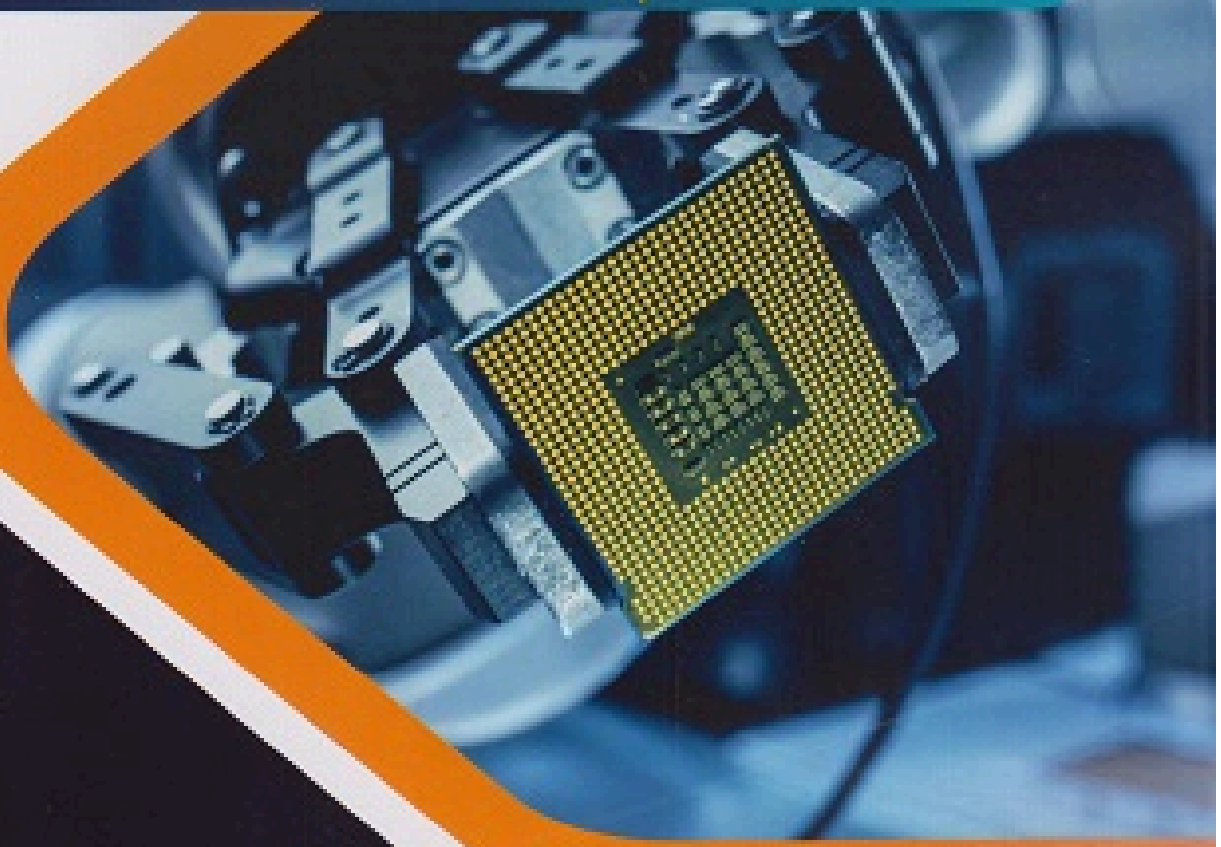
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INDUSTRIAL ELECTRONICS

Bachelor of Engineering
Second Year (S.E.) Degree Course
in **Mechanical Engineering Group | Semester 4**

Dr. SATISH S. SRIVASTAVA

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ADVANCEMENT OF KNOWLEDGE

A Text Book Of

INDUSTRIAL ELECTRONICS

MEC404

For

Semester - IV

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SECOND YEAR DEEGRE COURSE IN
MECHANICAL ENGINEERING GROUP

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WITH EFFECT FROM 2020 - 2021

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Preface ...

"Industrial Electronics" is an important subject for fourth-semester students of Mechanical Engineering. We have divided the subject into small chapters so that this textbook provides through understanding of the topics of the syllabus properly. The topics with in the chapters have been arranged in a proper sequence to ensure smooth flow of the subject.

Generally, numerical problems are expected in university examinations in this subject. The weightage given to problems in examination is more than 10-20%. Hence a large number of solved examples and exercise problems are included in each chapter of this book to help students to master problem solving skills required to appear any examination with confidence. So, I am sure that this book will provide all the student's needs for this subject.

We are thankful to my family members and friends. I also send a heartfelt thanks to my wife Sunita, and sons Suyash and Shivam for always motivating and supporting me during the preparation of project.

We also take this opportunity to express my gratitude to Shri Jignesh Furia, Shri Dherya Furia Nirali Prakashan who motivated me and supported me in getting this book into its shape. Mrs. Anagha (Co-ordinator), Mr. Ilyas Shaikh (D.T.P.), Mrs. Varsha Bodake (Figure Drawing) and Mr. Jayant Dhediya (Marketing Executive, Mumbai) deserve special thanks for the co-operation they have extended to me. I am also thankful to the staff members of 'Nirali Prakashan' and others for their efforts to make this book as good as it is.

We have jointly made every possible efforts to eliminate all the errors in this book. However, if you find any, please let us know, because that will help me to improve further.

Suggestions for improvements will always be welcome.

Dr. Satish S. Srivastava

Syllabus ...

1. Semiconductor Devices (08)

Review of diode, V-I characteristics and applications of: rectifier diode, zener diode, LED, photodiode; SCR V-I characteristics, UJT triggering circuit, turning-off of a SCR (preliminary discussion), basics of Gate Turn Off (GTO), Structure and V-I characteristics of Triac (modes of operation not needed) and Diac, Applications of Triac-Diac circuit.

Characteristics of Power BJT, power MOSFET, IGBT; Comparison of SCR, Triac, Power BJT, power MOSFET, IGBT.

2. Phase Controlled Rectifiers and Bridge Inverters (07)

Full wave controlled rectifier using SCR's (semi controlled, fully controlled) with R load and only, Block diagram of closed loop speed control of DC motors, Basic principle of single phase and three phase bridge inverters, block diagrams including rectifier and inverter for speed control of AC motors (frequency control only).

3. Operational Amplifiers and 555 Timer (05)

Operational amplifier circuits, Ideal OP-AMP behaviour, common OP-AMP ICs; Basic OP-AMP circuits- Inverting amplifier, Non-inverting amplifier, Voltage follower (Buffer), Comparator, Instrumentation Amplifier, Active first order filter: Low pass and high pass filter; Power Op-Amps, IC-555 timer-Operating modes: monostable, astable multivibrator.

4. Digital Logic and Logic Families (05)

Boolean algebra and logic gates, logic families; Logic Levels, Noise Immunity, Fan Out, Propagation Delay, TTL and CMOS logic families, Flip-flops; Set Reset (SR), Trigger (T), clocked F/Fs; Registers, Multiplexer and Demultiplexer applications.

5. Microprocessor and Microcontrollers (08)

Overview of generic microprocessor, architecture and functional block diagram, Comparison of microprocessor and microcontroller MSP430 architecture, assembly language programming, C complier programming, basics of interfacing with external input/output devices (like reading external analog voltages, digital input output) Applications of microcontroller: Temperature measurement, Speed Measurement using Proximity Sensor, Piezoelectric Actuator Drive.

6. Motors (06)

Review and comparison of DC motors and AC induction motors, Basic principles of speed control of AC induction motor, Basics of BLDC motor, Linear Actuator motor, Servo Motor; Motor Specifications, suitability of each motor for various industrial applications, Selection and sizing of motors for different applications. Applications for pumps, conveyors, machine tools, Microcontroller based speed control for Induction Motor.



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MODULE - I: SEMICONDUCTOR DEVICES

CHAPTER - 1

PN JUNCTION DIODE AND TYPES OF DIODES

SYNOPSIS

Review of diode, V-I characteristics and applications of: Rectifier diode, zener diode, LED, photodiode; SCR V-I characteristics.

1.1 SEMICONDUCTOR

Definition :

The material, whose electrical conductivity lies between those of conductors and insulators and have negative temperature coefficient of resistance, are known as semiconductors.

Semiconductor Materials :

- The few examples of semiconductor materials are as under :
  1. Carbon (C)
  2. Silicon (Si)
  3. Germanium (Ge)
  4. Selenium (Se)
  5. Arsenic (As)
  6. Gallium Arsenide (GaAs)
  7. Cadmium sulphide (CdS).

  The commonly used semiconductor materials are Germanium and Silicon. These are tetravalent elements.

Atomic Structure of Germanium and Silicon :

1. Atomic structure of Germanium and Silicon atoms :

- Fig. 1.1 (a) shows the atomic structure of a Ge atom in which first, second, third and fourth orbits have 2, 8, 18 and 4 electrons respectively, with the result that the atomic number for Ge is 32. This can be shown by Fig. 1.1 (a).

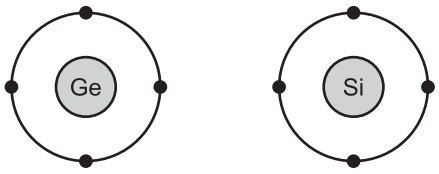


Fig. 1.1: Simple Atomic Structure

- Fig. 1.1 (b) shows the atomic structure of a Si atom in which first, second and third orbits have 2, 8, and 4 electrons respectively, with the result that the atomic number for Si is 14. This can be shown by Fig. 1.1 (b).

2. Atomic structure of Germanium and Silicon crystals :

- The tendency of an atom is to complete its outermost orbit by acquiring 8 electrons in it. If the outermost orbit of an atom has 8 valence electrons, it is said to be filled. It then becomes a stable structure.
- Fig. 1.2 shows a simplified two-dimensional representation of a crystalline structure of Germanium or Silicon crystal.
- Each Germanium atom is surrounded by 4 neighbouring Germanium atoms and each atom has 4 valence electrons. The core represents the nucleus.

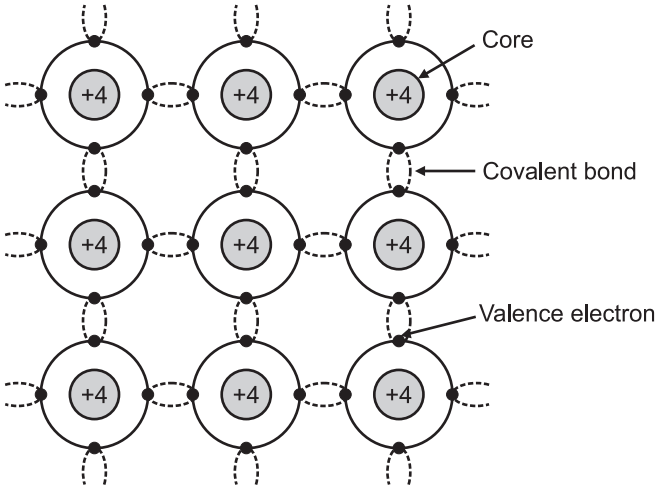


Fig. 1.2: Atomic Structure of Ge or Si Crystal

- At absolute zero, all the valence electrons are tightly bound to the parent atoms.
- No free electrons are available for electrical conduction.

3. Types of Semiconductors :

The semiconductors are of the following two types :

1. Intrinsic semiconductors
2. Extrinsic semiconductors (P- and N-types)

1.2 INTRINSIC SEMICONDUCTOR

Definition :

- *A semiconductor in an extremely pure form (i.e. without any impurity) is known as an intrinsic semiconductor.*
- A semiconductor could not be truly intrinsic, unless the impurity level is very small.
- For Germanium, the impurity level should be less than 1 part in 108 parts of Germanium and for Silicon, it is less than 1 part in 1012 parts of Silicon.

Conduction of Current :

- When electric field is applied across an intrinsic semiconductor, the current conduction takes place by two processes, by free electrons and by holes as shown in Fig. 1.3.
- The free electrons are generated due to the breaking up of some covalent bonds by thermal agitation (or energy). At the same time, holes are created in the covalent bonds.

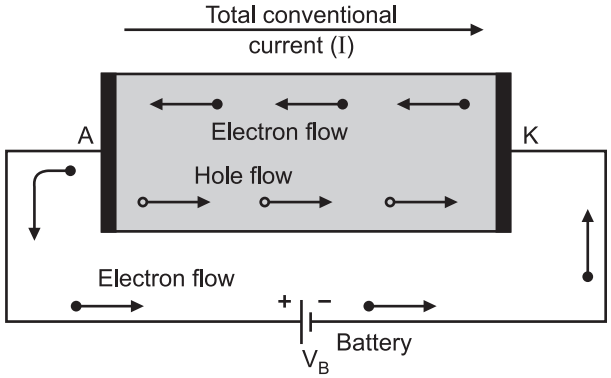


Fig. 1.3 : Conduction of current in an intrinsic semiconductor

- The electrons experience a force towards the positive terminal of the battery and holes towards the negative terminal of the battery.
- The random motion of electrons and holes gets modified.
- Over and above the random motion, there also occurs a net movement called drift.
- Since the random motion of electrons or holes does not contribute to any electric current, we need not consider it.

- The free electrons drift towards the positive terminal of the battery and the holes towards the negative terminal of the battery.
- This movement of charge carriers constitute the electric current under the influence of electric field and it flows through the semiconductor in the same direction as the holes are moving.
- Since the electrons are negatively charged, the direction of electric current (conventional) is opposite to the direction of their motion.
- The two types of charge carriers move in opposite direction, the two currents are in the same direction and they add together.
- *The total current inside the semiconductor crystal is the sum of electric currents due to the free electrons and holes.*
- *When the flow of charge carriers is due to an applied voltage (as shown in Fig. 1.3), the resultant current is called a drift current.*
- A second type of current may also exist in a semiconductor. This current is called *diffusion current* and it flows as a result of a gradient of carrier concentration (i.e. the difference of carrier concentration from one region to another).
- A gradient of carrier concentration arises near the boundary of a PN junction.
- The *diffusion current* may also be due to the motion of both free electrons and holes.

Effect of Temperature on Conductivity of Intrinsic Semiconductor :

- At absolute zero temperature (–273°C or 0°K), the intrinsic semiconductor materials behave as a perfect insulator because there are no free electrons for conduction.
- When the temperature of intrinsic semiconductor materials is increased to room temperature, the covalent bonds are broken and the number of electrons become free for conduction. Thus, the conductivity of intrinsic semiconductor materials increases and behaves as a moderate conductor at room temperature.

1.3 EXTRINSIC SEMICONDUCTOR

Definition :

- *The intrinsic semiconductor containing small amount of desired impurity atoms is known as an extrinsic semiconductor. It is also defined as a doped intrinsic semiconductor.*
- *The impure form of a semiconductor is known as an extrinsic semiconductor.*

Doping :

- *The process of deliberately adding or diffusing impurity atoms to the intrinsic semiconductor crystal is called doping.*
- *The purpose of adding impurity is to increase either the number of free electrons or holes in the semiconductor crystal i.e. to increase the conductivity of the intrinsic semiconductors.*

Types of Impurity Elements :

- To increase the conductivity of the intrinsic semiconductor, trivalent and pentavalent impurity elements are doped to it.
- There are two types of impurity elements as under :

1. Trivalent
2. Pentavalent.

1. Trivalent (or Acceptor) impurity elements :

- *The impurity elements that accept the free electrons from the intrinsic semiconductor is called trivalent impurity elements.* These are third group elements.
- Typical examples are Boron (B), Gallium (Ga), Aluminium (Al) and Indium (In).
- These impurities are also called *acceptor impurities* because the holes created have affinity to accept free electrons.

2. Pentavalent (or Donor) impurity elements :

- *The impurity element that provides (or donate) excess of free electrons to the intrinsic semiconductor is called pentavalent impurity elements.* These are pentavalent group elements.
- Typical examples are Phosphorus (P), Arsenic (As) and Antimony (Sb).
- These impurities are also called *donor impurities* because these impurities donate or provide excess of free electrons.

Types of Extrinsic Semiconductors :

The extrinsic semiconductors are of the following two types :

1. P-type semiconductors
2. N-type semiconductors.

1.3.1 P-Type Semiconductor

Definition :

- *When a small amount of trivalent (i.e. acceptor) impurity is added to the intrinsic semiconductor, then it is known as P-type semiconductor.*
- The P-type semiconductor is formed by adding a small amount of trivalent (Boron, Gallium or Aluminium) impurity element to the intrinsic semiconductor (pure Silicon or Germanium) material which acts as a base material.
- The addition of trivalent impurity provides a large number of holes in the intrinsic semiconductor.

Working Principle:

- Consider the structure of a P-type semiconductor as shown in Fig. 1.4 (a).
- The Boron atom in the crystal has only 3 valence electrons.
- Each Boron atom is surrounded by 4 neighbouring Germanium (or Silicon) atoms.
- Three valence electrons of Boron atom share with the three electrons of three neighbouring Germanium atoms forming three covalent bonds.
- The fourth neighbouring Germanium atom is unable to form a covalent bond with Boron atom, because Boron atom does not have fourth electron in its valence orbit.
- The fourth covalent bond remains incomplete for want of fourth electron in Boron atom. This deficit of one electron in the Boron atom gives rise to a hole.
- The number of holes generated in the Germanium (or Silicon) crystal depends upon the amount of Boron impurity atoms added to the crystal.
- The hole has a great tendency to snatch valence electron from the neighbouring atom to form a covalent bond.
- This tendency is so great that an electron in an adjacent covalent bond, having very small additional energy, can jump to occupy the vacant position.
- This electron then completes the covalent bond around the Boron atom.
- At room temperature, the thermal energy is sufficient to provide this energy so as to fill the incomplete bond around all the Boron atoms.
- To make-up the fourth covalent bond, Boron atom takes one electron from the neighbouring Germanium atom by breaking a covalent bond. Now two things happen.

1. A vacancy is created in the adjacent covalent bond from where the electron had jumped. This vacancy has a positive charge associated with it, hence, it is a *hole* as shown in Fig. 1.4 (b).

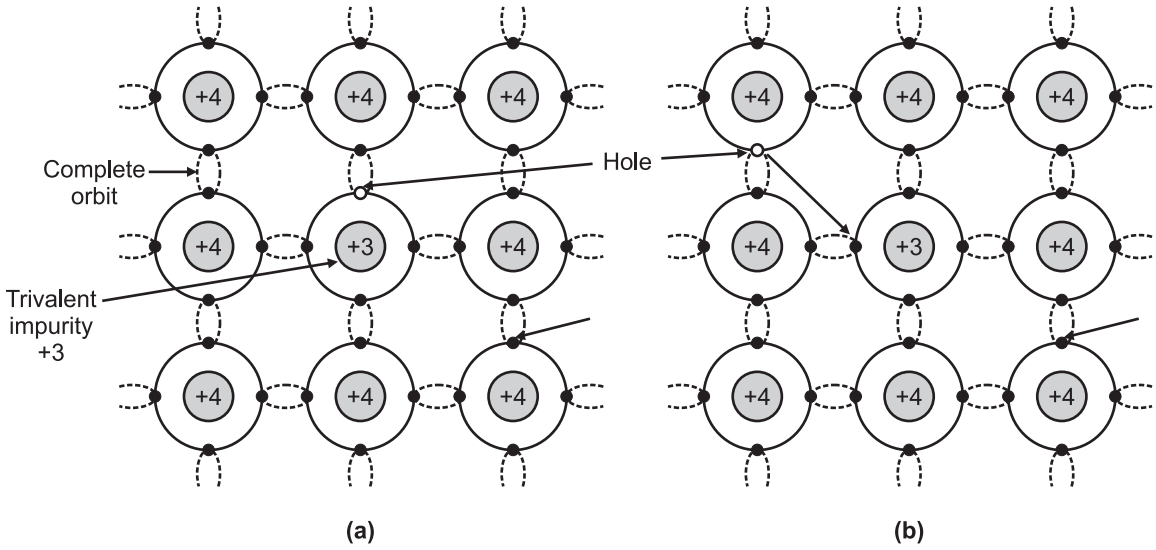


Fig. 1.4: P-type Semiconductor

2. Due to the filling of the incomplete fourth covalent bond around the Boron atom, it now becomes a *negative ion* known as negative immobile ion.
   - At absolute zero temperature, there is no movement of electrons and holes due to zero thermal energy.
   - Hence P-type semiconductor behaves as a perfect insulator at absolute zero temperature.
   - At room temperature, some of the covalent bonds may get broken because of thermal energy. This gives rise to electron-hole pairs. These holes add to the existing holes.
   - There exist a large number of holes (i.e. positively charged carriers).
   - In P-type semiconductor, holes are majority carriers, whereas free electrons are minority carriers and it also has negative immobile ions.

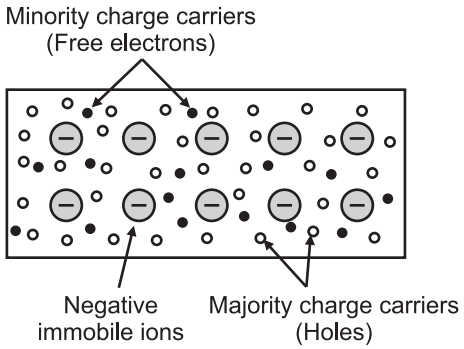


Fig. 1.4 (c): P-type Semiconductor

1.3.2 N-Type Semiconductor

Definition :

- *When a small amount of pentavalent (i.e. donor) impurity is added to the intrinsic semiconductor, then it is known as N-type semiconductor.*
- The N-type semiconductor is formed by adding a small amount of pentavalent impurity (Phosphorus or Arsenic or Antimony) to the intrinsic semiconductor (pure Silicon or Germanium) material which acts as a base material.
- The addition of pentavalent impurity provides a large number of electrons in the intrinsic semiconductor.

Working Principle :

- Consider the structure of an N-type semiconductor as shown in Fig. 1.5 (a).
- The Phosphorus atom in the crystal has only five valence electrons.
- Each Phosphorus atom is surrounded by 4 neighboring Germanium (or Silicon) atoms.
- This Phosphorus atom fits in the Ge (or Si) crystal in such a way that its 4 valence electrons share with 4 valence electrons of 4 different neighboring (or adjacent) Germanium atoms forming 4 covalent bonds with these Germanium atoms.
- The fifth valence electron of Phosphorus atom finds no place in the covalent bond and is unable to form a covalent bond with Germanium (or Silicon) atom for want of an additional electron in their orbit.

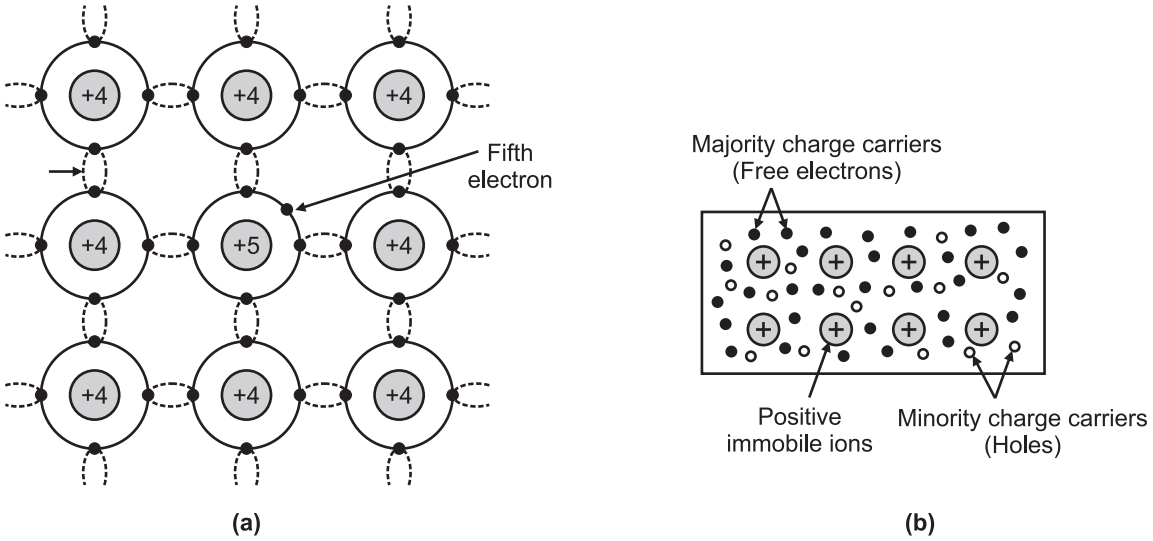


Fig. 1.5 : N-Type Semiconductor

- Since it is not associated with any covalent bond and is quite far from the nucleus, it is very loosely bound. It requires very little energy to free itself from the attractive force of its nucleus.
- At absolute zero temperature, there is no movement of electrons and holes due to zero thermal energy.
- *N-type semiconductor behaves as a perfect insulator at absolute zero temperature.*
- The additional energy required to detach the fifth valence electron from its nucleus is so small that at room temperature practically all such electrons become free.
- At room temperature, all those donated electrons acquire sufficient thermal energy and become detached from its nucleus.
- It then becomes free to move anywhere within the Germanium (or Silicon) crystal.
- At the time when this electron has become free from the Phosphorus atom, the remaining atom becomes a positive ion (known as positive immobile ion).
- The number of thermally generated electron-hole pairs will be very small compared to the number of free electrons donated by impurity atoms.
- Further, as the number of free electrons is very large, the changes of their recombination with holes increases.
- Consequently, the concentration of holes is much less than its intrinsic value.
- *In N-type semiconductor, free electrons are majority carriers, whereas holes are minority carriers* and it also has positive immobile ions.

1.3.3 Comparison of Intrinsic and Extrinsic Semiconductor

The comparison of intrinsic and extrinsic semiconductors is as under :

Table 1.1 : Comparison of Intrinsic and Extrinsic Semiconductor

Intrinsic Semiconductor	Extrinsic Semiconductor
1. It is an extremely pure form of semiconductor.	1. It is a doped semiconductor.
2. The number of free electrons and holes generated due to thermal energy are equal.	2. The number of free electrons and holes generated due to thermal energy are not equal.
3. The current conduction is due to electrons and holes.	3. The major part of current conduction is due to either holes or free electrons.
4. The Fermi level is at the centre of forbidden energy gap and is unchanged with change in temperature.	4. The Fermi level shifts upward or downward with change in temperature and type of doping material.
5. The electrical conductivity is very poor at room temperature.	5. The electrical conductivity is comparatively high at room temperature.
6. Less or almost no direct application.	6. All semiconductor devices are made up of extrinsic semiconductors.

1.4 P-N JUNCTION

Definition :

- P-type and N-type semiconductors have very limited use in actual practice.
- A P-N junction cannot be formed by simply connecting or welding or pushing the two pieces together because it would not lead to a single structure, but it would produce a discontinuous crystal structure. Special fabrication technique is needed to form a P-N junction.
- *When a P-type semiconductor is suitably joined to an N-type semiconductor under suitable condition by using special technique to form a junction, the contact surface is known as a P-N junction.*

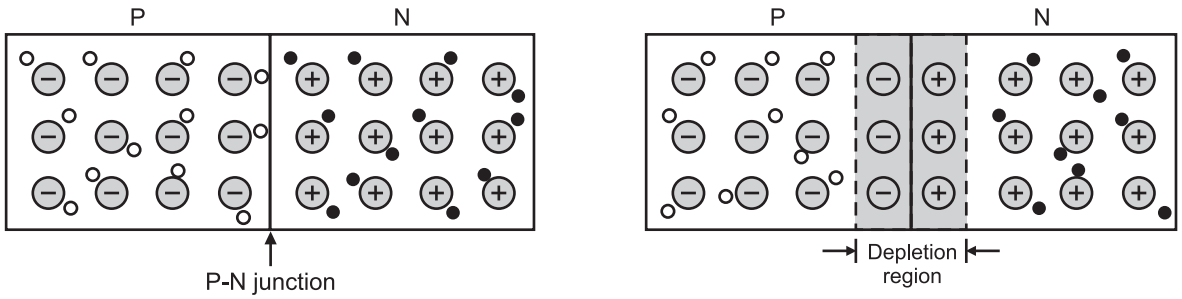
Structure :

- The structure of a P-N junction is as shown in Fig. 1.6.

1.4.1 Formation of Depletion Layer in Unbiased P-N Junction

1. Constructional Details :

- Fig. 1.6 (a) shows a P-N junction just immediately it is formed. It is a single crystal having P-type and N-type semiconductor made from Germanium or Silicon.
- The P-region has high concentration of holes (i.e. majority carriers) and less negatively charged ions, whereas the N-region has high concentration of free electrons (i.e. majority carriers) and less positively charged ions.
- For simplicity, minority carriers are not shown in Fig. 1.6.
- Holes and free electrons are the mobile charge carriers, but ions are immobile. In P-region, the positive charge on holes is equal to the total charges on its free electrons and immobile ions.
- Similarly, in N-region, the negative charge of its majority carriers is compensated by the charge of minority carriers and immobile ions.



(a) When Just Formed (b) After Formation of Junction

Fig. 1.6 : P-N junction Without Bias

- Therefore, the single crystal (P-N junction) as a whole is electrically neutral, and so the P-region and N-region are considered separately.

2. Working Principle :

- As soon as the P-N junction is formed, some of the holes, which are near the junction, from the P-region diffuse into the N-region.
- They then combine with the free electrons in the N-region.
- Similarly some of the free electrons, which are near the junction, from the N-region diffuse into the P-region.
- These electrons also combine with the holes. The diffusion of holes from P-region to N-region and free electrons from N-region to P-region take place, because they move randomly due to thermal energy and also because there is a difference in their concentrations in the two regions.
- Thus some of the holes and free electrons diffuse towards each other across the junction and recombine.
- The diffusion of holes and free electrons across the P-N junction occurs for a very short time.
- In this process, the negative acceptor ions in the P-region and the positive donor ions in the N-region in the immediate neighbourhood of the junction are left uncompensated.
- This situation is shown in Fig. 1.6 (b). Additional holes trying to diffuse into the N-region are now repelled by the uncompensated positive charge of the donor ions.
- The free electrons trying to diffuse into the P-region are repelled by the uncompensated negative charge of the acceptor ions.
- As a result, total recombination of holes and free electrons cannot occur and also the further diffusion of free electrons and holes across the junction is stopped.
- The depletion layer will only contain positive charge on N-side and negative charge on P-side of the crystal as shown in Fig. 1.6 (b).
- As the depletion layer builds-up the space-charge across the P-N junction increase and as a result a potential difference builds-up across the P-N junction.

1.4.2 Barrier Potential

- The electric field between the positive and negative ions (i.e. acceptor and donor ions) is called a barrier.
- The physical distance from one side of the barrier to the other is referred to as the *width of the barrier*.
- *The difference of potential from one side of the barrier to the other side is referred to as the height of the barrier, i.e. barrier potential.*
- With no external batteries connected, the barrier height is of the order of tenths of a volt.
- At room temperature, the *barrier potential is about 0.7 V for a Silicon P-N junction whereas it is about 0.3 V for a Germanium P-N junction*.

1.4.3 Current Conduction in Unbiased PN Junction

- *A P-N junction, across which no external voltage source is connected, is known as an unbiased P-N junction.*
- We have seen that immediately after the formation of a P-N junction, a depletion layer is formed in the vicinity of a P-N junction.

- Because of this, there exists a potential barrier (V_B) as shown in Fig. 1.7, which stops the further diffusion (or crossover) of majority carriers across the P-N junction.
- If the P-N junction is at room temperature, the thermal energy is added continuously.
- As a result of this, few holes and electrons will acquire enough energy to diffuse the P-N junction.

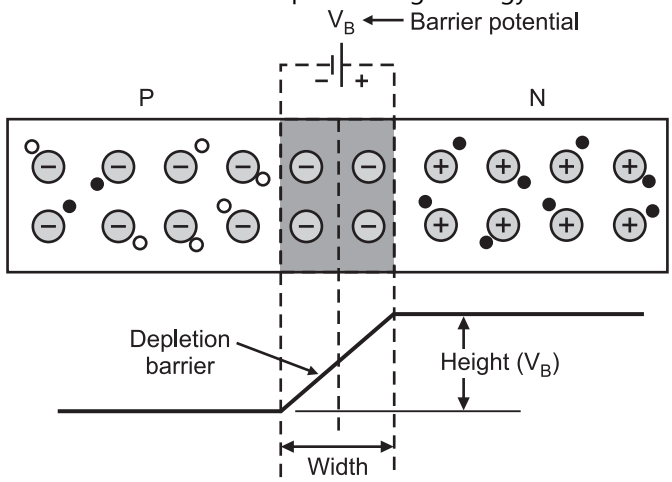


Fig. 1.7 : Barrier Potential in a P-N Junction

1.4.4 PN Junction with DC Voltage

Concept of Biasing :

- *The external DC voltage applied to the semiconductor device is called a bias.*
- *A P-N junction connected to an external voltage source (i.e. battery) is known as a biased P-N junction.*
- Biased P-N junction has a variety of applications in semiconductor devices.
- There are two ways of connecting a battery to a P-N junction as forward bias and reverse bias.

1. **Forward bias :**
   - *If we connect a battery to the P-N junction in such a way that the positive terminal of the battery is connected to the P-region, whereas the negative terminal to the N-region, then the biasing is called forward biasing.*
   - *It is also defined that when the external voltage applied to the P-N junction is in such a direction that it cancels (or opposes) the potential barrier, thus permitting current flow, it is called forward biasing.*
2. **Reverse bias :**
   - *If we connect a battery to the P-N junction in such a way that the negative terminal of the battery is connected to the P-region, whereas the positive terminal to the N-region, then the biasing is called reverse biasing.*
   - *It is also defined that when the external voltage applied to the P-N junction is in such a direction that it aids the potential barrier, thus permitting no current flow, it is called reverse biasing.*

1.4.5 Working Principle

1. **P-N junction with Forward Bias :**
   - Consider a forward biased P-N junction as shown in Fig. 1.8.
   - When a P-N junction is forward biased as shown in Fig. 1.8, the holes are repelled from the positive terminal of the battery (B) and are forced to move towards the junction.
   - Similarly the free electrons are repelled from the negative terminal of the battery and drift towards the P-N junction.
   - Because of their acquired energy (from the battery V_F), some of the holes and the free electrons enter into the depletion region and recombine themselves.
   - This reduces the potential barrier and also reduces the width of the depletion layer as well as the height of the potential barrier.
   - In other words, the width of depletion layer and the barrier potential reduces with the increase in forward bias.

- As a result of this, more majority carriers diffuse across the junction. Therefore, it causes a large current to flow through the P-N junction. This is called forward current.

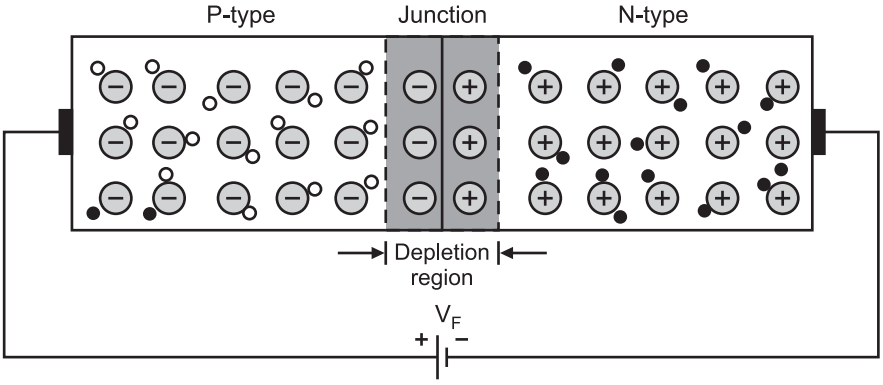


Fig. 1.8 : Forward Biased P-N Junction

2. P-N junction with Reverse Bias :

- Consider a reverse biased P-N junction as shown in Fig. 1.9.
- When a P-N junction is reverse biased as shown in Fig. 1.9, the holes in the P-region are attracted towards the negative terminal of the battery, and the free electrons in the N-region are attracted to the positive terminal of the battery.
- Thus the majority carriers are drawn away from the P-N junction.
- This widens the depletion layer and increases the barrier potential.
- The increased barrier potential makes it very difficult for the majority carriers to diffuse across the P-N junction.
- Thus there is no current due to the majority carriers in a reverse biased P-N junction.
- In fact, as soon as a minority carrier is generated, it swepts (i.e. drifts) across the junction because of the barrier potential.

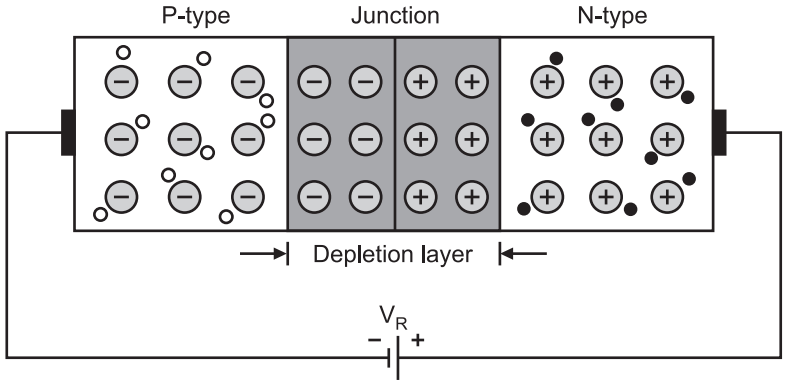


Fig. 1.9 : Reverse biased P-N junction

- Hence a small amount of current flows through the reverse biased P-N junction due to minority carriers.
- The current due to the flow of minority carriers remains constant, whether the applied voltage is increased or decreased. *Because of this reason, this current is known as reverse saturation current (I_o).*
- It is of the order of nanoamperes (nA) in Silicon P-N junctions and microamperes (μA) in Germanium P-N junctions. *This current increases with the increase in temperature i.e. doubles for every 10°C rise in temperature.*

1.4.6 Effect of Temperature on Barrier Potential

Effect of Temperature on Barrier Potential :

- The barrier potential of a P-N junction depends upon three factors, namely (a) density, (b) electronic charge and (c) temperature.
- For a given P-N junction, the first two factors are constant and not variable.
- These two factors cannot be now changed for a specific P-N junction.
- Thus the barrier potential V_B of a P-N junction is dependent only on temperature.

- It has been observed that for both Germanium and Silicon, the value of V_B decreases by 2.5 mV/°C. Mathematically, the decrease in barrier potential is given by,

$$\Delta V_B = -0.0025 \times \Delta t \quad \ldots (1.1)$$

where, Δt is the increase in temperature in °C.

Effect of Barrier Potential on Forward Bias

- Consider the barrier potential as shown in Fig. 1.10.
- The barrier potential V_B of the depletion region in P-N junction can be considered as a small (imaginary or fictitious) battery which opposes the external forward biased DC voltage.
- These resistances R_p and R_n represent the bulk resistances of the P-type and N-type semiconductors respectively.

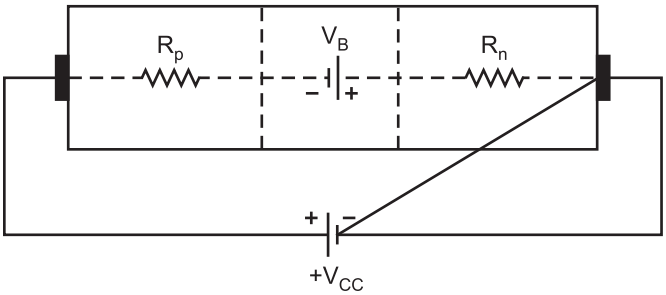


Fig. 1.10 : Barrier Potential

- The P-N junction does not permit the current to flow, until the external bias voltage overcomes the barrier potential i.e. $V_S > V_B$.
- For example, the Germanium P-N junction does not conduct as long as the external applied voltage is below 0.3 V.
- Similarly the Silicon P-N junction does not conduct as long as the external applied voltage is below 0.7 V.
- It may be noted that once the current starts flowing through the P-N junction, the voltage drop remains equal to the barrier potential.
- It changes very little with the change in current, except for bulk resistance effects.

1.4.7 Mobility and Conductivity

- Mobility is the speed with which a particle moves. It depends upon the applied electric field.
- Conductivity is the ability to transport the charge carriers, that is physical and chemical characteristics of the material.
- Conductivity is inverse of resistivity.
- In solid-state physics, the electron mobility is known for how quickly an electron can move through a metal or semiconductor, when pulled by an electric field. It is same for holes, called hole mobility. The term carrier mobility refers in general to both electron and hole mobility.
- Electron mobility is almost always specified in units of $cm^2/(V{\cdot}s)$. This is different from the SI unit of mobility, $m^2/(V{\cdot}s)$. They are related by $1m^2/(V{\cdot}s) = 10^4\ cm^2/(V{\cdot}s)$.
- Conductivity is proportional to the product of mobility and carrier concentration.

  For example, the same conductivity could come from a small number of electrons with high mobility for each, or a large number of electrons with a small mobility for each. For most metals electrical behavior depends on conductivity alone. Therefore mobility is relatively unimportant in metal physics. On the other hand, for semiconductors, the behavior of transistors and other devices can be very different depending on whether there are many electrons with low mobility or few electrons with high mobility. Therefore mobility is a very important parameter for semiconductor materials. Almost always, higher mobility leads to better device performance.
- Semiconductor mobility depends on the impurity concentrations (including donor and acceptor concentrations), defect concentration, temperature, and electron and hole concentrations. It also depends on the electric field, particularly at high fields when velocity saturation occurs.
- Without any applied electric field, in a solid, electrons and holes move around randomly. Therefore, on average there will be no overall motion of charge carriers in any particular direction over time.

- The two charge carriers, electrons and holes, will typically have different drift velocities for the same electric field.
- The SI unit of velocity is m/s, and the SI unit of electric field is V/m. Therefore the SI unit of mobility is (m/s)/(V/m) = $m^2/(V{\cdot}s)$. However, mobility is much more commonly expressed in $cm^2/(V{\cdot}s) = 10^{-4}\ m^2/(V{\cdot}s)$.
- There is a simple relation between mobility and electrical conductivity.

1.4.8 Fermi-Dirac Distribution

- For a system of identical fermions with thermodynamic equilibrium, the average number of fermions in a single-particle state *i* is given by a logistic function, or sigmoid function: the Fermi–Dirac (F–D) distribution.
- At zero temperature, μ is equal to the Fermi energy plus the potential energy per electron. For the case of electrons in a semiconductor, μ, the point of symmetry, is typically called the Fermi level or electrochemical potential.
- The F–D distribution is only valid if the number of fermions in the system is large enough so that adding one more Fermi on to the system has negligible effect Fermi–Dirac distribution.

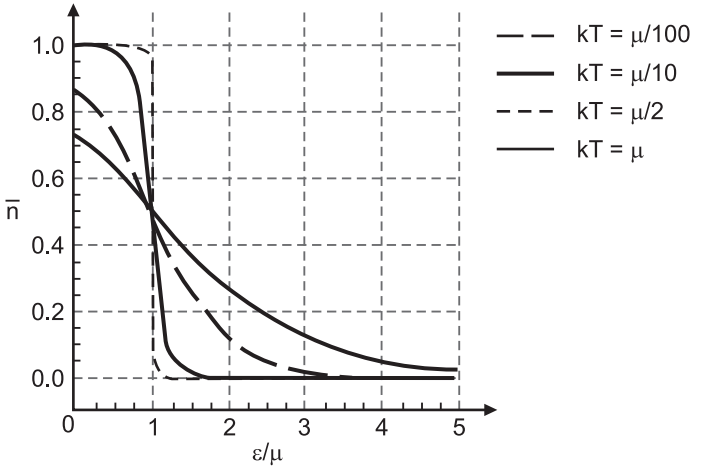


Fig. 1.11 : Energy dependence. More gradual at higher T = 0.5

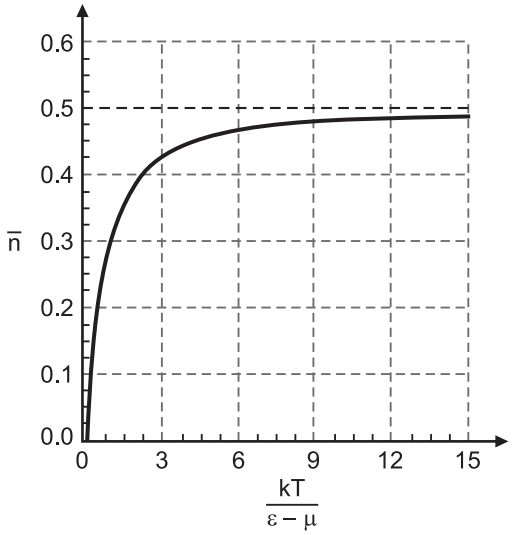


Fig. 1.12 : Temperature dependence

1.5 P-N JUNCTION DIODE

Definition :

- *When a P-type semiconductor is suitably joined to on N-type semiconductor under suitable condition by using a special technique to form a P-N junction, the device so constructed is called a P-N junction diode or a semiconductor diode.*
- The P-N junction itself forms the most basic semiconductor device called *semiconductor diode*. It is also known as a *rectifier diode*. The meaning of the term *diode* is that *the device having two electrodes*, i.e. diode.
- It is a unidirectional device.

Construction Details :

- A P-N junction diode consists of a P-N junction formed either in Germanium or Silicon crystal as shown in Fig. 1.13 (a).
- A P-N junction diode is constructed by joining a P-type semiconductor to an N-type semiconductor under suitable condition by using a special technique.
- It has two terminals called anode A and cathode K.
- The P-region of a diode is called *anode* (A) and the N-region is called *cathode (K)*.

Schematic Symbol :

- The P-N junction (or semiconductor diode) is represented by its schematic symbol as shown in Fig. 1.18 (b).
- The symbol looks like an arrow pointing from the P-region to the N-region.
  The arrow head, shown in the circuit symbol, points the direction of conventional current flow, when it is forward biased.
- *It may be noted that it is in the same direction in which the movement of holes takes place.*

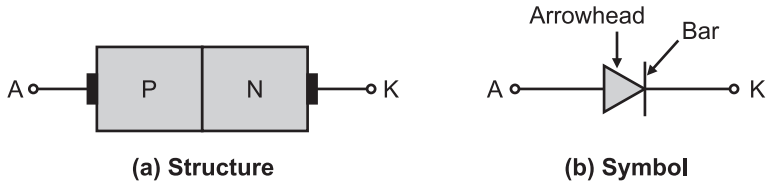


Fig. 1.13 : P-N Junction Diode

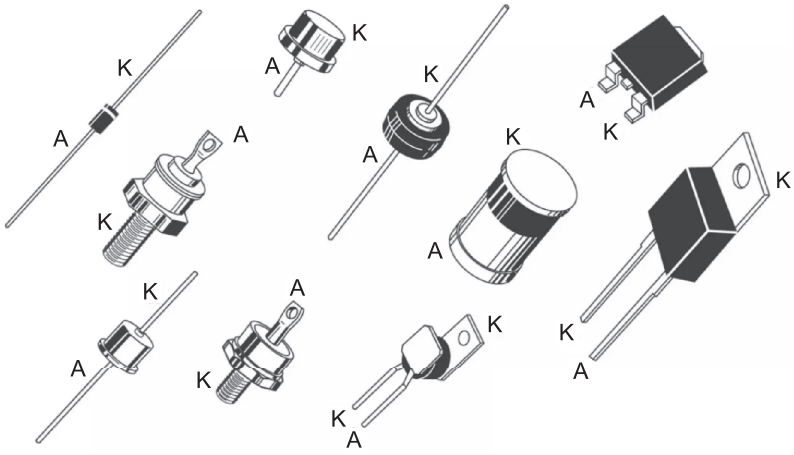


Fig. 1.14 : Typical Diode Packages with Terminal Identification

1.5.1 Working Principle

Working Principle :

1. **Forward Bias :**
   - Consider a P-N junction diode as shown in Fig. 1.15 (a).
   - When the battery is not connected, there is a barrier potential of 0.3 V for Germanium and 0.7 V for Silicon across the P-N junction of a diode.
   - The external applied voltage of forward bias is opposed by the barrier voltage and the diode does not conduct the current due to the majority charge carriers.
   - As the applied voltage is increased above the barrier potential, it overcomes the opposition of barrier potential and the diode conducts the current due to majority carriers. This current is called *forward current* (I_f) and flows from anode to cathode through the diode.
   - It is of the order of 20 to 50 mA at about 1 V.
2. **Reverse bias :**
   - Consider a P-N junction diode as shown in Fig. 1.15 (b).
   - The barrier potential of fictitious battery across the P-N junction add with the external applied voltage. But, diode does not conduct the current due to majority charge carriers.
   - As the applied reverse voltage is increased, very small amount of current (negligible as compared to forward current) flows through the diode due to minority charge carriers. This current is called *reverse saturation current* (I_o).
   - It is of the order of nanoamperes (1 μA = 10^{-9} A) for Silicon and microamperes (1 μA = 10^{-6} A) for Germanium diode.

1.5.2 Specification

The important specifications of a P-N junction diode are listed below :

1. Maximum reverse voltage (V)
2. Repetitive peak voltage (V)
3. Maximum forward current (mA)
4. Power disspation.
5. Repetitive peak forward current
6. Average forward current (A)
7. Surge current (A)
8. Operating ambient temperature (°C)
9. Maximum junction temperature (°C)
10. Forward voltage (V)
11. Reverse saturation current (μA)
12. Cut-in voltage (knee voltage) V_z

1.5.3 Applications

The P-N junction diode has the following important applications :

1. It is used as a *rectifier* in DC power supply.
2. It is used as a *free wheel diode* across relay or inductive load.
3. It is used as a *switch* in logic circuits used in computers.
4. It is used as a *detector* in demodulation circuits of communication receiver.
5. It is used for *wave shaping* in clipping and clamping circuits.
6. It is used as a *voltage doubler, tripler, quadrupler* in *voltage multiplier circuits*.

1.5.4 Types of Diodes

There are different types of semiconductor diodes. They are:

(1)	P-N junction.	(2)	Zener diode.	(7)	Photodiode	(10) Power diode
(3)	Tunnel diode.	(4)	LED.	(8)	Gunn diode	
(5)	Varactor.	(6)	Schottky diode.	(9)	PIN diode	

1.5.5 V-I static Characteristics of P-N Junction Diode

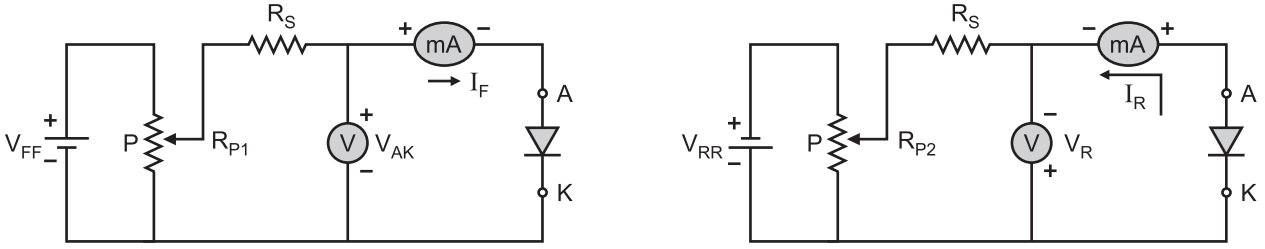
Definition :

- It is very important to know how an electronic device responds (or behaves) when it is connected in an electrical circuit. This information is obtained by means of a graph known as its volt-ampere (V-I) characteristic.
- *The V-I characteristic is a graph between the voltage applied across the terminals of an semiconductor device and the resulting current that flows through it.*

Experimental Set-up :

1. For Forward characteristics :

- Fig. 1.21 (a) shows the experimental set-up for obtaining the forward characteristic of P-N junction diode.



(a) Experimental Set-up for Forward Characteristics (b) Experimental Set-up for Reverse Characteristics

Fig. 1.15 : Experimental Set-up for a P-N Junction Diode

2. For Reverse characteristics :

- Fig. 1.16 shows the experimental set-up for obtaining the reverse characteristics of a P-N junction diode.

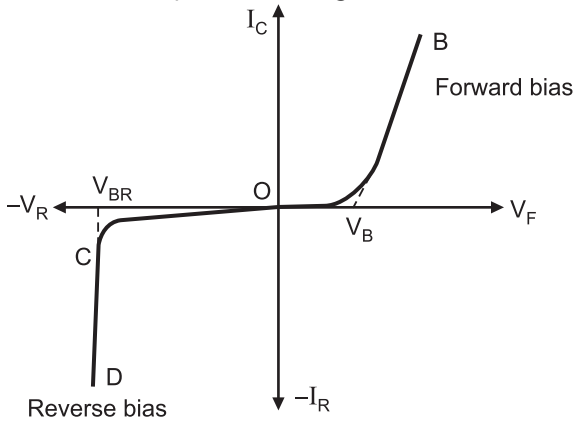


Fig. 1.16 : V-I Characteristics of a P-N Junction Diode

Forward Characteristics :

- Consider the experimental set-up as shown in Fig. 1.15 (a).
- *A graph between the forward voltage across the terminals of a P-N junction diode and the current flowing through it is known as a forward characteristic.*
- A forward characteristic of a P-N junction diode is as shown in Fig. 1.16.
- It is observed that the P-N junction conducts the forward current only after the cut-in (i.e. knee voltage) voltage.

Reverse Characteristics :

- Consider the experimental set-up as shown in Fig. 1.15. It is 0.7 V for Si and 0.3 V for Ge.
- *A graph plotted between the reverse voltage across the terminals of a P-N junction diode and the current flowing through it is known as a reverse characteristic.*
- A reverse characteristic of a P-N junction diode is as shown in Fig. 1.16.
- It is observed that the flow of reverse current is very small till the breakdown voltage V_{BR} is reached.

Static and Dynamic Forward Resistance :

1. Static Forward Resistance :

- It is calculated from forward characteristics of a P-N junction diode.
- It is defined as the ratio of a d.c (constant) voltage across the P-N junction to the resulting small change in d.c. current. It denoted as R.

$$R = \frac{V_{ak}}{I_a} \quad \ldots (1.2)$$

Dynamic Forward Resistance :

- It is also calculated from forward characteristics of a P-N junction diode.
- It is defined as the ratio of change in voltage to the resulting change in d.c. current.

$$R = \frac{V_2 - V_1}{I_2 - I_1} = \frac{\Delta V_{ak}}{I_a} \quad \ldots (1.3)$$

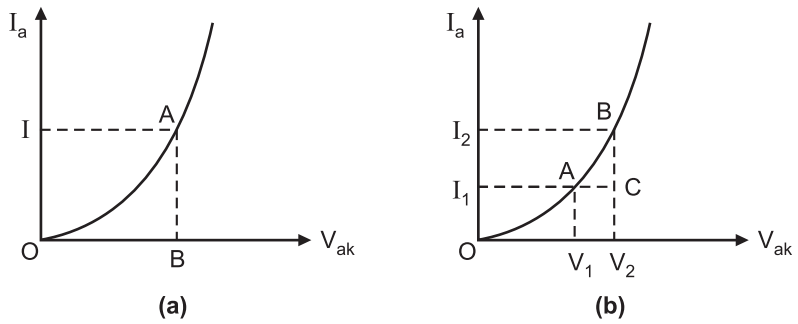


Fig. 1.17

1.5.6 Effect of Temperature on V-I Characteristics

- We have already discussed that, the current that a P-N junction diode can conduct at a given voltage and it is dependent upon the operating temperature.

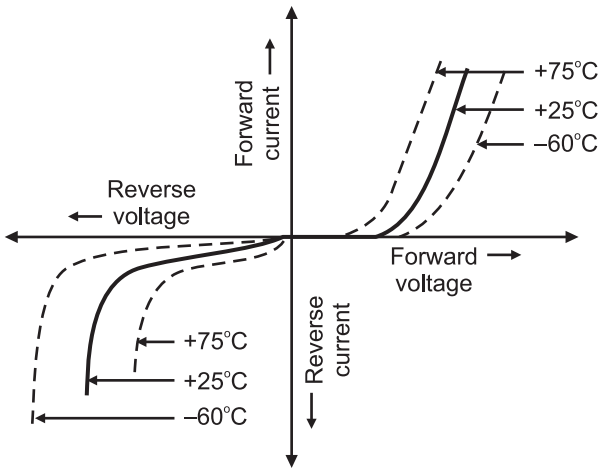


Fig. 1.18 : Effect of Temperature on Diode Characteristics

- The increased temperature of a diode will result in a large number of broken covalent bonds thereby increasing the large number of majority and minority carriers.
- As a result, this amounts to large current flowing through the diode.
- The above phenomenon applies both to forward current and reverse current.
- The effect of temperature on the V-I characteristic curve of a PN junction diode is as shown in Fig. 1.24. It may be noted that the forward characteristic shifts upwards with the increase in temperature (say from 25°C to 75°C).
- On the other hand, the reverse characteristic shifts downwards with the increase in temperature.

1.5.7 Comparison Between Germanium and Silicon Diodes

The comparison of Germanium diode and Silicon diode is given in Table 1.2.

Table 1.2

Property	Germanium Diode	Silicon Diode
1. Cut-in voltage	0.3 V	0.7 V
2. Reverse saturation current	more (μA)	less (μA)
3. Maximum operating temperature	upto 85°C	upto 175°C
4. Rate of decrease of barrier potential with temperature	2.5 mV/°C	2.5 mV/°C
5. Applications	In low and medium power	In high power

1.5.8 Comparison Between Ideal and Practical Diodes

The difference between ideal diode and practical (real) diode is given in Table 1.3.

Table 1.3

Ideal Diode	Practical (Real) Diode
1. It can act as perfect conductor and as a perfect insulator.	1. It cannot act as perfect conductor and as perfect insulator.
2. It has zero voltage drop across it, when forward biased.	2. It has very low voltage drop (< 1 V) across it, when forward biased.
3. It draws zero reverse saturation current, when reverse biased.	3. It draws negligibly small reverse saturation current, when reverse biased.
4. It has zero cut-in (knee) voltage.	4. It has very low cut-in (knee, < 1 V) voltage.
5. It offers zero resistance, when forward biased.	5. It offers very low resistance, when forward biased.
6. It offers infinite resistance, when reverse biased.	6. It offers very high resistance, when reverse biased.
7. It cannot be manufactured.	7. It can be manufactured.

1.6 DIODE CURRENT EQUATION

A *p-n* junction diode creates the following current: under reverse bias, there is a small, constant reverse current, and under forward bias, there is a forward current that increases with voltage. The current-voltage function (also called the "*i-v* characteristic") for an ideal diode is;

$$i(v) = I_S\left[\exp\left(\frac{v}{\eta V_T}\right) - 1\right], v > V_Z \quad \ldots (1.4)$$

where,

- I_s is the reverse saturation current,
- V_v is the applied voltage (reverse bias is negative),
- $V_T = \frac{T}{11{,}586}$ is the volt equivalent of temperature, and
- η is the *emission coefficient*, which is 1 for germanium devices and 2 for silicon devices.

Note that 'i' is defined as positive when flowing from p to n. Equation is also called the **Shockley ideal diode** equation or the diode law. Note also that for $v < V_z$, the diode is in breakdown and the ideal diode equation no longer applies; for $v \le V_z$, $I = -\infty$. The ideal diode i-v characteristic curve is shown Fig. 1.19.

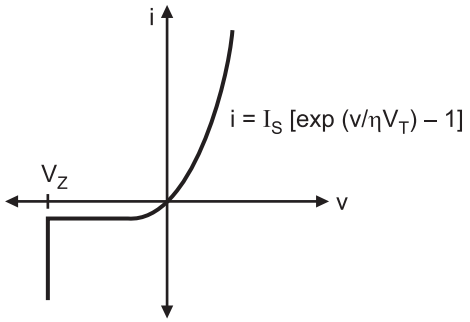


Fig. 1.19: Ideal Diode Equation

The ideal diode equation is very useful as a formula for current as a function of voltage. However, at times the inverse relation may be more useful; if the ideal diode equation is inverted and solved for voltage as a function of current, we find:

$$v(i) = \eta V_T \, ln\left[\left(\frac{i}{I_s}\right) + 1\right] \quad \ldots (1.5)$$

Approximations

Infinite step function

A number of approximations of diode behaviour can be made from the ideal diode equation. The simplest approximation to make is to represent the diode as a device that allows no current through - that is, it acts as an open circuit - under reverse bias, and allows an unlimited amount of current through - a closed circuit -- under forward bias. In this simplified model, the current-voltage relation (also called the "i-v characteristic") is an infinite step function:

$$I = \begin{cases} 0, v \le 0 \\ \infty, v > 0 \end{cases}$$

This characteristic is depicted below:

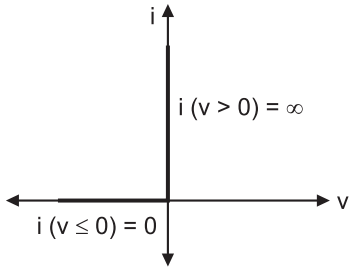


Fig. 1.20: Characteristic of Diode

Forward Current Approximation:

In the case of large forward bias, a good approximation of the ideal diode equation is to simply set the second term of Equation to zero. This approximation is valid because the ideal diode I-V curve increases very quickly, and because reverse saturation current I_S is typically very small. This approximation is acceptable for $v > 0.2$ V. The forward current approximation, as we will call it, results in the following formula:

$$i(v) \approx I_S \exp\left(\frac{v}{n\eta V_T}\right) v \ge 0.2 \text{ V} \quad \ldots (1.6)$$

Reverse Current Approximation:

Under reverse bias, the resulting current can be treated as simply the reverse saturation current, I_S. In reality, the current under reverse bias will asymptotically approach I_S, but the small magnitude of the reverse saturation current makes this discrepancy negligible. The reverse current approximation is valid over the range $V_Z < v < 0$ (the diode enters breakdown for $v \le V_Z$):

$$i(v) \approx I_S, V_Z \le v \le 0 \quad \ldots (1.7)$$

1.7 PROBLEMS BASED ON DIODE EQUATION

Example 1.1 : *The voltage across a silicon diode at room temperature of 300°K is 0.71 V when 2.5 mA current flows through it. If the voltage increases to 0.8 V, calculate the new diode current.*

Solution : The current equation of a diode is

$$I = I_0 (e^{V/\eta V_T} - 1)$$

At 300°K, $V_T = 26 \text{ mV} = 26 \times 10^{-3} \text{ V}$

$V = 0.71 \text{ V for } I = 2.5 \text{ mA}$

and $\eta = 2$ for silicon

$$\therefore \quad 2.5 \times 10^{-3} = I_0 [e^{(0.71/2 \times 26 \times 10^{-3})} - 1]$$

$$\therefore \quad I_0 = 2.93 \times 10^{-9} \text{ V}$$

Now, V = 0.8 V

$$\therefore \quad I = 2.93 \times 10^{-9} [e^{(0.8/2 \times 26 \times 10^{-3})} - 1]$$

$$= 0.0141 \text{ A} = 14.11 \text{ mA}$$

Example 1.2 : *For a silicon p-n junction diode.*

(i) For what value of reverse voltage will the reverse current reach 90% of its saturation value at room temperature.

(ii) find the ratio of current for a forward bias of 0.2 V to the reverse saturation current for the same magnitude of reverse bias voltage.

Solution : For silicon $\eta = 2$ and $V_T = 26$ mV at 300°K.

(i) Let I_0 be the reverse saturation current at room temperature.

The new current is $-0.9\ I_0$ due to new voltage applied.

So $I = -0.9\ I_0$, negative as it is reverse current.

The current equation of diode is,

$$I = I_0 (e^{V/\eta V_T} - 1)$$

$$\therefore \quad -0.9\ I_0 = I_0 (e^{V/2 \times 26 \times 10^{-3}} - 1)$$

$$\therefore \quad 0.9 = e^{V/52 \times 10^{-3}} - 1$$

$$\therefore \quad e^{V/52 \times 10^{-3}} = 0.1$$

$$\therefore \quad \frac{V}{52 \times 10^{-3}} = \ln (0.1) = -2.3025$$

$$\therefore \quad V = -0.1198 \text{ V}$$

The negative sign indicates it is reverse biased voltage.

Note : The current equation of diode is applicable for both forward and reverse biased condition of a diode.

(ii) Now forward voltage V = 0.2 V.

$$\therefore \quad I = I_0 [e^{0.2/2 \times 26 \times 10^{-3}} - 1]$$

$$I = 45.812\ I_0$$

While for reverse bias $V = -0.2$ V

$$\therefore \quad I = I_0 [e^{-0.2/2 \times 26/10^{-3}} - 1]$$

$$\therefore \quad I = -0.9786\ I_0$$

So the ratio of currents for a 0.2 V of forward and reverse biased conditions is

$$\frac{I \text{ when forward biased}}{I \text{ when reverse biased}} = \frac{45.812\ I_0}{-0.9786\ I_0}$$

$$= -46.811$$

So the ratio is 46.811 while negative sign indicates that the two current directions are opposite to each other.

Example 1.3 : *A germanium diode has a reverse saturation current of 3 μA. Calculate the voltage at which 1% of the rated current will flow through the diode, at room temperature if diode is rated for 1 A.*

Solution : η = 1 for germanium.

$$I_0 = 3\ \mu A = 3 \times 10^{-6}\ A$$

Rated current is 1 A

and I = 1% of rated current = 0.01 A

V_T = 26 mV at room temperature.

Using current equation of a diode,

$$I = I_0 [e^{V/\eta V_T} - 1]$$

$$\therefore \quad 0.01 = 3 \times 10^{-6} [e^{V/1 \times 26 \times 10^{-3}} - 1]$$

$$\therefore \quad 3333.33 = e^{V/1 \times 26 \times 10^{-3}} - 1$$

$$\therefore \quad e^{V/1 \times 26 \times 10^{-3}} = 3334.33$$

$$\therefore \quad \frac{V}{26 \times 10^{-3}} = 8.112$$

$$\therefore \quad V = 0.2109\ V$$

Example 1.4 : *The reverse saturation current of a germanium diode is 100 μA at room temperature of 27°C. Calculate the current in forward biased condition, if forward bias voltage is 0.2 V at room temperature. If temperature is increased by 20°C, calculate the reverse saturation current and the forward current, for same forward voltage, at new temperature.*

Solution : At T_1 = 27°C = 300°K, V_T = 26 mV.

$$(I_0)_1 = 100\ \mu A,\ V = 0.2\ V$$

$$\therefore \quad I = I_0 (e^{V/\eta V_T} - 1)$$

$$\therefore \quad I = 100 \times 10^{-6} [e^{0.2/1 \times 26 \times 10^{-3}} - 1]$$

$$\therefore \quad = 219.04\ mA$$

This is forward current at room temperature.

Now using the experimental result that

$$(I_0)_2 = (1.07)^{\Delta T} \times (I_0)_1$$

where, $(I_0)_2$ = I_0 at new temperature T_2.

$(I_0)_1$ = I_0 at original temperature T_1.

ΔT = Rise in temperature.

In this problem, $\Delta T = 20$, $(I_0)_1 = 100\ \mu A$

$(I_0)_1$ = I_0 at original temperature T_1.

ΔT = Rise in temperature.

In this problem, $\Delta T = 20$, $(I_0)_1 = 100\ \mu A$

$$\therefore \quad (I_0)_2 = (1.07)^{20} \times 100$$

$$= 386.96\ \mu A$$

New reverse current at 27 + 20 = 47°C is 386.96 μA. So for V = 0.2 V, the new forward current can be calculated using current equation of diode.

$$V_T \text{ at } T_2 = 47 + 273 = 320°K = kT.$$

$$= 8.62 \times 10^{-5} \times 320.$$

$$= 27.584\ mV.$$

$$\therefore \quad I = I_0 (e^{V/\eta V_T} - 1)$$

$$= 386.96 \times 10^{-6} [e^{0.2/1 \times 27.584 \times 10^{-3}} - 1]$$

$$= 544.8\ mA.$$

Example 1.5 : *A p-n junction germanium diode has a reverse saturation current of 10 μA at the room temperature of 27°C. It is observed to be 30 μA, when the room temperature is increased. Calculate the new room temperature.*

Solution : Let $(I_0)_1$ be the reverse saturation current at T_1 and $(I_0)_2$ be the reverse saturation current at T_2.

$\therefore$ $(I_0)_1 = 10\ \mu A$ and $(I_0)_2 = 30\ \mu A$

Now, $(I_0)_2 = (1.07)^{\Delta T} \times (I_0)_1$

$\therefore$ $30 \times 10^{-6} = (1.07)^{\Delta T} \times 10 \times 10^{-6}$

$\therefore$ $\Delta T\ ln\ 1.07 = ln\ 3$

$\therefore$ $\Delta T = 16.237$

$\therefore$ $T_2 - T_1 = 16.237$

$\therefore$ $T_2 = 16.237 + 27$

$= 42.23°C$

The new room temperature is 42.23°C.

Example 1.6 : *For a germanium diode with reverse saturation current of 5 μA. Calculate the dynamic forward and reverse resistance at a voltage of 0.25 V and −0.25 V respectively, applied across the diode. Assume room temperature of 27°C.*

Solution : The general expression for the dynamic resistance is

$$r = \frac{\eta V_T}{I_0\, e^{V/\eta V_T}}$$

For germanium, $\eta = 1$ and $V_T = 25$ mV at room temperature of 27°C.

$V = +0.25$ V forward bias

$\therefore$ $$r_f = \frac{1 \times 26 \times 10^{-3}}{5 \times 10^{-6}\, e^{0.25/1 \times 26 \times 10^{-3}}}$$

$= 0.3468\ \Omega$

For reverse resistance, $V = -0.25$ V

$\therefore$ $$r_f = \frac{1 \times 26 \times 10^{-3}}{5 \times 10^{-6} \times e^{-0.25/1 \times 26 \times 10^{-3}}}$$

$= 77.96\ M\Omega$

Example 1.7 : *A silicon diode operates at a forward voltage of 0.45 V. Calculate the factor by which the current will be multiplied if the temperature is increased from 27°C to 152°C.*

Solution : At $T = T_1 = 27 + 273 = 300°K$, $(V_T)_1 = kT = 8.62 \times 10^{-5} \times 300 = 26$ mV.

At $T = T_2 = 152 + 273 = 425°K$

$(V_T)_2 = kT = 8.62 \times 10^{-5} \times 425$

$= 36.63$ mV

$V = 0.45$ V is forward voltage

Now at T_1, let $I_0 = (I_0)_1$ while T_2, let $I_0 = (I_0)_2$

and $(I_0)_2 = (1.07)^{\Delta T}\ (I_0)_1$

$\therefore$ $$\frac{(I_0)_2}{(I_0)_1} = (1.07)^{1.25} = 4709.47$$

While the forward current at T_1 be I_1 and at T_2 be I_2.

$\therefore$ $I_1 = (I_0)_1\ [e^{V/\eta V_{T_1}} - 1]$

and $I_2 = (I_0)_2\ [e^{V/\eta V_{T_2}} - 1]$

where, $\eta = 2$ for silicon

$$\therefore \quad \frac{I_1}{I_2} = \frac{(I_0)_1}{(I_0)_2} \cdot \frac{[e^{0.45/2 \times 26 \times 10^{-3}} - 1]}{[e^{0.45/2 \times 2 \times 36.63 \times 10^{-3}} - 1]}$$

$$\therefore \quad \frac{I_1}{I_2} = \frac{1}{4709.47} \times 12.3458$$

$$\therefore \quad \frac{I_2}{I_1} = 381.46$$

So the factor by which current will be multiplied is 381.46.

1.8 REVERSE BREAKDOWN IN P-N JUNCTION

A P-N junction allows to flow a very small amount of current (called reverse saturation current), when it is reverse biased. This current is due to the movement of minority carriers across the P-N junction and is almost independent of the applied reverse bias.

- If the reverse bias is increased to a large value, the reverse current through the P-N junction increases abruptly.
- *The voltage, at which the abrupt increase in reverse current through the P-N junction occurs, is known as breakdown voltage.*
- At the breakdown voltage, the P-N junction diode junction breaks down.
- It may be noted that the P-N junction breakdown is to be avoided in normal applications of a P-N junction diode.
- If the excess reverse bias is removed, the P-N junction diode will return to normal, provided that overheating has not permanently damaged the structure.

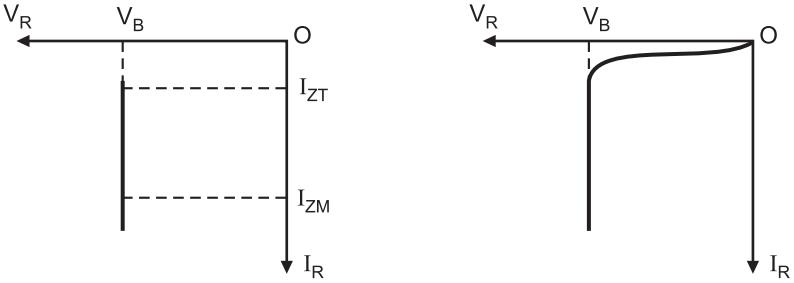
Types of Breakdown :

- The breakdown phenomenon in reverse biased P-N junction is caused by either of the two effects, namely (a) *Zener* or (b) *Avalanche*.
- There are two types of reverse breakdowns in a P-N junction as under :

  (1) Zener breakdown, (2) Avalanche breakdown.

1.8.1 Zener Breakdown

- Zener breakdown occurs in the P-N junctions which are heavily doped.
- The heavily doped P-N junctions have a narrow depletion region.
- When the reverse voltage is increased, the electric field across the P-N junction also increases. The high value of electric field causes a covalent bond to break from the crystal structure of a P-N junction.



(a) Zener Breakdown (b) Avalanche Breakdown

Fig. 1.21 : Breakdown in Diode

- As a result of this, a large number of minority carriers are generated and a large current flows through the P-N junction. This mechanism of breakdown is called *Zener breakdown*.
- In certain cases, especially in Silicon P-N junctions, the Zener breakdown can be represented by a straight line which corresponds to a constant reverse voltage as shown in Fig. 1.21 (a).
- The Zener breakdown principle is used in the construction of a Zener diode.

1.8.2 Avalanche Breakdown

- Under reverse bias condition, the minority carriers flowing through the P-N junction acquire a kinetic energy depending upon the velocity with which they move.
- The increase in reverse voltage increases the amount of kinetic energy imparted to minority carriers, as they diffuse across the P-N junction.
- When sufficient voltage is applied, the minority carriers acquire a large amount of kinetic energy (or momentum).
- When these minority carriers collide with semiconductor (Germanium or Silicon) atoms within the crystal structure of a P-N junction they impart sufficient energy to break covalent bond and generate additional carriers (i.e. electron-hole pairs).
- They knock out the electrons from the covalent bonds of a P-N junction.
- These additional carriers pick-up the energy from the applied voltage and generate still more carriers. As a result of this, the reverse current through the P-N junction increases rapidly.
- *The cumulative process of carrier generation (i.e. multiplication) is known as avalanche breakdown*.
- Under breakdown condition, the reverse current is no longer limited by the P-N junction. But it can be limited only by the circuit components.
- The value of breakdown voltage depends upon the degree of doping in P-N junction.
- The principle of avalanche breakdown is used in the power electronic devices such as SCR, Diac, Triac etc.
- In this breakdown, reverse bias current increases as voltage increases gradually.

1.8.3 Comparison of Avalanche and Zener Breakdowns

The difference between Avalanche breakdown and Zener breakdown is as under :

Table 1.5 : Avalanche Breakdown and Zener Breakdown

Avalanche Breakdown	Zener Breakdown
1. It occurs in junctions which are lightly doped and have wide depletion widths.	1. It occurs in junctions which are heavily doped and have narrow depletion widths.
2. It occurs at higher reverse voltages when thermally generated electrons get enough kinetic energy to produce more electrons by collision.	2. It occurs due to rupture of covalent bonds by strong electric field set up in depletion region by the reverse voltage.
3. At reverse voltages above 6 V, break-down is due to Zener effect.	3. At reverse voltage below 6 V, break-down is due to avalanche effect.

1.9 ZENER DIODE

Concept :

- The Zener diodes are designed to operate in the breakdown region of a P-N junction without any damage.
- By varying the doping level, it is possible to construct Zener diodes with breakdown voltage ranging from about 1.8 V to 2 kV.
- Zener effect is predominant for breakdown voltage less than 4 V and avalanche effect for breakdown voltage greater than 6 V. Both effects are present between 4 and 6 V.
- It is the Zener effect that was first discovered by an American Scientist C. Zener in the year 1934.
- *A properly doped P-N junction diode, which has a sharp reverse breakdown, is known as a Zener diode*. It is also called as a *voltage reference, voltage regulator or breakdown diode*.
- Doping concentration is very high.

Construction :

- The Zener diodes are Silicon P-N junction diodes which differ from rectifier diodes in the sense, they are operated in the reverse breakdown region and the breakdown voltage is set by carefully controlling the doping level during manufacturing process.

- Thus by controlling the junction width and doping concentration of a P-N junction diode, it is possible to make it to breakdown at a sharp specified Zener voltage.
- The construction of a Zener diode is similar to a Silicon P-N junction diode with a high level of doping concentration.

Schematic Symbol:

- A Zener diode is represented by a schematic symbol as shown in Fig. 1.22.
- It has two terminals namely, anode A and cathode K.

  As a memory aid, it may be noted that at the end of the arrow looks like a letter Z.

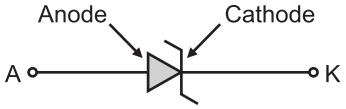
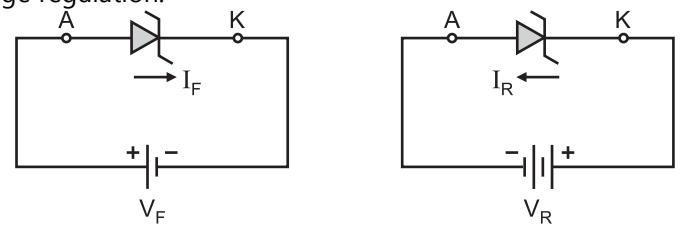


Fig. 1.22 : Symbol of Zener Diode

1.9.1 Working Principle

- Consider the circuit of a Zener diode as shown in Fig. 1.23.
- When a Zener diode is forward biased as shown in Fig. 1.23 (a), it conducts the forward current due to majority carriers and behaves as an ordinary P-N junction diode.
- It's forward characteristic will be similar to that of an ordinary P-N junction diode.
- When a Zener diode is reverse biased as shown in Fig. 1.23 (b), it conducts the reverse current due to minority carriers and this reverse current will be very small so long as the reverse voltage is less than breakdown voltage.
- As the reverse voltage is increased to breakdown voltage, a large number of electron-hole pairs are produced and the reverse current sharply increases.
- This reverse current is known as *Zener current* and the breakdown voltage is known as *Zener voltage*.
- If the voltage is again increased beyond the Zener voltage, then the Zener (i.e. reverse) current increases, but the voltage across the Zener diode remains constant.
- Thus it provides a constant voltage and can be used as a constant voltage source.
- It is mainly used in voltage regulation.



(a) Forward Bias **(b) Reverse Bias**

Fig. 1.23 : Current Conduction Through Zener Diode

Specifications :

The Zener diodes are generally specified in terms of the following important factors :

1. Zener voltage (V_z).
2. Maximum power dissipation.
3. Breakover current (I_{zk})
4. Zener (reverse) resistance (r_z)
5. Maximum Zener current (I_{ZM}).
6. Dynamic resistawnce (r_z).
7. Breakover (knee) current (I_{zk}).
8. Maximum junction temperature.
9. Temperature coefficient (T_c).

The Zener diodes are available with reverse breakdown voltages ranging from 1.8 V to 2 kV and with power ratings ranging from 150 mW to 50 W.

Applications :

The Zener diode has the following important applications :

1. It is used as a *voltage regulator* in regulated power supply.
2. It is used in the *pulse amplifier*.
3. It is used as a fixed *reference voltage* in transistor biasing circuits.

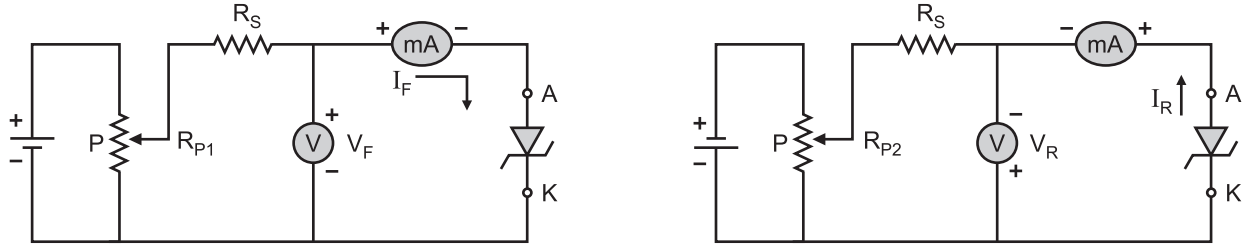
4. It is used as a *voltage reference* in emitter follower type power supply.
5. It is used as *a* peak *clipper* or limiter in waveshaping circuits.
6. It is used in the *protection circuit* for MOSFET.
7. It is used for meter *protection against damage* from accidental applications.

1.9.2 V-I Static Characteristics of a Zener Diode

Experimental Set-Up :

1. Forward Characteristics :

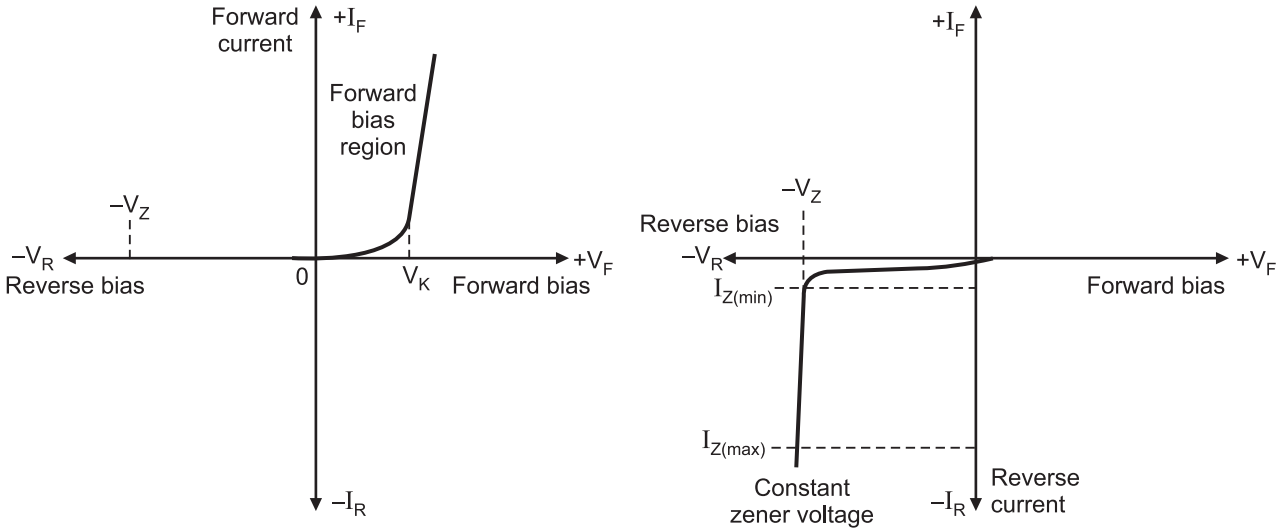
- Fig. 1.24 (a) shows the experimental set-up for obtaining the forward characteristics of a Zener diode.



(a) Forward Bias (b) Reverse Bias

Fig. 1.24

- Fig. 1.24 : Experimental set-up for Zener diode characteristics



(a) Forward Characteristics (b) Reverse Characteristics

Fig. 1.25 : V-I Characteristics of a Zener Diode

2. Reverse characteristics :

- Fig. 1.24 (b) shows the experimental set-up for obtaining the reverse characteristics of a Zener diode.

V-I Static Characteristics :

1. Forward Characteristic :

- Fig. 1.25 (a) shows the forward characteristic of a Zener diode.
- This characteristic is similar to that of an ordinary P-N junction Silicon diode.
- It indicates that the forward current is very small for voltages below knee voltage and large for voltages above knee (i.e. cut-in) voltage.

2. Reverse characteristic :

- Fig. 1.25 (b) shows the reverse characteristic of a Zener diode.
- The reverse characteristic curve indicates that negligible reverse saturation current flows until we reach the breakdown (i.e. Zener) voltage V_z.

- The breakdown has a very sharp knee, followed by an almost vertical increase in reverse current.
- *Note* that *the voltage across the Zener diode is approximately constant and equal to Zener voltage V_z over most of the Zener breakdown region.*
- It will come out of the breakdown region, when the applied reverse voltage is reduced below the Zener breakdown voltage.

3. Complete V-I characteristics :

- The complete V-I characteristics for forward bias and reverse bias are as shown in Fig. 1.26.

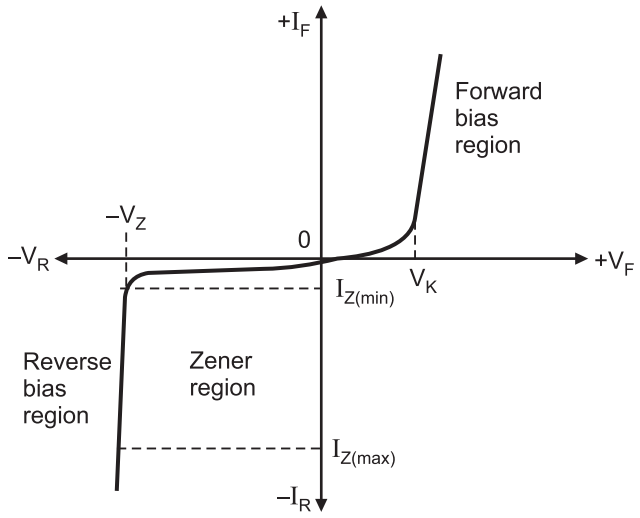


Fig. 1.26 : Complete V-I Characteristics of a Zener Diode

1.9.3 V-I Static Characteristics of a Zener Diode

Comparison of P-N Junction Diode and Zener Diode :

The comparison between P-N junction diode and Zener diode is as given below :

Table 1.6 : P-N Junction Diode and Zener Diode

P-N Junction Diode	Zener Diode
1. It is not properly doped to control reverse breakdown.	1. It is properly doped to control reverse breakdown.
2. It conducts only in one direction.	2. It conducts in both the directions.
3. It is always operated in forward-bias condition.	3. It is always operated in reverse-bias condition.
4. It has no sharp reverse breakdown.	4. It has quite sharp reverse breakdown.
5. It may damage immediately, if applied voltage exceeds the breakdown voltage.	5. It will not damage, but functions properly in breakdown region.
6. It is commonly used for rectification purpose.	6. It cannot be used for rectification, but commonly used for voltage regulation.

1.10 DIODE PARAMETERS

The important parameters related to semiconductor diodes are as discussed under :

1. Electron volt :

- *The energy which an electron acquires in moving through a potential difference of one volt is called an electron volt.*
- It is a unit of energy and abbreviated as eV.

2. Forbidden energy gap :

- *The energy required to break a covalent bond in a semiconductor is known as forbidden energy gap.*