Chapter 1

Introduction to Electronics

1.1 Basic Semiconductor Theory

A semiconductor is a solid material whose electrical conductivity falls in between conductors and insulators. A semiconductor material is one whose electrical properties lie in between those of insulators and good conductors. Examples are: germanium and silicon.
A material that is neither a good conductor of electricity nor a good insulator, but has properties of electrical conductivity somewhere between the two.

Midway between conductors and insulators is a third classification of atoms known as semiconductors. Silicon and germanium are the most common semiconductor elements. Also semiconductor compounds such as copper oxide, cadmium-sulfide, and gallium arsenide are frequently used. Semiconductor materials are generally classified as type IVB elements. This type of atom has four valence electrons.

Semiconductors possess specific electrical properties. A substance that conducts electricity is called a conductor, and a substance that does not conduct electricity is called an insulator. Conductors such as gold, silver and copper have low resistance and conduct electricity easily. The semiconductor materials are either elementary such as silicon and germanium or compound such as gallium arsenide. Silicon is the most used semiconductor for discrete devices and integrated circuits.

1.1.1 Semiconductor materials and their types

The prefix semi-is normally applied to a range of levels midway between two limits.

- ◇ 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, therefore, is a material that has a conductivity level somewhere between the extremes of an insulator and a conductor.

Inversely related to the conductivity of a material is its resistance to the flow of charge, or current. That is, the higher the conductivity level, the lower the resistance level.

Resistivity (ρ, Greek letter rho) is often used when comparing the resistance levels of materials. In metric units, the resistivity of a material is measured in $\Omega.cm$ or $\Omega.m$. The units of $\Omega.cm$ are derived from the substitution of the units to the equation (derived from the basic resistance equation $R = \rho\frac{l}{A}$:

$$\rho = \frac{RA}{l} = \frac{(\Omega)(cm^2)}{cm} \Rightarrow \Omega.cm \tag{1.1}$$

Table 1.1: Typical resistivity values

Conductor	**Semiconductor**	**Insulator**
$\rho \cong 10^{-6}\Omega.cm$ (copper)	$\rho \cong 50\Omega.cm$ (germanium) $\rho \cong 50 \times 10^3\Omega.cm$ (sillicon)	$\rho \cong 10^{12}\Omega.cm$ (mica)

Germanium and Silicon

Both Germanium and Silicon are referred to as tetravalent atoms because they each have four valence electrons. As you might expect, the best semiconductors have four valence electrons. The atomic structures of silicon and germanium are compared in Figure 1.1. Silicon is used in diodes, transistors, integrated circuits, and other semiconductor devices. Notice that both silicon and germanium have the characteristic four valence electrons.

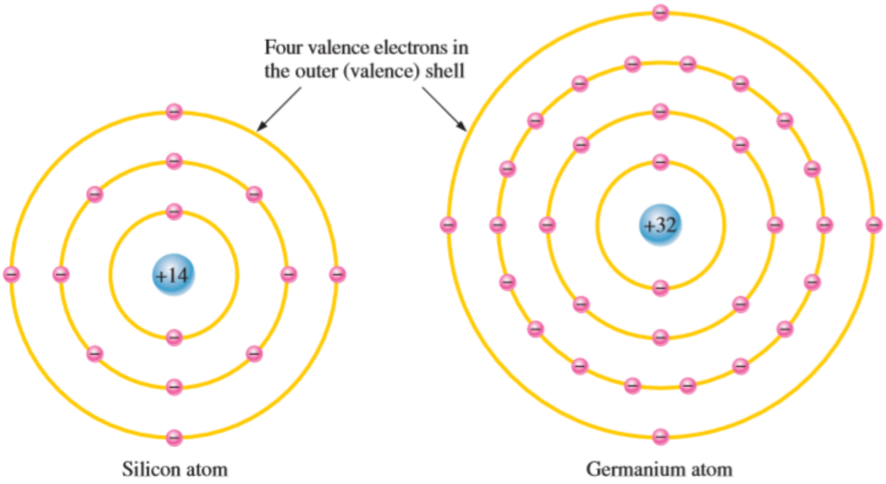


Figure 1.1: Diagrams of the silicon and germanium atoms

The valence electrons in germanium are in the fourth shell while those in silicon are in the third shell, closer to the nucleus. This means that the germanium valence electrons are at higher energy levels than those in silicon and, therefore, require a smaller amount of additional energy to escape from the atom. This property makes germanium more unstable at high temperatures and results in excessive reverse current. This is why silicon is a more widely used semiconductive material.

An isolated silicon atom has 14 protons and 14 electrons. As shown in Fig.1.2, the first orbit contains two electrons and the second orbit contains eight electrons. The four remaining electrons are in the valence orbit. In Fig.1.2a, the core has a net charge of 14 because it contains 14 protons in the nucleus and 10 electrons in the first two orbits. Figure1.2b shows the core diagram of a silicon atom. The four valence electrons tell us that silicon is a semiconductor.

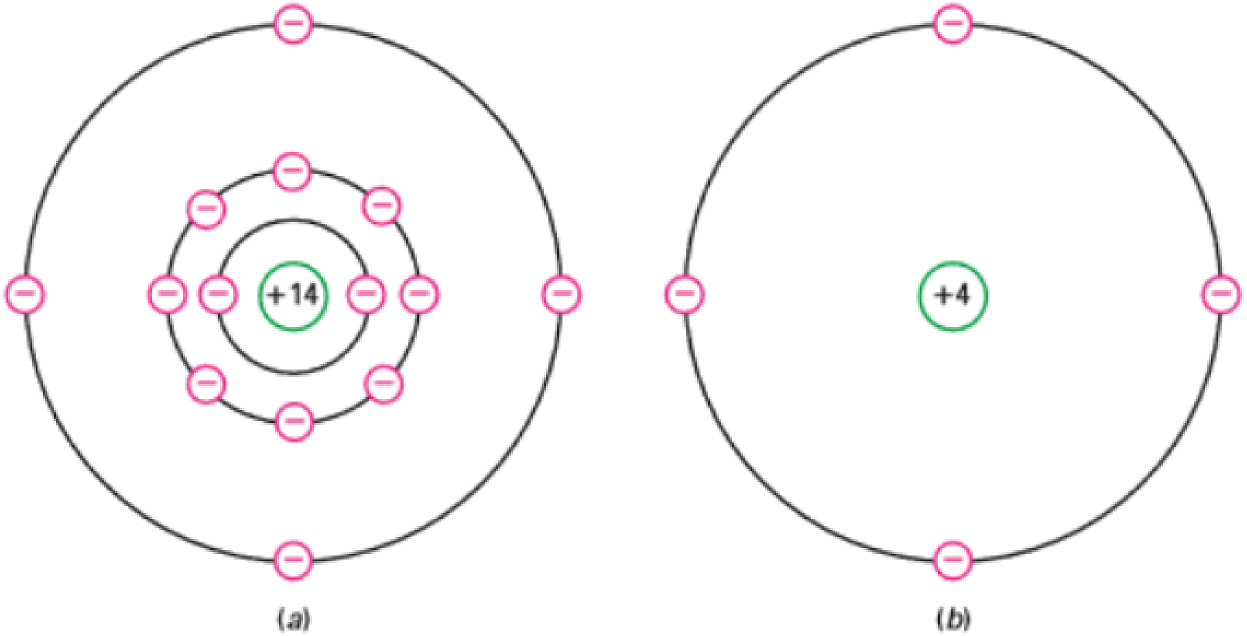


Figure 1.2: (a) Silicon atom; (b) core diagram.

Semiconductor materials are the backbone of solid state electronics. Devices that are constructed by the semiconductor materials like transistors are credited with small size, long life, low operating voltage and low cost. These pure semiconductor materials generally possess the following properties.

- They are tetravalent (have 4 valance electrons)
- They have negative temperature coefficient (their resistivity decreases as the temperature rises).
- At room temperature, their conductivity lies between conductor and insulator.
- Their conductivity can be improved by adding a suitable impurities; it also increases with the incidence of light.
- The current in the semiconductor is due to the movement of holes and electrons.

Generally semiconductor materials are classified as: Intrinsic semiconductors and extrinsic semiconductors.

Question 1: What is Intrinsic and Extrinsic semiconductor mean?

1.1.2 Atomic theory

Atoms are the basic units of matter and the defining structure of elements. The term "atom" comes from the Greek word for indivisible, because it was once thought that atoms were the smallest things in the universe and could not be divided. An atom is the simplest unit of matter and it is made from particles called protons (which carry a positive electrical charge), neutrons (which carry no electrical charge) and electrons (which carry a negative electrical charge). The Protons and neutrons are heavier than electrons and reside in the nucleus at the center of the atom. Electrons are extremely lightweight and exist in a cloud orbiting the nucleus. The electron cloud has a radius 10,000 times greater than the nucleus. Protons and neutrons have approximately the same mass. However, one proton weighs more than 1,800 electrons. Electrically neutral Atoms always have an equal number of protons and electrons, and the number of protons and neutrons is usually the same as well. Adding a proton to an atom makes a new element, while adding a neutron makes an isotope, or heavier version, of that atom.

1.1.3 Energy level

Electrons orbit the nucleus of an atom at certain distances from the nucleus. Electrons near the nucleus have less energy than those in more distant orbits. Only discrete (separate and distinct) values of electron energies exist within atomic structures. Therefore, electrons must orbit only at discrete distances from the nucleus. Each discrete distance (orbit) from the nucleus corresponds to a certain energy level.

In an atom, the orbits are grouped into energy levels known as shells. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons. The shells (energy levels) are designated 1, 2, 3, and so on, with 1 being closest to the nucleus. The Bohr model of the silicon atom is shown in Figure 1.3. Notice that there are 14 electrons and 14 each of protons and neutrons in the nucleus.

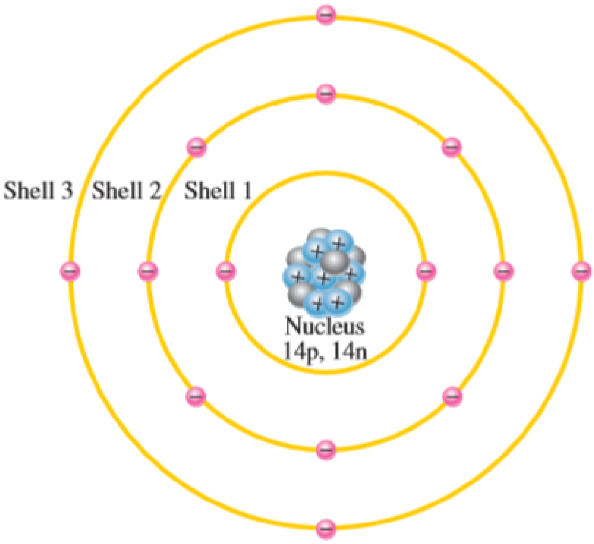


Figure 1.3: Illustration of the Bohr model of the silicon atom.

When there are more than two electrons in an atom the electrons are arranged into shells at various distances from the nucleus. The maximum number of electrons present in the first shell is two, in the second shell eight, and in the third, fourth and n^{th} shells are 18, 32 and $2n^2$ respectively.

The Maximum Number of Electrons in Each Shell The maximum number of electrons (Ne) that can exist in each shell of an atom is a fact of nature and can be calculated by the formula,

$$N_e = 2n^2$$

where n is the number of the shell. The maximum number of electrons that can exist in the innermost shell (shell 1) is

$$N_e = 2n^2 = 2(1)^2 = 2$$

The maximum number of electrons that can exist in shell 2 is

$$N_e = 2n^2 = 2(2)^2 = 8$$

The maximum number of electrons that can exist in shell 3 is

$$N_e = 2n^2 = 2(3)^2 = 18$$

The maximum number of electrons that can exist in shell 4 is

$$N_e = 2n^2 = 2(4)^2 = 32$$

Valence Electrons

Electrons that are in orbits farther from the nucleus have higher energy and are less tightly bound to the atom than those closer to the nucleus. This is because the force of attraction between the positively charged nucleus and the negatively charged electron decreases with increasing distance from the nucleus. Electrons with the highest energy exist in the outermost shell of an atom and are relatively loosely bound to the atom. This outermost shell is known as the valence shell and electrons in this shell are called valence electrons. These valence electrons contribute to chemical reactions and bonding within the structure of a material and determine its electrical properties. When a valence electron gains sufficient energy from an external source, it can break free from its atom. This is the basis for conduction in materials.

Insulators, Conductors, and Semiconductors

All materials are made up of atoms. These atoms contribute to the electrical properties of a material, including its ability to conduct electrical current. For purposes of discussing electrical properties, an atom can be represented by the valence shell and a core that consists of all the inner shells and the nucleus. This concept is illustrated in Figure 1.4 for a carbon atom. Carbon is used in some types of electrical resistors. Notice that the carbon atom has four electrons in the valence shell and two electrons in the inner shell. The nucleus consists of six protons and six neutrons, so the $+6$ indicates the positive charge of the six protons. The core has a net charge of $+4$ ($+6$ for the nucleus and -2 for the two inner-shell electrons).

Insulators: An insulatoris a material that does not conduct electrical current under normal conditions. Most good insulators are compounds rather than single-element materials and have very high resistivities. Valence electrons are tightly bound to the atoms; therefore, there are very few free electrons in an insulator. Examples of insulators are rubber, plastics, glass, mica, and quartz.

Conductors: A conductor is a material that easily conducts electrical current. Most metals are good conductors. The best conductors are single-element materials, such as copper (Cu), silver (Ag), gold (Au), and aluminum (Al), which are characterized by atoms with only one valence electron very loosely bound to the atom. These loosely bound valence electrons become free electrons. Therefore, in a conductive material the free electrons are valence electrons.

Semiconductors: A semiconductoris a material that is between conductors and insulators in its ability to conduct electrical current. A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator. Single-element semiconductors are antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), silicon (Si), and germanium (Ge). Compound semiconductors such as gallium arsenide, indium phosphide, gallium nitride, silicon carbide, and silicon germanium are also commonly used. The single-element semiconductors are characterized by atoms with four valence electrons. Silicon is the most commonly used semiconductor.

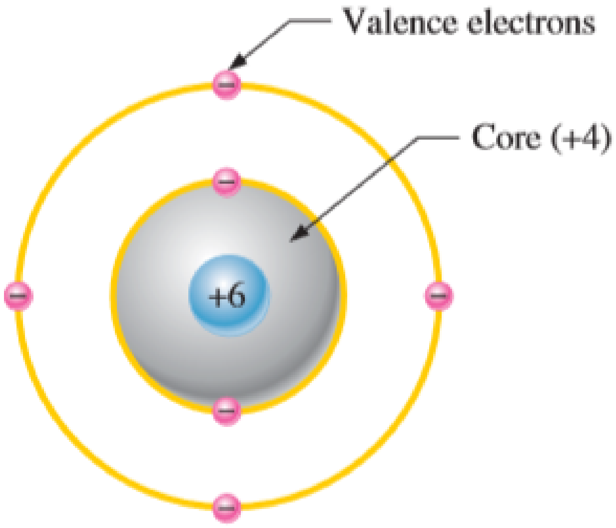


Figure 1.4: Diagram of a carbon atom

1.1.4 Band Gap

Recall that the valence shell of an atom represents a band of energy levels and that the valence electrons are confined to that band. When an electron acquires enough additional energy, it can leave the valence shell, become a free electron, and exist in what is known as the conduction band.

The difference in energy between the valence band and the conduction band is called an energy gap or band gap. This is the amount of energy that a valence electron must have in order to jump from the valence band to the conduction band. Once in the conduction band, the electron is free to move throughout the material and is not tied to any given atom. Figure 1.5 shows energy diagrams for insulators, semiconductors, and conductors. The energy gap or band gap is the difference between two energy levels. It is a region in insulators and semiconductors where no electron states exist. Although an electron may not exist in this region, it can "jump" across it under certain conditions. For insulators, the gap can be crossed only when breakdown conditions occurs when a very high voltage is applied across the material. The band gap is illustrated in Figure 1.5(a) for insulators.

In semiconductors the band gap is smaller, allowing an electron in the valence band to jump into the conduction band if it absorbs a photon. The band gap depends on the semiconductor material. This is illustrated in Figure 1.5(b).

In conductors, the conduction band and valence band overlap, so there is no gap, as shown in Figure 1.5(c). This means that electrons in the valence band move freely into the conduction band, so there are always electrons available as free electrons.

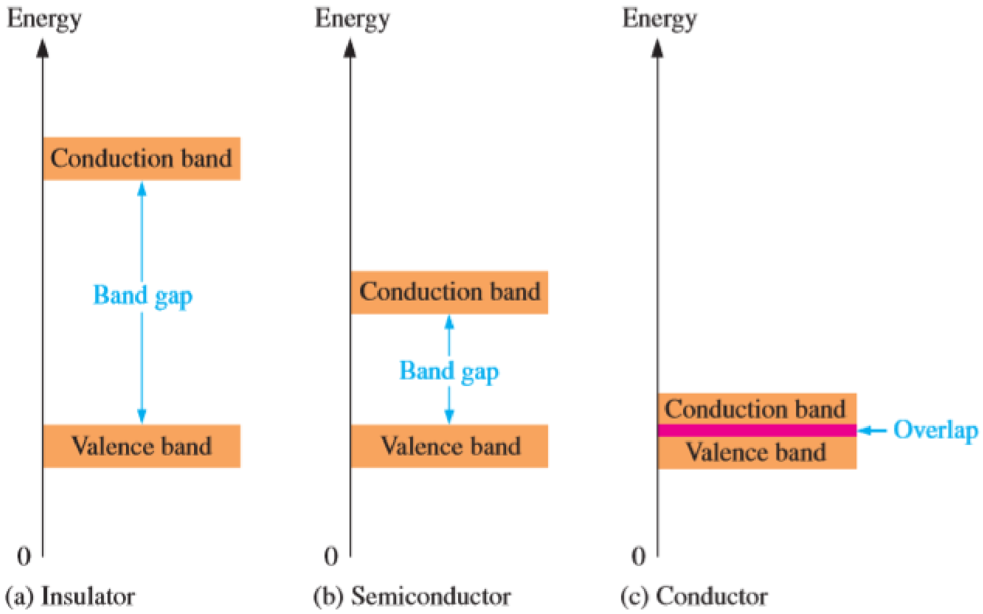


Figure 1.5: Energy diagrams for the three types of materials

1.2 P-N junction diode

A p-n junction is an interface or a boundary between two semiconductor material types, namely the p-type and the n-type, inside a semiconductor. The p-side or positive side of the semiconductor has an excess of holes and n-side or negative side has an excess of electrons. In a semiconductor the p-n junction is created by the methode of doping.

Doping is the process of adding impurities to intrinsic semiconductors to alter their properties. Normally Trivalent (atoms with three valence electrons such as boron (B), indium (In), and gallium (Ga)) and Pentavalent (atoms with five valence electrons such as arsenic (As), phosphorus (P), bismuth (Bi), and antimony (Sb)) elements are used to dope Silicon and Germanium. When an intrinsic semiconductor is doped with Trivalent impurity it becomes a P-Type semiconductor. Which means the semiconductor is rich in holes or Positive charged ions. When we dope intrinsic material with Pentavalent impurities we get N-Type semiconductor. N-type semiconductors have Negative charged ions or in other words have excess electrons in it.

Atoms follow a rule called Octet Rule. According to Octet-rule atoms are stable when there are eight electrons in their valence shell. If not, atoms readily accept or share neighboring atoms to achieve eight electrons in their valence shell.

Biasing conditions for the p-n Junction Diode

There are two operating regions in p-n junction diode:

- ◇ P-type
- ◇ N-type

There are three biasing conditions for p-n junction diode and this is based on the voltage applied:

- **Zero bias**: There is no external voltage applied to the p-n junction diode.

- **Forward bias**: The positive terminal of the voltage potential is connected to the p-type while the negative terminal is connected to the n-type.
- **Reverse bias**: The negative terminal of the voltage potential is connected to the p-type and the positive is connected to the n-type.

Forward Bias

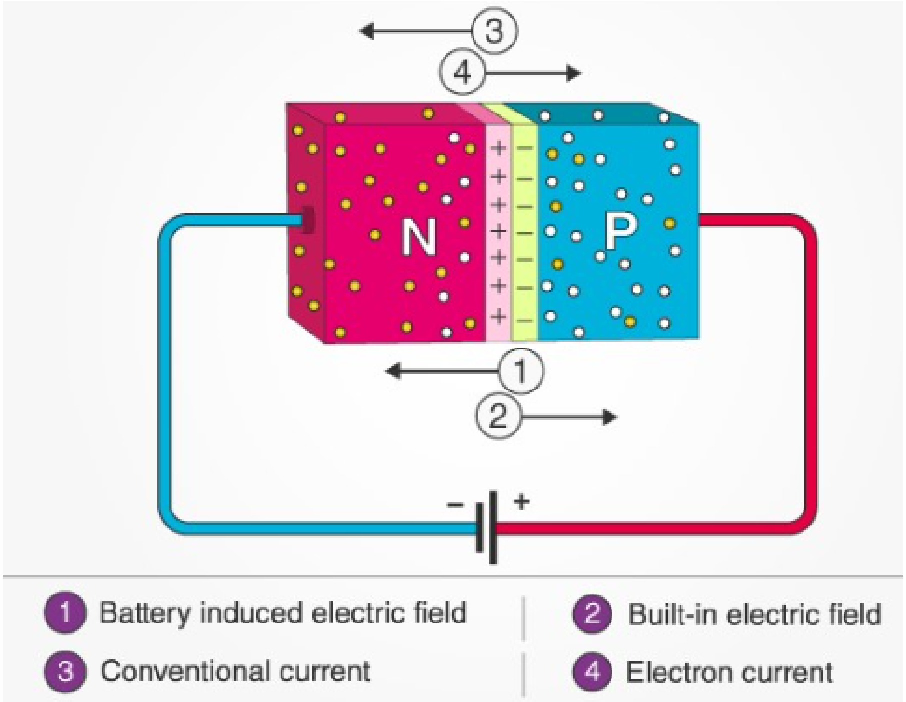


Figure 1.6: Forward Bias of p-n junction diode

When the p-type is connected to the positive terminal of the battery and the n-type to the negative terminal then the p-n junction is said to be forward biased. When the p-n junction is forward biased, the built-in electric field at the p-n junction and the applied electric field are in opposite directions. When both the electric fields add up the resultant electric field has a magnitude lesser than the built-in electric field. This results in a less resistive and thinner depletion region. The depletion region's resistance becomes negligible when the applied voltage is large.

Reverse Bias

When the p-type is connected to the negative terminal of the battery and the n-type is connected to the positive side then the p-n junction is said to be reverse biased. In this case, the built-in electric field and the applied electric field are in the same direction. When the two fields are added, the resultant electric field is in the same direction as the built-in electric field creating a more resistive, thicker depletion region. The depletion region becomes more resistive and thicker if the applied voltage becomes larger.

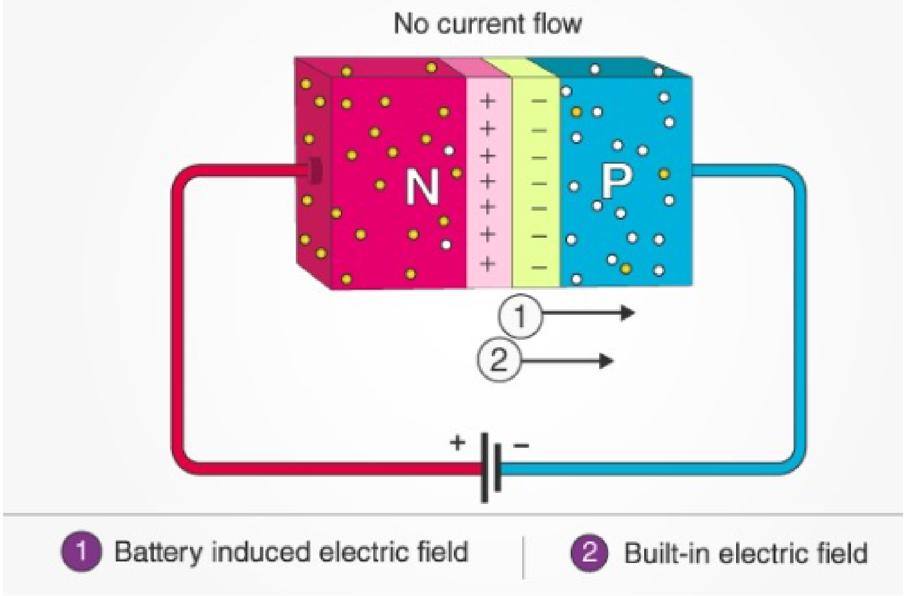


Figure 1.7: Reverse Bias of p-n junction diode

V-I Characteristics of P-N Junction Diode

If an abrupt change in impurity type from acceptors (p-type) to donors (n-type) occurs within a single crystal structure, a p-n junction is formed. On the p side, the holes constitute the dominant carriers and so are called majority carriers. A few thermally generated electrons will also exist in the p side; these are termed minority carriers. On the n side the electrons are the majority carriers, while the holes are the minority carriers. Near the junction is a region having no free-charge carriers. This region, called the depletion layer, behaves as an insulator.

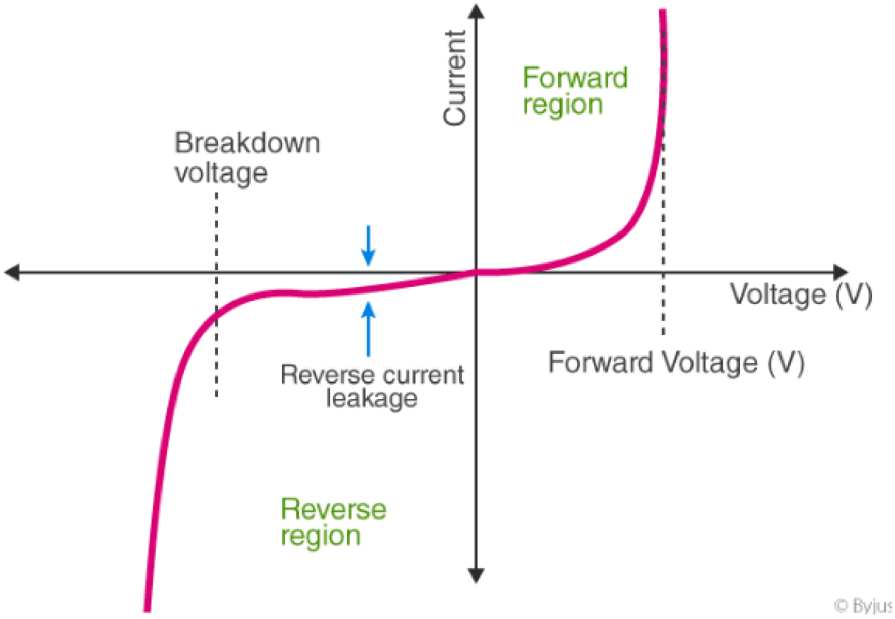


Figure 1.8: V-I Characteristics of P-N Junction Diode

The most important characteristic of p-n junctions is that they rectify; that is to say, they allow current to flow easily in only one direction. Figure 1.9A shows the current-voltage characteristics of a typical silicon p-n junction. When a forward bias is applied to the p-n junction as shown in Figure 1.9B, the majority charge carriers move across the junction so that a large current can flow. However, when a reverse bias is applied as shown in Figure 1.9C, the charge carriers introduced by the impurities move in opposite directions away from

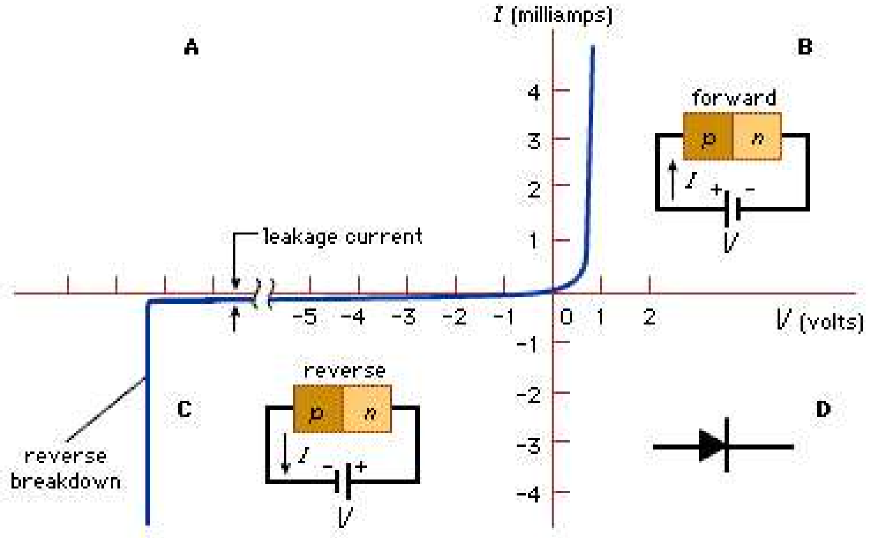


Figure 1.9: (A) voltage-current characteristics of a typical silicon p-n junction. (B) Forward-bias and (C) reverse-bias conditions. (D) The symbol for a p-n junction

the junction, and only a small leakage current flows initially. As the reverse bias is increased, the current remains very small until a critical voltage is reached, at which point the current suddenly increases. This sudden increase in current is referred to as the junction breakdown.

Applications of P-N Junction Diode

- p-n junction diode can be used as a photodiode as the diode is sensitive to the light when the configuration of the diode is reverse-biased.
- It can be used as a solar cell.
- When the diode is forward-biased, it can be used in LED lighting applications.
- It is used as rectifiers in many electric circuits and as voltage-controlled oscillator in varactors.

Question 2: What is deplation layer mean and how it forms?

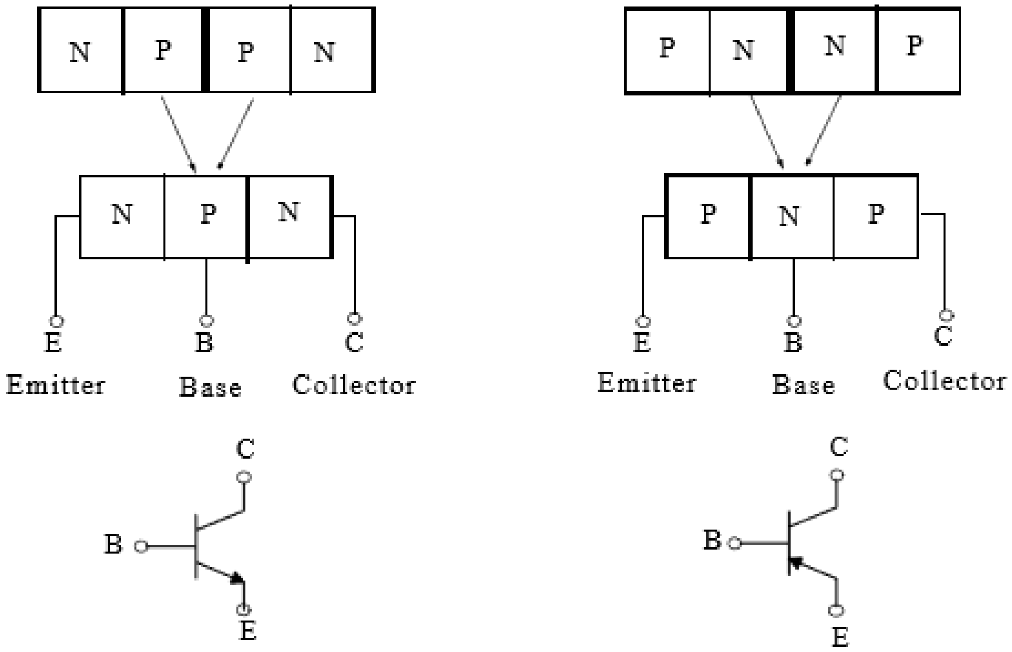
1.3 Transistor configuration

The transistor is a three-layer semiconductor device consisting of either two n- and one p-type layers of material or two p- and one n-type layers of material. The former is called an npn transistor, while the latter is called a pnp transistor.

A transistor has three terminals, the emitter, the base and the collector. Using these three terminals the transistor can be connected in a circuit with one terminal common to both input and output in a three diffrent possible configurations.

Transistors are three terminal devices that can be formed with the combination of two separate P-N junction materials into one block as shown in Figure 1.10.

As shown in Figure 1.10, an NPN transistor is formed with two P-N junctions with the P-type material at the center, whereas a PNP transistor is formed with two P-N junctions with the N-type material at the center. The three terminals of a transistor, whether it is an NPN or PNP transistor, are identified as the emitter, the base, and the collector. Geberally there are three different configurations of transistors and they are common base (CB) configuration, common collector (CC) configuration and common emitter (CE) configuration.



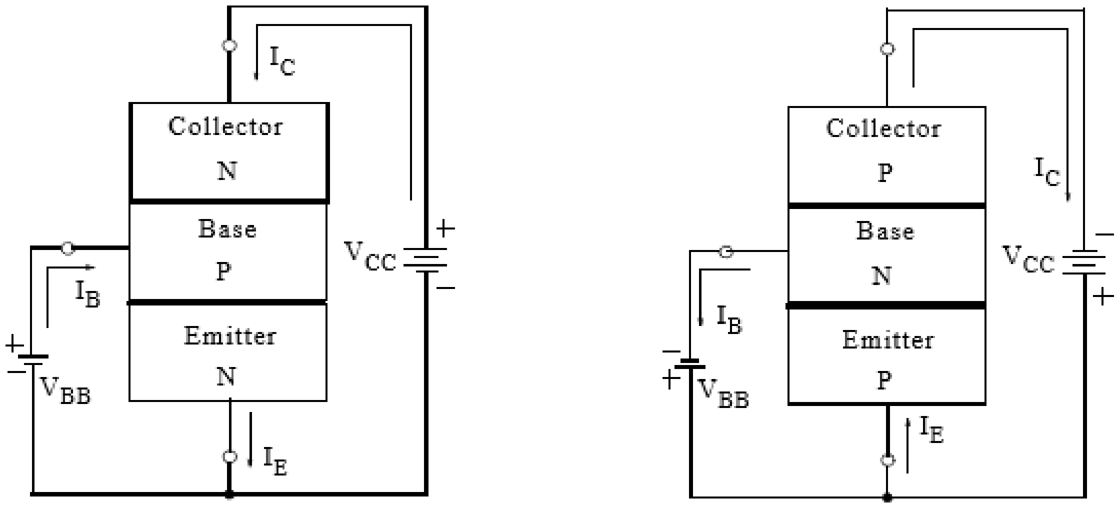
NPN Transistor formation and symbol

PNP Transistor formation and symbol

Figure 1.10: NPN and PNP transistor construction and symbols

NPN and PNP Transistor Operation

For proper operation, the NPN and PNP transistors must be biased as shown in Figure 1.11.



NPN Transistor

PNP Transistor

Figure 1.11: Biased NPN and PNP Transistors for proper operation

The bias voltage sources are for the base voltage and for the collector voltage. Typical values for are about or less, and for about to . The difference in these bias voltages is necessary to cause current flow from the collector to the emitter in an NPN transistor and from the emitter to collector in a PNP transistor.
Since a transistor is a 3-terminal device, there are three currents, the base current, denoted as ,* the collector current, denoted as , and the emitter current, denoted as . They are shown in Figures 1.11 and 1.12.

For any transistor, NPN or PNP, the three currents are related as

$$i_B + i_C = i_E$$

NPN Transistor

PNP Transistor

Figure 1.12: The base, collector, and emitter currents in a transistor

A very useful parameter in transistors is the common-emitter gain β, a constant whose value typically ranges from 75 to 300. Its value is specified by the manufacturer. The base current i_B is much smaller than the collector current i_C and these two currents are related in terms of the constant β as

$$i_B = \frac{i_C}{\beta}$$

$$i_E = i_B + i_C = \frac{i_C}{\beta} + i_C = \frac{\beta + 1}{\beta} i_C$$

Another important parameter in transistors is the common-base current gain denoted as α and it is related to β as

$$\alpha = \frac{\beta}{\beta + 1}$$

From this equation we observe that α is always less than 1.
we can express β in terms of α by rearranging. Then,

$$\beta = \frac{\alpha}{1 - \alpha}$$

Another lesser known ratio is the common-collector current gain ratio denoted as γ and it is defined as the ratio of the change in the emitter current to the change in the base current. Thus,

$$\gamma = \frac{di_E}{di_B}$$

Therefor, the relationships of these three parametres are

$\alpha = \frac{\beta}{\beta+1}$ $\beta = \frac{\alpha}{1-\alpha}$ $\gamma = \beta + 1$

A. Common base configuration

In common base configuration, emitter is the input terminal, collector is the output terminal and base terminal is connected as a common terminal for both input and output. That means the emitter terminal and common base terminal are known as input terminals whereas the collector terminal and common base terminal are known as output terminals.

In common base configuration, the base terminal is grounded so the common base configuration is also known as grounded base configuration. Sometimes common base configuration is referred to as common base amplifier, CB amplifier, or CB configuration.

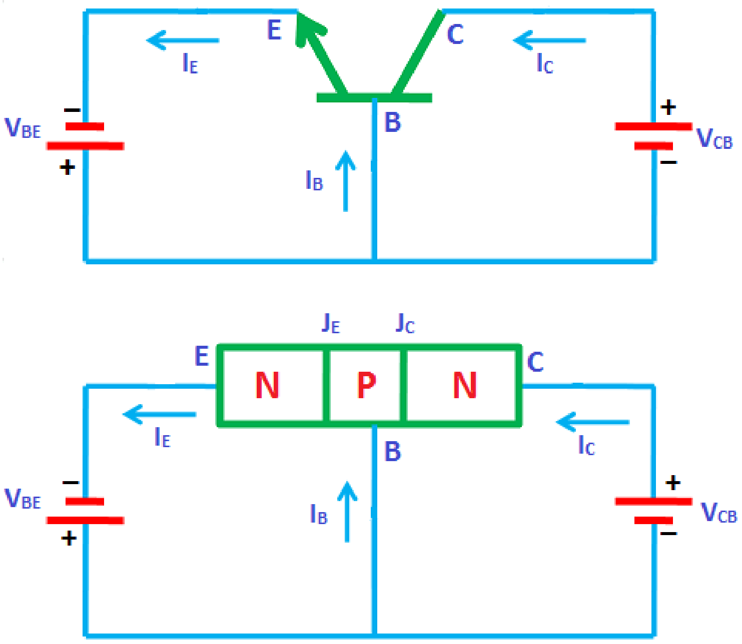
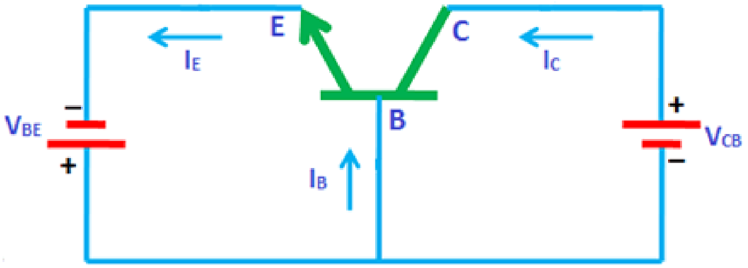


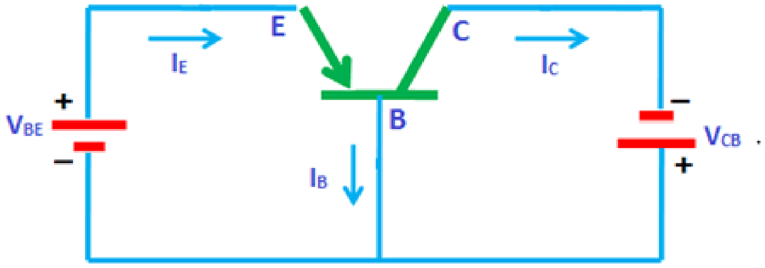
Figure 1.13: The common base configuration

The input signal is applied between the emitter and base terminals while the corresponding output signal is taken across the collector and base terminals. Thus the base terminal of a transistor is common for both input and output terminals and hence it is named as common base configuration.

The supply voltage between base and emitter is denoted by V_{BE} while the supply voltage between collector and base is denoted by V_{CB}.
In every configuration, the base-emitter junction J$_E$ is always forward biased and collector-base junction J_C is always reverse biased. Therefore, in common base configuration, the base-emitter junction J$_E$ is forward biased and collector-base junction J$_C$ is reverse biased. The common base configuration for both NPN and PNP transistors is shown in the below figure.



NPN Transistor



PNP transistor

Figure 1.14: Circuit diagrams of npn and pnp transistors

From the above circuit diagrams of npn and pnp transistors, it can be seen that for both npn and pnp transistors, the input is applied to the emitter and the output is taken from the collector. The common terminal for both the circuits is the base.

Input characteristics

The input characteristics describe the relationship between input current (I_E) and the input voltage (V_{BE}). To determine the input characteristics, the output voltage V_{CB} (collector-base voltage) is kept constant at zero volts and the input voltage V_{BE} is increased from zero volts to different voltage levels. For each voltage level of the input voltage (V_{BE}), the input current (I_E) is recorded.

A curve is then drawn between input current I_E and input voltage V_{BE} at constant output voltage VCB (0 volts). Next, the output voltage (V_{CB}) is increased from zero volts to a certain voltage level (8 volts) and kept constant at 8 volts. While increasing the output voltage (V_{CB}), the input voltage (V_{BE}) is kept constant at zero volts. After we kept the output voltage (V_{CB}) constant at 8 volts, the input voltage V_{BE} is increased from zero volts to different voltage levels. For each voltage level of the input voltage (V_{BE}), the input current (I_E) is recorded.

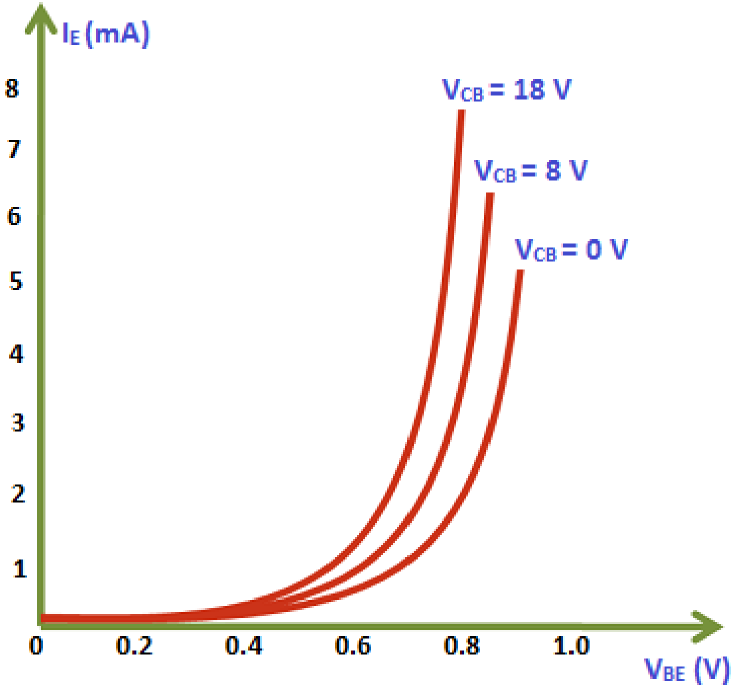


Figure 1.15: Input characteristics of CB configuration

Output characteristics

The output characteristics describe the relationship between output current (I_C) and the output voltage (V_{CB}). To determine the output characteristics, the input current or emitter current I_E is kept constant at zero mA and the output voltage V_{CB} is increased from zero volts to different voltage levels. For each voltage level of the output voltage V_{CB}, the output current (I_C) is recorded.

A curve is then drawn between output current I_C and output voltage V_{CB} at constant input current I_E (0 mA). When the emitter current or input current I_E is equal to 0 mA, the transistor operates in the cut-off region. Next, the input current (I_E) is increased from 0 mA to 1 mA by adjusting the input voltage V_{BE} and the input current I_E is kept constant at 1 mA. While increasing the input current I_E, the output voltage V_{CB} is kept constant.

After we kept the input current (I_E) constant at 1 mA, the output voltage (V_{CB}) is increased from zero volts to different voltage levels. For each voltage level of the output voltage (V_{CB}), the output current (I_C) is recorded. A curve is then drawn between output current I_C and output voltage V_{CB} at constant input current I_E (1 mA). This region is known as the active region of a transistor. This is repeated for higher fixed values of input current I_E (I.e. 2 mA, 3 mA, 4 mA and so on).
From the above characteristics, we can see that for a constant input current I_E, when the output voltage V_{CB} is increased, the output current I_C remains constant.

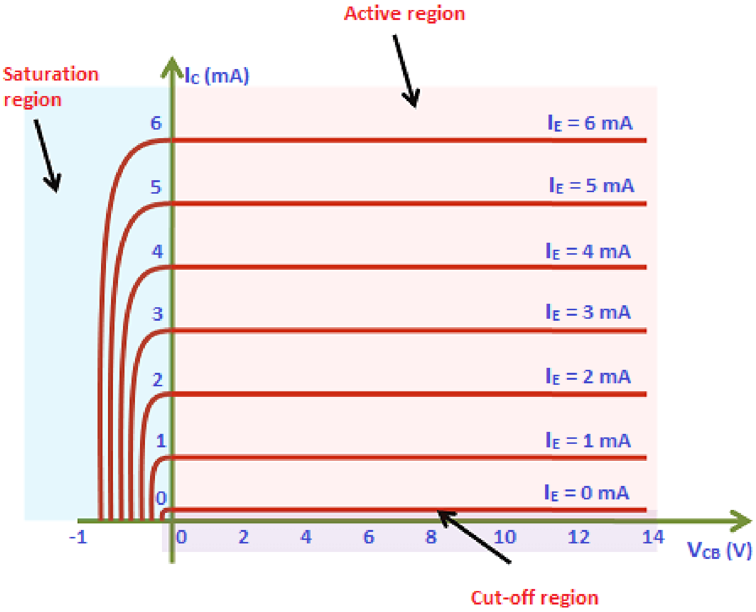


Figure 1.16: Oput characteristics of CB configuration

B. Common collector configuration (CC)

The configuration in which the collector is common between emitter and base is known as CC configuration. In CC configuration, the input circuit is connected between emitter and base and the output is taken from the collector and emitter. The collector is common to both the input and output circuit and hence the name common collector connection or common collector configuration.

In this configuration we use collector terminal as common for both input and output signals. This configuration is also known as emitter follower configuration because the emitter voltage follows the base voltage. This configuration is mostly used as a buffer. These configurations are widely used in impedance matching applications because of their high input impedance.

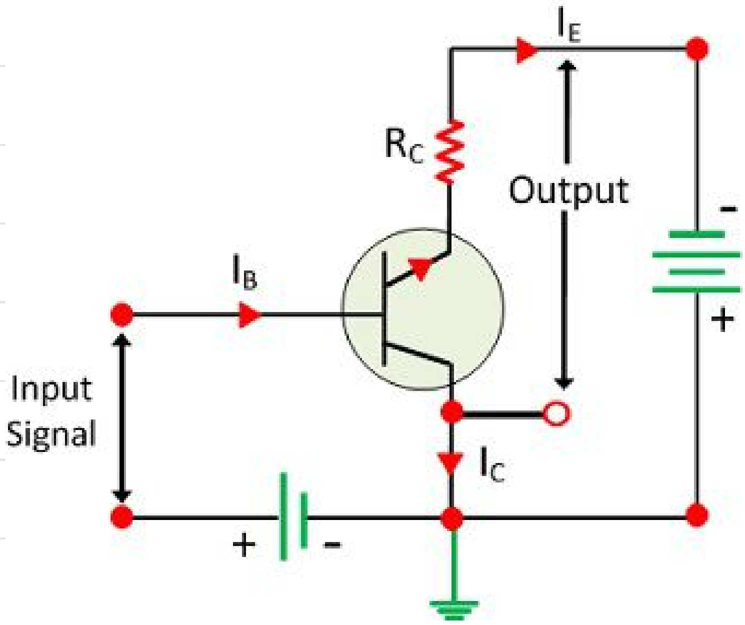


Figure 1.17: npn transistor CC configuration

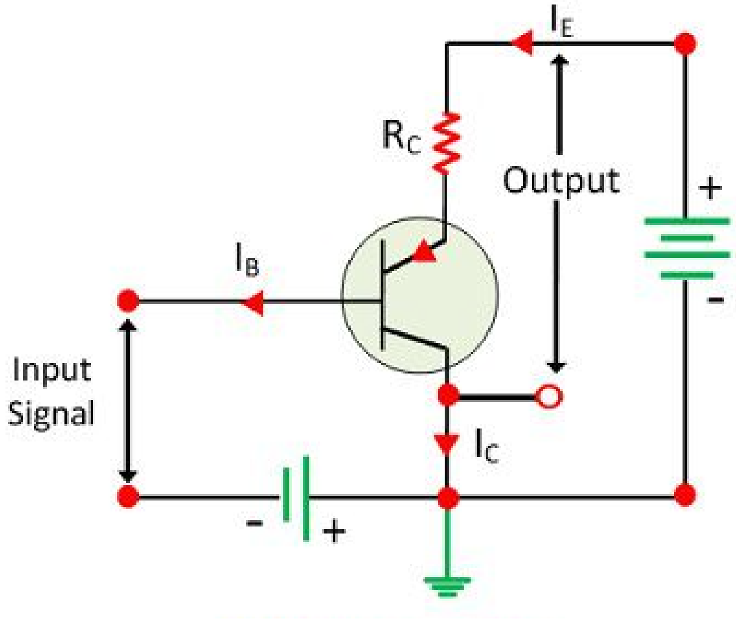


Figure 1.18: pnp transistor CC configuration

In this configuration the input signal is applied between the base-collector region and the output is taken from the emitter-collector region. Here the input parameters are V_{BC} and I_B and the output parameters are V_{EB} and I_B. The common collector configuration has high input impedance and low output impedance. The input and output signals are in phase. Here also the emitter current is equal to the sum of collector current and the base current. Now let us calculate the current gain for this configuration.

Current gain,

$$A_i = \frac{Output\ current}{Input\ current}$$

$$A_i = \frac{I_E}{I_B} = \frac{I_C + I_B}{I_B} = \frac{I_C}{I_B} + 1$$

$$A_i = \beta + 1$$

Input Characteristics

The input characteristics of a common-collector configuration are obtained between inputs current I_B and the input voltage V_{CB} at constant output voltage V_{EC}. Keep the output voltage V_{EC} constant at different levels and vary the input voltage V_{BC} for different points and record the I_B values for each point. Now using these values we need to draw a graph between the parameters of V_{BC} and I_B at constant V_{EC}.

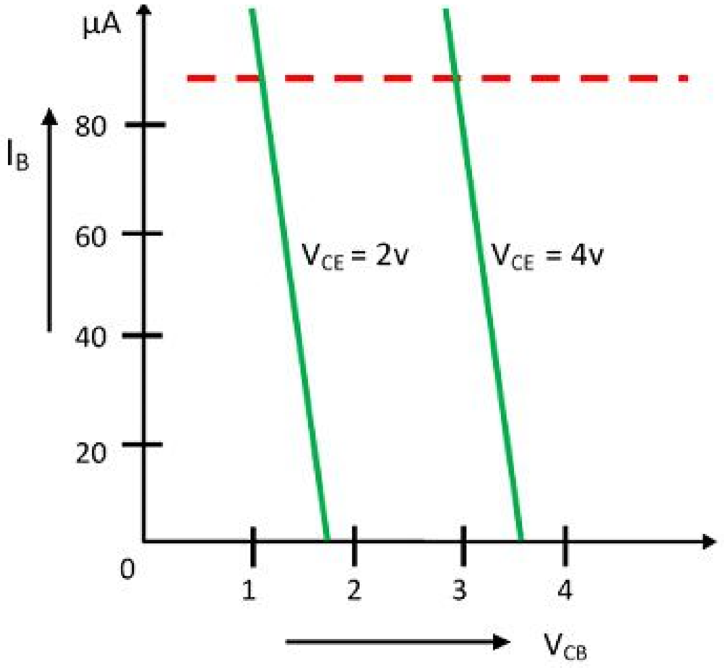


Figure 1.19: Input characteristics of CC configuration

Output Characteristics

The operation of the common collector circuit is same as that of common emitter circuit. The output characteristics of a common collector circuit are obtained between the output voltage V_{EC} and output current IE at constant input current I_B. In the operation of common collector circuit if the base current is zero then the emitter current also becomes zero. As a result no current flows through the transistor. If the base current increases then the transistor operates in active region and finally reaches to saturation region. To plot the graph first we keep the I_B at constant value and we will vary the V_{EC} value for various points, now we need to record the value of I_E for each point. Repeat the same process for different I_B values. Now using these values we need to plot the graph between the parameters of I_E and V_{CE} at constant values of I_B. The below figure show the output characteristics of common collector.

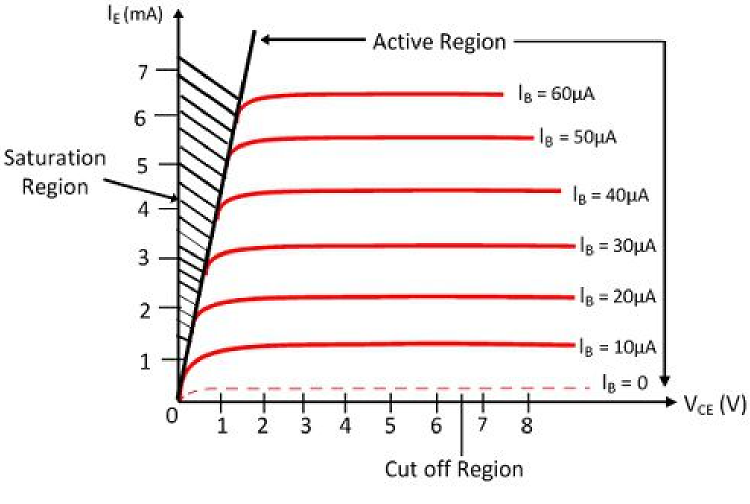


Figure 1.20: Output characteristics of CC configuration

C. Common emitter configuration (CE)

The configuration in which the emitter is connected between the collector and base is known as a common emitter configuration. The input circuit is connected between emitter and base, and the output circuit is taken from the collector and emitter. Thus, the emitter is common to both the input and the output circuit, and hence the name is the common emitter configuration. The common emitter arrangement for NPN and PNP transistor is shown in the figure below.

In this configuration we use emitter as common terminal for both input and output. This common emitter configuration is an inverting amplifier circuit. Here the input is applied between base-emitter region and the output is taken between collector and emitter terminals. In this configuration the input parameters are V_{BE} and I_B and the output parameters are V_{CE} and I_C.

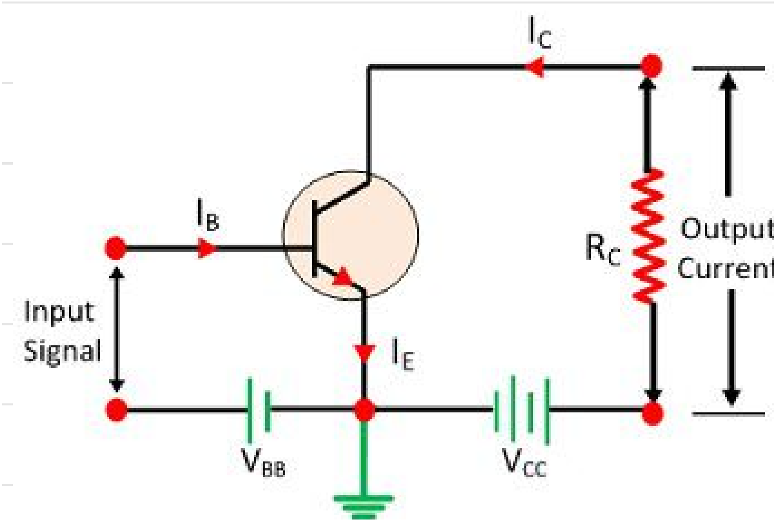


Figure 1.21: npn transistor CE configuration

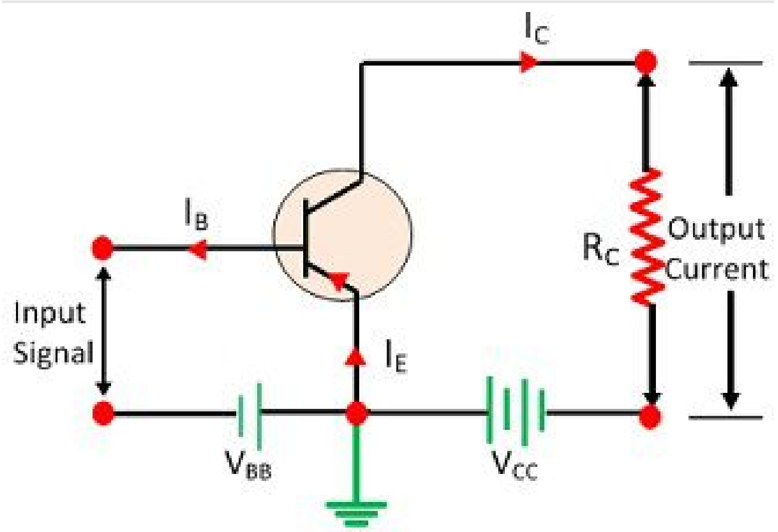


Figure 1.22: pnp transistor CE configuration

This type of configuration is mostly used in the applications of transistor based amplifiers. In this configuration the emitter current is equal to the sum of small base current and the large collector current. i.e. $I_E = I_C + I_B$. We know that the ratio between collector current and emitter current gives current gain alpha in Common Base configuration similarly the ratio between collector current and base current gives the current gain beta in common emitter configuration.

Now let us see the relationship between these two current gains.

Current gain (α) $= \frac{I_c}{I_E}$
Current gain (β) $= \frac{I_C}{I_B}$
Collector current $I_C = \alpha I_E = \beta I_B$

This configuration is mostly used one among all the three configurations. It has medium input and output impedance values. It also has the medium current and voltage gains. But the output signal has a phase shift of 1800 i.e. both the input and output are inverse to each other.

Input Characteristics

The input characteristics of common emitter configuration are obtained between input current I_B and input voltage V_{BE} with constant output voltage V_{CE}. Keep the output voltage V_{CE} constant and vary the input voltage V_{BE} for different points, now record the values of input current at each point. Now using these values we need to draw a graph between the values of I_B and V_{BE} at constant V_{CE}. The equation to calculate the input resistance R_{in} is given below.

$$R_{in} = \frac{V_{BE}}{I_B}$$

when V_{CE} is at constant

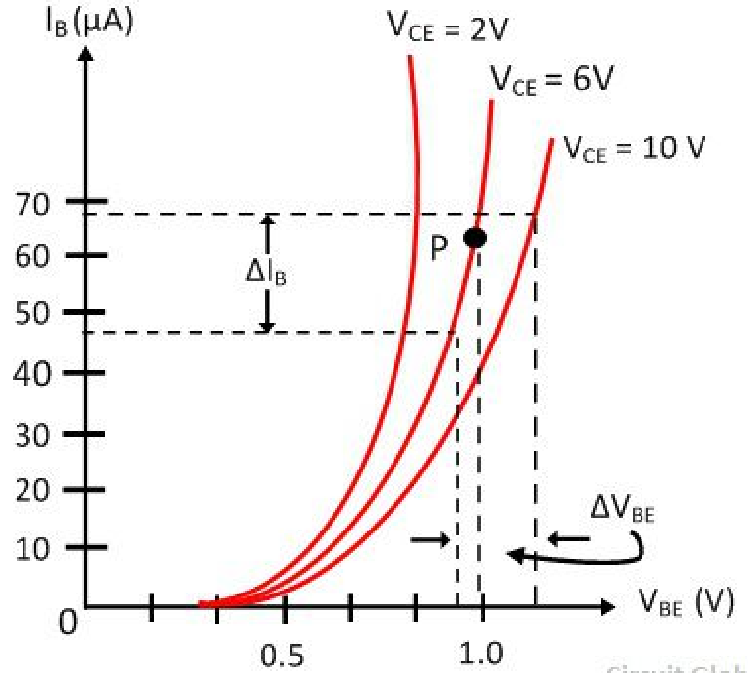


Figure 1.23: Intput characteristics of CE configuration

Output Characteristics

The output characteristics of common emitter configuration are obtained between the output current I_C and output voltage V_{CE} with constant input current I_B. Keep the base current I_B

constant and vary the value of output voltage V_{CE} for different points, now note down the value of collector I_C for each point. Plot the graph between the parameters I_C and V_{CE} in order to get the output characteristics of common emitter configuration. The equation to calculate the output resistance from this graph is given below.

$$R_{out} = \frac{V_{CE}}{I_C}$$

when I_B is at constant

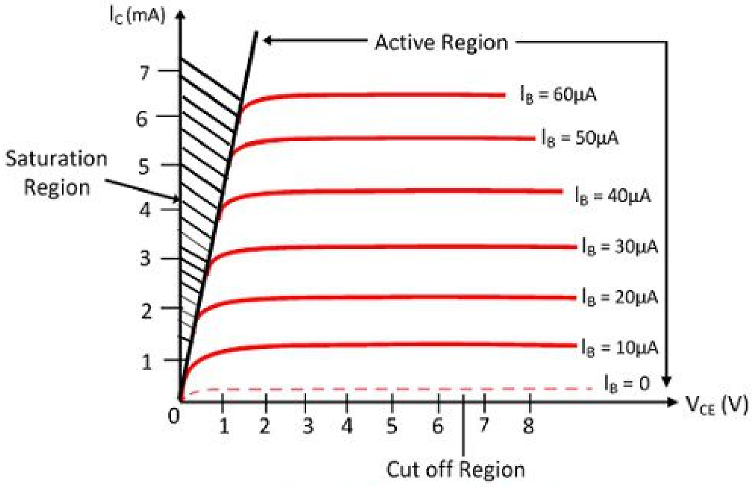


Figure 1.24: Output characteristics of CE configuration

1.4 Performance and characteristic of SCR, UJT, TRIAC and DIAC

1.4.1 Silicon controlled rectifier (SCR)

The term SCR stands for silicon controlled rectifier which is one of the most important members of the thyristor family. It is more popular than the other Thyristors like TRIAC, UJT, DIAC, etc. that some people even use the words Thyristor and SCR interchangeably.
SCRs are constructed from silicon and are most commonly used for converting AC current to DC current (rectification). They are also used in other applications such as regulation of power, inversion, etc. The SCRs have an ability to handle high value of current and Voltage hence they are used in most of the industrial applications.

Figure 1.25a shows the basic construction of an SCR, and Figure 1.25b shows the schematic symbol. Notice that the SCR has three external leads: the **anode**, **cathode**, and **gate**. An SCR differs from an ordinary rectifier diode in that the SCR will remain in a nonconducting state, although forward-biased, until the forward breakover voltage, V_{BRF} , is reached. Once the breakover voltage is reached, the SCR conducts and its voltage drop decreases sharply. The most important feature of an SCR is that the forward breakover voltage, V_{BRF} , can be controlled by changing the level of the gate current, I_G.

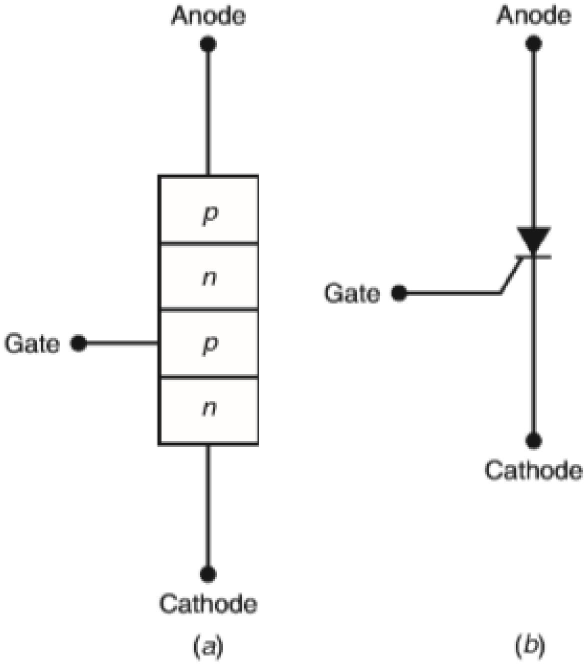


Figure 1.25: Silicon-controlled rectifier (SCR) (a) Construction (b) Schematic symbol

Construction of SCR

The SCR is a four-layered semiconductor device that forms NPNP or PNPN structure, which eventually forms three junctions J1, J2, and J3. Among the three terminals of the SCR, the Anode is a positive electrode, it will be on the P-layer and Cathode is a negative electrode, it will be on the N-layer of the SCR, the Gate acts as a control terminal of the SCR.

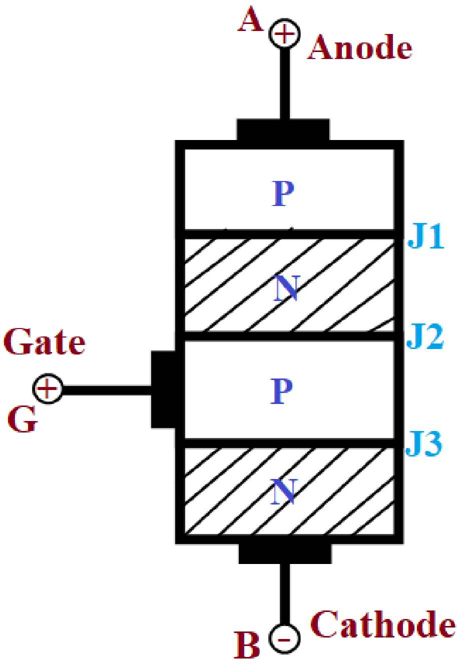


Figure 1.26: Construction of SCR

The outer P and N layers where the two electrodes are placed will be heavily doped and the middle P and N layers will be lightly doped, the gate terminal will be connected to the P-layer in the middle.

How SCR works?

To understand the SCR working principle we have to look into the different ways it can operate. Depending on the polarity of the voltage applied and the gate pulse given to the SCR, it can operate in three different modes such as

- Forward Blocking mode
- Forward Conduction mode
- Reverse Blocking mode

Forward Blocking Mode

In this mode of operation, the positive voltage is applied to the anode and the negative voltage applied to the cathode, there will not be any pulse applied to the gate, it will be kept in the open state. Once the voltage is applied, the junctions J1 and J3 will be forward biased and the junction J2 will be reverse biased. Since J2 is reverse biased the width of the depletion region increases and it acts as an obstacle for conduction, so only a small amount of current will be flowing from J1 to J3. When the voltage applied to the SCR is increased and if it reaches the breakdown voltage of the SCR, the junction J2 gets depleted due to avalanche breakdown. Once the Avalanche breakdown occurs the current will start flowing through the SCR. In this mode of operation, the SCR is forward biased, but, there will not be any current flow.

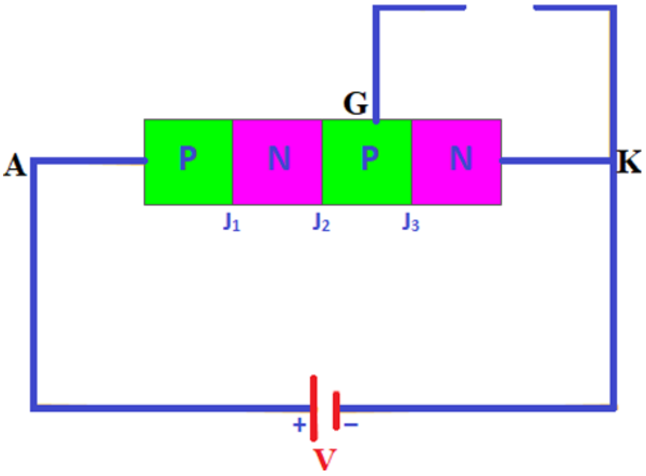


Figure 1.27: Forward blocking mode of SCR

Forward Conduction Mode

The Forward Conduction Mode is the only mode at which the SCR will be in the ON state and will be conducting. We can make the SCR conduct in two different ways, one we can increase the applied forward bias voltage beyond the breakdown voltage or else we can apply a positive voltage to the gate terminal. When we increase the Applied forward bias voltage between the anode and cathode the junction J2 will be depleted due to the avalanche breakdown and the SCR will start conducting. We are not able to do this for all the applications and this method of activating the SCR will eventually reduce the lifetime of the SCR.

If you want to use the SCR for low voltage applications you can apply a positive voltage to the gate of the SCR. The applied positive voltage will help the SCR to move to the conduction state. During this mode of operation, the SCR will be operating in forward bias and current will be flowing through it.

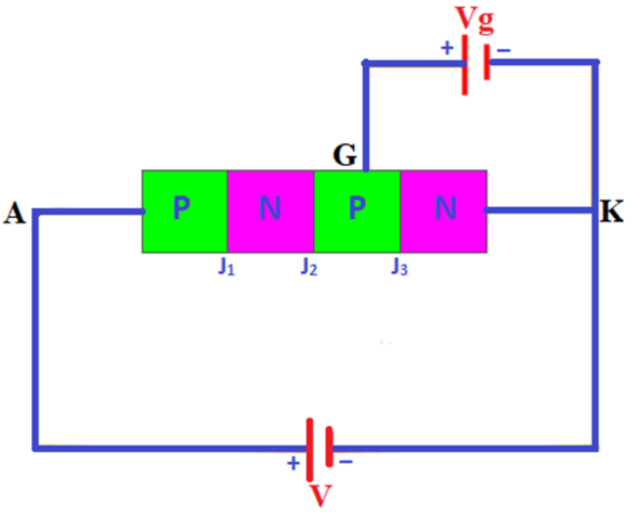


Figure 1.28: Forward conducting mode of SCR

Reverse Blocking Mode

In the reverse blocking mode, the positive voltage is applied to the Cathode (-) and the Negative voltage is given to the Anode (+), There will not be any pulse given to the gate, it will be kept as an open circuit. During this mode of operation the Junctions J1 and J3 will be reverse biased and the junction J2 will be forward biased. Since the junctions J1 and J3 are reverse biased there will not be any current flowing through the SCR. Although there will be a small leakage current flowing due to the drift charge carriers in the forward-biased Junction J2, it is not enough to turn on the SCR.

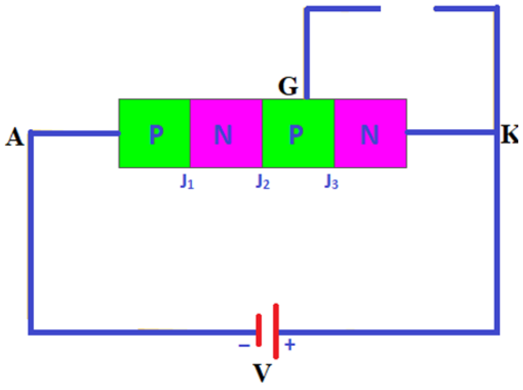


Figure 1.29: Forward blocking mode of SCR

VI Characteristics of SCR

The VI characteristics of the SCR are obtained by operating the SCR in three different regions, namely forward blocking region, forward conduction region and reverse blocking region.

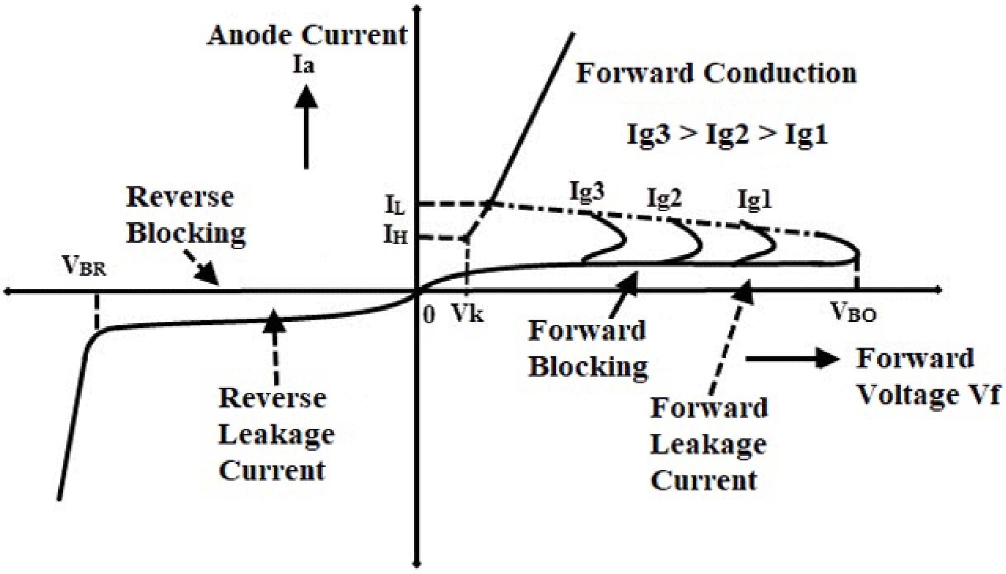


Figure 1.30: VI Characteristics of SCR

When the SCR is operating in the reverse blocking mode, there will be small leakage current flowing in the reverse direction of the SCR which is mentioned as the reverse leakage current in the graph, the reverse leakage current will be located at the negative quadrants of the graph. Now if you apply positive voltage to anode and negative voltage to cathode the SCR will start operating in the forward blocking mode and a small leakage current will be flowing through the SCR in the positive direction, hence the curve starts rising to a certain level in the positive quadrants of the graph which is mentioned as the forward leakage current.

Once the graph reaches a certain voltage level called the Breakdown voltage or if the gate current Ig is applied to the SCR, the SCR moves to the conduction mode and a high amount of current starts flowing through the SCR. The current flow is represented as the forward conduction in the VI curve. The gate current applied are mentioned as Ig1, Ig2 and Ig3, higher the applied gate current faster the SCR goes to the conduction state as Ig3 $>$ Ig2 $>$ Ig1.

An SCR has only two distinct states of operation: on or off. When the forward voltage is below the value of V_{BRF}, the SCR acts like an open switch. When the forward voltage exceeds the breakover voltage, V_{BRF} , the SCR conducts and acts like a closed switch. As a reminder, note that the SCR remains in the on state as long as the anode current is greater than the holding current, I_H.

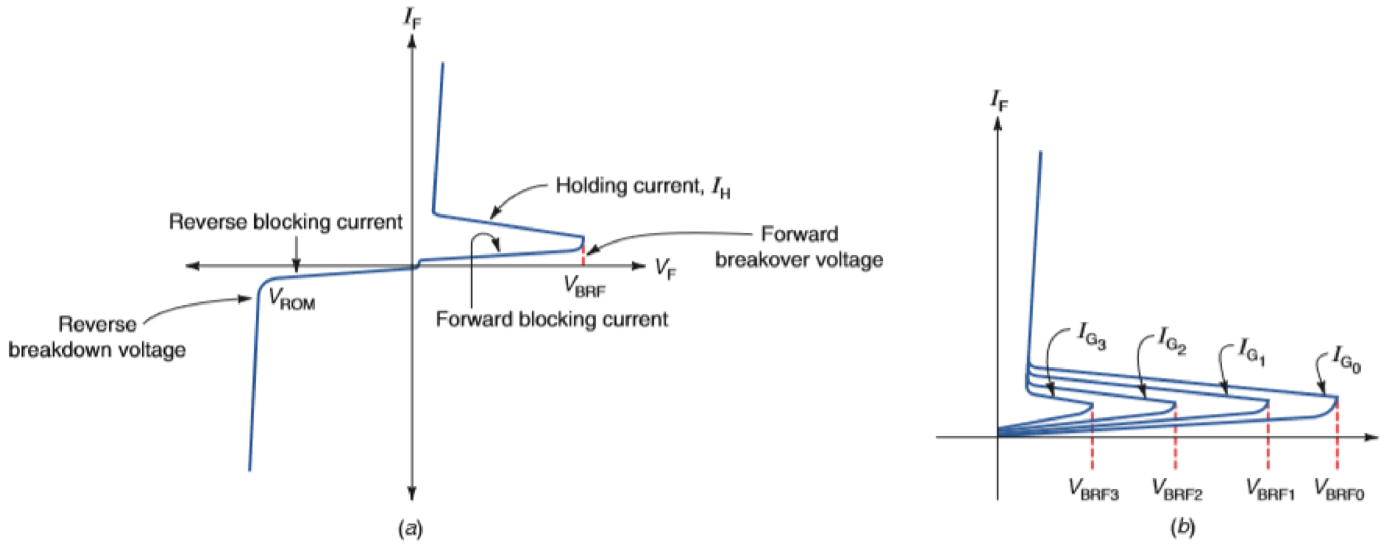


Figure 1.31: Current-voltage characteristics of an SCR. (a) Gate open. (b) Forward breakover voltage, V_{BRF}, decreases as the gate current, I_G, increases.

1.4.2 Unijunction Transistor (UJT)

UJT stands for **U**ni**J**unction **T**ransistor. It is a three terminal semiconductor switching device. The Unijunction Transistor is a simple device that consists of a bar of n-type silicon material with a non-rectifying contact at either end (base 1 and base 2), and with a rectifying contact (emitter) alloyed into the bar part way along its length, to form the only junction within the device (hence the name 'Unijunction').

The Unijunction Transistor is also known as Double Base Diode.

Symbol and Construction of UJT

In Unijunction Transistor, the PN Junction is formed by lightly doped N type silicon bar with heavily doped P type material on one side. The ohmic contact on either ends of the silicon bar is termed as Base 1 (B1) and Base 2 (B2) and P-type terminal is named as emitter. The

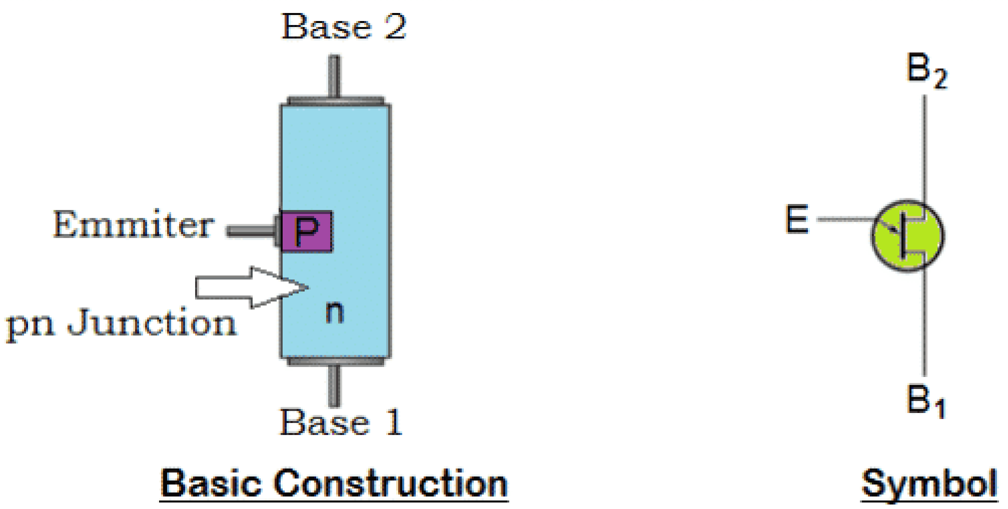


Figure 1.32: Basic Construction & Symbol of UJT

emitter junction is placed such that it is more close to terminal Base 2 than Base 1.

How does a Unijunction Transistor (UJT) works

The simplified equivalent circuit (at Figure 3 below) shows that N-type channel consists of two resistors RB2 and RB1 in series with an equivalent diode, D representing the PN junction. The emitter PN junction is fixed along the ohmic channel during its manufacturing process.

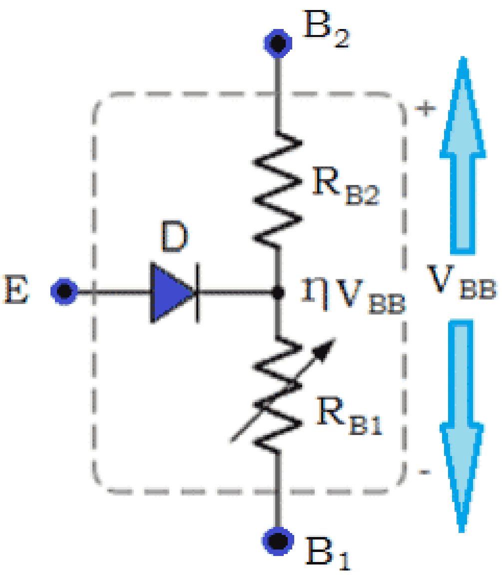


Figure 1.33: Simplified Equivalent Circuit of UJT

The variable resistance RB1 is provided between the terminals Emitter (E) and Base 1 (B1), the RB2 between the terminals Emitter (E) and Base 2 (B2). Since the PN junction is more close to B2, the value of RB2 will be less than the variable resistance RB1.
A voltage divider network is formed by the series resistances RB2 and RB1. When a voltage is applied across the semiconductor device, the potential will be in proportion to the position of base points along the channel.
The Emitter (E) will act as input when employed in a circuit, as the terminal B1 will be grounded. The terminal B2 will be positive biased to B1, when a voltage (VBB) applied across the terminals B1 and B2. When the emitter input is zero, the voltage across resistance RB1 of the voltage divider circuit is calculated by:

$$VRB1 = \frac{RB1}{RB1 + RB2} VBB$$

The important parameter of Unijunction Transistor is 'intrinsic stand-off ratio' (η), which is resistive ratio of RB1 to RBB. Most UJT's have η value ranging from 0.5 to 0.8. The PN junction is reverse biased; when small amount of voltage which is less than voltage developed across resistance RB1 (ηVBB) is applied across the terminal emitter (E). The forward biased is achieved when voltage applied across emitter terminal is increased and becomes more than VRB1. This results in larger flow of emitter current from emitter region to base region. Increase in emitter current reduces the resistance between emitter and Base 1, resulting in negative resistance at emitter terminal.

The Unijunction Transistor (UJT) will act as voltage breakdown device, when the input applied between emitter and base 1 reduces below breakdown value i.e., RB1 increases to a higher value. This shows that RB1 depends on the emitter current and it is variable.

Characteristics Curve of UJT

The characteristics of Unijunction Transistor (UJT) can be explained by three parameters:

- Cutoff Region
- Negative Resistance Region
- Saturation Region

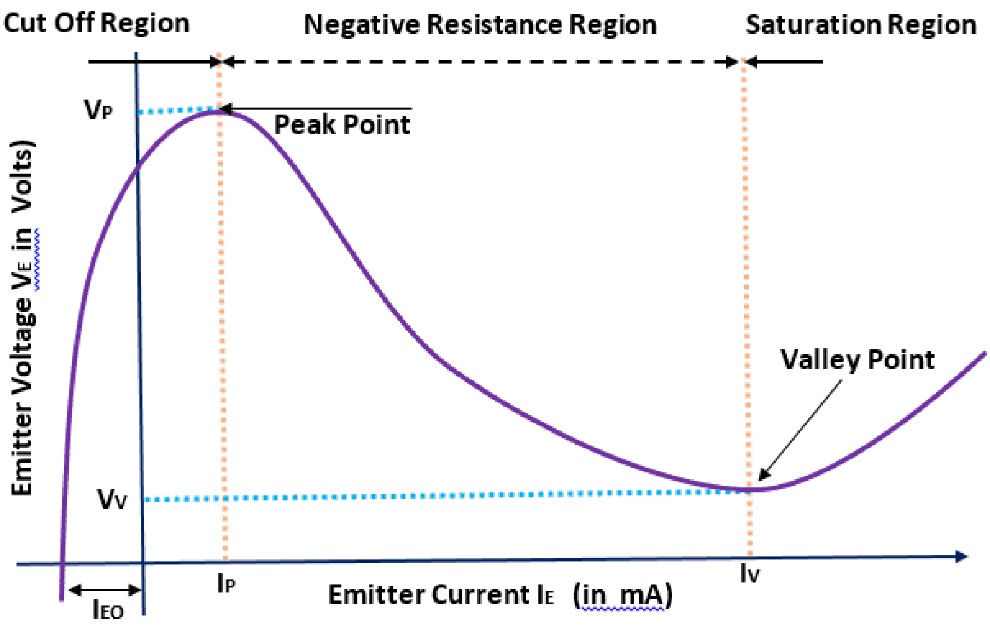


Figure 1.34: Characteristics of UJT

Cutoff Region

Cutoff region is the area where the Unijunction Transistor (UJT) doesn't get sufficient voltage to turn on. The applied voltage hasn't reached the triggering voltage, thus making transistor to be in off state.

Negative Resistance Region

When the transistor reaches the triggering voltage, V_{TRIG}, Unijunction Transistor (UJT) will turn on. After a certain time, if the applied voltage increases to the emitter lead, it will reach out at V_{PEAK}. The voltage drops from V_{PEAK} to Valley Point even though the current increases (negative resistance).

Saturation Region

Saturation region is the area where the current and voltage raises, if the applied voltage to emitter terminal increases.

Applications of UJT

The Unijunction Transistor can be employed in variety of applications such as:

- Switching Device
- Triggering Device for Triacs and SCR's

- Timing Circuits
- For phase control
- In sawtooth generators
- In simple relaxation oscillators

Advantages of UJT

- low cost
- negative resistance characteristics
- Requires low value of triggering current
- A stable triggering voltage
- Low power absorbing device

Disadvantage of UJT

The main disadvantage of Unijunction Transistor is its inability to provide appropriate amplification.

1.4.3 TRIAC

A Triac is defined as a three terminal AC switch which is different from the other silicon controlled rectifiers in the sense that it can conduct in both the directions that is whether the applied gate signal is positive or negative, it will conduct. Thus, this device can be used for AC systems as a switch.

This is a three terminal, four layer, bi-directional semiconductor device that controls AC power. The triac of maximum rating of 16 kw is available in the market.

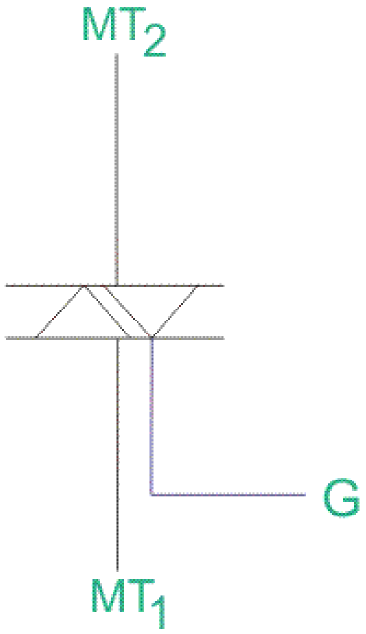


Figure 1.35: Symbol of triac

Figure 1.35 shows the symbol of triac, which has two main terminals MT1 and MT2 connected in inverse parallel and a gate terminal.

Construction of Triac

Two SCRs are connected in inverse parallel with gate terminal as common. Gate terminals is connected to both the N and P regions due to which gate signal may be applied which is irrespective of the polarity of the signal. Here, we do not have anode and cathode since it works for both the polarities which means that device is bilateral. It consists of three terminals namely, main terminal 1(MT1), main terminal 2(MT2), and gate terminal G. Figure shows the construction of a triac. There are two main terminals namely MT1 and MT2 and the remaining terminal is gate terminal.

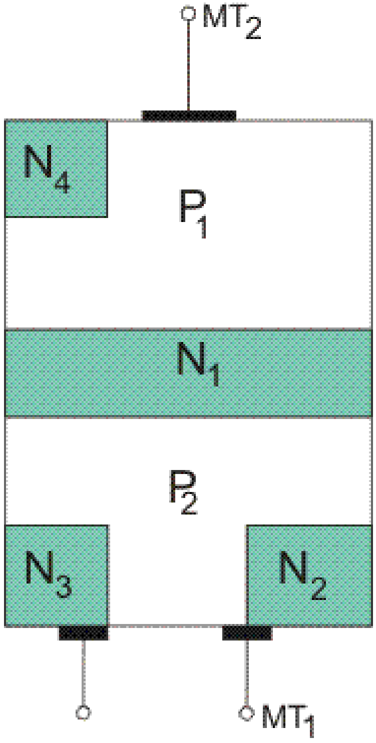


Figure 1.36: Construction of triac

Operation of Triac

The triac can be turned on by applying the gate voltage higher than break over voltage. However, without making the voltage high, it can be turned on by applying the gate pulse of 35 micro seconds to turn it on. When the voltage applied is less than the break over voltage, we use gate triggering method to turn it on.

There are four different modes of operations, they are-

1. When MT2 and Gate being Positive with Respect to MT1
   When this happens, current flows through the path P1-N1-P2-N2. Here, P1-N1 and P2-N2 are forward biased but N1-P2 is reverse biased. The triac is said to be operated in positively biased region. Positive gate with respect to MT1 forward biases P2-N2 and breakdown occurs.

2. When MT2 is Positive but Gate is Negative with Respect to MT1
   The current flows through the path P1-N1-P2-N2. But P2-N3 is forward biased and current carriers injected into P2 on the triac.

3. When MT2 and Gate are Negative with Respect to MT1
   Current flows through the path P2-N1-P1-N4. Two junctions P2-N1 and P1-N4 are

forward biased but the junction N1-P1 is reverse biased. The triac is said to be in the negatively biased region.

4. When MT2 is Negative but Gate is Positive with Respect to MT1 P2-N2 is forward biased at that condition. Current carriers are injected so the triac turns on. This mode of operation has a disadvantage that it should not be used for high (di/dt) circuits. Sensitivity of triggering in mode 2 and 3 is high and if marginal triggering capability is required, negative gate pulses should be used. Triggering in mode 1 is more sensitive than mode 2 and mode 3.

Characteristics of a Triac

The triac characteristics is similar to SCR but it is applicable to both positive and negative triac voltages. The operation can be summarized as follows-

First Quadrant Operation of Triac

Voltage at terminal MT2 is positive with respect to terminal MT1 and gate voltage is also positive with respect to first terminal.

Second Quadrant Operation of Triac

Voltage at terminal 2 is positive with respect to terminal 1 and gate voltage is negative with respect to terminal 1.

Third Quadrant Operation of Triac Voltage of terminal 1 is positive with respect to terminal 2 and the gate voltage is negative. **Fourth Quadrant Operation of Triac**

Voltage of terminal 2 is negative with respect to terminal 1 and gate voltage is positive. v-i characteristics of a triac When the device gets turned on, a heavy current flows through it which may damage the device, hence in order to limit the current a current limiting resistor should be connected externally to it. By applying proper gate signal, firing angle of the device may be controlled. The gate triggering circuits should be used for proper gate triggering. We can use diac for triggering the gate pulse. For firing of the device with proper firing angle, a gate pulse may be applied up to a duration of 35 micro seconds.

Advantages of Triac

It can be triggered with positive or negative polarity of gate pulses. It requires only a single heat sink of slightly larger size, whereas for SCR, two heat sinks should be required of smaller size. It requires single fuse for protection. A safe breakdown in either direction is possible but for SCR protection should be given with parallel diode.

Disadvantages of Triac

They are not much reliable compared to SCR. It has (dv/dt) rating lower than SCR. Lower ratings are available compared to SCR. We need to be careful about the triggering circuit as it can be triggered in either direction.

Uses of Triac

They are used in control circuits. It is used in High power lamp switching. It is used in AC power control.

1.4.4 DIAC

The term DIAC stands for the DIode for Alternating Current (DIAC), it is a bidirectional semiconductor switch that can be turned ON in both forward and reverse direction. The device is a member of the Thyristor family and it is mostly used in triggering TRIAC and other Thyristor based circuits. The DIAC starts conducting electric current if the applied voltage goes beyond its break-over voltage.

DIAC is a semiconductor device which has three layers and two junctions. The word DIAC consists of two parts, DI and AC. The DI stands for the diode (or two. Like Di, Tri, Quad, Penta etc.) and AC stands for Alternating Current. DIAC is the acronym of the diode for alternating current.
The DIAC is a combination of two diodes in parallel, one in forward bias and the other one is in reverse bias condition with respect to both sides. DIAC is a specially constructed diode, which allows current to pass in both directions when certain conditions are met.
One more interesting thing about the DIAC is, due to no specified direction of current flow, it is considered as a bidirectional device. DIAC only has two Anode pins, and no cathode pins are there. Those two anode terminals are often referred to Main Terminal 1 (MT1) and Main Terminal 2 (MT2).

Construction of DIAC

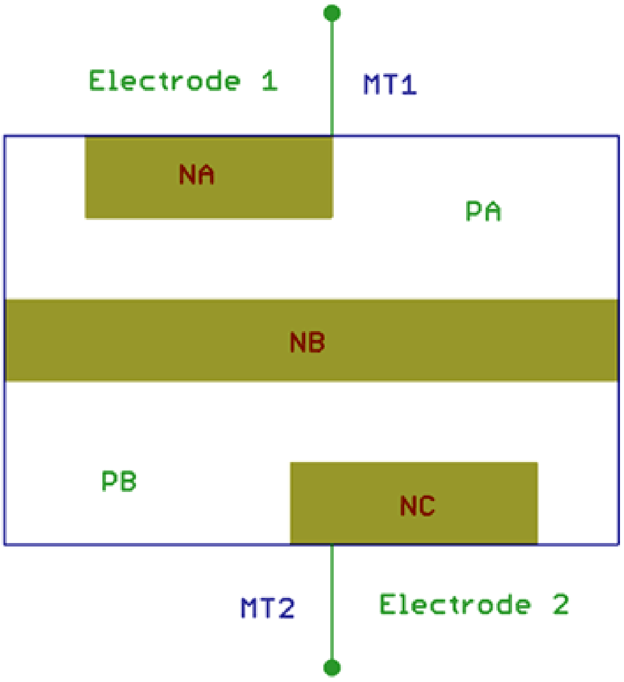


Figure 1.37: Characteristic of DIAC

DIAC construction follows the same rule as a typical transistor construction without the Base terminal. As discussed above, the DIAC construction has two main terminals, MT1, and MT2. The DIAC construction uses two P-type materials and three N-type materials without the gate terminal.
In the above image, Three N-type regions are shown with the name of NA, NB, and NC. P-type regions are shown as PA and PB. If MT1 terminal became more positive than MT2, the current will flow in the direction of PA -> NB -> PB -> NC. When the reverse situation occurs, the MT2 terminal became more positive than the MT1 and the current will flow in a direction of PB -> NB -> PA -> NA.

The DIAC only starts to conduct the current when the breakdown voltage is reached. During the breakdown situations, there is a sudden decrease in the voltage drop occurs across the DIAC and the current flow will increase through it. This state is called a negative dynamic resistance region. The conduction continues until the current decreases to a a certain value called as holding current. Below this holding current, the DIAC resistance becomes high and it will enter in non-conducting state.
As DIAC is a bidirectional device, it will happen for both directions of the current.

DIAC Characteristic Curve

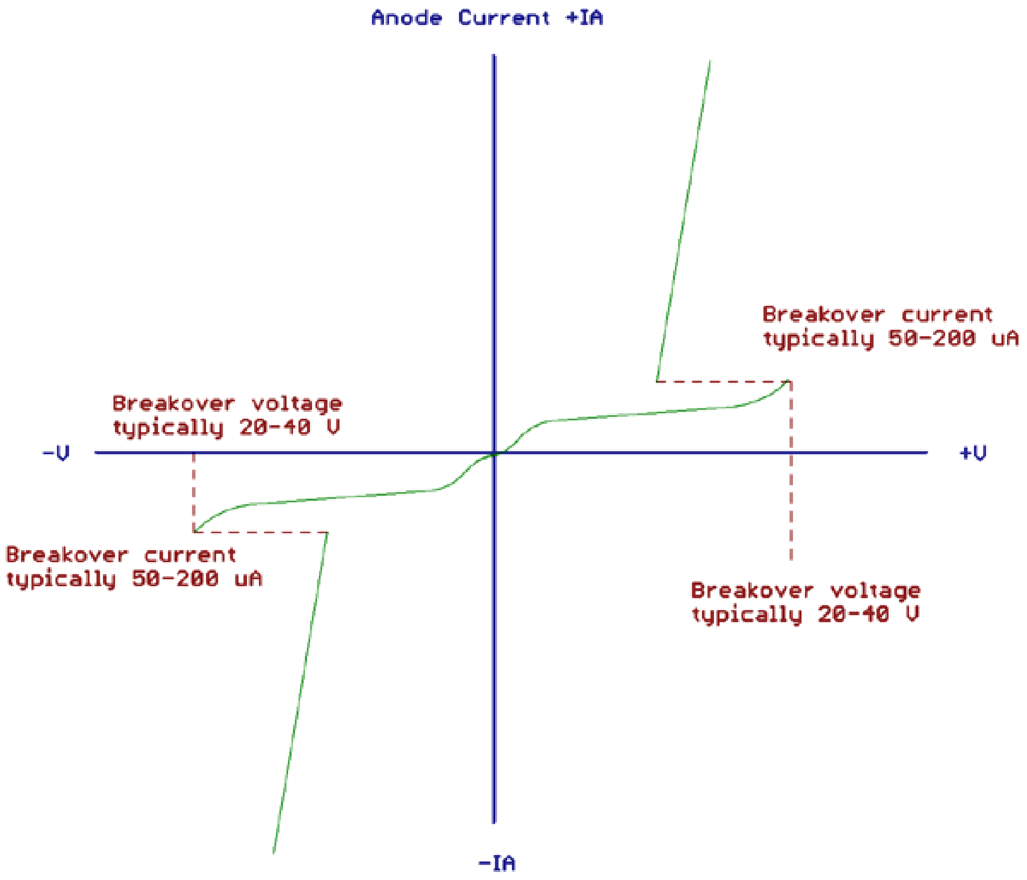


Figure 1.38: Characteristic of DIAC

In the above image, the actual I-V characteristic of DIAC is shown. The curve looks like the English word Z. The DIAC remains in the nonconductive state until the breakdown voltage is reached. The slow curve before going to the straight line is due to the leakage current. After the breakdown voltage is reached, the DIAC enters into the low resistance state and the current flow through the diode is rapidly increased which is shown as a straight line. But during the current conducting state the voltage drop across the diode is reduced, hence the line is not perfect 90 degrees.

DIAC Applications

The DIAC is designed specifically to trigger TRIAC or an SCR. As discussed above, the DIAC goes into avalanche conduction at the breakover voltage. Due to this, the device exhibits negative resistance characteristics and the voltage drop across it dramatically decreases, typically to about 5 Volts. This creates a break over current which is sufficient to turn on or trigger a TRIAC or an SCR.

1.5 Operational amplifier and timers

Operational Amplifiers are the basic building block of analogue electronics ckt. They are linear device with all properties of a DC amplifier. we can use external resistors or capacitors to the op amps is many different ways to make them different form of amplifiers such as Inverting amplifier, Non inverting amplifier, Voltage follower, Comparator, Differential amplifier Summing amplifier, Integrator etc.
The ideal op amp has three important terminals in addition to other terminals. The input terminals are inverting input and non inverting input. The third terminal is the out put which can sink and source current and voltage. The output signal is the amplifiers gain multiplied by the value of the input signal. Operational Amplifiers, also known as Op-amps, are basically a voltage amplifying device designed to be used with components like capacitors and resistors, between its in/out terminals. They are essentially a core part of analog devices. Feedback components like these are used to determine the operation of the amplifier. The amplifier can perform many different operations (resistive, capacitive, or both), giving it the name Operational Amplifier. Op-amps are linear devices that are ideal for DC amplification and are used often in signal conditioning, filtering or other mathematical operations (add, subtract, integration and differentiation).

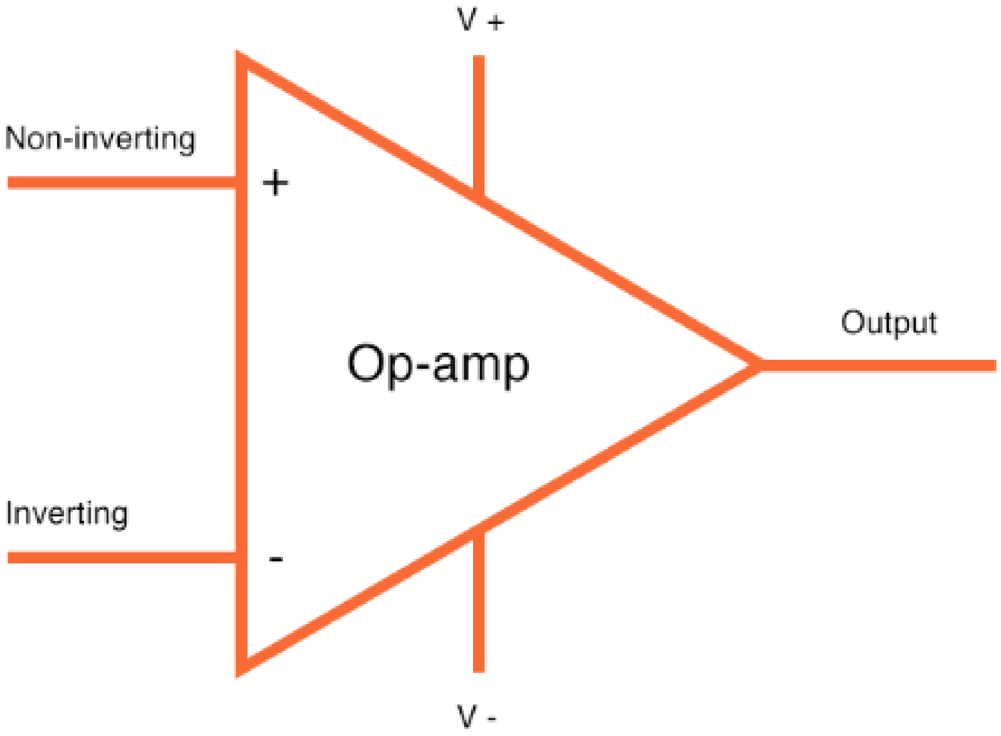


Figure 1.39: Example of an Op-amp in schematics

Scroll to continue with content The operational amplifier is arguably the most useful single device in analog electronic circuitry. With only a handful of external components, it can be made to perform a wide variety of analog signal processing tasks. It is also quite affordable, most general-purpose amplifiers selling for under a dollar apiece. Modern designs have been engineered with durability in mind as well: several "op-amps" are manufactured that can sustain direct short-circuits on their outputs without damage.

One key to the usefulness of these little circuits is in the engineering principle of feedback, particularly negative feedback, which constitutes the foundation of almost all automatic control processes. The principles presented in this section, extend well beyond the immediate scope of electronics. It is well worth the electronics student's time to learn these principles and learn them well.