig. 2.24.1. (*a*) Division of $n(x)$ into segments of length equal to a mean free path for the electrons ; (*b*) Expanded view of two of the segments centered at x_0.

5. In Fig. 2.24.1(*b*), the electrons in segment (1) to the left of x_0 have equal chances of moving left or right, and in a mean free time one-half of them will move into segment (2).
6. The same is true for electrons within one mean free path of x_0 to the right; one half of these electrons will move through x_0 from right to left in a mean free time.
7. Thus, the net number of electrons passing x_0 from left to right in one mean free time is,

$$\frac{1}{2}(n_1 \bar{l} A) - \frac{1}{2}(n_2 \bar{l} A) \quad ...(2.24.1)$$

where, area perpendicular to x is A.

8. The rate of electron flow in the $+x$ direction per unit area is given by,

$$\phi_n(x_0) = \frac{\bar{l}}{2\bar{t}}(n_1 - n_2) \quad ...(2.24.2)$$

9. Since the mean free path $\bar{l}$ is a small differential length, the difference in electron concentration $(n_1 - n_2)$ can be written as,

$$n_1 - n_2 = \frac{n(x) - n(x+\Delta x)}{\Delta x}\bar{l} \quad ...(2.24.3)$$

where, x is taken at the center of segment (1) and $\Delta x = \bar{l}$.

10. Eq. (2.24.2) can also be written in terms of carrier gradient $dn(x)/dx$

$$\phi_n(x) = \frac{\bar{l}^2}{2\bar{t}} \lim_{\Delta x \to 0} \frac{n(x) - n(x+\Delta x)}{\Delta x}$$

$$= \frac{-\bar{l}^2}{2\bar{t}} \frac{dn(x)}{dx} \quad ...(2.24.4)$$

Here the quantity $\frac{\bar{l}^2}{2\bar{t}}$ is called the electron diffusion coefficient D_n with unit cm^2/sec.

11. The minus sign in eq. (2.24.4) indicates that the net motion of electron due to diffusion is in the direction of decreasing electron concentration.

$\therefore$ We can say that

$$\phi_n(x) = -D_n \frac{dn(x)}{dx} \quad ...(2.24.5)$$

$$\phi_p(x) = -D_p \frac{dp(x)}{dx} \quad ...(2.24.6)$$

where, D_p = hole diffusion coefficient

12. The diffusion current crossing a unit area (the current density) is the particle flux density multiplied by the charge of carrier.

$$J_n\text{ (diff)} = -(-q)\, D_n \frac{dn(x)}{dx} = q\, D_n \frac{dn(x)}{dx}$$

$$J_p\text{ (diff)} = -(+q)\, D_p \frac{dp(x)}{dx} = -q\, D_p \frac{dp(x)}{dx}$$

Que 2.25. What do you mean by drift and diffusion of carriers ? Find total current density generated due to both of these transport mechanisms of carriers.

Answer

1. There are two kinds of current flow in a semiconductor :
   i. The first is drift current which is due to electric field.
   ii. The second is diffusion current which is due to gradient of carrier concentration.
2. If an electric field is present in addition to the carrier gradient, the current densities will each have a drift component and diffusion component

$$J_p(x) = \underbrace{q\mu_p\, p(x)\, E(x)}_{\text{drift}} - \underbrace{qD_p \frac{dp(x)}{dx}}_{\text{diffusion}} \quad ...(2.25.1)$$

$$J_n(x) = q\mu_n\, n(x)\, E(x) + qD_n \frac{dn\,(x)}{dx} \quad ...(2.25.2)$$

3. The total current density is the sum of the contribution due to electrons and holes :

$$J(x) = J_n(x) + J_p(x) \quad ...(2.25.3)$$

4. The relation between the particle flow and the current of eq. (2.25.1) and (2.25.2) can be visualized by considering a diagram such as shown in Fig. 2.25.1.
5. In Fig. 2.25.1, an electric field is assumed to be in the x-direction, along with carrier distributions $n(x)$ and $p(x)$ which decrease with increasing x.

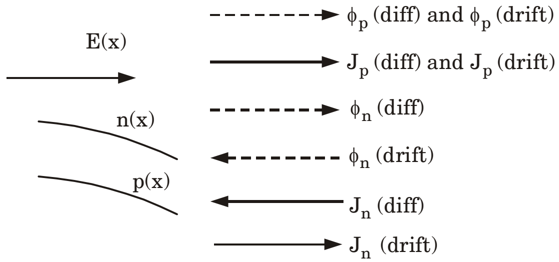


Fig. 2.25.1 Drift and diffusion directions for electrons and holes in a carrier gradient and an electric field. Particle flow directions are indicated by dashed arrows, and the resulting currents are indicated by solid lines.

6. Thus the derivatives in equations,

$$\phi_n(x) = -D_n \frac{dn(x)}{dx}$$

$$\phi_p(x) = -D_p \frac{dp(x)}{dx}$$

are negative, and diffusion takes place in the +x-direction.

7. The resulting electrons and hole diffusion currents [J_n(diff.) and J_p (diff.)] are in opposite directions.
8. Holes drift in the direction of the electric filed [ϕ_p (drift)], whereas electrons drift in the opposite direction because of their negative charge. The resulting drift current is in the +x-direction in each case.

Que 2.26. **Describe diffusion of carriers and derive the current equation resulting due to this phenomenon. Also, derive the Einstein relation.**

OR

What is Einstein relation ? Develop expressions to establish relations between diffusion coefficient and mobility of carriers or obtain the relation : $D/\mu = kT/q$.

AKTU 2017-18, 2018-19; Marks 07

Answer

A. Diffusion of carriers : Refer Q. 2.24, Page 2-22A, Unit-2.

B. Einstein relation :

1. Fig. 2.26.1 shows energy band diagram of a semiconductor in electric field $\varepsilon(x)$.
2. Since electrons drift in a direction opposite to the field therefore the potential energy for electrons will increase in the direction of the field.

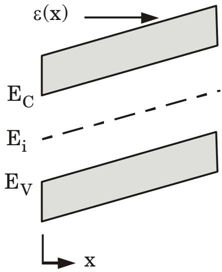


Fig. 2.26.1. Energy band diagram of a semiconductor in an electric field $\varepsilon(x)$.

3. The electrostatic potential $V(x)$ varies in the opposite direction, since it is defined in terms of positive charges therefore related to electron potential energy $\varepsilon(x)$ as,

$$V(x) = \frac{E(x)}{-q} \qquad ...(2.26.1)$$

4. We know, electric field $\varepsilon(x) = \frac{-dV(x)}{dx}$

choosing E_i as a convenient reference, the electric field can be related as,

$$\varepsilon(x) = \frac{-d}{dx}\left[\frac{E_i}{-q}\right] = \frac{1}{q}\frac{dE_i}{dx} \qquad ...(2.26.2)$$

5. At equilibrium, no net current flows in a semiconductor, therefore

$$J_p(x) = q\mu_p\, p(x)\,\varepsilon(x) - qD_p\,\frac{dp(x)}{dx} = 0$$

$$q\mu_p p(x)\,\varepsilon(x) = qD_p\,\frac{dp(x)}{dx}$$

$$\varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{p(x)}\frac{dp(x)}{dx} \qquad ...(2.26.3)$$

6. To calculate the value of $\frac{1}{p(x)}\frac{dp(x)}{dx}$

we know, $p = n_i\, e^{(E_i - E_F)/kT}$

$$\frac{p}{n_i} = e^{(E_i - E_F)/kT}$$

taking log on both sides,

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

$$\therefore \quad \ln p - \ln n_i = \frac{E_i - E_F}{kT} \quad \text{...(2.26.4)}$$

7. Differentiating eq. (2.26.4) with respect to x we get

$$\frac{1}{p}\frac{dp}{dx} - 0 = \frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right] \quad (\because n_i = \text{constant})$$

$$\frac{1}{p}\frac{dp}{dx} = \frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right] \quad \text{...(2.26.5)}$$

8. Putting the value of eq. (2.26.5) in eq. (2.26.3)

$$\varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right]$$

9. The equilibrium Fermi level does not vary with x, and derivative of E_i is given as $q\varepsilon(x)$

$$\therefore \quad \varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{kT} \times q\varepsilon(x)$$

$$\frac{1}{q} = \frac{D_p}{\mu_p} \times \frac{1}{kT}$$

$$\frac{kT}{q} = \frac{D_p}{\mu_p}$$

or

$$\frac{D}{\mu} = \frac{kT}{q} \quad \text{...(2.26.6)}$$

10. Eq. (2.26.6) is known as Einstein relation.

Que 2.27. **In Si semiconductor it is observed that three quarters of current is carried by holes and the rest part by electrons. What is the ratio of electrons to holes concentration ?**

Answer

Given : $I_p = \frac{3}{4}I, \; I_n = \frac{1}{4}I$

To Find : $n : p$

$$\frac{J_n(\text{drift})}{J_p(\text{drift})} = \frac{q\mu_n En}{q\mu_p Ep} \quad \left(\because J = \frac{I}{A}\right)$$

$$\frac{\frac{1}{4}I}{\frac{3}{4}I} = \frac{\mu_n}{\mu_p} \cdot \frac{n}{p}$$

$$\frac{1}{3} = V_T \frac{n}{p} \qquad \left(\because \frac{D_n}{D_p} = \frac{\mu_n}{\mu_p} = V_T \right)$$

$$n : p = \frac{1}{3 \times 0.026}$$

$$n : p = 12.82$$

PART-3

Sheet Resistance, Design of Resistors.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.28. **Write a short note on sheet resistance.**

Answer

1. Consider a uniform slab of conducting material of resistivity ρ, of width W, thickness t, and length between faces L. The arrangement is shown in Fig. 2.28.1.

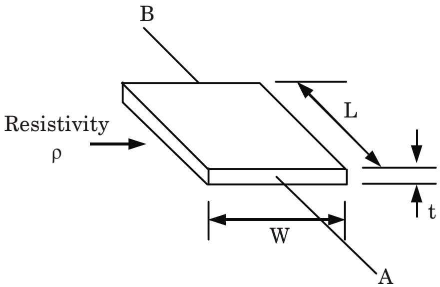


Fig. 2.28.1. Sheet resistance model.

2. Consider the R_{AB} between two opposite faces.

$$R_{AB} = \frac{\rho L}{A} \text{ ohm}$$

where A = Cross-section area

3. Thus $R_{AB} = \dfrac{\rho L}{tW}$ ohm $(\because A = tW)$

4. If $L = W$, *i.e.*, a square of resistive material, then

$$R_{AB} = \frac{\rho}{t} = R_S$$

where R_S = ohm per square or sheet resistance

5. Thus $$R_S = \frac{\rho}{t} \text{ ohm per square}$$

R_S is completely independent of the area of the square.

Que 2.29. **A particular layer of MOS circuit has resistivity $\rho = 1$ ohm cm. A section of this layer is 55 μm long and 5 μm wide and has a thickness of 1 μm. Calculate the resistance from one end of this section to the other (along the length). What is the value of R_S ?**

Answer

Given : $\rho = 1\ \Omega$-cm, $l = 55\ \mu$m $= 55 \times 10^{-4}$ cm, $W = 5\ \mu$m $= 5 \times 10^{-4}$ cm, $t = 1\ \mu$m $= 1 \times 10^{-4}$ cm
To Find : R, sheet resistance R_S

1. We have resistance, $$R = \frac{\rho l}{A} = \frac{\rho l}{tW}$$

$$R = \frac{1 \times 55 \times 10^{-4}}{10^{-4} \times 5 \times 10^{-4}}$$

$$R = 11 \times 10^4\ \Omega$$

2. Sheet resistance, $$R_S = \frac{\rho}{t}$$

$$= \frac{1}{10^{-4}}$$

$$R_S = 10^4\ \Omega/\text{square}$$

Que 2.30. **Define the resistance. Derive the expression of resistance of a rectangular slab of length l and area of cross-section A.**

Answer

Resistance :

1. According to ohm's law,

$$V \propto I$$

or $$V = RI$$

2. Here V be the potential difference between the ends of a conductor, I is the current flowing through a conductor.
3. The constant of proportionality R is called the resistance of the conductor.

Derivation :

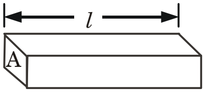


Fig. 2.30.1.

1. Resistance R is proportional to length l,
   i.e., $R \propto l$ ...(2.30.1)
2. Resistance R is inversely proportional to the cross-sectional area A,
   i.e., $R \propto \frac{1}{A}$ ...(2.30.2)
3. Combining eq. (2.30.1) and (2.30.2), we have
   $$R \propto \frac{l}{A}$$
4. For a given conductor, $R = \frac{\rho l}{A}$
   where the constant of proportionality ρ depends on the material of the conductor but not on its dimensions. ρ is called resistivity.

Que 2.31. **Name and describe in brief the layouts for designing the resistances.**

Answer

1. **Dogbone Layout :** This layout is used in analog applications and Electrostatic Discharge (ESD) circuitry where a high degree of matching is not required.
2. **Analog interdigitated layout :** Analog applications that require good matching characteristics introduce interdigitated layout design methodologies. In interdigitated designs, connections between resistor segments are electrically connected using jumpers.
3. **Dummy resistor layout :** Dummy resistors are introduced on the edge of the resistor segment array for good matching characteristics.
4. **Thermoelectric cancellation layout :** This layout introduce a thermoelectric potential variation between the ends of a segments. It has improper connections of segments to introduce the thermoelectric effect and has proper connections of segments to eliminate the thermoelectric effect.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Discuss extrinsic semiconductor with energy band diagram.

Ans. Refer Q. 2.2.

Q. 2. Differentiate between direct and indirect band gap semiconductor. Also discuss the variation of energy band with alloy composition.

Ans. Refer Q. 2.3.

Q. 3. The energy distribution function $\rho(E)$ is given by product of two factor $[\rho(E) = N(E) . f(E)]$. What is the interpretation to be given to each of these factors ?

Ans. Refer Q. 2.6.

Q. 4. What do you mean by mobility of a carrier ? How does it depend on temperature, doping concentrations and high field ? Explain.

Ans. Refer Q. 2.10.

Q. 5. Calculate minimum conductivity of Si at 300 K. Derive the expression used, if any.

Ans. Refer Q. 2.18.

Q. 6. What is Hall effect ? Derive the relation between Hall voltage and carrier concentration.

Ans. Refer Q. 2.19.

Q. 7. What is diffusion of carriers ? Derive the expression for the diffusion current crossing a unit area.

Ans. Refer Q. 2.24.

Q. 8. Describe diffusion of carriers and derive the current equation resulting due to this phenomenon. Also, derive the Einstein relation.

Ans. Refer Q. 2.26.

Q. 9. In Si semiconductor it is observed that three quarters of current is carried by holes and the rest part by electrons. What is the ratio of electrons to holes concentration ?

Ans. Refer Q. 2.27.

☺☺☺

3
UNIT

Generation and Recombination of Carrier

CONTENTS

PART-1

Generation and Recombination of Carriers.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.1. **Evaluate the absorption of incident photons by the material for the purpose of measuring the band gap energy of a semiconductor.**

Answer

1. The photons of selected wavelength are directed at the sample and relative transmission of various photons is observed.
2. Photons with energy greater than band gap energy are absorbed while photons with energy less than the band gap are transmitted and we can accurately measure the band gap energy.
3. The optical absorption of a photon with $h\nu > E_g$ is shown in Fig. 3.1.1.

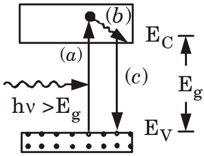


Fig. 3.1.1.

4. An electron excited to conduction band by optical absorption is shown in Fig. 3.1.1 at point (*a*). After reaching to conduction band, excited electron loses energy to the lattice shown at point (*b*). Finally the electron and hole created by this absorption process are combined at point (*c*).
5. A photon with energy less than E_g is unable to excite electron from the valence band. If a beam of photons with $h\nu > E_g$ falls on a semiconductor, then some absorption take place.
6. The total amount of energy absorbed by the sample per second (J/s) can be given by : $I_t = I_0 e^{-\alpha l}$
   where, α is the absorption coefficient, l is the thickness of the sample and I_0 is the photon beam intensity per cm^2-s.
7. The typical behaviour of the absorption coefficient α of a material with respect to the wavelength of the incident radiation is shown in Fig. 3.1.2.
8. The wavelength at which the transition from the opaque to transparent behaviour occurs is known as the absorption cut-off wavelength (λ_c) of the material, and is given by

$$\lambda_c \text{(in } \mu m) = 1.24/ E_g$$

where, E_g is band gap energy expressed in eV.

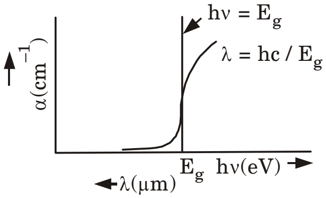


Fig. 3.1.2. Dependence of optical absorption for a semiconductor on the wavelength of incident light.

Que 3.2. **Explain absorption coefficient. A 0.46 micrometer thick sample of GaAs is illuminated with monochromatic light of $h\nu$ = 3 eV. The absorption coefficient is 6×10^4/cm. The power incident on the sample is 11 mW.**

i. Find the total energy absorbed by the sample per second.

ii. Find the rate of excess thermal energy given up by the electrons to the lattice before recombination.

iii. Find number of photons per second given off from recombination events, assuming perfect quantum efficiency.

AKTU 2014-15, Marks 10

Answer

Absorption coefficient : Refer Q. 3.1, Page 3–2A, Unit-3.

Numerical :

Given : l = 0.46 μm, $h\nu$ = 3 eV, $\alpha = 6 \times 10^4$/cm

Power incident = 11 mW

To Find : Total energy rate of excess thermal energy and η_{photon}.

i. We know, $I_t = I_o e^{-\alpha l} = 11 \times 10^{-3} e^{-(6 \times 10^4 \times 0.46 \times 10^{-4})}$

$= 6.96 \times 10^{-4} = 0.696$ mW

thus the total energy absorbed

$= 11 - 0.696 = 10.304$ mJ/s

ii. The fraction of each photon energy unit which is converted to heat is,

$$\frac{3 - 1.43}{2} = 0.785$$

thus the amount of energy converted to heat per second is

$0.785 \times 10.304 \times 10^{-3} = 8.088 \times 10^{-3}$J/s

iii. $$\eta_{\text{photon}} = \frac{I_{\text{absorbed}}}{\text{Charge} \times E_{\text{photon}}} = \frac{I_{\text{absorbed}}}{q \times E_{\text{photon}}}$$

$$= \frac{10.304 \times 10^{-3} \text{ J/s}}{1.6 \times 10^{-19} \text{ J/eV} \times 3 \text{ eV/photon}}$$

$$= \frac{9 \times 10^{16}}{1.6 \times 2} \frac{\text{photons}}{\text{s}} = 2.15 \times 10^{16} \text{ photons/sec}$$

Que 3.3. **Explain the mechanisms of recombination process.**

Answer

1. Electron-hole pairs can recombine in a semiconductor in two ways.
2. First, an electron can drop directly from the conduction band into an unoccupied state in the valence band. This is known as direct band-to-band recombination.
3. Second, an electron initially makes a transition to an energy level lying deep in the band gap, and it subsequently captures a hole from the valence band. This is known as indirect recombination.
4. In the process of electron-hole pair recombination, an energy equal to the difference between electron and hole energy is released.
5. This energy can be emitted as a photon, in which case the recombination is said to be radiative.
6. Alternatively, the energy can be dissipated to the lattice in the form of phonons.
7. A third possibility is that the energy can be imparted as a kinetic energy to a third mobile carrier. This process is called the Auger process.
8. Both the phonon and Auger recombination are nonradiative. These different processes will now be considered.

Que 3.4. **Describe briefly the direct recombination process in a semiconductor.**

Answer

1. In this type of recombination, an excess population of electrons and holes decays by electrons falling from the conduction band to empty states (holes) in the valence band.

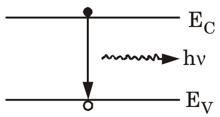


Fig. 3.4.1.

2. Energy lost by an electron in making the transition is given up as a photon.
3. Direct recombination occurs spontaneously; *i.e.*, the probability that an electron and a hole will recombine is constant in time, which leads to an exponential for the decay of the excess carriers.

Que 3.5. **Define and derive the expression for minority carrier life time.**

OR

A semiconductor sample is exposed to a photonic excitation for a long time ($t < 0$). Under low level injection, derive the equation governing the decay of excess carrier and life time of carrier if the excitation is removed at $t = 0$

AKTU 2015-16, Marks 10

Answer

1. In case of direct recombination of electrons and holes, at any time t, the rate of decay of electrons is proportional to the number of electrons remaining at time t and number of holes with constant of proportionality for recombination α_r.
2. Therefore, the net rate of change in the conduction band electron concentration is the thermal generation rate $a_r n_i^2$ minus the recombination rate.

$$\frac{dn(t)}{dt} = \alpha_r n_i^2 - \alpha_r n(t)\, p(t) \quad \text{...(3.5.1)}$$

where, $n(t)$ = Concentration of electrons at time t.
$p(t)$ = Concentration of holes at time t.

3. Let us assume the excess electron-hole population is created at $t = 0$ for example by a short flash of light, and the initial excess electron and hole concentrations Δn and Δp are equal.
4. If $\delta n(t)$ and $\delta p(t)$ be the instantaneous concentrations of excess carriers respectively, then eq. (3.5.1) can be written as

$$\frac{d}{dt}[\delta n(t)] = \alpha_r n_i^2 - \alpha_r [n_0 + \delta n(t)]\,[p_0 + \delta p(t)]$$

$$= -\alpha_r [(n_0 + p_0)\, \delta n(t) + \delta n^2(t)] \quad \text{...(3.5.2)}$$

$[\because \delta n(t) = \delta p(t)]$

5. Considering that excess of carrier concentrations are small, we can neglect $\delta n^2(t)$. Furthermore, if the material is p-type, then $p_0 >> n_0$. Applying these concepts, the eq. (3.5.2) is modified as

$$\frac{d}{dt}[\delta n(t)] = -\alpha_r\, p_0\, \delta n(t) \quad \text{...(3.5.3)}$$

6. The solution of eq. (3.5.3) is an exponential decay from the original excess carrier concentration given by

$$\delta n(t) = \Delta n\, e^{-\alpha_r p_0 t} \quad \text{...(3.5.4)}$$

7. Excess electrons in a p-type semiconductor recombine with a decay constant $\tau_n = (\alpha_r\, p_0)^{-1}$, called the recombination life time. Since the calculation is made in terms of minority carriers, τ_n is often called the minority carrier lifetime. The decay of excess holes in n-type material occurs with $\tau_p = (\alpha_r\, n_0)^{-1}$

$$\therefore \quad \delta n(t) = \Delta n\, e^{-t/\tau_n} \quad \text{...(3.5.5)}$$

8. In case of direct recombination, the excess majority carriers decay exactly at the same rate as minority carriers.
9. A more general expression for carrier life time is given by

$$\tau_n = \frac{1}{\alpha_r (n_0 + p_0)} \quad ...(3.5.6)$$

10. Eq. (3.5.6) is valid for n or p-type material if injection level is low.

Que 3.6. Excess electrons are generated in a semiconductor to a concentration of $\Delta n = 10^{16}$ cm^{-3}. The excess carrier lifetime in the semiconductor is 5×10^{-6} *s*. The source generating the excess carriers is switched off at $t = 0$. Calculate the recombination rate of excess electron for $t = 5$ µs.

Answer

Given : $\Delta n = 10^{16}$ cm^{-3}, $\tau_n = 5 \times 10^{-6}$ *s*, $t = 5$ µ *s*
To Find : Recombination rate R'_n.

1. We know that $\delta n(t) = \Delta n\, e^{-t/\tau_n}$

or
$$\delta n(5\ \mu s) = 10^{16}\, e^{-(5 \times 10^{-6})/(5 \times 10^{-6})}$$
$$= 10^{16} e^{-1} = 3.68 \times 10^{15} \text{ cm}^{-3}$$

2. The recombination rate R'_n for excess electrons is given by

$$R'_n = \frac{\delta n(t)}{\tau_n}$$

or
$$R'_n = \frac{3.68 \times 10^{15}}{5 \times 10^{-6}} = 0.74 \times 10^{21} \text{ cm}^{-3} s^{-1}$$

Que 3.7. Explain the principle of indirect recombination in band gap. Discuss its mechanism. **AKTU 2018-19, Marks 07**

Answer

1. When an electron initially makes a transition to an energy level lying deep in the band gap and it subsequently captures a hole from the valence band, then this is known as indirect recombination.
2. Many recombination centres have more than one energy level, but in most of the cases only one level dominates for the recombination.
3. Fig. 3.7.1 illustrates the recombination of an electron-hole pair through deep-level centre.
4. In Figure E_V and E_C are valence band and conduction band respectively. Here E_r is recombination level which is below Fermi level E_F at equilibrium. Therefore, E_r is substantially filled with electrons. Let the excess electrons and holes are created in this material.

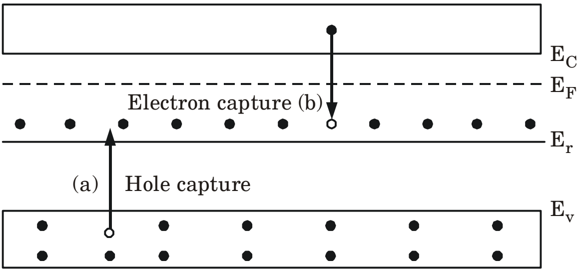


Fig. 3.7.1. Showing capture processes of recombination level.

5. The electron-hole pair (*EHP*) recombination at E_r is followed in the following two steps :

a. Hole capture :

i. In the hole capture process, an electron at E_r falls to valence band. This levels an empty state in recombination level.

ii. In hole capture, the energy is given up to the lattice.

b. Electron capture :

i. In the electron capture process, a conduction band electron subsequently falls to empty state in E_r.

ii. In this case too, the energy is given to the lattice.

6. When both the events [(a) and (b)] have occurred, the recombination centre returns back to its original state, *i.e.*, filled with electron.

7. Of course, an electron-hole pair is missing. In this way, one electron-hole pair recombination has taken place.

Que 3.8. **Write a short note on auger recombination.**

Answer

1. The Auger recombination process occurs by the transfer of the energy and momentum released by the recombination of an electron-hole pair to a third particle that can be either an electron or a hole.
2. The example of Auger recombination process is shown in Fig. 3.8.1.

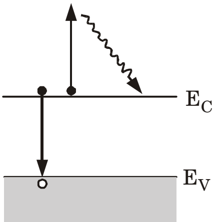


Fig. 3.8.1.

3. A second electron in the conduction band absorbs the energy released by the direct recombination. After the Auger process, the second electron becomes an energetic electron.

4. It loses its energy to the lattice by scattering events. Usually, Auger recombination is important when the carrier concentration is very high as a result of either high doping or high injection level.
5. The Auger process involves three particles, the rate of Auger recombination can be expressed as

$$R_{Aug} = Bn^2p \quad \text{or} \quad Bnp^2.$$

6. The proportionality constant B has strong temperature dependence.

PART-2

Poisson and Continuity Equation.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.9. Derive the expression for continuity equation and also write Poisson equation.

Answer

1. Consider a differential length Δx of a semiconductor sample with area A in the yz-plane.
2. The hole current density leaving the volume, $J_p(x + \Delta x)$, can be larger or smaller than the current density entering, $J_p(x)$, depending on the generation and recombination of carriers taking place within the volume.
3. The net increase in hole concentration per unit time, $\partial p/\partial t$, is the difference between the hole flux per unit volume entering and leaving, minus the recombination rate.
4. We can convert hole current density to hole particle flux density by dividing J_p by q.
5. The current densities are already expressed per unit area, thus dividing $J_p(x)/q$ by Δx gives the number of carriers per unit volume entering ΔxA per unit time, and $(1/q)J_p(x + \Delta x)/\Delta x$ is the number leaving per unit volume and time.

$$\left.\frac{\partial p}{\partial t}\right|_{x \to x+\Delta x} = \frac{1}{q}\,\frac{J_p(x) - J_p(x+\Delta x)}{\Delta x} - \frac{\delta p}{\tau_p}$$

Rate of hole buildup — increase of hole concentration in δxA per unit time — recombination rate ...(3.9.1)

5. As Δx approaches zero, we can write the current change in derivation form,

$$\frac{\partial p(x,t)}{\partial t} = \frac{\partial \delta p}{\partial t} = -\frac{1}{q}\frac{\partial J_P}{\partial x} - \frac{\delta p}{\tau_p} \quad ...(3.9.2)$$

6. The eq. (3.9.2) is called the continuity equation for holes. For electrons we can write,

$$\frac{\partial \delta n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n} \quad ...(3.9.3)$$

7. Since the electronic charge is negative

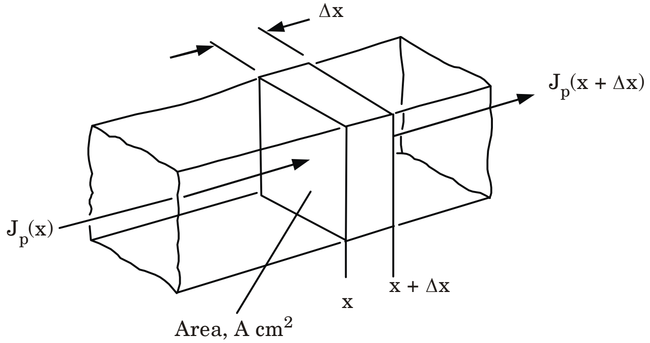


Fig. 3.9.1.

Poisson's equation :

The expression of Poisson's equation is,

$$\frac{\partial E}{\partial x} = \frac{\rho_s}{\varepsilon_s}$$

where ε_s is the semiconductor dielectric permittivity and ρ_s is the space charge density given by the algebraic sum of the charge carrier densities and the ionized impurity concentrations.

PART-3

P-N Junction, I-V Characteristics.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.10. **Discuss the current flow mechanism in a *p-n* junction under no bias condition.**

Answer

1. This is a two terminal device consisting of a *p-n* junction.
2. When *p*-type material is intimately joined (diffused) to *n*-type, a *p-n* junction is formed. Fig. 3.10.1 shows the *p-n* junction formation.

3. As *p*-type has high concentration of holes and *n*-type has high concentration of free electrons, hence there is a tendency of holes to diffuse to *n*-side and electrons to *p*-side. The process is known as diffusion.
4. Thus, a region is formed which is known as depletion layer or charge free region or space charge region.
5. The diffusion of electrons and holes continues till a potential barrier is developed which prevents further diffusion and such condition is no bias condition for *p-n* junction.

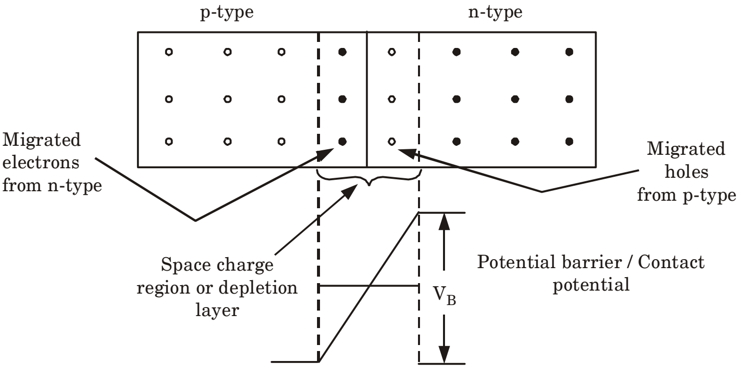


Fig. 3.10.1. p-n junction semiconductor.

Que 3.11. **Derive an expression for diode current in an ideal *p-n* junction diode.** **AKTU 2016-17, Marks 10**

OR

Derive the expression for the forward and reverse saturation current for P-N junction diode. **AKTU 2018-19, Marks 07**

Answer

Diode current equation :

1. The hole diffusion current at any point x_n in the *n*-region can be obtained with the help of following expression

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n}$$

$$I_p(x_n) = -qAD_p \frac{d}{dx_n}\{[p_n(e^{qV/kT} - 1)]e^{-x_n/L_p}\}$$

$$= qA\frac{D_p}{L_p}[p_n(e^{qV/kT} - 1)e^{-x_n/L_p}]$$

$$I_p(x_n = 0) = qA\frac{D_p}{L_p}[p_n(e^{qV/kT} - 1)]$$

2. Similarly, the electron current injected into p-region at the junction is given by

$$I_n(x_p = 0) = -\,qA\ \frac{D_n}{L_n}\ [n_p\ (e^{qV/kT} - 1)]$$

3. If we take + x-direction as the reference direction for total current, we have :

$$I = I_p(x_n = 0) - I_n(x_p = 0)$$

$$= qA\left(\frac{D_p}{L_p}\right)[p_n\ (e^{qV/kT} - 1)] + qA\left(\frac{D_n}{L_n}\right)[n_p\ (e^{qV/kT} - 1)]$$

$$= qA\left[\left(\frac{D_p}{L_p}\right)p_n + \left(\frac{D_n}{L_n}\right)n_p\right][e^{qV/kT} - 1]$$

$$I = I_0\ [e^{qV/kT} - 1]$$

4. The current can also be calculated for reverse bias by letting $V = -\,V_r$

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{-qV_r/kT} - 1)$$

5. If V_r is larger than a few kT/q, the total current is just the reverse saturation current.

$$I = -\,qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right) = -\,I_0$$

Que 3.12. **What is contact potential ? Explain. Also derive the expression for contact potential and equilibrium Fermi levels of a *p-n* junction.**

Answer

A. Contact potential :

1. In p-n junction due to concentration difference between holes and electrons, diffusion starts.
2. A layer of positive ions is formed in n-region and a layer of negative ions is formed in p-region when the holes and electrons recombine.
3. Due to positive ions and negative ions, a barrier is formed, which is known as potential barrier.
4. The region near the junction has immobile ions without any free electron or hole. This region is called depletion region. This is also called space-charge region.
5. Due to charge separation, voltage V_0 is developed across the junction under equilibrium conditions. This voltage is called contact potential (V_0).

B. Expression of contact potential :

1. The potential difference ($V_n - V_p$) developed across the depletion region is called as contact potential (V_0).

2. For depletion region, we have

V_p = Potential at left end of depletion region
V_n = Potential at right end of depletion region
$V_0 = V_n - V_p$ = Contact potential
N_a = Concentration of acceptors (acceptors/cm^3)
N_d = Concentration of donors (donors/cm^3)

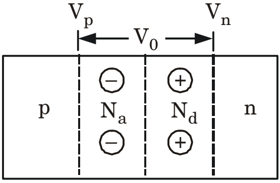


Fig. 3.12.1. Open-circuited *p-n* junction.

3. At equilibrium we have,

$$J_p(x) = q\left[\mu_p p(x)\,E(x) - D_p\,\frac{dp(x)}{dx}\right] = 0 \qquad ...(3.12.1)$$

where, $p(x)$ = Concentration of holes
D_p = Hole diffusion constant

4. The eq. (3.12.1) can be rearranged as

$$\frac{\mu_p}{D_p}\,E(x) = \frac{1}{p(x)}\,\frac{dp(x)}{dx} \qquad ...(3.12.2)$$

5. Using Einstein relation, $\mu_p/D_p = q/kT$, and putting the value of $E(x) = \dfrac{-\,dV(x)}{dx}$ in eq. (3.12.2) we get,

$$\frac{-\,q}{kT}\,\frac{dV(x)}{dx} = \frac{1}{p(x)}\,\frac{dp(x)}{dx} \qquad ...(3.12.3)$$

6. Integrating eq. (3.12.3), we get,

$$\frac{-\,q}{kT}\int_{V_p}^{V_n} dV = \int_{p_p}^{p_n}\frac{1}{p}\,dp$$

where, p_p and p_n are hole concentration at the edge of transition region on either side respectively.

Now, $$\frac{-\,q}{kT}(V_n - V_p) = \ln p_n - \ln p_p$$

$$\frac{-\,q}{kT}\,V_0 = \ln\frac{p_n}{p_p}$$

$$V_0 = \frac{kT}{q}\ln\frac{p_p}{p_n} \qquad ...(3.12.4)$$

7. In terms of donor and acceptor concentrations, eq. (3.12.4) can be written as

$$V_0 = \frac{kT}{q} \ln \frac{N_a}{n_i^2 / N_d} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2} \quad ...(3.12.5)$$

Eq. (3.12.5) gives the value of contact potential V_0.

Equilibrium Fermi levels :

1. From eq. (3.12.4), $\frac{p_p}{p_n} = e^{qV_0 / kT}$
2. Using equilibrium condition $p_p n_p = n_i^2 = p_n n_n$, we can write

$$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0 / kT} \quad ...(3.12.6)$$

This expression is very useful in calculating the *V-I* characteristics of *p-n* junction.

3. Eq. (3.12.6) can also be written as,

$$\frac{p_p}{p_n} = e^{qV_0/kT} = \frac{N_V e^{-(E_{Fp} - E_{Vp})/kT}}{N_V e^{-(E_{F_n} - E_{V_n})/kT}}$$

$$e^{qV_0/kT} = e^{(E_{Fn} - E_{Fp})/kT} e^{(E_{V_p} - E_{V_n})/kT}$$

$$\therefore \quad qV_0 = E_{V_p} - E_{V_n} \quad [\because \text{ at equilibrium } E_{F_n} - E_{F_p} = 0]$$

Que 3.13. **What is contact potential ? Explain. Derive an expression for it, assuming step junction at equilibrium condition. For Si *p-n* junction, donor and acceptor impurities at room temperature are 10^{16} cm^{-3} and 3×10^{18} cm^{-3} respectively. Calculate the contact potential and draw an equilibrium band diagram for the junction if intrinsic carrier concentration of Si is 1.5×10^{10} cm^{-3} at room temperature.**

Answer

Contact potential : Refer Q. 3.12, Page 3–11A, Unit-3.

Numerical :

Given : $N_d = 10^{16}$ cm^{-3}, $N_a = 3 \times 10^{18}$ cm^{-3}, $n_i = 1.5 \times 10^{10}$ cm^{-3}

To Find : V_0, and energy band diagram.

1. $$V_0 = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

$$= 0.0259 \ln \left(\frac{3 \times 10^{18} \times 10^{16}}{(1.5 \times 10^{10})^2} \right) = 0.842 \text{ V}$$

2. $$E_{ip} - E_F = kT \ln \frac{p_p}{n_i} = 0.0259 \ln \left(\frac{3 \times 10^{18}}{1.5 \times 10^{10}} \right) = 0.495 \text{ eV}$$

3. $$E_F - E_{in} = kT \ln \frac{n_n}{n_i} = 0.0259 \ln \left(\frac{10^{16}}{1.5 \times 10^{10}} \right) = 0.347 \text{ eV}$$

4. Equilibrium band diagram :

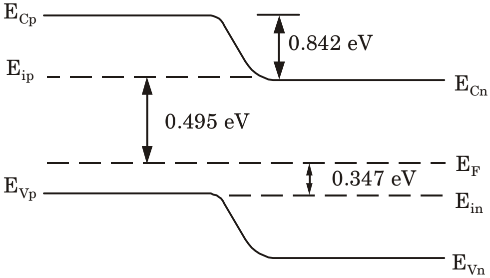


Fig. 3.13.1. Band diagram.

Que 3.14. **Explain the variation of charge density, electric field intensity and potential within depletion region.**

Answer

1. The variation of charge density (ρ), electric field intensity (*E*) and contact potential (V_0) within depletion region as a function of distance is shown in Fig. 3.14.1.

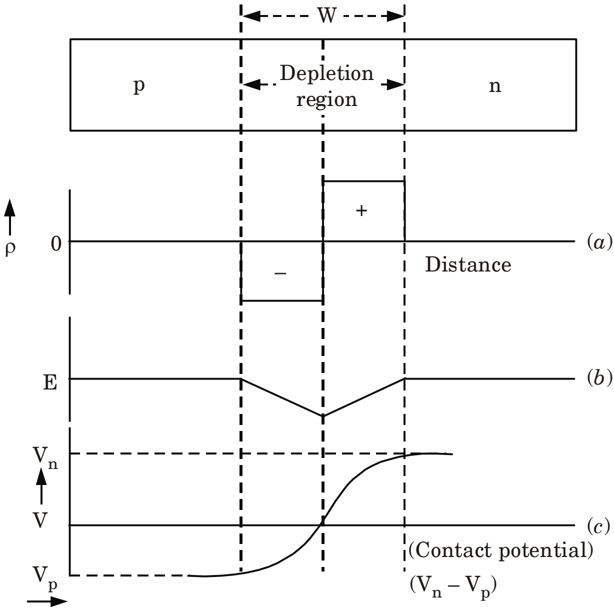


Fig. 3.14.1. Showing the variation of ρ, E and V as a function of distance within depletion region.

A. Charge density (ρ) :

1. Space charge region contains negative ions in *p*-region and positive ions in *n*-region.
2. Therefore, the charge density is negative in depletion region of *p*-side and positive for *n*-side and ρ is zero at the junction. This is shown in Fig. 3.14.1(*a*).

B. Electric field intensity (*E*) :

1. The depletion region towards the left of the junction contains negative charge and towards the right a positive charge. So, the depletion region constitutes an electric dipole layer.
2. In this way, there will be electric flux lines from right to left, *i.e.*, an electric field is established.
3. The electric field intensity (E) is related to charge density as

$$E = \int \left(\frac{\rho}{\varepsilon}\right) dx$$

where, ε is the permittivity of semiconductor material. The formation of E is shown in Fig. 3.14.1(*b*).

C. Electric potential :

1. The variation of electric potential is shown in Fig. 3.14.1(*c*). We know that $E(x) = -dV(x)/dx$. So, there will be a constant potential V_n in the neutral *n*-material and a constant potential V_p in the neutral *p*-material.
2. The potential difference between the two region $V_0 = V_n - V_p$, is called as contact potential.
3. Due to the influence of strong electric field set up by barrier potential, under open circuit condition, no mobile charge carriers (electrons and holes) cross the junction. So, there is no current through *p-n* junction.
4. Therefore, the drift and diffusion currents must cancel for each type of carrier, *i.e.*,

$$J_p \text{ (drift)} + J_p \text{ (diffusion)} = 0$$

and

$$J_n \text{ (drift)} + J_n \text{ (diffusion)} = 0$$

Que 3.15. What do you mean by space charge region at a junction ? Derive an expression for width of space charge region in a *p-n* junction at thermal equilibrium condition.

Answer

1. The space charge on *n*-side is positively charged and on *p*-side it is negatively charged. Fig. 3.15.1(*a*) shows the space charge region (or transition region) on the two sides of the junction.
2. Within the transition region, electrons and holes are in transit from one side of the junction to the other.
3. The charge density within W is plotted in Fig. 3.15.1(*b*) neglecting carriers within space charge region, the charge density on *n*-side is q times the concentration of donor ions N_d and negative charge density on the *p*-side is $-q$ times the concentration of acceptors N_a ($\because Q_+ = |Q_-|$).

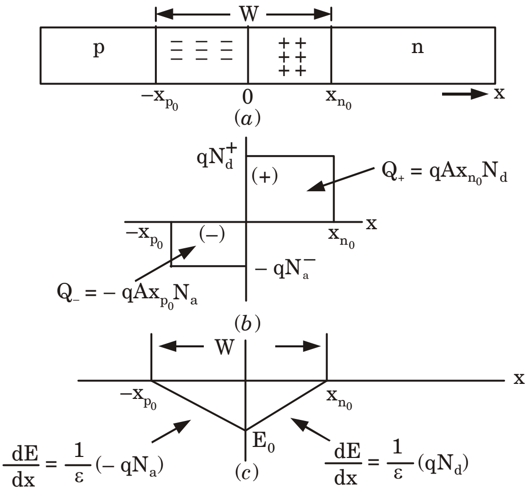


Fig. 3.15.1.

4. The assumption of carrier depletion within *W* and neutrality outside *W* is known as the depletion approximation. The electric field is shown in Fig. 3.15.1(*c*).
5. The uncompensated charge on either side of the junction is
$$qAx_{p_0}N_a = qAx_{n_0}N_d$$
where, x_{p_0} and x_{n_0} is the penetration of space charge region into *p* and *n* material respectively.
6. The electric field distribution uses Poisson's equation as,
$$\frac{dE(x)}{dx} = \frac{q}{\varepsilon}(p - n + N_d^+ - N_a^-),$$
7. Neglect the contribution of carriers $(p - n)$,
$$\frac{dE}{dx} = \frac{q}{\varepsilon}N_d \quad ; \qquad 0 < x < x_{n_0}$$
$$\frac{dE}{dx} = -\frac{q}{\varepsilon}N_a \quad ; \qquad -x_{p_0} < x < 0$$
8. Assume the maximum value of E as E_0 at $x = 0$
$$\int_{E_0}^{0} dE = \frac{q}{\varepsilon}N_d\int_0^{x_{n_0}} dx \qquad ; \quad 0 < x < x_{n_0}$$
$$\int_0^{E_0} dE = -\frac{q}{\varepsilon}N_a\int_{-x_{p_0}}^{0} dx \quad ; -x_{p_0} < x < 0$$
the maximum value of electric field is
$$E_0 = -\frac{q}{\varepsilon}N_d\, x_{n_0} = -\frac{q}{\varepsilon}N_a\, x_{p_0}$$
9. Using relation,

$$E(x) = -\frac{dV(x)}{dx}$$

or $$-V_0 = \int_{-x_{p_0}}^{x_{n_0}} E(x)dx$$

$$V_0 = -\frac{1}{2}E_0W = \frac{1}{2}\frac{q}{\varepsilon}N_d\, x_{n_0}W = \frac{1}{2}\frac{q}{\varepsilon}\frac{N_aN_d}{(N_a+N_d)}W^2$$

Since, $x_{n_0}N_d = x_{p_0}N_a$, W is $x_{p_0} + x_{n_0}$, and $x_{n_0} = \dfrac{WN_a}{(N_a+N_d)}$

10. Solving for W, we get

$$W = \left[\frac{2\varepsilon V_0}{q}\left(\frac{N_a+N_d}{N_aN_d}\right)\right]^{1/2} = \left[\frac{2\varepsilon V_0}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\right]^{1/2}$$

11. For n and p materials

$$x_{p_0} = \frac{WN_d}{N_a+N_d} = \frac{W}{1+N_a/N_d} = \left\{\frac{2\varepsilon V_0}{q}\left[\frac{N_d}{N_a(N_a+N_d)}\right]\right\}^{1/2}$$

$$x_{n_0} = \frac{WN_a}{(N_a+N_d)} = \frac{W}{1+N_d/N_a} = \left\{\frac{2\varepsilon V_0}{q}\left[\frac{N_a}{N_d(N_a+N_d)}\right]\right\}^{1/2}$$

Que 3.16. **Derive the expression of contact potential for *p-n* homojunction diode. Boron is implanted into an *n*-type Si sample (N_d = 10[16] cm[–3]), forming an abrupt junction of square cross section with area = 2 × 10[– 3] cm[2]. Assume that the acceptor concentration in *p*-type region is $N_a = 4 \times 10^{18}$ cm[–3]. Calculate V_0, Q^+, E_0 and depletion region extension on either side of junction at room temperature. (Given $n_i = 1.5 \times 10^{10}$ cm[–3], $\varepsilon_r = 11.8$, $\varepsilon_0 = 8.85 \times 10^{-14}$ F/cm and kT = 0.0259 eV at room temperature).**

AKTU 2015-16, Marks 10

OR

Boron is implanted in to a *n*-type Si sample having donor concentration of 10[16]/cm[3], to form abrupt junction. If the acceptor concentration in *p*-type region is 4 × 10[18]/cm[3], determine the

i. Width of the depletion region.

ii. Depth of penetration on *n*-side and *p*-side at equilibrium. Take room temperature as 27°C; n_i = 1.5 × 10[10]/cm[3] and relative permittivity of boron as 11.8.

AKTU 2017-18, Marks 07

Answer

Expression of contact potential : Refer Q. 3.12, Page 3–11A, Unit-3.

Numerical :

Given : $N_d = 10^{16}$ cm^{-3}, $A = 2 \times 10^{-3}$ cm^2, $N_a = 4 \times 10^{18}$ cm^{-3}, $n_i = 1.5 \times 10^{10}$ cm^{-3}, $\varepsilon_r = 11.8\varepsilon_0$, $\varepsilon_0 = 8.85 \times 10^{-14}$ F/cm, $kT = 0.0259$ eV

To Find : V_0, Q^+, E_o, x_{p0}, x_{n0}

1. Contact potential, $V_0 = \dfrac{kT}{q} \ln\left(\dfrac{N_a N_d}{n_i^2}\right)$

$$= 0.0259 \ln\left(\frac{4 \times 10^{18} \times 10^{16}}{(1.5 \times 10^{10})^2}\right)$$
$$= 0.0259 \ln (1.78 \times 10^{14})$$
$$V_0 = 0.85 \text{ V}$$

2.
$$W = \left[\frac{2\varepsilon V_0}{q}\left(\frac{N_a + N_d}{N_a \cdot N_d}\right)\right]^{1/2}$$
$$= \left[\frac{2 \times (11.8 \times 8.85 \times 10^{-14})(0.85)}{(1.6 \times 10^{-19})} \times \left(\frac{4 \times 10^{18} + 10^{16}}{4 \times 10^{18} \times 10^{16}}\right)\right]^{1/2}$$
$$= 3.34 \times 10^{-5} \text{ cm}$$
$$W = 0.334 \ \mu\text{m}$$

3.
$$x_{n0} = \frac{WN_a}{N_d + N_a} = \frac{W}{1 + N_d / N_a}$$
$$= \frac{0.334 \ \mu\text{m}}{1 + \{10^{16} / (4 \times 10^{18})\}} = \frac{0.334 \ \mu\text{m}}{1.0025}$$
$$x_{n0} = 0.333 \ \mu\text{m}$$

4.
$$x_{p0} = \frac{WN_d}{N_a + N_d} = \frac{W}{1 + N_a / N_d} = \frac{0.334 \ \mu\text{m}}{1 + 400} = \frac{0.334 \ \mu\text{m}}{401}$$
$$x_{p0} = 0.83 \text{ nm}$$

5.
$$Q^+ = q A x_{n0} N_d = q A x_{p0} N_a$$
$$= (1.6 \times 10^{-19}) \times (2 \times 10^{-3}) \times 3.33 \times 10^{-5} \times 10^{16}$$
$$Q^+ = 1.07 \times 10^{-10} \text{ C}$$

6.
$$E_0 = \frac{-q}{\varepsilon} x_{n_0} N_d = -\frac{(1.6 \times 10^{-19})(10^{16})(3.3 \times 10^{-5})}{11.8 \times 8.85 \times 10^{-14}}$$
$$E_0 = -5.1 \times 10^4 \text{ V/cm}$$

Que 3.17. Finding the space charge widths and the peak electric in a *p-n* junction. The parameters of a uniformly doped *p-n* junction for silicon semiconductors are :

$$V_T = 26 \text{ mV}, T = 25 \text{ °C}, N_a = 1 \times 10^{16} \text{ cm}^{-3},$$
$$N_d = 2 \times 10^{15} \text{ cm}^{-3}, \text{ and } n_i = 1.5 \times 10^{16} \text{ cm}^{-1}.$$

Find (*a*) the depletion width *W* and (*b*) the maximum field E_o.

Answer

Given : $T = 25\ °C$, $N_a = 1 \times 10^{16}\ cm^{-3}$, $N_d = 2 \times 10^{15}\ cm^{-3}$, $\in_r = 11.7$, $\in_o = 8.85 \times 10^{-14}$, $q = 1.6 \times 10^{-19}$, $n_i = 1.5 \times 10^{10}\ cm^{-3}$.

To Find : a. Depletion width, W

b. Maximum field, E_o.

a. As
$$V_o = \frac{kT}{q} \ln\left(\frac{N_a N_d}{n_i^2}\right)$$
$$= 26 \times 10^{-3} \times \ln\left[\frac{1 \times 10^{16} \times 2 \times 10^{15}}{(1.5 \times 10^{10})^2}\right] = 0.655\ V$$

As
$$W = \left\{\frac{2 \in V_o}{q}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$
$$W = \sqrt{\frac{2 \times 11.7 \times 8.85 \times 10^{-14} \times 0.655}{1.6 \times 10^{-19}}\left[\frac{1 \times 10^{16} + 2 \times 10^{15}}{1 \times 10^{16} \times 2 \times 10^{15}}\right]}$$
$$= 0.7131\ \mu m$$

b. As
$$E_o = \frac{-qN_d x_{no}}{\in}$$

Here
$$x_{no} = \frac{WN_a}{N_a + N_d} = 0.5942\ \mu m$$

So,
$$E_o = \frac{-1.6 \times 10^{-19} \times 2 \times 10^{15} \times 0.5942 \times 10^{-4}}{11.7 \times 8.85 \times 10^{-14}}$$
$$= -1.836 \times 10^4\ V/cm$$

Que 3.18. **Explain the effect of a bias on the important features of the junction.**

OR

Discuss the qualitative description of current flow at junction.

Answer

1. The effect of a bias on some important features of the junction can be explained by the Fig. 3.18.1.
2. Here, the electrostatic potential at the junction is lowered by a forward bias V_f from the equilibrium contact potential V_0 to the smaller value $(V_0 - V_f)$.
3. This lowering of potential barrier occurs because a forward bias raises the electrostatic potential on p-side relative to n-side.
4. For reverse bias, *i.e.*, $(V = -V_r)$ the electrostatic potential of the p-side is depressed relative to n-side and thus potential barrier at the junction becomes larger $(V_0 + V_r)$.

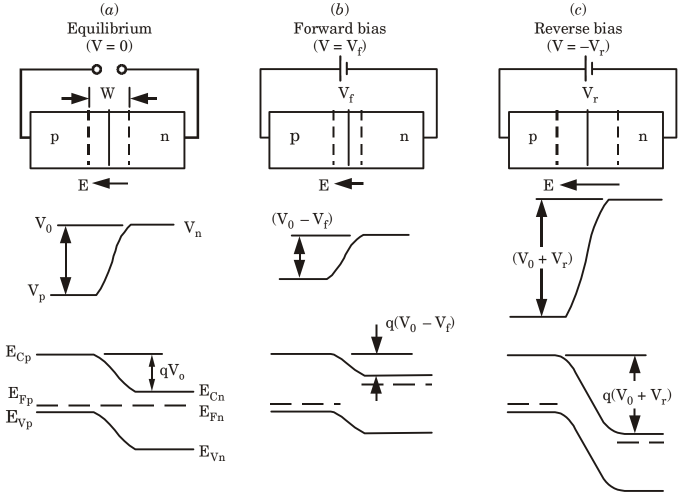


Fig. 3.18.1.

5. The field decreases with forward biased as the applied electric field opposes the built-in field whereas it increases with reverse biased.
6. The change in electric field at junction produces a change in the transition region width *W*. Since proper number of positive and negative charges are necessary to be exposed for the given value of electric field. Thus, the width *W* decreased under forward biased and increased under reverse biased.
7. The separation of the energy bands is a direct function of the electrostatic potential barrier at the junction. Thus the bands are separated less $[q(V_0 - V_f)]$ under forward biased and more $[q(V_0 + V_r)]$ under reverse biased.
8. The diffusion current is due to majority carriers, *i.e.*, electron in *n*-side and hole in *p*-side overcoming the potential barrier to diffuse to *p*-side and *n*-side respectively.
9. The electron diffusion current is large for forward bias because barrier is lowered and thus electrons have sufficient energy to diffuse from *n* to *p*. The diffusion current is negligible for reverse bias.
10. Drift current is insensitive to the height of potential barrier. It is composed of minority carriers.
11. The total current crossing the junction is sum of the diffusion and drift current.
12. The net current crossing the junction is zero at equilibrium, since the drift and diffusion components cancel for each type of carrier.

Que 3.19. **Explain the V-I characteristics of *p-n* junction diode.**

Answer

i. Forward bias :

1. For the forward bias of a p-n junction, p-type is connected to the positive terminal while the n-type to negative terminal of battery.
2. The potential can be varied with potential divider. At some forward voltage (0.3 V for Ge and 0.7 V for Si) the potential barrier is altogether eliminated and current starts flowing. This voltage is known as threshold or knee voltage (V_K).
3. As the forward applied voltage increases beyond threshold voltage, the forward current rises exponentially as shown in Fig. 3.19.1.

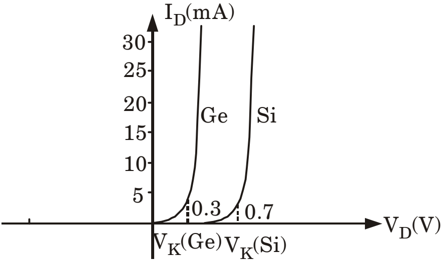


Fig. 3.19.1. Forward bias.

4. Beyond a certain safe value, it produces an extremely large current which may destroy the junction due to overheating.
5. The total width W of the depletion or space charge region is

$$W = \left[\frac{2 \in (V_o - V_F)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

6. The maximum electric field, E_o is $E_o = \dfrac{-2(V_o - V_F)}{W}$

ii. Reverse bias :

1. The p-type is connected to the negative terminal while n-type is connected to the positive terminal of a battery.
2. In this case the junction resistance becomes very high and practically no current flows through the circuit.
3. In practical, a small current of the order of μA flows in the circuit due to minority carriers. This is known as reverse current. The reverse current is shown in Fig. 3.19.2.
4. As the reverse bias is increased from zero, the reverse current quickly rises to its maximum or saturation value. The slight increase is due to impurities on the surface, which behaves as a resistor and hence obeys ohm's law. This gives rise to a current called surface leakage current.
5. If the reverse voltage is further increased, the kinetic energy of electrons becomes so high that they knock out from the semiconductor atoms. At this stage breakdown of junction occurs and there is a sudden rise of reverse current. Now the junction is destroyed completely.

6. Thus, *p-n* junction diode is one-way device which offers a low resistance when forward biased and behaves like an insulator when reverse biased. Thus, it can be used as a rectifier *i.e.*, for converting alternating current into direct current.

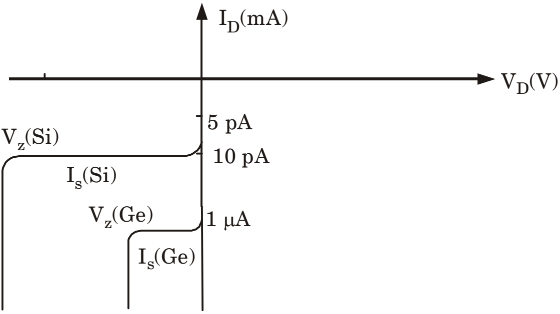


Fig. 3.19.2. Reverse bias.

7. The total space charge width can be written as

$$W = \left\{\frac{2\in(V_o + V_R)}{q}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

8. Maximum field is $E_o = \dfrac{-2(V_o + V_R)}{W}$

Thus, the maximum field increases with V_R and decreases with W.

Que 3.20. **Find the depletion width in a reverse-biased *p-n* junction. The parameters of a uniformly doped *p-n* junction for silicon semiconductor are V_R = 10 V, V_T = 26 mV, T = 25° C, $N_a = 1 \times 10^{16}$ cm^{-3}, $N_d = 2 \times 10^{15}$ cm^{-3}, $q = 1.6 \times 10^{-19}$, and $k = 1.3806 \times 10^{-23}$. Find**

a. The depletion width *W*.

b. The maximum field E_0.

Answer

Given : T = 25° C, $N_a = 1 \times 10^{16}$ cm^{-3}, $N_d = 2 \times 10^{15}$ cm^{-3}, $\varepsilon_r = 11.7$, $\varepsilon_0 = 8.85 \times 10^{-14}$, $q = 1.6 \times 10^{-19}$, V_R = 10 V, V_T = 26 mV, $k = 1.3806 \times 10^{-23}$

To Find : (a) Depletion width, W (b) Maximum field, E_0.

a. As
$$V_o = \frac{kT}{q}\ln\left[\frac{N_a N_d}{n_i^2}\right]$$

$$= 26 \times 10^{-3} \times \ln\left[\frac{1\times10^{16}\text{ cm}^{-3} \times 2\times10^{15}\text{ cm}^{-3}}{(1.5\times10^{10}\text{ cm}^{-3})^2}\right] = 0.655 \text{ V}$$

As
$$W = \left\{\frac{2\in(V_o + V_R)}{q}\left[\frac{(N_a + N_d)}{N_a N_d}\right]\right\}^{1/2}$$

$$W = \left\{\frac{2\times 11.7\times 8.85\times 10^{-14}}{1.6\times 10^{-19}}(0.655+10)\left[\frac{1\times 10^{16}+2\times 10^{15}}{(1\times 10^{16})(2\times 10^{15})}\right]\right\}^{1/2} = 2.876\ \mu\text{m}$$

b. As $$E_o = \frac{-2(V_o+V_R)}{W}$$

$$= \frac{-2\times(0.655+10)\ V}{2.876\times 10^{-4}\ \text{cm}} = -7.409\times 10^4\ \text{V/cm}$$

Que 3.21. **Find the depletion width in a forward-biased *p-n* junction. The parameters of a uniformly doped *p-n* junction for silicon semiconductor are $V_F = 0.60$ V, $V_T = 25°$ C, $N_a = 1\times 10^{16}\ \text{cm}^{-3}$, and $N_d = 2\times 10^{15}\ \text{cm}^{-3}$.**

a. The depletion width W. b. The maximum field E_o.

Answer

Given : $V_F = 0.65$ V, $N_a = 1\times 10^{16}\ \text{cm}^{-3}$, $N_d = 2\times 10^{15}\ \text{cm}^{-3}$, $\varepsilon_r = 11.7$, $\varepsilon_o = 8.85\times 10^{-14}$, $q = 1.6\times 10^{-19}$, $V_R = 10$ V, $V_T = 26$ mV

To Find : (a) Depletion width, W (b) Maximum field, E_o.

a. As $$V_o = \frac{kT}{q}\ln\left[\frac{N_aN_d}{n_i^2}\right]$$

$$= 0.026\times\ln\left[\frac{1\times 10^{16}\times 2\times 10^{15}}{(1.5\times 10^{10})^2}\right] = 0.655\ \text{V}$$

As $$W = \sqrt{\frac{2\in(V_o-V_F)}{q}\left[\frac{(N_a+N_d)}{N_aN_d}\right]}$$

$$W = \sqrt{\frac{2\times 11.7\times 8.85\times 10^{-14}}{1.6\times 10^{-19}}(0.655-0.65)\left[\frac{1\times 10^{16}+2\times 10^{15}}{(1\times 10^{16})(2\times 10^{15})}\right]}$$

$$= 0.0623\ \mu\text{m}$$

b. As $$E_o = \frac{-2(V_o-V_F)}{W} = \frac{-2\times(0.655-0.65)}{0.0623}$$

$$= -1.605\times 10^3\ \text{V/cm}$$

PART-4

Small Signal Switching Model.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.22. **Explain small signal model of a *p-n* junction.**

Answer

1. The small-signal model (also known as the incremental model) for a device is developed by linearizing its behaviour around the quiescent operating point (*Q*-point).
2. The diode current equation is,
$$I_D = I_o\,(e^{V_D/V_T} - 1) \qquad ...(3.22.1)$$
3. The small-signal diode resistance r_D can be obtained by computing the inverse slope of the diode current-voltage characteristic around the *Q* point.
4. This can be obtained by differentiating eq. (3.22.1) with respect to V_D (thus getting the diode conductance g_D), and then taking the inverse of it. Thus,
$$r_D = (g_D)^{-1} = \left.\left(\frac{\partial I_D}{\partial V_D}\right)^{-1}\right|_{I_D = I_{DQ}} = \frac{V_T}{I_{DQ}} \qquad ...(3.22.2)$$
5. The diode also has a capacitance C_D across its junction, which can be given by the sum of the depletion and the diffusion capacitances, *i.e.*,
$$C_D = C_{\text{dep}} + C_{\text{diff}} = \frac{C_{\text{dep}0}}{\left(1 - \dfrac{V_{DQ}}{V_0}\right)^m} + \frac{\tau_p}{r_D} \qquad ...(3.22.3)$$
6. Here, C_{dep0} is the zero bias depletion capacitance of the junction (*i.e.*, $V_D = 0$), V_{DQ} is the quiescent DC voltage drop across diode.
7. V_0 is the built in potential across diode.
8. Here, τ_p is the hole lifetime in the *n*-region for a p^+-*n* diode.
9. *m* being referred to as the grading coefficient, and carries the information about the doping profile of the junction.
10. The two elements r_D and C_D come in parallel across the junction, and for completeness, the series resistances r_p and r_n of the two neutral regions of the diode should also be added to the small-signal equivalent circuit as shown in Fig. 3.22.1.

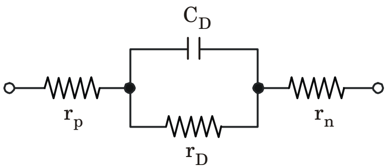


Fig. 3.22.1.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Define and derive the expression for minority carrier life time.

Ans. Refer Q. 3.5.

Q. 2. Excess electrons are generated in a semiconductor to a concentration of $\Delta n = 10^{16}$ cm^{-3}. The excess carrier lifetime in the semiconductor is 5×10^{-6} *s*. The source generating the excess carriers is switched off at $t = 0$. Calculate the recombination rate of excess electron for $t = 5$ μ*s*.

Ans. Refer Q. 3.6.

Q. 3. Derive the expression for continuity equation and also write Poisson equation.

Ans. Refer Q. 3.9.

Q. 4. What is contact potential ? Explain. Also derive the expression for contact potential and equilibrium Fermi levels of a *p-n* junction.

Ans. Refer Q. 3.12.

Q. 5. What is contact potential ? Explain. Derive an expression for it, assuming step junction at equilibrium condition. For Si *p-n* junction, donor and acceptor impurities at room temperature are 10^{16} cm^{-3} and 3×10^{18} cm^{-3} respectively. Calculate the contact potential and draw an equilibrium band diagram for the junction if intrinsic carrier concentration of Si is 1.5×10^{10} cm^{-3} at room temperature.

Ans. Refer Q. 3.13.

Q. 6. Explain the variation of charge density, electric field intensity and potential within depletion region.

Ans. Refer Q. 3.14.

Q. 7. Explain the effect of a bias on the important features of the junction.

Ans. Refer Q. 3.18.

☺☺☺

4 UNIT

BJT

CONTENTS

PART-1

Avalanche Breakdown, Zener Diode.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.1. **What is zener diode ?**

Answer

1. Zener diode is a reverse-biased heavily doped *p-n*-junction diode which is operated in the breakdown region. Fig. 4.1.1 shows the symbol of zener diode.

Fig. 4.1.1. Zener diode.

2. When a zener diode is forward biased, its characteristics are just same as the ordinary diode and it is shown in Fig. 4.1.2.

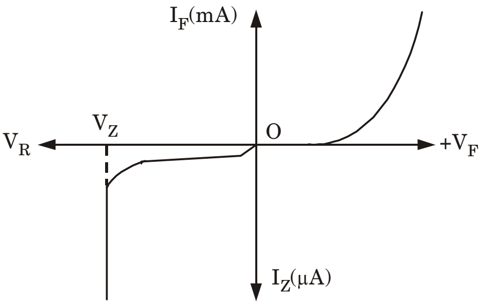


Fig. 4.1.2. V-I characteristic of zener diode.

3. When zener diode is reverse biased then it gives constant current upto a certain voltage. When the reverse bias voltage is increased beyond that voltage, the current increased rapidly as shown in Fig. 4.1.2.
4. The cut-off value of voltage beyond which zener diode reverse current increases rapidly is called zener voltage V_Z or breakdown voltage.
5. The breakdown or zener voltage depends upon the amount of doping.
6. A zener diode can be used as a voltage regulator to provide a constant voltage to a load.

Que 4.2. **Explain reverse breakdown of a diode.**

Answer

Reverse breakdown can occur by two mechanisms that are zener breakdown and avalanche breakdown.

Zener breakdown :

1. It takes place in very thin junction (*i.e.*, depletion layer is narrow due to heavily doped junctions on both sides).
2. When a small reverse bias voltage is applied, a very strong electric field (approximately 10^7 V/m) is set up across the thin depletion layer.
3. This field is enough to break the covalent bonds. This breaking of covalent bonds produces large number of electrons and holes which constitute the reverse saturation current (*i.e.*, zener current).
4. Zener current is independent of the applied voltage. It depends only on the external resistance.
5. This breakdown is called as zener breakdown as shown in Fig. 4.2.1. This breakdown occurs at low voltage.

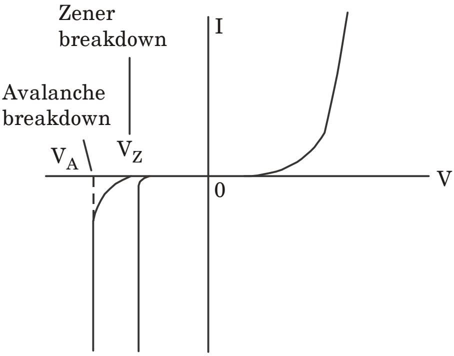


Fig. 4.2.1. The I-V characteristics comparison between Zener and avalanche breakdown

Avalanche breakdown :

1. Avalanche breakdown takes place in slightly thick junction than the zener breakdown case. It means both sides of junction are lightly doped.
2. In this case, the electric field across the depletion region (layer) is not so strong to produce zener breakdown for the same applied voltage of zener breakdown case.
3. Here, the minority carriers accelerated by the field collide with the semiconductor atoms in the depletion region.
4. During collision the kinetic energy of electrons is transferred to other covalent bonds, thus the energy transferred to covalent bonds increases the band energy, hence covalent bonds are broken and electron-hole pairs are generated.
5. The newly generated carriers transfer their energy to other covalent bonds and break more bonds and thus extremely large numbers of carriers are generated due to cumulative process of avalanche multiplication.

6. This breakdown is called avalanche breakdown as shown in Fig. 4.2.1. This breakdown occurs at higher voltages.

Que 4.3. **What is the difference between Zener and Avalanche breakdown ? For the given Zener diode network shown in Fig. 4.3.1, determine V_L, V_R, I_Z and I_R.**

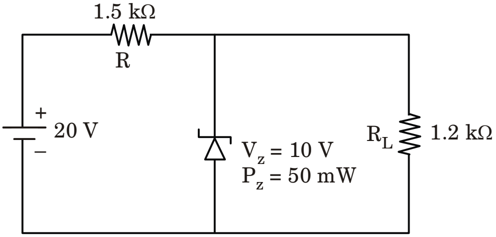


Fig. 4.3.1.

Answer

A. Difference :

S. No.	Zener Breakdown	Avalanche Breakdown
1.	The process in which the electrons move across the barrier from the valence band of *p*-type material to the conduction band of *n*-type material is known as zener breakdown.	The process of applying high voltage and increasing the free electrons or electric current in semiconductors and insulating materials is called an avalanche breakdown.
2.	This is observed in zener diodes having a zener breakdown voltage, V_z of 5 to 8 volts.	This is observed in zener diode having a zener breakdown voltage, V_z greater than 8 volts.
3.	The valence electrons are pulled into conduction due to the high electric field in the narrow depletion region.	The valence electrons are pushed to conduction due to the energy imparted by accelerated electrons, which gains its velocity due to its collision with other atoms.
4.	The increase in temperature decreases the breakdown voltage.	The increase in temperature increases the breakdown voltage.
5.	It occurs in diodes that are highly doped.	It occurs in diodes that are lightly doped.

B. Numerical :

1. Voltage across zener diode,

$$V_o = V_L = \frac{R_L.V_i}{R + R_L} = \frac{1.2 \times 20}{1.5 + 1.2} = 8.88 \text{ V}$$

2. $$V_z = 10 \text{ V}$$

Here, $V_o < V_z$.

3. So, the zener diode is OFF and no current will flow through it.

$$I_z = 0$$

4. Voltage across R, $V_R = V_i - V_L = 20 - 8.88 = 11.12$ V

$$I_R = I_z + I_L = 0 + \frac{8.88}{1.2} = 7.4 \text{ mA}$$

Que 4.4. How zener diode is used as voltage regulator ? Explain with suitable circuits.

Answer

1. The circuit diagram for zener voltage regulator is shown in Fig. 4.4.1.

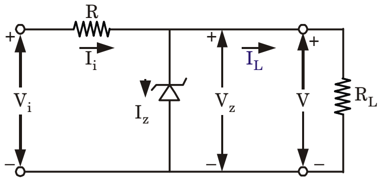


Fig. 4.4.1. Zener voltage regulator.

2. The zener diode is selected with V_z equal to the voltage desired across the load.
3. Under reverse biased condition, voltage across zener diode practically remains constant, even if the current through it changes by a large extent.
4. Under normal conditions, the input current $I_i = I_L + I_z$ flows through resistor R. The input voltage V_i can be written as

$$V_i = I_i R + V_z = (I_L + I_z) R + V_z$$

5. When the input voltage V_i increases, as the voltage across zener diode remains constant, the drop across R will increase with a corresponding increase in $I_L + I_z$.
6. As V_z is a constant, the voltage across the load will also remains constant and hence, I_L will be a constant.
7. Therefore, an increase in $I_L + I_z$ will result in an increase in I_z which will not alter the voltage across load. Thus, zener diode is used as a voltage regulator.
8. To operate zener diode as voltage regulator, the reverse voltage applied to zener diode never exceeds PIV of the diode and at the same time, the applied input voltage must be greater than the breakdown voltage of the zener diode.

Que 4.5. **Justify the sentence : the zener diodes are used as voltage regulators and limiters.**
Design the network of Fig. 4.5.1 to maintain V_L at 12 V for a load variation (I_L) from 0 mA to 200 mA *i.e.*, determine R_s and V_z.

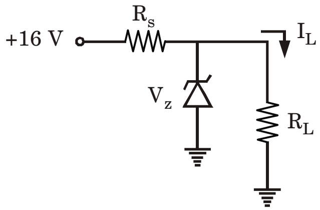


Fig. 4.5.1.

Answer

A. Zener diode as voltage regulators and limiters : Refer Q. 4.4, Page 4–5A, Unit-4.

B. Numerical :

1. Since load is to be maintained at 12 V, we will use a zener diode of 12 V
$$V_z = 12 \text{ V}$$
2. The voltage across R_s is to be remain constant at $16 - 12 = 4$ V
3. As the load current changes from 0 to 200 mA. The minimum zener current will occur when load current will maximum.
$$R_s = \frac{V_i - V_Z}{(I_z)_{\min} + (I_L)_{\max}} = \frac{16 - 12}{0 + 200 \times 10^{-3}} = \frac{4}{200} \times 10^3$$
$$R_s = 20 \ \Omega$$

Que 4.6. **For the network of Fig. 4.6.1, determine the range of R_L and I_L that will result in V_{RL} being maintained at 10 V. Also determine the maximum wattage rating of diode.**

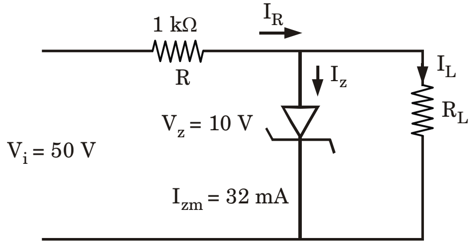


Fig. 4.6.1.

Answer

1. $$V_R = V_i - V_z = 50 - 10 = 40 \text{ V}$$

$$I_R = \frac{V_R}{R} = \frac{40\text{ V}}{1\text{ k}\Omega} = 40\text{ mA}$$

2. $$I_{L\,max} = I_R = 40\text{ mA}$$

$$R_{L\,min} = \frac{V_z}{I_{L\,max}} = \frac{10\text{ V}}{40\text{ mA}} = 250\ \Omega$$

3. $$I_{L\,min} = I_R - I_{zm} = 40\text{ mA} - 32\text{ mA} = 8\text{ mA}$$

$$R_{L\,max} = \frac{V_z}{I_{L\,min}} = \frac{10\text{ V}}{8\text{ mA}} = 1.25\text{ k}\Omega$$

4. $$P_{i\,max} = V_z I_{zm} = (10\text{ V})(32\text{ mA}) = 320\text{ mW}$$

PART-2

Schottky Diode.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.7. **Explain the construction and working of Schottky diode.**

Answer

Construction :

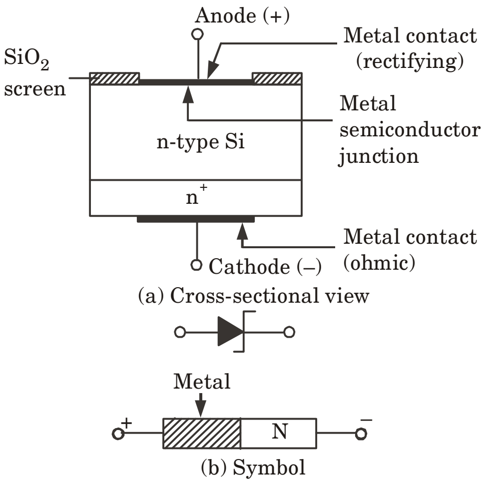


Fig. 4.7.1. Schottky diode.

1. Fig. 4.7.1 shows the symbol and cross-sectional view of a Schottky diode. It is a metal-semiconductor junction diode without depletion layer.
2. On one side of the junction a metal (like gold, silver, platinum or tungsten, etc.) is used and on the other side the *n*-type doped semiconductor is used.
3. *p*-type of material can also be used for device fabrication.
4. A layer of metal is deposited on a thin epitaxial layer of *n*-type silicon. For protection purpose the metal layer is surrounded by gold or silver leaf (thin sheet).
5. The metal film forms the positive electrode (anode) and the semiconductor is the cathode.

Working :

1. The operation of Schottky diode is due to the fact that electrons in different materials have different absolute potential energies.
2. *n*-type semiconductor electrons have higher potential energy as compared to electrons of metal.
3. When the two are brought in contact, there is flow of electrons in both directions across the metal-semiconductor interface when the contact is first made.
4. The flux of electrons from the semiconductor into the metal is much larger due to higher absolute potential energy.
5. As a result, the metal will become negatively charged and the semiconductor will acquire a positive charge.
6. The net result is a "Surface barrier" between the two materials which prevents any further current.
7. It is much like but not exactly the depletion layer in the *p-n* diode.
8. At this point, the thermal equilibrium is established. There are no minority carriers (holes in this case) in establishing the equilibrium.
9. This is the major difference between a Schottky diode and a *p-n* junction diode.
10. Schottky diodes are termed majority-carrier devices and *p-n* junctions are labelled minority carrier devices or bipolar devices (since they use both electrons and holes in their basic operation).
11. Now a voltage is applied to the Schottky diode such that metal is positive with respect to the semiconductor.
12. This voltage will oppose the built-in potential and makes it easier for the current to flow.
13. Biasing the metal negative with respect to the semiconductor increases the potential barrier to majority-carrier current flow.
14. Thus, the metal-semiconductors junction has rectifying characteristics similar to those of a *p-n* junction.

Que 4.8. **Write advantages of Schottky diode over *p-n* junction diode.**

Answer

1. A Schottky diode turns-ON and OFF faster than an ordinary *p-n* junction diode. The basic reason is that Schottky diodes are majority-carrier

devices and have no stored minority carriers that must be injected into the device during turn-ON and pulled out during turn-OFF.
2. As no minority carriers are available in metal, there is no depletion layer or stored charges.
3. The junction contact area between semiconductor and metal is larger than in point contact diode. Hence, the forward resistance is lower.
4. Schottky diodes have much less voltage overshoot.

PART-3

Bipolar Junction Transistor, I-V Characteristics.

CONCEPT OUTLINE

- BJT is a bipolar device which can operate in one of four possible modes : cut-off, active, saturation, and reverse active.
- The basic principle involved is the use of the voltage between two terminals to control the current flowing in the third terminal.

Note : i_E, i_B, i_C, v_{BE}, v_{CE}, v_{BC}, v_E, v_B, v_C represents AC + DC parameters.
I_E, I_B, I_C, V_{BE}, V_{CE}, V_{BC}, V_E, V_B, V_C represents DC parameters.
i_e, i_b, i_c, v_{be}, v_{ce}, v_{bc}, v_e, v_b, v_c represents AC parameters.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.9. **Explain the simplified structure of BJT.**

Answer

1. BJT (bipolar junction transistor) consists of three regions, emitter region, base region and collector region.

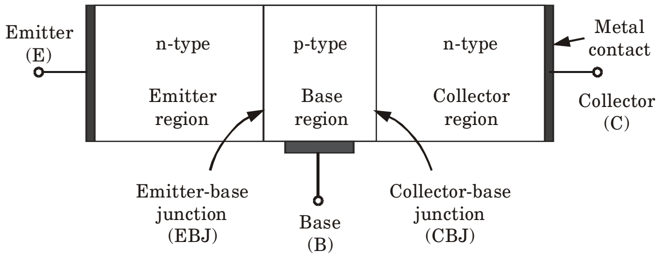


Fig. 4.9.1. A simplified structure of the *npn* transistor.

2. The transistor consists of a *n*-type emitter, *p*-type base and *n*-type collector then such transistor is *npn* transistor. If a transistor consists of a *p*-type emitter, *n*-type base and *p*-type collector, then such transistor is *pnp* transistor.
3. It consists of two *p-n* junctions, the emitter-base junction and the collector-base junction.
4. A transistor has following section :

i. Emitter : The main function of this region is to supply majority charge carriers (either electrons or holes) to the base and hence it is more heavily doped in comparison to other regions.

ii. Base : This is very lightly doped and is very thin as compared to either emitter or collector so that it may pass most of the injected charge carriers to the collector.

iii. Collector : The main function of the collector is to collect majority charge carriers through the base. This is moderately doped and largest among the three regions.

Que 4.10. Describe the structure of an *npn* transistor and explain the operation in the active mode. **AKTU 2014-15, Marks 05**

Answer

A. Structure of *npn* transistor : Refer Q. 4.9, Page 4–9A, Unit-4.

B. Operation in the active mode :

1. The physical operation of the transistor in the active mode is shown in the Fig. 4.10.1.

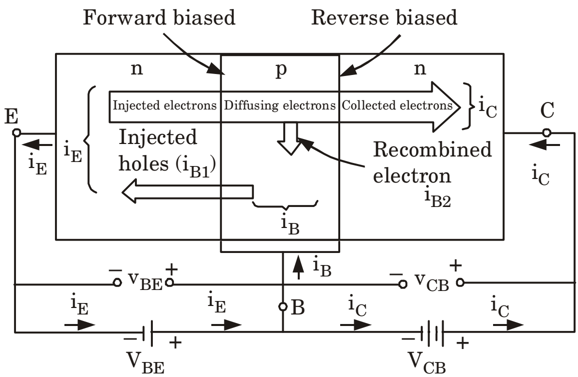


Fig. 4.10.1. Current flow in an *npn* transistor biased to operate in the active mode.

2. Here, the voltage v_{BE} causes the *p*-type base to be higher in potential than the *n*-type emitter, thus forward biasing the emitter-base junction and voltage v_{CB} causes the *n*-type collector to be at higher potential than *p*-type base thus, reverse biasing the collector-base junction.

3. The forward bias on the emitter-base junction will cause the current to flow across this junction.
4. When the electrons are injected from the emitter into base then these electrons will be minority carrier in the *p*-type base region because base is very thin.
5. The collector current i_C can be expressed as

$$i_C = I_S e^{(v_{BE}/V_T)} \quad ...(4.10.1)$$

where, I_S = Saturation current

6. The base current i_B can be given as

$$i_B = i_C / \beta$$

$$\therefore \quad i_B = \left(\frac{I_S}{\beta}\right) e^{(v_{BE}/V_T)} \quad ...(4.10.2)$$

where, β = Common emitter current gain.

7. The emitter current is equal to sum of collector current and base current, *i.e.*,

$$i_E = i_C + i_B = i_C + \frac{i_C}{\beta} = \frac{(\beta+1)}{\beta} i_C \quad ...(4.10.3)$$

8. From eq. (4.10.1)

$$i_E = \frac{(\beta+1)}{\beta} I_S e^{(v_{BE}/V_T)} \quad ...(4.10.4)$$

Que 4.11. A *pnp* power transistor operates with an emitter to collector voltage of 5 V, an emitter current of 10 A, and v_{EB} = 0.85 V. For β = 15, what base current is required ? What is I_S for this transistor ? Compare the emitter-base junction area of this transistor with that of small signal transistor that conducts i_C = 1 mA with v_{EB} = 0.70 V. How much larger is it ?

Answer

Given : v_{EC} = 5 V, i_E = 10 A, v_{EB} = 0.85 V, β = 15, i_C = 1 mA

To Find : i_B, I_S

1. For β = 15,

$$i_E = (\beta + 1)i_B$$

$$10 = (15 + 1)i_B$$

$$\frac{10}{16} = i_B$$

$$i_B = 0.625 \text{ A}$$

2. To calculate I_{S_1}

$$i_C = \frac{\beta}{\beta+1} i_E$$

$$i_C = I_{S_1} e^{v_{EB}/V_T}$$

$$\frac{\beta}{\beta+1} i_E = I_{S_1} e^{(v_{EB}/V_T)}$$

$$\frac{15}{16} \times 10 = I_{S_1} e^{0.85/0.025}$$

$\therefore$ $$I_{S_1} = 1.606 \times 10^{-14} \text{ A}$$

3. Comparing this to small signal transistor,

$$I_{S_2} = i_C e^{(-v_{EB}/V_T)} = 1 \times 10^{-3} \times e^{-0.7/0.025}$$
$$= 6.914 \times 10^{-16} \text{ A}$$

$\because$ $I_S \propto$ Area

$$\frac{\text{Area 1}}{\text{Area 2}} = \frac{I_{S_1}}{I_{S_2}} = \frac{1.606 \times 10^{-14}}{6.914 \times 10^{-16}} = 23.2 \text{ times larger}$$

Que 4.12. **Sketch a family of common base output characteristics for a transistor. Indicate the active, cut-off and saturation region.**

Answer

1. A conceptual experimental setup for measuring common base characteristics is shown in Fig. 4.12.1(a).
2. Here, the base voltage is held constant, *i.e.*, at ground potential, and thus the base serves as a common terminal between the input and output ports.
3. Consequently, the resulting set of characteristics, shown in Fig. 4.12.1(b), is known as common base characteristics.

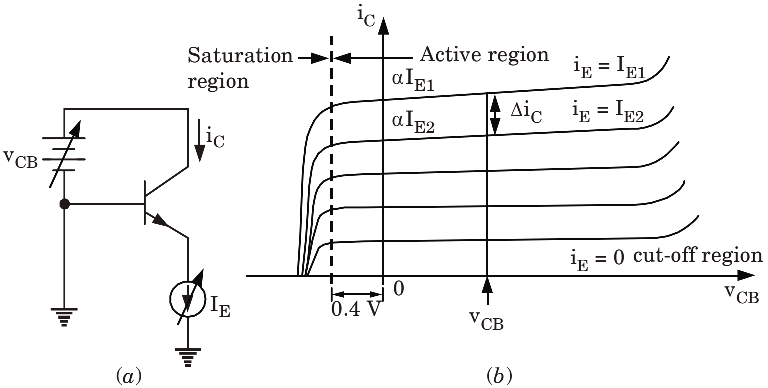


Fig. 4.12.1. The $i_C - v_{CB}$ characteristics of an *npn* transistor.

4. In the active region of operation, obtained for $v_{CB} \geq -0.4$ V, the $i_C - v_{CB}$ curves deviate from the expectations in two ways.
5. First, the curves are not horizontal straight lines but show a small positive slope, indicating that i_C depends slightly on v_{CB} in the active mode.

6. Second, at relatively large values of v_{CB}, the collector current shows a rapid increase, which is a breakdown phenomenon.
7. As indicated in Fig. 4.12.1(*b*), each of the characteristics curves intersects the vertical axis at a current level equal to αI_E.
8. α is called the common base current gain. An incremental or small-signal can be determined by measuring the change in i_C, Δi_C, obtained as a result of changing i_E by an increment Δi_E,

$$\alpha = \Delta i_C / \Delta i_E.$$

9. This measurement is usually made at a constant v_{CB}, as shown in Fig. 4.12.1(*b*).
10. Finally, turning to the saturation region, the Ebers-Moll equations can be used to obtain the following expression for the $i_C - v_{CB}$ curve in the saturation region (for $i_E = I_E$),

$$i_C = \alpha_F I_E - I_S \left(\frac{1}{\alpha_R} - \alpha_F \right) e^{v_{BC}/V_T} \qquad \text{...(4.12.1)}$$

We can use eq. (4.12.1) to determine the value of v_{BC} at which i_C is reduced to zero.

Que 4.13. **Draw input and output characteristics of common emitter amplifier.**

AKTU 2016-17, Marks 05

Answer

Transfer Characteristics :

A. Input characteristic :

1. The forward biased diode curve is expected because the base-emitter section of transistor is a diode and it is forward-biased.

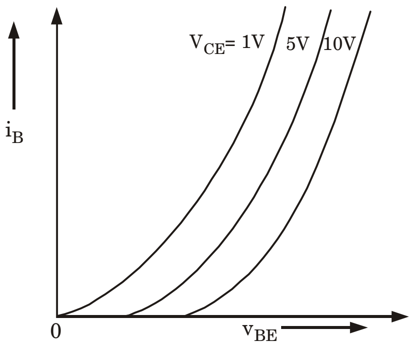


Fig. 4.13.1. Input characteristics.

2. In this case, i_B increases less rapidly with v_{BE} as compared to common base configuration *i.e.*, input resistance of common emitter is higher than common base circuit.

B. Output characteristic :

1. The characteristic of common emitter output configuration is illustrated in Fig. 4.13.2.
2. Each i_C-v_{CE} curve is measured with the base fed with a constant current I_B.
3. Consider a transistor operating in the active region at the point labeled Q in Fig. 4.13.2, *i.e.*, at a collector current I_{CQ}, a base current I_{BQ}, and a collector-emitter voltage V_{CEQ}.

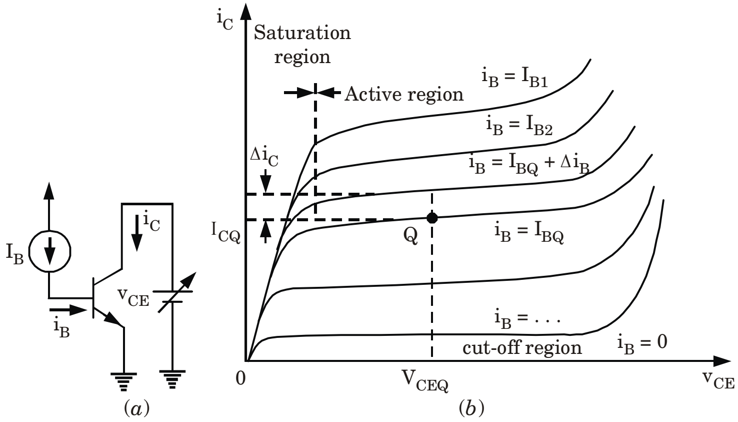


Fig. 4.13.2. Common emitter output characteristics.

4. The ratio of the collector current to base current is the large-signal or β_{DC}.

$$\beta_{DC} = \frac{I_{CQ}}{I_{BQ}}$$

5. Referring to Fig. 4.13.2, while keeping v_{CE} constant at the value V_{CEQ}, changing i_B from I_{BQ} to $(I_{BQ} + \Delta i_B)$ results in i_C increasing from I_{CQ} to $(I_{CQ} + \Delta i_C)$.
6. Thus we can define the incremental or AC β, β_{AC}, $\beta_{AC} = \left.\dfrac{\Delta i_C}{\Delta i_B}\right|_{v_{CE} = \text{Constant}}$

Que 4.14. **Show that $I_E = I_B + \alpha I_E + I_{CBO}$. In which way I_{CBO} depend on temperature ?**

AKTU 2018-19, Marks 07

Answer

A.

1. For *npn* transistor $\alpha = \dfrac{I_C}{I_E}$

$$I_C = \alpha I_E \quad \ldots(4.14.1)$$

2. If the emitter is open then there will be collector current because of minority carriers I_{CBO}.

   Thus, $$I_C = \alpha I_E + I_{CBO} \quad ...(4.14.2)$$

3. And we know $$I_E = I_C + I_B$$
   $$I_C = I_E - I_B \quad ...(4.14.3)$$

4. Putting the value of I_C in eq. (4.14.2) then we get
   $$I_E - I_B = \alpha I_E + I_{CBO}$$
   $$I_E = I_B + \alpha I_E + I_{CBO}$$

B. The reverse saturation current (I_{CBO}) approximately doubles for every 10° C rise on temperature.

Que 4.15. **Define α and β of a transistor and derive the relationship between them.**

AKTU 2018-19, Marks 07

Answer

1. α is the current amplification factor in common base transistor. It is defined as the ratio of the collector current to the emitter current of a transistor when no signal is applied.
   $$\alpha = \left|\frac{I_C}{I_E}\right|$$
2. β is the current gain in common emitter configuration. It is defined as the ratio of the collector current to the base current, when no signal is applied.
   $$\beta = \left|\frac{I_C}{I_B}\right|$$

Relation :

1. We know, $$\alpha = \frac{i_C}{i_E} \text{ and } \beta = \frac{i_C}{i_B}$$
   $$i_E = i_B + i_C \Rightarrow i_B = i_E - i_C$$
2. Now, $$\beta = \frac{i_C}{i_E - i_C} = \frac{i_C / i_E}{1 - i_C / i_E} = \frac{\alpha}{1-\alpha}$$
   $$\beta\,(1 - \alpha) = \alpha \text{ or } \beta - \beta\alpha = \alpha$$
   $$\beta = \alpha\,(1 + \beta)$$
   $$\therefore \quad \alpha = \frac{\beta}{1+\beta}$$

Que 4.16. **Explain the working of common-collector (CC) configuration. Establish the relation in between γ, β and α.**

Answer

A. Working of common collector configuration :

1. In this configuration, the input signal is applied between base and collector and the output is taken from the emitter as shown in Fig. 4.16.1.

2. Current amplification factor, γ is defined as the ratio of emitter current to the base current of the transistor, when no signal is applied.

$$\gamma_{DC} = \gamma = \frac{I_E}{I_B}$$

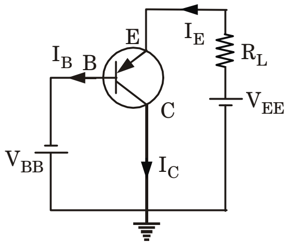


Fig. 4.16.1. Common collector pnp transistor amplifier.

3. When signal is applied, then the ratio of change in emitter current to the change in base current is known as current amplification factor γ.

$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

4. This configuration provides the same current gain as common emitter circuit as $\Delta I_E \approx \Delta I_C$ but the voltage gain is always less than one.
5. Total emitter current

$$I_E = I_B + I_C$$
$$I_C = \alpha I_E + I_{CBO}$$
$$I_E = I_B + (\alpha I_E + I_{CBO})$$
$$I_E (1 - \alpha) = I_B + I_{CBO}$$
$$I_E = \frac{I_B}{(1-\alpha)} + \frac{I_{CBO}}{(1-\alpha)}$$
$$I_E = (1 + \beta) I_B + (1 + \beta) I_{CBO} \qquad \left(\because \frac{1}{1-\alpha} = 1 + \beta\right)$$

6. The voltage gain is always less than one. Hence this configuration is rarely used for amplification.

B. Relation between γ, β and α :

1. $$\gamma = \frac{I_E}{I_B} \text{ and } \alpha = \frac{I_C}{I_E}$$
2. Also $$I_B = I_E - I_C$$
3. $$\gamma = \frac{I_E}{I_E - I_C} = \frac{1}{1-(I_C / I_E)} = \frac{1}{1-\alpha} \qquad ...(4.16.1)$$
4. We have, $$1 - \alpha = \frac{1}{1+\beta} \qquad ...(4.16.2)$$
5. Put values of eq. (4.16.2) in eq. (4.16.1)

$$\gamma = \frac{1}{1-\alpha} = 1 + \beta$$

Que 4.17. **Explain the input and output characteristics of a BJT in the common emitter configuration. If the base current in transistor is 30 μA when the emitter current is 7.2 mA. What are the values of α and β ?**

Answer

A. Input and output characteristics : Refer Q. 4.13, Page 4–13A, Unit-4.

B. Numerical :

Given : $I_B = 30\ \mu\text{A}$, $I_E = 7.2$ mA
To Find : α, β

1. We have

$$I_E = I_B + I_C$$
$$I_C = I_E - I_B = 7.2\ \text{mA} - 30\ \mu\text{A} = 7.17\ \text{mA}$$
$$\beta = \frac{I_C}{I_B} = \frac{7.17 \times 10^{-3}}{30 \times 10^{-6}} = 239$$
$$\alpha = \frac{\beta}{1+\beta} = \frac{239}{240} = 0.9958$$

Que 4.18. **What is Early effect and explain the dependence of i_C on the collector voltage ?**

Answer

1. At given value of v_{BE}, increasing v_{CE} increases the reverse bias voltage of the collector-base junction and thus, increases the width of the depletion region of this junction which in turn results in a decrease in the effective base width W.

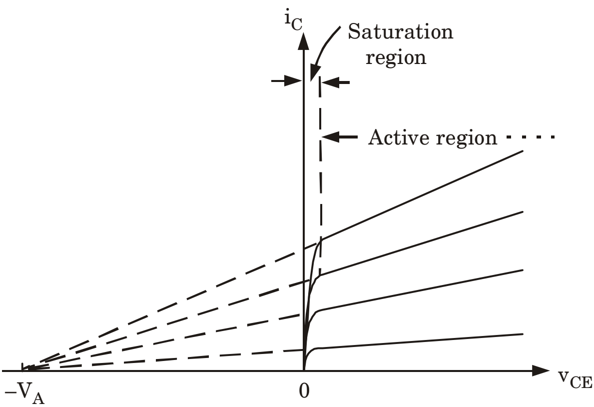


Fig. 4.18.1. i_C-v_{CE} characteristics of a practical BJT.

2. Thus, increase in depletion region width due to increase in reverse bias across collector-base junction is called Early effect.
3. The linear dependence of i_C on v_{CE} can be accounted by assuming that I_S remains constant and including the factor $\left(1+\frac{v_{CE}}{V_A}\right)$ in the equation for i_C is

$$i_C = I_S e^{(v_{BE}/V_T)}\left[1+\frac{v_{CE}}{V_A}\right] \quad ...(4.18.1)$$

where, V_A = Early voltage

4. The non-zero slope of the i_C-v_{CE} straight lines indicates that the output resistance looking into the collector is not infinite. It is defined by,

$$r_0 = \left[\left.\frac{\partial i_C}{\partial v_{CE}}\right|_{v_{BE} = \text{constant}}\right]^{-1} \quad ...(4.18.2)$$

5. Using eq. (4.18.1), we can show

$$r_0 = \frac{V_A + V_{CE}}{I_C} \quad ...(4.18.3)$$

where, I_C and V_{CE} are the coordinates of the point at which BJT is operating on the particular i_C-v_{CE} curve.

6. Alternatively, we can write $r_0 = \frac{V_A}{I'_C}$

where, I'_C is the collector current with Early effect neglected and is given by,

$$I'_C = I_S e^{v_{BE}/V_T}$$

Que 4.19. **Calculate β for two transistors for which α = 0.99 and 0.98. For collector currents of 10 mA, find the base current of each transistor.**

Answer

Given : α = 0.99 and 0.98, I_C = 10 mA
To Find : I_B

1. For α = 0.99, $\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99} = 99$

and base current, $I_B = \frac{I_C}{\beta} = \frac{10\text{ mA}}{99} = 0.101\text{ mA}$

2. For α = 0.98, $\beta = \frac{0.98}{1-0.98} = 49$

and base current, $I_B = \frac{I_C}{\beta} = \frac{10\text{ mA}}{49} = 0.204\text{ mA}$

Que 4.20. **Calculate the values of β and I_S for the transistor shown in Fig. 4.20.1, if $V_{CB} = V_{BE} = 0.7$ V, and $I_B = 0.2$ mA, and $I_E = 10$ mA.**

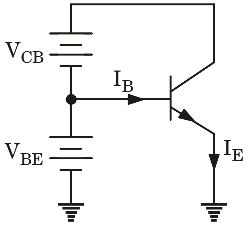


Fig. 4.20.1.

Answer

Given : $V_{BE} = 0.7$ V, $I_B = 0.2$ mA, $I_E = 10$ mA
To Find : β, I_s

1. We know that,
$$I_E = I_C + I_B$$
$$I_C = I_E - I_B = 10\text{ mA} - 0.2\text{ mA} = 9.8\text{ mA}$$
$$\alpha = \frac{I_C}{I_E} = \frac{9.8}{10} = 0.98$$
2. Relation between α and β is given by
$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.98}{1-0.98} = 49$$
3.
$$I_C = I_S\, e^{(V_{BE}/V_T)}$$
$$I_S = \frac{I_C}{e^{(V_{BE}/V_T)}} = \frac{9.8 \times 10^{-3}}{e^{0.7/(25 \times 10^{-3})}} = \frac{9.8 \times 10^{-3}}{1.45 \times 10^{12}}$$
$$I_S = 6.75 \times 10^{-15}\text{ A}$$

Que 4.21. **Explain the operation of BJT as a switch and as an amplifier.**

AKTU 2015-16, Marks 10

OR

Explain the working of BJT as an amplifier and as a switch with the help of neat diagram and necessary equations. Also calculate the amplifier gain.

AKTU 2014-15, Marks 10

OR

How BJT can be used as a amplifier and as a switch ? Justify using required circuit waveform, mathematical expression.

AKTU 2017-18, Marks 07

OR

Explain transistor characteristics in CE configuration. Explain the behaviour of the transistor in active and cut-off mode.

AKTU 2018-19, Marks 07

Answer

Transfer characteristics : Refer Q. 4.13, Page 4–13A, Unit-4.

BJT as an amplifier :

1. Fig. 4.21.1 shows common emitter circuit and Fig. 4.21.2 shows the voltage transfer characteristics of the *CE* circuit.

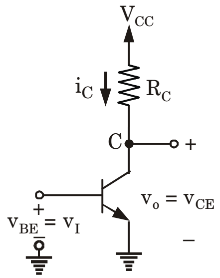


Fig. 4.21.1. Basic common emitter amplifier circuit.

2. To operate the BJT as a linear amplifier, it must be biased at a point in the active region.
3. Fig. 4.21.2 shows such a bias point, labeled *Q*, and characterized by v_{BE} and v_{CE}.

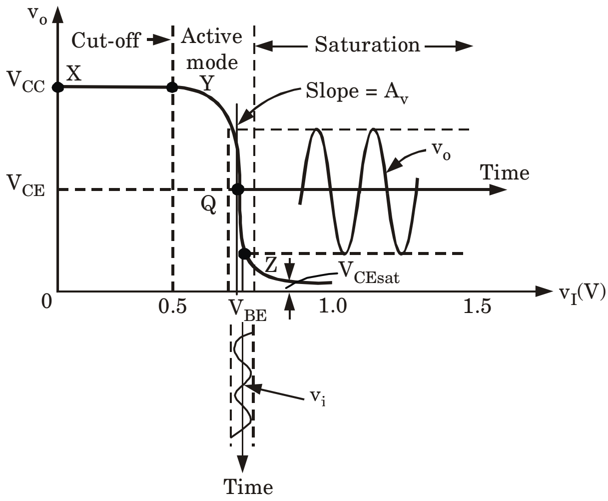


Fig. 4.21.2. Transfer characteristic.

4. If the collector current at this value of v_{BE} is

$$i_C = I_S\, e^{v_{BE}/V_T} \quad ...(4.21.1)$$

then from the circuit in Fig. 4.21.1

$$v_0 = v_{CE} = V_{CC} - R_C\, i_C \quad ...(4.21.2)$$

5. Now, if the signal to be amplified, v_I is superimposed on V_{BE} and kept sufficiently small as the instantaneous operating point will be constrained to a relatively short, almost linear segment of the transfer curve around the bias point Q.
6. The slope of this linear segment will be equal to the slope of the tangent to the transfer curve at Q.
7. This slope is the voltage gain of amplifier.

$$A_v = \left.\frac{dv_o}{dv_I}\right|_{v_I = V_{BE}} \quad ...(4.21.3)$$

8. Thus,

$$A_v = -\frac{1}{V_T} I_S\, e^{V_{BE}/V_T} R_C$$

$$= -\frac{I_C\, R_C}{V_T} = -\frac{V_{RC}}{V_T} \quad \text{[Using eq. (4.21.1)]}$$

where V_{RC} is the DC voltage drop across R_C.

$$V_{RC} = V_{CC} - V_{CE} \quad ...(4.21.4)$$

$$\therefore \quad A_v = -\frac{V_{CC} - V_{CEsat}}{V_T}$$

9. Biasing at the edge of saturation

Thus,
$$A_{v\,\max} \simeq -\frac{V_{CC}}{V_T}$$

BJT as a switch :

When the transistor leaves the active region, it enters in cut-off region or in saturation region. But these regions are very useful if the transistor is to be used as a switch.

i. Cut-off region :

If v_I is smaller than 0.5 V, the emitter-base junction will conduct negligible current and the collector-base junction is reversed biased. The device will be in cut-off mode.

$$i_B = 0,\ i_E = 0,\ i_C = 0,\ v_C = V_{CC}$$

ii. Saturation region :

1. If we increase i_B then i_C increase as a result of which v_{CE} will fall down. The process will continue until the collector-base junction becomes forward biased.
2. The forward voltage drop of collector-base junction is small because of relatively large areas.
3. This mode of working is achieved in saturation region.

$$I_{C\text{sat}} = \frac{V_{CC} - V_{CE\,\text{sat}}}{R_C}$$

4. Forcing more current into the base has very little effect on I_{Csat} and V_{CEsat}. In this state the switch is closed.

Que 4.22. **What is meant by load line of a transistor ? Explain with a simple circuit diagram consisting of an *npn* transistor.**

Answer

1. Consider the circuit shown in Fig. 4.22.1 using *npn* transistor.

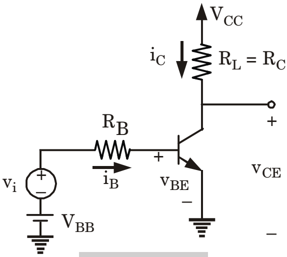


Fig. 4.22.1.

2. For drawing DC load line of a transistor, we require only its cut-off and saturation points. Then the line joining these two points is known as DC load line.
3. The voltage equation of collector-emitter circuit is :

$$V_{CC} = v_{CE} + i_C R_L$$

$$i_C = \frac{V_{CC}}{R_L} - \frac{v_{CE}}{R_L}$$

Hence, V_{CC} and R_L are fixed values and thus, it is a first degree equation which can be represented by a straight line.

4. When collector current $i_C = 0$, then collector-emitter voltage is maximum and is equal to V_{CC}.

i.e., $$v_{CE} = V_{CC} - i_C R_L = V_{CC} \qquad (\because i_C = 0)$$

This gives the cut-off point *B* as shown in Fig. 4.22.2.

5. When collector-emitter voltage $v_{CE} = 0$, then the collector current is maximum equal to V_{CC} / R_L.

i.e., $$v_{CE} = V_{CC} - i_C R_L$$

$$0 = V_{CC} - i_C R_L \text{ or } i_C = V_{CC} / R_L$$

6. This gives the saturation point *A* as shown in Fig. 4.22.2. The line joining the two points *A* and *B* is known as load line.

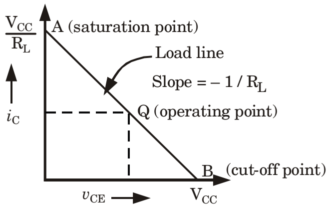


Fig. 4.22.2. DC load line.

Operating point (Q) : This is a point on DC load line which represents the values of i_C and v_{CE} that exist in a transistor circuit when no signal is applied. This is also known as working point.

Que 4.23. Mention the different biasing technique in BJT. Explain any two of them. **AKTU 2017-18, Marks 07**

Answer

Biasing in BJT amplifier circuit :

i. Voltage divider biasing
ii. Two power supply version of the classical bias arrangement.
iii. Biasing using a collector to base feedback resistor.
iv. Biasing using a constant current source.

i. Voltage divider biasing (Classical discrete circuit bias arrangement) :

1. Fig. 4.23.1(a) shows the arrangement most commonly used for biasing a discrete circuit transistor amplifier if only a single power supply is available.

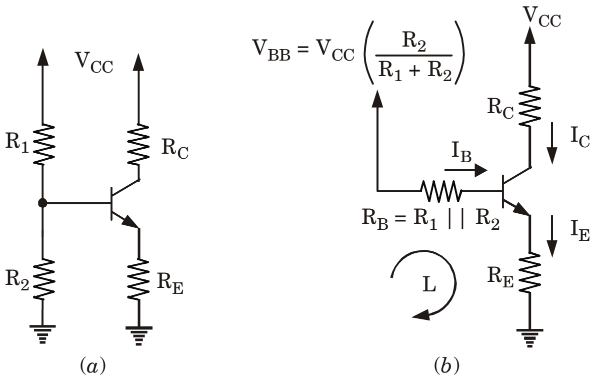


Fig. 4.23.1. Classical biasing for BJTs using a single power supply.

2. Fig. 4.23.1(b) shows the same circuit with the voltage divider network replaced by its Thevenin's equivalent,

$$V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC} \quad ...(4.23.1)$$

$$R_B = \frac{R_1 R_2}{R_1 + R_2} \quad ...(4.23.2)$$

3. The current I_E can be determined by writing a Kirchhoff's loop equation for the base-emitter ground loop labeled L, as

$$V_{BB} - I_B R_B - V_{BE} - I_E R_E = 0$$

Substituting, $$I_B = \frac{I_E}{\beta + 1}$$

$$V_{BB} - I_E\left(\frac{R_B}{\beta+1}\right) - V_{BE} - I_E R_E = 0$$

$$\therefore \qquad I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{(\beta+1)}} \qquad ...(4.23.3)$$

4. To make I_E insensitive to temperature and β variation, we design the circuit to satisfy the following two constraints :

$$V_{BB} >> V_{BE}$$

and
$$R_E >> \frac{R_B}{\beta+1} \qquad ...(4.23.4)$$

ii. Two power supply version of the classical bias arrangement :

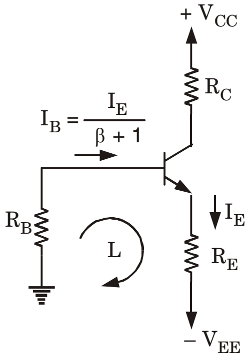


Fig. 4.23.2. Biasing the BJT using two power supplies.

1. In Fig. 4.23.2, two power supplies are available. Writing a loop equation for loop labeled L gives

$$I_E = \frac{V_{EE} - V_{BE}}{R_E + \dfrac{R_B}{(\beta+1)}} \qquad ...(4.23.5)$$

2. Note that if the transistor is to be used with the base grounded, then R_B can be eliminated. On the other hand, if the input signal is to be coupled to the base, then R_B is needed.

Que 4.24. **Do the analysis of DC biasing circuit of the *npn* transistor to derive *Q*-point and self stability factor.**

AKTU 2016-17, Marks 10

Answer

***Q*-point :** Refer Q. 4.22, Page 4–22A, Unit-4.

Self stability factor :

1. Applying Thevenin's theorem to the circuit of Fig. 4.24.1(*a*), for finding the base current, we have

$$V_{BB} = \frac{R_2 V_{CC}}{R_1 + R_2} \quad \text{and} \quad R_B = \frac{R_1 R_2}{R_1 + R_2}$$

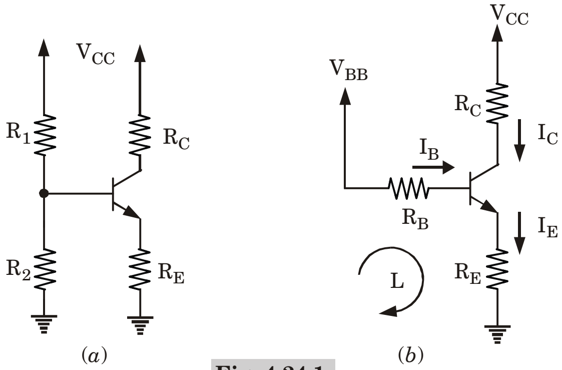


Fig. 4.24.1.

2. The loop equation around the base circuit of Fig. 4.24.1(*b*) can be written as

$$V_{BB} = I_B R_B + V_{BE} + (I_B + I_C) R_E \qquad \text{...(4.24.1)}$$

3. Differentiating eq. (4.24.1) with respect to I_C, we get,

$$\frac{dI_B}{dI_C} = -\frac{R_E}{R_E + R_B}$$

4. The stability factor for *CE* amplifier is given by,

$$S = \left.\frac{dI_C}{dI_{CBO}}\right|_{V_{BE},\, \beta = \text{constant}}$$

5. For common emitter configuration,

$$I_C = \beta I_B + (I + \beta)\, I_{CBO} \qquad \text{...(4.24.2)}$$

6. Differentiating eq. (4.24.2) with respect to I_C

$$1 = \beta \frac{dI_B}{dI_C} + (1 + \beta) \frac{dI_{CBO}}{dI_C}$$

$$\frac{dI_{CBO}}{dI_C} = \frac{1 - \beta\left(\dfrac{dI_B}{dI_C}\right)}{1 + \beta}$$

$$\frac{dI_C}{dI_{CBO}} = S = \frac{1 + \beta}{1 - \beta\left(\dfrac{dI_B}{dI_C}\right)} \qquad \text{...(4.24.3)}$$

7. Substituting the value of $\dfrac{dI_B}{dI_C}$ in eq. (4.24.3), we get

$$S = \frac{1+\beta}{1+\beta\left(\dfrac{R_E}{R_E+R_B}\right)} = (1+\beta)\frac{1+\dfrac{R_B}{R_E}}{1+\beta+\dfrac{R_B}{R_E}}$$

Que 4.25. **For the circuit in Fig. 4.25.1, find the value to which the base voltage should be changed so that the transistor operates in saturation with a forced β of 5.**

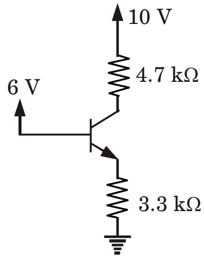


Fig. 4.25.1.

Answer

Given : $\beta_{forced} = 5$
To Find : V_B

1. In circuit shown in Fig. 4.25.1, value of V_B given is 6 V. Now we have to calculate the same transistor to be operated in saturation region.

$$\beta = \frac{I_C}{I_B} = 5$$

$$I_C = 5I_B$$

$$I_E = I_B + I_C = 6I_B = \frac{6I_C}{5} = 1.2\, I_C \quad \text{...(4.25.1)}$$

and here, $V_E = V_B - 0.7$

$$I_E = \frac{V_E}{3.3} = \frac{V_B - 0.7}{3.3} = 1.2\, I_C \quad \text{...(4.25.2)}$$

$$I_C = \frac{10 - V_C}{4.7} = \frac{10 - (V_E + V_{CEsat})}{4.7}$$

$$= \frac{10 - (V_B - 0.7 + 0.2)}{4.7} = \frac{10 - V_B + 0.5}{4.7} = \frac{10.5 - V_B}{4.7} \quad \text{...(4.25.3)}$$

2. From eq. (4.25.2) and (4.25.3)

$$\frac{V_B - 0.7}{3.96} = \frac{10.5 - V_B}{4.7}$$

$$1.19\,(V_B - 0.7) = 10.5 - V_B$$
$$1.19\,V_B - 0.83 = 10.5 - V_B$$
$$2.19\,V_B = 11.33$$
$$V_B = 5.175\text{ V}$$

Que 4.26. **Design the circuit of Fig. 4.26.1 to establish a collector current of 0.5 mA and a reverse bias voltage on the collector-base junction of 2 V. Assume $\alpha \simeq 1$.**

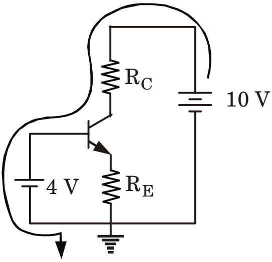


Fig. 4.26.1.

Answer

Given : $I_C = 0.5$ mA, $V_{CB} = 2$ V, $\alpha \simeq 1$
To Find : R_C, R_E

1. From the circuit in Fig. 4.26.1, base-emitter junction will be forward bias. Assuming that V_{BE} is approximately 0.7 V. It follows the emitter voltage to be,

$$V_E = 4 - V_{BE} = 4 - 0.7 = 3.3\text{ V}$$

and
$$I_E = \frac{V_E - 0}{R_E} = \frac{V_E}{R_E} \qquad ...(4.26.1)$$

2. As given $\quad \alpha \simeq 1$
so, $\quad I_B \simeq 0,$
and $\quad I_C = I_E \qquad (\because\ I_B + I_C = I_E)$

3. From eq. (4.26.1),
$$I_C = \frac{V_E}{R_E}$$
$$R_E = \frac{V_E}{I_C} = \frac{3.3\text{ V}}{0.5\text{ mA}} = 6.6\text{ k}\Omega$$

4. Now applying KVL to outer loop,
$$10 - I_C R_C - V_{CB} - 4 = 0$$
Putting given values, $\quad I_C R_C = 10 - 2 - 4 = 4$
$$R_C = \frac{4}{0.5\text{ mA}} = 8\text{ k}\Omega$$

Que 4.27. **Discuss the various internal capacitances in detail for BJT.**

Answer

i. **Base charging or diffusion capacitance, C_{de} :** When the transistor is operating in the active or saturation modes, minority carrier charge, Q_n, is stored in the base region. Q_n can be calculated in terms of the collector current i_c.

$$Q_n = \frac{W^2}{2D_n} i_C = \tau_F i_C$$

where, τ_F is a device constant.

$$\tau_F = \frac{W^2}{2D_n}$$

τ_F is known as the forward base transit time.

For small signals we can define the small signal diffusion capacitance

$$C_{de} = \frac{dQ_n}{dv_{BE}} = \tau_F \frac{di_C}{dv_{BE}} = \tau_F g_m = \tau_F \frac{I_C}{V_T}$$

ii. **Base-emitter junction capacitance, C_{je} :**

$$C_{je} = \frac{C_{je0}}{\left(1 - \frac{V_{BE}}{V_{0e}}\right)^m}$$

where, C_{je0} is the value of C_{je} at zero voltage, V_{0e} is the emitter-base junction (EBJ) built in voltage and m is the grading coefficient of the EBJ junction. One typically uses an approximate value of C_{je}.

$$C_{je} \simeq 2\, C_{je0}$$

iii. **Collector-base junction capacitance, C_μ :** In active mode operation, the collector-base junction is reversed biased, and its junction or depletion capacitance, C_μ becomes

$$C_\mu = \frac{C_{\mu 0}}{\left(1 - \frac{V_{CB}}{V_{0c}}\right)^m}$$

where, $C_{\mu 0}$ is the value of C_μ at zero voltage, V_{0c} is the CBJ built in voltage and m is the grading coefficient.

Que 4.28. **Explain the hybrid-π model of the *npn* transistor.**

Answer

1. Fig. 4.28.1, shows the expressions for the current increment (i_c, i_b, and i_e) obtained when a small signal v_{be} is applied.
2. An equivalent circuit model for the BJT is shown in Fig. 4.28.2(*a*). This includes the input resistance looking into the base, r_π. The model obviously yields $i_c = g_m v_{be}$ and $i_b = v_{be}/r_\pi$.

3. At the emitter node we have,

$$i_e = \frac{v_{be}}{r_\pi} + g_m v_{be} = \frac{v_{be}}{r_\pi}(1 + g_m r_\pi)$$

$$= \frac{v_{be}}{r_\pi}(1 + \beta) = v_{be} \Big/ \left(\frac{r_\pi}{1+\beta}\right) = v_{be} / r_e \qquad ...(4.28.1)$$

4. Expressing the current of the controlled source ($g_m v_{be}$) in terms of the base current i_b as follows :

$$g_m v_{be} = g_m (i_b r_\pi) = (g_m r_\pi) i_b = \beta i_b \qquad ...(4.28.2)$$

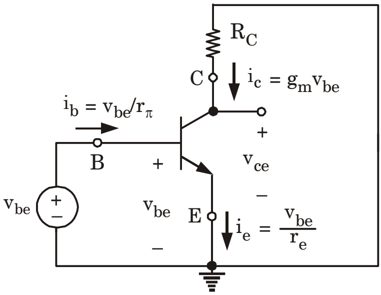


Fig. 4.28.1. The amplifier circuit with the DC sources (V_{BE} and V_{CC}) eliminated (short circuited).

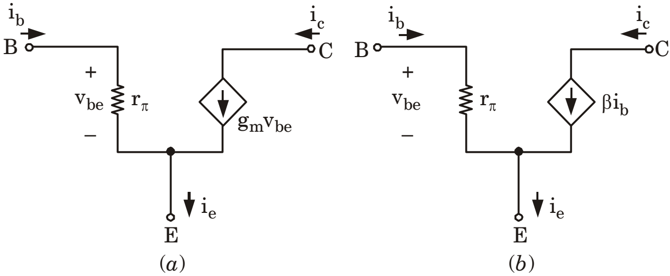


Fig. 4.28.2. Two slightly different versions of the simplified hybrid-π model.

5. The results of eq. (4.28.2) in the alternative equivalent circuit model shown in Fig. 4.28.2(*b*). Hence the transistor is represented as a current-controlled current source, with the control current being i_b.

6. The two models of Fig. 4.28.2 are known as the hybrid-π model. This is the most widely used model for the BJT.

Que 4.29. **Calculate the voltage gain for the circuit given in Fig. 4.29.1. Assume β = 100.**

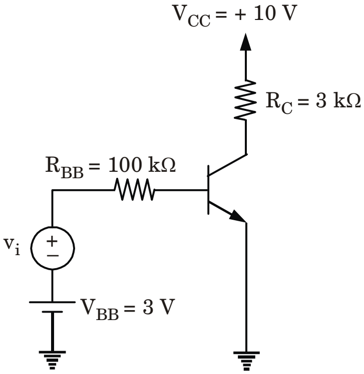


Fig. 4.29.1.

AKTU 2014-15, Marks 10

Answer

Given : $\beta = 100$

To Find : $\dfrac{v_o}{v_I}$

1. To determine the quiescent operating point, assume $v_i = 0$. Analysis of circuit at DC is shown in Fig. 4.29.2.

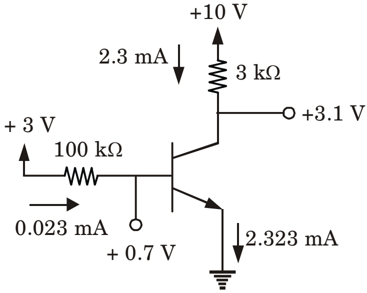


Fig. 4.29.2.

2. The DC base current will be

$$I_B = \frac{V_{BB} - V_{BE}}{R_{BB}} = \frac{3 - 0.7}{100\text{ k}\Omega} = 0.023\text{ mA}$$

3. The DC collector current will be

$$I_C = \beta I_B = 100 \times 0.023 = 2.3\text{ mA}$$

4. The DC voltage at the collector will be

$$V_C = V_{CC} - I_C R_C$$
$$= +10 - 2.3 \times 3 = +3.1\text{ V}$$

5. Since $V_B = +0.7$ V, it follows that in the quiescent the transistor will be operating in the active mode.

Small signal parameters :

1. Fig. 4.29.3 shows small signal model of given circuit shown in Fig. 4.29.1.

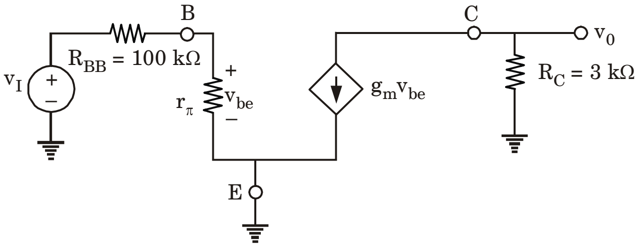


Fig. 4.29.3.

2. $$g_m = \frac{I_C}{V_T} = \frac{2.3 \text{ mA}}{25 \text{ mV}} = 92 \text{ mA/V}$$

3. $$r_\pi = \frac{\beta}{g_m} = \frac{100}{92} = 1.09 \text{ k}\Omega$$

4. From Fig. 4.29.3,

$$v_{be} = v_I \frac{r_\pi}{r_\pi + R_{BB}} = v_I \frac{1.09}{101.09} = 0.011\, v_I$$

5. The output voltage v_0 is given by,

$$v_0 = -g_m\, v_{be}\, R_C$$
$$= -92 \times 0.011 v_I \times 3 = -3.036 v_I$$

6. Thus, the voltage gain will be

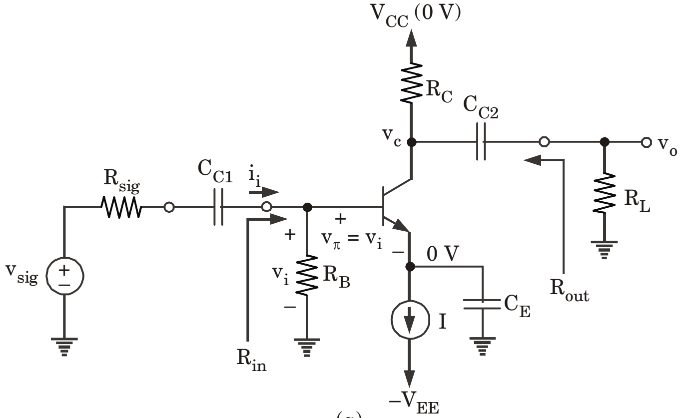
$$\frac{v_0}{v_I} = -3.036$$

Negative sign shows phase reversal.

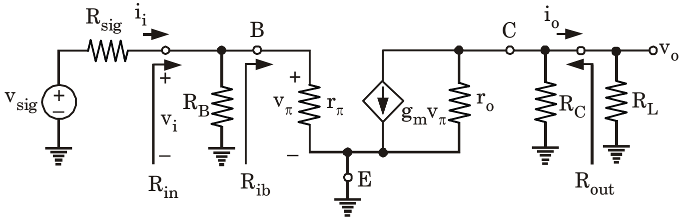
Que 4.30. Draw the circuit diagram of *CE* amplifier. Replacing the transistor with its hybrid-π model deduce the expression for its voltage gain.

Answer

1. Fig. 4.30.1(*a*) shows a *CE* amplifier. Here C_E is used to establish a signal ground and to provide very low impedance to ground. C_E is called bypass capacitor.
2. C_{C1} known as coupling capacitor, is required to act as a perfect short circuit at all signal frequencies of interest while blocking DC.
3. v_c is coupled to the load resistance R_L via another coupling capacitor C_{C2}.
4. We are assuming that C_{C2} also act as a prefect short circuit at all signal frequencies of interest.



(*a*)



(*b*)

Fig. 4.30.1.

5. From the circuit in Fig. 4.30.1(*b*)

$$R_{in} = R_B \,||\, R_{ib} = r_\pi \qquad (\because \quad R_B >> r_\pi)$$

$$v_i = v_{sig} \frac{R_{in}}{R_{in} + R_{sig}} = v_{sig} \frac{r_\pi}{r_\pi + R_{sig}} = v_\pi$$

6. At the output, $\quad v_o = -g_m v_\pi (r_o \,||\, R_C \,||\, R_L)$

$\therefore \quad A_v = -g_m (r_o \,||\, R_C \,||\, R_L)$

7. The open circuit gain by setting $R_L = \infty$,

$$A_{vo} = -g_m (r_o \,||\, R_C) \simeq -g_m R_C \qquad (\because \quad r_0 >> R_C)$$

8. The overall voltage gain from source to load, G_v

$$G_v = -\frac{R_{in}}{R_{in} + R_{sig}} g_m (r_o \,||\, R_C \,||\, R_L)$$

9. For the case $R_B >> r_\pi$, $G_v \simeq -\dfrac{\beta (R_C \,||\, R_L \,||\, r_o)}{r_\pi + R_{sig}}$

10. If $R_{sig} << r_\pi$, $\quad G_v = -g_m (R_C \,||\, R_L \,||\, r_o)$

Que 4.31. **Draw the CE amplifier with a resistance connected in emitter and derive the expression for different characterising parameters.**

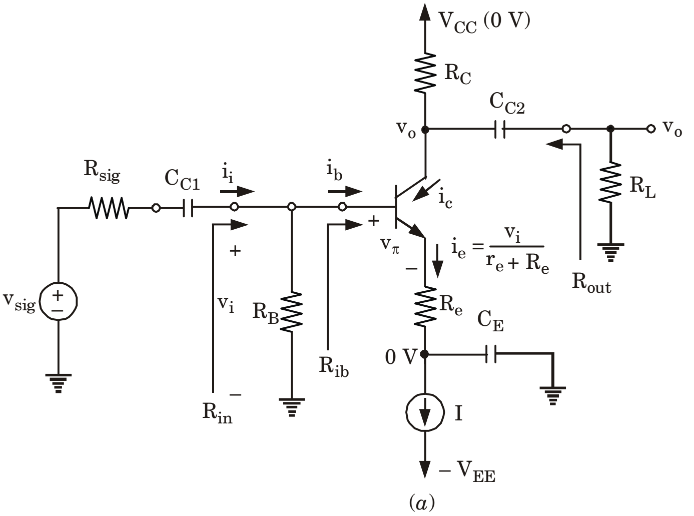
AKTU 2017-18, Marks 07

OR

Do the small signal analysis of common emitter amplifier with emitter resistance. Derive input resistance, voltage gain (from base to collector), overall voltage gain (source to load), open circuit voltage gain and output resistance. **AKTU 2016-17, Marks 15**

Answer

1. Fig. 4.31.1(*a*) shows a common emitter amplifier with an emitter resistance R_e. This resistor can be utilized by the designer as an effective design tool for tailoring the amplifier characteristics to fit the design requirement.



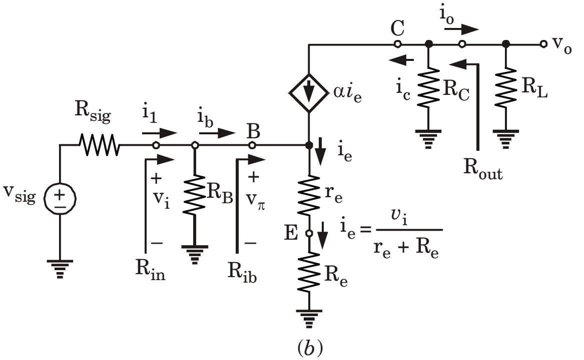


Fig. 4.31.1. (*a*) A common emitter amplifier with an emitter resistance R_e. (*b*) Equivalent circuit obtained by replacing the transistor with its *T* model.

2. $$R_{in} = R_B \,||\, R_{ib}$$

where, $$R_{ib} = \frac{v_i}{i_b} = (\beta + 1)\,(r_e + R_e) \text{ and } v_o = -\,i_c\,(R_C \,||\, R_L)$$

3. The voltage gain, $$A_v = \frac{v_o}{v_i} = -\,\alpha\,\frac{(R_C \,||\, R_L)}{r_e + R_e}$$

4. The open loop voltage gain, $$A_{vo} = -\,\alpha\,\frac{R_c}{r_e + R_e} \qquad (\because R_L = \infty)$$

5. The output resistance, $R_{\text{out}} = R_C$

6. For $R_B >> R_{ib}$, short circuit current gain, $A_{is} = \dfrac{-\,\alpha\,(\beta + 1)\,(r_e + R_e)}{R_e + r_e} = -\,\beta$

7. Overall voltage gain from source to load can be obtained by multiplying A_v by $\left(\dfrac{v_i}{v_{sig}}\right)$

$$G_v = \frac{v_i}{v_{sig}} A_v = -\,\frac{R_{in}}{R_{sig} + R_{in}} \cdot \frac{\alpha\,(R_C \,||\, R_L)}{r_e + R_e}$$

Substituting R_{in} and assuming $R_B >> R_{ib}$ and substituting R_{ib}

$$G_v = -\,\frac{\beta\,(R_C \,||\, R_L)}{R_{sig} + (\beta + 1)\,(r_e + R_e)}$$

Que 4.32. **Draw the circuit for *CB* amplifier and find expression for short circuit current gain.** **AKTU 2015-16, Marks 7.5**

Answer

1. Fig. 4.32.1 shows a *CB* amplifier. The small signal equivalent circuit model (*T*-model) of the amplifier is shown in Fig. 4.32.2.

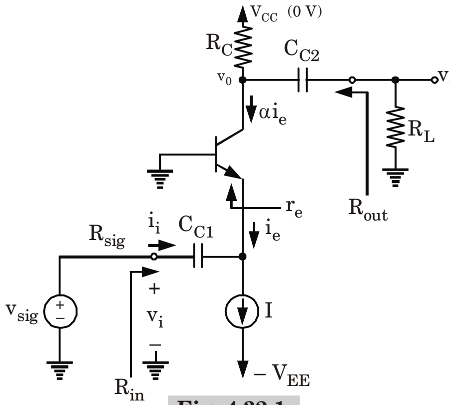


Fig. 4.32.1.

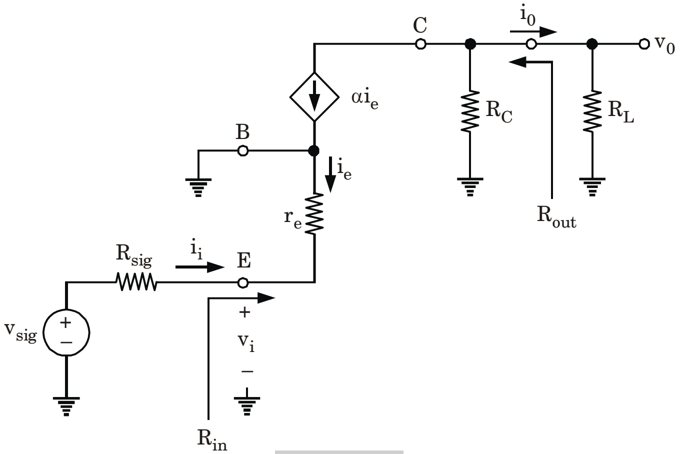


Fig. 4.32.2.

2. From inspection of Fig. 4.32.2, input resistance is $R_{in} = r_e$
At the collector node $v_o = -\alpha i_e(R_C \parallel R_L)$
and the emitter current

$$i_e = -\frac{v_i}{r_e}$$

hence,
$$A_v \equiv \frac{v_0}{v_i} = \frac{\alpha}{r_e}(R_C \parallel R_L) = g_m(R_C \parallel R_L) \quad ...(4.32.1)$$

3. The open circuit voltage gain A_{v0} can be found from eq. (4.32.1) by setting $R_L = \infty$
$$A_{v0} = g_m R_C \quad ...(4.32.2)$$

4. The output resistance of the *CB* circuit can be found by inspection from the circuit in Fig. 4.32.2 as
$$R_{out} = R_C$$

5. The short circuit current gain A_{is} is given by
$$A_{is} = \frac{-\alpha i_e}{i_i} = \frac{-\alpha i_e}{-i_e} = \alpha$$

PART-4

Eber-Moll Model.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.33. **Briefly describe the Ebers-Moll model of an *npn* transistor.**

Answer

1. The Ebers-Moll model of an *npn* transistor is shown in Fig. 4.33.1.

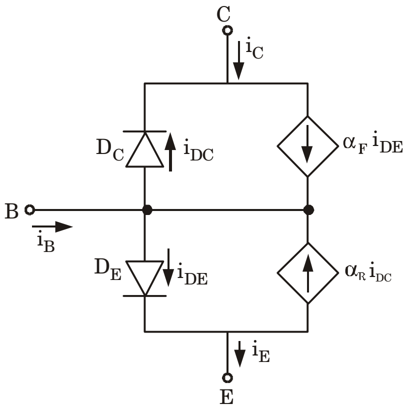


Fig. 4.33.1. The Ebers-Moll (EM) model of the *npn* transistor.

2. According to Ebers and Moll, this composite model can be used to predict the operation of the BJT in all of its possible modes.

3. The expression for the current at each of the three nodes of the model is as follows :

$$i_E = i_{DE} - \alpha_R i_{DC} \quad ...(4.33.1)$$

$$i_C = -i_{DC} + \alpha_F i_{DE} \quad ...(4.33.2)$$

$$i_B = (1-\alpha_F)\, i_{DE} + (1-\alpha_R)\, i_{DC} \quad ...(4.33.3)$$

4. Using diode equation, i_{DE} and i_{DC} can be expressed as

$$i_{DE} = I_{SE}\,(e^{v_{BE}/V_T} - 1) \quad ...(4.33.4)$$

$$i_{DC} = I_{SC}\,(e^{v_{BC}/V_T} - 1) \quad ...(4.33.5)$$

5. Substituting the values of i_{DE} and i_{DC} in eq. (4.33.1), (4.33.2) and (4.33.3), we get

$$i_E = \left(\frac{I_S}{\alpha_F}\right)(e^{v_{BE}/V_T} - 1) - I_S(e^{v_{BC}/V_T} - 1) \quad ...(4.33.6)$$

$$i_C = I_S(e^{v_{BE}/V_T} - 1) - \left(\frac{I_S}{\alpha_R}\right)(e^{v_{BC}/V_T} - 1) \quad ...(4.33.7)$$

$$i_B = \left(\frac{I_S}{\beta_F}\right)(e^{v_{BE}/V_T} - 1) + \left(\frac{I_S}{\beta_R}\right)(e^{v_{BC}/V_T} - 1) \quad ...(4.33.8)$$

where, $\beta_F = \dfrac{\alpha_F}{1-\alpha_F}$ and $\beta_R = \dfrac{\alpha_R}{1-\alpha_R}$

6. If e^{v_{BC}/V_T} is very small and can be neglected then

$$i_E \simeq \left(\frac{I_S}{\alpha_F}\right) e^{v_{BE}/V_T} + I_S\left(1 - \frac{1}{\alpha_F}\right) \quad ...(4.33.9)$$

$$i_C \simeq I_S e^{v_{BE}/V_T} + I_S\left(\frac{1}{\alpha_R} - 1\right) \quad ...(4.33.10)$$

$$i_B \simeq \left(\frac{I_S}{\beta_F}\right) e^{v_{BE}/V_T} - I_S\left(\frac{1}{\beta_F} + \frac{1}{\beta_R}\right) \quad ...(4.33.11)$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Describe the structure of an *npn* transistor and explain the operation in the active mode.

Ans. Refer Q. 4.10.

Q. 2. Draw input and output characteristics of common emitter amplifier.

Ans. Refer Q. 4.13.

Q. 3. Show that $I_E = I_B + \alpha I_E + I_{CBO}$. In which way I_{CBO} depend on temperature ?

Ans. Refer Q. 4.14.

Q. 4. Define α and β of a transistor and derive the relationship between them.

Ans. Refer Q. 4.15.

Q. 5. Explain the operation of BJT as a switch and as an amplifier.

Ans. Refer Q. 4.21.

Q. 6. Mention the different biasing technique in BJT. Explain any two of them.

Ans. Refer Q. 4.23.

Q. 7. Do the analysis of DC biasing circuit of the *npn* transistor to derive *Q*-point and self stability factor.

Ans. Refer Q. 4.24.

Q. 8. Calculate the voltage gain for the circuit given in Fig. 1. Assume β = 100.

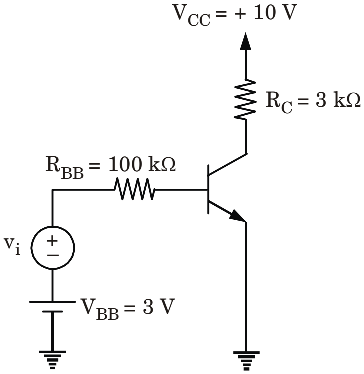


Fig. 1.

Ans. Refer Q. 4.29.

Q. 9. Draw the CE amplifier with a resistance connected in emitter and derive the expression for different characterising parameters.

Ans. Refer Q. 4.31.

Q. 10. Draw the circuit for *CB* amplifier and find expression for short circuit current gain.

Ans. Refer Q. 4.32.

☺☺☺

5

UNIT

MOSFET and OPTOELECTRONIC Devices

CONTENTS

PART-1

MOSFET, I-V Characteristics.

CONCEPT OUTLINE

- MOSFET (Metal oxide semiconductor field effect transistor) is the common term for the insulated gate field effect transistor (IGFET). It is a unipolar device.
- There are two types of MOSFET :
  1. Depletion MOSFET
  2. Enhancement MOSFET

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.1. **What is difference between BJT and MOSFET ?**

Answer

S. No.	BJT	MOSFET
1.	This is a bipolar device. It means output current depends upon the flow of majority as well as minority carriers.	This is a unipolar device. It means output current depends upon the flow of majority carriers only.
2.	It exhibits low input impedance.	High input impedance (typically in MΩ).
3.	More noisy.	Less noisy.
4.	Poor thermal stability.	Good thermal stability.
5.	Finite offset voltage.	No offset voltage at zero drain current.

Que 5.2. **Explain the construction and working of *n*-type enhancement MOSFET.** **AKTU 2016-17, Marks 05**

Answer

A. Construction :

1. The construction of an *n*-channel enhancement MOSFET is shown in Fig. 5.2.1.

2. Two highly doped n^+ regions are diffused in a lightly doped p-type silicon substrate. One n^+ region is called the source S and the other one is called the drain D.

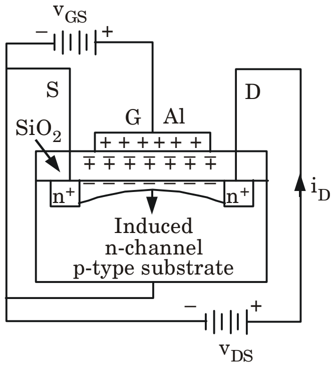


Fig. 5.2.1. n-channel enhancement MOSFET.

3. A thin insulating layer of SiO_2 is grown over the surface of the structure and holes are cut into the oxide layer, allowing contact with source and drain.
4. Then a thin layer of metal aluminium is formed over the layer of SiO_2 which covers the entire channel region and it forms the gate G.
5. The metal area of the gate, the insulating oxide layer of SiO_2 and the semiconductor channel forms a parallel plate capacitor.
6. This device is called the insulated gate FET because of the insulating layer of SiO_2. It gives extremely high input impedance for the MOSFET.

B. Working :

1. If the substrate is grounded and a positive voltage is applied at the gate, the positive charge on gate (G) induces an equal negative charge on the substrate side between the source and drain regions.
2. Thus, an electric field is produced between the source and drain regions which is perpendicular to the plates of the capacitor through the oxide.
3. The negative charge of electrons which are minority carriers in the p-type substrate forms an inversion layer.
4. As the positive voltage on the gate increases, the induced negative charge in the semiconductor increases.
5. Hence, the conductivity increases and current flows from drain to source through the induced channel. Thus the drain current is enhanced by the positive gate voltages.

Que 5.3. **Explain the operation of enhancement type n-channel MOSFET as v_{DS} is increased.**

OR

Explain the operation and characteristics of *n*-channel MOSFET.

AKTU 2018-19, Marks 07

Answer

Operation of *n*-channel MOSFET : Refer Q. 5.2, Page 5–2A, Unit-5.

Operation of enhancement type *n*-channel MOSFET as v_{DS} is increased :

1. Let v_{GS} be held constant at a value greater than V_t.
2. The voltage between the gate and points along the channel decreases from v_{GS} at source end to $v_{GS} - v_{DS}$ at the drain end.
3. Therefore, as v_{DS} is increased, the channel becomes more tapered and its resistance increases correspondingly. Thus, the i_D-v_{DS} curve does not continue as a straight line but bends.
4. When v_{DS} is increased to the value that reduces the voltage between the gate and the channel at the drain end to V_t *i.e.*, $v_{GS} - v_{DS} = V_t$, the channel depth at the drain end decreases to zero and the channel is said to be pinched-off.

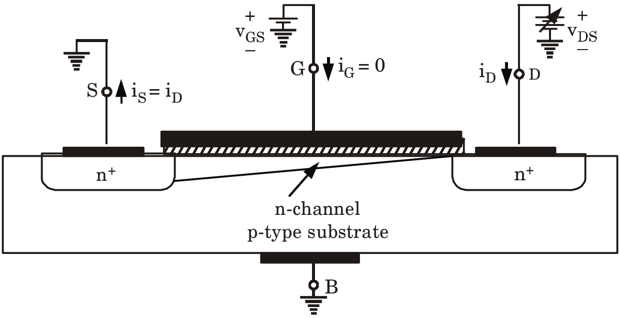


Fig. 5.3.1.

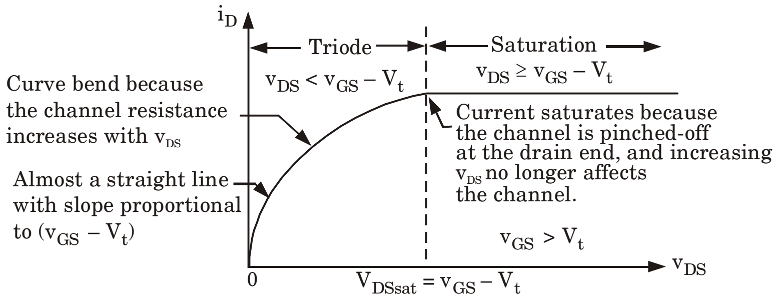


Fig. 5.3.2. i_D-v_{DS} characteristic for an enhancement type NMOS operated with $v_{GS} > V_t$.

5. Increasing v_{DS} beyond this value has no effect on channel shape and the current remains constant at the value reached for $v_{DS} = v_{GS} - V_t$.
6. The drain current saturates at this value and the MOSFET enters the saturation region of operation.

$$\therefore \qquad V_{DS\text{sat}} = v_{GS} - V_t$$

The device operates in the saturation region if $v_{DS} > V_{DSsat}$.

7. The region of the $i_D - v_{DS}$ characteristics obtained for $v_{DS} < V_{DS\text{sat}}$ is called triode region.

Que 5.4. **Construct *p*-channel enhancement MOSFET. Draw and explain the I-V characteristics when V_{DS} is increased.**

AKTU 2017-18, Marks 07

Answer

***p*-channel MOSFET :**

1. Fig. 5.4.1 shows a cross-sectional view of a *p*-channel enhancement-type MOSFET.
2. The structure is similar to that of the NMOS device except that here the substrate is *n* type and the source and the drain regions are p^+ type; that is, all semiconductor regions are reversed in polarity relative to their counterparts in the NMOS case.

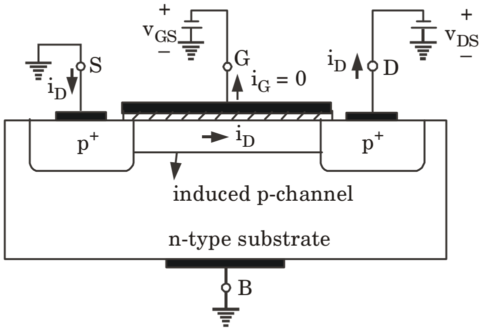


Fig. 5.4.1. Physical structure of the PMOS transistor.

I-V Characteristics when v_{DS} is increased : Refer Q. 5.3, Page 5–3A, Unit-5.

Que 5.5. **Derive the relation between i_D and v_{DS} for NMOS transistor (triode region and saturation region).**

OR

Derive the i_D – v_{DS} relationship for NMOS working in saturation region.

AKTU 2014-15, Marks 05

Answer

1. Consider an operation in the triode region for which channel must be continuous and $v_{DS} < v_{GS} - V_t$.
2. If the capacitance per unit gate area is denoted by C_{ox} and thickness of oxide layer is t_{ox}, then

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \quad ...(5.5.1)$$

where, ε_{ox} = permittivity of silicon oxide = $3.9\,\varepsilon_0 = 3.45 \times 10^{-11}$ F/m
3. Consider the extremely small strip of the gate at distance x from the source. The capacitance of this strip is $C_{ox}Wdx$.
4. The electron charge dq in the extremely small portion of the channel at point x is

$$dq = -C_{ox}(Wdx)\,[v_{GS} - v(x) - V_t]$$

$$\frac{dq}{dx} = -C_{ox}W\,[v_{GS} - v(x) - V_t] \quad ...(5.5.2)$$

where, negative sign indicates that dq is negative charge and $v(x)$ = voltage in the channel at point x.
5. At point x, field can be expressed as,

$$E(x) = -\frac{dv(x)}{dx}$$

6. The electric field $E(x)$ causes the electron charge dq to drift toward the drain with a velocity dx/dt.

$$\frac{dx}{dt} = -\mu_n E(x) = \mu_n \frac{dv(x)}{dx} \quad ...(5.5.3)$$

7. The drift current, i can be obtained as,

$$i = \frac{dq}{dt} = \frac{dq}{dx} \times \frac{dx}{dt} \quad ...(5.5.4)$$

8. Substituting the value of $\frac{dq}{dx}$ from eq. (5.5.2) and value of $\frac{dx}{dt}$ from eq. (5.5.3) in eq. (5.5.4)

$$i = -\mu_n C_{ox} W[v_{GS} - v(x) - V_t]\frac{dv(x)}{dx}$$

$$\therefore \quad i_D = -i = \mu_n C_{ox} W[v_{GS} - v(x) - V_t]\frac{dv(x)}{dx} \quad ...(5.5.5)$$

9. The eq. (5.5.5) can be arranged as,

$$i_D dx = \mu_n C_{ox} W\,[v_{GS} - v(x) - V_t]\,dv(x) \quad ...(5.5.6)$$

10. Integrating both the sides of eq. (5.5.6) from $x = 0$ to L for $v(x) = 0$ to v_{DS}.

$$\int_0^L i_D dx = \int_0^{v_{DS}} \mu_n C_{ox} W[v_{GS} - V_t - v(x)]\,dv(x)$$

$$i_D = (\mu_n C_{ox})\left(\frac{W}{L}\right)\left[(v_{GS} - V_t)v_{DS} - \frac{1}{2}v_{DS}^2\right] \quad ...(5.5.7)$$

The eq. (5.5.7) is the $i_D - v_{DS}$ expression in the triode region.

11. The value of the current at the beginning of the saturation region can be obtained by substituting $v_{DS} = v_{GS} - V_t$

$$\therefore \quad i_D = \frac{1}{2}(\mu_n C_{ox})\left(\frac{W}{L}\right)(v_{GS} - V_t)^2$$

12. Here, $\mu_n C_{ox}$ is known as process transconductance parameter and is denoted by k'_n.

$$\therefore \quad k'_n = \mu_n C_{ox}$$

13. The $i_D - v_{DS}$ expressions can be written in terms of k'_n as follows :

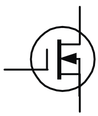
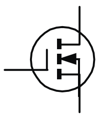
$$i_D = k'_n \frac{W}{L}\left[(v_{GS} - V_t)v_{DS} - \frac{1}{2}v_{DS}^2\right] \quad \text{(Triode region)}$$

$$i_D = \frac{1}{2}k'_n \frac{W}{L}(v_{GS} - V_t)^2 \quad \text{(Saturation region)}$$

Que 5.6. **Differentiate between *D*-MOSFET and *E*-MOSFET.**

AKTU 2016-17, Marks 05

Answer

S. No.	*D*-MOSFET	*E*-MOSFET
1.	Operates in depletion mode and enhancement mode.	Operates only in enhancement mode.
2.	The channel is already formed between source and drain.	There is no physical channel from source to drain. We have to enhance it by applying V_{GS}.
3.	Commonly used bias circuits : Gate bias, Self bias, Voltage-divider bias, Zero bias	Commonly used bias circuits : Gate bias, Voltage divider bias, Drain-feedback bias.
4.	Schematic symbol of *D*-MOSFET 	Schematic symbol of *E*-MOSFET 

Que 5.7. **Discuss the i_D – v_{DS} characteristics for an *n*-channel enhancement type MOSFET.**

OR

Show that, $r_{DS} = \dfrac{1}{\left[k_n' \dfrac{W}{L}(V_{ov})\right]^{-1}}$ **where** $V_{ov} = v_{GS} - V_t$

Answer

1. The characteristic curve given in the Fig. 5.7.1(b) indicates that there are three different regions of operation : the cut-off region, the triode region and the saturation region.
2. The device is cut-off when $v_{GS} < V_t$.
3. To operate the MOSFET in the triode region,

$$v_{GS} \geq V_t \text{ (Induced channel)} \quad ...(5.7.1)$$

and $$v_{GD} \geq V_t \text{ (Continuous channel)} \quad ...(5.7.2)$$

as $$v_{GD} = v_{GS} + v_{SD} = v_{GS} - v_{DS}$$

$\therefore$ $$v_{GS} - v_{DS} \geq V_t \quad ...(5.7.3)$$

4. The eq. (5.7.3) can be rearranged as,

$$v_{DS} < v_{GS} - V_t \quad ...(5.7.4)$$

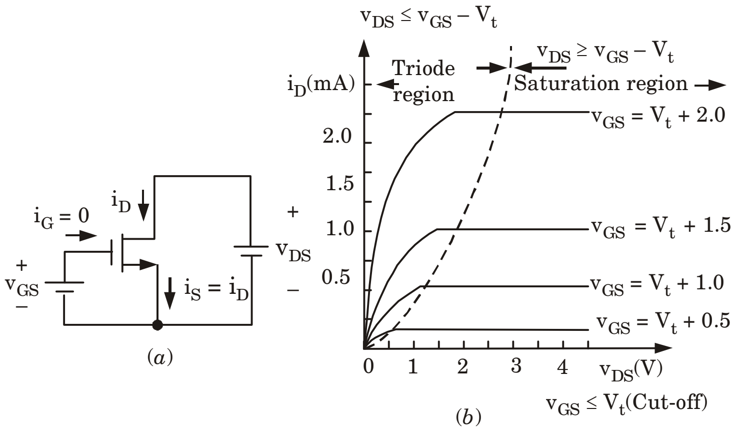


Fig. 5.7.1.

5. The $i_D - v_{DS}$ characteristics for triode region can be explained as,

$$i_D = k_n' \frac{W}{L}\left[(v_{GS} - V_t)v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

where, $$k_n' = \mu_n C_{ox}$$

6. If v_{DS} is small then we can neglect v^2_{DS} term.

$\therefore$ $$i_D = k_n' \frac{W}{L}[(v_{GS} - V_t)v_{DS}]$$

$$r_{DS} = \frac{v_{DS}}{i_D} = \left[k'_n \frac{W}{L}(v_{GS} - V_t)\right]^{-1}$$

as, $$V_{ov} = v_{GS} - V_t$$

$\therefore$ $$r_{DS} = \left[k'_n \frac{W}{L}(V_{ov})\right]^{-1}$$

7. To operate the MOSFET in the saturation region,

$$v_{GS} \geq V_t \text{ (Induced channel)}$$
$$v_{GD} \leq V_t \text{ (Pinched-off channel)}$$

8. The condition can be expressed in terms of v_{DS},

$$v_{DS} \geq v_{GS} - V_t$$

9. The boundary between triode and saturation region is given by

$$v_{DS} = v_{GS} - V_t \quad \text{(Boundary)}$$

$\therefore$ $$i_D = \frac{1}{2}k'_n \frac{W}{L}(v_{GS} - V_t)^2$$

or, $$i_D = \frac{1}{2}k'_n \frac{W}{L}v_{DS}^2$$

Que 5.8. **In the circuit of Fig. 5.8.1 let R_G = 10 MΩ, R_D = 10 kΩ, and V_{DD} = 10 V. Find the value of V_D and V_G for V_t = 1 V and k_n' (W/L) = 0.5 mA/V².**

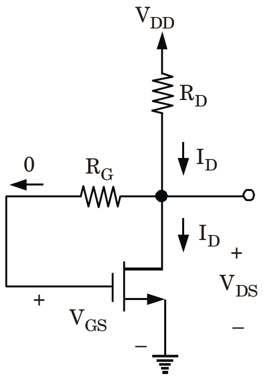


Fig. 5.8.1.

AKTU 2014-15, Marks 05

Answer

Given : R_G = 10 MΩ, R_D = 10 kΩ, V_{DD} = 10 V, V_t = 1 V, k'_n (W/L) = 0.5 mA/V²

To Find : V_D, V_G

1. From Fig. 5.8.1, we can write,

$$V_{GS} = V_{DS} = V_{DD} - R_D I_D$$

$V_D = V_G$, so transistor is in saturation.

2. $$I_D = \frac{V_{DD} - V_{DS}}{R_D} = \frac{V_{DD} - V_D}{R_D}$$

$$= \frac{10 - V_D}{10\ \text{k}\Omega} \qquad ...(5.8.1)$$

3. Also, $$I_D = \frac{1}{2} k_n' \,(W/L)\,(V_{GS} - V_t)^2$$

$$= \frac{1}{2} \times 0.5\,(V_D - 1)^2 \quad [\because V_{GS} = V_G = V_D] \qquad ...(5.8.2)$$

4. From eq. (5.8.1) and (5.8.2)

$$\frac{10 - V_D}{10} = \frac{0.5}{2}\,(V_D - 1)^2$$

$$20 - 2\,V_D = 5(V_D^{\,2} + 1 - 2\,V_D)$$

$$5\,V_D^{\,2} - 10\,V_D + 5 = 20 - 2\,V_D$$

$$5\,V_D^{\,2} - 8\,V_D - 15 = 0$$

$$V_D = -1.107,\ 2.707$$

Taking only positive value,

$$V_D = V_G = 2.707\ \text{V}$$

Que 5.9. **Design the circuit shown in Fig. 5.9.1 so that transistor operates at I_D = 0.4 mA and V_D = + 0.5 V. The NMOS transistor has V_t = 0.7 V, $\mu_n C_{ox}$ = 100 μA/V², L = 1 μm and W = 32 μm. Neglect the channel length modulation.**

AKTU 2015-16, Marks 10

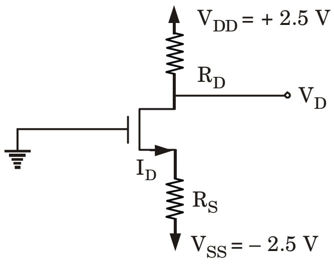


Fig. 5.9.1.

Answer

Given : $I_D = 0.4$ mA, $V_D = 0.5$ V, $V_t = 0.7$ V, $\mu_n C_{ox} = 100\ \mu A/V^2$, $L = 1\ \mu m$, $W = 32\ \mu m$

To Find : R_D, R_S

1. Since $V_D = 0.5\text{ V} > V_G$, the NMOS transistor is operating in the saturation region.

2. Therefore,
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_t)^2$$
$$0.4\text{ mA} = \frac{1}{2} \times 100\ \mu A/V^2 \times \frac{32}{1}(V_{GS} - V_t)^2$$
$$400 = \frac{1}{2} \times 100 \times \frac{32}{1} \times (V_{GS} - V_t)^2$$
$$V_{GS} - V_t = 0.5$$
$$V_{GS} = 0.7 + 0.5 = 1.2\text{ V}$$

3. $$R_S = \frac{V_S - V_{SS}}{I_D} = \frac{-1.2 - (-2.5)}{0.4 \times 10^{-3}} \quad (\because V_G = 0)$$
$$= 3.25\text{ k}\Omega.$$

4. $$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{2.5 - 0.5}{0.4 \times 10^{-3}} = 5\text{ k}\Omega$$

Que 5.10. **Design the circuit shown in the Fig. 5.10.1 to establish a drain of 0.1 V, what is the effective resistance between drain and source at this operating point ? Let $V_t = 1$ V, and $k'_n(W/L) = 1$ mA/V².**

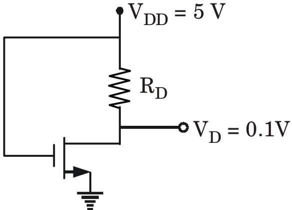


Fig. 5.10.1.

AKTU 2017-18, Marks 07

Answer

Given : $V_{DD} = 5$ V, $V_D = 0.1$ V, $V_t = 1$ V, $k'_n\left(\frac{W}{L}\right) = 1$ mA/V²

To Find : Effective resistance (r_{DS}).

1. For triode region, $V_{GS} - V_t > V_{DS}$

$$5 - 1 > 0.1$$
$$4 > 0.1$$

So the MOSFET is operating in the triode region.

2. In triode region,

$$I_D = k_n' \frac{W}{L}\left[(V_{GS} - V_t)\, V_{DS} - \frac{1}{2} V_{DS}^2\right]$$
$$= 1\left[(5-1) \times 0.1 - \frac{1}{2} \times 0.01\right]$$
$$= 0.395 \text{ mA}$$

3. The value of R_D is, $R_D = \dfrac{V_{DD} - V_D}{I_D} = \dfrac{5 - 0.1}{0.395} = 12.4 \text{ k}\Omega$

4. The effective drain to source resistance is,

$$r_{DS} = \frac{V_{DS}}{I_D} = \frac{0.1}{0.395} = 253\ \Omega$$

Que 5.11. **Draw the *T* equivalent circuit of common source amplifier, with a source resistance and obtain the expressions for R_{in}, R_{out}, and G_v.**

AKTU 2015-16, Marks 7.5

OR

Explain the working of common source with a resistance is connected in source lead. Draw its small signal equivalent circuit. Deduce the expression for overall voltage gain.

AKTU 2017-18, Marks 07

Answer

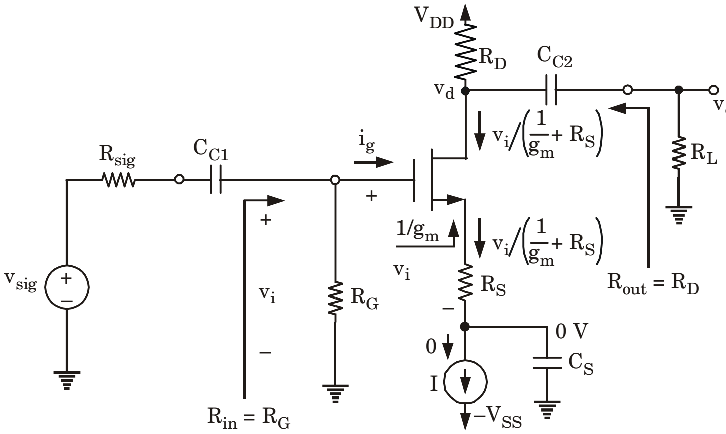


Fig. 5.11.1. CS amplifier with R_S in source lead.

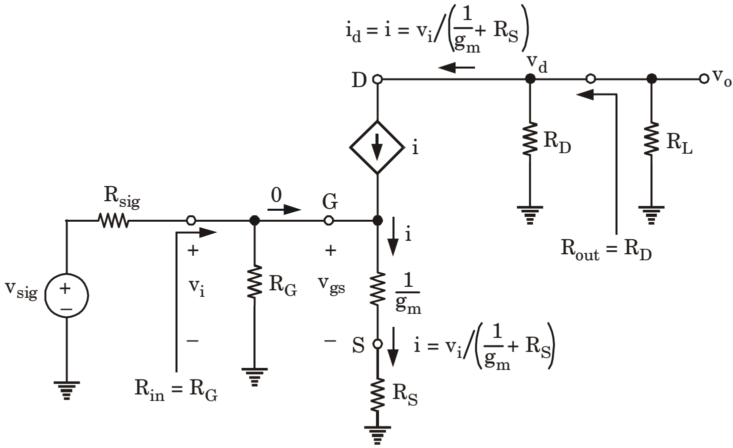


Fig. 5.11.2. Small-signal equivalent circuit with r_o neglected.

1. Since, R_{in} does not depend on R_L and therefore $R_{in} = R_i$.
2. At the point $i_g = 0$, $R_{in} = R_G$

$$v_i = v_{sig} \frac{R_{in}}{R_{in} + R_{sig}} = v_{sig} \frac{R_G}{R_G + R_{sig}}$$

and

$$v_{gs} = v_i \frac{1/g_m}{\frac{1}{g_m} + R_S} = \frac{v_i}{1 + g_m R_S}$$

thus, R_S can be used to control the magnitude of the signal v_{gs}.

3. The current, $i_d = i = v_i/[(1/g_m) + R_S)] = \dfrac{g_m v_i}{1 + g_m R_S}$
4. Output voltage $v_o = -i_d (R_D \,||\, R_L)$

$\therefore$
$$A_v = -\frac{g_m (R_D || R_L)}{1 + g_m R_S}$$

5. If $R_L = \infty$, $A_{vo} = \dfrac{-g_m R_D}{1 + g_m R_S}$
6. Overall voltage gain

$$G_v = -\frac{R_G}{R_G + R_{sig}} \frac{g_m (R_D || R_L)}{1 + g_m R_S}$$

7. The output resistance is given by

$$R_{out} = R_D$$

Que 5.12. **Draw a biasing circuit of MOSFET amplifier and explain it.**

AKTU 2018-19, Marks 07

Answer

The different biasing methods of MOSFET are as follows :

i. Biasing by fixing the gate-to-source voltage V_{GS}.

ii. Biasing by fixing DC voltage at the gate (V_G).

iii. Biasing with a drain to gate feedback resistor.

iv. Biasing with a constant current source.

Biasing with a constant current source :

1. Fig. 5.12.1(*a*) shows biasing using a constant current source I.
2. R_G presents a large resistance to an input signal source that can be capacitively coupled to the gate.
3. Resistor R_D establishes an appropriate DC voltage at the drain to allow for the required output signal swing while the transistor always remains in the saturation region.

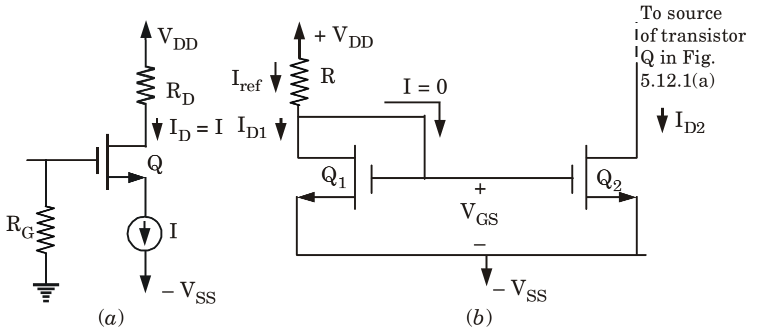


Fig. 5.12.1.

4. Fig. 5.12.1(*b*) shows a circuit for implementing the constant current source using current mirror. The transistor Q_1 has its drain shorted to gate and so it is operating in saturation region. Then

$$I_{D1} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_1 (V_{GS} - V_t)^2 \qquad ...(5.12.1)$$

Since gate current is zero,

$$I_{ref} = I_{D1} = \frac{V_{DD} - V_{GS} - (-V_{SS})}{R} \qquad ...(5.12.2)$$

5. The value of R can be obtained when a desired value of $I_{ref.}$ is known along with the parameter of Q_1.
6. V_{GS} for Q_1 and Q_2 will be same. Assuming that Q_2 is working in saturation which gives

$$I_{D2} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_2 (V_{GS} - V_t)^2 \qquad ...(5.12.3)$$

where, V_t is assumed to be same for both Q_1 and Q_2

then, $$\frac{I_{D2}}{I_{ref}} = \frac{I_{D2}}{I_{D1}} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}$$

7. If $\left(\frac{W}{L}\right)_2 = \left(\frac{W}{L}\right)_1$ then $I_{D2} = I_{D1} = I_{ref}$

when $I_{D2} = I_{ref.}$ we can also say that I_{D2} is mirror image of I_{ref}. Therefore, this circuit is also known as current mirror.

PART-2

MOS Capacitor, C-V Characteristics

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.13. Draw the high-frequency equivalent circuit model for the MOSFET and list all the MOSFET internal capacitances.

OR

Discuss the various capacitances for BJT and MOSFET.

AKTU 2017-18, Marks 07

Answer

BJT internal capacitance : Refer Q. 4.27, Page 4–28A, Unit-4.

A. High frequency equivalent circuit :

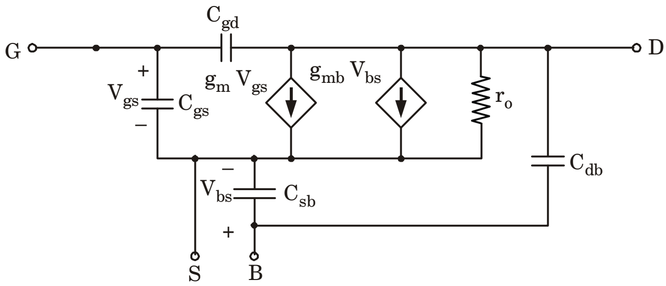


Fig. 5.13.1. High frequency equivalent circuit model for the MOSFET.

B. Types of internal capacitances of MOSFET :

a. The gate capacitive effect :

1. It can be modeled by the three capacitances C_{gs}, C_{gd}, C_{gb}. The values of these capacitances are as follows :

i. When the MOSFET is operating in the triode region at small v_{DS}, the channel will be of uniform depth, thus,

$$C_{gs} = C_{gd} = \frac{1}{2} WL\, C_{ox} \qquad \text{(triode region)}$$

ii. When the MOSFET operates in saturation, the channel has a tapered shape and is pinched off at or near the drain end, thus,

$$C_{gs} = \frac{2}{3} WL\, C_{ox} \qquad \text{(saturation region)}$$

$$C_{gd} = 0$$

iii. When the MOSFET is cut off, the channel disappears, and thus,

$$C_{gs} = C_{gd} = 0$$

$$C_{gb} = WL\, C_{ox} \qquad \text{(cut-off region)}$$

iv. There is an additional small capacitive component that should be added to C_{gs} and C_{gd}. If the overlap length is denoted L_{ov}, the overlap capacitance component is

$$C_{ov} = WL_{ov}\, C_{ox}$$

b. The junction capacitances :

1. For the source diffusion, we have the source body capacitance, C_{sb},

$$C_{sb} = \frac{C_{sb0}}{\sqrt{1+\dfrac{V_{SB}}{V_0}}}$$

where C_{sb0} is the value of C_{sb} at zero body source bias, V_{SB} is the magnitude of the reverse bias voltage and V_0 is the junction built-in-voltage.

2. Similarly for the drain diffusion, the drain-body capacitance C_{db},

$$C_{db} = \frac{C_{db0}}{\sqrt{1+\dfrac{V_{DB}}{V_0}}}$$

where C_{db0} is the capacitance value at zero reverse-bias voltage and V_{DB} is the magnitude of the reverse-bias voltage.

Que 5.14. **Discuss the *C-V* characteristics of MOS capacitor.**

Answer

1. MOS system is in thermal equilibrium at zero bias. Under this condition, the bands are flat and there is no charge in the semiconductor.

2. Let a small AC signal now be applied to measure the capacitance of the system.
3. The perturbation of the semiconductor surface by the small test signal produces an effective dynamic depletion region in the semiconductor whose thickness equals the extrinsic Debye length L_D given by

$$L_D = \sqrt{\frac{kT\varepsilon_s}{q^2(p_o + n_o)}} \quad \text{...(5.14.1)}$$

4. In n-mos, when the gate voltage is negative, the hole concentration in the surface layer increases above p_o. This causes a decrease in the effective Debye length.
5. Thus, the ratio C/C_{ox} starts increasing with the negative bias on the gate as shown by the solid curve in Fig. 5.14.1.

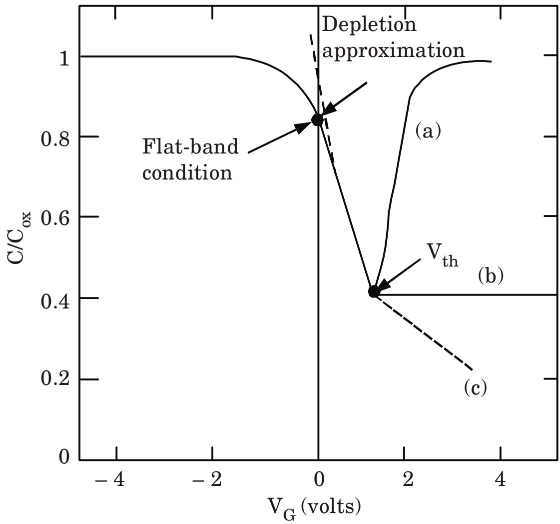


Fig. 5.14.1. Ideal MOS capacitance voltage curves (a) low-frequency, (b) high-frequency, and (c) deep depletion.

6. Finally, at a sufficiently large negative gate voltage, a large number of excess holes are pulled very close to the oxide causing strong accumulation at the surface. As a result the ratio C/C_{ox} approaches unity.
7. For a positive value of V_G, holes are pushed away from the oxide-semiconductor interface creating a depletion region in the semiconductor.
8. The depletion region capacitance in series with the oxide capacitance reduces the total capacitance well below C_{ox}.

9. As the gate bias continues to rise, the depletion region widens. This causes a gradual decrease in C/C_{ox} as V_G is made more and more positive.
10. Finally, when V_G becomes sufficiently large to create strong inversion at the surface, the depletion region width reaches its maximum value. Then C/C_{ox} attains a constant value independent of the gate bias as shown by the solid curve (*b*) in Fig. 5.14.1.
11. At high frequencies, the increase in the negative charge is caused by holes. So the measured capacitance under this situation will be the oxide capacitance in series with the depletion region capacitance.
12. Since the depletion region capacitance has reached its minimum value, the ratio C/C_{ox} also reaches its minimum as shown by the solid curve (*b*) in Fig. 5.14.1.
13. Thus, it is clear that after the onset of strong inversion, curve (*a*) corresponds to low-frequency measurements, while curve (*b*) shows the high-frequency behavior of the MOS capacitor.

Que 5.15. **Draw the high frequency hybrid-π model of MOSFET and show that $f_T = g_m/2\pi(C_{gs} + C_{gd})$**

AKTU 2017-18, Marks 07

Answer

1. A parameter used to judge the operation of a high-frequency MOSFET as an amplifier, is the unity-gain bandwidth.

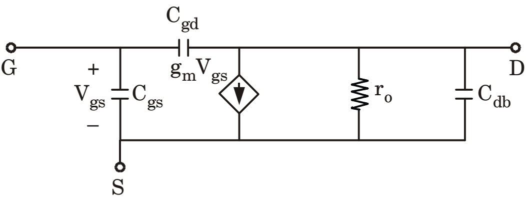


Fig. 5.15.1. High-frequency MOSFET model when the source is connected to the body.

2. The frequency at which short-circuit current gain of the common-source arrangement becomes unity, is known as the unity-gain frequency. This analysis is done using a hybrid π model with a common-source configuration.
3. Again, in the model, as shown in Fig. 5.15.1, when C_{db} is neglected, the resulting circuit is as given by Fig. 5.15.2.
4. It can be noticed easily that the current in the short circuit is given by :

$$I_0 = g_m V_{gs} - sC_{gd} V_{gs} \quad ...(5.15.1)$$

where, *s* is a complex variable.

5. Since C_{gd} is very small, eq. (5.15.1) can be written as $I_0 \approx g_m V_{gs}$.

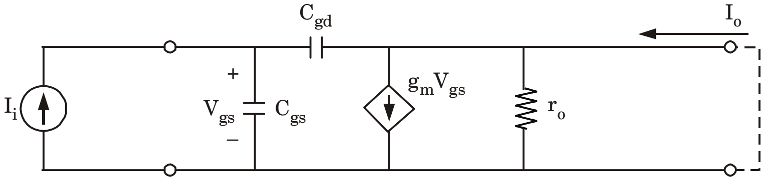


Fig. 5.15.2. Circuit representation for obtaining short-circuit current gain.

And from Fig. 5.15.2, we get :

$$V_{gs} = \frac{I_i}{s(C_{gs} + C_{gd})} \quad \text{...(5.15.2)}$$

6. Substituting, $I_0 = g_m V_{gs}$ we obtain : $\dfrac{I_0}{g_m} = \dfrac{I_i}{s(C_{gs} + C_{gd})}$

$$\frac{I_0}{I_i} = \frac{g_m}{s(C_{gs} + C_{gd})} \quad \text{...(5.15.3)}$$

7. Taking $s = j\omega$ (where, ω is the frequency of the applied voltage), and since the magnitude of current gain becomes unity at this frequency, we can write :

$$\omega_T = \frac{g_m}{(C_{gs} + C_{gd})} \quad \text{...(5.15.4)}$$

$$\Rightarrow \quad f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} \quad (\because \quad \omega_T = 2\pi f_T)$$

PART-3

Small Signal Models of MOS Transistor.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.16. Write a short note on small signal operation and models. Also represent small signal equivalent circuit models.

OR

Explain the terms : single stage MOS amplifier, MOSFET internal capacitances.

AKTU 2018-19, Marks 07

Answer

A. MOSFET internal capacitance : Refer Q. 5.13, Page 5–15A, Unit-5.

B. Small signal operation (single stage MOS amplifier) :

1. For this purpose, we utilize the conceptual common source amplifier circuit shown in Fig. 5.16.1.

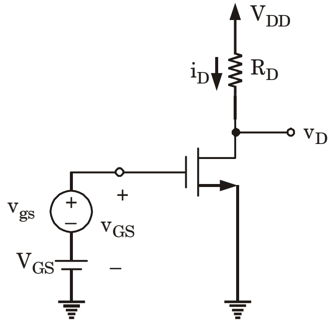


Fig. 5.16.1. Conceptual circuit.

2. For the circuit, the DC bias current I_D can be given by setting the signal $v_{gs} = 0$,

$$\therefore \quad I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2 \quad ...(5.16.1)$$

and
$$V_D = V_{DD} - R_D I_D \quad ...(5.16.2)$$

3. Now, consider, $v_{GS} = v_{gs} + V_{GS}$ resulting in a total instantaneous drain current i_D,

$$i_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} + v_{gs} - V_t)^2$$

$$= \underbrace{\frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2}_{\text{DC bias current } I_D} + \underbrace{k_n' \frac{W}{L} (V_{GS} - V_t) v_{gs}}_{\text{current proportional to } v_{gs}} + \underbrace{\frac{1}{2} k_n' \frac{W}{L} v_{gs}^2}_{\text{current proportional to } v_{gs}^2 \text{ (non-linear distortion)}} \quad ...(5.16.3)$$

4. To reduce non-linear distortion the input signal is kept small so that,

$$\frac{1}{2} k_n' \frac{W}{L} v_{gs}^2 << k_n' \frac{W}{L} (V_{GS} - V_t) v_{gs}$$

$$v_{gs} << 2 V_{OV} \quad (\because V_{OV} = V_{GS} - V_t)$$

If this small signal condition is satisfied, we may neglect 3rd term from eq. (5.16.3).

$$\therefore \quad i_D \simeq I_D + i_d \quad ...(5.16.4)$$

5. **Transconductance :** The parameter that relates i_d and v_{gs} is the MOSFET transconductance g_m.

$$\therefore \qquad g_m = \frac{i_d}{v_{gs}} = k_n' \frac{W}{L}(V_{GS} - V_t)$$

or
$$g_m = k_n' \frac{W}{L} V_{OV} = \sqrt{2k_n'(W/L) I_D} = \frac{2I_D}{V_{ov}}$$

6. **The voltage gain :**

1. From Fig. 5.16.1,
$$v_D = V_{DD} - R_D\, i_D = V_{DD} - R_D(I_D + i_d)$$
$$\therefore \qquad v_D = V_D - R_D\, i_d$$
2. Thus, the signal component of the drain voltage is
$$v_d = -i_d R_D = -g_m v_{gs} R_D$$
3. Voltage gain, $$A_v = \frac{v_d}{v_{gs}} = -g_m R_D$$

C. Small-signal Equivalent-circuit models :

1. In Fig. 5.16.2(a), FET is replaced by equivalent circuit model and ideal constant DC voltage sources are replaced by short circuits. This resulting circuit can be used to perform signal analysis for example calculating voltage gain.
2. Fig. 5.16.2(b) shows one extra r_o, this is one of the shortcomings of small signal model as it assumes that I_D in saturation is independent of drain voltage.

$$A_v = \frac{v_d}{v_{gs}} = -g_m(R_D \parallel r_o)$$

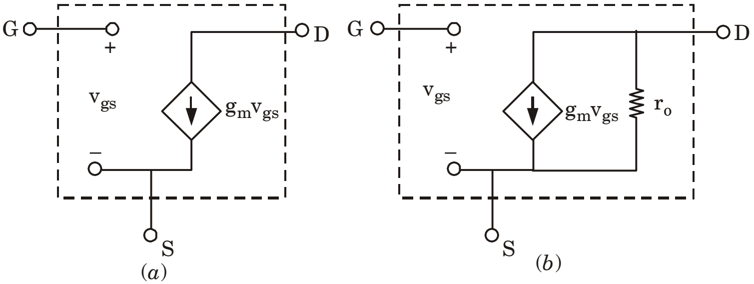


Fig. 5.16.2.

Que 5.17. **A MOSFET is to operate at I_D = 0.1 mA and is to have g_m = 1 mA/V. If k'_n = 50 μA/V², find the required W/L ratio and the over drive voltage.** **AKTU 2015-16, Marks 10**

Answer

Given : $I_D = 0.1$ mA, $g_m = 1$ mA/V, $k'_n = 50$ µA/V²

To Find : $\dfrac{W}{L}$, V_{OV}

1. We know,

$$g_m = \sqrt{2k_n'} \cdot \sqrt{\left(\frac{W}{L}\right)} \sqrt{I_D}$$

$$1 \text{ mA/V} = \sqrt{(2 \times 50\mu \text{ A/V}^2)} \sqrt{\left(\frac{W}{L}\right)} \sqrt{0.1 \times 10^{-3} \text{ A}}$$

$$10^{-3} \text{ A/V} = \sqrt{(10^2 \times 10^{-6} \text{ A/V}^2)} \sqrt{\left(\frac{W}{L}\right)} \sqrt{10^{-4} \text{ A}}$$

$$10^{-3} = 10^{-4/2} \times 10^{-4/2} \times \left(\frac{W}{L}\right)^{1/2}$$

$$\frac{W}{L} = 10^2$$

2.

$$g_m = k_n' \left(\frac{W}{L}\right)(V_{GS} - V_t)$$

$$10^{-3} = 50 \times 10^{-6} \times 10^2 \times (V_{GS} - V_t)$$

$$V_{OV} = (V_{GS} - V_t) = \frac{10^{-3}}{50 \times 10^{-4}} = 0.2 \text{ V}$$

Que 5.18. **Consider the FET amplifier of Fig. 5.18.1 for the case $V_t = 2$ V, $k_n'(W/L) = 1$ mA/ V², $V_{GS} = 4$ V, $V_{DD} = 10$ V and $R_D = 3.6$ kΩ.**

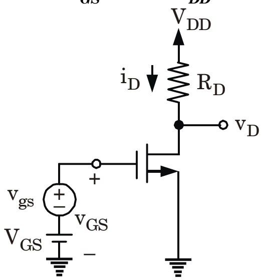


Fig. 5.18.1.

i. **Find the DC quantities I_D and V_D.**
ii. **Calculate the value of g_m at the bias point.**
iii. **Calculate the value of voltage gain.**
iv. **If the MOSFET has λ = 0.0001 V⁻¹, find r_o at the bias point and calculate the voltage gain.**

AKTU 2014-15, Marks 05

Answer

Given : $V_t = 2$ V, $k'_n\,(W/L) = 1$ mA/V², $V_{GS} = 4$ V, $V_{DD} = 10$ V, $R_D = 3.6$ kΩ $\lambda = 0.0001$ V⁻¹

To Find : I_D, V_D, g_m, A_v, r_o

i. For the given circuit, DC quantities can be found by setting the signal $v_{gs} = 0$ V.

$$I_D = \frac{1}{2} k'_n \left(\frac{W}{L}\right) (V_{GS} - V_t)^2$$

$$I_D = \frac{1}{2} \times 1\,(4-2)^2$$

$$I_D = 2 \text{ mA}$$

and

$$V_D = V_{DD} - I_D R_D$$

$$= 10 - 2 \times 3.6$$

$$V_D = 2.8 \text{ V}$$

ii.

$$g_m = k_n' \left(\frac{W}{L}\right) (V_{GS} - V_t)$$

$$g_m = 1 \times (4-2) = 2 \text{ mA/V}$$

iii. Voltage gain, $A_v = \dfrac{v_d}{v_{gs}} = -g_m R_D$

$$A_v = -2 \times 3.6$$

$$A_v = -7.2$$

iv.

$$V_A = \frac{1}{\lambda} = \frac{1}{0.0001} = 10 \text{ kV}$$

Now,

$$r_o = \frac{|V_A|}{I_D} = \frac{10 \times 10^3}{2 \times 10^{-3}} = 5 \times 10^6 = 5000 \text{ k}\Omega$$

Voltage gain,

$$A_v = -g_m\,(R_D \,||\, r_o) = -2\,(3.6 \,||\, 5000)$$

$$= -2 \times 3.59 = -7.18$$

Que 5.19. **Calculate the overall gain $G_v = V_o / V_{sig}$, input resistance and output resistance for a common source amplifier.**

AKTU 2014-15, Marks 05

Answer

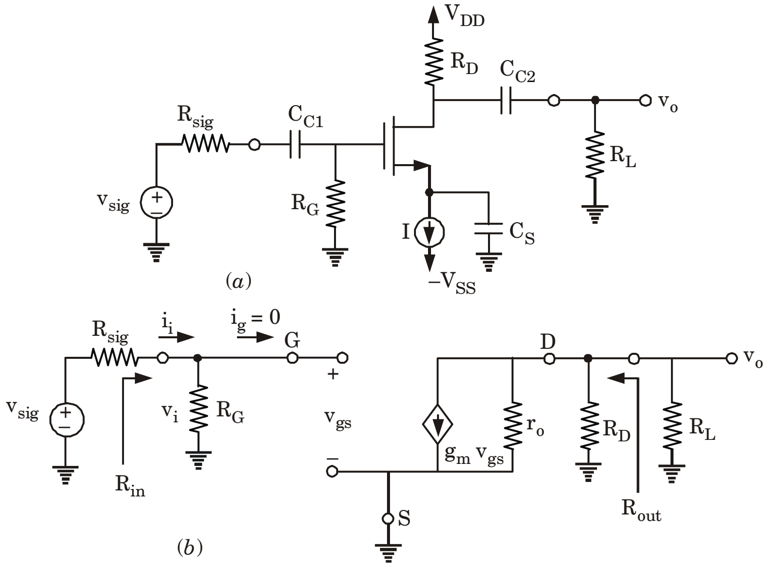


Fig. 5.19.1. (*a*) Common-source amplifier, (*b*) Equivalent circuit of the amplifier for small signal analysis.

1. At the input,

$$i_g = 0$$
$$R_{in} = R_G$$
$$v_i = v_{sig} \frac{R_{in}}{R_{in} + R_{sig}} = v_{sig} \frac{R_G}{R_G + R_{sig}}$$

2. Usually R_G is very large, and in many applications $R_G >> R_{sig}$ and

$$v_i \simeq v_{sig}$$

Now $$v_{gs} = v_i$$

And $$v_o = -g_m v_{gs} (r_o||R_D||R_L)$$

3. Thus the voltage gain A_v is

$$A_v = -g_m (r_o||R_D||R_L)$$

and the open circuit voltage gain A_{vo} is

$$A_{vo} = -g_m (r_o||R_D)$$

4. The overall voltage gain from signal source to the load will be

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_v = -\frac{R_G}{R_G + R_{sig}} g_m (r_o||R_D||R_L)$$

5. To determine output resistance R_{out}, we set $v_{sig} = 0$; *i.e.*, we replace the signal generator v_{sig} with a short circuit

$\therefore$ $$R_{out} = r_o||R_D$$

PART-4

LED

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.20. What is LED ? Give its principle, working, construction, merits, demerits and applications.

Answer

LED : LED is a special type of semiconductor *p-n* junction that under forward bias emits external radiations in ultraviolet, visible and infrared regions of electromagnetic spectrum.

Construction of LED :

1. LED is just not an ordinary *p-n* junction diode where silicon is used. Here we use compound having elements like gallium, arsenic and phosphorus which are semitransparent unlike silicon which is opaque.
3. In all semiconductor *p-n* junctions, some of its energy will be given off as heat and some in the form of photons.
4. In the materials, such as gallium arsenide phosphide (GaAsP) or gallium phosphide (GaP), the number of photons of light energy emitted is sufficient to create a visible light source.

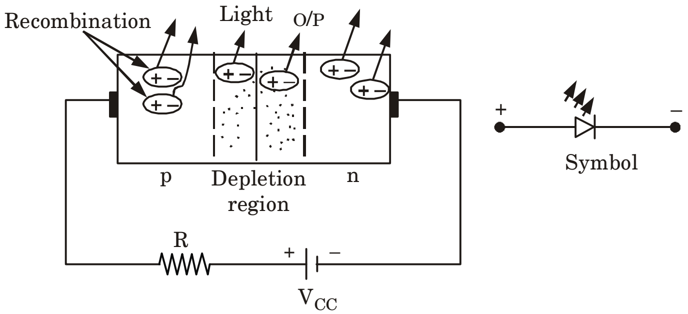


Fig. 5.20.1.

Principle of LED :

1. The process involves :
   i. Generation of electron-hole pair (EHP) by excitation of semiconductor.
   ii. Recombination of EHP.
   iii. Extraction of photons from the semiconductor.
2. The characteristic for LED is given in Fig. 5.20.2.

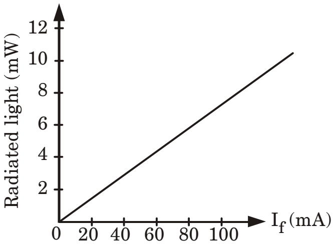


Fig. 5.20.2. Characteristics.

Working :

1. When LED is in forward bias condition, the electrons from *n*-type material cross the *p-n* junction and recombines with holes in the *p*-type material.
2. When recombination takes place, the recombining electrons release energy in the form of heat and light.
3. The emission depends upon the type of material, *i.e.*,

   GaAs → infrared radiation (invisible)

   GaP → red or green light (visible)

   GaAsP → red or yellow light (visible).

Applications :

1. Display LEDs like calculator, digital clocks etc.
2. Light source in optical fibre communication.
3. Light source in a source detector package like smoke detectors, tachometers, proximity detectors etc.

Merits :

1. Low voltage of operation.
2. Long life (more than 15 years).
3. Fast on-off switching.
4. Cheap in cost.
5. Available in wide range of colours.

Demerits :

1. It draws considerable current requiring frequent replacement of battery in low power battery operated devices.
2. Luminous efficiency of LED is low which is about 1.5 lumen/watt.
3. Characteristics are affected by temperature.
4. Need large power for the operation as compared to normal *p-n* junction diode.
5. Sensitivity to damage by over voltage and over current.

Que 5.21. **An LED is connected across a voltage source of + 10 V through a series resistance of 820 Ω. Calculate the LED current. Assume the voltage drop across an LED of 1.5 volt.**

Answer

Given : $V_S = 10$ V, $V_D = 1.5$ V, $R_S = 820\ \Omega$
To find : LED current (I_S)

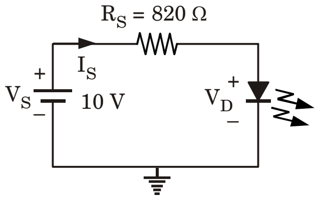


Fig. 5.21.1.

Applying KVL in the loop, we get

$$V_S = I_S R_S + V_D$$

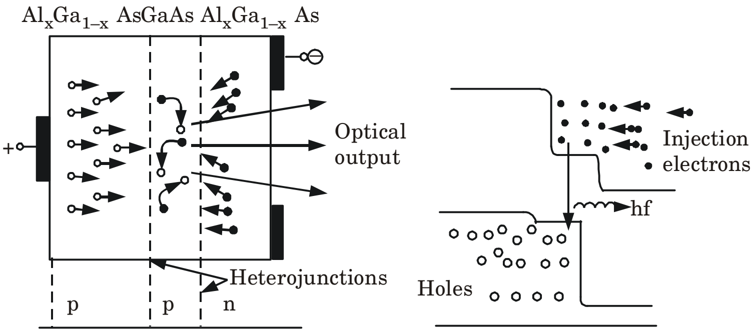
$$I_S = \frac{V_S - V_D}{R_S} = \frac{10 - 1.5}{820}$$

$$I_S = 10.36 \text{ mA}$$

Que 5.22. **Write a short note on double heterojunction LED.**

Answer

1. The principle of operation of the Double heterojunction LED is shown in a Fig. 5.22.1.



(*a*) The double heterojunction LED, layer structure.

(*b*) The corresponding energy band diagram

Fig. 5.22.1.

2. The device consists of a *p*-type GaAs layer sandwiched between a *p*-type AlGaAs and an *n*-type AlGaAs layer.
3. When a forward bias is applied electrons from *n*-type layer are injected through the *p*-*n*-junction into the *p*-type GaAs layer where they become minority carriers.

4. These carriers diffuse away from the junction recombining with majority carriers, photons are produced with energy corresponding to the bandgap energy of the *p*-type GaAs layers.
5. The injected electrons are inhibited from diffusing into the *p*-type AlGaAs layer because of the potential barrier presented by the *p-p* heterojunction.
6. Hence electroluminescence only occurs in GaAs junction layer, providing both good internal quantum efficiency and high radiance emission.

PART-5

Photodiode

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.23. **What is photodiode ? What are its different types ? Describe the construction of a photodiode with its operation. Also draw V-I characteristics of photodiode.**

OR

What is a photodiode ? Explain its construction and operation.

AKTU 2018-19, Marks 07

Answer

A. Photodiodes :

1. Two terminal devices designed to respond to photon absorption are called photodiodes.
2. Photodiode is a semiconductor *p-n* junction device whose operation is limited to reverse bias region.
3. The types of photodiode are :
   i. *p-n* diode
   ii. *p-i-n* diode
   iii. Avalanche diode
4. The output current of a reverse bias *p-n* junction changes when device is exposed to illumination.
5. The variation in the output current is linear with respect to luminous flux. The construction and symbol is shown in Fig. 5.23.1.

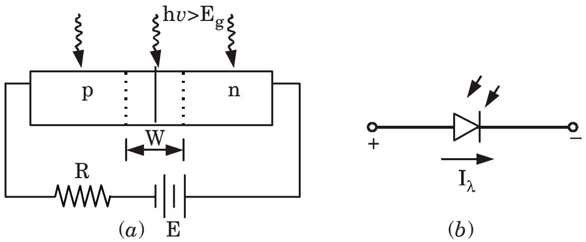


Fig. 5.23.1.

6. This diode is designed in such a manner that the rays are allowed to fall only on one surface across the junction. The remaining sides are restricted for the light to penetrate.
7. As the temperature due to illumination increases, more and more electron-hole pairs are generated and results in increasing the reverse saturation current.
8. When light rays fall on depletion width *W*, it creates electron-hole pair and electrons are swept into *n*-region and holes into *p*-region very rapidly. This gives rise to a photo current. This is the basic principle of operation of photodiode.

B. Photodiode characteristics :

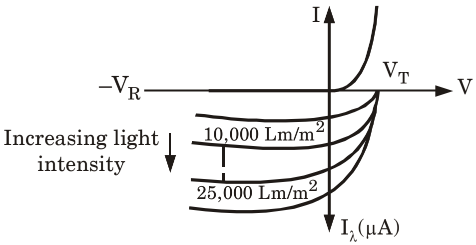


Fig. 5.23.2.

1. The Fig. 5.23.2 shows the I-V characteristics of *p-n* junction photodiode with different illumination level.
2. When no light ray is incident, the diode has a small reverse current I_λ known as dark current.
3. The dark current is that current which exists only with no applied illumination.
4. The increase in reverse voltage does not increase the reverse current significantly because all available charge carriers have already being swept across the junction.
5. The photodiode can also be used as a variable resistor controlled by light intensity.
6. Photodiode operates in quadrants *i.e.*, in third quadrant, both *I* and *V* are negative and power is being delivered to the device from external circuit.

7. In fourth quadrant, V is positive and I is negative and power is delivered from the junction to the external circuit. In applications, usually third quadrant operation is preferred.

Que 5.24. What is photodetector ? Explain the working mechanism of a photodetector.

Answer

A. Photodetector :
Photodetectors are semiconductor devices that can detect optical signals and convert time-varying optical signals into electrical signals.

B. Working mechanism :
1. The working mechanism of photodetector is shown in Fig. 5.24.1.
2. The junction is reverse-biased. When depletion region is exposed to light, the electrons reach to n-region and holes reach to p-region. This movement of electrons and holes results in reverse leakage current.

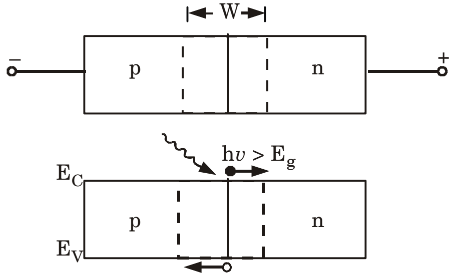


Fig. 5.24.1.

3. The system involves fundamental processes like :
i. Carrier generation by incident light.
ii. Carrier transport.
iii. Interaction of current with external circuit.
4. The depletion region should be thick so that the EHP generation is maximum. To achieve a high speed device, the carrier transit time through depletion region should be small, possibly 1 ns.
5. The photodiode is the most common photodetector. In its third quadrant, the current is independent of voltage but it is proportional to optical generation rate.
6. When the carriers are generated primarily within the depletion layer W, the detector is called a depletion layer photodiode.
7. The photo generated minority carriers must diffuse to the junction and should be swept to the other side as soon as possible so that the response of photodetector is quite fast.

Que 5.25. Explain the operation of *p-i-n* photodetector.

Answer

1. One convenient method of controlling the width of the depletion region to satisfy the requirements of high emission efficiency and improved response speed is to build a *p-i-n* photodetector.
2. It consists of high doped *p* and *n* regions separated by a neutral layer of semiconductor known as intrinsic layer *i*.
3. The intrinsic silicon reduces the transit time of photo-induced electron-hole pairs. The reason is that carriers generated by light photons incident on middle of this layer have less distance to travel than if generated at one side or the other of the layer.
4. The *p-i-n* diode is operated in reverse bias mode with depletion region exposed to the incident light.

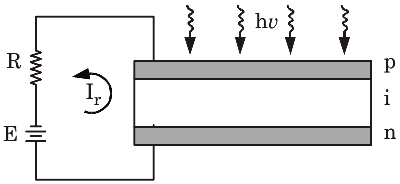


Fig. 5.25.1. Schematic representation of a *p-i-n* photodiode.

5. The intrinsic region has a relatively low conductivity. Therefore, most of the reverse applied voltage appears across the intrinsic layer.
6. The intrinsic layer increases the size of the depletion region. This in turn leads to an increased light sensitive area.
7. The increased area allows the detector to pick up a wide range of incoming light. As a result, the amount of current increases with the amount of light absorbed.
8. The *p* region of photodiode is made very thin so that it is transparent to the incoming light. On the other hand, the depletion region is made relatively thick so that it may absorb all the incident light.
9. The photons incident on the depletion region produce electron-hole pairs. They are separated by the high electric field present in the depletion region.
10. The positive charges move toward *p*-region while the negative charges move toward *n*-regions. This gives rise to a photo current flow in the external circuit.

Que 5.26. **Why *p-i-n* photodiode does not provide gain. How can it be made more sensitive to low-level optical signals ? Briefly explain the principle of operation, construction and working of avalanche photodiode and also draw its *V-I* characteristics.**

Answer

A. Reason :

1. *p-i-n* photodiode does not provide gain because when a photon is incident on the intrinsic layer, it generates only one electron-hole pair. So, no internal gain is achieved.
2. This diode cannot detect low-level optical signals. To detect low level signals, avalanche multiplication is required.

B. Principle of operation :

1. The principle of avalanche photodiode is that when a photodiode is operated in its reverse breakdown or avalanche breakdown, the current sensitivity is increased by 30 – 100 times.
2. These photodiodes are operated at high reverse bias voltages such that avalanche multiplication takes place.
3. The electron-hole pairs that are generated by incident photons are accelerated by the high electric field. They acquire extremely high kinetic energy.
4. Impact ionization then occurs and initiates the avalanche multiplication process. These high velocity electrons 'kick' new electrons from the valence to conduction band.

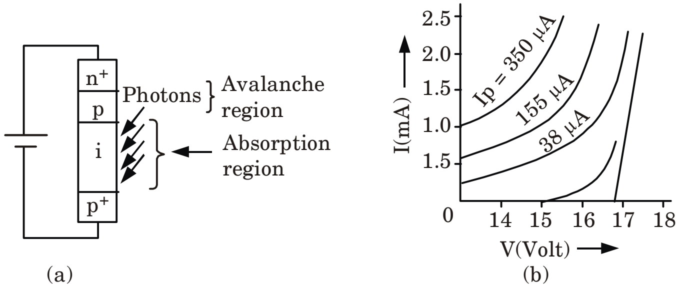


Fig. 5.26.1. (a) Avalanche photodiode (b) Static volt-amp. characteristics for Ge avalanche photodiode.

C. Construction and working :

1. Avalanche photodiode is shown in Fig. 5.26.1(a). A typical construction has four regions. n^+ and p^+ are heavily doped semiconductors and hence have very low resistances.
2. The *i* region is very lightly doped and hence nearly intrinsic. Light enter the diode through *i* region and is absorbed in the intrinsic region.
3. Now electron-hole pairs are generated which are separated by the electric field in intrinsic region *i*. The photo generated electrons drift to pn^+ junction through intrinsic region. Here a high electric field exists. This high electric field region is also known as avalanche region or multiplication region.
4. Here photo generated electrons are accelerated and collide with the bound electrons of valence band. They release more number of electrons as free or conduction electrons. This effect is known as avalanche effect.

5. Fig. 5.26.1(b) shows typical *V-I* characteristics for Ge avalanche photodiode.

PART-6

Solar Cell.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.27. What is solar cell ? Explain construction and working of solar cell.

OR

Explain the working of solar cell. Discuss open circuit output voltage characteristic and short circuit current characteristic.

OR

Explain the terms : solar cell, LED. **AKTU 2018-19, Marks 07**

Answer

LED : Refer Q. 5.20, Page 5–25A, Unit-5.

Solar cell :

1. Solar cells are semiconductor junction devices which are used for converting optical radiation into electrical energy.
2. The generated electric voltage is proportional to the intensity of incident light. Due to their capability of generating voltage, they are called photovoltaic cells.
3. Silicon is the most widely used material for solar cells.

Construction :

1. The construction of a solar cell is shown in Fig. 5.27.1.
2. The *p*-type layer is made thin to intercept the light radiation falling on the junction. The doping of *p*-type material is very high.

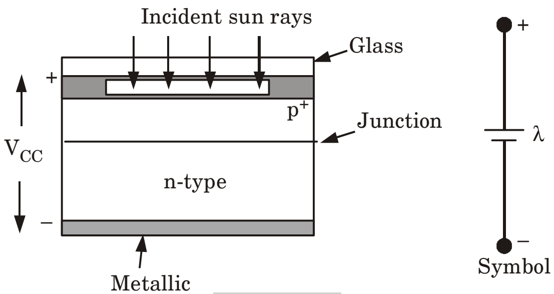


Fig. 5.27.1.

3. *p*-type is surrounded by a nickel plated ring which serves as positive terminal and the contact at bottom acts as a negative terminal.

Working :

1. When photons are incident on surface, it releases sufficient energy to the electrons to leave its orbit.
2. As a result, free electrons and holes are created. These free electrons and holes constitute the minority current.
3. In this way, depletion region potential causes the photo current to flow through the external load.

Open-circuit output voltage characteristics :

1. Fig. 5.27.2 shows the open-circuit output voltage V_{OC} characteristic of a typical photovoltaic cell. The graph is logarithmic on light intensity axis.
2. It is obvious from the graph that the cell is more sensitive for low light intensity levels than for higher light intensity level.
3. The reason is that a small change in light intensity produces the same increase in V_{OC} as a large change in light intensity.

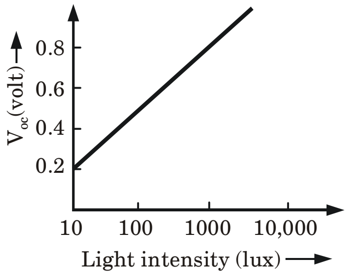


Fig. 5.27.2. V_{OC} as a function of light intensity.

C. Short-circuit current characteristics :

1. The three most important parameters of solar cell are the short-circuit current I_{SC}, the open-circuit voltage V_{OC} and fill factor *FF*.
2. Fig. 5.27.3 shows the *V-I* characteristics of a solar cell.

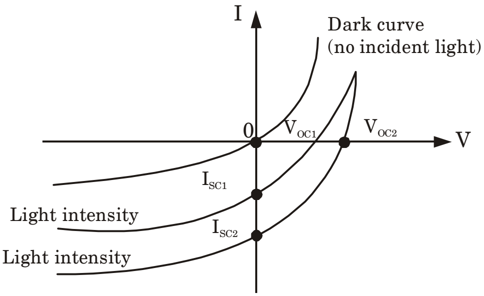


Fig. 5.27.3. Showing short circuit current and open circuit-voltage versus light intensity for a solar cell.

3. On the vertical axis, $V = 0$ anywhere and hence represents a short-circuit condition. The current at this intersection is called as short-circuit current.
4. Under open circuit condition I_{SC} is zero and the photovoltaic voltage will result. This is known as open circuited voltage and is represented by V_{OC}.

Que 5.28. **What is photodiode ? Explain how is it used as solar cell ? Describe the working of solar cell.**

Answer

A. Photodiode : Refer Q. 5.23, Page 5–28A, Unit-5.

B. Photodiode used as solar cell :

1. When the photodiode is operated in the fourth quadrant of its *I-V* characteristic, *V* is positive and *I* is negative and power is delivered from the junction to the external circuit.
2. Such a device provides a useful means of measuring illumination levels or of converting time-varying optical signals, into electrical signals.

C. Working of solar cell : Refer Q. 5.27, Page 5–33A, Unit-5.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. What is difference between BJT and MOSFET ?

Ans. Refer Q. 5.1.

Q. 2. Explain the construction and working of *n*-type enhancement MOSFET.

Ans. Refer Q. 5.2.

Q. 3. Explain the operation of enhancement type *n*-channel MOSFET as v_{DS} is increased.

Ans. Refer Q. 5.3.

Q. 4. Derive the relation between i_D and v_{DS} for NMOS transistor (triode region and saturation region).

Ans. Refer Q. 5.5.

Q. 5. Differentiate between *D*-MOSFET and *E*-MOSFET.

Ans. Refer Q. 5.6.

Q. 6. In the circuit of Fig. 1, let R_G = 10 MΩ, R_D = 10 kΩ, and V_{DD} = 10 V. Find the value of V_D and V_G for V_t = 1 V and $k_n'(W/L)$ = 0.5 mA/V².

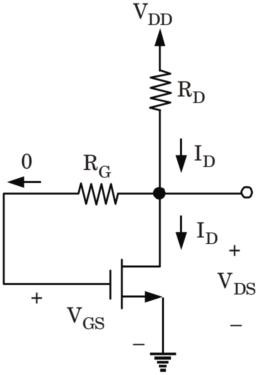


Fig. 1.

Ans. Refer Q. 5.8.

Q. 7. Write a short note on small signal operation and models. Also represent small signal equivalent circuit models.

Ans. Refer Q. 5.16.

Q. 8. What is LED ? Give its principle of working, construction, merits, demerits and applications.

Ans. Refer Q. 5.20.

Q. 9. Write a short note on double heterojunction LED.

Ans. Refer Q. 5.22.

Q. 10. What is solar cell ? Explain construction and working of solar cell.

Ans. Refer Q. 5.27.

☺☺☺

1 UNIT

Introduction to Semiconductor Physics (2 Marks Questions)

1.1. Define Heisenberg's uncertainty principle.

Ans. According to Heisenberg's principle, it is impossible to measure the exact position and momentum of a moving particle simultaneously.

1.2. If uncertainty in the position of a particle is equal to de-Broglie wavelength, what will be uncertainty in the measurement of velocity ?

Ans.

1. We have,

$$\Delta x = \lambda = \frac{h}{p} \quad \text{...(1.2.1)}$$

where, h = Planck's constant,
p = Momentum of particle

2. According to Heisenberg's uncertainty principle,

$$\Delta x \,.\, \Delta p \geq \frac{h}{2\pi} \quad \text{...(1.2.2)}$$

3. Let Δv be the uncertainty in velocity,

$$\Delta p = m.\Delta \text{v} \quad \text{...(1.2.3)}$$

4. Putting eq. (1.2.1) and eq. (1.2.3) in eq. (1.2.2)

$$\frac{h}{p} \cdot m \cdot \Delta \text{v} = \frac{h}{2\pi} \quad [\because \; p = m\text{v}]$$

5. So, uncertainty in velocity,

$$\Delta \text{v} = \frac{\text{v}}{2\pi}$$

1.3. Define wave function.

Ans. The quantity in quantum mechanics undergoes periodic changes and gives information about the particle within the wave packet. It is called wave function.

1.4. What do you mean by normalization of wave function ?

Ans. If the wave function ψ of any system is such that it gives value of integral a finite quantity say N

$$\int_{-\infty}^{\infty} \psi\psi^* \, dx = \int_{-\infty}^{\infty} |\psi|^2 \, dx = N \text{ (integral)}$$

when ψ^* = complex conjugate

Then, ψ is called normalization of wave function.

1.5. Define orthogonal wave function.

Ans. When the value of the integral is equal to zero ($N = 0$), the wave function ψ is known as orthogonal wave function.

1.6. What are eigen values and eigen functions ?

Ans. The values of energy for which steady state equation can be solved are called eigen values and the corresponding wave functions are called eigen functions.

1.7. Write the characteristics of wave function.

Ans.

1. The wave function ψ contains all the measurable information about the particle.
2. It can interfere with itself. This property explains the phenomenon of electron diffraction.
3. The wave function ψ permits the calculation of most probable value of a given variable.

1.8. What are the applications of Heisenberg's uncertainty principle ?

Ans.

1. Non-existence of electrons in the nucleus.
2. The zero point energy.
3. Finite width of spectral lines.

1.9. Classify semiconductors on the basis of energy band gap with the help of suitable diagram.

Ans. **Direct band gap semiconductors :**

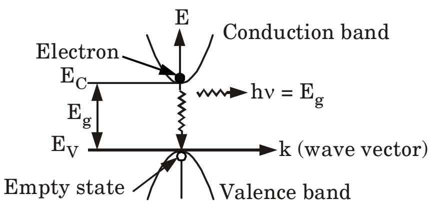


Fig. 1.9.1.

Indirect band gap semiconductors :

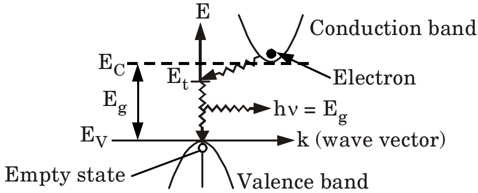


Fig. 1.9.2.

1.10. Give the difference between direct and indirect band gap semiconductors.

Ans.

S. No.	Direct band gap semiconductor	Indirect band gap semiconductors
1.	The electron fall directly from conduction band to valance band.	The electron cannot fall directly from conduction band to valance band.
2.	The energy is released in the form of light.	The energy is released in the form of heat.

1.11. What are indirect band gap semiconductors ?

AKTU 2015-16, Marks 02

Ans. In indirect band gap semiconductors, an electron in conduction band fall indirectly to valence band giving a part of energy to the lattice in the form of heat. It undergoes a change in momentum as well as energy.

Example : Si, Ge etc.

☺☺☺

2 UNIT

Energy Bands of Semiconductor (2 Marks Questions)

2.1. Compare the intrinsic and extrinsic semiconductor.

Ans.

S. No.	Intrinsic Semiconductor	Extrinsic Semiconductor
1.	Doping or addition of impurity does not take place in intrinsic semiconductor.	A small amount of impurity is doped in a pure semiconductor for preparing extrinsic semiconductor.
2.	The number of free electrons in the conduction band is equal to the number of holes in the valence band.	The number of electrons and holes are not equal.
3.	Conductivity is low.	Conductivity is high.
4.	The Fermi level lies in between conduction band and valence band.	The Fermi level lies near valence band in *p*-type and near conduction band in *n*-type.

2.2. Define diffusion current.

Ans. Diffusion current is a current in a semiconductor caused by the diffusion of charge carriers (holes and/or electrons). This is the current which is due to the transport of charges occurring because of non-uniform concentration of charged particles in a semiconductor.

2.3. What is drift current ?

Ans. The drift current is due to the motion of charge carriers, due to the force exerted on them by an electric field. Diffusion current can be in the same or opposite direction of a drift current.

2.4. Differentiate between diffusion and drift current.

Ans.

S. No.	Diffusion Current	Drift Current
1.	Diffusion current occurs even though there is not an electric field applied to the semiconductor.	Drift current occurs when the electric field is applied on the *p-n* junction.
2.	Direction of the diffusion current depends on the charge in the carrier concentrations.	Direction of the drift current depends on the polarity of the applied field.

2.5. State Hall effect.

Ans. When a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B, then an electric field E is induced in the direction perpendicular to both I and B. This phenomenon is called Hall effect.

2.6. Which semiconductor parameters are measured from Hall effect ?

Ans. The Hall effect may be used to :

1. Determine whether a semiconductor is p-type or n-type.
2. Determine the carrier concentration.
3. Measure the mobility μ by measuring the conductivity σ.

2.7. The single carrier holes in a silicon sample are 2.05×10^{22} m^{-3}. Calculate its Hall coefficient.

Ans.

$$R_H = \frac{1}{ne} = \frac{1}{(2.05 \times 10^{22})(1.6 \times 10^{-19})}$$

$$= 3.048 \times 10^{-4} \text{ m}^3/\text{C}$$

2.8. The resistivity of a sample semiconductor is 9 milli-ohm-meter. Its holes have mobility of 0.03 m²/V-s. Calculate Hall coefficient.

Ans. Conductivity, $\sigma = \dfrac{1}{\rho} = \dfrac{1}{9 \times 10^{-3}} = 111.\ 11 / \Omega\text{-m}$

Hall coefficient, $R_H = \dfrac{\mu}{\sigma} = \dfrac{0.03}{111.11}$

$$= 2.7 \times 10^{-4} \text{ m}^3/\text{C}$$

2.9. The mobility of electron in silicon is 0.15 m² V⁻¹ s⁻¹ at 300 K. Calculate the diffusion coefficient.

Ans. Diffusion coefficient is given by,

$$D_n = \mu_n \left[\frac{kT}{q}\right] = \frac{0.15 \times 1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}}$$

$$= 3.88 \times 10^{-3} \text{ m}^2/\text{s}$$

2.10. In an *n*-type GaAs crystal at 300 K, the electron concentration varies along the *x*-axis as

$$n(x) = 10^{16}\ e^{-\frac{x}{L}} \text{ cm}^{-3}; x > 0.$$

where *L* is 1 μm. Calculate the diffusion current density at *x* = 0 if the electron diffusion coefficient is 220 cm²/s.

Ans.

$$J_n \text{ (diffusion)} = q\, D_n \left.\frac{d}{dx} n(x)\right|_{x=0}$$

$$= 1.6 \times 10^{-19} (220) \left[\frac{d}{dx} 10^{16}\ e^{-\frac{x}{L}}\right]$$

$$= 1.6 \times 10^{-19} \times 220 \times 10^{16} \left[\frac{-1}{10^{-4}}\right]$$

$$= -3.52 \text{ kA/cm}^2$$

2.11. What do you mean by diffusion of carriers ?

AKTU 2018-19, Marks 02

Ans. Diffusion is the natural result of the random motion of the individual molecules from a region of high carrier concentration to region of low carrier concentration when the electron and hole concentrations vary with position in the sample. This type of phenomenon is called diffusion of carrier.

2.12. Name the layouts for designing the resistances.

Ans.

1. Dogbone layout.
2. Analog interdigitated layout.
3. Dummy resistor layout.
4. Thermoelectric cancellation layout.

☺☺☺

3 UNIT

Generation and Recombination of Carrier (2 Marks Questions)

3.1. Define direct recombination process.

Ans. An electron can drop directly from the conduction band into the valence band. This is known as direct recombination process.

3.2. Discuss indirect recombination in brief.

Ans. An electron initially makes a transition to an energy level lying deep in the band gap, and it subsequently captures a hole from the valence band. This is known as indirect recombination.

3.3. What is auger recombination process ?

Ans. The auger recombination process occurs by the transfer of the energy and momentum released by the recombination of an election-hole pair to a third particle that can be either an election or a hole.

3.4. Write the expression for Poisson equation.

Ans. The expression of Poisson's equation is,

$$\frac{\partial E}{\partial x} = \frac{\rho_s}{\varepsilon_s}$$

where ε_s is the semiconductor dielectric permittivity and ρ_s is the space charge density given by the algebraic sum of the charge carrier densities and the ionized impurity concentrations.

3.5. What is Einstein relation ?

Ans. Einstein relation is given by,

$$\frac{D}{\mu} = \frac{kT}{q}$$

where, D = Diffusion constant
μ = Mobility
k = Boltzmann's constant

3.6. Define contact potential.

Ans. The potential difference ($V_n - V_p$) developed across the depletion region is called as contact potential (V_o).

3.7. Draw the V-I characteristics of *p-n* junction.

Ans.

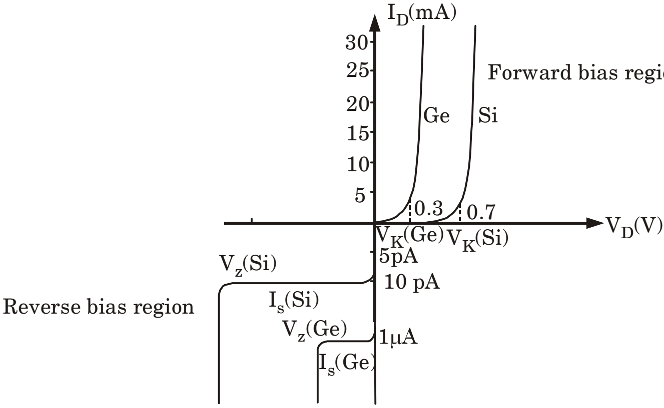


Fig. 3.7.1. Volt-ampere characteristics of p-n junction.

3.8. How does direct recombination lifetime differ from indirect recombination lifetime ? **AKTU 2017-18, Marks 02**

Ans. Carrier lifetime is the time taken by carrier to recombine. In direct recombination, the process of transition of electrons from conduction band to valence band occurs simultaneously. Carrier will take less time to recombine. Therefore, carrier lifetime tends to be very short, typically in nanoseconds.

In case of indirect recombination, carrier takes more time to recombine, therefore lifetime of carrier is more in this case.

3.9. Obtain the value of contact potential of an abrupt junction at room temperature, if intrinsic concentration is $n_i = 1.6 \times 10^{16}/\text{m}^3$ and doping level is $N_a = N_d = 10^{21}/\text{m}^3$.

Ans. Given, $n_i = 1.6 \times 10^{16} / \text{m}^3$, $N_a = N_d = 10^{21} / \text{m}^3$.

$$V_0 = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

$$= 0.0259 \ln \frac{10^{21} \times 10^{21}}{(1.6 \times 10^{16})^2}$$

$$= 0.57 \text{ V}$$

3.10. What do you mean by space charge region at a junction ?

Ans. The space charge on *n*-side is positively charged and on *p*-side it is negatively charged. Fig. 2 shows the space charge region (or transition region) on the two sides of the junction.

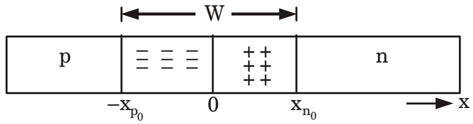


Fig. 3.10.1.

3.11. Draw small signal model of *p-n* junction ?

Ans.

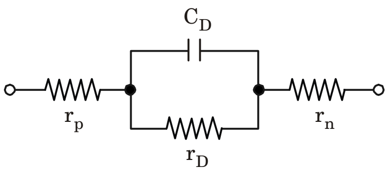


Fig. 3.11.1.

where, r_D = Small-signal diode resistance.

C_D = Capacitance across junction.

r_p and r_n = Series resistances.

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4 UNIT

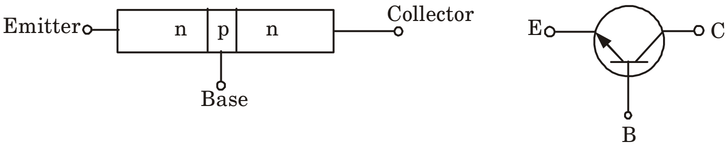
BJT (2 Marks Questions)

4.1. Define BJT.

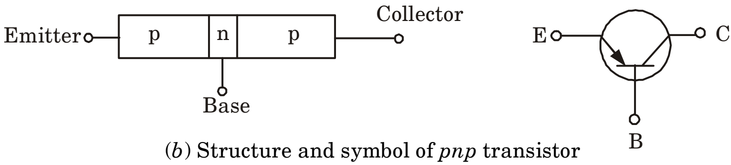
Ans. BJT is a bipolar device which can operate in one of four possible modes : cut-off, active, saturation, and reverse active.

4.2. Draw the structure and symbol of *npn* and *pnp* transistors.

Ans.



(*a*) Structure and symbol of *npn* transistor



(*b*) Structure and symbol of *pnp* transistor

Fig. 4.2.1.

4.3. Compare *CB*, *CE* and *CC* configuration.

Ans.

S. No.	Property	*CB*	*CE*	*CC*
1.	Input resistance	Low	Moderate	High
2.	Output resistance	High	Moderate	Low
3.	Current gain	Less than 1	High	Highest
4.	Phase shift	0° or 360°	180°	0° or 360°

4.4. What are the internal capacitances of BJT ?

AKTU 2016-17, Marks 02

Ans. The various internal capacitances are as follows :

1. Base-charging or diffusion capacitance, C_{de}.

2. Base-emitter junction capacitance, C_{je}.
3. Collector-base junction capacitance, C_{μ}.

4.5. Define α and β of transistor.

Ans.

1. α is the current amplification factor in common base transistor. It is defined as the ratio of the collector current to the emitter current of a transistor when no signal is applied.

$$\alpha = \left|\frac{I_C}{I_E}\right|$$

2. β is the current gain in common emitter configuration. It is defined as the ratio of the collector current to the base current, when no signal is applied.

$$\beta = \left|\frac{I_C}{I_B}\right|$$

4.6. Give one application of *CB*, *CE* and *CC* transistors.

Ans.

1. *CB* amplifier is useful as a high frequency amplifier.
2. The *CE* configuration is the one best suited for realizing the bulk of the gain required in an amplifier.
3. The *CC* has application as a voltage buffer for connecting a high resistance source to a low resistance load and as the output stage in a multistage amplifier.

4.7. What are the effects of including a resistance in the emitter of the *CE* amplifier ?

Ans.

1. The input resistance increase by the factor $(1 + g_m R_e)$.
2. The voltage gain from base to collector is reduced by the factor $(1 + g_m R_e)$.
3. The high frequencies response significantly improved.
4. The overall voltage gain is less dependent on the value of β.

4.8. Why the collector region is made physically larger than the emitter region ?

Ans. Collector region is made physically larger than the emitter region because collector has to dissipate much more power or heat.

4.9. Why *CE* configuration is the most preferred transistor configuration when used as a switch ?

Ans. Because it requires low voltage or current for operating the switch.

4.10. Brief the Avalanche breakdown mechanism.

AKTU 2017-18, Marks 02

Ans.

1. Avalanche breakdown is caused by a process known as secondary multiplication, and it occurs in junctions having thicker depletion regions, which makes tunneling less probable.

2. In a reverse-biased junction, the thermally generated minority carriers (mainly holes in a p^+-n junction) injected into the space-charge region is accelerated by the field and gain kinetic energy from the field.

4.11. A transistor is having α = 0.98. For collector current of 10 mA, find the base current of transistor.

OR

Find the current gain β in CE configuration of BJT, if α = 0.98. **AKTU 2017-18, Marks 02**

Ans.

1. Given, $\alpha = 0.98$
2. We have, $$\beta = \frac{\alpha}{1-\alpha}$$ $$= \frac{0.98}{1-0.98} = 49$$
3. Base current, $$I_B = \frac{I_C}{\beta} = \frac{10 \times 10^{-3}}{49}$$ $$I_B = 0.204 \text{ mA}$$

4.12. A *CE* amplifier is having I_C = 1 mA, β_0 = 100, V_A = 100 V. Calculate g_m, r_π, r_0.

Ans.

$$g_m = \frac{I_C}{V_T} = \frac{1 \times 10^{-3}}{25 \times 10^{-3}}$$

$$g_m = 40 \text{ mA/V}$$

$$r_\pi = \frac{\beta_0}{g_m} = \frac{100}{40 \times 10^{-3}}$$

$$r_\pi = 2.5 \text{ k}\Omega$$

$$r_0 = \frac{V_A}{I_C} = \frac{100}{1 \times 10^{-3}} = 100 \text{ k}\Omega$$

4.13. What do you mean by base width modulation in BJT ?

AKTU 2017-18, Marks 02

Ans. Base width modulation or the early effect is the variation in the width of the base in the bipolar transistor due to variation in the applied base-to-collector voltage. For example, greater reverse bias across the collector-base junction increases the collector base depletion width.

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5 UNIT

MOSFET and Optoelectronic Devices (2 Marks Questions)

5.1. What is MOSFET ?

Ans. MOSFET stands for Metal Oxide Semiconductor Field Effect Transistor. MOSFET is one of the most widely used electronic devices. In this device, the channel current is controlled by a voltage applied at a gate electrode that is isolated from the channel by an insulator.

5.2. What is transistor ? Explain its types.

AKTU 2018-19, Marks 02

Ans. A transistor is a semiconductor device to amplify or switch electronic signals and electrical power.

Types :

1. **BJT :** Refer Q. 4.1, Page SQ–1A, Unit-4, 2 Marks Questions.
2. **FET :** It is a unipolar device depending solely on either election or hole.

5.3. What are the types of MOSFET ? Also give their two major differences.

OR

Differentiate E-MOSFET with D-MOSFET.

AKTU 2017-18, Marks 02

Ans. Types of MOSFET :

1. Enhancement type MOSFET. 2. Depletion type MOSFET.

Differences :

S. No.	*E*-MOSFET	*D*-MOSFET
1.	Operates only in enhancement mode.	Operates in both depletion mode and enhancement mode.
2.	There is no physical channel from source to drain. We have to enhance it by applying v_{GS}.	The channel is already formed between source and drain.
3.	Commonly used bias circuits : gate bias, voltage divider bias, drain-feedback bias.	Commonly used bias circuits : gate bias, self bias, voltage-divider bias, zero bias.

5.4. Mention the difference between *n*-channel and *p*-channel MOSFET.

Ans.

S. No.	*n*-channel MOSFET	*p*-channel MOSFET
1.	Current carriers are electrons.	Current carriers are holes.
2.	Faster	Slower
3.	Transconductance is high.	Transconductance is low.

5.5. Define the unity gain frequency.

Ans. Unity gain frequency (f_T) is a figure of merit for high frequency operation of the MOSFET as an amplifier. At this frequency, the short circuit current gain of the common source configuration becomes unity. It is given by

$$f_T = \frac{g_m}{2\pi (C_{gs} + C_{gd})}$$

5.6. Why the *CS* amplifier have a large input capacitance C_{in} and hence a low f_H?

Ans. It is because of the Miller effect that causes the *CS* amplifier to have a large total input capacitance C_{in} and hence a low f_H.

5.7. Define responsivity of photodiode.

OR

What is figure of merit of photodiode ?

Ans. Figure of merit of photodiode is given by its responsivity. The responsivity of photodiode is defined as the photo current generated per unit optical power, *i.e.*,

$$R = \frac{i}{P} = \frac{\eta e}{h\nu} = \frac{\eta}{h\nu / e}$$

5.8. What are solar cells ?

Ans. Solar cells are semiconductor junction devices which are used for converting optical radiation into electrical energy. The generated electric voltage is proportional to the intensity of incident light.

5.9. What are advantages of solar cells ?

Ans.

1. The solar cell is self generating device, *i.e.*, it does not require any external power source.
2. The solar cells can be operated satisfactorily over a wide range of temperature.
3. It is a pollution-free energy conversion system.

5.10. What are the limitations of solar cells ?

Ans.

1. It does not convert all solar radiation into electric energy.
2. The efficiency is low.
3. The efficiency is temperature dependent.

5.11. Define fill factor of solar cell.

Ans. Fill factor is used to define the power extraction of the cell. It is given by,

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}}$$

5.12. What do you understand by LED ?

Ans. Light emitting diode (LED) is a special type of semiconductor *p-n* junction diode that under forward bias emits external radiation in ultraviolet, visible and infrared regions of electromagnetic spectrum.

5.13. Give the comparison between photodiode and LED.

Ans.

S. No.	Photodiode	LED
1.	It is a light detecting device.	It is a light emitting device.
2.	Electric current is produced which is proportional to light.	Electric energy is converted into light energy.
3.	It is always reverse biased.	It is always forward biased.

5.14. In the linear region operation of MOSFET drain current decreases as the temperature increases. Explain.

AKTU 2018-19, Marks 02

Ans. Since mobility decreases as temperature increases, so in MOSFETs current I_{DS} decreases with rise in temperature.

5.15. What is meant by threshold voltage ?

AKTU 2018-19, Marks 02

Ans. It means that the minimum voltage required to activate any active components. Minimum gate voltage to turn ON the transistor is called threshold voltage.

5.16. What do you mean by optoelectronic devices ?

AKTU 2018-19, Marks 02

Ans. Optoelectronic devices are the electronic devices that detect and control light.

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B. Tech.
(SEM. III) ODD SEMESTER THEORY EXAMINATION, 2017-18
ELECTRONIC DEVICES AND CIRCUITS

Time : 3 Hours **Max. Marks : 70**

Note : Attempt **all** sections. If require any missing data; then choose suitably.

SECTION-A

1. Attempt **all** questions in brief. **(2 × 7 = 14)**

a. Mention the advantages of negative feedback.

b. What do you mean by base width modulation in BJT ?

c. What is fluorescence ?

d. How does direct recombination lifetime differ from indirect recombination lifetime ?

e. Brief the Avalanche breakdown mechanism.

f. Differentiate E-MOSFET with D-MOSFET.

g. Find the current gain β in CE configuration of BJT, if $\alpha = 0.98$.

SECTION-B

2. Attempt any **three** of the following : **(7 × 3 = 21)**

a. Draw the CE amplifier with a resistance connected in emitter and derive the expression for different characterising parameters.

b. Discuss the various capacitances for BJT and MOSFET.

c. Explain the phenomenon of luminescence. What are its different types ? How does fluorescence differ from phosphorescence ? Discuss its application as a fluorescence lamp.

d. What is Einstein relation ? Develop an expression to establish relation between diffusion coefficient and mobility of carriers.

e. Boron is implanted in to a *n*-type Si sample having donor concentration of $10^{16}/cm^3$, to form abrupt junction. If the acceptor concentration in *p*-type region is $4 \times 10^{18}/cm^3$, determine the

i. Width of the depletion region.

ii. Depth of penetration on *n*-side and *p*-side at equilibrium. Take room temperature as 27 °C; $n_i = 1.5 \times 10^{10}/cm^3$ and relative permittivity of boron as 11.8.

SECTION-C

3. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. Draw the four basic feedback topologies. Compare the input and output resistance among the feedback topologies.

b. Explain the working of common source with a resistance is connected in source lead. Draw its small signal equivalent circuit. Deduce the expression for overall voltage gain.

4. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. Differentiate between direct and indirect band gap semiconductor. Also discuss the variation of energy band with alloy composition.

b. What do you mean by Fermi level ? Discuss the effect of temperature and doping on mobility. A Si sample is doped with 10^{17} As atoms/cm³. What is the equilibrium hole concentration on P_0 at 300 K ? Where is E_F relative to E_i.

5. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. Design the circuit shown in the Fig. 1 to establish a drain of 0.1 V, what is the effective resistance between drain and source at this operating point ? Let V_t = 1 V, and $k'_n (W/L) = 1$ mA/V².

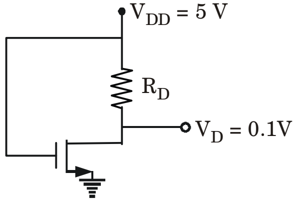

Fig. 1.

b. Construct *p*-channel enhancement MOSFET. Draw and explain the I-V characteristics when V_{DS} is increased.

6. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. How BJT can be used as an amplifier and as a switch ? Justify using required circuit waveform, mathematical expression.

b. Mention the different biasing technique in BJT. Explain any two of them.

7. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. Draw the high frequency hybrid-π model of MOSFET and show that $f_T = g_m/2\pi(C_{gs} + C_{gd})$.

b. Mention the conditions for oscillation. Derive the expression for frequency of oscillation in phase shift oscillator.

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SOLUTION OF PAPER (2017-18)

Note : Attempt **all** sections. If require any missing data; then choose suitably.

SECTION-A

1. Attempt **all** questions in brief. **(2 × 7 = 14)**

a. Mention the advantages of negative feedback.

Ans. This question is out of syllabus from session 2019-20.

b. What do you mean by base width modulation in BJT ?

Ans. Base width modulation or the early effect is the variation in the width of the base in the bipolar transistor due to variation in the applied base-to-collector voltage. For example, greater reverse bias across the collector-base junction increases the collector base depletion width.

c. What is fluorescence ?

Ans. This question is out of syllabus from session 2019-20.

d. How does direct recombination lifetime differ from indirect recombination lifetime ?

Ans. Carrier lifetime is the time taken by carrier to recombine. In direct recombination, the process of transition of electrons from conduction band to valence band occurs simultaneously. Carrier will take less time to recombine. Therefore, carrier lifetime tends to be very short, typically in nanoseconds.
In case of indirect recombination, carrier takes more time to recombine, therefore lifetime of carrier is more in this case.

e. Brief the Avalanche breakdown mechanism.

Ans.

1. Avalanche breakdown is caused by a process known as secondary multiplication, and it occurs in junctions having thicker depletion regions, which makes tunneling less probable.
2. In a reverse-biased junction, the thermally generated minority carriers (mainly holes in a p^+-n junction) injected into the space-charge region is accelerated by the field and gain kinetic energy from the field.

f. Differentiate E-MOSFET with D-MOSFET.

Ans.

S. No.	*E*-MOSFET	*D*-MOSFET
1.	Operates only in enhancement mode.	Operates in both depletion mode and enhancement mode.
2.	There is no physical channel from source to drain. We have to enhance it by applying v_{GS}.	The channel is already formed between source and drain.
3.	Commonly used bias circuits : gate bias, voltage divider bias, drain-feedback bias.	Commonly used bias circuits : gate bias, self bias, voltage-divider bias, zero bias.

g. Find the current gain β in CE configuration of BJT, if α = 0.98.

Ans.

1. Given, $\alpha = 0.98$
2. We have, $$\beta = \frac{\alpha}{1-\alpha}$$ $$= \frac{0.98}{1-0.98} = 49$$

SECTION-B

2. Attempt any **three** of the following : **(7 × 3 = 21)**

a. Draw the CE amplifier with a resistance connected in emitter and derive the expression for different characterising parameters.

Ans.

1. Fig. 1(*a*) shows a common emitter amplifier with an emitter resistance R_e. This resistor can be utilized by the designer as an effective design tool for tailoring the amplifier characteristics to fit the design requirement.
2. $$R_{in} = R_B \,||\, R_{ib}$$ where, $$R_{ib} = \frac{v_i}{i_b} = (\beta + 1)\,(r_e + R_e) \text{ and } v_o = -\,i_c\,(R_C \,||\, R_L)$$
3. The voltage gain, $$A_v = \frac{v_o}{v_i} = -\,\alpha\,\frac{(R_C \,||\, R_L)}{r_e + R_e}$$
4. The open loop voltage gain, $$A_{vo} = -\,\alpha\,\frac{R_c}{r_e + R_e} \qquad (\because R_L = \infty)$$
5. The output resistance, $R_{out} = R_C$

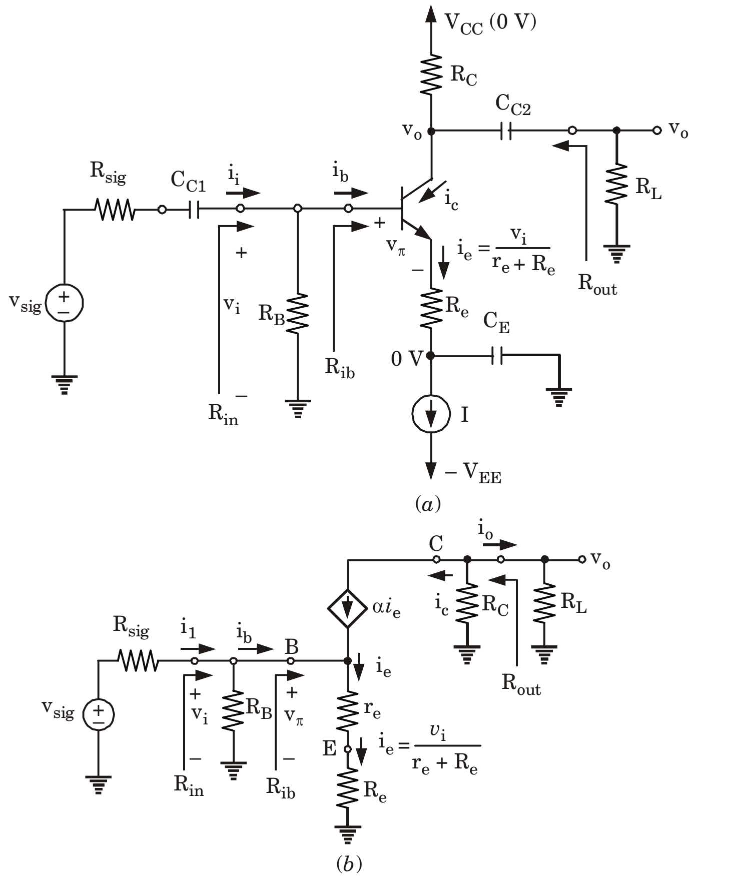

Fig. 1. (*a*) A common emitter amplifier with an emitter resistance R_e.
(*b*) Equivalent circuit obtained by replacing the transistor with its *T* model.

6. For $R_B >> R_{ib}$, short circuit current gain,

$$A_{is} = \frac{-\alpha\,(\beta + 1)\,(r_e + R_e)}{R_e + r_e} = -\beta$$

7. Overall voltage gain from source to load can be obtained by multiplying A_v by $\left(\frac{v_i}{v_{sig}}\right)$

$$G_v = \frac{v_i}{v_{sig}} A_v = -\frac{R_{in}}{R_{sig} + R_{in}} \cdot \frac{\alpha\,(R_C \parallel R_L)}{r_e + R_e}$$

Substituting R_{in} and assuming $R_B >> R_{ib}$ and substituting R_{ib}

$$G_v = -\frac{\beta(R_C \parallel R_L)}{R_{sig} + (\beta+1)(r_e + R_e)}$$

b. Discuss the various capacitances for BJT and MOSFET.

Ans.

A. BJT internal capacitance :

i. Base charging or diffusion capacitance, C_{de} : When the transistor is operating in the active or saturation modes, minority carrier charge, Q_n, is stored in the base region. Q_n can be calculated in terms of the collector current i_c.

$$Q_n = \frac{W^2}{2D_n} i_C = \tau_F i_C$$

where, τ_F is a device constant.

$$\tau_F = \frac{W^2}{2D_n}$$

τ_F is known as the forward base transit time.

For small signals we can define the small signal diffusion capacitance

$$C_{de} = \frac{dQ_n}{dv_{BE}} = \tau_F \frac{di_C}{dv_{BE}} = \tau_F g_m = \tau_F \frac{I_C}{V_T}$$

ii. Base-emitter junction capacitance, C_{je} :

$$C_{je} = \frac{C_{je0}}{\left(1 - \frac{V_{BE}}{V_{0e}}\right)^m}$$

where, C_{je0} is the value of C_{je} at zero voltage, V_{0e} is the emitter-base junction (EBJ) built in voltage and m is the grading coefficient of the EBJ junction. One typically uses an approximate value of C_{je}.

$$C_{je} \simeq 2\, C_{je0}$$

iii. Collector-base junction capacitance, C_μ : In active mode operation, the collector-base junction is reversed biased, and its junction or depletion capacitance, C_μ becomes

$$C_\mu = \frac{C_{\mu 0}}{\left(1 - \frac{V_{CB}}{V_{0c}}\right)^m}$$

where, $C_{\mu 0}$ is the value of C_μ at zero voltage, V_{0c} is the CBJ built in voltage and m is the grading coefficient.

B. Types of internal capacitances of MOSFET :

a. The gate capacitive effect :

1. It can be modeled by the three capacitances C_{gs}, C_{gd}, C_{gb}. The values of these capacitances are as follows :
   i. When the MOSFET is operating in the triode region at small v_{DS}, the channel will be of uniform depth, thus,

$$C_{gs} = C_{gd} = \frac{1}{2} WL\, C_{ox} \qquad \text{(triode region)}$$

ii. When the MOSFET operates in saturation, the channel has a tapered shape and is pinched off at or near the drain end, thus,

$$C_{gs} = \frac{2}{3} WL\, C_{ox} \qquad \text{(saturation region)}$$

$$C_{gd} = 0$$

iii. When the MOSFET is cut off, the channel disappears, and thus,

$$C_{gs} = C_{gd} = 0$$

$$C_{gb} = WL\, C_{ox} \qquad \text{(cut-off region)}$$

iv. There is an additional small capacitive component that should be added to C_{gs} and C_{gd}. If the overlap length is denoted L_{ov}, the overlap capacitance component is

$$C_{ov} = WL_{ov}\, C_{ox}$$

b. The junction capacitances :

1. For the source diffusion, we have the source body capacitance, C_{sb},

$$C_{sb} = \frac{C_{sb0}}{\sqrt{1+\dfrac{V_{SB}}{V_0}}}$$

where C_{sb0} is the value of C_{sb} at zero body source bias, V_{SB} is the magnitude of the reverse bias voltage and V_0 is the junction built-in-voltage.

2. Similarly for the drain diffusion, the drain-body capacitance C_{db},

$$C_{db} = \frac{C_{db0}}{\sqrt{1+\dfrac{V_{DB}}{V_0}}}$$

where C_{db0} is the capacitance value at zero reverse-bias voltage and V_{DB} is the magnitude of the reverse-bias voltage.

c. Explain the phenomenon of luminescence. What are its different types ? How does fluorescence differ from phosphorescence ? Discuss its application as a fluorescence lamp.

Ans. This question is out of syllabus from session 2019-20.

d. What is Einstein relation ? Develop an expression to establish relation between diffusion coefficient and mobility of carriers.

Ans.

1. Fig. 2 shows energy band diagram of a semiconductor in electric field $\varepsilon(x)$.
2. Since electrons drift in a direction opposite to the field therefore the potential energy for electrons will increase in the direction of the field.

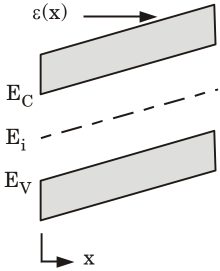

Fig. 2. Energy band diagram of a semiconductor in an electric field $\varepsilon(x)$.

3. The electrostatic potential $V(x)$ varies in the opposite direction, since it is defined in terms of positive charges therefore related to electron potential energy $\varepsilon(x)$ as,

$$V(x) = \frac{E(x)}{-q} \qquad ...(1)$$

4. We know, electric field $\varepsilon(x) = \dfrac{-dV(x)}{dx}$

choosing E_i as a convenient reference, the electric field can be related as,

$$\varepsilon(x) = \frac{-d}{dx}\left[\frac{E_i}{-q}\right] = \frac{1}{q}\frac{dE_i}{dx} \qquad ...(2)$$

5. At equilibrium, no net current flows in a semiconductor, therefore

$$J_p(x) = q\mu_p\, p(x)\, \varepsilon(x) - qD_p \frac{dp(x)}{dx} = 0$$

$$q\mu_p p(x)\, \varepsilon(x) = qD_p \frac{dp(x)}{dx}$$

$$\varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{p\,(x)}\frac{dp(x)}{dx} \qquad ...(3)$$

6. To calculate the value of $\dfrac{1}{p(x)}\dfrac{dp(x)}{dx}$

we know, $\quad p = n_i\, e^{(E_i - E_F)/kT}$

$$\frac{p}{n_i} = e^{(E_i - E_F)/kT}$$

taking log on both sides,

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

$$\therefore \qquad \ln p - \ln n_i = \frac{E_i - E_F}{kT} \qquad ...(4)$$

7. Differentiating eq. (4) with respect to x we get

$$\frac{1}{p}\frac{dp}{dx} - 0 = \frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right] \qquad (\because n_i = \text{constant})$$

$$\frac{1}{p}\frac{dp}{dx} = \frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right] \qquad ...(5)$$

8. Putting the value of eq. (5) in eq. (3)

$$\varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right]$$

9. The equilibrium Fermi level does not vary with x, and derivative of E_i is given as $q\varepsilon(x)$

$$\therefore \qquad \varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{kT} \times q\varepsilon(x)$$

$$\frac{1}{q} = \frac{D_p}{\mu_p} \times \frac{1}{kT}$$

$$\frac{kT}{q} = \frac{D_p}{\mu_p}$$

or

$$\frac{D}{\mu} = \frac{kT}{q} \qquad ...(6)$$

10. Eq. (6) is known as Einstein relation.

e. Boron is implanted in to a n-type Si sample having donor concentration of 10^{16}/cm^3, to form abrupt junction. If the acceptor concentration in p-type region is 4×10^{18}/cm^3, determine the

i. Width of the depletion region.

ii. Depth of penetration on n-side and p-side at equilibrium. Take room temperature as 27 °C; $n_i = 1.5 \times 10^{10}$/cm^3 and relative permittivity of boron as 11.8.

Ans.

Given : $N_d = 10^{16}$ cm^{-3}, $N_a = 4 \times 10^{18}$ cm^{-3},
$n_i = 1.5 \times 10^{10}$ cm^{-3}, $\varepsilon_r = 11.8\varepsilon_0$, $\varepsilon_0 = 8.85 \times 10^{-14}$ F/cm
To Find : Width of the depletion region, Depth of penetration on n-side and p-side at equilibrium.

1. Contact potential,

$$V_0 = \frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$= 0.0259 \ln \left(\frac{4 \times 10^{18} \times 10^{16}}{(1.5 \times 10^{10})^2}\right)$$

$$= 0.0259 \ln (1.78 \times 10^{14})$$

$$V_0 = 0.85 \text{ V}$$

2. $$W = \left[\frac{2\varepsilon V_0}{q}\left(\frac{N_a + N_d}{N_a \cdot N_d}\right)\right]^{1/2}$$

$$= \left[\frac{2 \times (11.8 \times 8.85 \times 10^{-14})(0.85)}{(1.6 \times 10^{-19})} \times \left(\frac{4 \times 10^{18} + 10^{16}}{4 \times 10^{18} \times 10^{16}}\right)\right]^{1/2}$$

$$= 3.34 \times 10^{-5} \text{ cm}$$

$$W = 0.334 \ \mu\text{m}$$

3. $$x_{n0} = \frac{WN_a}{N_d + N_a} = \frac{W}{1 + N_d / N_a}$$

$$= \frac{0.334 \ \mu\text{m}}{1 + \{10^{16} / (4 \times 10^{18})\}} = \frac{0.334 \ \mu\text{m}}{1.0025}$$

$$x_{n0} = 0.333 \ \mu\text{m}$$

4. $$x_{p0} = \frac{WN_d}{N_a + N_d} = \frac{W}{1 + N_a / N_d} = \frac{0.334 \ \mu\text{m}}{1 + 400} = \frac{0.334 \ \mu\text{m}}{401}$$

$$x_{p0} = 0.83 \text{ nm}$$

SECTION-C

3. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. Draw the four basic feedback topologies. Compare the input and output resistance among the feedback topologies.

Ans. This question is out of syllabus from session 2019-20.

b. Explain the working of common source with a resistance is connected in source lead. Draw its small signal equivalent circuit. Deduce the expression for overall voltage gain.

Ans.

1. Since, R_{in} does not depend on R_L and therefore $R_{in} = R_i$.
2. At the point $i_g = 0$, $R_{in} = R_G$

$$v_i = v_{sig} \frac{R_{in}}{R_{in} + R_{sig}} = v_{sig} \frac{R_G}{R_G + R_{sig}}$$

and $$v_{gs} = v_i \frac{1/g_m}{\dfrac{1}{g_m} + R_S} = \frac{v_i}{1 + g_m R_S}$$

thus, R_S can be used to control the magnitude of the signal v_{gs}.

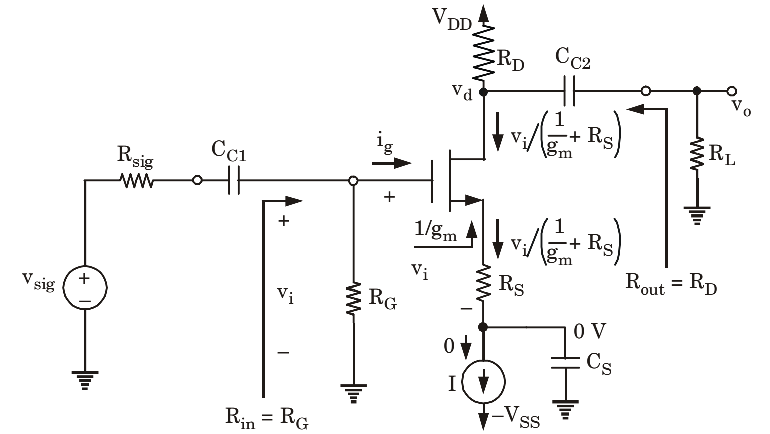

Fig. 3. CS amplifier with R_S is source lead.

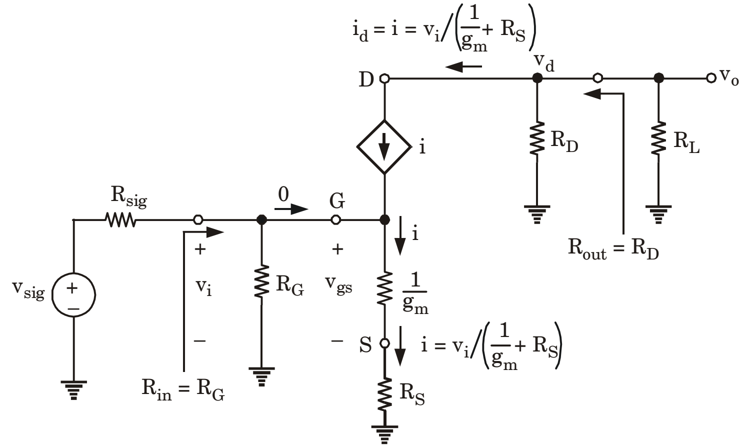

Fig. 4. Small-signal equivalent circuit with r_o reglected.

3. The current, $i_d = i = v_i/[(1/g_m) + R_S)] = \dfrac{g_m\, v_i}{1 + g_m\, R_S}$

4. Output voltage $v_o = -\, i_d\, (R_D \,||\, R_L)$

$\therefore \qquad A_v = -\dfrac{g_m\,(R_D\,||\,R_L)}{1 + g_m\, R_S}$

5. If $R_L = \infty$, $\qquad A_{vo} = \dfrac{-\, g_m\, R_D}{1 + g_m\, R_S}$

6. Overall voltagegain $G_v = -\dfrac{R_G}{R_G + R_{sig}} \dfrac{g_m\,(R_D\,||\,R_L)}{1 + g_m\, R_S}$

7. The output resistance is given by $R_{out} = R_D$

4. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. Differentiate between direct and indirect band gap semiconductor. Also discuss the variation of energy band with alloy composition.

Ans.

A. Difference :

S. No.	Direct band gap semiconductor	Indirect band gap semiconductor
1.	A direct band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band aligns with the minimum energy level of the conduction band with respect to momentum.	An indirect band-gap (IBG) semiconductor is one in which the maximum energy level of the valence band are misaligned with the minimum energy level of the conduction band with respect to momentum.
2.	In a DBG semiconductor, a direct recombination takes place with the release of the energy equal to the energy difference between the recombining particles.	Due to a relative difference in the momentum, first the momentum is conserved by release of energy and only after both the momentum aligns themselves, a recombination occurs accompanied with the release of energy.
3.	The efficiency factor of a DBG semiconductor is more.	The probability of a radiative recombination is less.
4.	Example of DBG semiconductor is gallium arsenide (GaAs)	Examples of IBG semiconductors are silicon and Germanium.
5.	DBG semiconductors emit light.	IBG semiconductors emit heat.

B. Variation of energy bands with alloy composition :

1. The energy band gap E_g is a very important parameter of a semiconductor. The wavelength (colour) of the light emitted by a direct semiconductor depends on this gap.
2. This means that we can only get certain limited wavelengths from the semiconductors. But that is not true. We can get number of wavelengths using alloy semiconductor.
3. Alloy semiconductors provide a class of semiconductor materials where the band gap can be varied continuously by having proper percentage of alloying.

4. A particular alloy semiconductor may behave as direct semiconductor for certain of its alloying range and starts behaving as an indirect semiconductor for the remaining range.
5. Let consider a particular case of $Al_xGa_{1-x}As$. GaAs is a column III-V compound semiconductor. Ga and Al both belong to column III, so they can easily replace each other.
6. In this alloy, let x % of Ga are replaced by Al in GaAs and one gets $Al_xGa_{1-x}As$. The band gap variation with alloy composition is shown in Fig. 5.
7. This alloy has three energy bands in conduction band variation of x (*i.e.*, x in Al_x). The energy of these bands change, therefore band gap will change. Further the alloy behaves as a direct semiconductor up to $x = 0.38$.

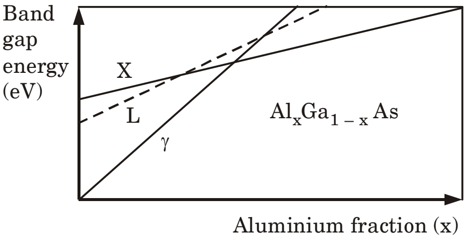

Fig. 5. Band gap variation with alloy composition.

b. What do you mean by Fermi level ? Discuss the effect of temperature and doping on mobility. A Si sample is doped with 10^{17} As atoms/cm³. What is the equilibrium hole concentration on P_0 at 300 K ? Where is E_F relative to E_i.

Ans.

A. Fermi level : It is the energy state having probability of half of being occupied by an electron.

B. Effect of temperature on mobility : The mobility is determined by scattering of the carriers. Scattering mechanism influence electron and hole mobility.

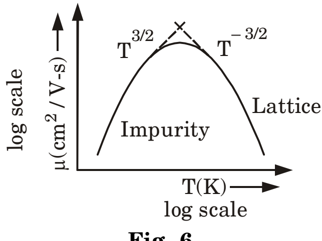

Fig. 6.

i. Lattice scattering :

1. If scattering occurs due to vibrations of lattice atom then it is called lattice scattering.

2. As the temperature increases, the frequency of lattice vibration increases. As a result, the mobility decreases.
3. The approximate temperature dependency is given by $T^{-3/2}$ as shown in Fig. 6.

ii. Impurity scattering :

1. If scattering occurs under the influence of interaction with impurity atoms, it is called impurity scattering.
2. Such scattering dominates at low temperature. At low temperature the thermal motion of carriers is slow. So, there is an increase in mobility (μ) as the temperature increases. The dependency is expressed by $T^{3/2}$ as shown in Fig. 6.

C. Numerical :

Given : $N_d = 10^{17}$ atoms/cm^3, $T = 300$ K.
To Find : p_0, $E_F - E_i$

1. Since, $N_d > n_i$ we can approximate $n_0 = N_d$ and $n_i = 1.5 \times 10^{10}$ cm^{-3} (For Si)

$$p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{17}}$$

$$p_0 = 2250 \text{ atoms/cm}^3$$

2. Fermi level,

$$E_F - E_i = kT \ln\left(\frac{n_0}{n_i}\right) = 0.0259 \ln\left(\frac{10^{17}}{1.5 \times 10^{10}}\right) = 0.406 \text{ eV}$$

3. The resulting band diagram is shown in Fig. 7.

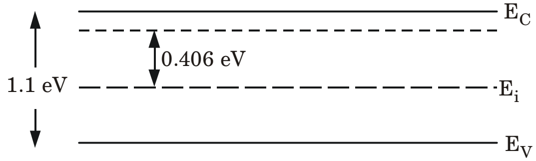

Fig. 7.

5. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. Design the circuit shown in the Fig. 8 to establish a drain of 0.1 V, what is the effective resistance between drain and source at this operating point ? Let V_t = 1 V, and $k'_n (W/L) = 1$ mA/V^2.

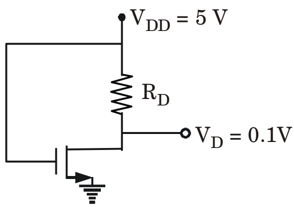

Fig. 8.

Ans.

Given : $V_{DD} = 5$ V, $V_D = 0.1$ V, $V_t = 1$ V, $k'_n\left(\frac{W}{L}\right) = 1$ mA/V^2

To Find : Effective resistance (r_{DS}).

1. For triode region, $V_{GS} - V_t > V_{DS}$

$$5 - 1 > 0.1$$
$$4 > 0.1$$

So the MOSFET is operating in the triode region.

2. In triode region,

$$I_D = k'_n \frac{W}{L}\left[(V_{GS} - V_t)\, V_{DS} - \frac{1}{2} V_{DS}^2\right]$$

$$= 1\left[(5-1) \times 0.1 - \frac{1}{2} \times 0.01\right] = 0.395 \text{ mA}$$

3. The value of R_D is,

$$R_D = \frac{V_{DD} - V_D}{I_D} = \frac{5 - 0.1}{0.395} = 12.4 \text{ k}\Omega$$

4. The effective drain to source resistance is,

$$r_{DS} = \frac{V_{DS}}{I_D} = \frac{0.1}{0.395} = 253\ \Omega$$

b. Construct *p*-channel enhancement MOSFET. Draw and explain the I-V characteristics when V_{DS} is increased.

Ans.

A. *p*-channel MOSFET :

1. Fig. 9 shows a cross-sectional view of a *p*-channel enhancement-type MOSFET.
2. The structure is similar to that of the NMOS device except that here the substrate is *n* type and the source and the drain regions are p^+ type; that is, all semiconductor regions are reversed in polarity relative to their counterparts in the NMOS case.

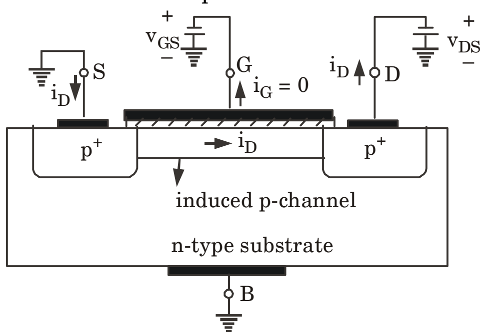

Fig. 9. Physical structure of the PMOS transistor.

B. I-V characteristics when V_{DS} is increased :

1. Let v_{GS} be held constant at a value greater than V_t.
2. The voltage between the gate and points along the channel decreases from v_{GS} at source end to $v_{GS} - v_{DS}$ at the drain end.
3. Therefore, as v_{DS} is increased, the channel becomes more tapered and its resistance increases correspondingly. Thus, the i_D-v_{DS} curve does not continue as a straight line but bends.
4. When v_{DS} is increased to the value that reduces the voltage between the gate and the channel at the drain end to V_t *i.e.*, $v_{GS} - v_{DS} = V_t$, the channel depth at the drain end decreases to zero and the channel is said to be pinched-off.

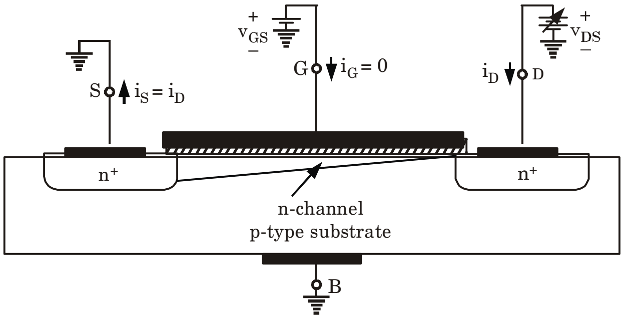

Fig. 10.

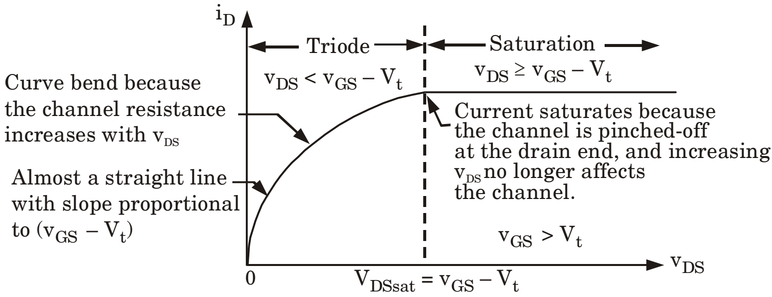

Fig. 11. $i_D - v_{DS}$ characteristic for an enhancement type NMOS operated with $v_{GS} > V_t$.

5. Increasing v_{DS} beyond this value has no effect on channel shape and the current remains constant at the value reached for $v_{DS} = v_{GS} - V_t$.
6. The drain current saturates at this value and the MOSFET enters the saturation region of operation.

$$\therefore \qquad V_{DSsat} = v_{GS} - V_t$$

The device operates in the saturation region if $v_{DS} > V_{DSsat}$.

7. The region of the $i_D - v_{DS}$ characteristics obtained for $v_{DS} < V_{DSsat}$ is called triode region.

6. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. How BJT can be used as an amplifier and as a switch ? Justify using required circuit waveform, mathematical expression.

Ans.

A. BJT as an amplifier :

1. Fig. 12 shows common emitter circuit and Fig. 13 shows the voltage transfer characteristics of the *CE* circuit.

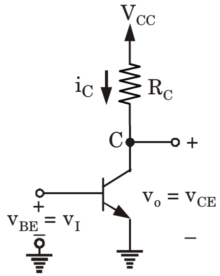

Fig. 12. Basic common emitter amplifier circuit.

2. To operate the BJT as a linear amplifier, it must be biased at a point in the active region.
3. Fig. 13 shows such a bias point, labeled *Q*, and characterized by v_{BE} and v_{CE}.

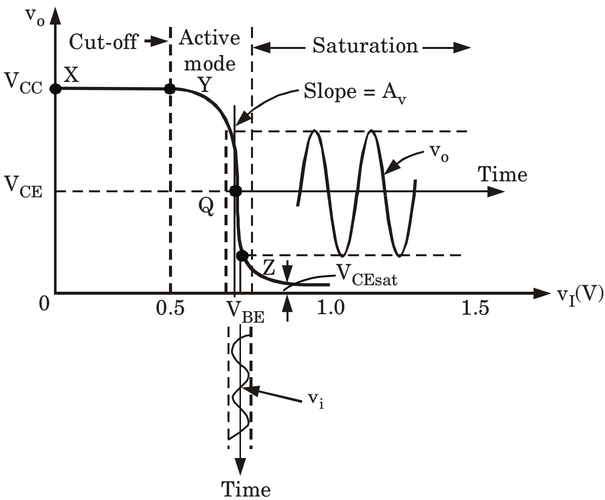

Fig. 13. Transfer characteristic.

4. If the collector current at this value of v_{BE} is
$$i_C = I_S\, e^{v_{BE}/V_T} \quad ...(1)$$
then from the circuit in Fig. 13
$$v_0 = v_{CE} = V_{CC} - R_C\, i_C \quad ...(2)$$
5. Now, if the signal to be amplified, v_I is superimposed on V_{BE} and kept sufficiently small as the instantaneous operating point will be constrained to a relatively short, almost linear segment of the transfer curve around the bias point Q.
6. The slope of this linear segment will be equal to the slope of the tangent to the transfer curve at Q.
7. This slope is the voltage gain of amplifier.
$$A_v = \left.\frac{dv_o}{dv_I}\right|_{v_I = V_{BE}} \quad ...(3)$$
8. Thus,
$$A_v = -\frac{1}{V_T} I_S\, e^{V_{BE}/V_T} R_C$$
$$= -\frac{I_C\, R_C}{V_T} = -\frac{V_{RC}}{V_T} \quad \text{[Using eq. (1)]}$$
where V_{RC} is the DC voltage drop across R_C.
$$V_{RC} = V_{CC} - V_{CE} \quad ...(4)$$
$$\therefore \quad A_v = -\frac{V_{CC} - V_{CEsat}}{V_T}$$
9. Biasing at the edge of saturation

Thus,
$$A_{v\,\max} \simeq -\frac{V_{CC}}{V_T}$$

B. BJT as a switch :

When the transistor leaves the active region, it enters in cut-off region or in saturation region. But these regions are very useful if the transistor is to be used as a switch.

i. Cut-off region :

If v_I is smaller than 0.5 V, the emitter-base junction will conduct negligible current and the collector-base junction is reversed biased. The device will be in cut-off mode.
$$i_B = 0,\ i_E = 0,\ i_C = 0,\ v_C = V_{CC}$$

ii. Saturation region :

1. If we increase i_B then i_C increase as a result of which v_{CE} will fall down. The process will continue until the collector-base junction becomes forward biased.
2. The forward voltage drop of collector-base junction is small because of relatively large areas.
3. This mode of working is achieved in saturation region.
$$I_{C\text{sat}} = \frac{V_{CC} - V_{CE\,\text{sat}}}{R_C}$$

4. Forcing more current into the base has very little effect on I_{Csat} and V_{CEsat}. In this state the switch is closed.

b. Mention the different biasing technique in BJT. Explain any two of them.

Ans. Biasing in BJT amplifier circuit :

i. Voltage divider biasing
ii. Two power supply version of the classical bias arrangement.
iii. Biasing using a collector to base feedback resistor.
iv. Biasing using a constant current source.

i. Voltage divider biasing (Classical discrete circuit bias arrangement) :

1. Fig. 14(a) shows the arrangement most commonly used for biasing a discrete circuit transistor amplifier if only a single power supply is available.

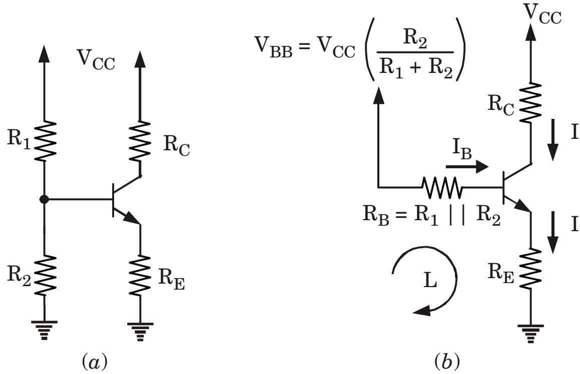

Fig. 14. Classical biasing for BJTs using a single power supply.

2. Fig. 14(b) shows the same circuit with the voltage divider network replaced by its Thevenin's equivalent,

$$V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC} \quad ...(1)$$

$$R_B = \frac{R_1 R_2}{R_1 + R_2} \quad ...(2)$$

3. The current I_E can be determined by writing a Kirchhoff 's loop equation for the base-emitter ground loop labeled L, as

$$V_{BB} - I_B R_B - V_{BE} - I_E R_E = 0$$

Substituting, $$I_B = \frac{I_E}{\beta + 1}$$

$$V_{BB} - I_E\left(\frac{R_B}{\beta + 1}\right) - V_{BE} - I_E R_E = 0$$

$$\therefore \qquad I_E = \frac{V_{BB} - V_{BE}}{R_E + \dfrac{R_B}{(\beta+1)}} \qquad ...(3)$$

4. To make I_E insensitive to temperature and β variation, we design the circuit to satisfy the following two constraints :

$$V_{BB} >> V_{BE}$$

and $$R_E >> \frac{R_B}{\beta + 1} \qquad ...(4)$$

ii. Two power supply version of the classical bias arrangement :

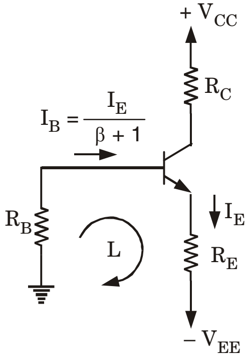

Fig. 15. Biasing the BJT using two power supplies.

1. In Fig. 15, two power supplies are available. Writing a loop equation for loop labeled L gives

$$I_E = \frac{V_{EE} - V_{BE}}{R_E + \dfrac{R_B}{(\beta+1)}} \qquad ...(5)$$

2. Note that if the transistor is to be used with the base grounded, then R_B can be eliminated. On the other hand, if the input signal is to be coupled to the base, then R_B is needed.

7. Attempt any **one** part of the following : **(7 × 1 = 7)**

a. Draw the high frequency hybrid-π model of MOSFET and show that $f_T = g_m/2\pi(C_{gs} + C_{gd})$.

Ans.

1. A parameter used to judge the operation of a high-frequency MOSFET as an amplifier, is the unity-gain bandwidth.
2. The frequency at which short-circuit current gain of the common-source arrangement becomes unity, is known as the unity-gain frequency. This analysis is done using a hybrid π model with a common-source configuration.

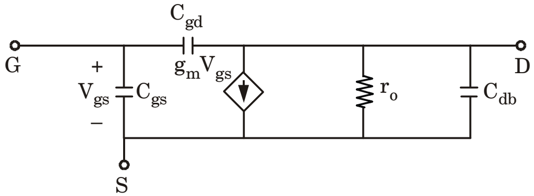

Fig. 16. High-frequency MOSFET model when the source is connected to the body.

3. Again, in the model, as shown in Fig. 16, when C_{db} is neglected, the resulting circuit is as given by Fig. 17.
4. It can be noticed easily that the current in the short circuit is given by :

$$I_0 = g_m V_{gs} - sC_{gd} V_{gs} \qquad ...(1)$$

where, s is a complex variable.

5. Since C_{gd} is very small, eq. (1) can be written as $I_0 \approx g_m V_{gs}$.

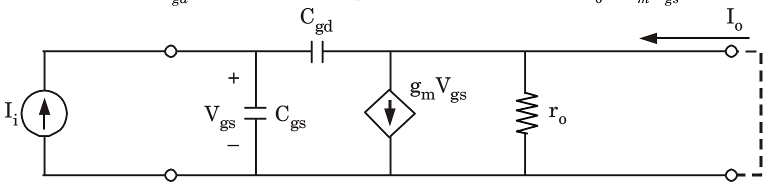

Fig. 17. Circuit representation for obtaining short-circuit current gain.

And from Fig. 17, we get :

$$V_{gs} = \frac{I_i}{s(C_{gs} + C_{gd})} \qquad ...(2)$$

6. Substituting, $I_0 = g_m V_{gs}$ we obtain : $\dfrac{I_0}{g_m} = \dfrac{I_i}{s(C_{gs} + C_{gd})}$

$$\frac{I_0}{I_i} = \frac{g_m}{s(C_{gs} + C_{gd})} \qquad ...(3)$$

7. Taking $s = j\omega$ (where, ω is the frequency of the applied voltage), and since the magnitude of current gain becomes unity at this frequency, we can write :

$$\omega_T = \frac{g_m}{(C_{gs} + C_{gd})} \qquad ...(4)$$

$$\Rightarrow \quad f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} \qquad (\because \quad \omega_T = 2\pi f_T)$$

b. Mention the conditions for oscillation. Derive the expression for frequency of oscillation in phase shift oscillator.

Ans. This question is out of syllabus from session 2019-20.

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B. Tech.
(SEM. III) ODD SEMESTER THEORY EXAMINATION, 2018-19
ELECTRONIC DEVICES AND CIRCUITS

Time : 3 Hours **Max. Marks : 70**

Note : Attempt **all** sections. If require any missing data; then choose suitably.

SECTION-A

1. Attempt **all** questions in brief. **(2 × 7 = 14)**

a. **What type of semiconductor material is suitable for luminescence effect ?**

b. **What do you mean by diffusion of carriers ?**

c. **In the linear region operation of MOSFET drain current decreases as the temperature increases. Explain.**

d. **What is meant by threshold voltage ?**

e. **What is a transistor ? Explain its types.**

f. **What do you mean by optoelectronic devices ?**

g. **What is negative feedback and positive feedback ?**

SECTION-B

2. Attempt any **three** of the following questions : **(7 × 3 = 21)**

a. **Explain the principle of indirect recombination in band gap. Discuss its mechanism.**

b. **What is a photodiode ? Explain its construction and operation.**

c. **Explain the operation and characteristics of *N*-channel MOSFET.**

d. **Explain transistor characteristics in CE configuration. Explain the behaviour of the transistor in active and cut-off mode.**

e. What is an oscillator ? How does it differ from an amplifier ?

SECTION-C

3. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. Explain the terms : solar cell, LED.

b. Derive the expression for the forward and reverse saturation current for *p-n* junction diode.

4. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. The energy distribution function $\rho(E)$ is given by product of two factor [$\rho(E) = N(E). f(E)$]. What is the interpretation to be given to each of these factors ?

b. What is Einstein relation ? Develop expressions to establish relations between diffusion coefficient and mobility of carriers or obtain the relation : $D/\mu = kT/q$.

5. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. Show that $I_E = I_B + \alpha I_E + I_{CBO}$. In which way I_{CBO} depend on temperature.

b. Define α and β of a transistor and derive the relationship between them.

6. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. Explain the terms : single stage MOS amplifier, MOSFET internal capacitances.

b. Draw a biasing circuit of MOSFET amplifier and explain it.

7. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. Draw the circuit diagram of LC oscillators. What is the condition of oscillation ?

b. Explain the four types of feedback topologies with the help of schematic diagram.

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SOLUTION OF PAPER (2018-19)

Note : Attempt **all** sections. If require any missing data; then choose suitably.

SECTION-A

1. Attempt **all** questions in brief. **(2 × 7 = 14)**

a. What type of semiconductor material is suitable for luminescence effect ?

Ans. This question is out of syllabus from session 2019-20.

b. What do you mean by diffusion of carriers ?

Ans. Diffusion is the natural result of the random motion of the individual molecules from a region of high carrier concentration to region of low carrier concentration when the electron and hole concentrations vary with position in the sample. This type of phenomenon is called diffusion of carrier.

c. In the linear region operation of MOSFET drain current decreases as the temperature increases. Explain.

Ans. Since mobility decreases as temperature increases, so in MOSFETs current I_{DS} decreases with rise in temperature.

d. What is meant by threshold voltage ?

Ans. It means that the minimum voltage required to activate any active components. Minimum gate voltage to turn ON the transistor is called threshold voltage.

e. What is a transistor ? Explain its types.

Ans. A transistor is a semiconductor device to amplify or switch electronic signals and electrical power.

Types :

1. **BJT :** BJT is a bipolar device which can operate in one of four possible modes : cut-off, active, saturation, and reverse active.
2. **FET :** It is a unipolar device depending solely on either electron or hole.

f. What do you mean by optoelectronic devices ?

Ans. Optoelectronic devices are the electronic devices that detect and control light.

g. What is negative feedback and positive feedback ?

Ans. This question is out of syllabus from session 2019-20.

SECTION-B

2. Attempt any **three** of the following questions :

a. Explain the principle of indirect recombination in band gap. Discuss its mechanism.

Ans.

1. When an electron initially makes a transition to an energy level lying deep in the band gap and it subsequently captures a hole from the valence band, then this is known as indirect recombination.
2. Many recombination centres have more than one energy level, but in most of the cases only one level dominates for the recombination.
3. Fig. 1 illustrates the recombination of an electron-hole pair through deep-level centre.
4. In Fig. 1 E_V and E_C are valence band and conduction band respectively. Here E_r is recombination level which is below Fermi level E_F at equilibrium. Therefore, E_r is substantially filled with electrons. Let the excess electrons and holes are created in this material.

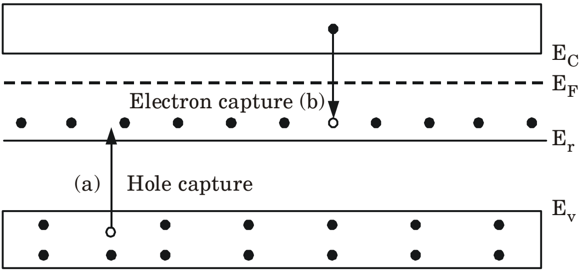

Fig. 1. Showing capture processes of recombination level.

5. The electron-hole pair (*EHP*) recombination at E_r is followed in the following two steps :

a. Hole capture :

i. In the hole capture process, an electron at E_r falls to valence band. This levels an empty state in recombination level.

ii. In hole capture, the energy is given up to the lattice.

b. Electron capture :

i. In the electron capture process, a conduction band electron subsequently falls to empty state in E_r.

ii. In this case too, the energy is given to the lattice.

6. When both the events [(a) and (b)] have occurred, the recombination centre returns back to its original state, *i.e.*, filled with electron.
7. Of course, an electron-hole pair is missing. In this way, one electron-hole pair recombination has taken place.

b. What is a photodiode ? Explain its construction and operation.

Ans.

A. Photodiodes : Two terminal devices designed to respond to photon absorption are called photodiodes.

B. Construction and operation :

1. Photodiode is a semiconductor *p-n* junction device whose operation is limited to reverse bias region.
2. The types of photodiode are :
   i. *p-n* diode
   ii. *p-i-n* diode
   iii. Avalanche diode
3. The output current of a reverse bias *p-n* junction changes when device is exposed to illumination.
4. The variation in the output current is linear with respect to luminous flux. The construction and symbol is shown in Fig. 2.

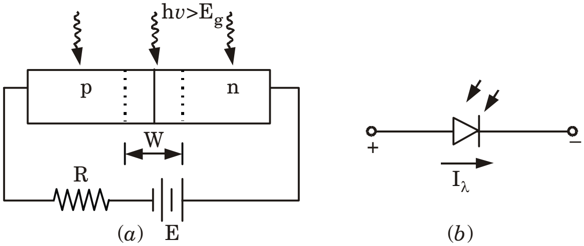

Fig. 2.

5. This diode is designed in such a manner that the rays are allowed to fall only on one surface across the junction. The remaining sides are restricted for the light to penetrate.
6. As the temperature due to illumination increases, more and more electron-hole pairs are generated and results in increasing the reverse saturation current.
7. When light rays fall on depletion width *W*, it creates electron-hole pair and electrons are swept into *n*-region and holes into *p*-region very rapidly. This gives rise to a photo current. This is the basic principle of operation of photodiode.

c. Explain the operation and characteristics of *N*-channel MOSFET.

Ans.

A. Operation of *n*-channel MOSFET :

Construction :

1. The construction of an *n*-channel enhancement MOSFET is shown in Fig. 3.
2. Two highly doped n^+ regions are diffused in a lightly doped *p*-type silicon substrate. One n^+ region is called the source *S* and the other one is called the drain *D*.

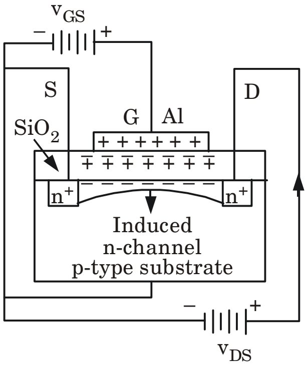

Fig. 3. n-channel enhancement MOSFET.

3. A thin insulating layer of SiO_2 is grown over the surface of the structure and holes are cut into the oxide layer, allowing contact with source and drain.
4. Then a thin layer of metal aluminium is formed over the layer of SiO_2 which covers the entire channel region and it forms the gate *G*.
5. The metal area of the gate, the insulating oxide layer of SiO_2 and the semiconductor channel forms a parallel plate capacitor.
6. This device is called the insulated gate FET because of the insulating layer of SiO_2. It gives extremely high input impedance for the MOSFET.

Working :

1. If the substrate is grounded and a positive voltage is applied at the gate, the positive charge on gate (*G*) induces an equal negative charge on the substrate side between the source and drain regions.
2. Thus, an electric field is produced between the source and drain regions which is perpendicular to the plates of the capacitor through the oxide.
3. The negative charge of electrons which are minority carriers in the *p*-type substrate forms an inversion layer.
4. As the positive voltage on the gate increases, the induced negative charge in the semiconductor increases.
5. Hence, the conductivity increases and current flows from drain to source through the induced channel. Thus the drain current is enhanced by the positive gate voltages.

Characteristics of *n*-channel MOSFET :

1. Let v_{GS} be held constant at a value greater than V_t.
2. The voltage between the gate and points along the channel decreases from v_{GS} at source end to $v_{GS} - v_{DS}$ at the drain end.
3. Therefore, as v_{DS} is increased, the channel becomes more tapered and its resistance increases correspondingly. Thus, the i_D-v_{DS} curve does not continue as a straight line but bends.

4. When v_{DS} is increased to the value that reduces the voltage between the gate and the channel at the drain end to V_t *i.e.*, $v_{GS} - v_{DS} = V_t$, the channel depth at the drain end decreases to zero and the channel is said to be pinched-off.

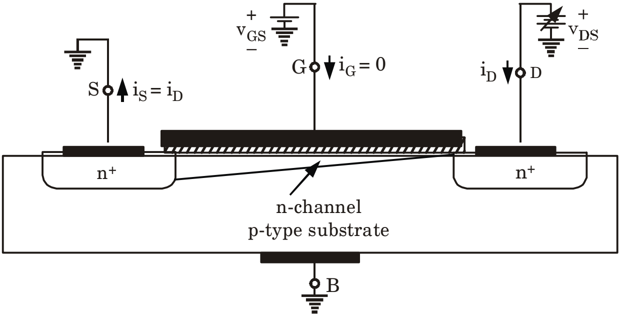

Fig. 4.

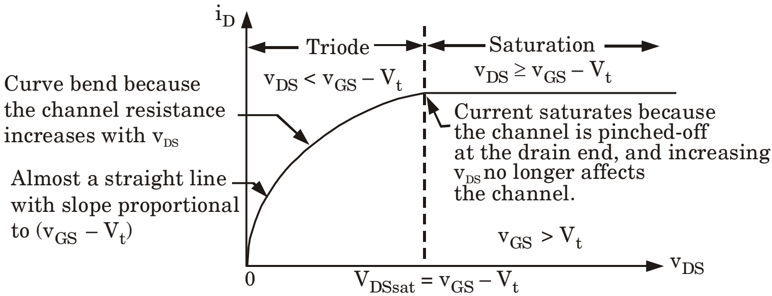

Fig. 5. i_D-v_{DS} characteristic for an enhancement type NMOS operated with $v_{GS} > V_t$.

5. Increasing v_{DS} beyond this value has no effect on channel shape and the current remains constant at the value reached for $v_{DS} = v_{GS} - V_t$.
6. The drain current saturates at this value and the MOSFET enters the saturation region of operation.

   $\therefore \qquad V_{DSsat} = v_{GS} - V_t$

   The device operates in the saturation region if $v_{DS} > V_{DSsat}$.
7. The region of the $i_D - v_{DS}$ characteristics obtained for $v_{DS} < V_{DSsat}$ is called triode region.

d. Explain transistor characteristics in CE configuration. Explain the behaviour of the transistor in active and cut-off mode.

Ans.

A. Transfer Characteristics :

i. Input characteristic :

1. The forward biased diode curve is expected because the base-emitter section of transistor is a diode and it is forward-biased.

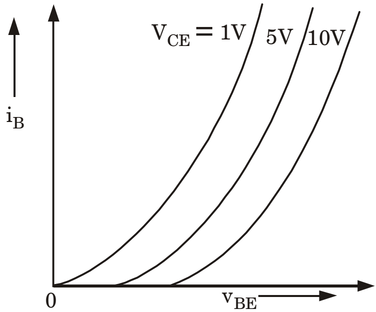

Fig. 6. Input characteristics.

2. In this case, i_B increases less rapidly with v_{BE} as compared to common base configuration *i.e.*, input resistance of common emitter is higher than common base circuit.

ii. Output characteristic :

1. The characteristic of common emitter output configuration is illustrated in Fig. 7.
2. Each i_C-v_{CE} curve is measured with the base fed with a constant current I_B.
3. Consider a transistor operating in the active region at the point labeled Q in Fig. 7, *i.e.*, at a collector current I_{CQ}, a base current I_{BQ}, and a collector-emitter voltage V_{CEQ}.

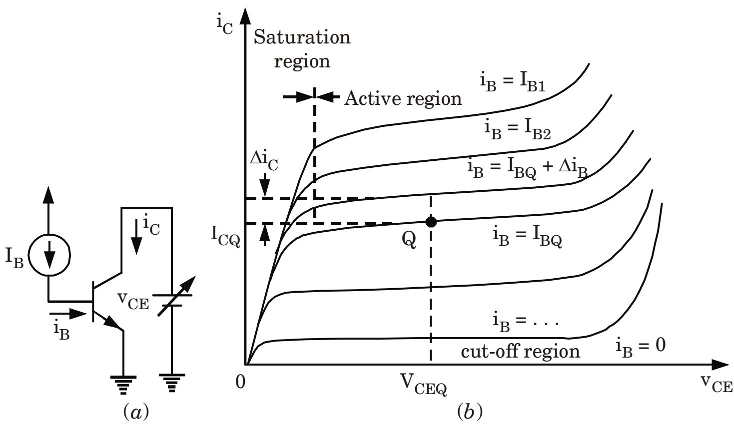

Fig. 7. Common emitter output characteristics.

4. The ratio of the collector current to base current is the large-signal or β_{DC}.

$$\beta_{DC} = \frac{I_{CQ}}{I_{BQ}}$$

5. Referring to Fig. 7, while keeping v_{CE} constant at the value V_{CEQ}, changing i_B from I_{BQ} to $(I_{BQ} + \Delta i_B)$ results in i_C increasing from I_{CQ} to $(I_{CQ} + \Delta i_C)$.
6. Thus we can define the incremental or AC β, β_{AC}, $\beta_{AC} = \left.\frac{\Delta i_C}{\Delta i_B}\right|_{v_{CE} = \text{Constant}}$

B. Behaviour of transistor :

1. In the active mode, transistor behaves as amplifier. In this, emitter junction is forward biased and the collector junction is reverse biased.
2. In the cut-off mode, transistor behaves as an open switch. In this, both the emitter and the collector junctions are reversed biased.

e. What is an oscillator ? How does it differ from an amplifier ?

Ans. This question is out of syllabus from session 2019-20.

SECTION-C

3. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. Explain the terms : solar cell, LED.

Ans.

A. Solar cell :

1. Solar cells are semiconductor junction devices which are used for converting optical radiation into electrical energy.
2. The generated electric voltage is proportional to the intensity of incident light. Due to their capability of generating voltage, they are called photovoltaic cells.
3. Silicon is the most widely used material for solar cells.

Construction :

1. The construction of a solar cell is shown in Fig. 8.

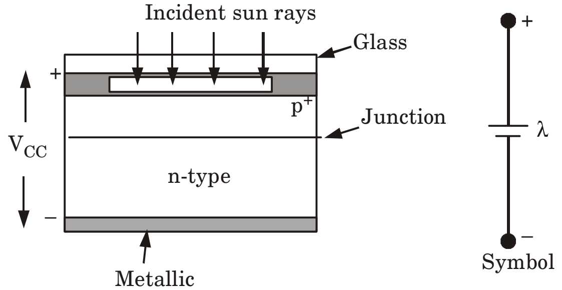

Fig. 8.

2. The *p*-type layer is made thin to intercept the light radiation falling on the junction. The doping of *p*-type material is very high.
3. *p*-type is surrounded by a nickel plated ring which serves as positive terminal and the contact at bottom acts as a negative terminal.

Working :

1. When photons are incident on surface, it releases sufficient energy to the electrons to leave its orbit.
2. As a result, free electrons and holes are created. These free electrons and holes constitute the minority current.
3. In this way, depletion region potential causes the photo current to flow through the external load.

B. LED :

LED is a special type of semiconductor *p-n* junction that under forward bias emits external radiations in ultraviolet, visible and infrared regions of electromagnetic spectrum.

Construction of LED :

1. LED is just not an ordinary *p-n* junction diode where silicon is used. Here we use compound having elements like gallium, arsenic and phosphorus which are semitransparent unlike silicon which is opaque.
3. In all semiconductor *p-n* junctions, some of its energy will be given off as heat and some in the form of photons.
4. In the materials, such as gallium arsenide phosphide (GaAsP) or gallium phosphide (GaP), the number of photons of light energy emitted is sufficient to create a visible light source.

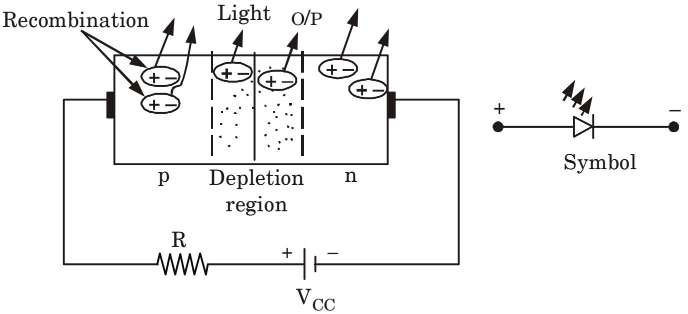

Fig. 9.

Principle of LED :

1. The process involves :
   i. Generation of electron-hole pair (EHP) by excitation of semiconductor.
   ii. Recombination of EHP.
   iii. Extraction of photons from the semiconductor.
2. The characteristic for LED is given in Fig. 10.

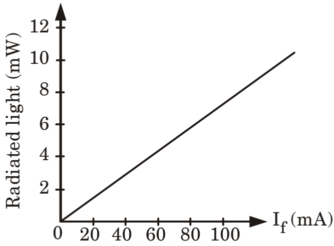

Fig. 10. Characteristics.

Working :

1. When LED is in forward bias condition, the electrons from n-type material cross the p-n junction and recombines with holes in the p-type material.
2. When recombination takes place, the recombining electrons release energy in the form of heat and light.
3. The emission depends upon the type of material, *i.e.*,
   GaAs $\rightarrow$ infrared radiation (invisible)
   GaP $\rightarrow$ red or green light (visible)
   GaAsP $\rightarrow$ red or yellow light (visible).

b. Derive the expression for the forward and reverse saturation current for *p-n* junction diode.

Ans. Diode current equation :

1. The hole diffusion current at any point x_n in the n-region can be obtained with the help of following expression

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n}$$

$$I_p(x_n) = -qAD_p \frac{d}{dx_n}\{[p_n(e^{qV/kT}-1)]e^{-x_n/L_p}\}$$

$$= qA\frac{D_p}{L_p}[p_n(e^{qV/kT}-1)e^{-x_n/L_p}]$$

$$I_p(x_n = 0) = qA\frac{D_p}{L_p}[p_n(e^{qV/kT}-1)]$$

2. Similarly, the electron current injected into p-region at the junction is given by

$$I_n(x_p = 0) = -qA\frac{D_n}{L_n}[n_p(e^{qV/kT}-1)]$$

3. If we take $+x$-direction as the reference direction for total current, we have :

$$I = I_p(x_n = 0) - I_n(x_p = 0)$$

$$= qA\left(\frac{D_p}{L_p}\right)[p_n(e^{qV/kT}-1)] + qA\left(\frac{D_n}{L_n}\right)[n_p(e^{qV/kT}-1)]$$

$$= qA \left[\left(\frac{D_p}{L_p} \right) p_n + \left(\frac{D_n}{L_n} \right) n_p \right] [e^{qV/kT} - 1]$$

$$I = I_0 \, [e^{qV/kT} - 1]$$

4. The current can also be calculated for reverse bias by letting $V = -V_r$

$$I = qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) (e^{-qV_r/kT} - 1)$$

5. If V_r is larger than a few kT/q, the total current is just the reverse saturation current.

$$I = -qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) = -I_0$$

4. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. The energy distribution function ρ(*E*) is given by product of two factor [ρ(*E*) = *N*(*E*). *f*(*E*)]. What is the interpretation to be given to each of these factors ?

Ans.

1. The energy distribution function of the electrons can be interpreted as a product of two factors.

i. The first is called the degeneracy, or the density of states per unit energy. This factor is independent of the statistical nature of the particles.

ii. The second is the average number of electrons with energy.

b. What is Einstein relation ? Develop expressions to establish relations between diffusion coefficient and mobility of carriers or obtain the relation : *D*/μ = *kT*/*q*.

Ans. **Einstein relation :**

1. Fig. 11 shows energy band diagram of a semiconductor in electric field ε(x).

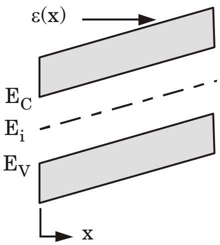

Fig. 11. Energy band diagram of a semiconductor in an electric field ε(x).

2. Since electrons drift in a direction opposite to the field therefore the potential energy for electrons will increase in the direction of the field.

3. The electrostatic potential $V(x)$ varies in the opposite direction, since it is defined in terms of positive charges therefore related to electron potential energy $\varepsilon(x)$ as,

$$V(x) = \frac{E(x)}{-q} \quad ...(1)$$

4. We know, electric field $\varepsilon(x) = \dfrac{-dV(x)}{dx}$

choosing E_i as a convenient reference, the electric field can be related as,

$$\varepsilon(x) = \frac{-d}{dx}\left[\frac{E_i}{-q}\right] = \frac{1}{q}\frac{dE_i}{dx} \quad ...(2)$$

5. At equilibrium, no net current flows in a semiconductor, therefore

$$J_p(x) = q\mu_p\, p(x)\, \varepsilon(x) - qD_p \frac{dp(x)}{dx} = 0$$

$$q\mu_p p(x)\, \varepsilon(x) = qD_p \frac{dp(x)}{dx}$$

$$\varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{p\,(x)}\frac{dp(x)}{dx} \quad ...(3)$$

6. To calculate the value of $\dfrac{1}{p(x)}\dfrac{dp(x)}{dx}$

we know, $\quad p = n_i\, e^{(Ei - EF)/kT}$

$$\frac{p}{n_i} = e^{(Ei - EF)/kT}$$

taking log on both sides,

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

$$\therefore \quad \ln p - \ln n_i = \frac{E_i - E_F}{kT} \quad ...(4)$$

7. Differentiating eq. (4) with respect to x we get

$$\frac{1}{p}\frac{dp}{dx} - 0 = \frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right] \quad (\because n_i = \text{constant})$$

$$\frac{1}{p}\frac{dp}{dx} = \frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right] \quad ...(5)$$

8. Putting the value of eq. (5) in eq. (3)

$$\varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right]$$

9. The equilibrium Fermi level does not vary with x, and derivative of E_i is given as $q\varepsilon(x)$

$$\therefore \qquad \varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{kT} \times q\varepsilon(x)$$

$$\frac{1}{q} = \frac{D_p}{\mu_p} \times \frac{1}{kT}$$

$$\frac{kT}{q} = \frac{D_p}{\mu_p}$$

or
$$\frac{D}{\mu} = \frac{kT}{q} \qquad ...(6)$$

10. Eq. (6) is known as Einstein relation.

5. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. Show that $I_E = I_B + \alpha I_E + I_{CBO}$. In which way I_{CBO} depend on temperature ?

Ans.

A. To show :

1. For *npn* transistor $\alpha = \dfrac{I_C}{I_E}$

$$I_C = \alpha I_E \qquad ...(1)$$

2. If the emitter is open then there will be collector current because of minority carriers I_{CBO}.

Thus, $$I_C = \alpha I_E + I_{CBO} \qquad ...(2)$$

3. And we know $I_E = I_C + I_B$

$$I_C = I_E - I_B \qquad ...(3)$$

4. Putting the value of I_C in eq. (2) then we get

$$I_E - I_B = \alpha I_E + I_{CBO}$$
$$I_E = I_B + \alpha I_E + I_{CBO}$$

B. The reverse saturation current (I_{CBO}) approximately doubles for every 10° C rise on temperature.

b. Define α and β of a transistor and derive the relationship between them.

Ans.

1. α is the current amplification factor in common base transistor. It is defined as the ratio of the collector current to the emitter current of a transistor when no signal is applied.

$$\alpha = \left|\frac{I_C}{I_E}\right|$$

2. β is the current gain in common emitter configuration. It is defined as the ratio of the collector current to the base current, when no signal is applied.

$$\beta = \left|\frac{I_C}{I_B}\right|$$

Relation :

1. We know, $\alpha = \dfrac{i_C}{i_E}$ and $\beta = \dfrac{i_C}{i_B}$

$$i_E = i_B + i_C \Rightarrow i_B = i_E - i_C$$

2. Now, $\beta = \dfrac{i_C}{i_E - i_C} = \dfrac{i_C / i_E}{1 - i_C / i_E} = \dfrac{\alpha}{1-\alpha}$

$$\beta\,(1 - \alpha) = \alpha \text{ or } \beta - \beta\alpha = \alpha$$

$$\beta = \alpha\,(1 + \beta)$$

$\therefore$ $$\alpha = \frac{\beta}{1+\beta}$$

6. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. Explain the terms : single stage MOS amplifier, MOSFET internal capacitances.

Ans.

A. Small signal operation (single stage MOS amplifier) :

1. For this purpose, we utilize the conceptual common source amplifier circuit shown in Fig. 12.

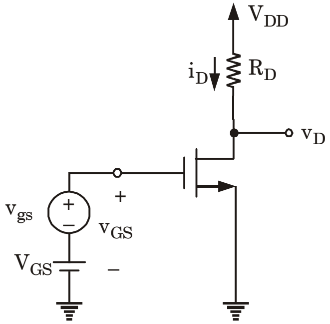

Fig. 12. Conceptual circuit.

2. For the circuit, the DC bias current I_D can be given by setting the signal $v_{gs} = 0$,

$\therefore$ $$I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2 \quad \text{...(1)}$$

and $$V_D = V_{DD} - R_D I_D \quad \text{...(2)}$$

3. Now, consider, $v_{GS} = v_{gs} + V_{GS}$ resulting in a total instantaneous drain current i_D,

$$i_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} + v_{gs} - V_t)^2$$

$$= \underbrace{\frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2}_{\text{DC bias current } I_D} + \underbrace{k_n' \frac{W}{L} (V_{GS} - V_t) v_{gs}}_{\text{current proportional to } v_{gs}} + \underbrace{\frac{1}{2} k_n' \frac{W}{L} v_{gs}^2}_{\text{current proportional to } v_{gs}^2 \text{ (non-linear distortion)}} \quad ...(3)$$

4. To reduce non-linear distortion the input signal is kept small so that,

$$\frac{1}{2} k_n' \frac{W}{L} v_{gs}^2 << k_n' \frac{W}{L} (V_{GS} - V_t) v_{gs}$$

$$v_{gs} << 2 V_{OV} \qquad (\because V_{OV} = V_{GS} - V_t)$$

If this small signal condition is satisfied, we may neglect 3rd term from eq. (3).

$$\therefore \quad i_D \simeq I_D + i_d \quad ...(4)$$

5. **Transconductance :** The parameter that relates i_d and v_{gs} is the MOSFET transconductance g_m.

$$\therefore \quad g_m = \frac{i_d}{v_{gs}} = k_n' \frac{W}{L} (V_{GS} - V_t)$$

or

$$g_m = k_n' \frac{W}{L} V_{OV} = \sqrt{2k_n' (W/L) I_D} = \frac{2I_D}{V_{ov}}$$

6. **The voltage gain :**
1. From Fig. 12,

$$v_D = V_{DD} - R_D i_D = V_{DD} - R_D (I_D + i_d)$$

$$\therefore \quad v_D = V_D - R_D i_d$$

2. Thus, the signal component of the drain voltage is

$$v_d = - i_d R_D = - g_m v_{gs} R_D$$

3. Voltage gain, $A_v = \dfrac{v_d}{v_{gs}} = - g_m R_D$

B. Types of internal capacitances of MOSFET :

a. The gate capacitive effect :

1. It can be modeled by the three capacitances C_{gs}, C_{gd}, C_{gb}. The values of these capacitances are as follows :

i. When the MOSFET is operating in the triode region at small v_{DS}, the channel will be of uniform depth, thus,

$$C_{gs} = C_{gd} = \frac{1}{2} WL\, C_{ox} \qquad \text{(triode region)}$$

ii. When the MOSFET operates in saturation, the channel has a tapered shape and is pinched off at or near the drain end, thus,

$$C_{gs} = \frac{2}{3} WL\, C_{ox} \qquad \text{(saturation region)}$$

$$C_{gd} = 0$$

iii. When the MOSFET is cut off, the channel disappears, and thus,

$$C_{gs} = C_{gd} = 0$$

$$C_{gb} = WL\, C_{ox} \qquad \text{(cut-off region)}$$

iv. There is an additional small capacitive component that should be added to C_{gs} and C_{gd}. If the overlap length is denoted L_{ov}, the overlap capacitance component is

$$C_{ov} = WL_{ov} C_{ox}$$

b. The junction capacitances :

1. For the source diffusion, we have the source body capacitance, C_{sb},

$$C_{sb} = \frac{C_{sb0}}{\sqrt{1+\frac{V_{SB}}{V_0}}}$$

where C_{sb0} is the value of C_{sb} at zero body source bias, V_{SB} is the magnitude of the reverse bias voltage and V_0 is the junction built-in-voltage.

2. Similarly for the drain diffusion, the drain-body capacitance C_{db},

$$C_{db} = \frac{C_{db0}}{\sqrt{1+\frac{V_{DB}}{V_0}}}$$

where C_{db0} is the capacitance value at zero reverse-bias voltage and V_{DB} is the magnitude of the reverse-bias voltage.

b. Draw a biasing circuit of MOSFET amplifier and explain it.

Ans. The different biasing methods of MOSFET are as follows :

i. Biasing by fixing the gate-to-source voltage V_{GS}.
ii. Biasing by fixing DC voltage at the gate (V_G).
iii. Biasing with a drain to gate feedback resistor.
iv. Biasing with a constant current source.

Biasing with a constant current source :

1. Fig. 13(a) shows biasing using a constant current source I.
2. R_G presents a large resistance to an input signal source that can be capacitively coupled to the gate.
3. Resistor R_D establishes an appropriate DC voltage at the drain to allow for the required output signal swing while the transistor always remains in the saturation region.

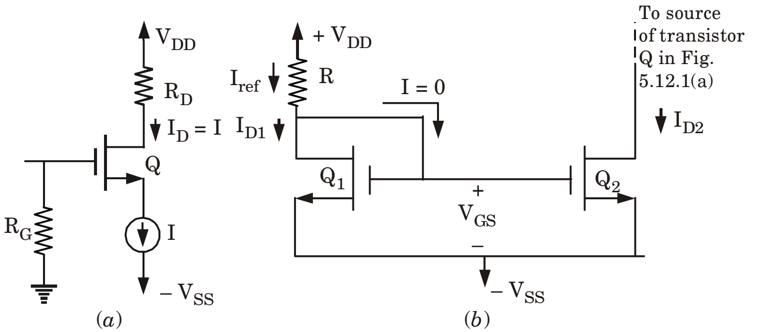

Fig. 13.

4. Fig. 13(*b*) shows a circuit for implementing the constant current source using current mirror. The transistor Q_1 has its drain shorted to gate and so it is operating in saturation region. Then

$$I_{D1} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_1 (V_{GS} - V_t)^2 \quad ...(1)$$

Since gate current is zero,

$$I_{ref} = I_{D1} = \frac{V_{DD} - V_{GS} - (-V_{SS})}{R} \quad ...(2)$$

5. The value of R can be obtained when a desired value of $I_{ref.}$ is known along with the parameter of Q_1.
6. V_{GS} for Q_1 and Q_2 will be same. Assuming that Q_2 is working in saturation which gives

$$I_{D2} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_2 (V_{GS} - V_t)^2 \quad ...(3)$$

where, V_t is assumed to be same for both Q_1 and Q_2

then, $$\frac{I_{D2}}{I_{ref}} = \frac{I_{D2}}{I_{D1}} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}$$

7. If $$\left(\frac{W}{L}\right)_2 = \left(\frac{W}{L}\right)_1 \text{ then } I_{D2} = I_{D1} = I_{ref}$$

when $I_{D2} = I_{ref.}$ we can also say that I_{D2} is mirror image of I_{ref}. Therefore, this circuit is also known as current mirror.

7. Attempt any **one** of the following questions : **(7 × 1 = 7)**

a. Draw the circuit diagram of LC oscillators. What is the condition of oscillation ?

Ans. This question is out of syllabus from session 2019-20.

b. Explain the four types of feedback topologies with the help of schematic diagram.

Ans. This question is out of syllabus from session 2019-20.

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B. Tech.
(SEM. III) ODD SEMESTER THEORY EXAMINATION, 2019-20
ELECTRONIC DEVICES

Time : 3 Hours **Max. Marks : 100**

Note : Attempt **all** sections. If require any missing data; then choose suitably.

SECTION-A

1. Attempt **all** questions in brief. **(2 × 10 = 20)**

a. What is base width modulation ?

b. What is difference between direct and indirect semiconductor ?

c. Differentiate EMOSFET with DMOSFET.

d. Brief the avalanche breakdown mechanism.

e. In which mode BJT can be used as switch and amplifier ?

f. What is fluorescence ?

g. What do you mean by effective mass of carriers ?

h. How does direct recombination lifetime differ from indirect recombination lifetime ?

i. Write difference between drift and diffusion.

j. Define sheet resistance.

SECTION-B

2. Attempt any **three** of the following : **(10 × 3 = 30)**

a. Differentiate between direct and indirect band gap semiconductor. Also discuss the variation of energy band with alloy composition.

b. Calculate the Fermi level position in Si containing 10^{16} Phosphorus atoms/cm^3 at 100 °K assuming 50 % of the

impurities are ionized at this temperature. Also calculate the equilibrium electrons and holes concentrations.

c. Define mobility of a charge carrier. Show that $\mu/D = e/kT$.

d. Explain the single stage MOS amplifier and MOS capacitances.

SECTION-C

3. Attempt any **one** of the following : **(10 × 1 = 10)**

a. Derive the expression for Schrodinger wave equation.

b. What is the principle of Heisenberg uncertainty and why is it important ? Write its applications.

4. Attempt any **one** of the following : **(10 × 1 = 10)**

a. What do you mean by Fermi level ? Discuss the effect of temperature and doping on mobility.

b. Draw the schematic band diagram of Fermi level, density of states, Fermi-Dirac distribution function, and carrier concentrations for intrinsic and extrinsic semiconductor.

5. Attempt any **one** of the following : **(10 × 1 = 10)**

a. Explain and draw the small signal models of MOS transistor.

b. Explain the working principle and characteristics of following :

i. LED

ii. Solar cell

6. Attempt any **one** of the following : **(10 × 1 = 10)**

a. Explain Ebers-Moll model.

b. Explain Schottky diode in detail and also write its applications.

7. Attempt any **one** of the following : **(10 × 0 = 10)**

a. Using the concept of diffusion and drift of carriers derive the continuity equation and diffusion length.

b. Derive an expression for diode current in *p-n* junction diode.

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SOLUTION OF PAPER (2019-20)

Note : Attempt **all** sections. If require any missing data; then choose suitably.

SECTION-A

1. Attempt **all** questions in brief. **(2 × 10 = 20)**

a. What is base width modulation ?

Ans. Base width modulation or the early effect is the variation in the width of the base in the bipolar transistor due to variation in the applied base-to-collector voltage. For example, greater reverse bias across the collector-base junction increases the collector base depletion width.

b. What is difference between direct and indirect semiconductor ?

Ans.

S. No.	Direct band gap semiconductor	Indirect band gap semiconductors
1.	The electron fall directly from conduction band to valance band.	The electron cannot fall directly from conduction band to valance band.
2.	The energy is released in the form of light.	The energy is released in the form of heat.

c. Differentiate EMOSFET with DMOSFET.

Ans.

S. No.	*E*-MOSFET	*D*-MOSFET
1.	Operates only in enhancement mode.	Operates in both depletion mode and enhancement mode.
2.	There is no physical channel from source to drain. We have to enhance it by applying v_{GS}.	The channel is already formed between source and drain.
3.	Commonly used bias circuits : gate bias, voltage divider bias, drain-feedback bias.	Commonly used bias circuits : gate bias, self bias, voltage-divider bias, zero bias.

d. Brief the avalanche breakdown mechanism.

Ans.
1. Avalanche breakdown is caused by a process known as secondary multiplication, and it occurs in junctions having thicker depletion regions, which makes tunneling less probable.
2. In a reverse-biased junction, the thermally generated minority carriers (mainly holes in a p^+-n junction) injected into the space-charge region is accelerated by the field and gain kinetic energy from the field.

e. In which mode BJT can be used as switch and amplifier.

Ans. BJT will operate as an amplifier if transistor is biased into linear region. BJT can be used as a switch if the transistor is biased into saturation region.

f. What is fluorescence ?

Ans. This question is out of syllabus from session 2019-20.

g. What do you mean by effective mass of carriers ?

Ans. The effective mass is a quantity that is used to simplify band structures by modelling the behaviour of free particle with that mass.

h. How does direct recombination lifetime differ from indirect recombination lifetime ?

Ans. Carrier lifetime is the time taken by carrier to recombine. In direct recombination, the process of transition of electrons from conduction band to valence band occurs simultaneously. Carrier will take less time to recombine. Therefore, carrier lifetime tends to be very short, typically in nanoseconds.
In case of indirect recombination, carrier takes more time to recombine, therefore lifetime of carrier is more in this case.

i. Write difference between drift and diffusion.

Ans.

S. No.	Diffusion Current	Drift Current
1.	Diffusion current occurs even though there is not an electric field applied to the semiconductor.	Drift current occurs when the electric field applied on the p-n junction.
2.	Direction of the diffusion current depends on the charge in the carrier concentrations.	Direction of the drift current depends on the polarity of the applied field.

j. Define sheet resistance.

Ans. Sheet resistance (also known as surface resistance or surface resistivity) is a common electrical property used to characterize thin films of conducting and semiconducting materials.

SECTION-B

2. Attempt any **three** of the following : **(10 × 3 = 30)**

a. Differentiate between direct and indirect band gap semiconductor. Also discuss the variation of energy band with alloy composition.

Ans.

A. Difference :

S. No.	Direct band gap semiconductor	Indirect band gap semiconductor
1.	A direct band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band aligns with the minimum energy level of the conduction band with respect to momentum.	An indirect band-gap (IBG) semiconductor is one in which the maximum energy level of the valence band are misaligned with the minimum energy level of the conduction band with respect to momentum.
2.	In a DBG semiconductor, a direct recombination takes place with the release of the energy equal to the energy difference between the recombining particles.	Due to a relative difference in the momentum, first the momentum is conserved by release of energy and only after both the momentum aligns themselves, a recombination occurs accompanied with the release of energy.
3.	The efficiency factor of a DBG semiconductor is more.	The probability of a radiative recombination is less.
4.	Example of DBG semiconductor is gallium arsenide (GaAs)	Examples of IBG semiconductors are silicon and Germanium.
5.	DBG semiconductors emit light.	IBG semiconductors emit heat.

B. Variation of energy bands with alloy composition :

1. The energy band gap E_g is a very important parameter of a semiconductor. The wavelength (colour) of the light emitted by a direct semiconductor depends on this gap.

2. This means that we can only get certain limited wavelengths from the semiconductors. But that is not true. We can get number of wavelengths using alloy semiconductor.
3. Alloy semiconductors provide a class of semiconductor materials where the band gap can be varied continuously by having proper percentage of alloying.
4. A particular alloy semiconductor may behave as direct semiconductor for certain of its alloying range and starts behaving as an indirect semiconductor for the remaining range.
5. Let consider a particular case of Al_xGa_{1-x} As. GaAs is a column III-V compound semiconductor. Ga and Al both belong to column III, so they can easily replace each other.
6. In this alloy, let x % of Ga are replaced by Al in GaAs and one gets Al_xGa_{1-x} As. The band gap variation with alloy composition is shown in Fig. 1.
7. This alloy has three energy bands in conduction band variation of x (*i.e.*, x in Al_x). The energy of these bands change, therefore band gap will change. Further the alloy behaves as a direct semiconductor up to $x = 0.38$.

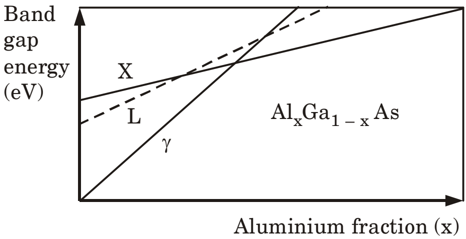


Fig. 1. Band gap variation with alloy composition.

b. Calculate the Fermi level position in Si containing 10^{16} Phosphorus atoms/cm^3 at 100 °K assuming 50 % of the impurities are ionized at this temperature. Also calculate the equilibrium electrons and holes concentrations.

Ans.

i.

1. The fraction of impurities ionized is,

$$1 - \frac{n_d}{N_d} = 0.50$$

$$\frac{n_d}{N_d} = 0.50$$

$$\frac{n_d}{N_d} = \frac{1}{2}$$

$$\Rightarrow \quad N_d = 2n_d \qquad \text{...(1)}$$

2. We know, $$n_d = \frac{N_d}{1+\exp\left\{\dfrac{(E_d - E_f)}{KT}\right\}}$$
3. At $T = 100$ K
$$n_d = \frac{2n_d}{1+\exp\left\{\dfrac{(E_d - E_f)}{(8.617\times 10^{-5}\ \text{eVK}^{-1}\times 100)}\right\}}$$
[where $K = 8.617 \times 10^{-5}$ eVK^{-1}]
$$1+\exp\left\{\frac{(E_d - E_f)}{(0.0086)}\right\} = 2$$
$$\exp\left\{\frac{(E_d - E_f)}{(0.0086)}\right\} = 1$$
$$\frac{E_d - E_f}{0.0086} = e^1$$
$$E_d - E_f = 2.718 \times 0.0086$$
$$= 0.0233 \text{ eV}$$

ii.
1. Given, $N_d = 10^{16}$ cm^{-3}
2. Assuming $N_a = 0$ and $n_i = 1.5 \times 10^{10}$ cm^{-3}
3. The majority carrier electron concentration is
$$n_o = \frac{1}{2}\{(N_d - N_a) + ((N_d - N_a)^2 + 4n_i^{\,2})^{1/2}\}$$
$$n_o = \frac{1}{2}\{(10^{16} - 0) + ((10^{16} - 0)^2 + 4\times(1.5\times 10^{10})^2)^{1/2}\}$$
$$n_o = \frac{1}{2}\{10^{16} + (10^{32} + 9\times 10^{20})^{1/2}\}$$
$$n_o = \frac{1}{2}\{10^{16} + 10^{16}\} = 10^{16}\ \text{cm}^{-3}$$
4. The minority carrier hole concentration is,
$$p_o = \frac{n_i^{\,2}}{n_o} = \frac{(1.5\times 10^{10})^2}{10^{16}} = 2.25 \times 10^4\ \text{cm}^{-3}$$

c. Define mobility of a charge carrier. Show that μ/D = e/kT.

Ans.

A. Mobility :

The mobility of a carrier is a measure of its ease of motion, and is defined as the drift velocity per unit electric field,

i.e., $$\mu = \frac{v_d}{E}$$

where, v_d = drift velocity, and E = applied electric field . It is a positive quantity and has a unit of cm^2/ V-sec.

B. To show :

1. Fig. 2 shows energy band diagram of a semiconductor in electric field $\varepsilon(x)$.
2. Since electrons drift in a direction opposite to the field therefore the potential energy for electrons will increase in the direction of the field.

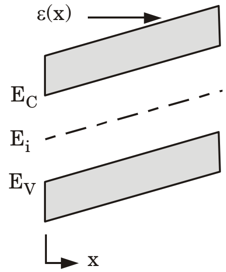


Fig. 2. Energy band diagram of a semiconductor in an electric field $\varepsilon(x)$.

3. The electrostatic potential $V(x)$ varies in the opposite direction, since it is defined in terms of positive charges therefore related to electron potential energy $\varepsilon(x)$ as,

$$V(x) = \frac{E(x)}{-q} \quad ...(1)$$

4. We know, electric field $\varepsilon(x) = \frac{-dV(x)}{dx}$

choosing E_i as a convenient reference, the electric field can be related as,

$$\varepsilon(x) = \frac{-d}{dx}\left[\frac{E_i}{-q}\right] = \frac{1}{q}\frac{dE_i}{dx} \quad ...(2)$$

5. At equilibrium, no net current flows in a semiconductor, therefore

$$J_p(x) = q\mu_p\, p(x)\, \varepsilon(x) - qD_p \frac{dp(x)}{dx} = 0$$

$$q\mu_p p(x)\, \varepsilon(x) = qD_p \frac{dp(x)}{dx}$$

$$\varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{p(x)}\frac{dp(x)}{dx} \quad ...(3)$$

6. To calculate the value of $\frac{1}{p(x)}\frac{dp(x)}{dx}$

we know, $p = n_i \, e^{(Ei - EF)/kT}$

$$\frac{p}{n_i} = e^{(Ei - EF)/kT}$$

taking log on both sides,

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

$$\therefore \quad \ln p - \ln n_i = \frac{E_i - E_F}{kT} \quad ...(4)$$

7. Differentiating eq. (4) with respect to x we get

$$\frac{1}{p}\frac{dp}{dx} - 0 = \frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right] \quad (\because n_i = \text{constant})$$

$$\frac{1}{p}\frac{dp}{dx} = \frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right] \quad ...(5)$$

8. Putting the value of eq. (5) in eq. (3)

$$\varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{kT}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right]$$

9. The equilibrium Fermi level does not vary with x, and derivative of E_i is given as $q\varepsilon(x)$

$$\therefore \quad \varepsilon(x) = \frac{D_p}{\mu_p}\frac{1}{kT} \times q\varepsilon(x)$$

$$\frac{1}{q} = \frac{D_p}{\mu_p} \times \frac{1}{kT}$$

$$\frac{kT}{q} = \frac{D_p}{\mu_p}$$

$$\text{or} \quad \frac{D}{\mu} = \frac{kT}{q} \quad ...(6)$$

10. Eq. (6) is known as Einstein relation.
[**Note :** Charge, $q = e$]

d. Explain the single stage MOS amplifier and MOS capacitances.

Ans.

A. Small signal operation (single stage MOS amplifier) :

1. For this purpose, we utilize the conceptual common source amplifier circuit shown in Fig. 3.

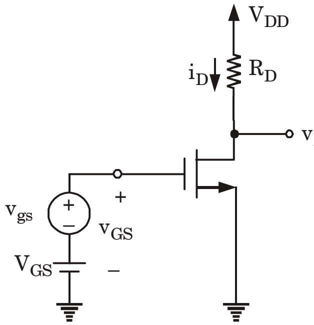


Fig. 3. Conceptual circuit.

2. For the circuit, the DC bias current I_D can be given by setting the signal $v_{gs} = 0$,

$$\therefore \qquad I_D = \frac{1}{2} k'_n \frac{W}{L} (V_{GS} - V_t)^2 \qquad ...(1)$$

and
$$V_D = V_{DD} - R_D I_D \qquad ...(2)$$

3. Now, consider, $v_{GS} = v_{gs} + V_{GS}$ resulting in a total instantaneous drain current i_D,

$$i_D = \frac{1}{2} k'_n \frac{W}{L} (V_{GS} + v_{gs} - V_t)^2$$

$$= \underbrace{\frac{1}{2} k'_n \frac{W}{L} \left(V_{GS} - V_t\right)^2}_{\text{DC bias current } I_D} + \underbrace{k'_n \frac{W}{L} \left(V_{GS} - V_t\right) v_{gs}}_{\text{current proportional to } v_{gs}} + \underbrace{\frac{1}{2} k'_n \frac{W}{L} v_{gs}^2}_{\text{current proportional to } v^2_{gs} \text{ (non-linear distortion)}} \qquad ...(3)$$

4. To reduce non-linear distortion the input signal is kept small so that,

$$\frac{1}{2} k'_n \frac{W}{L} v_{gs}^2 << k'_n \frac{W}{L} (V_{GS} - V_t) v_{gs}$$

$$v_{gs} << 2 V_{OV} \qquad (\because V_{OV} = V_{GS} - V_t)$$

If this small signal condition is satisfied, we may neglect 3rd term from eq. (3).

$$\therefore \qquad i_D \simeq I_D + i_d \qquad ...(4)$$

5. **Transconductance :** The parameter that relates i_d and v_{gs} is the MOSFET transconductance g_m.

$$\therefore \qquad g_m = \frac{i_d}{v_{gs}} = k'_n \frac{W}{L} (V_{GS} - V_t)$$

or
$$g_m = k'_n \frac{W}{L} V_{OV} = \sqrt{2k'_n (W / L) I_D} = \frac{2I_D}{V_{ov}}$$

6. **The voltage gain :**
1. From Fig. 3,

$$v_D = V_{DD} - R_D i_D = V_{DD} - R_D (I_D + i_d)$$

$\therefore \qquad v_D = V_D - R_D\, i_d$

2. Thus, the signal component of the drain voltage is

$$v_d = -\,i_d\, R_D = -\,g_m\, v_{gs}\, R_D$$

3. Voltage gain, $A_v = \dfrac{v_d}{v_{gs}} = -\,g_m\, R_D$

B. Types of internal capacitances of MOSFET :

a. The gate capacitive effect :

1. It can be modeled by the three capacitances C_{gs}, C_{gd}, C_{gb}. The values of these capacitances are as follows :

i. When the MOSFET is operating in the triode region at small v_{DS}, the channel will be of uniform depth, thus,

$$C_{gs} = C_{gd} = \frac{1}{2} WL\, C_{ox} \qquad \text{(triode region)}$$

ii. When the MOSFET operates in saturation, the channel has a tapered shape and is pinched off at or near the drain end, thus,

$$C_{gs} = \frac{2}{3} WL\, C_{ox} \qquad \text{(saturation region)}$$
$$C_{gd} = 0$$

iii. When the MOSFET is cut off, the channel disappears, and thus,

$$C_{gs} = C_{gd} = 0$$
$$C_{gb} = WL\, C_{ox} \qquad \text{(cut-off region)}$$

iv. There is an additional small capacitive component that should be added to C_{gs} and C_{gd}. If the overlap length is denoted L_{ov}, the overlap capacitance component is

$$C_{ov} = WL_{ov}\, C_{ox}$$

b. The junction capacitances :

1. For the source diffusion, we have the source body capacitance, C_{sb},

$$C_{sb} = \frac{C_{sb0}}{\sqrt{1 + \dfrac{V_{SB}}{V_0}}}$$

where C_{sb0} is the value of C_{sb} at zero body source bias, V_{SB} is the magnitude of the reverse bias voltage and V_0 is the junction built-in-voltage.

2. Similarly for the drain diffusion, the drain-body capacitance C_{db},

$$C_{db} = \frac{C_{db0}}{\sqrt{1 + \dfrac{V_{DB}}{V_0}}}$$

where C_{db0} is the capacitance value at zero reverse-bias voltage and V_{DB} is the magnitude of the reverse-bias voltage.

e. Explain the working principle and V-I characteristics of Zener diode.

Ans.

1. Zener diode is a reverse-biased heavily doped *p-n*-junction diode which is operated in the breakdown region. Fig. 4 shows the symbol of zener diode.

Fig. 4. Zener diode.

2. When a zener diode is forward biased, its characteristics are just same as the ordinary diode and it is shown in Fig. 5.

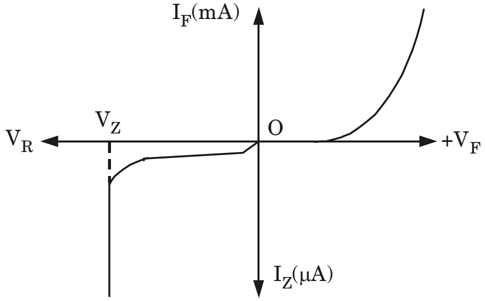


Fig. 5. V-I characteristic of zener diode.

3. When zener diode is reverse biased then it gives constant current upto a certain voltage. When the reverse bias voltage is increased beyond that voltage, the current increased rapidly as shown in Fig. 5.
4. The cut-off value of voltage beyond which zener diode reverse current increases rapidly is called zener voltage V_Z or breakdown voltage.
5. The breakdown or zener voltage depends upon the amount of doping.
6. A zener diode can be used as a voltage regulator to provide a constant voltage to a load.

SECTION-C

3. Attempt any **one** of the following : **(10 × 1 = 10)**

a. Derive the expression for Schrodinger wave equation.

Ans. **Schrodinger's equation :**

Schrodinger's equation which is the fundamental equation of quantum mechanics is a wave equation in the variable ψ.

A. Time Independent Schrodinger Wave Equation :

1. Consider a system of stationary wave to be associated with particle and the position coordinate of the particle (x, y, z) and ψ is the periodic displacement of any instant time 't'.
2. The general wave equation in 3-*D* in differential form is :

$$\nabla^2\psi = \frac{1}{v^2}\frac{\partial^2\psi}{\partial t^2} \qquad ...(1)$$

where, v = velocity of wave, and

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} = \text{Laplacian operator.}$$

3. The wave function may be written as

$$\psi = \psi_o e^{-i\omega t} \qquad ...(2)$$

4. Differentiate eq. (2) with respect to time, we get

$$\frac{\partial\psi}{\partial t} = -i\,\omega\,\psi_o e^{-i\omega t} \qquad ...(3)$$

5. Again differentiating eq. (3)

$$\frac{\partial^2\psi}{\partial t^2} = +\,i^2\,\omega^2\,\psi_o e^{-i\omega t}$$

$$\frac{\partial^2\psi}{\partial t^2} = -\,\omega^2\psi \qquad ...(4)$$

6. Putting these value in eq. (1),

$$\nabla^2\psi = \frac{-\omega^2}{v^2}\psi \qquad ...(5)$$

7. But $\omega = 2\pi\nu = \frac{2\pi v}{\lambda} \Rightarrow \frac{\omega}{v} = \frac{2\pi}{\lambda}$

8. Eq. (5) becomes

$$\nabla^2\psi = -\frac{4\pi^2}{\lambda^2}\psi \qquad ...(6)$$

9. From de-Broglie's wavelength, $\lambda = \frac{h}{mv}$

then

$$\nabla^2\psi = \frac{-4\pi^2 m^2 v^2}{h^2}\psi \qquad ...(7)$$

10. If E and V are the total and potential energies of a particle and E_k is kinetic energy, then

$$E_k = E - V \text{ or } \frac{1}{2}mv^2 = E - V \quad \text{or} \quad m^2v^2 = 2m\,(E - V)$$

11. Now eq. (7) becomes

$$\nabla^2\psi = \frac{-4\pi^2 2m[E-V]\psi}{h^2} \qquad \left[\text{Since } \hbar = \frac{h}{2\pi}\right]$$

$$\therefore \quad \nabla^2\psi + \frac{2m[E-V]\psi}{\hbar^2} = 0 \qquad ...(8)$$

This is required time-independent Schrodinger wave equation.

12. For free particle ($V = 0$)

$$\therefore \quad \nabla^2\psi + \frac{2m}{\hbar^2}E\psi = 0$$

b. What is the principle of Heisenberg uncertainty and why is it important ? Write its applications.

Ans.

A. Heisenberg uncertainty principle :

1. According to this principle, "It is impossible to determine the exact position and momentum of a particle simultaneously".
2. If Δx and Δp are the uncertain position and momentum of particle then according to this principle

$$\Delta x \, \Delta p \geq \frac{h}{2\pi}$$

or $$\Delta x \, \Delta p \geq \hbar$$

where $$\hbar = \frac{h}{2\pi}$$

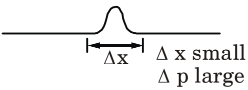
The product of uncertainty position and uncertainty momentum of particle is greater than or equal to $h/2\pi$.

3. Relation between uncertainty energy ΔE and uncertainty time Δt is

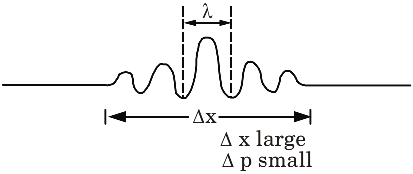
$$\Delta E \, \Delta t \geq \frac{h}{2\pi}$$

4. If $\Delta\theta$ and ΔJ are uncertainty angular position and angular momentum then

$$\Delta\theta \, \Delta J \geq \frac{h}{2\pi}$$



Narrow wave packet
(a)



Wide wave packet
(b)

Fig. 6.

B. Application and important :

a. Non-existence of Electrons in the nucleus :

1. We know that the radius of nucleus is the order of 10^{-14} m.
2. If an electron is confined within nucleus the uncertainty position of electron is

$$\Delta x = 2 \times 10^{-14} \text{ m}$$

3. Now according to uncertainty principle,

$$\Delta x \, \Delta p \geq \frac{h}{2\pi}$$

and $$\Delta p = \frac{h}{2\pi\Delta x} = \frac{6.63 \times 10^{-34}}{2 \times \pi \times 2 \times 10^{-14}}$$
$$= 5.276 \times 10^{-21} \text{ kg m/s}$$

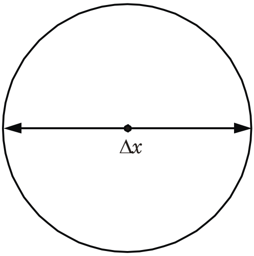


Fig. 7.

4. Using relativistic formula for the energy of the electron
$$E^2 = p^2 c^2 + m_o^{\ 2} c^4$$
As the rest energy $m_o c^2$ of an electron is of the order of 0.511 MeV, which is much smaller than the value of first term.
5. Hence the second term is neglected therefore,
$$E^2 = p^2 c^2$$
$$E = pc = (5.276 \times 10^{-21}) \times (3 \times 10^8) \text{ J}$$
$$E = \frac{5.276 \times 10^{-21} \times 3 \times 10^8}{1.6 \times 10^{-19}} \text{ eV} \approx 9.9 \text{ MeV}$$
6. Thus, if an electron exists inside the nucleus then its energy should be of the order of 9.9 MeV. But the experiment shows that no electron in the atom possesses kinetic energy greater than 4 MeV.
7. Hence, no electron can exist inside the nucleus.

b. Binding energy of an electron in atom :

1. The uncertainty in position Δx of an electron is of order of $2R$, where R is radius of orbit.
2. The corresponding uncertainty in its momentum is
$$\Delta p \geq \frac{h}{2\pi . 2R}$$
$$R = 10^{-10} \text{ m}$$
then $\Delta p \approx 0.527 \times 10^{-24}$ kg-m/s
3. Kinetic energy of electron is
$$E_k = \frac{p^2}{2m_0} = \left(\frac{h}{4\pi R}\right)^2 \frac{1}{2m_o} = \frac{h^2}{32\pi^2 m_o R^2}$$
4. Potential energy of electron in electrostatic field of the nucleus is
$$V = \frac{-Ze^2}{4\pi \epsilon_o R}$$
5. So the total energy of its orbit will be
$$E = E_k + V$$

$$= \frac{h^2}{32\pi^2 m_o R^2} - \frac{Ze^2}{4\pi \in_o R}$$

$$= \frac{(6.63 \times 10^{-34})^2}{32 \times (3.14)^2 \times 9.1 \times 10^{-31} \times R^2}$$

$$- \frac{Z(1.6 \times 10^{-19})^2}{4 \times 3.14 \times 8.85 \times 10^{-12} R}$$

$$E = \frac{10^{-20}}{R^2} - \frac{15 \times 10^{-10} Z}{R} \text{ eV}$$

Taking $R = 10^{-10}$ m

$$E = (1 - 15Z) \text{ eV}$$

6. Now the binding energy of outermost electron in H is – 13.6 eV
7. For H atom

$$E = (1 - 15) = -14 \text{ eV} \qquad (\because \text{ for } H \text{ atom, } Z = 1)$$

It is very near to – 13.6 eV.

8. Hence, binding energy of an electron can be calculated.

c. Radius of Bohr's first orbit :

1. The energy of electron in a hydrogen atom is given by

$$E = KE + PE = \frac{p^2}{2m_0} + \frac{(-e^2)}{4\pi\varepsilon_0 x} \qquad ...(1)$$

where x is the distance between the electron and the centre of the nucleus.

2. Eq. (1) in terms of uncertainty can be expressed as

$$\Delta E = \frac{(\Delta p)^2}{2m_0} - \frac{e^2}{4\pi\varepsilon_0 \Delta x} \qquad ...(2)$$

3. Using the Heisenberg's uncertainty principle

$$\Delta p \Delta x \approx \hbar \qquad ...(3)$$

4. Putting equation (3) in equation (2)

$$\Delta E = \frac{(\hbar)^2}{2m_0 (\Delta x)^2} - \frac{e^2}{4\pi\varepsilon_0 \Delta x} \qquad ...(4)$$

5. For minimum energy (*i.e.*, for ground state) of electron,

$$\frac{\partial(\Delta E)}{\partial(\Delta x)} = 0$$

$$\frac{\partial}{\partial(\Delta x)}\left[\frac{\hbar^2}{2m_0(\Delta x)^2} - \frac{e^2}{4\pi\varepsilon_0 \Delta x}\right] = 0$$

$$\frac{\partial}{\partial(\Delta x)}\left[\frac{\hbar^2}{2m_0}(\Delta x)^{-2} - \frac{e^2}{4\pi\varepsilon_0}(\Delta x)^{-1}\right] = 0$$

$$-2\frac{\hbar^2}{2m_0}(\Delta x)^{-3} + \frac{e^2}{4\pi\varepsilon_0}(\Delta x)^{-2} = 0$$

$$-\frac{\hbar^2}{m_0(\Delta x)^3}+\frac{e^2}{4\pi\varepsilon_0(\Delta x)^2} = 0$$

$$\frac{\hbar^2}{m_0(\Delta x)^3} = \frac{e^2}{4\pi\varepsilon_0(\Delta x)^2}$$

$$\Delta x = \frac{4\pi\varepsilon_0\hbar^2}{m_0e^2}$$

6. For this value of Δx,

$$\frac{\partial^2(\Delta E)}{(\partial(\Delta x))^2} > 0$$

7. Hence for the given value of Δx the value of ΔE will give the minimum or ground state energy of an electron, *i.e.*,

$$E_{\min} = [\Delta E]_{\Delta x = \frac{4\pi\varepsilon_0\hbar^2}{m_0e^2}} = \left[\frac{(\hbar)^2}{2m_0(\Delta x)^2} - \frac{e^2}{4\pi\varepsilon_0\Delta x}\right]_{\Delta x = \frac{4\pi\varepsilon_0\hbar^2}{m_0e^2}}$$

i.e., $$E_{\min} = \left[\frac{(\hbar)^2}{2m_0\left(\frac{4\pi\varepsilon_0\hbar^2}{m_0e^2}\right)^2} - \frac{e^2}{4\pi\varepsilon_0\left(\frac{4\pi\varepsilon_0\hbar^2}{m_0e^2}\right)}\right]$$

$$E_{\min} = \left[\frac{m_0e^4}{32\pi^2\,\varepsilon_0^2\,\hbar^2} - \frac{m_0e^4}{16\pi^2\,\varepsilon_0^2\,\hbar^2}\right]$$

$$E_{\min} = \frac{-\,m_0e^4}{32\pi^2\,\varepsilon_0^2\,\hbar^2}$$

8. This is the required expression for the minimum or ground state energy of an electron in the hydrogen atom.
9. Also, the value of Δx for which the ground state energy of an electron is obtained gives the value of radius for the first Bohr's orbit.
10. This value is known as Bohr's radius and it is denoted by r_0.
11. Thus the Bohr's radius is given by

$$r_0 = \Delta x = \frac{4\pi\varepsilon_0\hbar^2}{m_0e^2}$$

12. Using the values of m, e and $\hbar$, we get

$$r_0 = \frac{4\times 3.14\times(8.85\times 10^{-12})\times(1.054\times 10^{-34})^2}{(9.1\times 10^{-31})\times(1.6\times 10^{-19})^2}$$

$$= 0.53\ \text{Å}$$

4. Attempt any **one** of the following : **(10 × 1 = 10)**

a. What do you mean by Fermi level ? Discuss the effect of temperature and doping on mobility.

Ans.

A. Fermi level : It is the energy state having probability of half of being occupied by an electron.

B. Effect of temperature on mobility :

The mobility is determined by scattering of the carriers. Scattering mechanism influence electron and hole mobility.

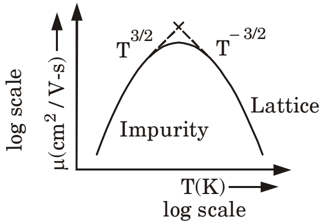


Fig. 8.

i. Lattice scattering :

1. If scattering occurs due to vibrations of lattice atom then it is called lattice scattering.
2. As the temperature increases, the frequency of lattice vibration increases. As a result, the mobility decreases.
3. The approximate temperature dependency is given by $T^{-3/2}$ as shown in Fig. 8.

ii. Impurity scattering :

1. If scattering occurs under the influence of interaction with impurity atoms, it is called impurity scattering.
2. Such scattering dominates at low temperature. At low temperature the thermal motion of carriers is slow. So, there is an increase in mobility (μ) as the temperature increases. The dependency is expressed by $T^{3/2}$ as shown in Fig. 8.

b. Draw the schematic band diagram of Fermi level, density of states, Fermi-Dirac distribution function, and carrier concentrations for intrinsic and extrinsic semiconductor.

Ans.

1. The Fermi-Dirac distribution function can be used to calculate the concentrations of electrons and holes in a semiconductor, if the densities of available states in the valence and conduction bands are known.
2. The concentration of electrons in the conduction band is

$$n_0 = \int_{E_C}^{\infty} f(E)N(E)dE \qquad ...(1)$$

where $N(E)\,dE$ is the density of states (cm^{-3}) in the energy range dE. The electron and hole concentration symbol (n_0, p_0) indicates equilibrium conditions.

3. The number of electrons per unit volume in the energy range dE is the product of the density of states and the probability of occupancy $f(E)$.
4. Thus the total electron concentration is the integral over the entire conduction band, as in eq. (1).
5. $N(E)$ is proportional to $E^{1/2}$, so the density of states in the conduction band increases with electron energy.
6. On the other hand, the fermi function becomes extremely small for large energies. This result that the product $f(E)\ N(E)$ decreases rapidly above E_C, and very few electrons occupy energy states far above the conduction band edge.
7. Similarly, the probability of finding an empty state (hole) in the valence band $[1 - f(E)]$ decreases rapidly below E, and most holes occupy states near the top of the valence band.
8. This effect is demonstrated in Fig. 9, which shows the fermi function, and the resulting number of electrons and holes occupying available energy states in the conduction and valence bands at thermal equilibrium.

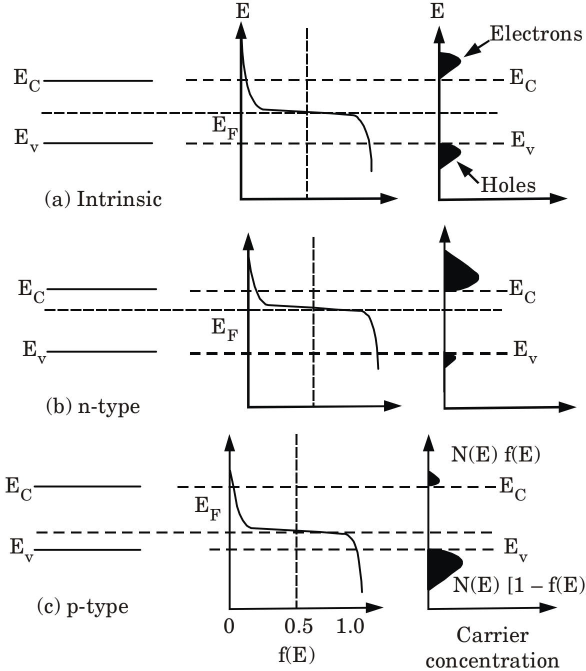


Fig. 9. Schematic band diagram, Fermi-Dirac distribution, and the carrier concentration for (a) intrinsic, (b) n-type (c) p-type at thermal equilibrium.

9. The conduction band electron concentration is the effective density of state (N_C) at E_C times the probability of occupancy at E_C.

$$n_0 = N_c f(E_c) \quad ...(2)$$

10. In this expression we assume the fermi level E_F lies at least several kT below the conduction band. Then the exponential term is large compared with unity, and the fermi function $f(E_C)$ can be simplified as

$$f(E_C) = \frac{1}{1+e^{(E_C - E_F)/kT}} \simeq e^{-[(EC - EF)/kT]} \quad ...(3)$$

Since kT at room temperature is only 0.026 eV.

11. For this condition the concentration of electrons in the conduction band is,

$$n_0 = N_C e^{-(EC - EF)/kT} \quad ...(4)$$

Here, the effective density of states N_C is,

$$N_C = 2\left(\frac{2\pi m_n^* \, kT}{h^2}\right)^{3/2}$$

m^*_n is the density-of-states effective mass for electrons.

12. The concentration of holes in the valence band is

$$p_0 = N_v[1 - f(E_v)] \quad ...(5)$$

where N_v is the effective density of states in the valence band.

13. The probability of finding an empty state at E_v is

$$1 - f(E_v) = 1 - \frac{1}{1+e^{(E_v - E_F)/kT}} \simeq e^{-(EF - Ev)/kT} \quad ...(6)$$

for E_F larger than E_v by several kT.

14. So, the concentration of holes in the valence band is

$$p_0 = N_v e^{-(EF - Ev)/kT} \quad ...(7)$$

15. The effective density of states in the valence band reduced to the band edge is

$$N_v = 2\left(\frac{2\pi m_p^* \, kT}{h^2}\right)^{3/2}$$

5. Attempt any **one** of the following : **(10 × 1 = 10)**

a. Explain and draw the small signal models of MOS transistor.

Ans.

1. For this purpose, we utilize the conceptual common source amplifier circuit shown in Fig. 10.

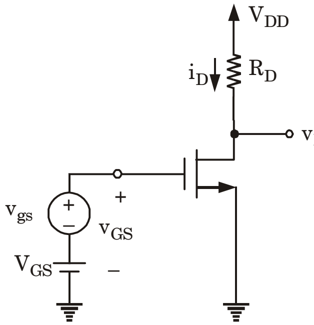


Fig. 10. Conceptual circuit.

2. For the circuit, the DC bias current I_D can be given by setting the signal $v_{gs} = 0$,

$$\therefore \qquad I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2 \qquad \text{...(1)}$$

$$\text{and} \qquad V_D = V_{DD} - R_D I_D \qquad \text{...(2)}$$

3. Now, consider, $v_{GS} = v_{gs} + V_{GS}$ resulting in a total instantaneous drain current i_D,

$$i_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} + v_{gs} - V_t)^2$$

$$= \underbrace{\frac{1}{2} k_n' \frac{W}{L} \left(V_{GS} - V_t\right)^2}_{\text{DC bias current } I_D} + \underbrace{k_n' \frac{W}{L} \left(V_{GS} - V_t\right) v_{gs}}_{\text{current proportional to } v_{gs}} + \underbrace{\frac{1}{2} k_n' \frac{W}{L} v_{gs}^2}_{\text{current proportional to } v_{gs}^2 \text{ (non-linear distortion)}} \qquad \text{...(3)}$$

4. To reduce non-linear distortion the input signal is kept small so that,

$$\frac{1}{2} k_n' \frac{W}{L} v_{gs}^2 << k_n' \frac{W}{L} (V_{GS} - V_t) v_{gs}$$

$$v_{gs} << 2 V_{OV} \qquad (\because V_{OV} = V_{GS} - V_t)$$

If this small signal condition is satisfied, we may neglect 3rd term from eq. (3).

$$\therefore \qquad i_D \simeq I_D + i_d \qquad \text{...(4)}$$

5. **Transconductance :** The parameter that relates i_d and v_{gs} is the MOSFET transconductance g_m.

$$\therefore \qquad g_m = \frac{i_d}{v_{gs}} = k_n' \frac{W}{L} (V_{GS} - V_t)$$

$$\text{or} \qquad g_m = k_n' \frac{W}{L} V_{OV} = \sqrt{2k_n' (W/L) I_D} = \frac{2I_D}{V_{ov}}$$

6. **The voltage gain :**
1. From Fig. 10,

$$v_D = V_{DD} - R_D i_D = V_{DD} - R_D (I_D + i_d)$$

$\therefore \qquad v_D = V_D - R_D\, i_d$

2. Thus, the signal component of the drain voltage is

$$v_d = -\, i_d\, R_D = -\, g_m\, v_{gs}\, R_D$$

3. Voltage gain, $A_v = \dfrac{v_d}{v_{gs}} = -\, g_m\, R_D$

C. Small-signal Equivalent-circuit models :

1. In Fig. 11(*a*), FET is replaced by equivalent circuit model and ideal constant DC voltage sources are replaced by short circuits. This resulting circuit can be used to perform signal analysis for example calculating voltage gain.
2. Fig. 11(*b*) shows one extra r_o, this is one of the shortcomings of small signal model as it assumes that I_D in saturation is independent of drain voltage.

$$A_v = \frac{v_d}{v_{gs}} = -\, g_m\, (R_D \parallel r_o)$$

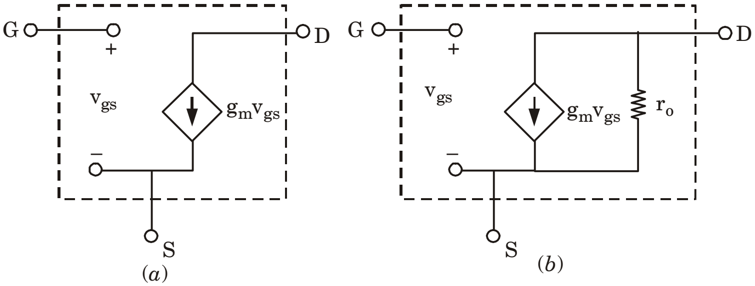


Fig. 11.

b. Explain the working principle and characteristics of following :
i. LED
ii. Solar cell

Ans.

i. LED : LED is a special type of semiconductor *p-n* junction that under forward bias emits external radiations in ultraviolet, visible and infrared regions of electromagnetic spectrum.

Construction of LED :

1. LED is just not an ordinary *p-n* junction diode where silicon is used. Here we use compound having elements like gallium, arsenic and phosphorus which are semitransparent unlike silicon which is opaque.
3. In all semiconductor *p-n* junctions, some of its energy will be given off as heat and some in the form of photons.
4. In the materials, such as gallium arsenide phosphide (GaAsP) or gallium phosphide (GaP), the number of photons of light energy emitted is sufficient to create a visible light source.

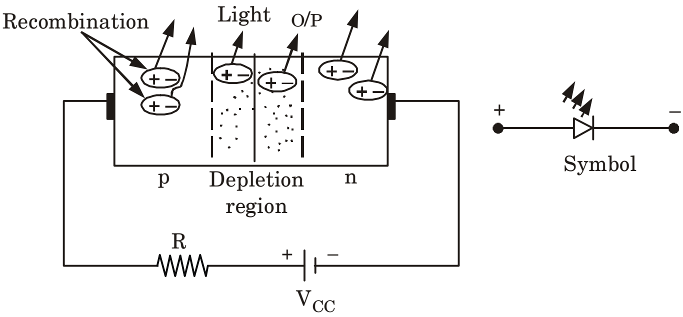


Fig. 12.

Principle of LED :

1. The process involves :
   i. Generation of electron-hole pair (EHP) by excitation of semiconductor.
   ii. Recombination of EHP.
   iii. Extraction of photons from the semiconductor.
2. The characteristic for LED is given in Fig. 13.

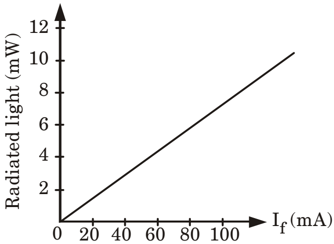


Fig. 13. Characteristics.

Working :

1. When LED is in forward bias condition, the electrons from *n*-type material cross the *p-n* junction and recombines with holes in the *p*-type material.
2. When recombination takes place, the recombining electrons release energy in the form of heat and light.
3. The emission depends upon the type of material, *i.e.*,
   GaAs → infrared radiation (invisible)
   GaP → red or green light (visible)
   GaAsP → red or yellow light (visible).

ii. Solar cell :

1. Solar cells are semiconductor junction devices which are used for converting optical radiation into electrical energy.
2. The generated electric voltage is proportional to the intensity of incident light. Due to their capability of generating voltage, they are called photovoltaic cells.
3. Silicon is the most widely used material for solar cells.

Construction :

1. The construction of a solar cell is shown in Fig. 14.
2. The *p*-type layer is made thin to intercept the light radiation falling on the junction. The doping of *p*-type material is very high.

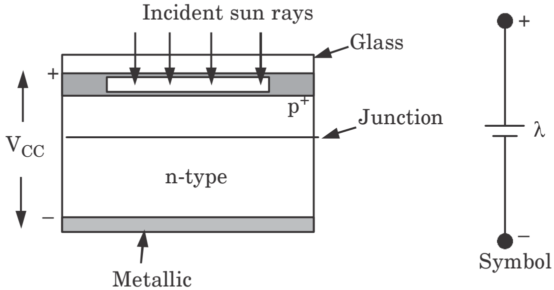


Fig. 14.

3. *p*-type is surrounded by a nickel plated ring which serves as positive terminal and the contact at bottom acts as a negative terminal.

Working :

1. When photons are incident on surface, it releases sufficient energy to the electrons to leave its orbit.
2. As a result, free electrons and holes are created. These free electrons and holes constitute the minority current.
3. In this way, depletion region potential causes the photo current to flow through the external load.

6. Attempt any **one** of the following : **(10 × 1 = 10)**

a. Explain Ebers-Moll model.

Ans.

1. The Ebers-Moll model of an *npn* transistor is shown in Fig. 15.

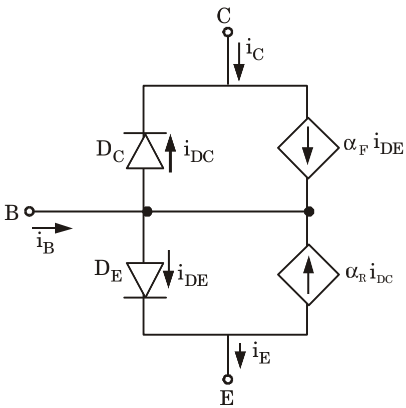


Fig. 15. The Ebers-Moll (EM) model of the *npn* transistor.

2. According to Ebers and Moll, this composite model can be used to predict the operation of the BJT in all of its possible modes.
3. The expression for the current at each of the three nodes of the model is as follows :

$$i_E = i_{DE} - \alpha_R i_{DC} \quad ...(1)$$

$$i_C = -i_{DC} + \alpha_F i_{DE} \quad ...(2)$$

$$i_B = (1 - \alpha_F)\, i_{DE} + (1 - \alpha_R)\, i_{DC} \quad ...(3)$$

4. Using diode equation, i_{DE} and i_{DC} can be expressed as

$$i_{DE} = I_{SE}\,(e^{v_{BE}/V_T} - 1) \quad ...(4)$$

$$i_{DC} = I_{SC}\,(e^{v_{BC}/V_T} - 1) \quad ...(5)$$

5. Substituting the values of i_{DE} and i_{DC} in eq. (1), (2) and (3), we get

$$i_E = \left(\frac{I_S}{\alpha_F}\right)(e^{v_{BE}/V_T} - 1) - I_S(e^{v_{BC}/V_T} - 1) \quad ...(6)$$

$$i_C = I_S(e^{v_{BE}/V_T} - 1) - \left(\frac{I_S}{\alpha_R}\right)(e^{v_{BC}/V_T} - 1) \quad ...(7)$$

$$i_B = \left(\frac{I_S}{\beta_F}\right)(e^{v_{BE}/V_T} - 1) + \left(\frac{I_S}{\beta_R}\right)(e^{v_{BC}/V_T} - 1) \quad ...(8)$$

where, $\beta_F = \dfrac{\alpha_F}{1-\alpha_F}$ and $\beta_R = \dfrac{\alpha_R}{1-\alpha_R}$

6. If e^{v_{BC}/V_T} is very small and can be neglected then

$$i_E \simeq \left(\frac{I_S}{\alpha_F}\right) e^{v_{BE}/V_T} + I_S\left(1 - \frac{1}{\alpha_F}\right) \quad ...(9)$$

$$i_C \simeq I_S e^{v_{BE}/V_T} + I_S\left(\frac{1}{\alpha_R} - 1\right) \quad ...(10)$$

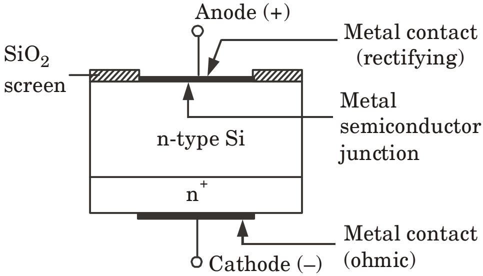
$$i_B \simeq \left(\frac{I_S}{\beta_F}\right) e^{v_{BE}/V_T} - I_S\left(\frac{1}{\beta_F} + \frac{1}{\beta_R}\right) \quad ...(11)$$

b. Explain Schottky diode in detail and also write its applications.

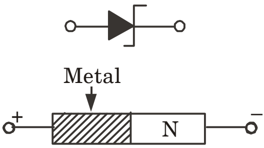
Ans. **Schottky diode :**

Construction :

1. Fig. 16 shows the symbol and cross-sectional view of a Schottky diode. It is a metal-semiconductor junction diode without depletion layer.



(a) Cross-sectional view



(b) Symbol

Fig. 16. Schottky diode.

2. On one side of the junction a metal (like gold, silver, platinum or tungsten, etc.) is used and on the other side the *n*-type doped semiconductor is used.
3. *p*-type of material can also be used for device fabrication.
4. A layer of metal is deposited on a thin epitaxial layer of *n*-type silicon. For protection purpose the metal layer is surrounded by gold or silver leaf (thin sheet).
5. The metal film forms the positive electrode (anode) and the semiconductor is the cathode.

Working :

1. The operation of Schottky diode is due to the fact that electrons in different materials have different absolute potential energies.
2. *n*-type semiconductor electrons have higher potential energy as compared to electrons of metal.
3. When the two are brought in contact, there is flow of electrons in both directions across the metal-semiconductor interface when the contact is first made.
4. The flux of electrons from the semiconductor into the metal is much larger due to higher absolute potential energy.
5. As a result, the metal will become negatively charged and the semiconductor will acquire a positive charge.
6. The net result is a "Surface barrier" between the two materials which prevents any further current.
7. It is much like but not exactly the depletion layer in the *p*-*n* diode.
8. At this point, the thermal equilibrium is established. There are no minority carriers (holes in this case) in establishing the equilibrium.
9. This is the major difference between a Schottky diode and a *p*-*n* junction diode.

10. Schottky diodes are termed majority-carrier devices and *p-n* junctions are labelled minority carrier devices or bipolar devices (since they use both electrons and holes in their basic operation).
11. Now a voltage is applied to the Schottky diode such that metal is positive with respect to the semiconductor.
12. This voltage will oppose the built-in potential and makes it easier for the current to flow.
13. Biasing the metal negative with respect to the semiconductor increases the potential barrier to majority-carrier current flow.
14. Thus, the metal-semiconductors junction has rectifying characteristics similar to those of a *p-n* junction.

Application :

1. Voltage clamping and clipping circuits.
2. Reverse current and discharge protection.
3. Rectify high frequencies signal.
4. Low power TTL logic.

7. Attempt any **one** of the following : **(10 × 1 = 10)**

a. Using the concept of diffusion and drift of carriers derive the continuity equation and diffusion length.

Ans. **Diffusion carrier :** Diffusion carrier is due to the thermal energy which causes the carriers to move at random even when no field is applied.

Drift carrier : When an electrical field is applied to a semiconductor, the carriers will move at a velocity that is proportional to the magnitude of the field.

Continuity equation :

1. Consider a differential length Δx of a semiconductor sample with area A in the yz-plane.
2. The hole current density leaving the volume, $J_p(x + \Delta x)$, can be larger orsmaller than the current density entering, $J_p(x)$, depending on the generation and recombination of carriers taking place within the volume.
3. The net increase in hole concentration per unit time, $\partial p/\partial t$, is the difference between the hole flux per unit volume entering and leaving, minus the recombination rate.
4. We can convert hole current density to hole particle flux density by dividing J_p by q.
5. The current densities are already expressed per unit area, thus dividing $J_p(x)/q$ by Δx gives the number of carriers per unit volume entering ΔxA per unit time, and $(1/q)J_p(x + \Delta x)/\Delta x$ is the number leaving per unit volume and time.

$$\left.\frac{\partial p}{\partial t}\right|_{x \to x + \Delta x} = \frac{1}{q}\,\frac{J_p(x) - J_p(x + \Delta x)}{\Delta x} - \frac{\delta p}{\tau_p}$$

Rate of hole buildup = increase of hole concentration in $\delta x A$ per unit time − recombination rate ...(1)

5. As Δx approaches zero, we can write the current change in derivation form,

$$\frac{\partial p(x,t)}{\partial t} = \frac{\partial \delta p}{\partial t} = -\frac{1}{q}\frac{\partial J_P}{\partial x} - \frac{\delta p}{\tau_p} \quad ...(2)$$

6. The eq. (2) is called the continuity equation for holes. For electrons we can write,

$$\frac{\partial \delta n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n} \quad ...(3)$$

7. Since the electronic charge is negative.

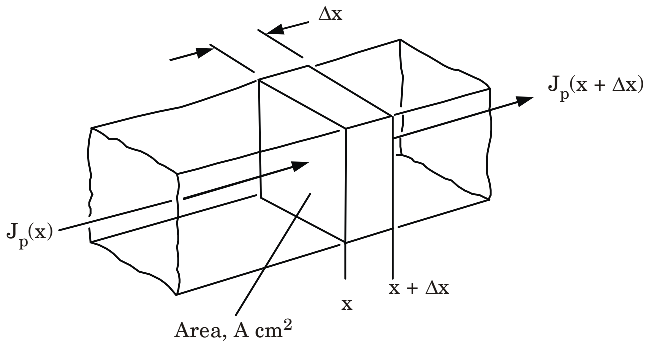


Fig. 17.

b. Derive an expression for diode current in *p-n* junction diode.

Ans. Diode current equation :

1. The hole diffusion current at any point x_n in the n-region can be obtained with the help of following expression

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n}$$

$$I_p(x_n) = -qAD_p \frac{d}{dx_n}\{[p_n(e^{qV/kT}-1)]e^{-x_n/L_p}\}$$

$$= qA\frac{D_p}{L_p}[p_n(e^{qV/kT}-1)e^{-x_n/L_p}]$$

$$I_p(x_n = 0) = qA\frac{D_p}{L_p}[p_n(e^{qV/kT}-1)]$$

2. Similarly, the electron current injected into p-region at the junction is given by

$$I_n(x_p = 0) = -qA \frac{D_n}{L_n} [n_p (e^{qV/kT} - 1)]$$

3. If we take + x-direction as the reference direction for total current, we have :

$$I = I_p(x_n = 0) - I_n(x_p = 0)$$

$$= qA \left(\frac{D_p}{L_p}\right) [p_n (e^{qV/kT} - 1)] + qA \left(\frac{D_n}{L_n}\right) [n_p (e^{qV/kT} - 1)]$$

$$= qA \left[\left(\frac{D_p}{L_p}\right) p_n + \left(\frac{D_n}{L_n}\right) n_p\right] [e^{qV/kT} - 1]$$

$$I = I_0 [e^{qV/kT} - 1]$$

4. The current can also be calculated for reverse bias by letting $V = -V_r$

$$I = qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right) (e^{-qV_r/kT} - 1)$$

5. If V_r is larger than a few kT/q, the total current is just the reverse saturation current.

$$I = -qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right) = -I_0$$

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