SEMICONDUCTOR PHYSICS

IAT-1 Question Bank – Complete Answers

Semester 2 | First Year BE | Mumbai University

SYNTAX SYNDICATE

SECTION A: 2 MARKS QUESTIONS

Q1. Define intrinsic and extrinsic semiconductors. (Differentiate between intrinsic and extrinsic semiconductors). [2 marks]

INTRINSIC SEMICONDUCTOR:

A pure semiconductor, without any impurity, is called an intrinsic semiconductor. The number of electrons in the conduction band equals the number of holes in the valence band (n = p = ni). Conductivity is purely due to thermally generated electron-hole pairs.

Examples: Pure Silicon (Si), Pure Germanium (Ge).

EXTRINSIC SEMICONDUCTOR:

A semiconductor that has been doped with specific impurity atoms (dopants) to increase its electrical conductivity is called an extrinsic semiconductor. The impurity atoms donate extra charge carriers. The number of electrons and holes are NOT equal.

Examples: Silicon doped with Phosphorus (n-type), Silicon doped with Boron (p-type).

Parameter	Intrinsic Semiconductor	Extrinsic Semiconductor
Purity	Pure material, no impurity	Impurity (dopant) added
Carrier concentration	n = p = ni	n ≠ p
Conductivity	Low	Higher, controllable
Conductivity depends on	Temperature	Doping concentration
Examples	Pure Si, Pure Ge	Si+P (n-type), Si+B (p-type)
Device use	Not useful for devices	Used in diodes, transistors, ICs

Key Differences:

- Intrinsic: Pure material; Extrinsic: Impurity added (doped material).
- Intrinsic: n = p = ni; Extrinsic: n ≠ p (one dominates).
- Intrinsic: Low conductivity; Extrinsic: Higher, controllable conductivity.
- Intrinsic: Conductivity depends on temperature; Extrinsic: Conductivity depends on doping concentration.
- Intrinsic: Not useful for devices; Extrinsic: Used in diodes, transistors, ICs.

Q2. Explain the concept of Fermi level in semiconductors. Show the Fermi level with diagram in p-type semiconductor. [2 marks]

FERMI LEVEL:

The Fermi level (EF) is a thermodynamic energy level that represents the highest energy level occupied by electrons at absolute zero temperature (0 K). It is the energy level at which the probability of finding an electron is exactly 0.5 (50%) at any temperature T > 0 K. It is defined by the Fermi-Dirac distribution function:

$$f(E) = 1 / [1 + \exp((E - EF) / kT)]$$

where k = Boltzmann's constant, T = absolute temperature.

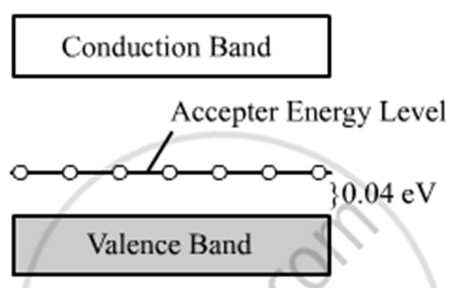
FERMI LEVEL IN INTRINSIC SEMICONDUCTOR:

The Fermi level lies exactly in the middle of the energy bandgap (midway between conduction band EC and valence band EV).

FERMI LEVEL IN P-TYPE SEMICONDUCTOR (Diagram description):

In a p-type semiconductor, the material is doped with acceptor impurities (e.g., Boron in Silicon). The acceptor energy level (EA) lies just above the valence band (EV). Holes are the majority carriers. The Fermi level (EF) shifts downward toward the valence band (EV), closer to EA.

Energy Band Diagram (p-type):



(a) *p*-type

The closer the Fermi level is to EV, the higher the hole concentration (p-type doping).

Q3. Define mobility of charge carriers and state its SI unit. [2 marks]

MOBILITY (μ):

Mobility of charge carriers is defined as the drift velocity acquired by a charge carrier per unit electric field applied. It represents how quickly a charge carrier (electron or hole) can move through a semiconductor or conductor under the influence of an electric field.

Mathematically:

$$\mu = vd / E$$

where:

- μ = mobility of charge carrier
- vd = drift velocity of the charge carrier (m/s)
- E = applied electric field (V/m)

SI Unit: $m^2/(V \cdot s)$ [meter squared per volt-second]

Note: Mobility of electrons (μe) is always greater than mobility of holes (μh) because electrons have lower effective mass and experience fewer collisions. For Silicon: $\mu e \approx 0.135$ m²/V·s, $\mu h \approx 0.048$ m²/V·s.

Q4. The resistivity of Cu is 1.72 × 10^{-8} Ω·m. Calculate the mobility of electrons in Cu. Given: n = 10.41 × 10^{28}/m³. [2 marks]

Given:

- Resistivity, $\rho = 1.72 \times 10^{-8}$ Ω·m
- Number density of electrons, $n = 10.41 \times 10^{28}$ /m³
- Charge of electron, $e = 1.6 \times 10^{-19}$ C

Formula: Conductivity $\sigma = 1/\rho = n \cdot e \cdot \mu e$

Therefore, Mobility:

$$\mu e = 1 / (n \times e \times \rho)$$

$$\mu e = 1 / (10.41 \times 10^{28} \times 1.6 \times 10^{-19} \times 1.72 \times 10^{-8})$$

$$\mu e = 1 / (10.41 \times 1.6 \times 1.72 \times 10^{28-19-8})$$

$$\mu e = 1 / (28.65 \times 10^{1})$$

$$\mu e = 1 / 286.5$$

$$\mu e \approx 3.49 \times 10^{-3}\ m^2/V\cdot s$$

Result: Mobility of electrons in Copper, $\mu e \approx 3.49 \times 10^{-3}$ m²/V·s

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Q5. What is a p-n junction? Give any three uses of it. [2 marks]

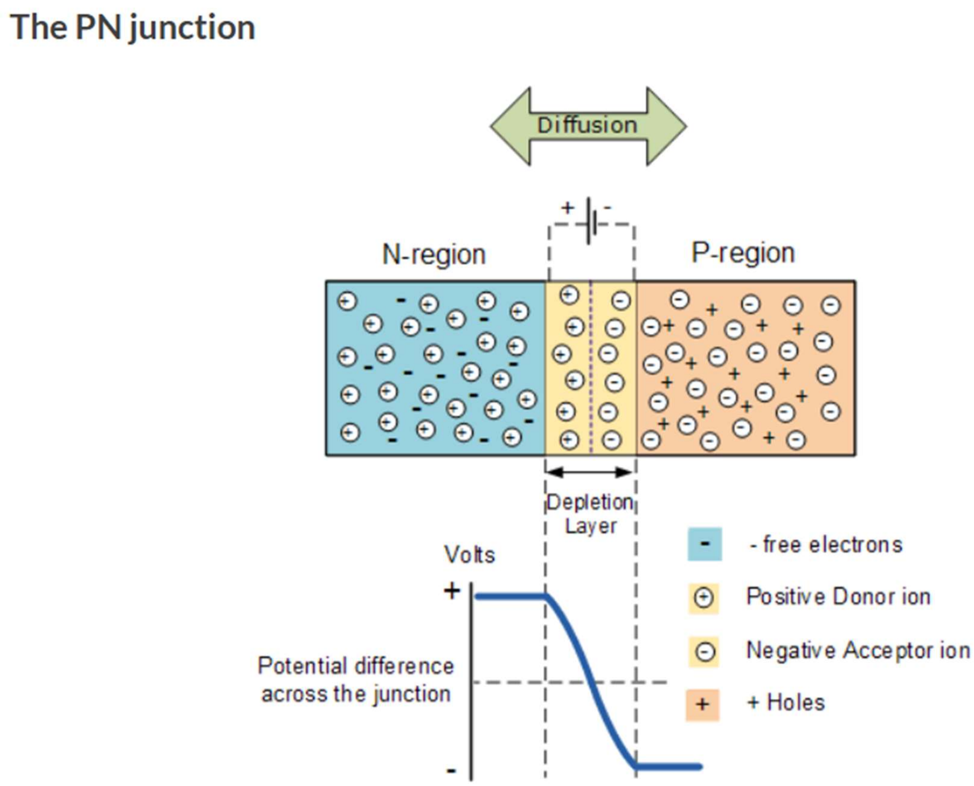
P-N JUNCTION:

A p-n junction is formed when a p-type semiconductor (having excess holes as majority carriers) is metallurgically joined to an n-type semiconductor (having excess electrons as majority carriers). At the junction, diffusion of carriers takes place, creating a depletion region with an internal electric field (built-in potential). This structure forms the basic building block of most semiconductor devices.

THREE USES OF P-N JUNCTION:

- Rectifier Diode: Converts AC (alternating current) to DC (direct current) – used in power supplies and chargers.
- Zener Diode: Used as voltage regulator to maintain a constant voltage across a load (reverse breakdown application).
- Light Emitting Diode (LED): When forward biased, electrons recombine with holes and emit photons (light) – used in displays, indicators, and lighting.
- (Also used in: Solar cells, photodiodes, and transistors.)

Q6. Explain how built-in potential and depletion layer are developed in a p-n junction. [2 marks]



FORMATION OF DEPLETION LAYER AND BUILT-IN POTENTIAL:

Step 1 – Diffusion:

When p-type and n-type semiconductors are joined, due to the concentration gradient, electrons from the n-side diffuse to the p-side, and holes from the p-side diffuse to the n-side.

Step 2 – Ionization and Depletion Region:

As electrons leave the n-side, positive donor ions (immobile) are left behind. As holes leave the p-side, negative acceptor ions are exposed. This creates a region near the junction that is depleted of free charge carriers — called the Depletion Layer (or Space Charge Region). Its width is typically 0.1–1 μm.

Step 3 – Built-in Electric Field:

The exposed positive ions (n-side) and negative ions (p-side) create an internal electric field directed from n to p (right to left). This field opposes further diffusion.

Step 4 – Built-in Potential (V_0):

The electric field across the depletion region gives rise to a potential difference called the built-in potential or contact potential (V_0). Equilibrium is reached when the drift current (due to built-in field) exactly balances the diffusion current. For Silicon, $V_0 \approx 0.6–0.7$ V; for Germanium, $V_0 \approx 0.2–0.3$ V.

$$V_0 = (kT/e) \times \ln(NA \times ND / ni^2)$$

Q7. List the factors affecting the Fermi level of intrinsic semiconductors. [2 marks]

Factors affecting Fermi Level (EF) in intrinsic semiconductors:

- Temperature (T): At T = 0 K, EF lies exactly at midgap. As temperature increases, EF shifts slightly (toward conduction band in n-type and toward valence band in p-type).
- Effective Masses of Carriers: If the effective mass of electrons (me*) equals that of holes (mh*), EF lies exactly at midgap. If me* ≠ mh*, EF shifts slightly. EF = (EC + EV)/2 + (3kT/4)·ln(mh*/me*). For Si and Ge, EF lies slightly below the midgap due to mh* > me*.
- Doping Concentration (for extrinsic): Increasing donor concentration raises EF toward EC (n-type). Increasing acceptor concentration lowers EF toward EV (p-type).
- Band Gap (Eg): The position of EF in the gap depends on the width of the bandgap.
- Crystal Structure and Material: Different semiconductors have different band structures, affecting EF.

Q8. Explain the concept of Hall Effect. State the significance of Hall Effect. [2 marks]

HALL EFFECT:

When a current-carrying conductor (or semiconductor) is placed in a perpendicular magnetic field, a transverse electric field (and hence a voltage) is developed perpendicular to both the current direction and the magnetic field. This phenomenon is called the Hall Effect, discovered by Edwin Hall in 1879.

Setup: Current (I) flows along x-direction, Magnetic field (B) along z-direction → Hall voltage (VH) developed along y-direction.

For n-type semiconductor (electrons):

Electrons moving in –x direction experience a Lorentz force F = –e(v × B), accumulating on one face, creating a Hall voltage.

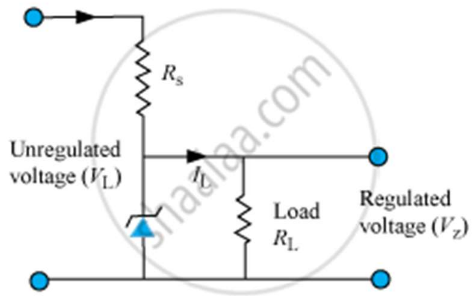
$$VH = RH \times I \times B / t$$

where RH = Hall coefficient = –1/(ne) for n-type; t = thickness of sample.

SIGNIFICANCE OF HALL EFFECT:

- Determines the type of semiconductor (n-type or p-type) from the sign of Hall coefficient.
- Calculates the carrier concentration (n or p) of the semiconductor.
- Measures carrier mobility: μ = σ × RH.
- Used in Hall sensors to measure magnetic field strength.
- Used in current sensors and position sensors in industry.

Q9. Explain the application of Zener diode as a voltage regulator with a suitable circuit diagram. [2 marks]



ZENER DIODE AS VOLTAGE REGULATOR:

A Zener diode is designed to operate in the reverse breakdown region. When reverse voltage exceeds the Zener breakdown voltage (VZ), the diode maintains a nearly constant voltage across it, regardless of changes in input voltage or load current. This property makes it an ideal voltage regulator.

Circuit Description:

- Input voltage (Vin, unregulated) is connected in series with a resistor RS (series resistor / current limiting resistor).
- The Zener diode is connected in reverse bias, in parallel with the load (RL).
- The output voltage across the load = VZ (Zener voltage), which remains constant.

Circuit Diagram (Text Representation):

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Vin ──[RS]──┬────── Vout = VZ
                  |
      [ZD] (Zener, reverse biased)
                  |
                 GND
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Working:

If Vin increases, the excess voltage drops across RS; VZ remains constant. If load current changes, the Zener current adjusts automatically to keep VZ constant. Condition: Vin > VZ always.

Q10. Differentiate between n-type and p-type extrinsic semiconductors. [2 marks]

Parameter	n-type	p-type
Dopant	Pentavalent (P, As, Sb)	Trivalent (B, Al, Ga)
Majority carriers	Electrons	Holes
Minority carriers	Holes	Electrons
Fermi level position	Near conduction band (EC)	Near valence band (EV)
Impurity energy level	Donor level (ED) just below EC	Acceptor level (EA) just above EV
Hall coefficient (RH)	Negative	Positive
Carrier relation	$nn > ni^2$	$pp > ni^2$

Q11a. Differentiate between Solar Cell and Photodiode. [2 marks]

Parameter	Solar Cell	Photodiode
Function	Converts light → electrical energy	Converts light → current (detection)
Effect used	Photovoltaic effect	Photoconductive effect
Bias	No external bias (self-powered)	Reverse biased
Area	Large area	Small area
Output	Voltage + current (power)	Current ∝ light intensity
Application	Power generation	Optical comm., sensors, remote control
External battery	Not needed	Required

Q11b (Hall Numerical). A sample of n-type silicon has a donor density of $10^{20}/m^3$. Thickness = 4.5 mm, B = 0.55 T, J = 500 A/m², μe = 0.17 m²/V·s. Find (i) Hall voltage, (ii) Hall coefficient, (iii) Hall angle. [2 marks]

Given:

- ND = n = 10^{20} /m³ (n-type, so majority carriers = electrons)
- t = 4.5 mm = 4.5×10^{-3} m
- B = 0.55 T
- J = 500 A/m²
- μe = 0.17 m²/V·s
- e = 1.6×10^{-19} C

(i) Hall Coefficient:

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RH = -1/(n·e)    [negative for n-type]
RH = -1 / (10²⁰ × 1.6 × 10⁻¹⁹)
RH = -1 / 16 = -0.0625 m³/C
|RH| = 0.0625 m³/C
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(ii) Hall Voltage (VH):

$$V_H = \frac{R_H \cdot (J \cdot w \cdot t) \cdot B}{t}$$

Actually: EH = RH × J × B (Hall field)

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VH = EH × t = RH × J × B × t
VH = 0.0625 × 500 × 0.55 × 4.5 × 10⁻³
VH = 0.0625 × 500 × 0.55 × 0.0045
VH = 0.0625 × 1.2375
VH ≈ 0.0773 V ≈ 77.3 mV
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(iii) Hall Angle (θH):

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tan(θH) = μe × B
tan(θH) = 0.17 × 0.55 = 0.0935
θH = tan(0.0935) ≈ 5.34°
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Q12. What is Fermi level? Explain the shift of Fermi level with impurity concentration. [2 marks]

FERMI LEVEL:

The Fermi level (EF) is a reference energy level in a solid at which the probability of finding an electron is exactly 0.5 (50%) at temperature T > 0K. It represents the electrochemical potential of electrons and determines how electrons are distributed among energy levels (Fermi-Dirac statistics).

SHIFT OF FERMI LEVEL WITH IMPURITY CONCENTRATION:

For n-type semiconductor (donor doping):

As donor concentration (ND) increases, more electrons are added to the conduction band. The Fermi level EF shifts upward toward the conduction band EC. At very high doping (degenerate semiconductor), EF may enter the conduction band.

$$EF = EC - kT \times \ln(NC / ND)$$

For p-type semiconductor (acceptor doping):

As acceptor concentration (NA) increases, more holes are created in the valence band. The Fermi level EF shifts downward toward the valence band EV. At very high doping, EF may enter the valence band.

$$EF = EV + kT \times \ln(NV / NA)$$

In Summary: EF moves toward EC with increasing n-type doping, and toward EV with increasing p-type doping. At very heavy doping, the semiconductor becomes 'degenerate' and behaves like a metal.

Q13. A sample of Ge at room temperature has carrier concentration ni = $2.4\times10^{19}/m^3$. Doped with Sb at 1 per million Ge atoms. Ge atom concentration = $4\times10^{28}/m^3$. Find hole concentration. [2 marks]

Given:

- ni = 2.4×10^{19} /m³ (intrinsic carrier concentration of Ge)
- NGe = 4×10^{28} /m³
- Doping ratio = 1 Sb per 10^6 Ge atoms (Sb is pentavalent → n-type dopant)

Step 1: Find donor concentration (ND):

$$ND = NGe / 10^6 = 4 \times 10^{28} / 10^6 = 4 \times 10^{22} /m^3$$

Step 2: Find electron concentration (n):

Since ND >> ni, the electron concentration is approximately:

$$n \approx ND = 4 \times 10^{22} /m^3$$

Step 3: Find hole concentration (p) using mass action law:

$$n \times p = ni^2$$

$$p = ni^2 / n = (2.4 \times 10^{19})^2 / (4 \times 10^{22})$$

$$p = 5.76 \times 10^{38} / 4 \times 10^{22}$$

$$p = 1.44 \times 10^{16} /m^3$$

Result: Hole concentration, $p \approx 1.44 \times 10^{16}$ /m³ (much less than n; Ge is now n-type)

Q14. Differentiate between Zener breakdown and Avalanche breakdown. [2 marks]

Parameter	Zener Breakdown	Avalanche Breakdown
Doping	Heavily doped junction	Lightly/moderately doped
Breakdown voltage	$V_Z < 6$ V	$V_{AV} > 6$ V
Mechanism	Quantum tunneling of electrons	Impact ionization (chain reaction)
Depletion layer	Very thin	Wider
Temperature coefficient	Negative (V_Z decreases with T↑)	Positive (V_{AV} increases with T↑)
Breakdown sharpness	Sharp, well-defined	Softer, less defined

Q15. What is meant by Drift current and Diffusion current? [2 marks]

DRIFT CURRENT:

Drift current is the flow of charge carriers (electrons and holes) due to the application of an external electric field. When an electric field E is applied, carriers experience a force and move (drift) in the direction of the field. Holes drift in the direction of E; electrons drift opposite to E.

$$J_{drift} = \sigma \times E = (n \cdot e \cdot \mu_e + p \cdot e \cdot \mu_h) \times E$$

where σ = conductivity, E = electric field.

DIFFUSION CURRENT:

Diffusion current is the flow of charge carriers from a region of higher concentration to a region of lower concentration, due to the concentration gradient (Fick's Law). This occurs even without any external electric field — it is driven purely by carrier concentration differences.

$$J_{diff}(\text{electrons}) = e \cdot D_e \cdot (dn/dx)$$

$$J_{diff}(\text{holes}) = -e \cdot D_h \cdot (dp/dx)$$

where D_e, D_h = diffusion coefficients for electrons and holes.

Key Difference: Drift → requires electric field; Diffusion → requires concentration gradient.

Q16. Mention diode equation of forward current (I) and potential barrier equation (V_0) with notation of terms. [2 marks]

DIODE EQUATION (Shockley's Equation):

$$I = I_0 \left[\exp(eV / \eta kT) - 1 \right]$$

where:

- I = forward current through the diode
- I_0 = reverse saturation current (dark current)
- e = charge of electron = 1.6×10^{-19} C
- V = applied voltage across the diode
- η (eta) = ideality factor (1 for Ge, 2 for Si; typically 1 for ideal diode)
- k = Boltzmann's constant = 1.38×10^{-23} J/K
- T = absolute temperature (K)

POTENTIAL BARRIER EQUATION (Built-in Potential V_0):

$$V_0 = (kT/e) \times \ln(NA \times ND / ni^2)$$

where:

- V_0 = contact potential / built-in potential
- k = Boltzmann's constant
- T = temperature in Kelvin
- e = electronic charge
- NA = acceptor concentration (p-side doping)
- ND = donor concentration (n-side doping)
- ni = intrinsic carrier concentration of the semiconductor

Q17. Calculate potential barrier for a Germanium p-n junction at room temperature if both p and n regions are doped equally at 1 atom per 10^6 Ge atoms. [2 marks]

Given:

- Semiconductor: Germanium (Ge)
- T = 300 K (room temperature)
- NGe = 4.4×10^{28} /m³ (Ge atom density)
- Doping = 1 per 10^6 Ge atoms → ND = NA = $4.4 \times 10^{28} / 10^6 = 4.4 \times 10^{22}$ /m³
- ni (Ge) = 2.4×10^{19} /m³
- kT/e at 300 K = 0.02585 V ≈ 26 mV

Using the potential barrier formula:

$$V_0 = (kT/e) \times \ln(NA \times ND / ni^2)$$

$$V_0 = 0.02585 \times \ln((4.4 \times 10^{22})^2 / (2.4 \times 10^{19})^2)$$

$$V_0 = 0.02585 \times \ln(19.36 \times 10^{44} / 5.76 \times 10^{38})$$

$$V_0 = 0.02585 \times \ln(3.361 \times 10^6)$$

$$V_0 = 0.02585 \times \ln(3.361 \times 10^6)$$

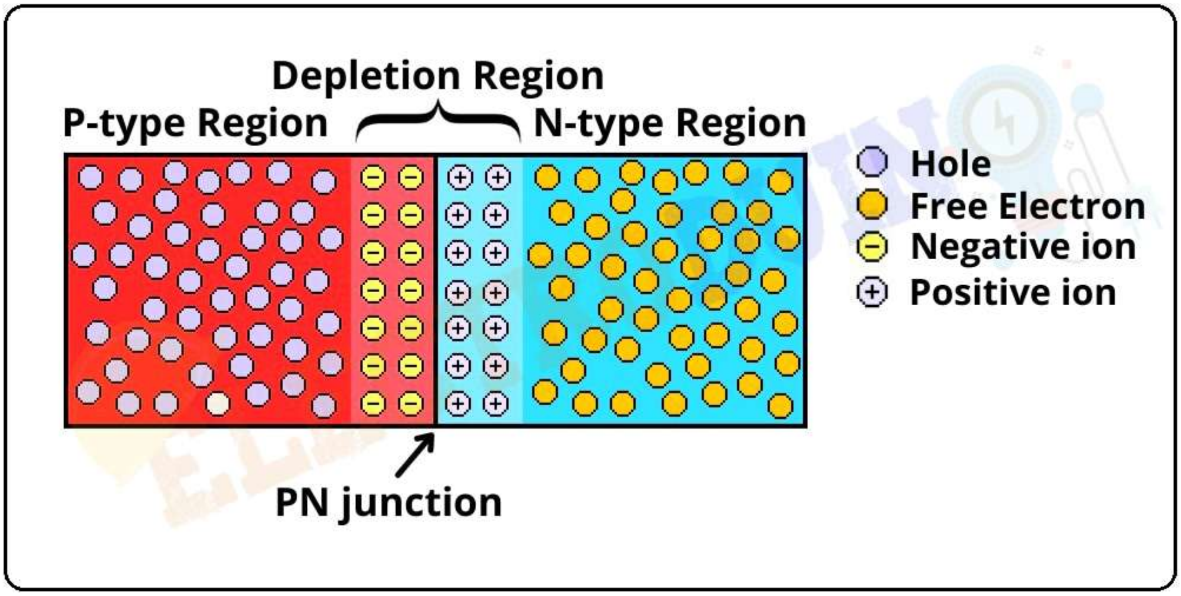
$$V_0 = 0.02585 \times 15.03$$

$$V_0 \approx 0.388 \text{ V}$$

Result: The potential barrier (built-in potential) for the Ge p-n junction ≈ 0.39 V at room temperature.

SECTION B: 4 & 5 MARKS QUESTIONS

Q1. Explain the formation of a p-n junction. Derive the expression for barrier potential. [5 marks]



Formation of P-N Junction:

A p-n junction is formed by joining a p-type semiconductor (doped with acceptor atoms, having excess holes) and an n-type semiconductor (doped with donor atoms, having excess electrons) in intimate contact — either by diffusion, ion implantation, or epitaxial growth.

Stage 1 – Before Contact (Separate regions):

- p-side: High hole concentration (pp >> np); Fermi level near EV.
- n-side: High electron concentration (nn >> pn); Fermi level near EC.

Stage 2 – At Contact (Diffusion begins):

Upon contact, electrons from n-side diffuse to p-side (high→low concentration), and holes from p-side diffuse to n-side. This diffusion of majority carriers is the diffusion current.

Stage 3 – Depletion Region:

As electrons leave n-side → positive donor ions (immobile) are exposed. As holes leave p-side → negative acceptor ions are exposed. This creates a depletion layer (space charge region), depleted of free carriers, with immobile ions creating an internal electric field from n to p.

Stage 4 – Equilibrium:

The built-in electric field opposes further diffusion. At equilibrium, drift current (due to built-in field) = diffusion current. Net current = 0. The Fermi levels of both sides align (EFp = EFn).

Derivation of Barrier Potential (V_0):

At equilibrium, the electron concentration on the p-side and n-side are related by Boltzmann statistics:

$$np = nn \times \exp(-eV_0 / kT)$$

where np = minority electron concentration on p-side, nn = majority electron concentration on n-side.

For non-degenerate semiconductor:

$$nn \approx ND \quad \text{and} \quad np \approx ni^2 / NA$$

Substituting:

$$ni^2 / NA = ND \times \exp(-eV_0 / kT)$$

$$\exp(-eV_0 / kT) = ni^2 / (NA \times ND)$$

$$\exp(eV_0 / kT) = (NA \times ND) / ni^2$$

Taking natural log on both sides:

$$eV_0 / kT = \ln(NA \times ND / ni^2)$$

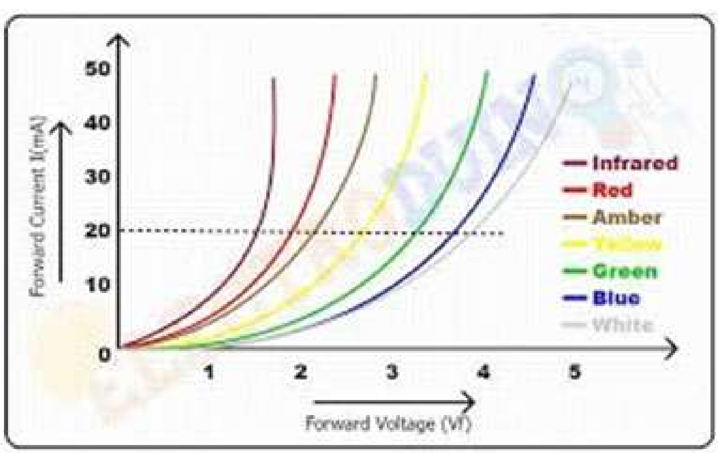
$$V_0 = (kT / e) \times \ln(NA \times ND / ni^2)$$

where:

- V_0 = contact / built-in potential (V)
- NA = acceptor concentration of p-side ($/m^3$)
- ND = donor concentration of n-side ($/m^3$)
- ni = intrinsic carrier concentration ($/m^3$)
- kT/e = thermal voltage = 0.026 V at 300 K

For Silicon at 300 K: $V_0 \approx 0.6$–0.7 V; For Germanium: $V_0 \approx 0.2$–0.3 V.

Q2. Describe the I-V characteristics of a p-n junction diode under forward and reverse bias. Analyze the operation of an LED with a suitable diagram. [5 marks]



I-V Characteristics of P-N Junction Diode:

The current-voltage (I-V) characteristic of a diode is described by Shockley's equation: $I = I_0[\exp(eV/\eta kT) - 1]$

A) FORWARD BIAS (V > 0):

The positive terminal of battery is connected to p-side and negative to n-side. The external field opposes the built-in field, reducing the potential barrier. Majority carriers (electrons from n, holes from p) are injected across the junction.

- For V < 0.3 V (Ge) or V < 0.6 V (Si): Very small current flows — called the cut-in / threshold / knee voltage.
- Beyond knee voltage: Current increases exponentially with voltage.
- The forward resistance is very small (~ few Ω).

B) REVERSE BIAS (V < 0):

The positive terminal is connected to n-side, negative to p-side. The external field adds to built-in field, increasing the barrier. Majority carriers are repelled from the junction, widening the depletion layer.

- Only minority carriers (electrons in p-side, holes in n-side) can cross the junction → very small reverse saturation current I_0 (nA range for Si).
- I_0 is nearly constant regardless of reverse voltage (up to breakdown).
- At Zener/Avalanche breakdown voltage: Sudden large increase in reverse current.

C) I-V Curve Summary:

Forward region: Exponential rise after knee voltage (~0.6-0.7V for Si)

Reverse region: Nearly flat at $-I_0$, until breakdown

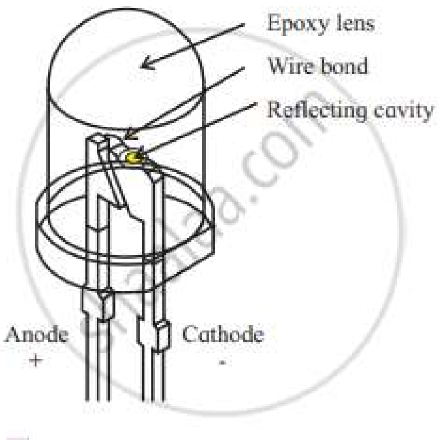
LED (Light Emitting Diode) – Operation:

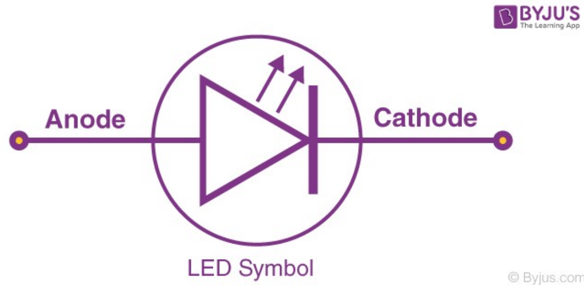
An LED is a p-n junction diode made from direct bandgap semiconductor materials such as GaAs, GaP, GaAsP, InGaN, etc. (Silicon and Germanium are indirect bandgap and do NOT emit light efficiently.)

Working Principle (Electroluminescence):

- When LED is forward biased, electrons from the n-side are injected into the p-side, and holes from p-side are injected into the n-side.
- Near the junction, electrons (in conduction band) recombine with holes (in valence band).
- In direct bandgap materials, this recombination is radiative — energy is released as a photon of light.
- The energy of the emitted photon: $E = h\nu = E_g$ (bandgap energy)
- Wavelength: $\lambda = hc / E_g$

Diagram :





Colour of light depends on bandgap:

- GaAs: Infrared (Eg ≈ 1.42 eV)
- GaP: Green/Red (Eg ≈ 2.26 eV)
- GaN: Blue/UV (Eg ≈ 3.4 eV)
- InGaN alloys: White, Blue, Green LEDs

Q3. A silicon diode is subjected to forward voltage of 0.7V at 27°C with saturation current $I_0 = 10^{-12}$ A. Calculate forward current (η = 1). [4 marks]

Given:

- V = 0.7 V (forward voltage)
- T = 27°C = 300 K
- $I_0 = 10^{-12}$ A
- η = 1 (ideality factor)
- $k = 1.38 \times 10^{-23}$ J/K
- $e = 1.6 \times 10^{-19}$ C

Thermal voltage:

$$VT = kT/e = (1.38 \times 10^{-23} \times 300) / 1.6 \times 10^{-19} = 0.02585 \text{ V} \approx 26 \text{ mV}$$

Using Shockley's equation:

$$I = I_0 [\exp(V / \eta \cdot VT) - 1]$$

$$I = 10^{-12} \times [\exp(0.7 / 1 \times 0.02585) - 1]$$

$$I = 10^{-12} \times [\exp(27.08) - 1]$$

$$\exp(27.08) \approx 5.76 \times 10^{11}$$

$$I = 10^{-12} \times (5.76 \times 10^{11} - 1)$$

$$I \approx 10^{-12} \times 5.76 \times 10^{11}$$

$$I \approx 0.575 \text{ A} \approx 575 \text{ mA}$$

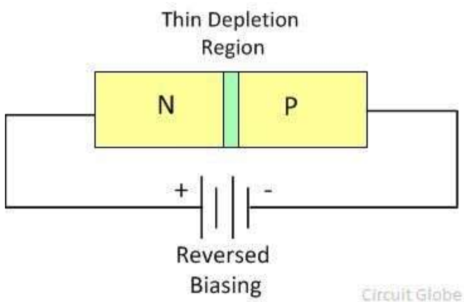
Result: Forward current through the Silicon diode ≈ 0.575 A (575 mA) at 0.7 V.

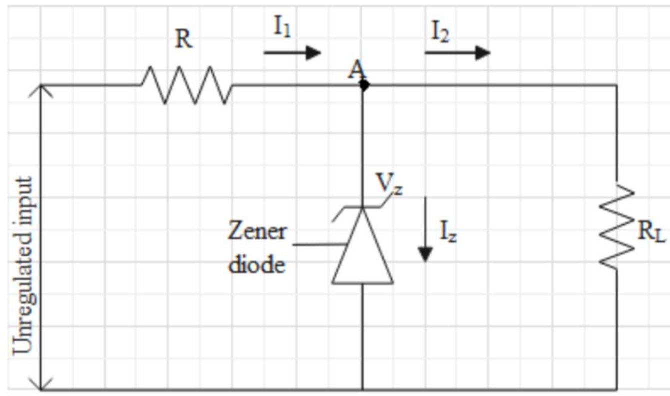
Q4. Explain the working principle and applications of a Zener diode. How does it differ from a regular p-n junction diode? [5 marks]

Zener Diode – Working Principle:

A Zener diode is a heavily doped p-n junction diode specifically designed to operate in the reverse breakdown region without being damaged. It maintains a nearly constant voltage (Zener voltage, VZ) across its terminals when reverse biased beyond VZ.

Construction: Both p and n regions are very heavily doped (NA, ND ~ $10^{23}/m^3$). This creates a very thin depletion region (~10 nm wide).





Two Breakdown Mechanisms:

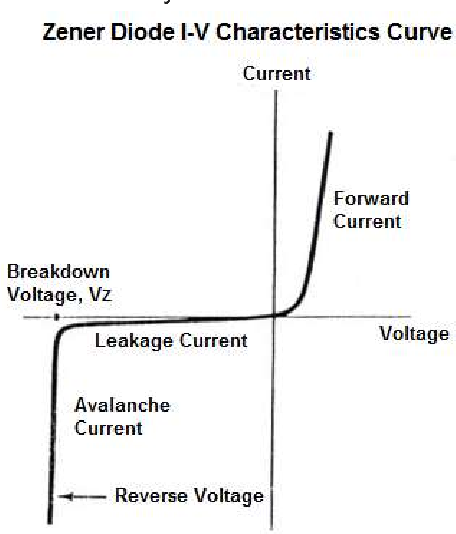
1. Zener Effect (Tunneling) – for VZ < 5–6 V:

Due to very heavy doping and thin depletion layer, the electric field is extremely intense. Valence electrons can quantum-mechanically tunnel through the thin barrier from valence band (p-side) to conduction band (n-side) — without needing extra energy. This results in sudden large current flow at VZ.

2. Avalanche Effect – for VZ > 6–8 V:

Minority carriers in reverse bias are accelerated by the electric field and gain sufficient kinetic energy to ionize covalent bonds, producing new electron-hole pairs. These new carriers also accelerate and ionize further — a chain (avalanche) reaction results in large current.

I-V Characteristic: In reverse bias, when V reaches VZ, current sharply increases while voltage remains nearly constant at VZ. This is the Zener breakdown region.



Applications of Zener Diode:

- Voltage Regulator: Maintains constant output voltage despite varying input voltage or load current.
- Voltage Reference: Provides precise, stable reference voltage in circuits.
- Overvoltage Protection: Protects sensitive circuits by clamping voltage to VZ.
- Waveform Clipper/Clamper: Used in signal shaping circuits.
- Meter Protection: Protects galvanometers from excess voltage.

Difference between Zener Diode and Regular P-N Junction Diode:

- Zener: Heavily doped; Regular: Lightly/moderately doped.
- Zener: Designed to operate in breakdown region safely; Regular: Should NOT be taken into breakdown.
- Zener: Breakdown voltage is sharp and well-defined; Regular: Avalanche breakdown at high, not well-controlled voltage.
- Zener: Used as voltage regulator in reverse bias; Regular: Used as rectifier in forward bias.
- Zener: Thin depletion layer; Regular: Wider depletion layer.

Q5. Describe the operation of a solar cell and a photodiode. Illustrate with suitable diagrams and mention their key applications. [5 marks]

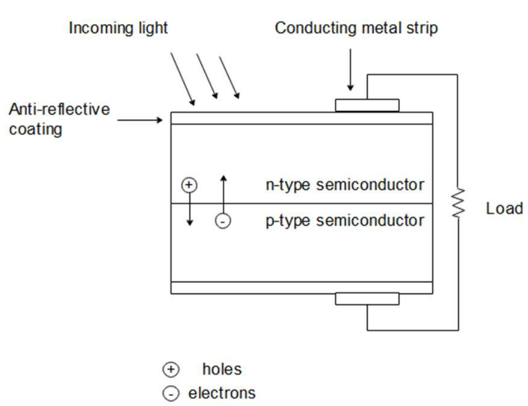
Solar Cell:

A solar cell (photovoltaic cell) is a p-n junction device that converts light energy directly into electrical energy using the photovoltaic effect.

Working Principle:

- The solar cell is a large-area p-n junction, usually made of Silicon (Si) with an anti-reflection coating and metallic grid contacts.
- When photons from sunlight strike the junction, photons with energy (hv) ≥ Eg of the semiconductor are absorbed and generate electron-hole pairs (EHP) in or near the depletion region.
- The built-in electric field of the p-n junction separates the generated carriers: electrons drift to the n-side, holes drift to the p-side.
- This charge separation creates a photovoltage (open-circuit voltage, VOC) across the junction.
- When connected to an external circuit, a photo-current (ISC) flows.

Energy Conversion: Light Energy → Electrical Energy (directly, no turbines needed).

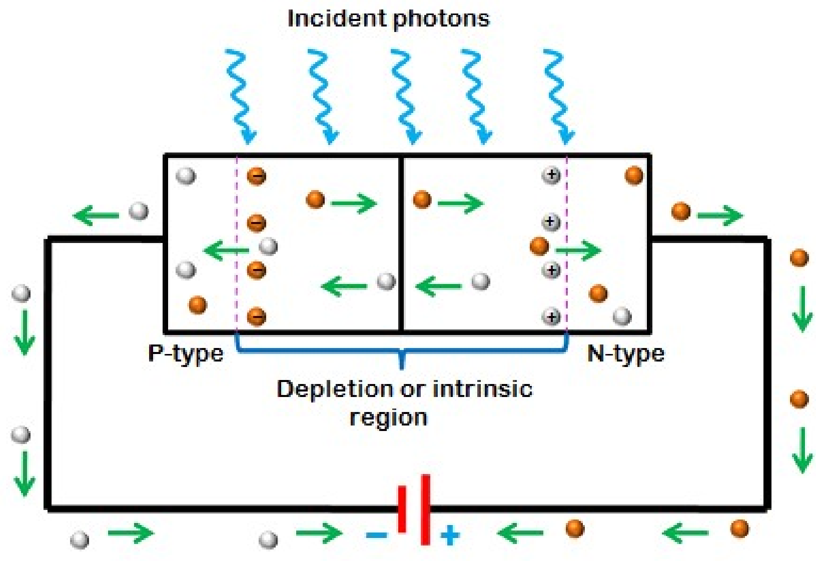


Key Applications:

- Solar panels for power generation (residential, commercial, space).
- Solar-powered calculators, watches, outdoor lighting.
- Satellite power supply.
- Off-grid rural electrification.

Photodiode:

A photodiode is a p-n junction device that converts light into electric current, operated in reverse bias mode.



PIN photodiode

Working Principle:

- The photodiode is reverse biased (wide depletion region for better light absorption).
- When light (photons with hν ≥ Eg) falls on the junction, electron-hole pairs are generated in the depletion region.
- The built-in field separates them: electrons move to n-side, holes to p-side, creating a reverse photo-current (IP).
- The photo-current IP is proportional to the intensity of incident light.
- In dark: Only reverse saturation current I_0 flows (very small).
- With light: $I = I_0 + IP$

Two Modes:

- Photoconductive mode: Reverse biased — fast response, used in communications.
- Photovoltaic mode: No bias — used like solar cell.

Key Applications:

- Optical fiber communication systems (light receivers).
- Remote control receivers (IR photodiodes).
- Smoke and flame detectors.
- Medical equipment: pulse oximeters, imaging.
- Camera light meters, barcode scanners.

Q6. What materials are used to construct LED? Explain working and I-V characteristics of LED. Determine wavelength and colour emitted by GaP LED (Eg = 2.25 eV). [5 marks]

Materials for LED Construction:

LEDs are made from direct bandgap III-V semiconductor compounds and alloys. Only direct bandgap materials emit light efficiently because in direct bandgap semiconductors, the recombination of electron-hole pairs releases energy as photons (radiative recombination). In indirect bandgap semiconductors (Si, Ge), the energy is released as heat (phonons).

Common LED Materials:

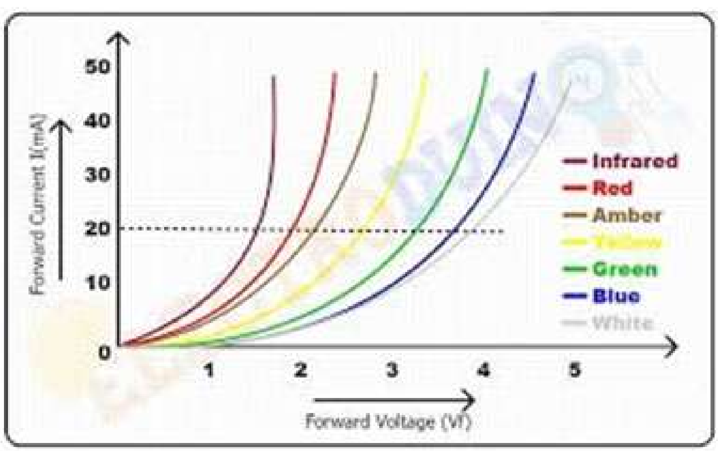
- GaAs (Gallium Arsenide): Infrared LEDs, Eg = 1.42 eV, λ ≈ 870 nm
- GaP (Gallium Phosphide): Green/Red LEDs, Eg = 2.26 eV
- GaAsP (Gallium Arsenide Phosphide): Red/Orange/Yellow LEDs
- GaN (Gallium Nitride): Blue/UV LEDs, Eg = 3.4 eV
- InGaN (Indium Gallium Nitride): Green, Blue LEDs; basis for white LEDs
- AlGaInP: High-brightness Red, Orange, Yellow LEDs
- SiC: Blue LEDs (indirect bandgap, but can be used with impurities)

Working of LED:

An LED is a forward-biased p-n junction made from a direct bandgap semiconductor. When forward biased:

- Electrons are injected from n-side into p-side across the junction.
- Holes are injected from p-side into n-side.
- In the p-side, injected electrons (minority carriers) recombine with majority holes.
- In direct bandgap material, this recombination releases energy as a photon (light) — called electroluminescence.
- The photon energy hv equals the bandgap energy Eg.
- The wavelength of emitted light: λ = hc/Eg

I-V Characteristics of LED:



The I-V characteristic of LED is similar to a regular p-n diode but with a higher forward voltage drop (typically 1.5–3.5 V depending on material):

- Forward Bias: Current increases exponentially after the knee voltage (1.5–2V for GaAs; ~2.5V for GaN).
- The LED emits light only when forward current exceeds the threshold (usually 5–20 mA).
- Brightness (luminous intensity) is proportional to the forward current.

- Reverse Bias: Very small reverse current; no light emission; reverse breakdown voltage is low (~5V).

Note: LEDs should always be used with a series resistor to limit current and prevent burnout.

Numerical: GaP LED (Eg = 2.25 eV)

Given: $E_g = 2.25\text{ eV} = 2.25 \times 1.6 \times 10^{-19}\text{ J} = 3.6 \times 10^{-19}\text{ J}$
$h = 6.626 \times 10^{-34}\text{ J·s}$, $c = 3 \times 10^{8}\text{ m/s}$

$$\lambda = hc / E_g$$
$$\lambda = (6.626 \times 10^{-34} \times 3 \times 10^{8}) / (3.6 \times 10^{-19})$$
$$\lambda = 19.878 \times 10^{-26} / 3.6 \times 10^{-19}$$
$$\lambda = 5.52 \times 10^{-7}\text{ m} = 552\text{ nm}$$

Result: λ ≈ 552 nm → This corresponds to GREEN colour light.
(Green light range: 520–565 nm)

Q7. Explain the concept of Hall effect with a diagram. Derive the expression for Hall voltage. [5 marks]

Hall Effect – Concept:

The Hall Effect is the phenomenon in which, when a current-carrying conductor or semiconductor is placed in a magnetic field perpendicular to the current direction, a transverse voltage (Hall voltage) is developed in a direction perpendicular to both the current and the magnetic field.

Experimental Setup:

- Consider an n-type semiconductor sample of length L (x-direction), width W (y-direction), and thickness t (z-direction).
- Current I flows in the +x direction (conventional current). Electrons flow in –x direction.
- Magnetic field B is applied in the +z direction.

Diagram :

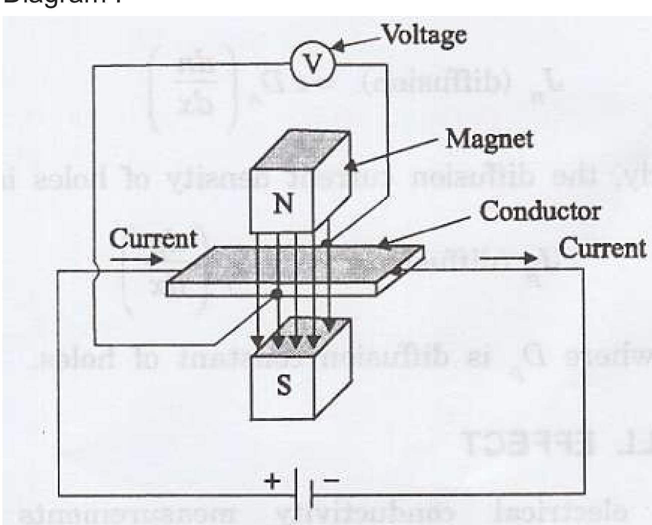


Fig. 3.15 Hall Effect

Derivation of Hall Voltage:

Step 1: Lorentz Force on electrons

Electrons moving in –x direction with drift velocity vd experience a magnetic force (Lorentz force):

$$F = -e\ (v \times B) = -e\ (-vd\ \hat{x} \times B\ \hat{z}) = -e \cdot vd \cdot B\ (-\hat{x} \times \hat{z})$$

$$F = e \cdot vd \cdot B\ \hat{y} \quad \text{(force is in +y direction for electrons)}$$

So electrons accumulate on the +y face → –y face becomes positive.

Step 2: Hall Electric Field

Accumulation of electrons on one face sets up a transverse electric field EH (Hall field) in the –y direction. This field exerts force on electrons opposing further accumulation.

Step 3: Equilibrium Condition

At equilibrium, the electric force = magnetic force:

$$e \cdot EH = e \cdot vd \cdot B$$

$$EH = vd \times B$$

Step 4: Hall Voltage

$$VH = EH \times W = vd \times B \times W$$

Now, current density J = n·e·vd, so vd = J/(n·e)

$$VH = (J\ /\ n \cdot e) \times B \times W$$

But J × W × t = I (total current), so J × W = I/t... Let's use:

$$VH = (I \times B)\ /\ (n \times e \times t)$$

Hall Coefficient:

$$RH = 1\ /\ (n \times e) \quad \text{[for n-type; negative sign for electrons: } RH = -1/(ne)\text{]}$$

$$VH = RH \times (I \times B)\ /\ t \ = \ RH \times J \times B \times W$$

where:

- VH = Hall voltage (V)
- I = current through sample (A)
- B = magnetic flux density (T)
- n = carrier concentration ($/m^3$)
- e = electron charge (C)
- t = thickness of sample (m)
- RH = Hall coefficient (m^3/C)

Q8. What is Fermi level? Prove that the Fermi level lies exactly in between conduction band and valence band of intrinsic semiconductor. [5 marks]

Fermi Level:

The Fermi level (EF) is the energy level at which the probability of finding an electron is exactly 0.5 (50%) at any temperature $T > 0$ K. It is the reference energy level for quantum statistical treatment of electrons (Fermi-Dirac statistics). The distribution function is:

$$f(E) = 1 / [1 + \exp((E - EF) / kT)]$$

Proof: Fermi Level at Midgap in Intrinsic Semiconductor

For an intrinsic semiconductor, the total number of electrons in the conduction band must equal the total number of holes in the valence band (charge neutrality):

$$n = p \quad ...(1)$$

The electron concentration in conduction band:

$$n = NC \times \exp(-(EC - EF) / kT) \quad ...(2)$$

where $NC = 2(2\pi me^*kT/h^2)^{(3/2)}$ = effective density of states in conduction band.

The hole concentration in valence band:

$$p = NV \times \exp(-(EF - EV) / kT) \quad ...(3)$$

where $NV = 2(2\pi mh^*kT/h^2)^{(3/2)}$ = effective density of states in valence band.

Applying condition n = p [from (1)]:

$$NC \times \exp(-(EC - EF)/kT) = NV \times \exp(-(EF - EV)/kT)$$

Taking natural log on both sides:

$$\ln(NC) - (EC - EF)/kT = \ln(NV) - (EF - EV)/kT$$

$$(EC - EF)/kT - (EF - EV)/kT = \ln(NC) - \ln(NV)$$

$$[(EC - EF) - (EF - EV)] / kT = \ln(NC/NV)$$

$$[EC + EV - 2EF] / kT = \ln(NC/NV)$$

$$EC + EV - 2EF = kT \times \ln(NC/NV)$$

$$EF = (EC + EV)/2 - (kT/2) \times \ln(NC/NV) \quad ...(4)$$

Now, $NC/NV = (me^*/mh^*)^{(3/2)}$

$$EF = (EC + EV)/2 - (3kT/4) \times \ln(me^*/mh^*)$$

SPECIAL CASE – When me* = mh* (effective masses equal):

$$\ln(me^*/mh^*) = \ln(1) = 0$$

$$\therefore EF = (EC + EV) / 2 = Emidgap$$

This PROVES that the Fermi level lies exactly at the midpoint of the energy bandgap in an intrinsic semiconductor (when me* = mh*). For real materials like Si and Ge, me* ≠ mh*, so EF lies slightly below the midgap (since mh* > me* in both Si and Ge), but is commonly approximated as at midgap for intrinsic semiconductors.

Q9. Hall Effect Numerical: n-type Si, ND = 10^{20}/m³, width = 4.5 mm, B = 0.55 T, J = 500 A/m², μe = 0.17 m²/V·s. Find Hall voltage, Hall coefficient, Hall angle. [5 marks]

Given (n-type Silicon):

- n = ND = 10^{20} /m³
- t (thickness) = 4.5 mm = 4.5×10^{-3} m
- B = 0.55 T
- J = 500 A/m²
- μe = 0.17 m²/V·s
- e = 1.6×10^{-19} C

(i) Hall Coefficient (RH):

For n-type semiconductor:

$$RH = -1 / (n \times e)$$

$$RH = -1 / (10^{20} \times 1.6 \times 10^{-19})$$

$$RH = -1 / 16$$

$$RH = -0.0625\ m^3/C$$

Magnitude: |RH| = 0.0625 m³/C (negative sign indicates n-type)

(ii) Hall Voltage (VH):

Hall field: EH = RH × J × B

$$EH = 0.0625 \times 500 \times 0.55 = 17.19\ V/m$$

Hall voltage: VH = EH × t

$$VH = 17.19 \times 4.5 \times 10^{-3}$$

$$VH = 0.07734\ V \approx 77.3\ mV$$

(iii) Hall Angle (θH):

$$\tan(\theta H) = \mu e \times B = 0.17 \times 0.55 = 0.0935$$

$$\theta H = \arctan(0.0935)$$

$$\theta H \approx 5.34°$$

Results Summary:

- Hall Coefficient: RH = –0.0625 m³/C (n-type confirmed)
- Hall Voltage: VH ≈ 77.3 mV
- Hall Angle: θH ≈ 5.34°

Q10. Derive the equation of current flowing through forward-biased P-N junction diode (Diode Equation). [5 marks]

Derivation of Diode Equation (Shockley's Equation):

Consider a p-n junction in forward bias. When forward voltage V is applied, the barrier potential reduces from V_0 to $(V_0 - V)$, enabling injection of minority carriers across the junction.

Assumptions:

- Abrupt junction; uniformly doped p and n regions.
- Low-level injection: minority carrier concentration << majority carrier concentration.
- No generation/recombination in the depletion region.
- Ohmic (non-rectifying) metal contacts at the ends.

Step 1: Minority Carrier Concentration at Junction Boundary

Due to Boltzmann factor, for forward bias V:

$$pn(0) = pn0 \times \exp(eV/kT)$$
$$np(0) = np0 \times \exp(eV/kT)$$

where pn0 = equilibrium minority hole concentration in n-side; np0 = equilibrium minority electron concentration in p-side.

Excess minority carriers:

$$\Delta pn(0) = pn(0) - pn0 = pn0[\exp(eV/kT) - 1]$$
$$\Delta np(0) = np0[\exp(eV/kT) - 1]$$

Step 2: Minority Carrier Diffusion Currents

The excess minority carriers diffuse away from the junction and recombine. By solving the diffusion equations (steady state), excess carrier concentrations decay exponentially:

$$\Delta pn(x) = \Delta pn(0) \times \exp(-x/Lp) \quad \text{for } x > 0 \text{ (n-side)}$$
$$\Delta np(x) = \Delta np(0) \times \exp(x/Ln) \quad \text{for } x < 0 \text{ (p-side)}$$

Step 3: Diffusion Currents

$$Jp = -e \times Dp \times d(\Delta pn)/dx = (e \times Dp / Lp) \times pn0 \times [\exp(eV/kT) - 1]$$
$$Jn = (e \times Dn / Ln) \times np0 \times [\exp(eV/kT) - 1]$$

Step 4: Total Current Density

$$J = Jp + Jn = e \times [Dp \times pn0/Lp + Dn \times np0/Ln] \times [\exp(eV/kT) - 1]$$

Total diode current:

$$I = A \times J = I_0 \times [\exp(eV/kT) - 1]$$

where the reverse saturation current:

$$I_0 = A \times e \times [Dp \times pn0/Lp + Dn \times np0/Ln]$$

Including ideality factor η:

$$I = I_0 \times [\exp(eV/\eta kT) - 1]$$

This is the Diode Equation (Shockley's Equation).

For V >> kT/e (forward bias): $I \approx I_0 \times \exp(eV/kT)$ — exponential rise.

For V << 0 (reverse bias): $I \approx -I_0$ — saturation current.

Q11. Current in PN junction = 0.2 μA at room temperature (large reverse bias). Calculate current when forward voltage of 0.1 V is applied. [4 marks]

Given:

- Reverse saturation current: $I_0 = 0.2\ \mu A = 0.2 \times 10^{-6}$ A
- T = 300 K (room temperature)
- Forward voltage: V = 0.1 V
- $\eta = 1$ (assume ideal)
- kT/e = VT = 0.02585 V

Using Shockley's equation:

$$I = I_0 \times [\exp(V/VT) - 1]$$
$$I = 0.2 \times 10^{-6} \times [\exp(0.1/0.02585) - 1]$$
$$I = 0.2 \times 10^{-6} \times [\exp(3.868) - 1]$$
$$\exp(3.868) \approx 47.87$$
$$I = 0.2 \times 10^{-6} \times (47.87 - 1)$$
$$I = 0.2 \times 10^{-6} \times 46.87$$
$$I = 9.374 \times 10^{-6}\ A$$
$$I \approx 9.37\ \mu A$$

Result: The forward current at V = 0.1 V is approximately 9.37 μA.

Q12. What do you mean by conductivity of a semiconductor? Obtain an expression for conductivity of Intrinsic, n-type and p-type semiconductors. [5 marks]

Conductivity of a Semiconductor:

Electrical conductivity (σ) is defined as the ability of a material to conduct electric current. It is the reciprocal of resistivity (ρ). For a semiconductor, both electrons and holes contribute to the current flow:

$$\sigma = 1/\rho = J/E \quad \text{(SI unit: S/m or } \Omega^{-1}m^{-1}\text{)}$$

1. Conductivity of Intrinsic Semiconductor:

In an intrinsic semiconductor, n = p = ni (equal concentrations of electrons and holes, both thermally generated). The current density due to both carriers:

$$J = J_{electrons} + J_{holes} = (n \cdot e \cdot \mu e + p \cdot e \cdot \mu h) \times E$$

For intrinsic (n = p = ni):

$$J = ni \cdot e(\mu e + \mu h) \times E$$

$$\sigma i = ni \times e \times (\mu e + \mu h)$$

ni depends strongly on temperature:

$$ni = \sqrt{(NC \times NV)} \times \exp(-Eg/2kT)$$

Hence conductivity increases exponentially with temperature.

2. Conductivity of n-type Semiconductor:

In n-type, ND >> ni, so n ≈ ND >> p. Electrons are the majority carriers.

$$J = (n \cdot e \cdot \mu e + p \cdot e \cdot \mu h) \times E$$

Since n >> p:

$$\sigma n \approx n \cdot e \cdot \mu e \approx ND \cdot e \cdot \mu e$$

The contribution of holes (minority carriers) is negligible.

3. Conductivity of p-type Semiconductor:

In p-type, NA >> ni, so p ≈ NA >> n. Holes are the majority carriers.

$$\sigma p \approx p \cdot e \cdot \mu h \approx NA \cdot e \cdot \mu h$$

The contribution of electrons (minority carriers) is negligible.

Summary Table:

- Intrinsic: σ = ni·e·(μe + μh) → depends on temperature
- n-type: σ ≈ ND·e·μe → depends on doping
- p-type: σ ≈ NA·e·μh → depends on doping

Q13. Explain the formation of potential barrier in a P-N junction with a neat labeled diagram. [5 marks]

The formation of the potential barrier in a p-n junction is a step-by-step process that occurs at the interface of p-type and n-type semiconductors:

Step 1 – Separate Semiconductors:

Before joining: p-side has high hole concentration (pp >> pn), n-side has high electron concentration (nn >> np). The Fermi levels are at different positions.

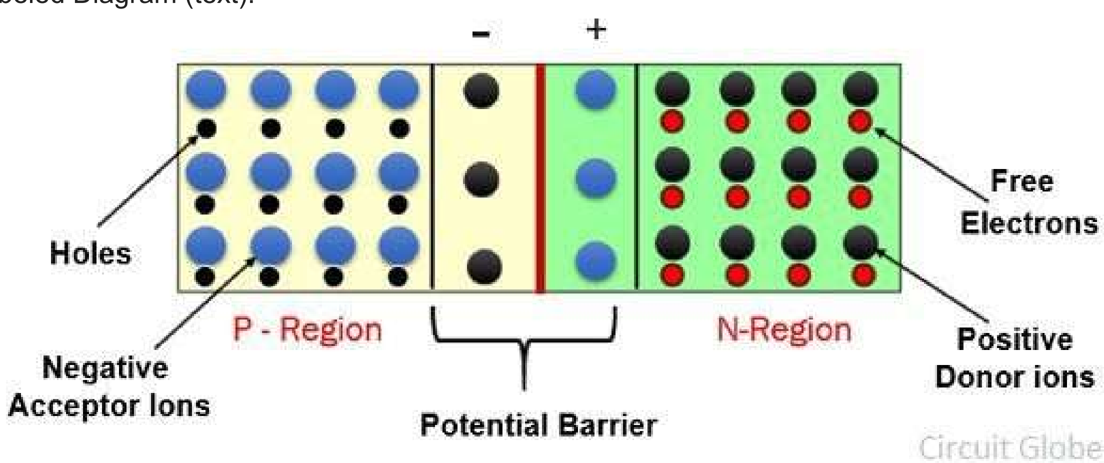
Step 2 – Diffusion (At the Moment of Joining):

On contact, majority carriers diffuse due to concentration gradient: electrons from n-side cross to p-side, holes from p-side cross to n-side. This sets up a diffusion current across the junction.

Step 3 – Formation of Depletion Region:

As electrons leave n-side, they expose positively charged donor ions. As holes leave p-side, they expose negatively charged acceptor ions. The region near the junction becomes depleted of free carriers — this is the Depletion Region (also called Space Charge Region or Transition Region).

Labeled Diagram (text):



VH measured → Potential rises n to p: V_0

Step 4 – Built-in Electric Field:

The positive ions (n-side) and negative ions (p-side) in the depletion layer create an internal electric field E directed from n to p. This field opposes the diffusion of majority carriers.

Step 5 – Equilibrium and Potential Barrier:

Equilibrium is reached when drift current (due to E field) exactly balances diffusion current. The electric potential variation across the depletion region is the potential barrier V_0 (built-in potential or contact potential).

$$V_0 = (kT/e) \times \ln(NA \times ND / ni^2)$$

Typical values: $V_0 \approx 0.6$–0.7 V for Si; $V_0 \approx 0.2$–0.3 V for Ge at 300 K.

Q14. In a solid, energy level lies 0.012 eV below Fermi level. What is the probability of this level NOT being occupied? [4 marks]

Given:

- Energy level E is 0.012 eV BELOW EF
- So: E – EF = –0.012 eV = –0.012 × 1.6 × 10^{-19} J
- T = 300 K (room temperature assumed)
- k = 1.38 × 10^{-23} J/K
- kT = 1.38 × 10^{-23} × 300 = 4.14 × 10^{-21} J = 0.02585 eV

Fermi-Dirac distribution gives probability of occupation:

$$f(E) = 1 / [1 + \exp((E - EF) / kT)]$$

$$f(E) = 1 / [1 + \exp(-0.012 / 0.02585)]$$

$$f(E) = 1 / [1 + \exp(-0.4642)]$$

$$\exp(-0.4642) \approx 0.6288$$

$$f(E) = 1 / (1 + 0.6288) = 1 / 1.6288 \approx 0.6141$$

Probability of NOT being occupied = 1 – f(E):

$$P(\text{not occupied}) = 1 - 0.6141 = 0.3859 \approx 38.59\%$$

Result: The probability that the energy level (0.012 eV below EF) is NOT occupied by an electron ≈ 38.6%.

Note: Since the level is below EF, it is more likely to be occupied (61.4%) than unoccupied (38.6%) — this is consistent with Fermi-Dirac statistics.

Q15. Find the resistance of an intrinsic Ge rod (1 cm long, 1mm wide, 1mm thick) at 300 K. Given: ni = $2.5\times10^{19}/m^3$, μe = 0.39 $m^2/V\cdot s$, μh = 0.19 $m^2/V\cdot s$. [4 marks]

Given:

- Length: $L = 1$ cm $= 1 \times 10^{-2}$ m
- Width: $W = 1$ mm $= 1 \times 10^{-3}$ m
- Thickness: $t = 1$ mm $= 1 \times 10^{-3}$ m
- $n_i = 2.5 \times 10^{19}\ /m^3$
- $\mu_e = 0.39\ m^2/V\cdot s$
- $\mu_h = 0.19\ m^2/V\cdot s$
- $e = 1.6 \times 10^{-19}$ C

Step 1: Calculate conductivity of intrinsic Ge:

$$\sigma = n_i \times e \times (\mu_e + \mu_h)$$

$$\sigma = 2.5 \times 10^{19} \times 1.6 \times 10^{-19} \times (0.39 + 0.19)$$

$$\sigma = 2.5 \times 10^{19} \times 1.6 \times 10^{-19} \times 0.58$$

$$\sigma = 4 \times 0.58 = 2.32\ S/m$$

Step 2: Calculate resistivity:

$$\rho = 1/\sigma = 1/2.32 = 0.4310\ \Omega\cdot m$$

Step 3: Calculate cross-sectional area:

$$A = W \times t = 1 \times 10^{-3} \times 1 \times 10^{-3} = 1 \times 10^{-6}\ m^2$$

Step 4: Calculate resistance:

$$R = \rho \times L / A$$

$$R = 0.4310 \times 10^{-2} / 10^{-6}$$

$$R = 0.4310 \times 10^{4}$$

$$R = 4310\ \Omega \approx 4.31\ k\Omega$$

Result: The resistance of the intrinsic Ge rod at 300 K ≈ 4.31 kΩ (4310 Ω).
