ELECTRICAL ENGINEERING

ANALOG ELECTRONICS

Comprehensive Theory
with Solved Examples *and* Practice Questions

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Analog Electronics

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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.

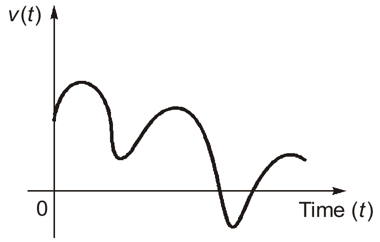

Figure (a)

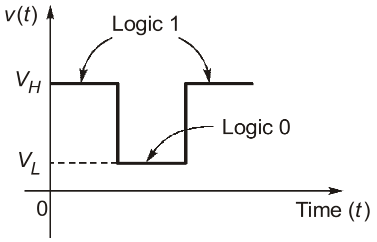

Figure (b)

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

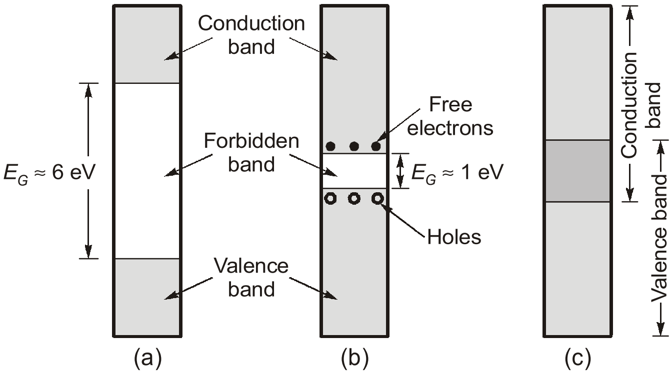


Figure : *Simplified energy band diagrams of (a) insulator (b) semiconductor (c) conductor*

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.

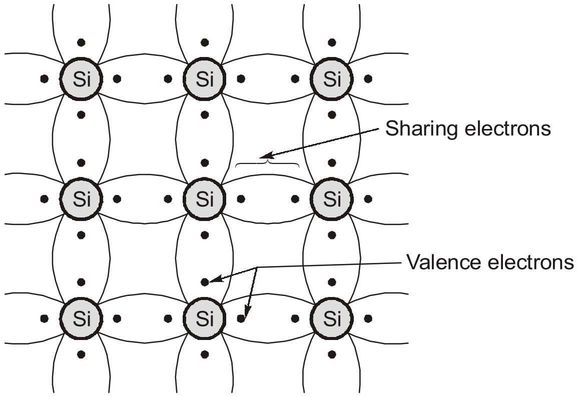


Figure : *Covalent bonding of the silicon atom*

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.

A covalent bond consists of two electrons, one from each adjacent atom. Both the electrons are shared by the two atoms. At absolute zero, all the valence electrons are tightly bound to the parent atoms. No free electrons are available for electrical conduction. **The semiconductor therefore behaves as a perfect insulator at absolute zero.**

Charge Carriers in Intrinsic Semiconductor

At room temperature (say 300°K) sufficient thermal energy is supplied to make a valence electron of a semiconductor atom to move away from the influence of its nucleus. Thus, a covalent bond is broken. When this happens, the electron becomes free to move in the crystal. This is shown in figure :

When an electron breaks a covalent bond and moves away, a vacancy is created in the broken covalent bond. This vacancy is called a **hole.** Free electrons and holes are always generated in pairs. Therefore, the concentration of free electrons and holes will always be equal in an intrinsic semiconductor

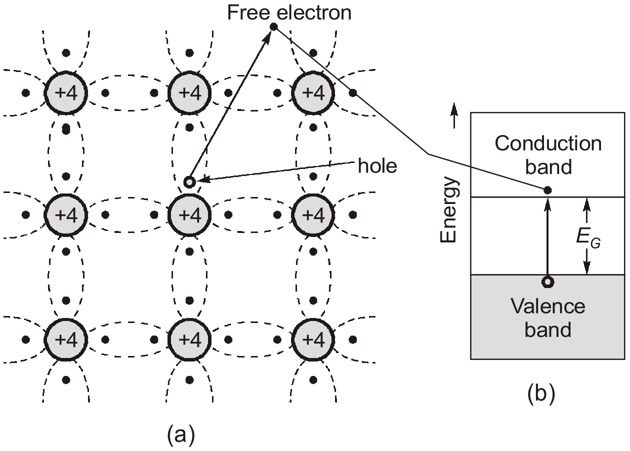


Figure : (a) Crystal structure (b) Energy band diagram

$$\boxed{n = p = n_i}$$

where n_i is called the intrinsic concentration.

Although, strictly speaking, a hole is not a particle; for all practical purposes we can view it as a positively charged particle capable of conducting current. This concept of a hole as a positively charged particle merely helps in simplifying the explanation of current flow in semiconductors.

Effect of Temperature on Conductivity of Intrinsic Semiconductor

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

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

E_{G0} : Energy gap at 0°K in eVs
k : Boltzman's constant in eV/°K
A_0 : Material constant independent of temperature

Extrinsic Materials

In addition to the intrinsic carriers generated thermally, it is possible to create carriers in semiconductors by purposely introducing impurities into the crystal. This process, called **doping**, is the most common technique for varying the conductivity of semiconductors. By doping, a crystal can be altered so that it has a predominance of either electrons or holes. Thus there are two types of doped semiconductors, n-type (majority carriers electrons) and p-type (majority carries holes). When a crystal is doped such that the equilibrium carrier concentrations n_0 and p_0 are different from the intrinsic carrier concentration n_i the material is said to be **extrinsic.**

n-type semiconductor

An n-type semiconductor is created by introducing impurity elements that have five valence electrons (pentavalent), such as antimony, arsenic and phosphorus. The effect of such impurity elements is indicated below in figure. Note that the four covalent bonds are still present. There is, however an additional fifth electron due to the impurity atom, which is unassociated with any particular covalent bond. This remaining electron loosely bound to its parent atom (antimony) atom, is relatively free to move within the newly formed n-type material. Since the inserted impurity atom has donated a relatively "free" electron to the structure;

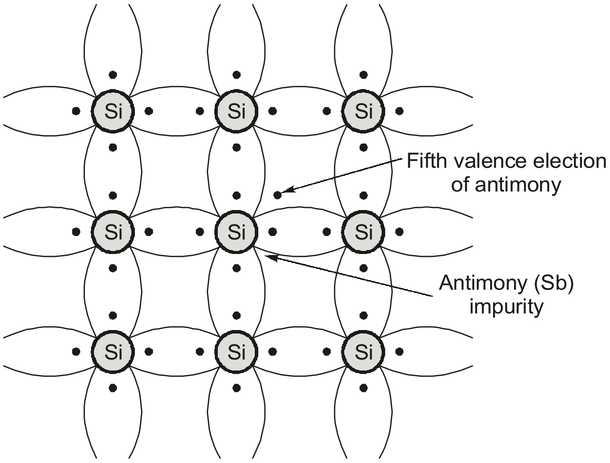


***Figure :** Antimony impurity in n-type material*

Diffused impurities with five valence electrons are called donor atoms.

When impurities or lattice defects are introduced into an otherwise perfect crystal, additional levels are created in the energy band structure, usually within the band gap. For example, an impurity from column V of the periodic table (P, As and Sb) introduces an energy level very near the conduction band in *Ge* or *Si*. Such an impurity level is called a donor level. In case of germanium, the distance of new discrete allowable energy level is only 0.01 *eV* (0.05 *eV* in silicon) below the conduction band, and therefore at room temperature almost all the "fifth" electrons of the donor material are raised into the conduction band.

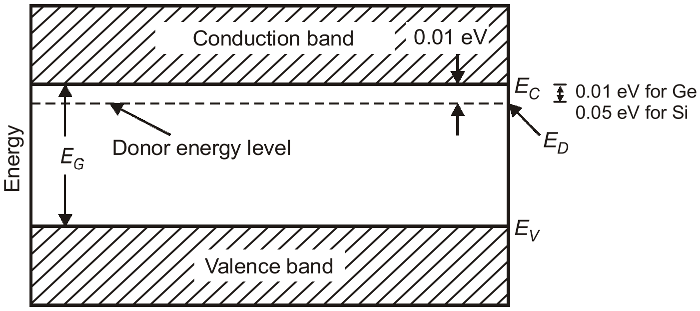


***Figure :** Energy-band diagram of n-type semiconductor*

NOTE n-type material is as a whole electrically neutral since ideally the number of positively charged protons in the nuclei is still equal to the number of free and orbiting negatively charged electrons in the structure.

p-type semiconductor

The p-type semiconductor is formed by doping a pure germanium or silicon crystal with impurity atoms having three valence electrons. The elements most frequently used for this purpose are boron, gallium and indium.

Note that, there is now an insufficient number of electrons to complete the covalent bonds of the newly formed lattice. The resulting vacancy is called a hole and is represented by a small circle or a plus sign, indicating the absence of a negative charge. Since the resulting vacancy will readily accept a free electron;

The diffused impurities with three valence electrons are called acceptor atoms.

The resulting p-type material is electrically neutral for the same reasons described for the n-type material.

Atoms from Column-III (B, Al, Ga and In) introduce impurity levels in Ge or Si near the valence band. These levels are empty of electrons at 0K. At low temperatures, enough thermal energy is available to excite electrons from the valence band into the impurity level, leaving behind holes in the valence band. Since this type of impurity level **"accepts"** electrons from the valence band, it is called an acceptor level.

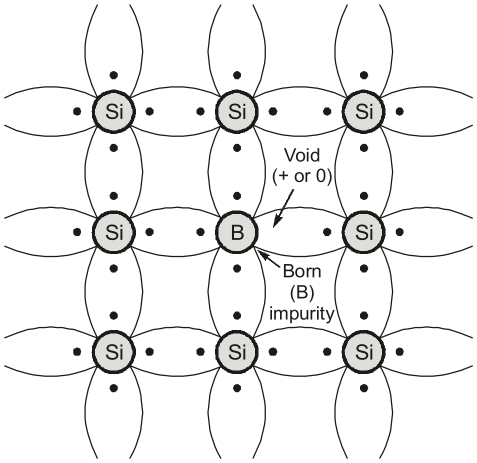


Figure : *Boron impurity in p-type material*

Standard Doping Levels

1. Moderate doping : 1 in ($10^6 - 10^8$) : *P*, *N*
2. Lightly doped : 1 in 10^{11} : P^-, N^-
3. Highly (heavily) doped : 1 in 10^3 : P^+, N^+

⇒ 1 : 10^6 or 1 in 10^6 or $1/10^6$ is read as "1 impurity atom in 10^6 atoms".

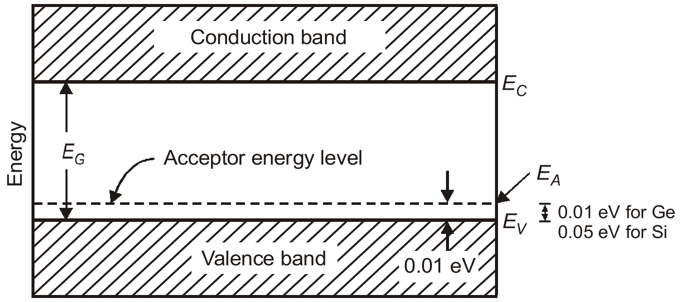


Figure : *Energy-band diagram of p-type semiconductor*

1.2 THE MASS-ACTION LAW

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

$$\boxed{np = n_i^2}$$

The intrinsic concentration n_i is a function of temperature.

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

For a p-type semiconductor, $\boxed{p_n = \dfrac{n_i^2}{n_n}}$; For an n-type semiconductor, $\boxed{n_n = \dfrac{n_i^2}{p_n}}$

or, $\text{Minority carrier concentration} = \dfrac{n_i^2}{\text{Majority carrier concentration}}$

but, $\text{Majority carrier concentration} \propto \text{Doping concentration}$

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

or, $\boxed{\text{Minority carrier concentration} \times \text{Doping concentration} = n_i^2}$

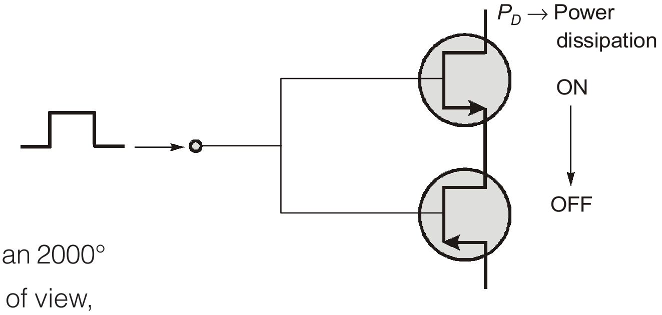
In a semiconductor, if majority carrier concentration increases the minority carrier concentration decreases this is due to the recombinations.

Note : As the energy gap between valence band and conduction band of GaAs is more than *Ge* and *Si*, so these are good semiconductor.

EXAMPLE : 1.1

Explain GaAs is used in C-MOS technology.

Solution:



From power dissipation (P_D) point of view,

Ge can withstand upto 100°C

Si can withstand upto 200°C

GaAs can withstand greater than 2000°

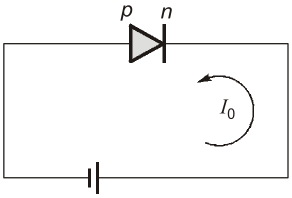
and mobility of electron, point of view,

$$\mu_e(Si) = 1300 \text{ cm}^2/\text{V-sec}$$
$$\mu_e(Ge) = 3800 \text{ cm}^2/\text{V-sec}$$
$$\mu_e(\text{GaAs}) = 8500 \text{ cm}^2/\text{V-sec}$$

EXAMPLE : 1.2

What is the importance of *Si* compared to *Ge*?

Solution:



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

   I_0 ideally should be zero but practically, it should be less in value.

2. Temperature withstand capacity

   Ge → 100°C *Si* → 200°C

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

   Ge → 400 V *Si* → 1000 V

4. Silicon is cheap compared to germanium.

NOTE: Drawback of *Si* is less conductivity due to more energy gap.

1.3 CHARGE NEUTRALITY EQUATION

Any part of a semiconductor bar is always electrically neutral.

or

Total positive charge densities = Total negative charge densities.

$$\boxed{P + N_D = n + N_A}$$

n-type

$$P + N_D = n + N_A$$

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

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

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

(*n* > 0, so only +ve sign)

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

$N_D >> n_i$ So, $\boxed{n \approx N_D}$

Similarly, for *p*-type

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

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

1.4 DRIFT CURRENT

It occurs in metals and semiconductor.

$V \propto E$

$V = \mu E$

$V \rightarrow$ drift velocity

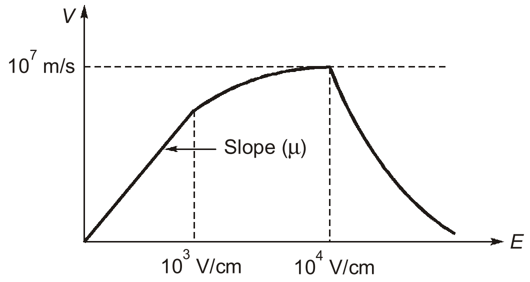
$E \rightarrow$ Electric field

$\mu \rightarrow$ proportionality constant (mobility)

Mobility (μ)

$$\mu = \frac{V}{E} = \frac{\text{Drift velocity}}{\text{electric field}} \frac{m^2}{V\text{sec.}}$$

Effect of Electric Field on Mobility

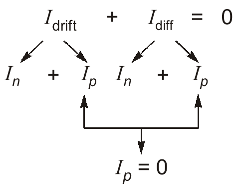


μ = constant	$E < 10^3$ V/cm
$\mu \propto \frac{1}{\sqrt{E}}$	$10^3 < E < 10^4$ V/cm
$\mu \propto \frac{1}{E}$	$E > 10^4$ V/cm

1.5 CURRENT DENSITY (*J*)

$$J = \frac{I}{A}$$

1.8 POTENTIAL VARIATION IN A OPEN CIRCUIT SEMICONDUCTOR BAR



As, $J = 0$

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

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

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

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

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

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

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

■■■■

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 τ_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 × 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, $\Delta n = 10^{15}$/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

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

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

Using mass action law $np = n_i^2$

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

8. (a)

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

9. (c)

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

Put, $v_d = \mu E$

∴ $J = n\,e\,\mu E$

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

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

∴ $$E_g \simeq 1.08 \text{ eV}$$