Semiconductor Materials and PN Junction Diode

1. Materials

Materials are classified as conductors, insulators, or semiconductors according to their electric conductivity.

*The term **conductor** is applied to any material that will support a generous flow of charge when a voltage source of limited magnitude is applied across its terminals.*

*An **insulator** is a material that offers a very low level of conductivity under pressure from an applied voltage source.*

*A **semiconductor** is a material that has a conductivity level somewhere between the extremes of an insulator and a conductor.*

Ge and Si have received the attention they have for a number of reasons:

- They can be manufactured to a **very high purity level** (1:10,000,000,000), this high purity is a very important factor in semiconductor materials, because the **addition of one part impurity** (of the proper type) per million in a wafer of silicon material **can change that material from a relatively poor conductor to a good conductor of electricity**. The ability to change the characteristics of the material significantly through this process, known as "**doping**,"
- **Their characteristics can be altered significantly through the application of heat or light**—an important consideration in the development of heat- and light-sensitive devices.

As is well known, the **atom is composed of three basic particles**: the **electron**, the **proton**, and the **neutron**. In the atomic lattice, the neutrons and protons form the nucleus, while the electrons revolve around the nucleus in a fixed orbit. The Bohr models of the two most commonly used semiconductors, germanium and silicon, are shown in Fig. 1.2. The germanium atom has 32 orbiting electrons, while silicon has 14 orbiting electrons. In each case, there are 4 electrons in the outermost (valence) shell. In a pure germanium or silicon crystal these 4 valence electrons are bonded to 4 adjoining atoms, as shown in Fig. 1.3 for silicon.

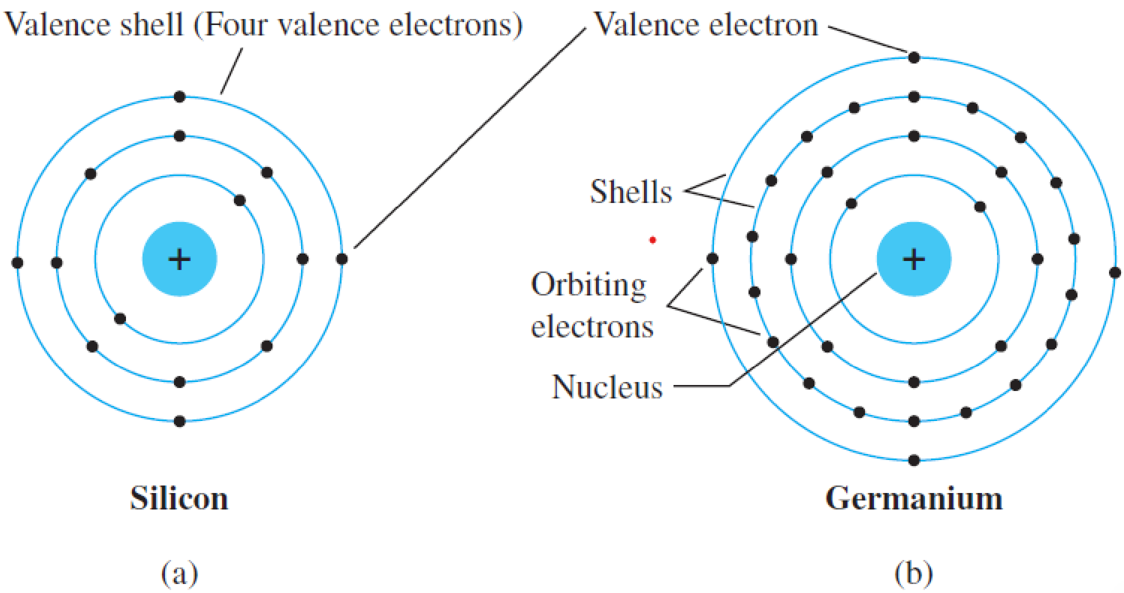


Fig. 1.2 atomic structure: (a) G; (b) Si

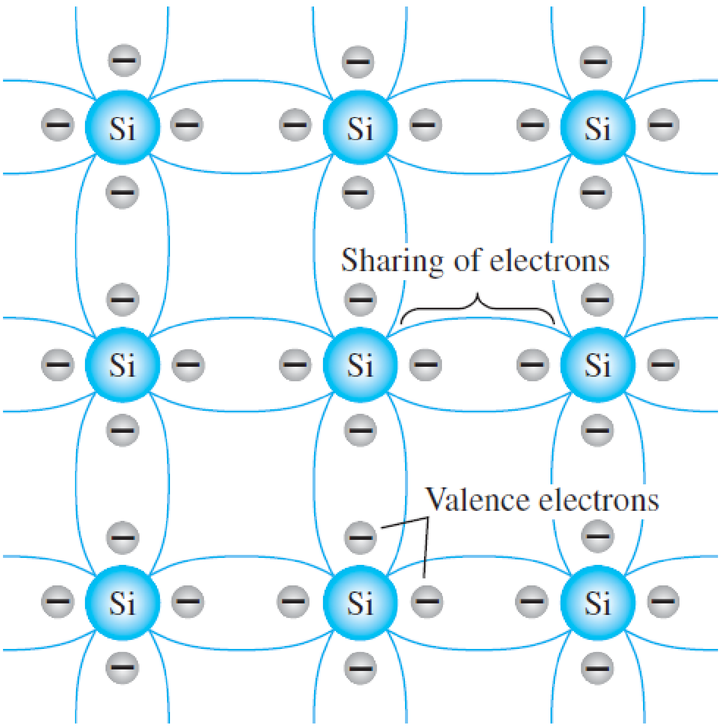


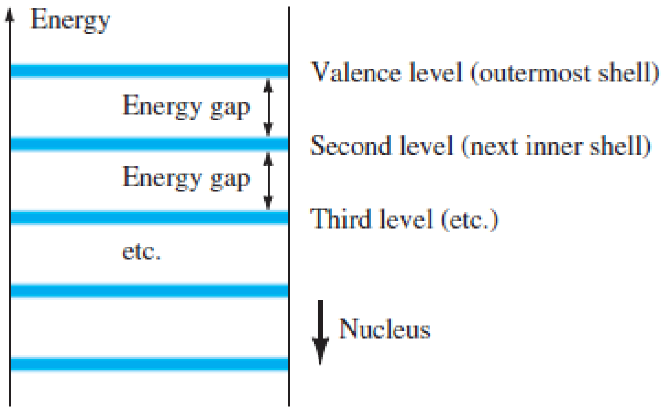
Fig. 1.3 Covalent bonding of the silicon atom.

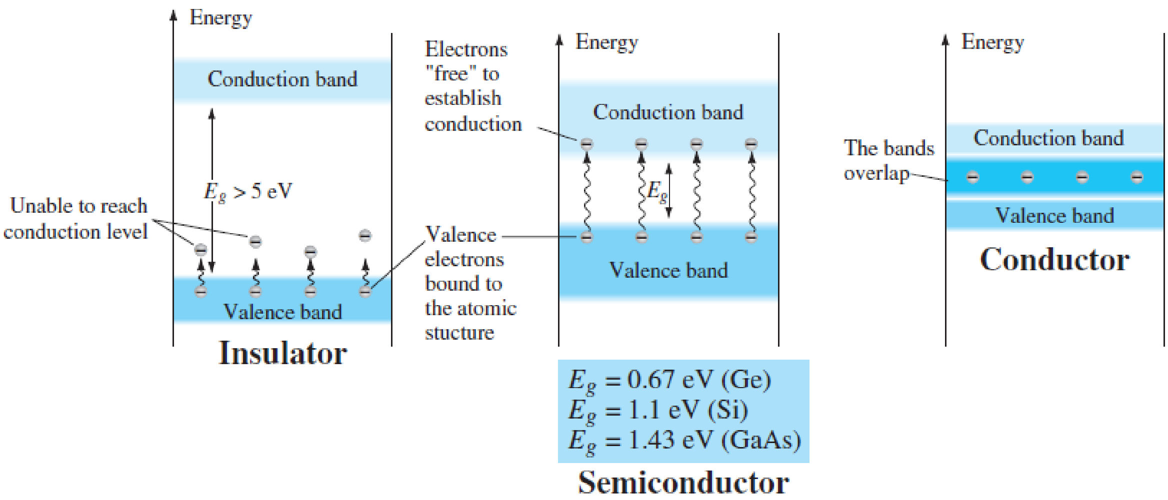
Intrinsic materials are those semiconductors that have been carefully refined to reduce impurities to a very low level-essentially as pure as can be made available through modern technology.

The free electrons in the material due only to natural causes are referred to as intrinsic carriers.

2. Energy Levels:

The more distant the electron is from the nucleus, the higher the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.





Between the discrete energy levels are gaps in which no electrons in the isolated atomic structure can appear.

Recall that **ionization** is the mechanism whereby an **electron can absorb sufficient energy to break away from the atomic structure and enter the conduction band**. You will note that the energy associated with each electron is measured in electron volts (eV). The unit of measure is appropriate, since

$$W = QV \qquad eV$$

Substituting the charge of an electron and a potential difference of 1volt will result in an energy level referred to as one electron volt. Since energy is also measured in joules and the charge of one electron 1.6×10^{-19}coulomb,

$$W = QV = (1.6 \times 10^{-19}C)(1V) = 1.6 \times 10^{-19}J$$

3. Extrinsic Materials (n- and p-Type)

Both the n- and p-type materials are formed by adding a predetermined number of impurity atoms into a germanium or silicon base. The n-type is created by introducing those impurity elements that have five valence electrons (pentavalent), such as antimony, arsenic, and phosphorus.

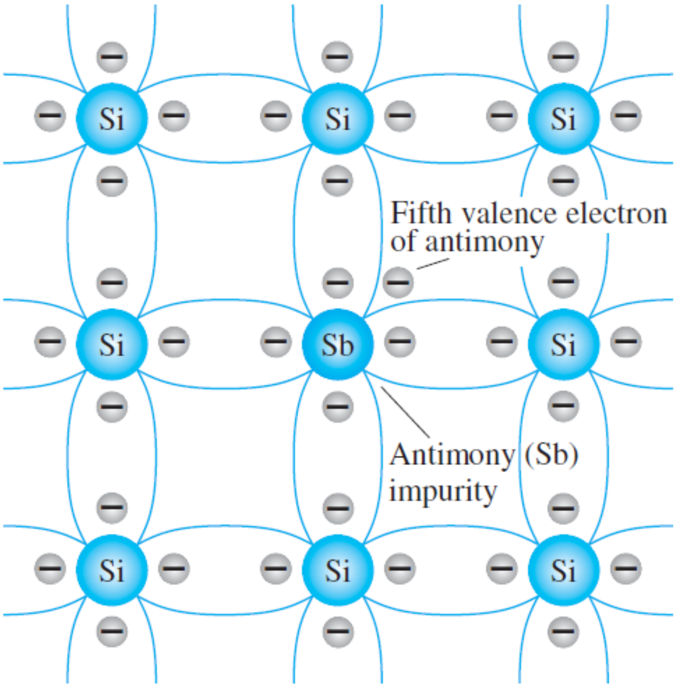


Fig. 1.4 Antimony impurity in n-type material.

Diffused impurities with five valence electrons are called **donor atoms**.

The p-type material is formed by doping a pure germanium or silicon crystal with impurity atoms having three valence electrons.

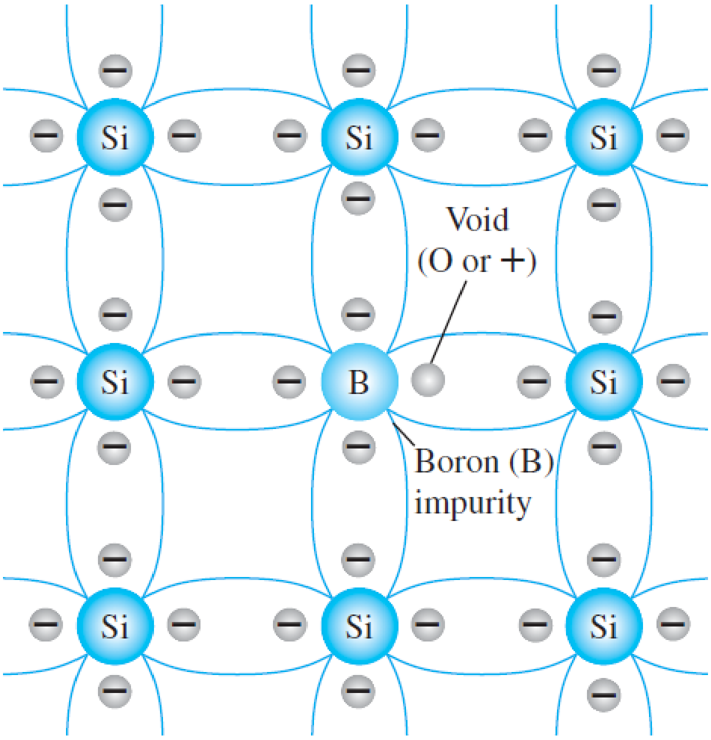


Fig. 1.5 Boron impurity in p-type material.

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

In an n-type material the electron is called the majority carrier and the hole the minority carrier. In a p-type material the hole is the majority carrier and the electron is the minority carrier.

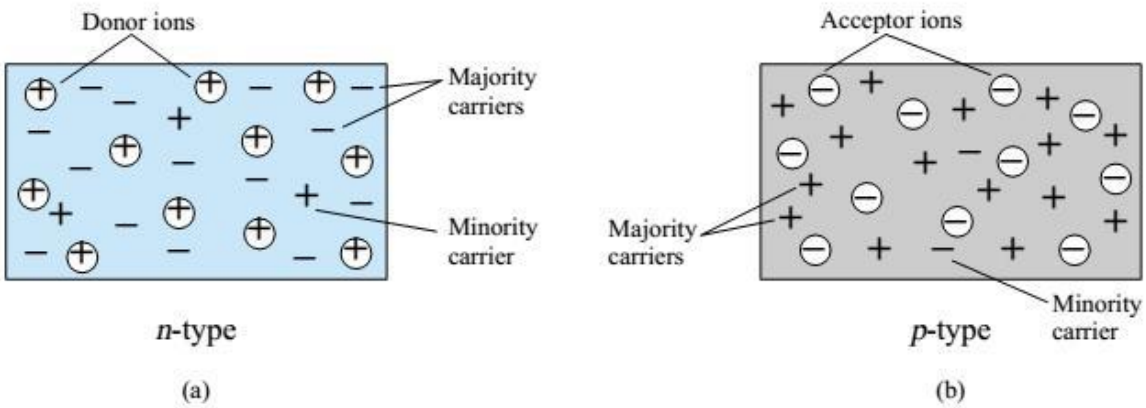
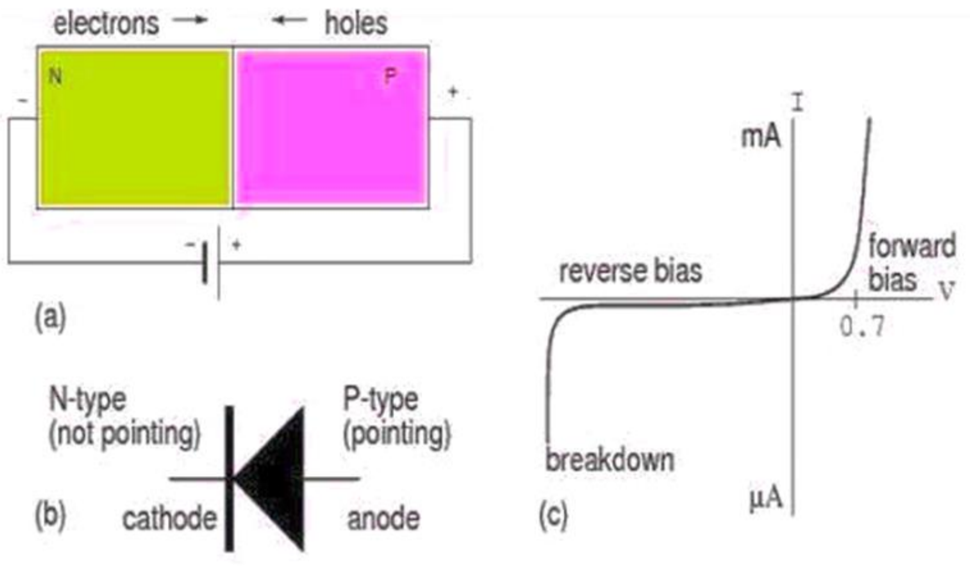


Fig.1.6 (a) n-type material; (b) p-type material.

4. Semiconductor Diode:

The PN junction diode is created by joining a block of N material with a block of P material. At the junction, holes diffuse from the P material into the N material and electrons diffuse from the N material into the P material. Every electron crossing the junction leaves behind an acceptor atom with a net negative charge as shown in Fig.1.7. Consequently, after the diffusion, there is a thin layer of positive ions on the N side of the junction and a thin layer of negative side ions on the P side. There are no mobile charge carriers in the region and it is called the depletion region. The P-N junction diode is a two-terminal device. This is the basic construction of the P-N junction diode. The diode is one of the simplest semiconductor devices as it allows current to flow in only one direction. The diode does not behave linearly with respect to the applied voltage, and it has an exponential V-I relationship.



There are two operating regions: P-type and N-type. And based on the applied voltage, there are three possible "biasing" conditions for the P-N Junction Diode, which are as follows:

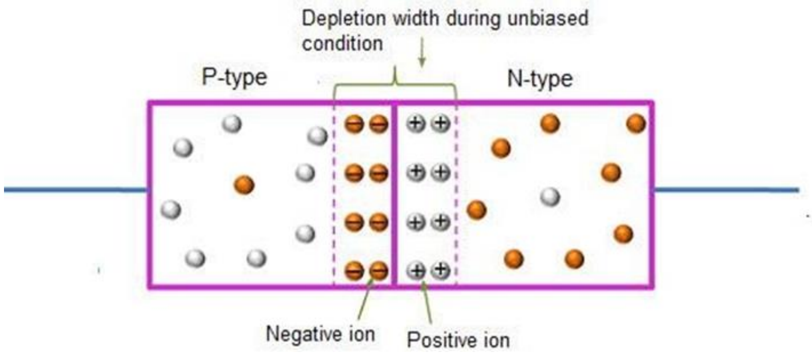
Zero Bias – No external voltage is applied to the PN junction diode.

Forward Bias– The voltage potential is connected positively to the P-type terminal and negatively to the N-type terminal of the Diode.

Reverse Bias– The voltage potential is connected negatively to the P-type terminal and positively to the N-type terminal of the Diode.

A. Zero Biased Condition

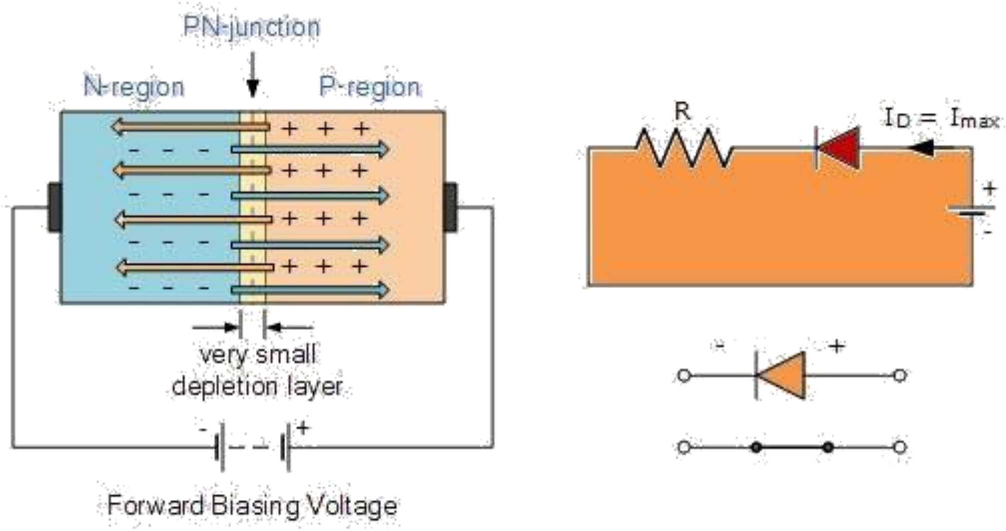
In this case, no external voltage is applied to the P-N junction diode; and therefore, the electrons diffuse to the P-side and simultaneously holes diffuse towards the N- side through the junction, and then combine with each other. Due to this an electric field is generated by these charge carriers. The electric field opposes further diffusion of charged carriers so that there is no movement in the middle region. This region is known as depletion width or space charge.



Unbiased Condition

B. Forward Bias

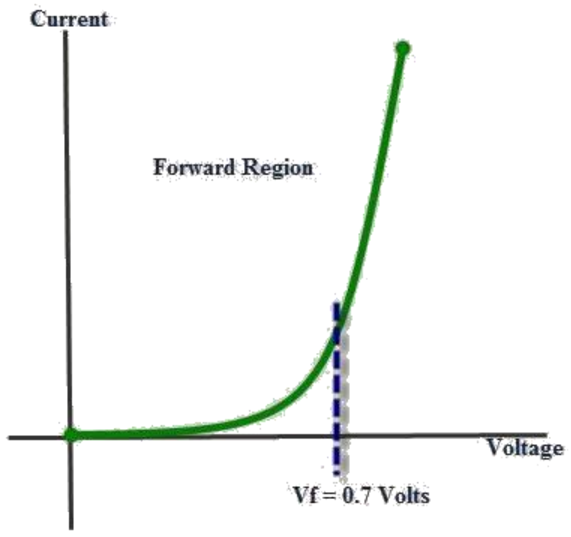
In the forward bias condition, the negative terminal of the battery is connected to the N-type material, and the positive terminal of the battery is connected to the P-type material. Electrons from the N-region cross the junction and enter the P-region. Due to the attractive force that is generated in the P-region the electrons are attracted and move towards the positive terminal. Simultaneously the holes are attracted to the negative terminal of the battery. By the movement of electrons and holes current flows. In this condition, the width of the depletion region decreases due to the reduction in the number of positive and negative ions.



Forward Bias Condition

V-I Characteristics

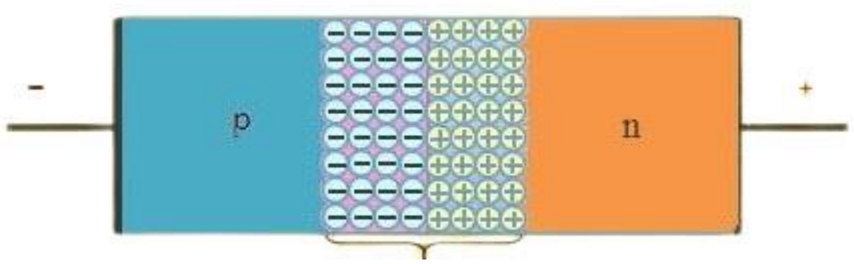
By supplying positive voltage, the electrons get enough energy to overcome the potential barrier (depletion layer) and cross the junction and the same thing happens with the holes as well. The amount of energy required by the electrons and holes for crossing the junction is equal to the barrier potential 0.3 V for Ge and 0.7 V for Si, 1.2V for GaAs. This is also known as Voltage drop. The voltage drop across the diode occurs due to internal resistance. This can be observed in the below graph.



Forward bias V-I Characteristic

<u>C.</u> <u>Reverse Bias</u>

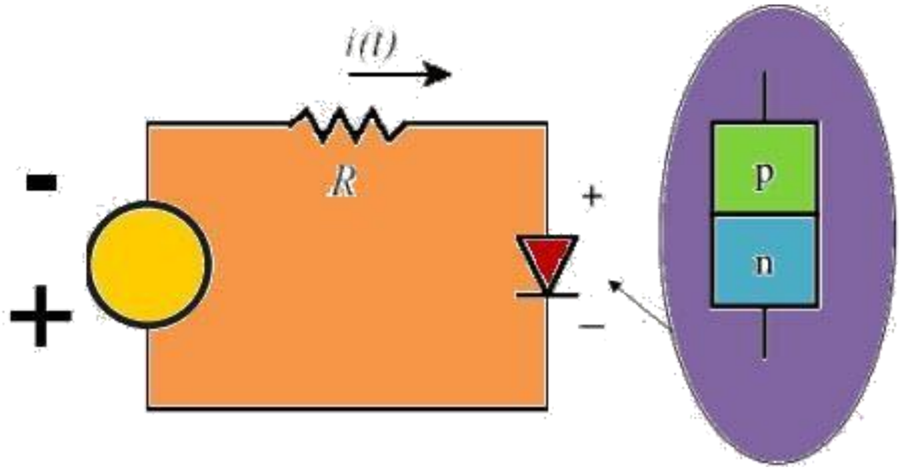
In the reverse bias condition, the positive terminal of the battery is connected to the N-type material and the negative terminal of the battery is connected to the P-type material. Hence, the **electric field due to both the voltage and depletion layer** is **in the same direction**. This makes the **electric field stronger than before**.



Depletion layer in Reverse Biased condition

The electrons from the N-type semiconductor are attracted towards the positive terminal and the holes from the P-type semiconductor are attracted to the negative terminal. This leads to the reduction of the number of electrons in N-type and holes in P-type. In addition, positive ions are created in the N-type region and negative ions are created in the P-type region. Therefore, the depletion layer width is increased due to the increasing number of positive and negative ions.

Due to this strong electric field, electrons and holes want more energy to cross the junction so they cannot diffuse to the opposite region. Hence, there is no current flow due to the lack of movement of electrons and holes.



Circuit diagram for Reverse bias

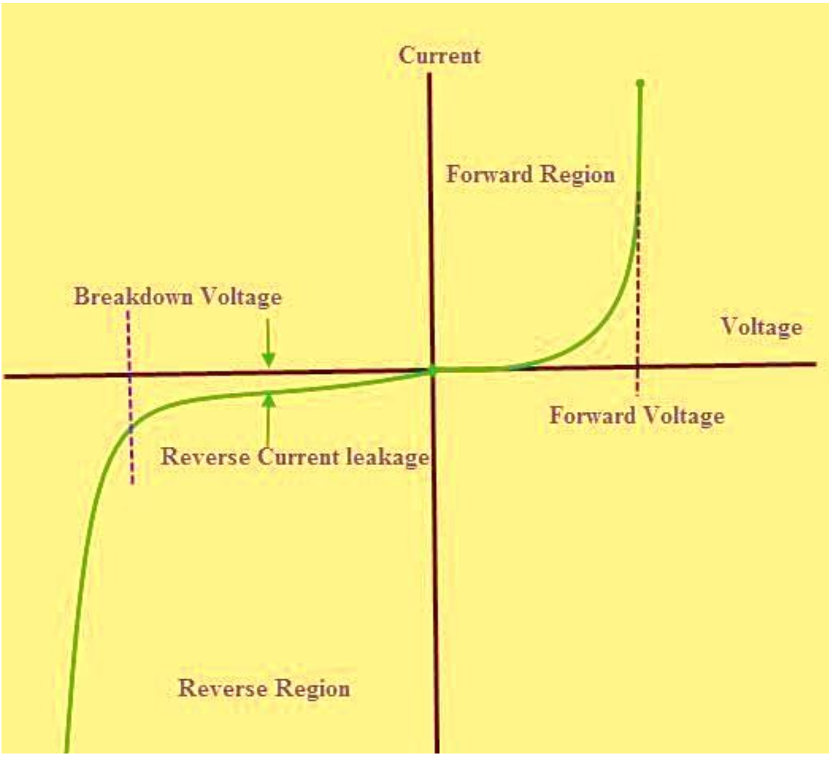
V-I Characteristics

Due to thermal energy in crystal minority carriers are produced. **Minority carriers mean a hole in N-type material and electrons in P-type material**. These minority carriers are the electrons and holes pushed toward the P-N junction by the negative terminal and positive terminal, respectively. Due to **the movement of minority carriers, a very little current flow, this is in the nano Ampere range** (for silicon). This current is called as **reverse saturation current**. Saturation means, after reaching its maximum value, a steady state is reached where in the current value remains the same with increasing voltage.

The magnitude of the reverse current is of the order of nano-amperes for silicon devices. When the reverse voltage is increased beyond the limit, then the reverse current increases drastically. This particular voltage that causes the drastic change in reverse current is called reverse breakdown voltage.

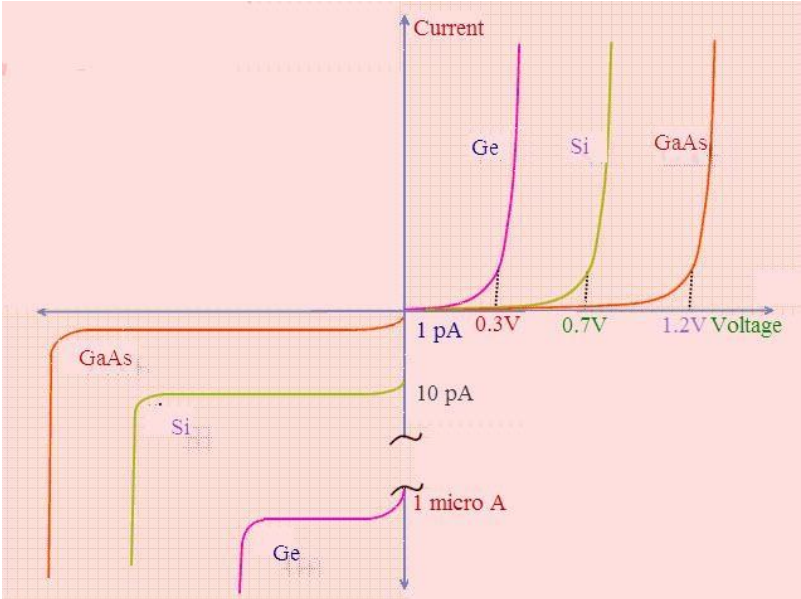
V-I Characteristics Graph for Reverse Bias

5. Characteristics of a semiconductor diode:



Characteristics of P-N junction Diode

The graph will be changed for different semiconductor materials used in the construction of a P-N junction diode. The below diagram depicts the changes.



Comparison with Silicon, Germanium, and Gallium Arsenide.

It can be demonstrated through the use of solid-state physics that the general characteristics of a semiconductor diode can be defined by the following equation, referred to as Shockley's equation, for the forward- and reverse-bias regions:

$$\boldsymbol{I_D = I_S(e^{\frac{V_D}{nV_T}} - 1),}$$

where $\boldsymbol{I_S}$ is the reverse saturation current,

$\boldsymbol{V_D}$ is the applied forward-bias voltage across the diode,

$\boldsymbol{n}$ is an ideality factor, which is a function of the operating conditions and physical construction; it has a range between 1 and 2 depending on a wide variety of factors (n =1 will be assumed throughout this text unless otherwise noted),

the voltage $\boldsymbol{V_T}$ is called the *thermal voltage* and is determined by

$$\boldsymbol{V_T = \frac{kT_K}{q}}$$

where **k** is Boltzmann's constant = $1.38 \times 10^{-23}\ J/K$,

$\boldsymbol{T_K}$ is the absolute temperature in kelvins = 273 + the temperature in °C,

q is the magnitude of electronic charge = 1.6×10^{-19}

Example:

a. Determine the thermal voltage for a diode at a temperature of 20°C.
b. For the same diode of part (a), find the diode current if $I_S = 40nA$, n=2 (low value of V_D), and the applied bias voltage is 0.5V.

Solution:

$$\text{a. } V_T = \frac{kT_K}{q} = \frac{(1.38\times10^{-23})(273+20)}{1.6\times10^{-19}} = 25.27\ mV$$

$$\text{b. } I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right) = 40nA(e^{\frac{0.5V}{2\times25.27mV}} - 1)$$

$$= 40nA(e^{9.89} - 1) = 0.789\ mA$$

Example: A silicon diode has saturation current 1 PA. Assuming the temperature is 25 C^o. Find the current in the diode when.

1- It is reverse biased by 0.1V (*n*=2)
2- The anode is shorted to the cathode (*n*=2)
3- It is forward biased by 0.5V (*n*=1)

Solution:

T=273 + 25 =298 K

$$V_T = \frac{KT}{q} = \frac{(1.38\times10^{-23})1(298)}{1.6\times10^{-19}} = 0.0257V$$

1- Since the diode reverse biased

V= -0.1V

$$I = I_S\left(e^{V/\eta V_T} - 1\right) = 1\ PA(\ e^{-0.1/2(0.0257)}\ \ -1)$$

= - 0.857 PA (negative result means the current reverse current).

2- since the anode is shorted to the cathode, V=0

I= (1 PA) ($e^{0/2(0.0257)}$ -1) = (1PA) (1-1) = 0 A

3- **H.W**