PN Junction Formation, PN Junction Capacitance, VI Characteristics

BPT: 401: Electronics and Modern Physics

Tutorial - 5

Banaras Hindu University 01/04/2021

Sterlin

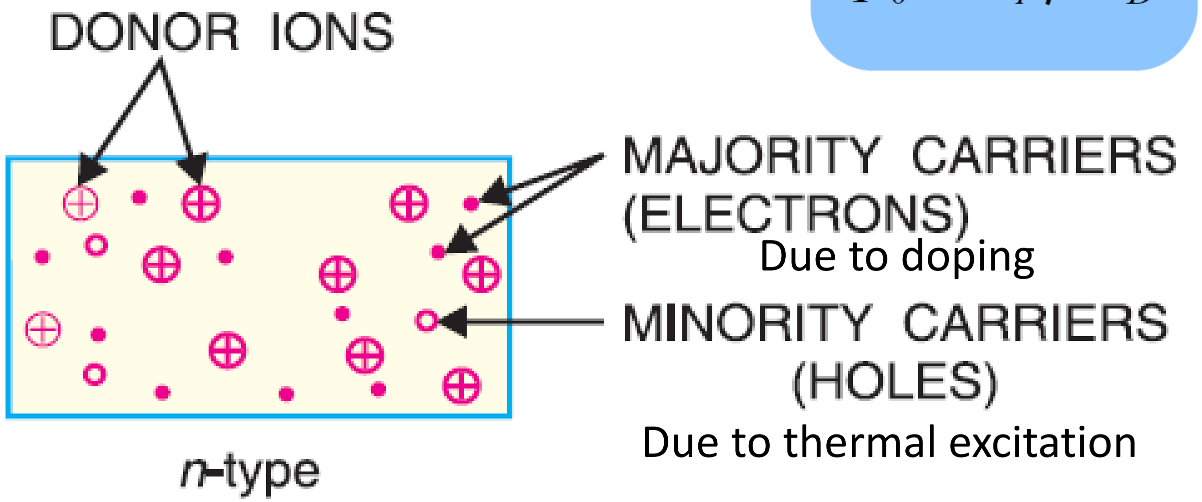
Majority and Minority Charge Carriers

N-type Semiconductor

$$n_0 \approx N_D^+$$

$$n_0 p_0 = n_i^2$$

$$p_0 = n_i^2 / N_D^+$$



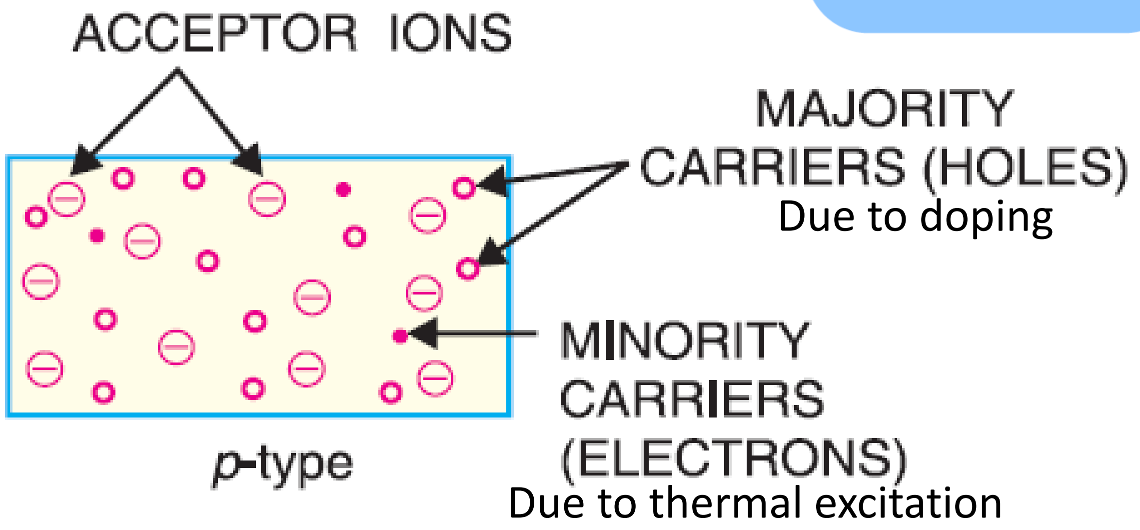
In *n*-type semiconductors, the free electrons are considered ***majority carriers*** (majority portion of current is by the flow of free electrons) and the holes are the ***minority carriers***.

P-type Semiconductor

$$p_0 \approx N_A^-$$

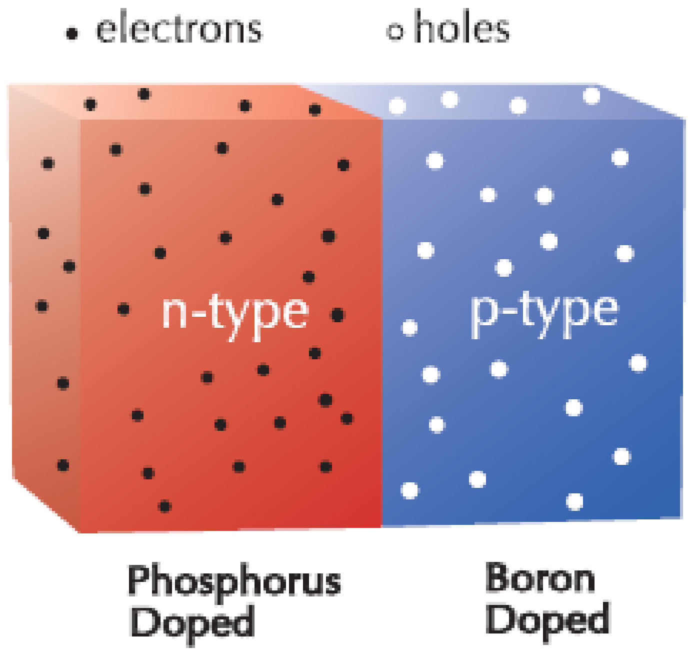
$$n_0 p_0 = n_i^2$$

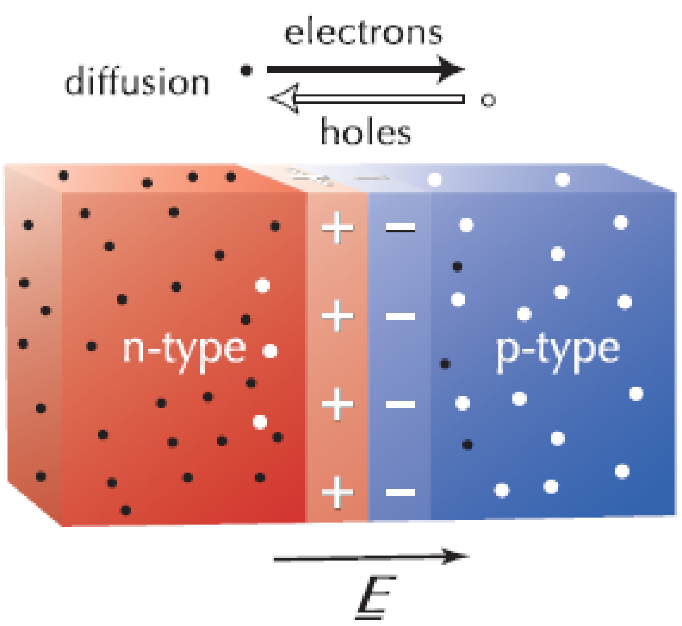
$$n_0 = n_i^2 / N_A^-$$



In a *p*-type semiconductors, holes are the ***majority carriers*** (majority portion of current is by the movement of holes) and free electrons are the ***minority carriers***.

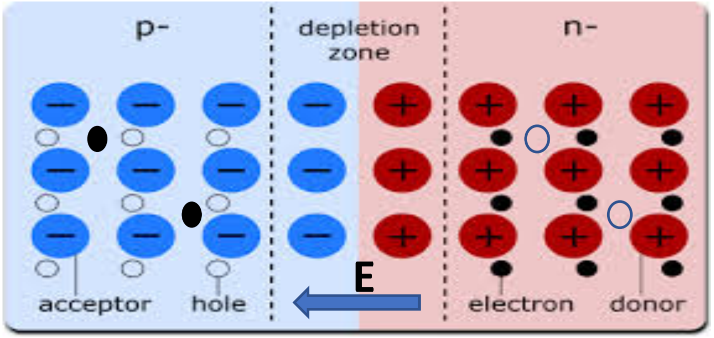
The PN Junction Formation





Due to the impurity doping, there are large numbers of mobile electrons on the n-type side (Conduction Band), but very few mobile electrons on the p-type side. Because of the random thermal motion of the free electrons, electrons from the n-type side start to diffuse into the p-type side.

Similarly, due to the impurity doping, there are large numbers of mobile holes on the p-type side (Valance Band), but very few mobile holes on the n-type side. Holes in the p-type side, therefore, start to diffuse across into the n-type side.



Electrons diffusion (J_n diff)

Holes diffusion (J_p diff)

Charge concentration gradient

J_n diff = $qD\frac{\partial n}{\partial x}$

$\frac{\partial n}{\partial x}$ *is the concentration gradient*

D is the diffusion coefficient

q is the carrier charge

J_n drift = $q\mu_n nE$

μ_n – Carrier mobility

n – charge carrier concentration

E- is the built-in electric field

As election diffuses from N to P type material (due to concentration gradient), it leaves positive charges (immobile donor ions) in the N type and vice versa. Once a majority carrier crosses the junction, it becomes a minority carrier. It will continue to diffuse away from the junction and can travel a distance on average equal to the diffusion length before it recombines with opposite charges. The current caused by the diffusion of carriers across the junction is called a **diffusion current**. As a result an electric field (E) is developed in the junction (depleted region). This built-in electric field push away the minority charge carriers, due to which a **drift current** is developed in the direction opposite to that of the direction of diffusion current. Under equilibrium, the drift current density is equal and opposite to that of the diffusion current density so there won't be further movement of charge carriers and the net current is zero in the depletion region. The electron drift current and electron diffusion current exactly balance out. Similarly, the hole current density also balance out.

$$J = J_p + J_n = 0$$

$$J_p = J_{p\ drift} + J_{p\ diff} = 0$$

$$J_n = J_{n\ drift} + J_{n\ diff} = 0$$

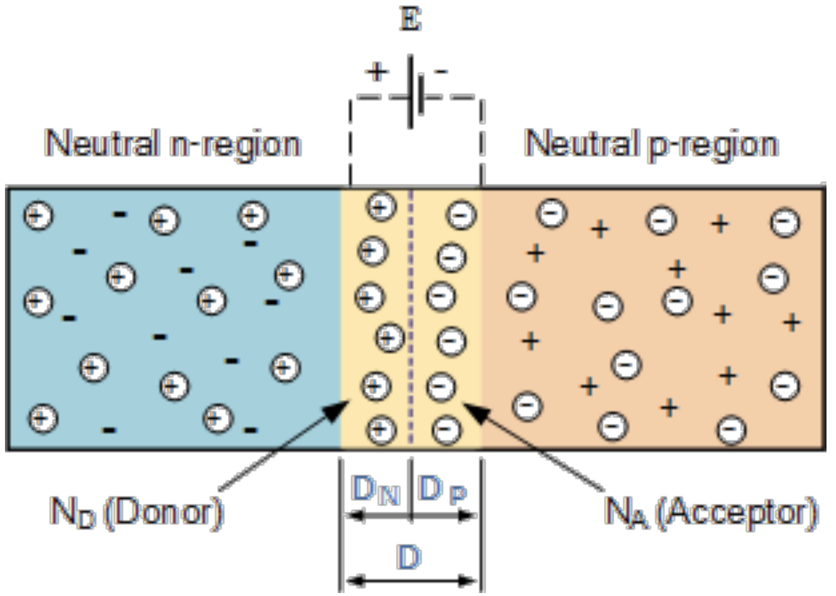
Diffusion current – due to Charge Concentration gradient

Drift current – due to Junction electric field

J - total current density, J_p – hole current density, J_n – electron current density

PN Junction Barrier or Built-in Potential

The total charge on each side of a *PN Junction* must be equal and opposite to maintain a neutral charge condition around the junction. If the depletion layer region has a distance $D = D_P + D_N$ (D_P for the positive side, and a distance of D_N for the negative side). in order to maintain charge neutrality also called equilibrium, $\mathbf{D_P * N_A = D_N * N_D}$.



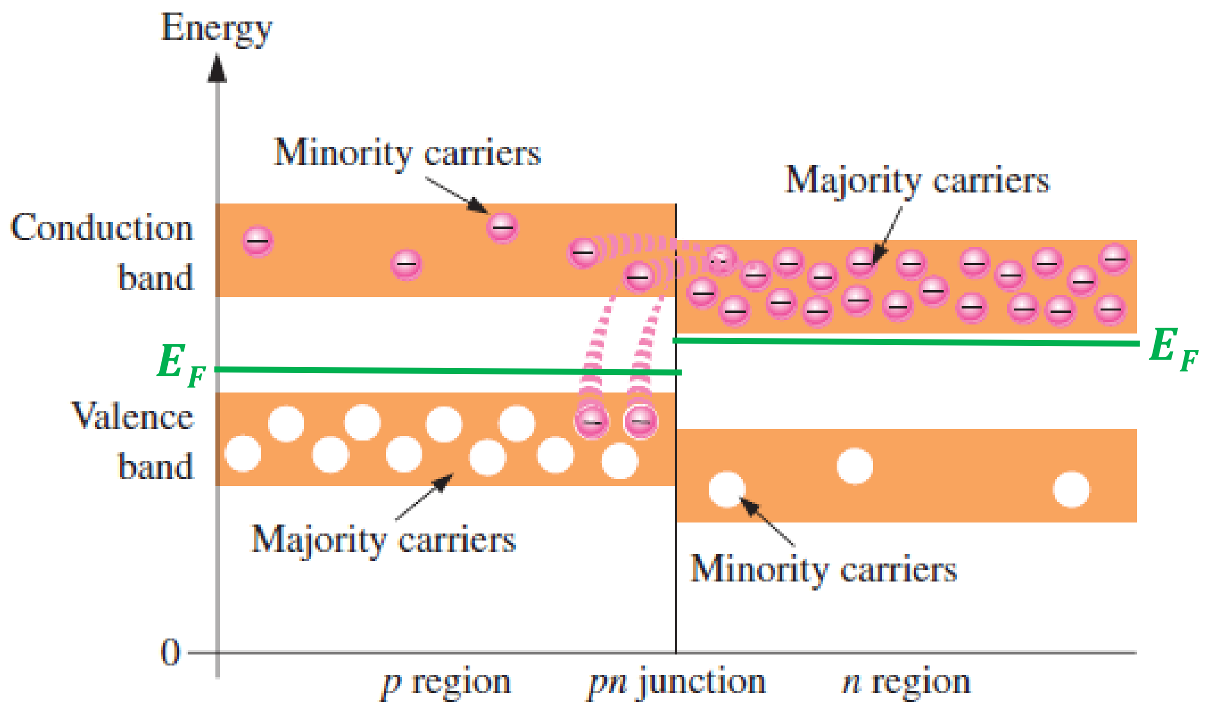
As the N-type material has lost electrons and the P-type has lost holes, the N-type material has become positive with respect to the P-type. Then the presence of impurity ions (immobile) on both sides of the junction cause an electric field to be established across this region with the N-side at a positive voltage relative to the P-side. The problem now is that a free charge requires some extra energy to overcome the barrier that now exists for it to be able to cross the depletion region junction. This electric field created by the diffusion process has created a "built-in potential difference" across the junction with an open-circuit (zero bias) potential of:

$$V_0 = VT \ln\left[\frac{N_D N_A}{n_i^2}\right]$$

Where, V_o is the zero bias junction voltage, V_T the thermal voltage of 26 mV at room temperature, N_D and N_A are the impurity concentrations and n_i is the intrinsic concentration.

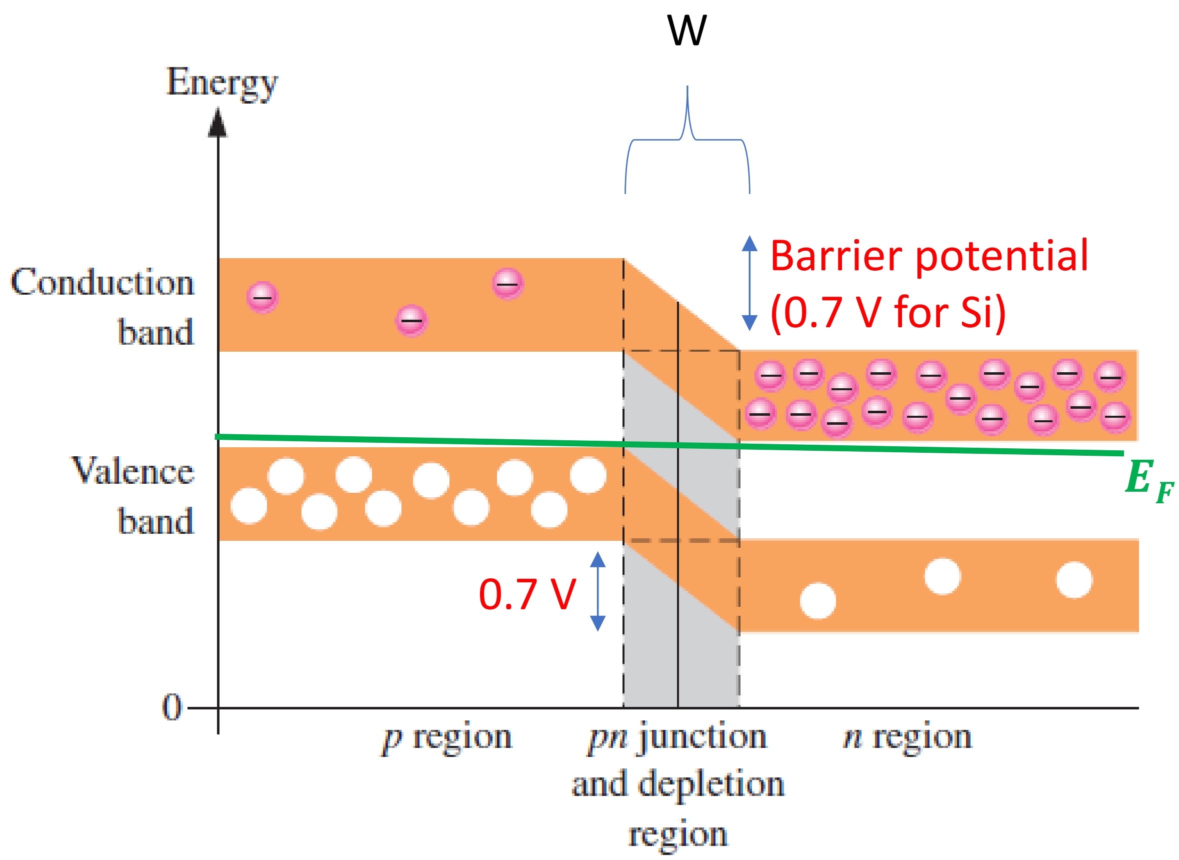
A suitable positive voltage (forward bias) applied between the two ends of the PN junction can supply the free electrons and holes with the extra energy. The external voltage required to overcome this potential barrier that now exists is very much dependent upon the type of semiconductor material used and its actual temperature. Typically at room temperature V_o for silicon is about 0.6 – 0.7 volts and for germanium V_o is about 0.3 – 0.35 volts. This potential barrier will always exist even if the device is not connected to any external power source, as seen in diodes.

Energy Diagrams of the PN Junction and Depletion Region



At the instant of PN junction formation

Depletion layer width at equilibrium (zero bias)

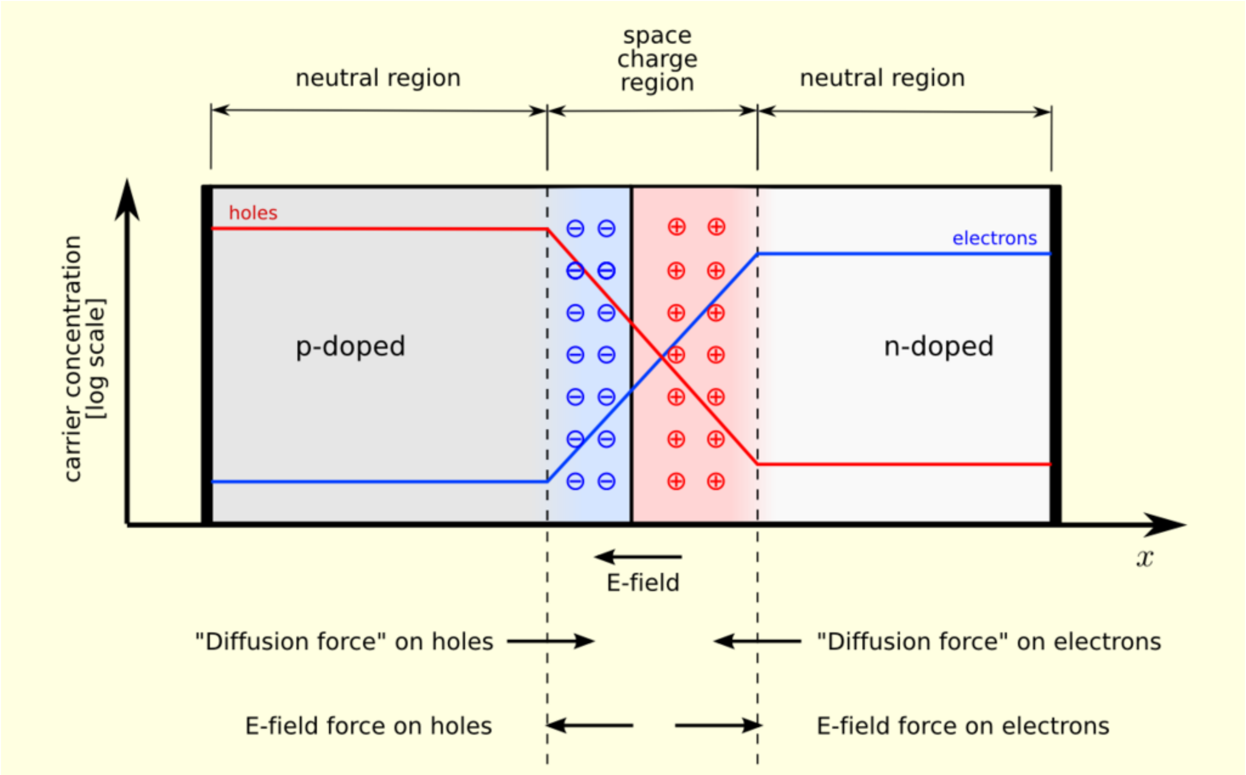


After PN junction formation

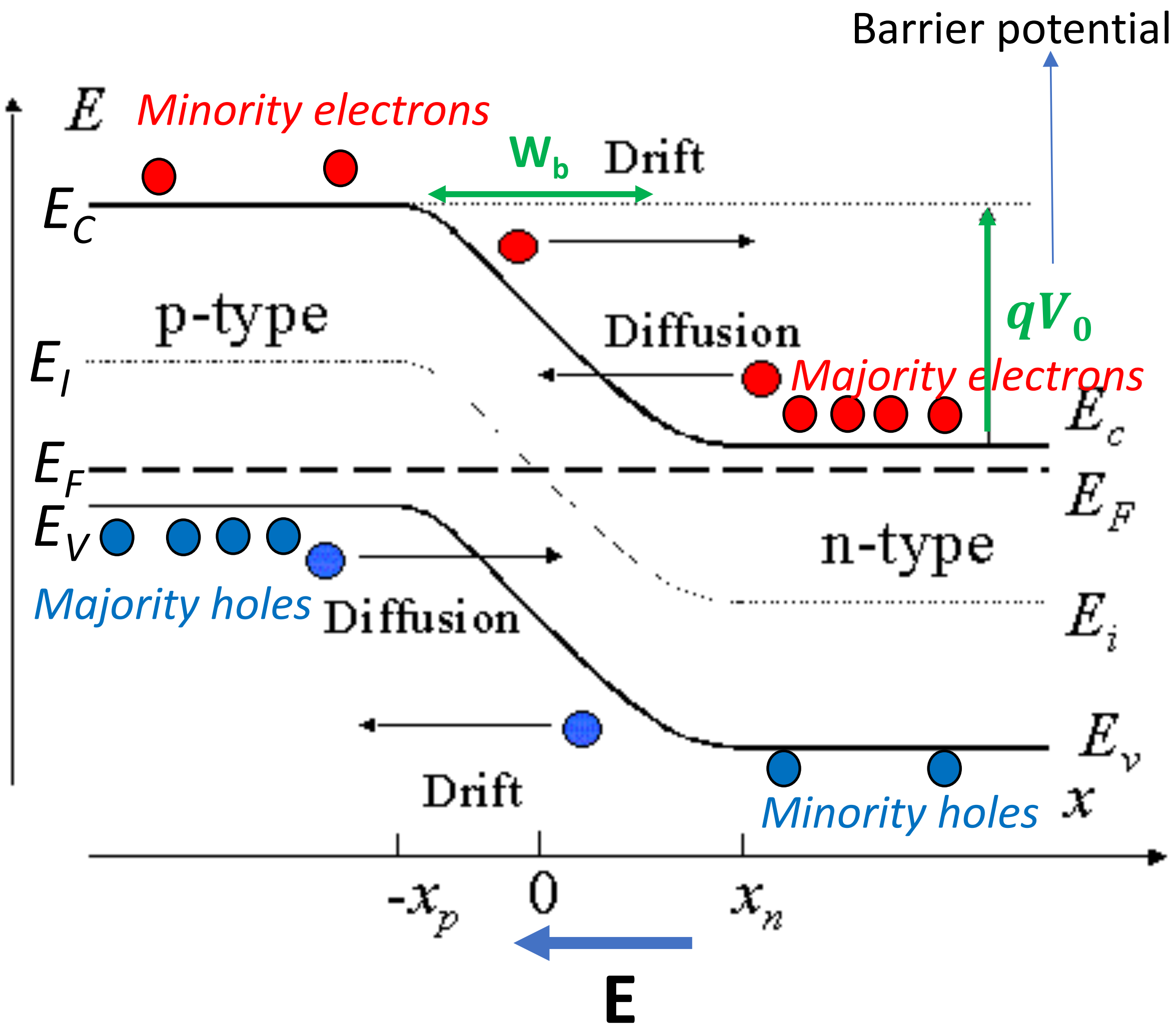
Barrier Potential

Silicon – 0.7 V
Germanium – 0.3 V

Energy Band diagram of PN junction

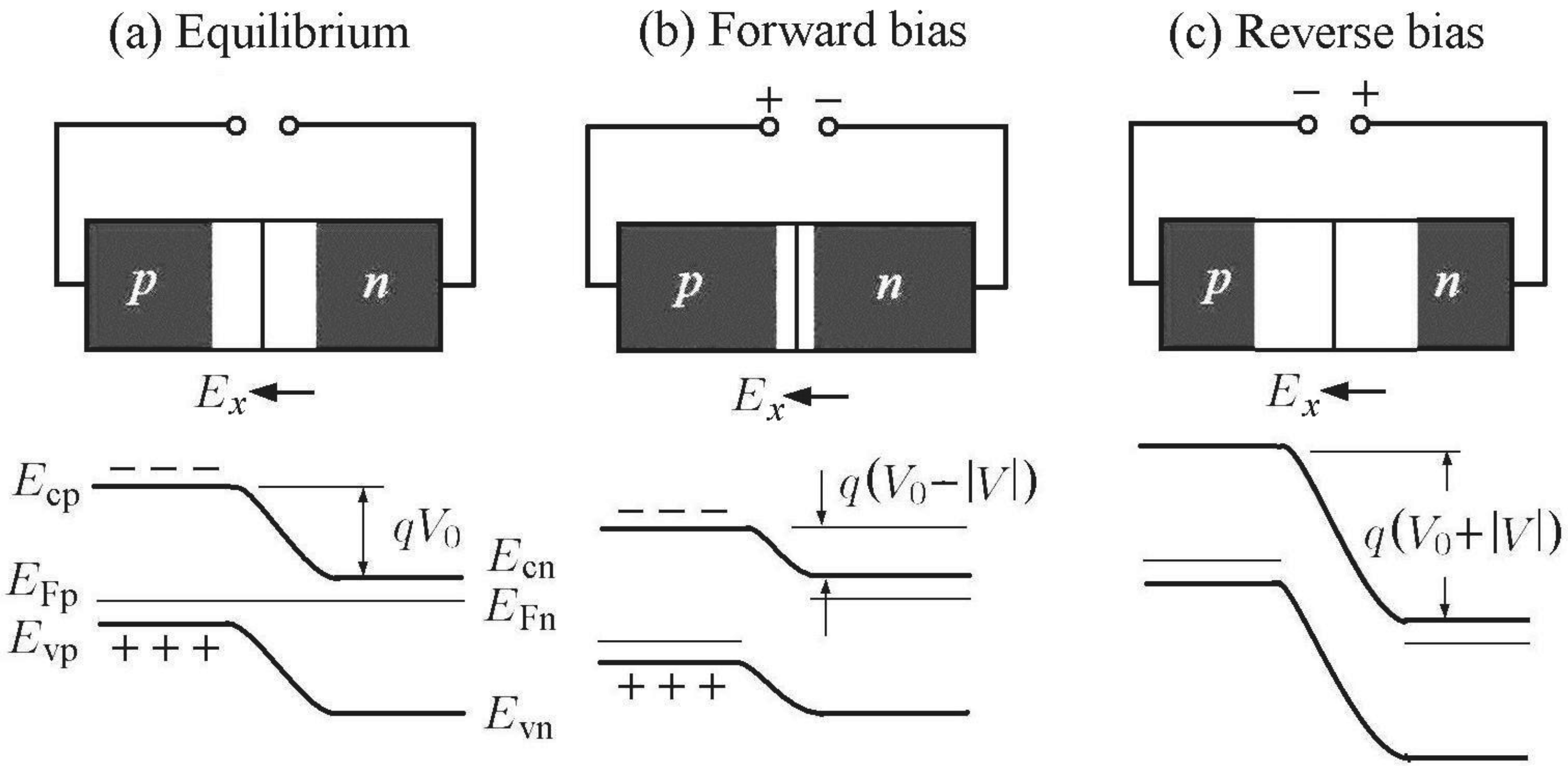


PN junction formation



Energy Band diagram of PN junction

Effect of bias in a *PN* junction



(a) At equilibrium, without external bias, the diffusion current and the drift current cancel each other. (b) A positive bias voltage pushes the holes to the *n*-side and the free electrons to the *p*-side. The potential barrier is reduced. Both diffusion currents of holes and free electrons are increased. The drift currents, depending on the available carriers, are unchanged. The net current is nonzero. (c) By applying a reversed bias, the holes are pushed further back into the *p*-region and the free electrons are pushed further back into the *n*-region. The diffusion current is reduced. Only the drift current persists.

PN Junction Capacitance

Basically, there are two types of capacitance associated with a p-n junction.

1. Transition Region Capacitance (C_T) or Depletion Layer Capacitance

- Due to the dipole in the transition region.
- Also called transition region capacitance or depletion layer capacitance.
- Dominates under reverse bias conditions.
- $C_T \propto W$ where, W is the Depletion layer width

2. Diffusion Capacitance (C_D) or Charge Storage Capacitance

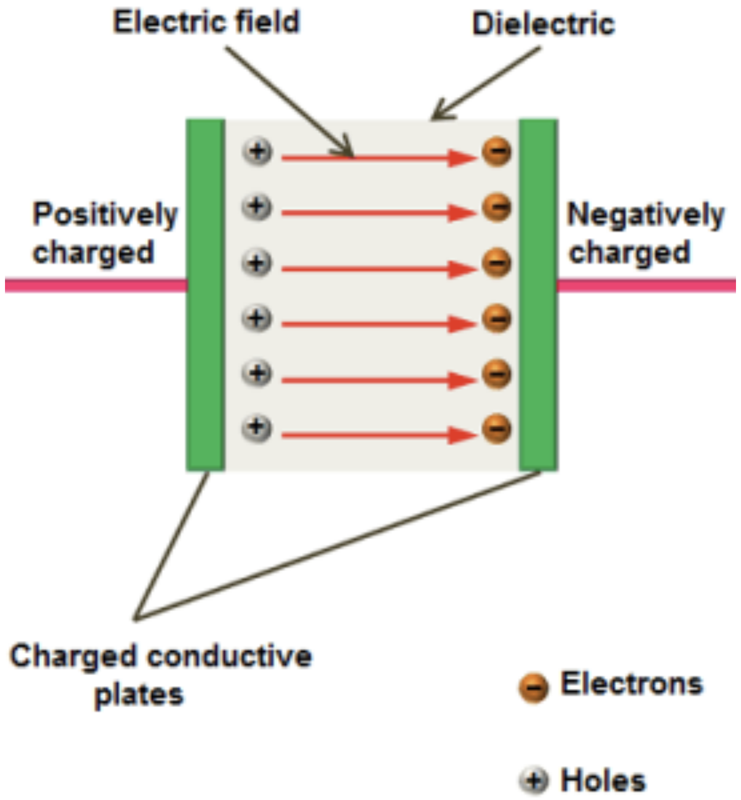
- Arises from the voltage lagging behind the current due to charge storage effects.
- Also referred to as diffusion capacitance.
- Dominant when the junction is forward biased.
-

PN junction capacitance

In a PN junction diode, two types of capacitance take place. They are,

- Transition capacitance (C_T)
- Diffusion capacitance (C_D)

We know that capacitors store electric charge in the form of electric field. This charge storage is done by using two electrically conducting plates (placed close to each other) separated by an insulating material called dielectric.



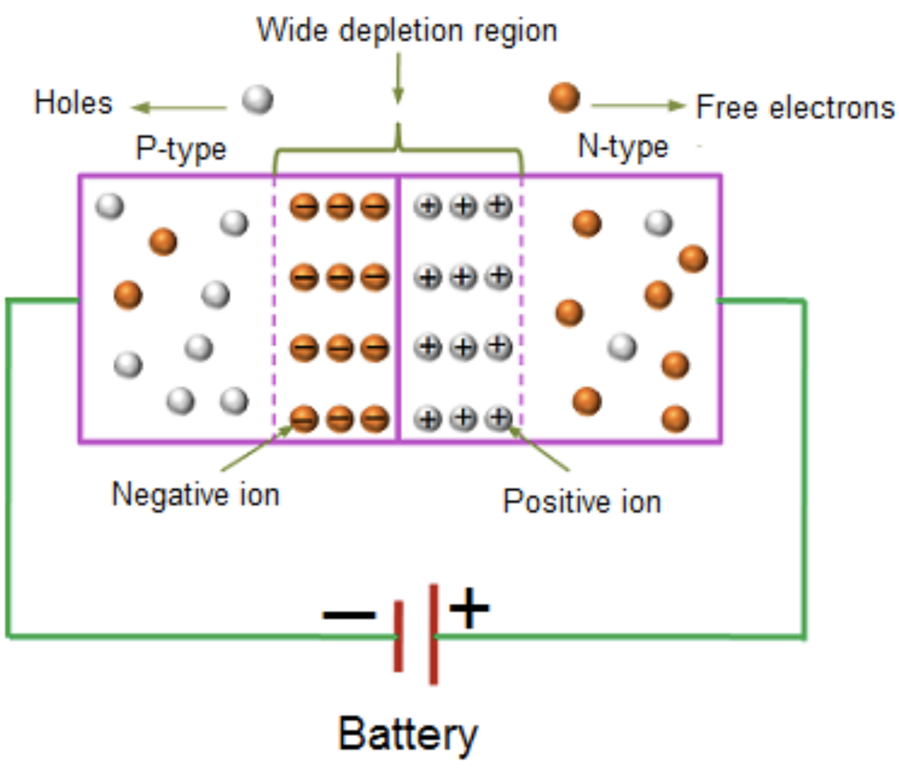
The conducting plates or electrodes of the capacitor are good conductors of electricity. Therefore, they easily allow electric current through them. On the other hand, dielectric material or medium is poor conductor of electricity. Therefore, it does not allow electric current through it. However, it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

When voltage is applied to the capacitor, a large number of charge carriers are trapped at the electrodes of the capacitor. These charge carriers cannot move between the plates due to dielectric medium in between the electrodes.

However, they exerts 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 ($C = \epsilon A/d$). $\varepsilon = \varepsilon_0 \varepsilon_r$

Transition capacitance (C_T)

Just like the capacitors, a reverse biased PN 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.



Reverse bias

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 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 PN junction. As a result, the width of depletion region increases whereas the size of p-type and n-type regions (plates) decreases.

Transition capacitance (C_T)

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 p-n junction, 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 (C_T). The transition capacitance is also known as depletion region capacitance, junction capacitance or barrier capacitance.

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

$$C_T = dQ / dV$$

Where,

CT = Transition capacitance

dQ = Change in electric charge

dV = Change in voltage

The transition capacitance can be mathematically written as,

$$C_T = \varepsilon A / W$$

Where,

ε = Permittivity of the semiconductor $\varepsilon = \varepsilon_0 \varepsilon_r$

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

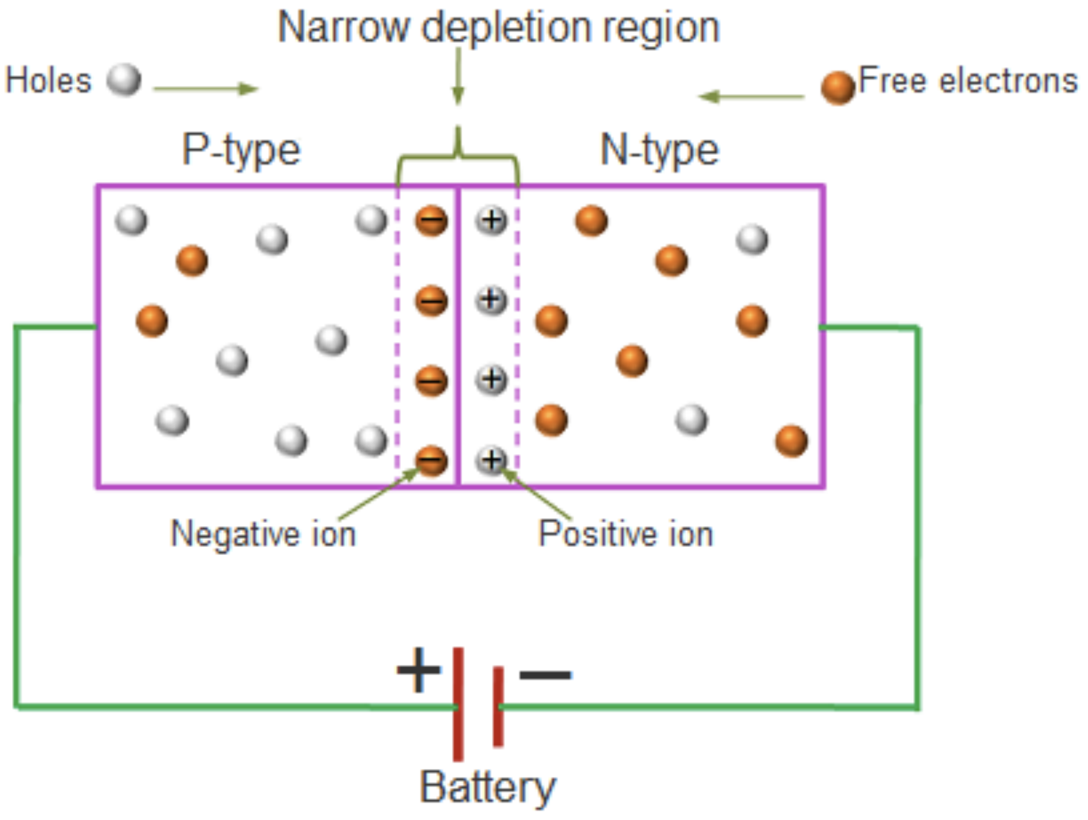
W = width of depletion region

Diffusion capacitance (C_D)

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

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



Forward bias

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 (C_D)

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).

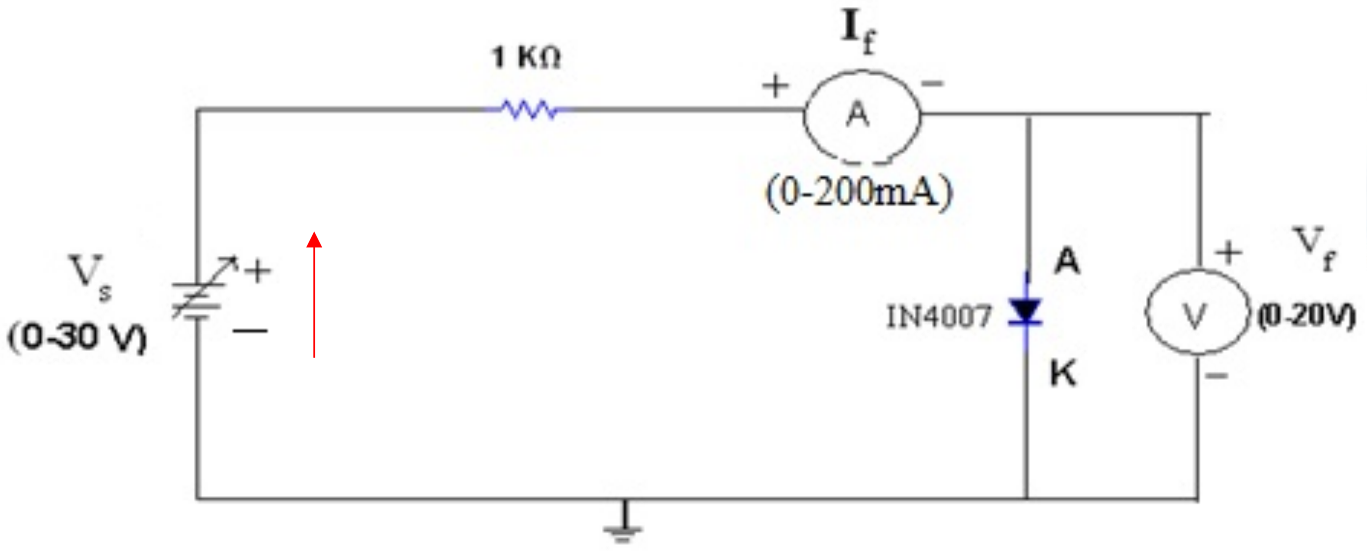
The formula for diffusion capacitance is

$$C_D = dQ / dV$$

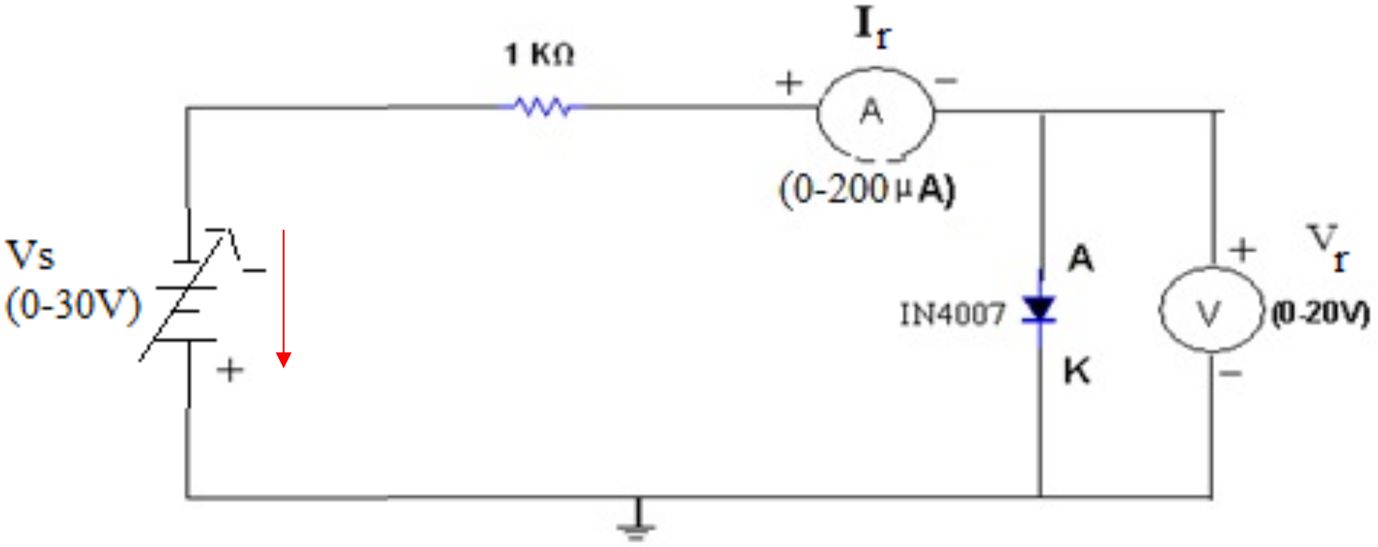
Where,

- C_D = Diffusion capacitance
- dQ = Change in number of minority carriers stored outside the depletion region
- dV = Change in voltage applied across diode

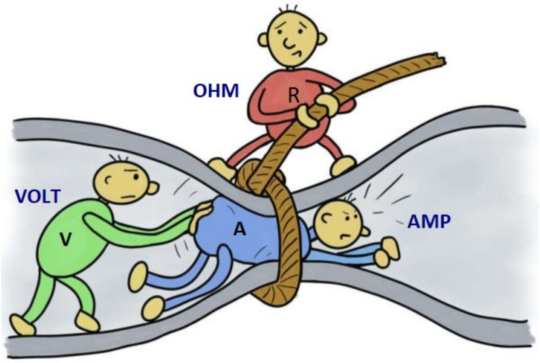
PN junction Biasing

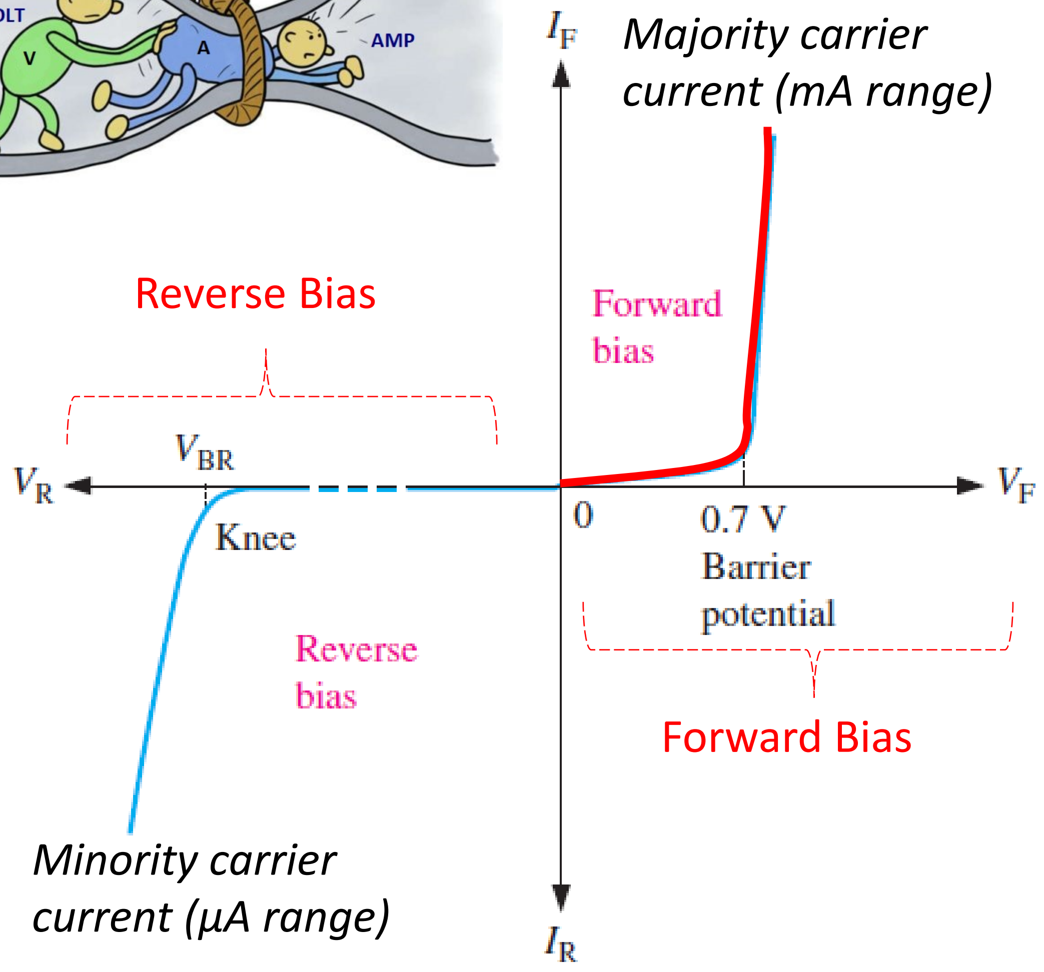


Forward Bias Condition



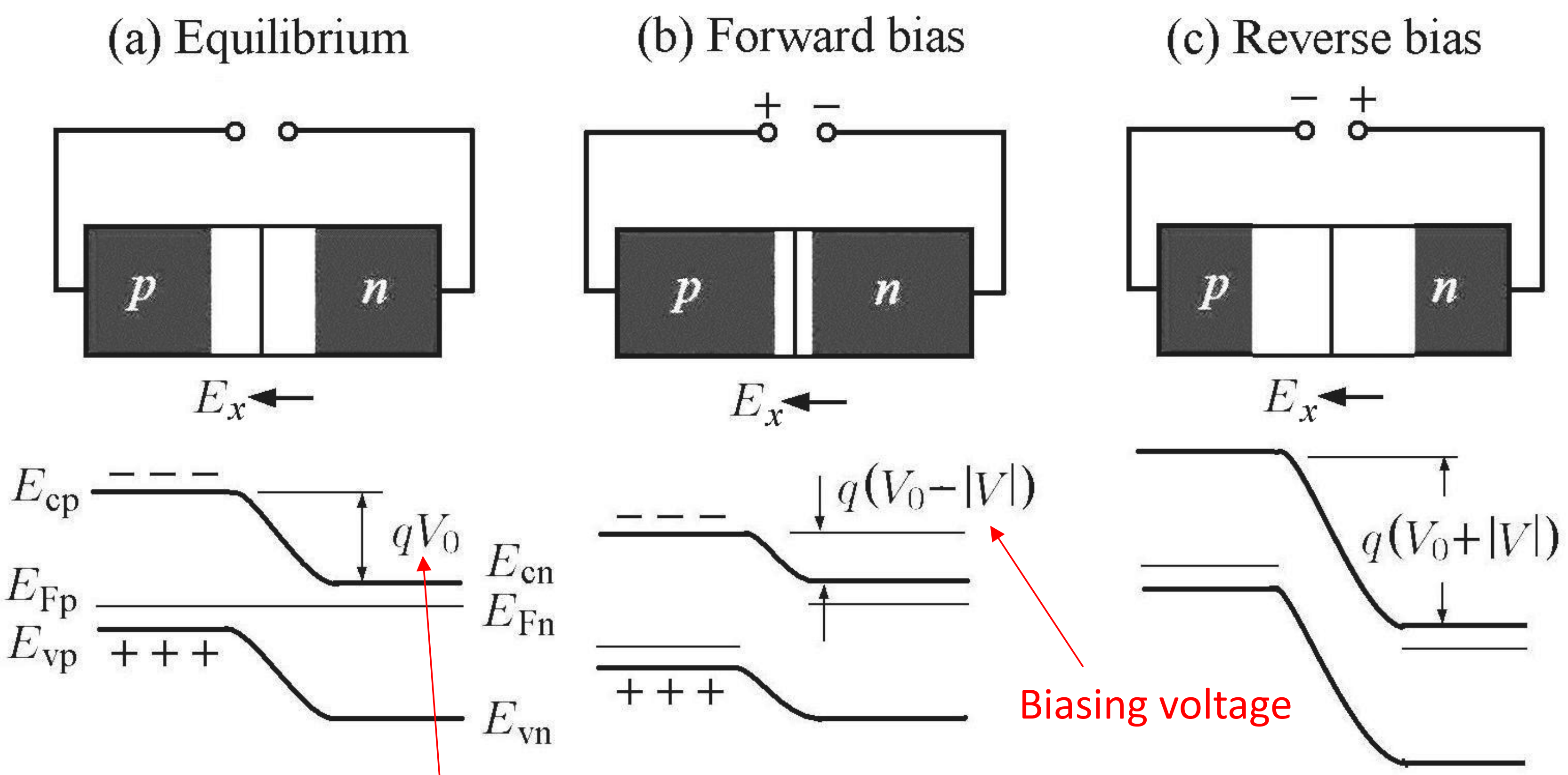
Reverse Bias Condition





V-I Characteristics of PN junction Diode

Effect of bias in a *PN* junction

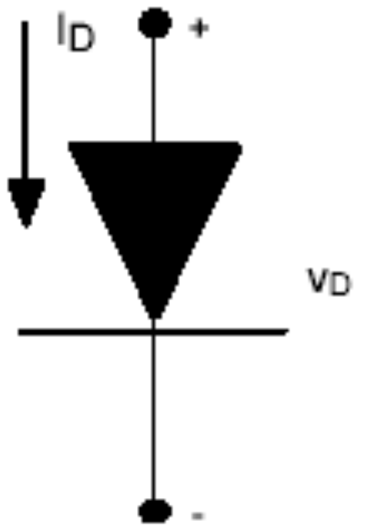


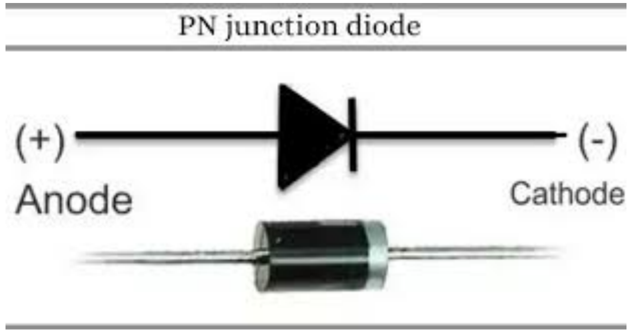
Biasing voltage

Barrier voltage

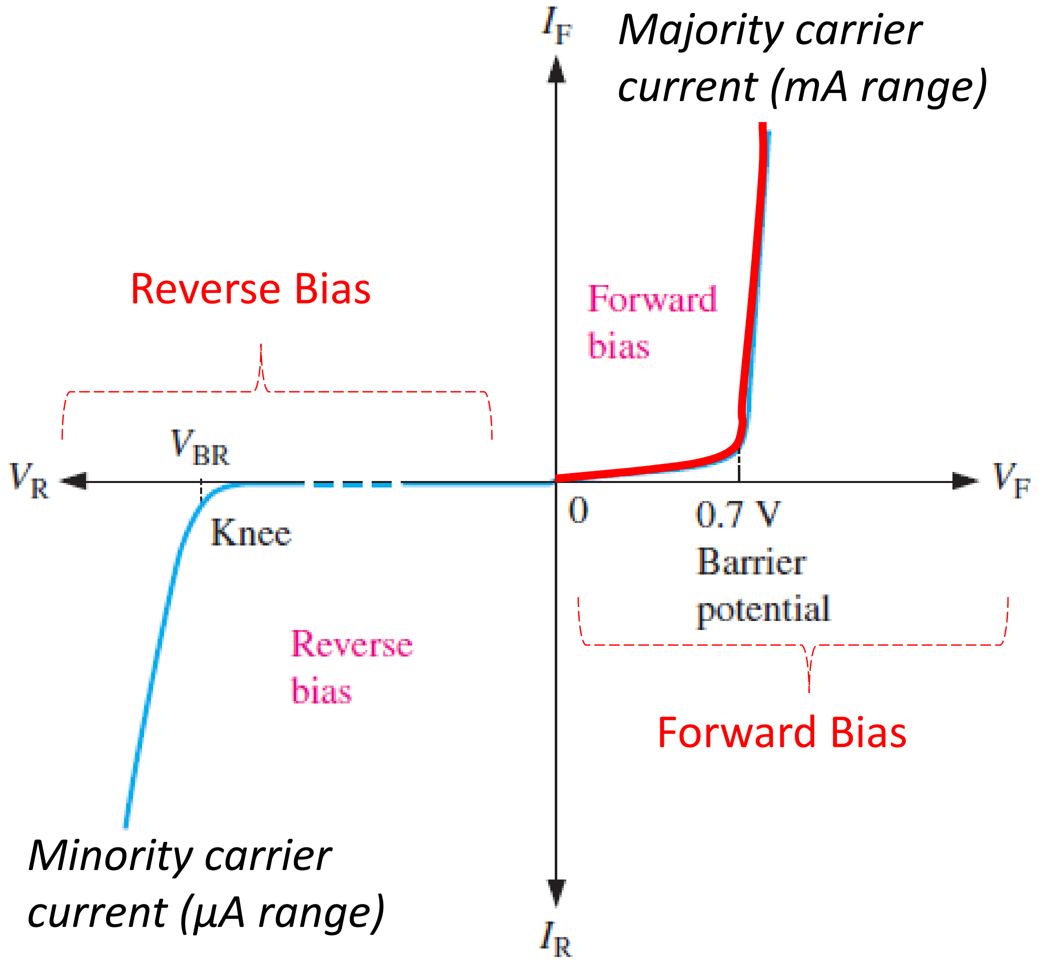
No external voltage

Circuit Symbol





V-I Characteristics of PN junction Diode



Static forward Resistance of diode, $R_F = \frac{\Delta VF}{\Delta IF}\,\Omega$

Static Reverse Resistance of diode, $R_R = \frac{\Delta V_R}{\Delta I_R}\,\Omega$

The volt-ampere characteristics of a diode explained by the following equations:

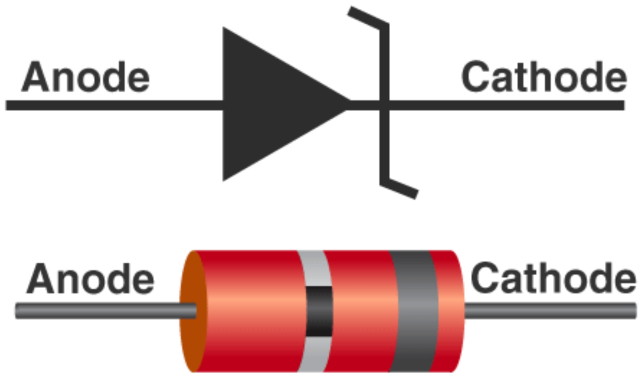
$$I = I_0\,(e^{\frac{V}{\eta V_T}} - 1)$$

Where, I = current flowing in the diode,
I_0 = reverse saturation current,
V = voltage applied to the diode,
V_T = volt- equivalent of temperature
= k T/q = T/ 11,600 = 26mV (@ room temp, 298 K)
(k - Boltzmann constant, q – charge of electron)
η = 2 (for Si) and 1 (for Ge)

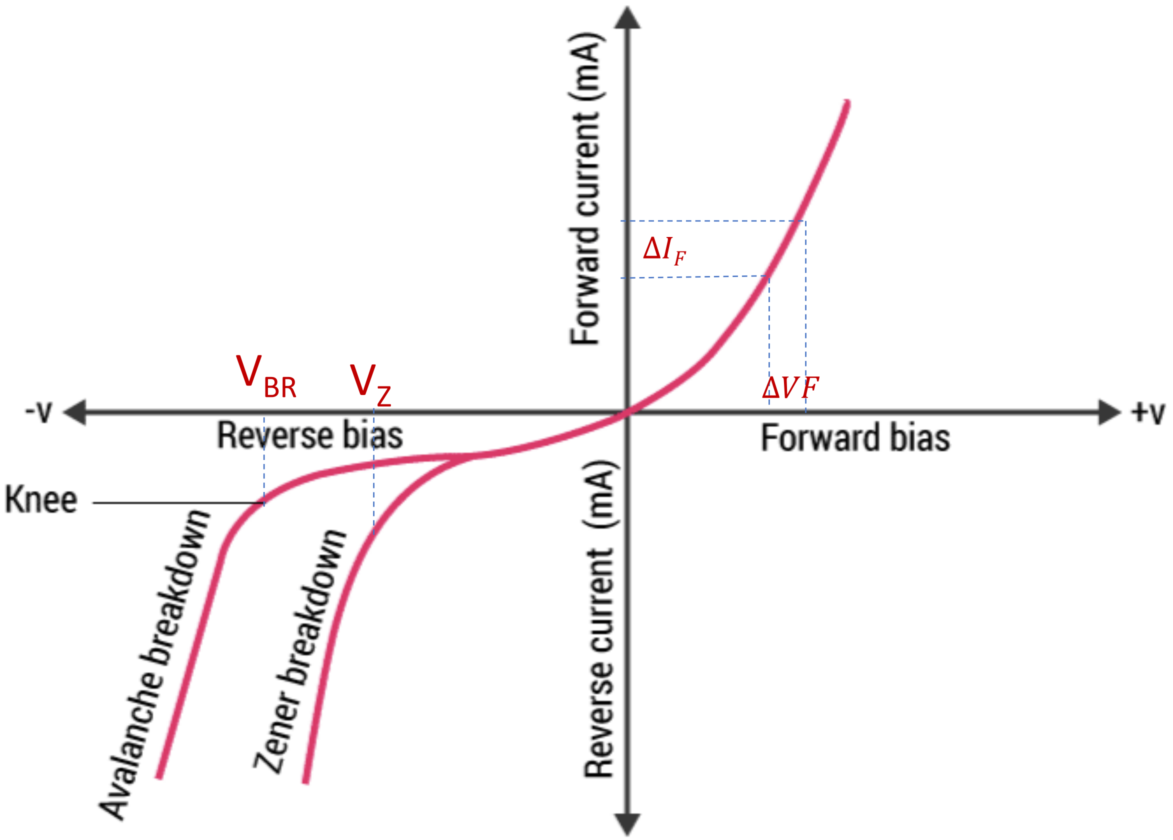
During reverse bias condition; when the voltage is increased the minority carriers obtain kinetic energy (drift current increases) and knocks out bonded electrons and these knocked off electrons have sufficient energy to collide and knock out further electrons and hence avalanche multiplication of electrons occur. This produces lot of heat inside the diode and damages the diode when operated under high reverse bias voltage.

V-I Characteristics of Zener Diode

In Zener diode, due to the high doping concentrations the width of depletion region is very narrow. Therefore the static electric field is much higher in the depletion region in comparison with that of PN junction diode. Therefore in the forward bias condition Zener diode has V-I characteristics same as that of PN junction diode but in the reverse bias condition, due to the very narrow depletion region and strong electric field in the depletion region pull electrons from their valence band. The valence electrons that gain sufficient energy from the strong electric field of the depletion region break free from the parent atom. At the Zener breakdown region, a small increase in the voltage results in the rapid increase of the electric current with out generating heat inside zener diode.



(Zener diode)



Static forward Resistance of diode, $R_F = \frac{\Delta VF}{\Delta IF} \Omega$