ELECTRICAL ENGINEERING

ANALOG ELECTRONICS

Comprehensive Theory
with Solved Examples *and* Practice Questions

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ANALOG ELECTRONICS

Introduction to
Analog Electronics

After studying the basic electronic devices and their characteristics, now we shall deal with more complex analog circuits, of which amplifiers is a very significant category. We shall start our analysis with applications of diode, a very fundamental component, in various circuit configurations such as clipper, clamper, regulator etc. Further, we shall proceed to applications of BJT and FET, particularly as an amplifier.

The other complex analog circuits, including circuits that form operational amplifiers, are also part of this book. These circuits are composed of fundamental configurations, such as differential amplifier, constant-current source, active load, and output stage, all of which have been discussed in detail.

The major emphasis throughout the book is on developing the reader's understanding for analyzing and designing various fundamental circuits, which are always an integral part of various competitive examinations. Throughout the book, a very sequential and comprehensive approach has been used, so that a beginner can also utilize the book in very efficient manner.

Prelude to Analog Electronics

ELECTRONICS

Electronics is defined as the science of motion of charges in a gas, vacuum, or semiconductor. Note that the charge motion in a metal is excluded from this definition.

This definition was used early in the 20th century to separate the field of electrical engineering, which dealt with motors, generators, and wire communications, from the new field of electronic engineering, which at that time dealt with the vacuum tubes.

ANALOG AND DIGITAL SIGNALS

- The voltage signal shown graphically in Figure (a) is called an analog signal. The magnitude of an analog signal may have any value ; that is, the amplitude may vary continuously with respect to time. Electronic circuits that process such signals are called analog circuits.
- An alternative signal is at one of two distinct levels and is called a digital signal (shown in figure (b)). Because the digital signal has discrete values, it is said to be quantized. Electronic circuits that process digital signals are called digital circuits.

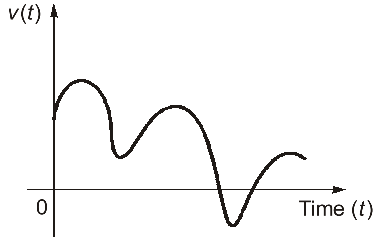

Figure (a)

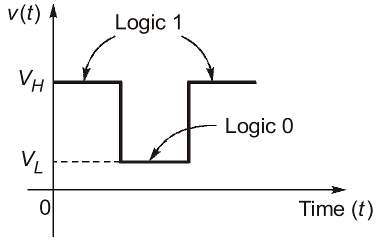

Figure (b)

Advantages of Analog Circuits

- Majority of signals in the "real world" are analog; so these signals can be directly processed in analog circuits whereas digital processing requires analog to digital and digital to analog conversion.
- Analog circuits can be designed to operate even at higher power levels.

Disadvantages of Analog Circuits

- Loss of information due to effect of noise is more.
- Lower quality signals than digital signals.

Advantages of Digital Circuits

- In digital circuits effect of noise is less.
- Digital data can be stored.
- Digital circuits can be programmed.

Disadvantages of Digital Circuits

- Expensive.
- High operational power is required.
- Operate on digital signals only.

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CHAPTER

1

Semiconductor Physics

1.1 CONDUCTOR, SEMICONDUCTOR AND INSULATOR

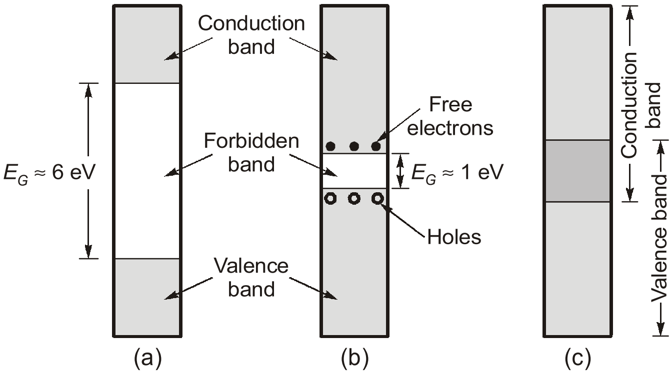


Figure : *Simplified energy band diagrams of (a) insulator (b) semiconductor (c) conductor*

1.1.1 Insulators

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

1.1.2 Semiconductors

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

1.1.3 Metals

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

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

NOTE Since the band-gap energy of a crystal is a function of interatomic spacing, it is not surprising that E_G depends somewhat on temperature. It has been determined experimentally that E_G for silicon decrease with temperature at the rate of 3.60×10^{-4} eV/°K. Hence, for silicon,

$$E_G(T) = 1.21 - 3.60 \times 10^{-4}\, T$$

and at room temperature (300°K), $E_G = 1.1$ eV

Similarly, for germanium, $E_G(T) = 0.785 - 2.23 \times 10^{-4}\, T$

and at room temperature, $E_G = 0.72$ eV

1.1.4 Semiconductor Materials: Ge, Si and GaAs

Semiconductors: A semiconductor has an energy-band gap as discussed before. At 0°K semiconductor materials have the same structure as insulators except the difference in the size of the band gap E_G, which is much smaller in semiconductors ($E_G \simeq 1\ eV$) than in insulators.

The relatively small band gaps of semiconductors allow for excitation of electrons from the lower (valence) band to the upper (conduction) band by reasonable amount of thermal or optical energy. The difference between semiconductors and insulators is that the conductivity of semiconductors can increase greatly by thermal or optical energy. **Example:** Ge and Si

Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.

Single crystal and compound crystal semiconductor are two classifications of semiconductor depending upon number of constitutional elements. Examples of single crystal semiconductors are germanium (Ge) and silicon (Si) whereas compound semiconductors are gallium arsenide (GaAs), cadmium sulphide (CdS), gallium nitride (GaN) and gallium arsenide phosphide (GaAsP) etc.

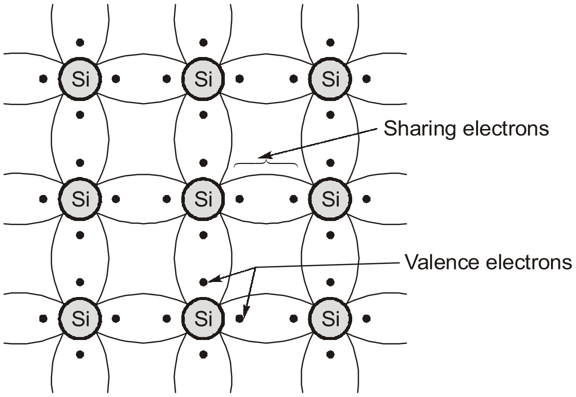


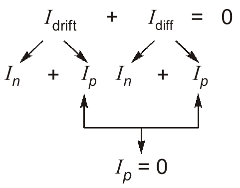
***Figure :** Covalent bonding of the silicon atom*

Intrinsic Materials and Covalent Bonding

Semiconductor in its purest form (without any impurity) is known as **intrinsic semiconductor**.

An intrinsic semiconductor (such as pure Ge or Si), has only four electrons in the outermost orbit of its atoms. When atoms bond together to form molecules of matter, each atom attempts to acquire eight electrons in its outermost shell. This is done by sharing one electron from each of the four neighbouring atoms. This sharing of electrons in semiconductors is known as **covalent bonding.** Figure below shows covalent bonding of the silicon atom.

1.8 POTENTIAL VARIATION IN A OPEN CIRCUIT SEMICONDUCTOR BAR



As, $J = 0$

or, $$J_{P\text{drift}} + J_{P\text{ diffusion}} = 0$$

$$pq\mu_p E - qD_p \frac{dp}{dx} = 0$$

$$E = \left(\frac{D_p}{\mu_p}\right).\frac{1}{P}.\frac{d_p}{dx} = -\frac{dv}{dx} = V_T.\frac{1}{P}.\frac{dP}{dx}$$

$$-\int_{V_1}^{V_2} dv = V_T \int_{P_1}^{P_2} \frac{1}{P}.dp$$

$$V_2 - V_1 = V_T(-l\text{n}\,p)_{P_1}^{P_2}$$

$$\boxed{V_{21} = V_T l\text{n}\left(\frac{P_1}{P_2}\right)}$$

$$\boxed{P_1 = P_2 e^{\frac{V_{21}}{V_T}}} \quad \text{or} \quad \boxed{P_2 = P_1 e^{-\frac{V_{21}}{V_T}}}$$

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OBJECTIVE BRAIN TEASERS

Q.1 A semiconductor is irradiated with light such that carriers are uniformly generated throughout its volume. The semiconductor is n-type with $N_D = 10^{19}/\text{cm}^3$. If the excess electron concentration in the steady state is $\Delta n = 10^{15}/\text{cm}^3$ and if $\tau_p = 10$ μsec. (minority carries life time) the generation rate due to irradiation

(a) is 10^{20} e-h pairs/cm^3/s

(b) is 10^{24} e-h pairs/cm^3/s

(c) is 10^{10} e-h pairs/cm^3/s

(d) cannot be determined, the given data is insufficient

Q.2 The intrinsic concentration in a semiconductor at 300°K is 10^{13} cm^{-3}. When it is doped with donor type impurities, the majority carrier concentration becomes 10^{17} cm^{-3}. What is the value of its minority carrier density?

(a) 0.999×10^{17} cm^{-3}

(b) 10^{17} cm^{-3}

(c) 10^4 cm^{-3}

(d) 10^9 cm^{-3}

Q.3 A Silicon sample A is doped with 10^{18} atoms/cm^3 of Boron. Another sample B of identical dimensions is doped with 10^{18} atoms/cm^3 of Phosphorus. The ratio of electron to hole mobility is 3. The ratio of conductivity of the sample A to B is

(a) 3 (b) 1/3

(b) 2/3 (d) 3/2

Q.4 The concentration of minority carriers in an extrinsic semiconductor under equilibrium is

(a) directly proportional to the doping concentration

(b) inversely proportional to the doping concentration

(c) directly proportional to the intrinsic concentration
(d) inversely proportional to the intrinsic concentration

Q.5 Under low level injection assumption, the injected minority carrier current for an extrinsic semiconductor is essentially the
(a) diffusion current
(b) drift current
(c) recombination current
(d) induced current

Q.6 A heavily doped n-typed semiconductor has the following data:
Hole-electron mobility ratio : 0.4
Doping concentration : 4.2×10^8 atoms/m^3
Intrinsic concentration : 1.5×10^4 atoms/m^3
The ratio of conductance of the n-type semiconductor to that of the intrinsic semiconductor of same material and at the same temperature is given by
(a) 0.00005 (b) 2,000
(c) 10,000 (d) 20,000

Q.7 The electron and hole concentrations in an intrinsic semiconductor are n_i per cm^3 at 300 K. Now, if acceptor impurities are introduced with a concentration of N_A per cm^3 (where $N_A >> n_i$) the electron concentration per cm^3 at 300 K will be
(a) n_i (b) $n_i + N_A$
(c) $N_A - n_i$ (d) $\dfrac{n_i^2}{N_A}$

Q.8 The ratio of the mobility to the diffusion coefficient in a semiconductor has the unit
(a) V^{-1} (b) cm $\times V^{-1}$
(c) $V \times$ cm^{-1} (d) $V \times s$

Q.9 Drift current in semiconductors depends upon
(a) only the electric field
(b) only the carrier concentration gradient
(c) both the electric field and the carrier concentration
(d) both the electric field and the carrier concentration gradient

ANSWER KEY

1. (a)	**2.** (d)	**3.** (b)	**4.** (b)	**5.** (a)
6. (d)	**7.** (d)	**8.** (a)	**9.** (c)	

HINTS & EXPLANATIONS

1. (a)

10^{20} e-h pairs/cm$_3$/s

Given that, $\Delta n = 10^{15}/\text{cm}^3$

$$\tau_p = 10\ \mu\text{sec} = 10 \times 10^{-6}\ \text{sec.}$$

$$\text{Generation rater} = \frac{\Delta n}{\tau_p} = \frac{10^{15}}{10 \times 10^{-6}}$$

$$= 10^{20}\ \text{e-h pairs/cm}^3\text{/s}$$

2. (d)

Donor type impurity ⇒ n-type semiconductor

∴ Minority carrier density;

$$p = \frac{n_i^2}{n} = \frac{(10^{13})^2}{10^{17}} = 10^9\ \text{cm}^{-3}\ [\because np = n_i^2]$$

3. (b)

$$\sigma_n = nq\mu_n$$

$$\frac{\sigma_p}{\sigma_n} = \frac{\mu_p}{\mu_n} = \frac{1}{3}$$

4. (b)

$$np = n_i^2$$

$$n_i = \text{constant}$$

For n-type p is minority carrier concentration

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

6. (d)

For n-type semiconductor, $\sigma_n = nq\mu_n$

For intrinsic semiconductor,

$$\sigma_i = n_i q(\mu_n + \mu_p)$$

$$\frac{\sigma_n}{\sigma_i} = \frac{n\mu_n}{n_i(\mu_n + \mu_p)}$$

$$= \frac{4.2\times10^{8}\times\mu_n}{1.5\times10^{4}\times\mu_n\left(1+\dfrac{\mu_p}{\mu_n}\right)}$$

$$= \frac{4.2\times10^{8}}{1.5\times10^{4}\times1.4} = 2\times10^{4}$$

7. (d)

By the law of electrical neutrality

$$p + N_D = n + N_A \qquad \text{as } N_D = 0$$

$$N_A \gg n_i \cong 0 \quad p = N_A$$

Using mass action law $np = n_i^2$

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

8. (a)

$$\frac{D}{\mu} = V_T \quad\Rightarrow\quad \frac{\mu}{D} = \frac{1}{V_T} \Rightarrow \text{units : } V^{-1}$$

9. (c)

$$J = n\,e\,v_d$$

Put, $v_d = \mu E$

$\therefore$ $J = n\,e\,\mu E$

Hence, $I = n\,e\,\mu\,EA$

So, I depends upon carrier concentration and electric field.

CONVENTIONAL BRAIN TEASERS

Q.1 A hypothetical semiconductor has an intrinsic carrier concentration of 1.0 × 10^{10}/cm^3 at 300 K, it has conduction and valence band effective density of states N_C and N_V, both equal to 10^{19}/cm^3.

(i) What is the energy band gap, E_g? Assume $KT = 0.026$ eV.

(ii) If the semiconductor is doped with $N_d = 1\times10^{16}$ donors/cm^3, what are the equilibrium electron and hole concentrations at 300 K?

(iii) If the same piece of semiconductor, already having $N_d = 1\times10^{16}$ donor/cm^3, is also doped with $N_a = 2\times10^{16}$ acceptors/cm^3, what are the new equilibrium electron and hole concentrations at 300 K?

(iv) Consistent with your answer to part (iii), what is the Fermi level position with respect to the intrinsic fermi level, $E_F - E_i$?

1. (Sol.)

Given, intrinsic carrier concentration, $n_i = 1.0\times10^{10}$/cm^3 ; Temperature, $T = 300$ K
effective density of states in conduction band, $N_C = 10^{19}$/cm^3,
effective density of states in valence band, $N_V = 10^{19}$/cm^3

(i) We know that,
intrinsic carrier concentration,

$$n_i = \sqrt{N_V\times N_C}\,e^{-E_g/2KT}$$

$$10^{10} = \sqrt{10^{19}\times10^{19}}\,e^{-E_g/2\times0.026} = 10^{19}e^{-E_g/2\times0.026}$$

$$10^{-9} = e^{-E_g/2\times0.026}$$

by taking 'ln' on both sides

$$\ln(10^{-9}) = \frac{-E_g}{2\times0.026} \quad\Rightarrow\quad -20.723 = \frac{-E_g}{2\times0.026}$$

$$\therefore \qquad E_g \simeq 1.08\text{ eV}$$

CHAPTER

2

Semiconductor Diode

Introduction

If we join a piece of p-type material to a piece of n-type material **such that the crystal structure remains continuous at the boundary**, a pn-junction is formed. Such a pn-junction makes a very useful device. It is called a **semiconductor (or crystal) diode.** These pn-junctions are fundamental to the performance of functions such as rectification, amplification, switching, and other applications in electronic circuit. In this chapter we shall discuss all the properties related with pn-junction. With the background provided in this chapter on junction properties, we can then discuss specific devices in later chapters.

2.1 REPRESENTATION FOR n-TYPE AND p-TYPE SEMICONDUCTORS

n-type semiconductor is also called donor i.e. the impurity atom will be donating one electron and it becomes a positive ion. The positive ion is also called donor ion.

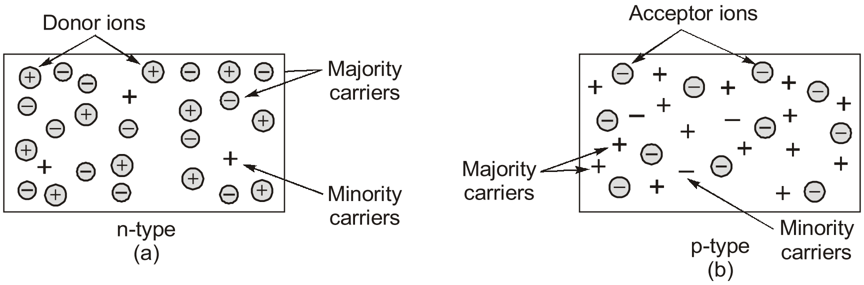
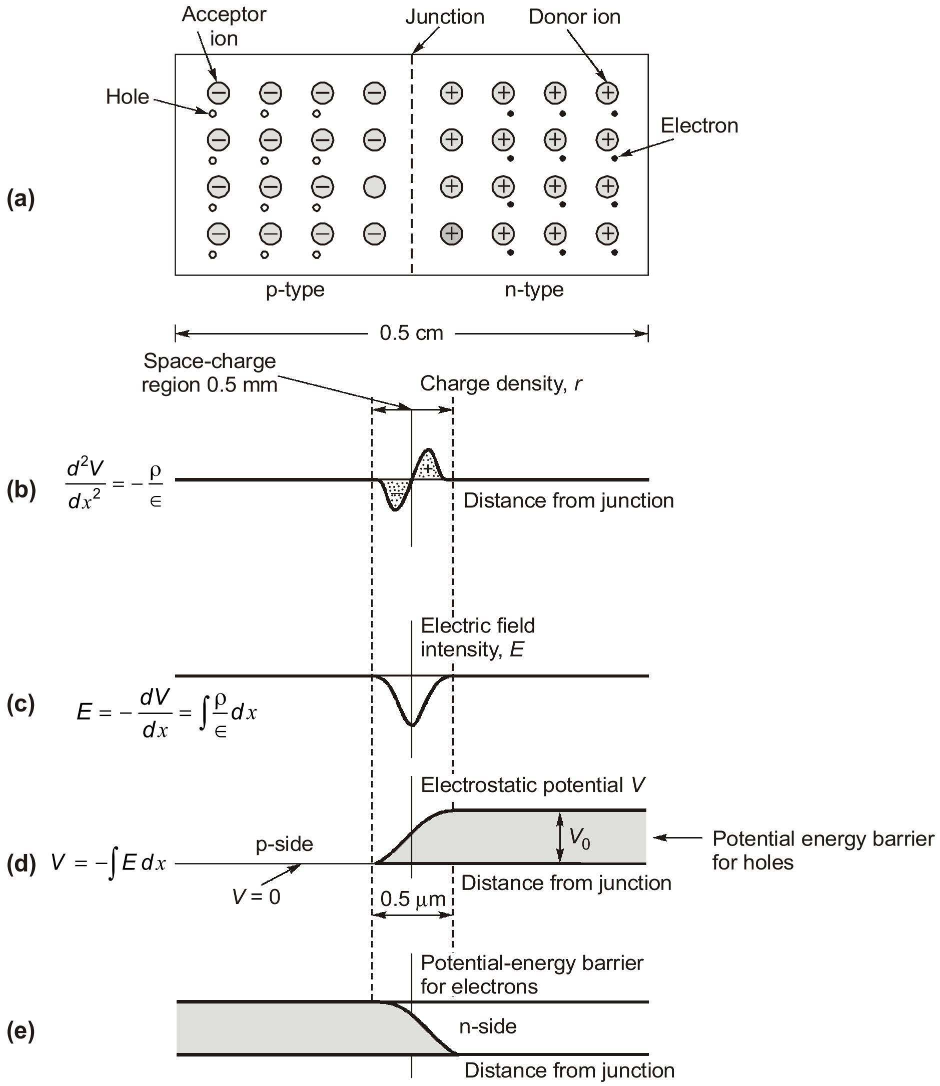


Figure : *(a) n-type material, (b) p-type material*

p-type semiconductor is also called acceptor, i.e., the impurity will be receiving one electron to complete its covalent bonding and it becomes a negative ion. The negative ion is also called acceptor ion.

2.2 p-n JUNCTION THEORY

Below figure shows a pn-junction just immediately it is formed. Note that it is a single crystal. Its left half is p-type and right half is n-type.



Note that no external voltage has been connected to the pn-junction of above figure. As soon as pn-junction is formed the following processes are initiated:

- Holes from the p-region diffuse into the n-region. They then combine with the free electrons in the n-region.
- Free electrons from the n-region diffuse into the p-region. These electrons combine with the holes.
- The diffusion of holes and electrons takes place because there is a difference in their concentrations in the two regions.
- After a few recombinations of holes and electrons in the immediate neighborhood of the junction, a restraining force is setup automatically. This force is called a barrier. Further diffusion of holes and electrons is stopped by this barrier.
- The region containing uncompensated acceptor and donor ions is called depletion region. That is, there is a depletion of mobile charges (holes and free electrons) in this region. Since this region has immobile (fixed) ions which are electrically charged, it is also referred to as the space charge region. It is also known as transition region. The thickness of this region is of the order of wavelength of visible light (0.5 mm).

OBJECTIVE BRAIN TEASERS

Q.1 The diffusion capacitance of a p-n junction
(a) decreases with increasing current and increasing temperature.
(b) decreases with decreasing current and increasing temperature.
(c) increases with increasing current and increasing temperature.
(d) does not depend on current and temperature

Q.2 For a pn-junction match the type of breakdown with phenomenon
1. Avalanche breakdown
2. Zener breakdown
3. Punch through
A. Collision of carriers with crystal ions
B. Early effect
C. Rupture of covalent bond due to strong electric field.
(a) 1-B, 2-A, 3-C (b) 1-C, 2-A, 3-B
(c) 1-A, 2-B, 3-C (d) 1-A, 2-C, 3-B

Q.3 In a Zener diode
(a) only the P-region is heavily doped.
(b) only the N-region is heavily doped.
(c) both P and N-regions are heavily doped.
(d) both P and P-regions are lightly doped.

Q.4 In a junction diode
(a) the depletion capacitance increases with increase in the reverse bias.
(b) the depletion capacitance decreases with increase in the reverse bias.
(c) the depletion capacitance increases with increase in the forward bias.
(d) the depletion capacitance is much higher than the depletion capacitance when it is forward biased.

Q.5 The built-in potential (diffusion potential) in a p-n junction
(a) is equal to the difference in the Fermi-level of the two sides, expressed in volts.
(b) increases with the increase in the doping levels of the two sides.
(c) increases with the increase in temperature.
(d) is equal to the average of the Fermi levels of the two sides.

Q.6 The depletion capacitance, C_j of an abruptly p-n junction with constant doping on either side varies with R.B.V_R as
(a) $C_J \propto V_R$ (b) $C_J \propto V_R^{-1}$
(c) $C_J \propto V_R^{-1/2}$ (d) $C_J \propto V_R^{-1/3}$

Q.7 A Silicon PN junction at a temperature of 20°C has a reverse saturation current of 10 pico-Amperes (pA). The reverse saturation current at 40°C for the same bias is approximately
(a) 30 pA (b) 40 pA
(c) 50 pA (d) 60 pA

Q.8 In a p^+n junction diode under reverse bias, the magnitude of electric field is maximum at
(a) the edge of the depletion region on the p-side.
(b) the edge of the depletion region on the n-side.
(c) the p^+n junction.
(d) the centre of the depletion region on the n-side.

Q.9 Compared to a p-n junction with $N_A = N_D = 10^{14}/\text{cm}^3$, which one of the following statements is TRUE for a p-n junction with $N_A = N_D = 10^{20}/\text{cm}^3$?
(a) Reverse breakdown voltage is lower and depletion capacitance is lower.
(b) Reverse breakdown voltage is higher and depletion capacitance is lower.
(c) Reverse breakdown voltage is lower and depletion capacitance is higher.
(d) Reverse breakdown voltage is higher and depletion capacitance is higher.

Q.10 A silicon PN junction is forward biased with a constant current at room temperature. When the temperature is increased by 10°C, the forward bias voltage across the PN junction

(a) increases by 60 mV
(b) decreases by 60 mV
(c) increases by 25 mV
(d) decreases by 25 mV

ANSWER KEY

1. (b)	**2.** (d)	**3.** (c)	**4.** (b)	**5.** (a, b)
6. (c)	**7.** (b)	**8.** (c)	**9.** (c)	**10.** (d)

HINTS & EXPLANATIONS

1. (b)

Decreases with decreasing current and increasing temperature.

$$\boxed{\text{Diffusion capacitance} = C_D = \tau g = \frac{\tau}{r}}$$

$$\boxed{r = \frac{\eta V_T}{I_f}}$$

$$\boxed{C_D = \frac{\tau I_f}{\eta V_T} = \frac{\tau I_f}{\eta kT}}$$

$$C_D \propto I_f$$

$$C_D \propto \frac{1}{T}$$

2. (d)

1-A, 2-C, 3-B

Avalanche breakdown → Collision of carriers with crystal ions.

Zener breakdown → Rupture of covalent bond due to strong electric field.

Punch through → Early effect.

3. (c)

Both P and N-regions are heavily doped.

In a Zener diode P and N both the regions are heavily doped.

Doping level of Zener diode is 1 : 10^5.

4. (b)

The depletion capacitance decreases with increase in the reverse bias.

Depletion width = W

$$\boxed{\begin{array}{c} W \propto \sqrt{V_{RB}} \\ \hline W \propto \sqrt{\text{Reverse bias voltage}} \end{array}}$$

$$\text{Capacitance} = C = \frac{A\xi}{W}$$

$$C \propto \frac{1}{W}$$

$$C \propto \frac{1}{\sqrt{\text{Reverse bias voltage}}}$$

5. (a, b)

Increases with the increase in the doping levels of the two sides.

Built in potential or diffusion potential across a p-n junction diode.

$$\boxed{V_0 = KT\,l\text{n}\left(\frac{N_A N_D}{n_i^2}\right)}$$

$$\text{So, } V_0 \propto n_i^2$$

$$V_0 \propto N_A \cdot N_D$$

So, option (a) and option (b) both are correct.

6. (c)

$$C_j \propto V_R^{-1/2}$$

The depletion layer capacitance of a diode is given

$$\boxed{C_T \propto V^{-n}}$$

$n = \frac{1}{2}$ for step graded or abrupt p-n junction

$$C_T \propto V_R^{-1/2}$$

10. (d)

$$\frac{dV}{dT} = -2.5 \text{ mV/°C}$$

For 10°C voltage across pn-junction will decrease by 25 mV.