1.6. BREAKDOWN IN PN JUNCTION DIODES

When a PN junction is reversed biased it allows very small current to flow through it. This current is due to the movement of minority charge carriers and it is almost independent of the voltage applied.

If reverse bias is made too high, the current through PN junction increases abruptly and the voltage at which this phenomenon occurs is called breakdown voltage.

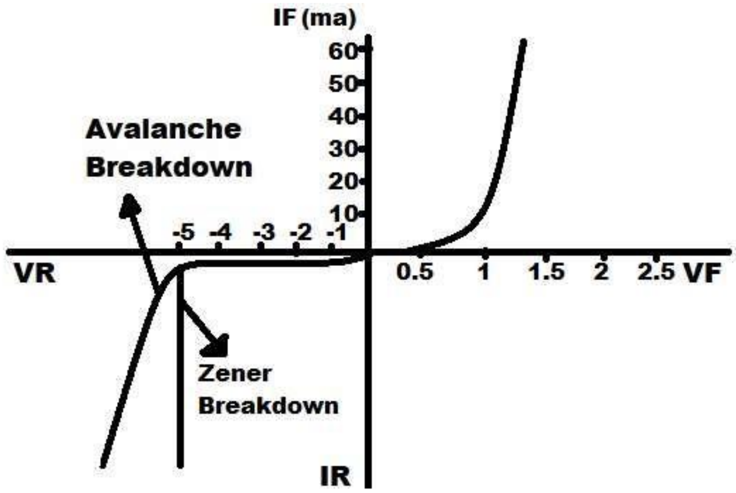

Fig:1.6.1 Avalanche Break down of Diode

At this breakdown voltage, the crystal structure breaks down. This crystal structure returns to the normal state when excess reverse bias is removed, provided that overheating has not permanently damaged the crystal.

There are two processes which causes junction breakdown. One is zener breakdown and another one is avalanche breakdown

Avalanche Breakdown

Avalanche breakdown is increased electric field causes increase in the velocities of the minority carriers. These high energy carriers break covalent bonds, thereby generating more carriers. Again these generated carriers are accelerated by electric field. They break more covalent bonds during their travel. A chain is thus established, creating a large number of carriers. This gives rise to a high reverse current. This mechanism of breakdown is called avalanche breakdown.

Zener Breakdown

When increase the reverse voltage across the pn junction diode, what really happens is that the electric field across the diode junction increases (both internal & external). This results in a force of attraction on the negatively charged electrons at junction. This force frees electrons from its covalent bond and moves those free electrons to conduction band. When the electric field increases (with applied voltage), more and more electrons are freed from its covalent bonds. This results in drifting of electrons across the junction and electron hole recombination occurs. So a net current is developed and it increases rapidly with increase in electric field.

Zener breakdown phenomena occurs in a pn junction diode with heavy doping & thin junction (means depletion layer width is very small). Zener breakdown does not result in damage of diode. Since current is only due to drifting of electrons, there is a limit to the increase in current as well.

1.3. DRIFT CURRENT AND DIFFUSION CURRENT DENSITIES

Drift Current

Drift current can be defined as the charge carrier's moves in a semiconductor because of the electric field. There are two kinds of charge carriers in a semiconductor like holes and electrons. Once the voltage is applied to a semiconductor, then electrons move toward the +Ve terminal of a battery whereas the holes travel toward the –Ve terminal of a battery.

Here, holes are positively charged carriers whereas the electrons are negatively charged carriers. Therefore, the electrons attract by the +Ve terminal of a battery whereas the holes attract by the -Ve terminal of a battery.

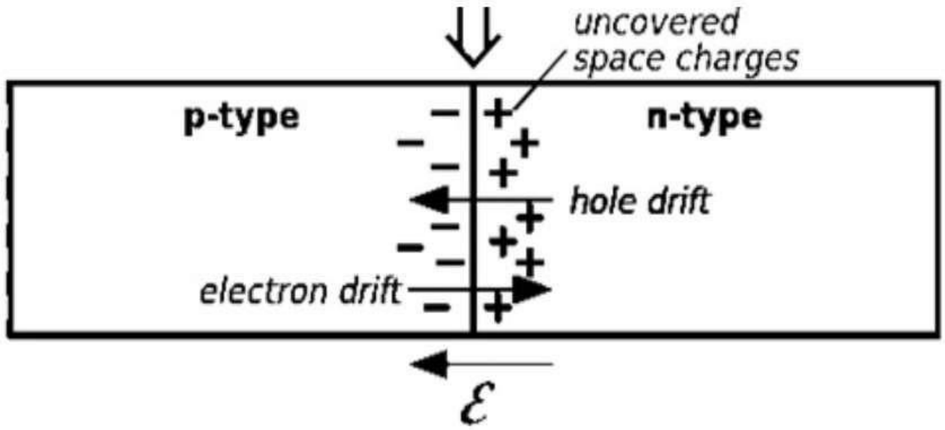

Fig:1.3.1 Drift Current

Diffusion Current

The diffusion current can be defined as the flow of charge carriers within a semiconductor travels from a higher concentration region to a lower concentration region. A higher concentration region is nothing but where the number of electrons present in the semiconductor. Similarly, a lower concentration region is where the less number of electrons present in the semiconductor. The process of diffusion mainly occurs when a semiconductor is doped non-uniformly.

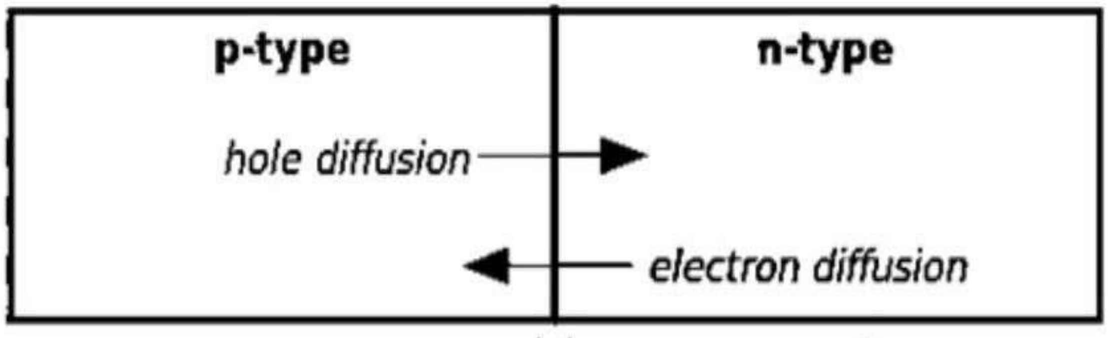

Fig:1.3.2 Diffusion Current

In an N-type semiconductor, when it is doped non-uniformly then a higher concentration region can be formed at the left side whereas the lower concentration region can be formed at the right side. The electrons in the higher concentration region are more in the semiconductor so they will experience a repulsive force from each other.

Difference between Drift Current and Diffusion Currents

Drift Current	Diffusion Current
The movement of charge carriers is because of the applied electric field is known as drift current.	The diffusion current can be occurred because of the diffusion in charge carriers.
It requires electrical energy for the process of drift current.	Some amount of external energy is enough for the process of diffusion current.
This current obeys Ohm's Law.	This current obeys Fick's Law.
The direction of charge carriers in the semiconductor is reverse to each other.	For charge carriers, the densities of diffusion are reverse in symbol to each other.
The direction of the drift current, as well as the electric field, will be the same.	The direction of this current can be decided by the concentration of the carrier slope.
It depends on the permittivity	It is independent of permittivity
The direction of this current mainly depends on the polarity of the applied electric field.	The direction of this current mainly depends on the charge within the concentrations of carrier

1.2. ENERGY BAND DIAGRAM

The region on the left is p-type with an acceptor density Na, while the region on the right is n-type with a donor density Nd. The dopants are assumed to be shallow, so that the electron (hole) density in the n-type (p-type) region is approximately equal to the donor (acceptor) density.

Thermal equilibrium

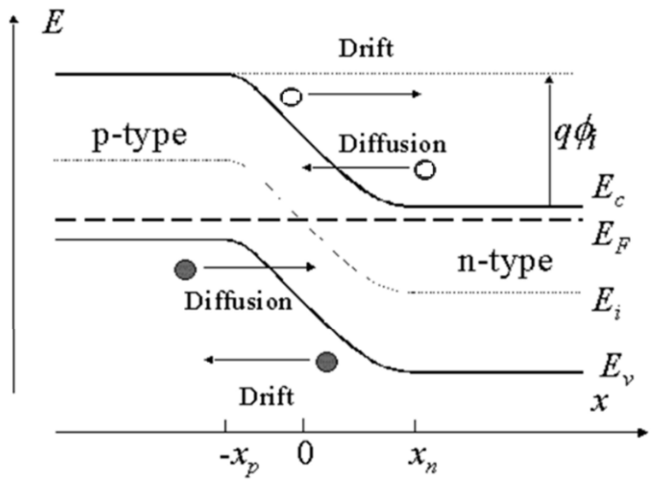

Fig:1.2.1 PN Diode Energy Band Diagram

(Source :https://ecee.colorado.edu)

To reach thermal equilibrium, electrons/holes close to the metallurgical junction diffuse across the junction into the p-type/n-type region where hardly any electrons/holes are present. This process leaves the ionized donors (acceptors) behind, creating a region around the junction, which is depleted of mobile carriers. This region the depletion region, extending from x = -xp to x = xn. The charge due to the ionized donors and acceptors causes an electric field, which in turn causes a drift of carriers in the opposite direction. The diffusion of carriers continues until the drift current balances the diffusion current, thereby reaching thermal equilibrium as indicated by a constant Fermi energy.

While in thermal equilibrium no external voltage is applied between the n-type and p-type material, there is an internal potential, which is caused by the work function difference between the n-type and p-type semiconductors.

Energy band diagram of a p-n junction under reverse and forward bias

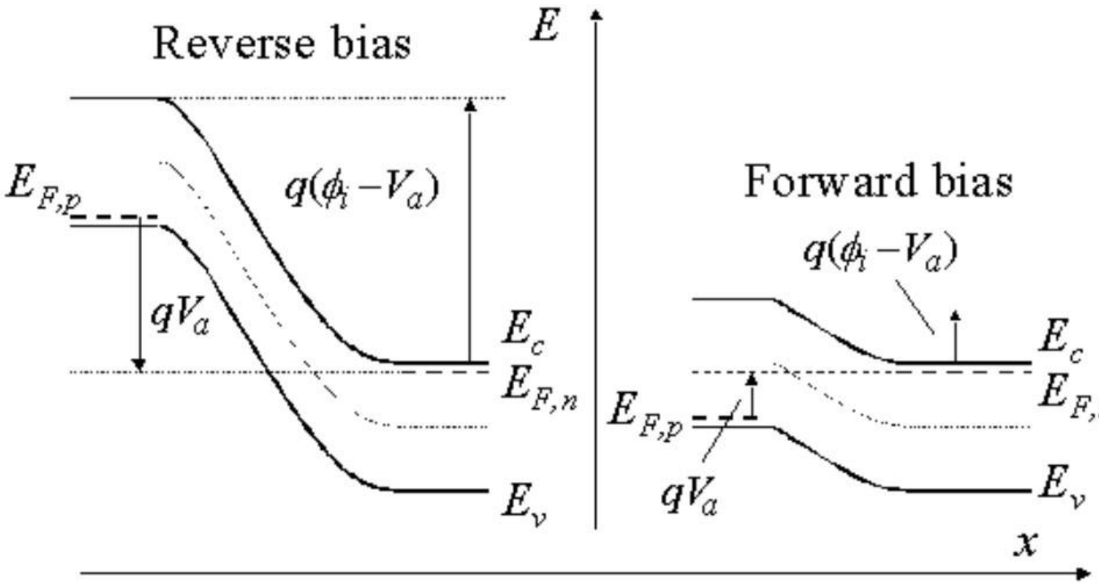

Fig:1.2.2 PN Diode Energy Band Diagram F.B & R.B

(Source :https://ecee.colorado.edu)

P-N diode with an applied bias voltage, Va. A forward bias corresponds to applying a positive voltage to the anode (the p-type region) relative to the cathode (the n-type region). A reverse bias corresponds to a negative voltage applied to the cathode. The applied voltage is proportional to the difference between the Fermi energy in the n-type and p-type quasi-neutral regions.

As a negative voltage is applied, the potential across the semiconductor increases and so does the depletion layer width. As a positive voltage is applied, the potential across the semiconductor decreases and with it the depletion layer width. The total potential across the semiconductor equals the built-in potential minus the applied voltage.

2.4 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.

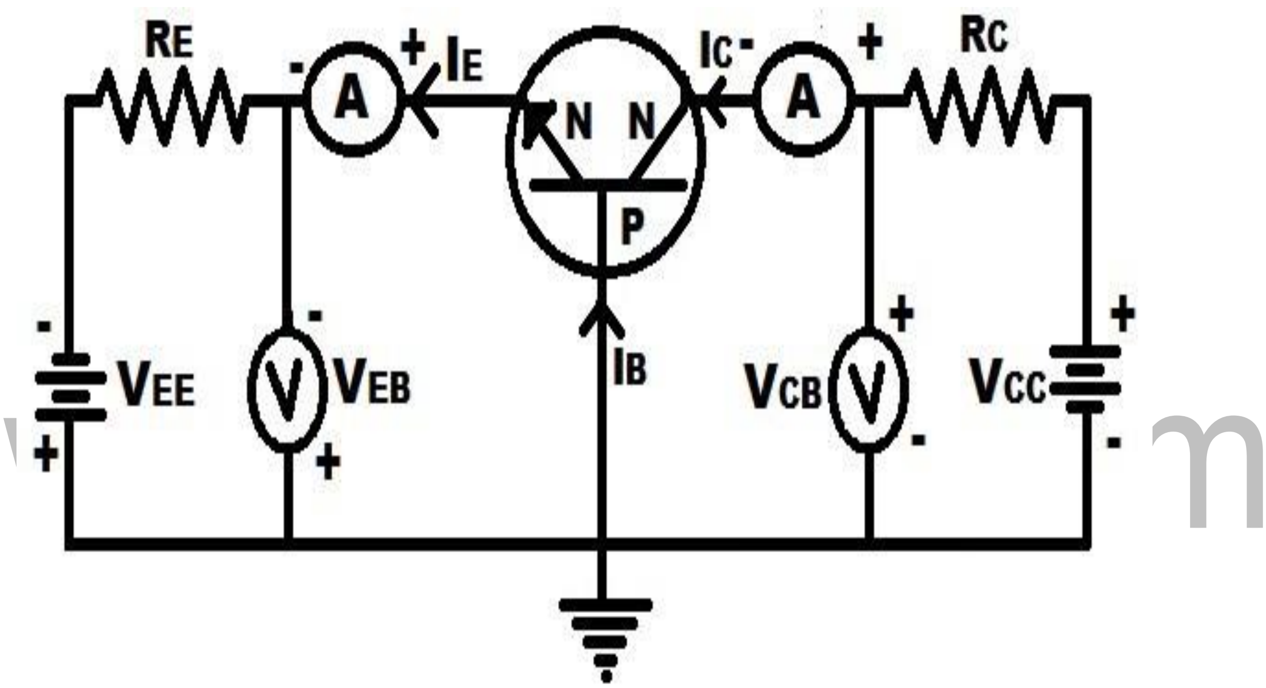

Fig:2.4.1 Common Base Configuration of NPN Transistor

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 VBE while the supply voltage between collector and base is denoted by VCB.

In every configuration, the base-emitter junction JE is always forward biased and collector-base junction JC is always reverse biased. Therefore, in common base configuration, the base-emitter junction JE is forward biased and collector-base junction JC is reverse biased.

Input characteristics

The input characteristics describe the relationship between input current (IE) and the input voltage (VBE).

First, draw a vertical line and horizontal line. The vertical line represents y-axis and horizontal line represents x-axis. The input current or emitter current (IE) is taken along the y-axis (vertical line) and the input voltage (VBE) is taken along the x-axis (horizontal line).

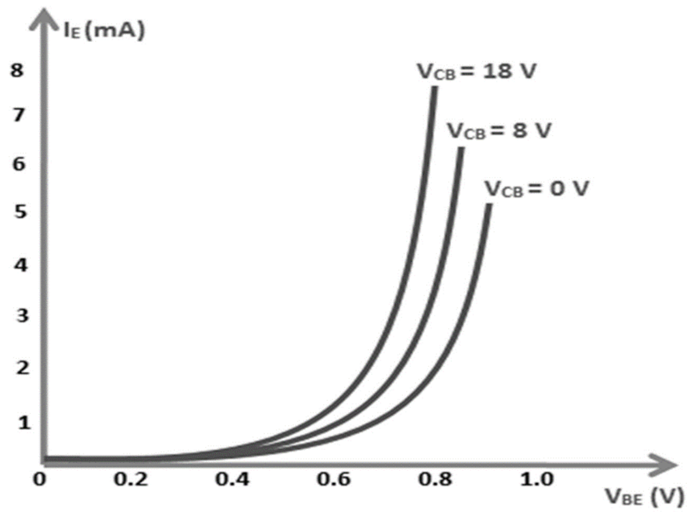

Fig:2.4.2 Input characteristics of Common Base Configuration

To determine the input characteristics, the output voltage VCB (collector-base voltage) is kept constant at zero volts and the input voltage VBE is increased from zero volts to different voltage levels. For each voltage level of the input voltage (VBE), the input current (IE) is recorded on a paper or in any other form.

A curve is then drawn between input current IE and input voltage VBE at constant output voltage VCB (0 volts).

The output voltage (VCB) is increased from zero volts to a certain voltage level (8 volts) and kept constant at 8 volts. While increasing the output voltage (VCB), the input voltage (VBE) is kept constant at zero volts. After kept the output voltage (VCB) constant at 8 volts, the input voltage VBE is increased from zero volts to different voltage levels. For each voltage level of the input voltage (VBE), the input current (IE) is recorded on a paper or in any other form.

A curve is then drawn between input current IE and input voltage VBE at constant output voltage VCB (8 volts).

This is repeated for higher fixed values of the output voltage (VCB).

When output voltage (VCB) is at zero volts and emitter-base junction JE is forward biased by the input voltage (VBE), the emitter-base junction acts like a normal p-n junction diode. So the input characteristics are same as the forward characteristics of a normal pn junction diode.

The cut in voltage of a silicon transistor is 0.7 volts and germanium transistor is 0.3 volts. In our case, it is a silicon transistor. So from the above graph, can see that after 0.7 volts, a small increase in input voltage (VBE) will rapidly increase the input current (IE).

When the output voltage (VCB) is increased from zero volts to a certain voltage level (8 volts), the emitter current flow will be increased which in turn reduces the depletion region width at emitter-base junction. As a result, the cut in voltage will be reduced. Therefore, the curves shifted towards the left side for higher values of output voltage VCB.

Output characteristics

The output characteristics describe the relationship between output current (IC) and the output voltage (VCB).

First, draw a vertical line and a horizontal line. The vertical line represents y-axis and horizontal line represents x-axis. The output current or collector current (IC) is taken along the y-axis (vertical line) and the output voltage (VCB) is taken along the x-axis (horizontal line).

To determine the output characteristics, the input current or emitter current IE is kept constant at zero mA and the output voltage VCB is increased from zero volts to different voltage levels. For each voltage level of the output voltage VCB, the output current (IC) is recorded.

A curve is then drawn between output current IC and output voltage VCB at constant input current IE (0 mA).

When the emitter current or input current IE is equal to 0 mA, the transistor operates in the cut-off region.

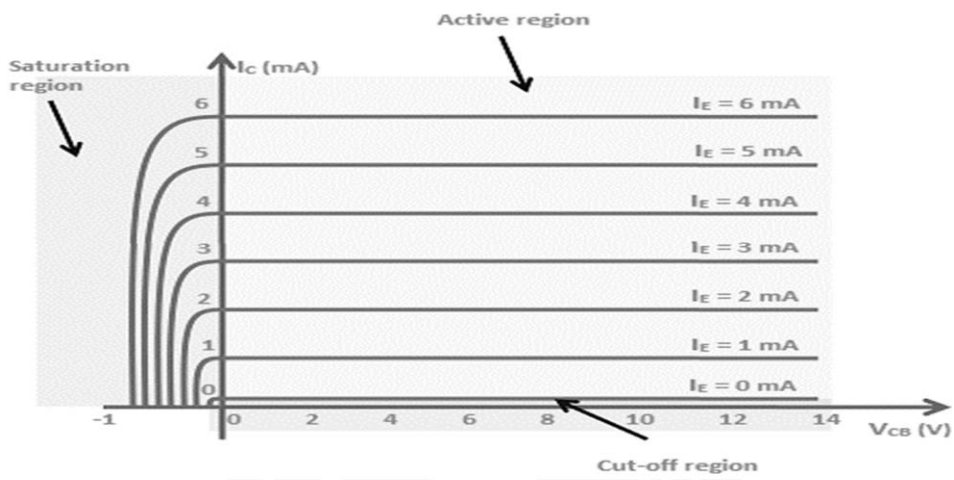

Fig:2.4.3 Output characteristics of Common Base Configuration

Next, the input current (IE) is increased from 0 mA to 1 mA by adjusting the input voltage VBE and the input current IE is kept constant at 1 mA. While increasing the input current IE, the output voltage VCB is kept constant.

After kept the input current (IE) constant at 1 mA, the output voltage (VCB) is increased from zero volts to different voltage levels. For each voltage level of the output voltage (VCB), the output current (IC) is recorded.

A curve is then drawn between output current IC and output voltage VCB at constant input current IE (1 mA). This region is known as the active region of a transistor.

This is repeated for higher fixed values of input current IE (I.e. 2 mA, 3 mA, 4 mA and so on).

From the above characteristics, can see that for a constant input current IE, when the output voltage VCB is increased, the output current IC remains constant.

At saturation region, both emitter-base junction JE and collector-base junction JCare forward biased. From the above graph, can see that a sudden increase in the collector current when the output voltage VCB makes the collector-base junction JC forward biased.

Early effect

Due to forward bias, the base-emitter junction JE acts as a forward biased diode and due to reverse bias, the collector-base junction JC acts as a reverse biased diode. Therefore, the width of the depletion region at the base-emitter junction JE is very small whereas the width of the depletion region at the collector-base junction JC is very large.

If the output voltage VCB applied to the collector-base junction JC is further increased, the depletion region width further increases. The base region is lightly doped as compared to the collector region. So the depletion region penetrates more into the base region and less into the collector region. As a result, the width of the base region decreases. This dependency of base width on the output voltage (VCB) is known as an early effect.

If the output voltage VCB applied to the collector-base junction JC is highly increased, the base width may be reduced to zero and causes a voltage breakdown in the transistor. This phenomenon is known as punch through.

Transistor parameters

Dynamic input resistance (ri)

Dynamic input resistance is defined as the ratio of change in input voltage or emitter voltage (VBE) to the corresponding change in input current or emitter current (IE), with the output voltage or collector voltage (VCB) kept at constant.

$$r_i = \frac{\Delta V_{BE}}{\Delta I_E}, \qquad V_{CB} = \text{constant}$$

The input resistance of common base amplifier is very low.

Dynamic output resistance (ro)

Dynamic output resistance is defined as the ratio of change in output voltage or collector voltage (VCB) to the corresponding change in output current or collector current (IC), with the input current or emitter current (IE) kept at constant.

$$r_o = \frac{\Delta V_{CB}}{\Delta I_C}, \qquad I_E = \text{constant}$$

The output resistance of common base amplifier is very high.

Current gain (α)

The current gain of a transistor in CB configuration is defined as the ratio of output current or collector current (IC) to the input current or emitter current (IE).

$$\alpha = \frac{I_C}{I_E}$$

The current gain of a transistor in CB configuration is less than unity. The typical current gain of a common base amplifier is 0.98.

1.5. SWITCHING CHARACTERISTICS

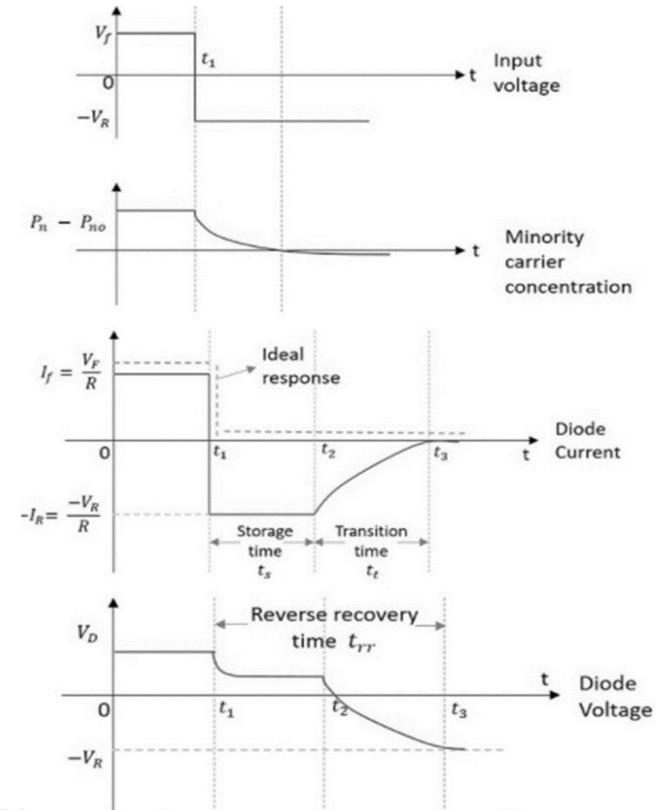

Fig:1.5.1 Switching Characteristics of Diode

(Source : https://www.tutorialspoint.com/)

Where

tF = forward bias time

tS = Storage time

tT = transition interval

tRR = reverse recovery time

Reverse recovery time:

Reverse recovery time is addition of storage time and transition interval. When the diode is in forward bias and immediately switched to reverse condition, the diode will still conduct current for certain amount of time. The time period for which the diode conduct electricity after switching the voltage is called “reverse recovery time”

The reason for reverse recovery time is:

1. In conduction state, electrons in p-type material and holes in n-type material as minority carrier.
2. When applied the reverse voltage diode to switch from conducting to nonconducting state immediately but due to minority carrier the reverse current flows through the diode and stays at measureable level for storage time (tS) required for minority carrier to return to their majority carrier state in the opposite material (n-type material for electron and p-type material for holes).
3. After this time period transition interval (tT) required for current to get back to level associated with nonconduction state.

Reverse recovery time depends on junction temperature, rate of fall of forward current.

Reverse recovery time should be small for high speed switching application and can be reduced by shortening the length of P region in PN junction diode or by introducing impurities for example Gold.

1.4. TRANSITION AND DIFFUSION CAPACITANCES

Transition capacitance (CT)

The conducting plates or electrodes of the capacitor are good conductors of electricity. Therefore, they easily allow electric current through them. On the other hand, dielectric material or medium is poor conductor of electricity. Therefore, it does not allow electric current through it. However, it efficiently allows electric field.

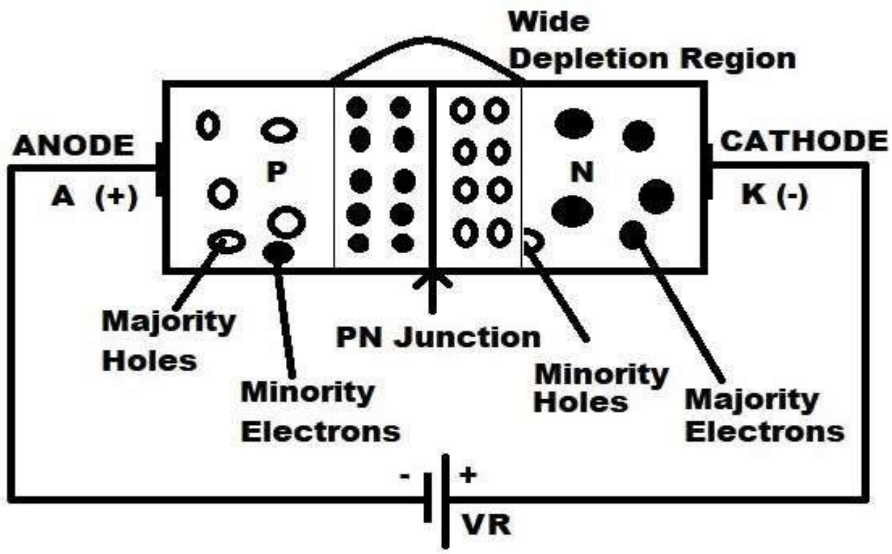

Fig:1.4.1 Transition capacitance

The capacitors store electric charge in the form of electric field. The capacitors store electric charge by using two electrically conducting plates

When voltage is applied to the capacitor, charge carriers starts flowing through the conducting wire. When these charge carriers reach the electrodes of the capacitor, they experience a strong opposition from the dielectric or insulating material. As a result, a large number of charge carriers are trapped at the electrodes of the capacitor. These charge carriers cannot move between the plates. However, they exert electric field between the plates. The charge carriers which are trapped near the dielectric material will stores electric charge. The ability of the material to store electric charge is called capacitance.

In a basic capacitor, the capacitance is directly proportional to the size of electrodes or plates and inversely proportional to the distance between two plates.

Just like the capacitors, a reverse biased p-n junction diode also stores electric charge at the depletion region. The depletion region is made of immobile positive and negative ions.

In a reverse biased p-n junction diode, the p-type and n-type regions have low resistance. Hence, p-type and n-type regions act like the electrodes or conducting plates of the capacitor. The depletion region of the p-n junction diode has high resistance. Hence, the depletion region acts like the dielectric or insulating material. Thus, p-n junction diode can be considered as a parallel plate capacitor.

In depletion region, the electric charges (positive and negative ions) do not move from one place to another place. However, they exert electric field or electric force. Therefore, charge is stored at the depletion region in the form of electric field. The ability of a material to store electric charge is called capacitance. Thus, there exists a capacitance at the depletion region.

The capacitance at the depletion region changes with the change in applied reverse bias voltage.

The capacitance at the depletion region changes with the change in applied voltage. When reverse bias voltage applied to the p-n junction diode is increased, a large number of holes (majority carriers) from p-side and electrons (majority carriers) from n-side are moved away from the p-n junction. As a result, the width of depletion region increases whereas the size of p-type and n-type regions (plates) decreases.

The capacitance means the ability to store electric charge. The p-n junction diode with narrow depletion width and large p-type and n-type regions will store large amount of electric charge whereas the p-n junction diode with wide depletion width and small p-type and n-type regions will store only a small amount of electric charge. Therefore, the capacitance of the reverse bias p-n junction diode decreases when voltage increases.

In a forward biased diode, the transition capacitance exist. However, the transition capacitance is very small compared to the diffusion capacitance. Hence, transition capacitance is neglected in forward biased diode.

The amount of capacitance changed with increase in voltage is called transition capacitance. The transition capacitance is also known as depletion region capacitance, junction capacitance or barrier capacitance. Transition capacitance is denoted as CT.

The change of capacitance at the depletion region can be defined as the change in electric charge per change in voltage.

CT = dQ / dV

Where,

CT = Transition capacitance

dQ = Change in electric charge

dV = Change in voltage

The transition capacitance can be mathematically written as,

CT = ε A / W

Where,

ε = Permittivity of the semiconductor

A = Area of plates or p-type and n-type regions

W = Width of depletion region

Diffusion capacitance (CD)

Diffusion capacitance occurs in a forward biased p-n junction diode. Diffusion capacitance is also sometimes referred as storage capacitance. It is denoted as CD.

In a forward biased diode, diffusion capacitance is much larger than the transition capacitance. Hence, diffusion capacitance is considered in forward biased diode.

The diffusion capacitance occurs due to stored charge of minority electrons and minority holes near the depletion region.

When forward bias voltage is applied to the p-n junction diode, electrons (majority carriers) in the n-region will move into the p-region and recombines with the holes. In the similar way, holes in the p-region will move into the n-region and recombines with electrons. As a result, the width of depletion region decreases.

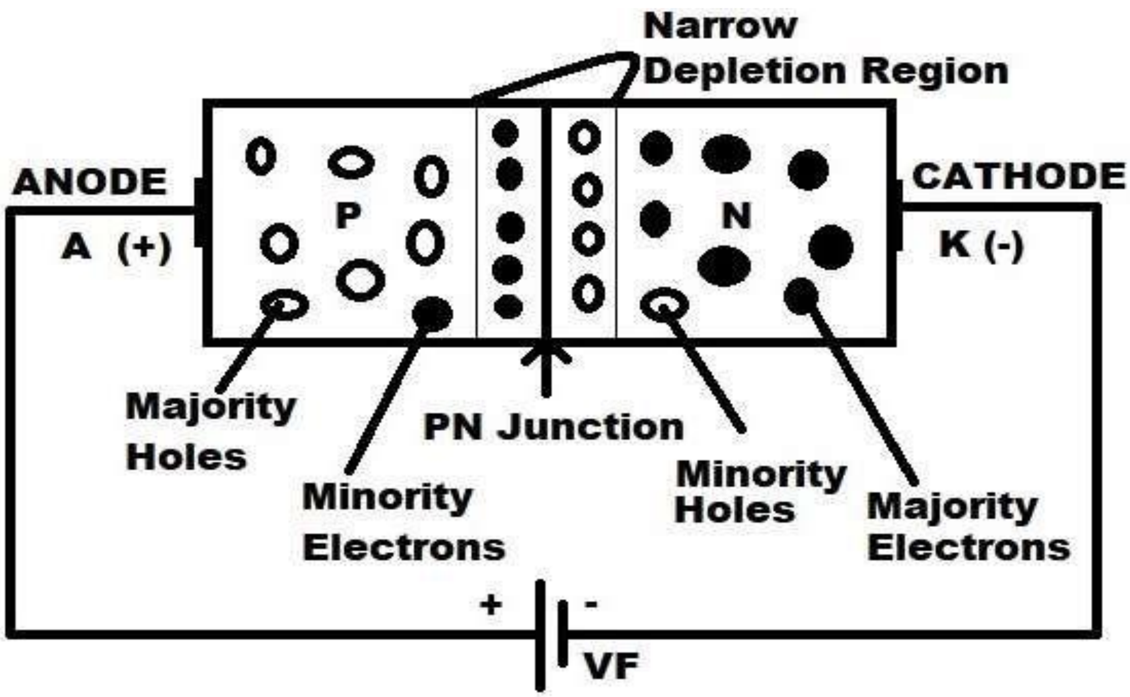

Fig:1.4.2 Diffusion capacitance

The electrons (majority carriers) which cross the depletion region and enter into the p-region will become minority carriers of the p-region similarly; the holes (majority carriers) which cross the depletion region and enter into the n-region will become minority carriers of the n-region.

A large number of charge carriers, which try to move into another region will be accumulated near the depletion region before they recombine with the majority carriers. As a result, a large amount of charge is stored at both sides of the depletion region.

Diffusion capacitance occurs in a forward biased p-n junction diode. Diffusion capacitance is also sometimes referred as storage capacitance. It is denoted as CD.

The accumulation of holes in the n-region and electrons in the p-region is separated by a very thin depletion region or depletion layer. This depletion region acts like dielectric or insulator of the capacitor and charge stored at both sides of the depletion layer acts like conducting plates of the capacitor.

Diffusion capacitance is directly proportional to the electric current or applied voltage. If large electric current flows through the diode, a large amount of charge is accumulated near the depletion layer. As a result, large diffusion capacitance occurs.

In the similar way, if small electric current flows through the diode, only a small amount of charge is accumulated near the depletion layer. As a result, small diffusion capacitance occurs.

When the width of depletion region decreases, the diffusion capacitance increases. The diffusion capacitance value will be in the range of nano farads (nF) to micro farads (μF).

The formula for diffusion capacitance is

$$CD = dQ / dV$$

Where,

CD = Diffusion capacitance

dQ = Change in number of minority carriers stored outside the depletion region

dV = Change in voltage applied across diode