Semiconductor Diodes

I. P-Type, N-Type Semiconductors

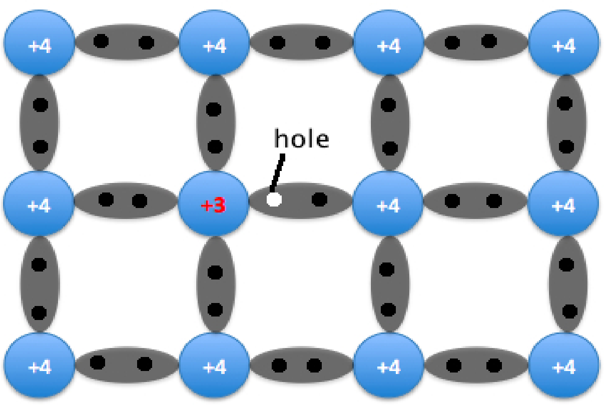
p-n junction diodes are made up of two adjacent pieces of p-type and n-type semiconducting materials. p-type and n-type materials are simply semiconductors, such as silicon (Si) or germanium (Ge), with atomic impurities; the type of impurity present determines the type of the semiconductor. The process of purposefully adding impurities to materials is called doping; semiconductors with impurities are referred to as "doped semiconductors".

P-type

In a pure (intrinsic) Si or Ge semiconductor, each nucleus uses its four valence electrons to form four covalent bonds with its neighbours (see figure below). Each ionic core, consisting of the nucleus and non-valent electrons, has a net charge of +4, and is surrounded by 4 valence electrons. Since there are no excess electrons or holes In this case, the number of electrons and holes present at any given time will always be equal.

An intrinsic semiconductor. Note each +4 ion is surrounded by four electrons.

Now, if one of the atoms in the semiconductor lattice is replaced by an element with three valence electrons, such as a Group 3 element like Boron (B) or Gallium (Ga), the electron-hole balance will be changed. This impurity will only be able to contribute three valence electrons to the lattice, therefore leaving one excess hole (see figure below). Since holes will "accept" free electrons, a Group 3 impurity is also called an acceptor.

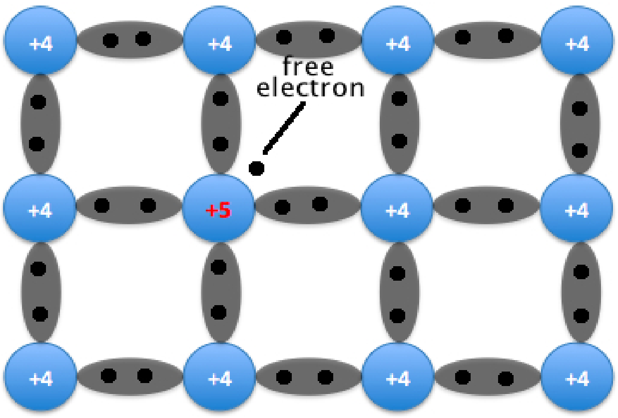


A semiconductor doped with an acceptor. An excess hole is now present.

Because an acceptor donates excess holes, which are considered to be positively charged, a semiconductor that has been doped with an acceptor is called a p-type semiconductor; "p" stands for positive. Notice that the material as a whole remains electrically neutral. In a p-type semiconductor, current is largely carried by the holes, which outnumber the free electrons. In this case, the holes are the majority carriers, while the electrons are the minority carriers.

N-type

In addition to replacing one of the lattice atoms with a Group 3 atom, we can also replace it by an atom with five valence electrons, such as the Group 5 atoms arsenic (As) or phosphorus (P). In this case, the impurity adds five valence electrons to the lattice where it can only hold four. This means that there is now one excess electron in the lattice (see figure below). Because it donates an electron, a Group 5 impurity is called a donor. Note that the material remains electrically neutral.



A semiconductor doped with a donor. A free electron is now present.

Donor impurities donate negatively charged electrons to the lattice, so a semiconductor that has been doped with a donor is called an n-type semiconductor; "n" stands for negative. Free electrons outnumber holes in an n-type material, so the electrons are the majority carriers and holes are the minority carriers.

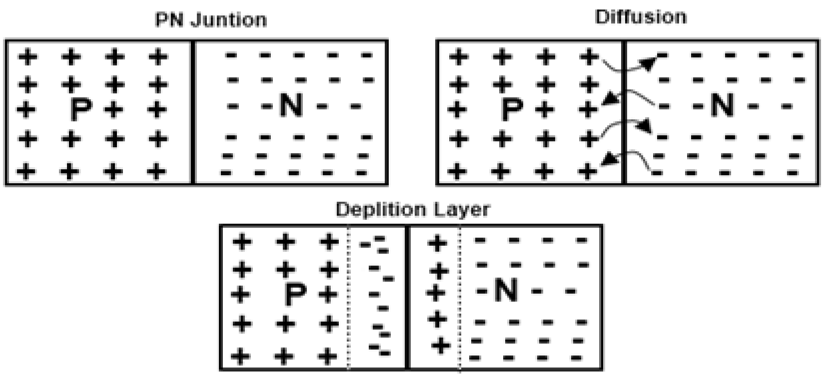
II. Barrier Formation in PN Junction Diode

p–n junction is a junction formed by joining p-type and n-type semiconductors together in very close contact. The term junction refers to the boundary interface where the two regions of the semiconductor meet. If they were constructed of two separate pieces this would introduce a grain boundary, so p–n junctions are more often created in a single crystal of semiconductor by doping, for example by ion implantation, diffusion of dopants, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant).

Formation of the Depletion Region-At the instant of the PN junction formation free electrons near the junction diffuse across the junction into the P region and combine with holes.

Filling a hole makes a negative ion and leaves behind a positive ion on the N side. These two layers of positive and negative charges form the depletion region, as the region near the junction is depleted of charge carriers. As electrons diffuse across the junction a point is reached where the negative charge repels any further diffusion of electrons. The depletion region now acts as a Barrier.

Barrier Potential, is the electric field formed in the depletion region acts as a barrier. External energy must be applied to get the electrons to move across the barrier of the electric field. The potential difference required to move the electrons through the electric field is called the barrier potential. Barrier potential of a PN junction depends on the type of semiconductor material, amount of doping and temperature. This is approximately 0.7V for silicon and 0.3V for germanium.



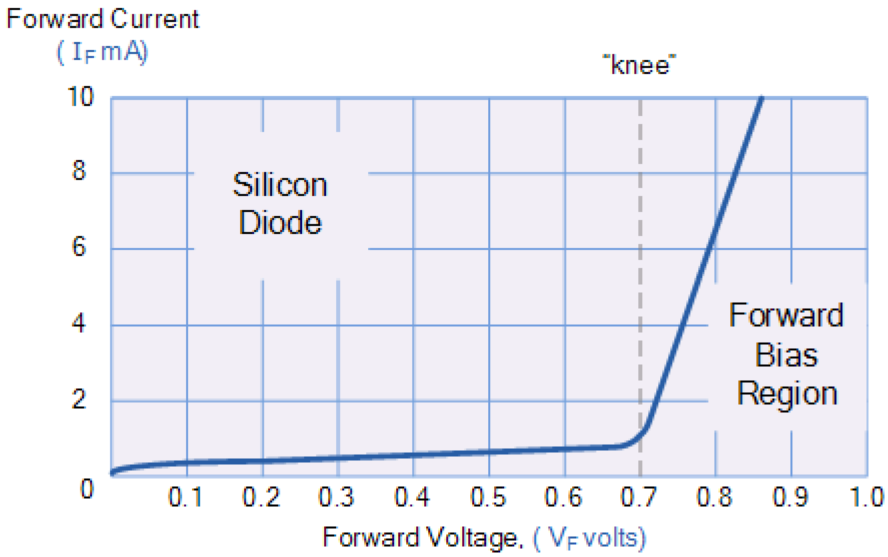
III. Biasing of a PN Junction

A. Forward Biased PN Junction Diode

When a diode is connected in a **Forward Bias** condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow.

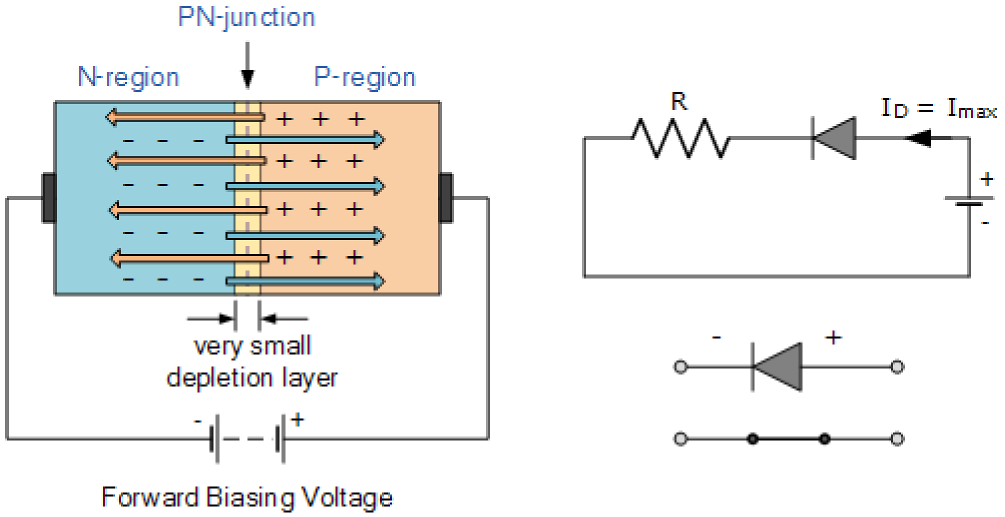
This is because the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage. This results in a characteristics curve of zero current flowing up to this voltage point, called the “knee” on the static curves and then a high current flow through the diode with little increase in the external voltage as shown below.

I. Forward Characteristics Curve



The application of a forward biasing voltage on the junction diode results in the depletion layer becoming very thin and narrow which represents a low impedance path through the junction thereby allowing high currents to flow. The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve above as the “knee” point.

II. Reduction in the Depletion Layer due to Forward Bias



This condition represents the low resistance path through the PN junction allowing very large currents to flow through the diode with only a small increase in bias voltage. The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at approximately 0.3v for germanium and approximately 0.7v for silicon junction diodes.

Since the diode can conduct "infinite" current above this knee point as it effectively becomes a short circuit, therefore resistors are used in series with the diode to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat than it was designed for resulting in a very quick failure of the device.

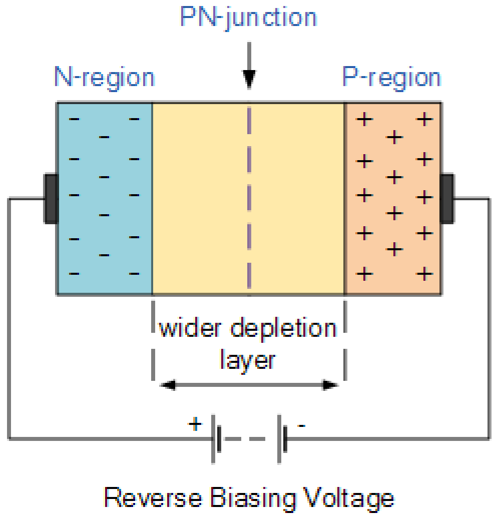
B. Reverse Biased PN Junction Diode

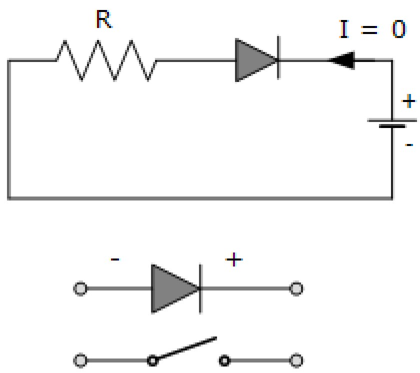
When a diode is connected in a **Reverse Bias** condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material.

The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode.

The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

I. Increase in the Depletion Layer due to Reverse Bias

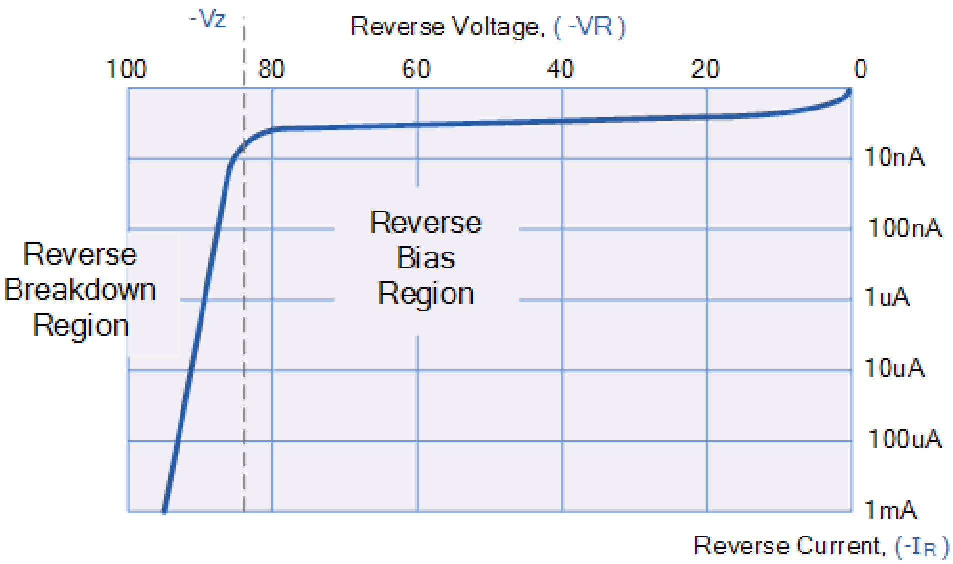




This condition represents a high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. However, a very small **leakage current** does flow through the junction which can be measured in micro-amperes, (μA).

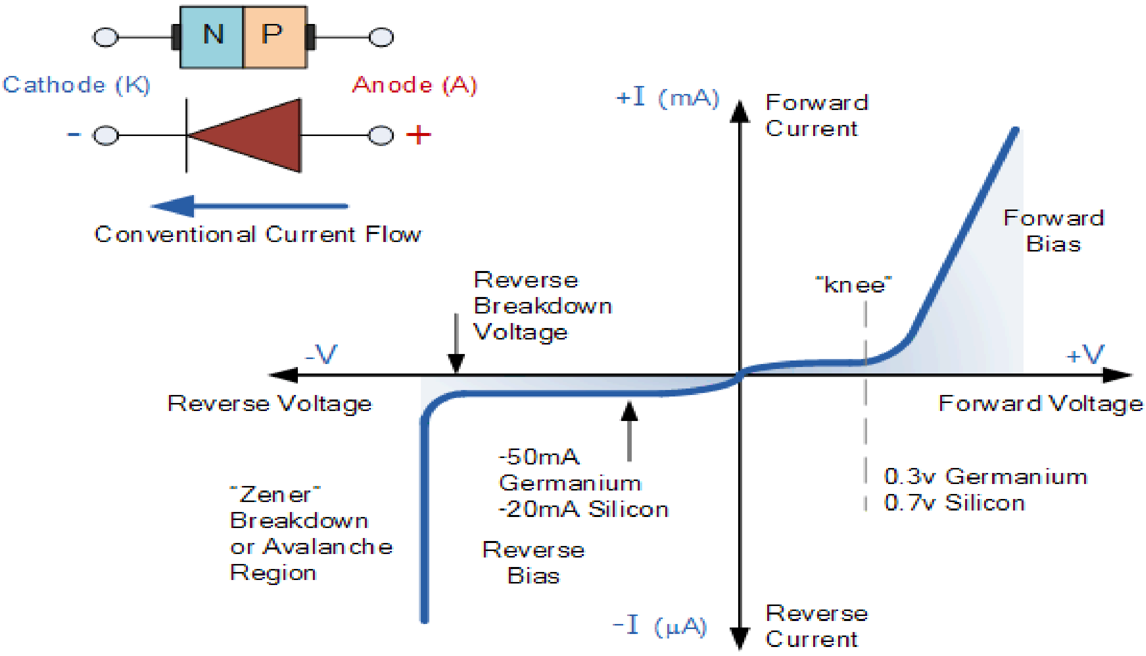
One final point, if the reverse bias voltage Vr applied to the diode is increased to a sufficiently high enough value, it will cause the diode's PN junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become shorted and will result in the flow of maximum circuit current, and this shown as a step downward slope in the reverse static characteristics curve below.

II. Reverse Characteristics Curve for a Junction Diode



Sometimes this avalanche effect has practical applications in voltage stabilising circuits where a series limiting resistor is used with the diode to limit this reverse breakdown current to a preset maximum value thereby producing a fixed voltage output across the diode.

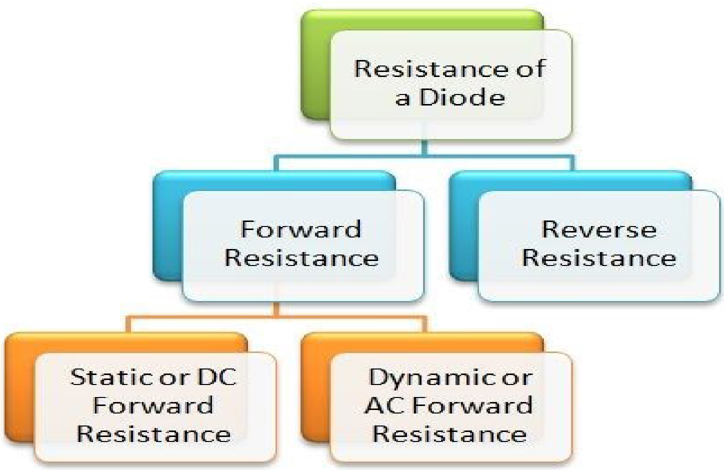
III. Junction Diode Symbol and Static I-V Characteristics



IV. Resistance of a PN Jn. Diode

In practice, no diode is an Ideal diode, this means neither it acts as a perfect conductor when forward biased nor it acts as an insulator when it is reverse biased. In other words an actual diode offers a very small resistance (not zero) when forward biased and is called a **forward resistance**. Whereas, it offers a very high resistance (not infinite) when reverse biased and is called as a **reverse resistance.**

The various resistances of a diode are as follows.



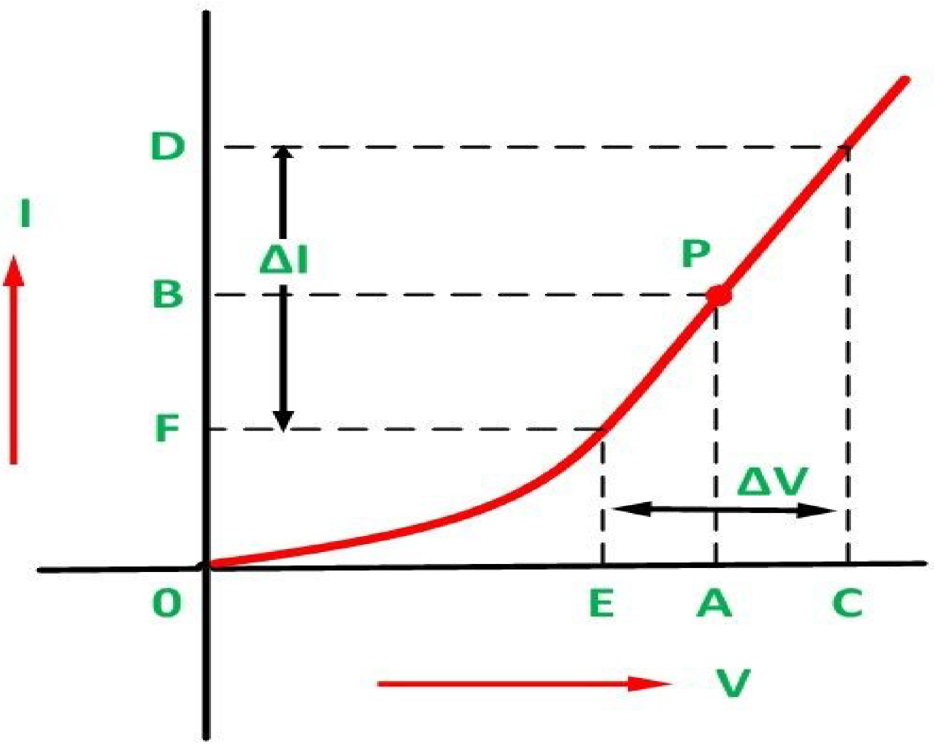
I. Forward Resistance

Under the Forward biased condition, the opposition offered by a diode to the forward current is known as Forward Resistance. The forward current flowing through a diode may be constant, i.e., direct current or changing i.e., alternating current. The forward resistance is classified as **Static Forward Resistance** and **Dynamic Forward Resistance.**

Static or DC Forward Resistance

The opposition offered by a diode to the direct current flowing forward bias condition is known as its **DC forward resistance** or Static Resistance. It is measured by taking the ratio of DC voltage across the diode to the DC current flowing through it.

The **forward characteristic** of a diode is shown below.



It is clear from the graph that for the operating point P, the forward voltage is OA and the corresponding forward current is OB. Therefore, the static forward resistance of the diode is given as

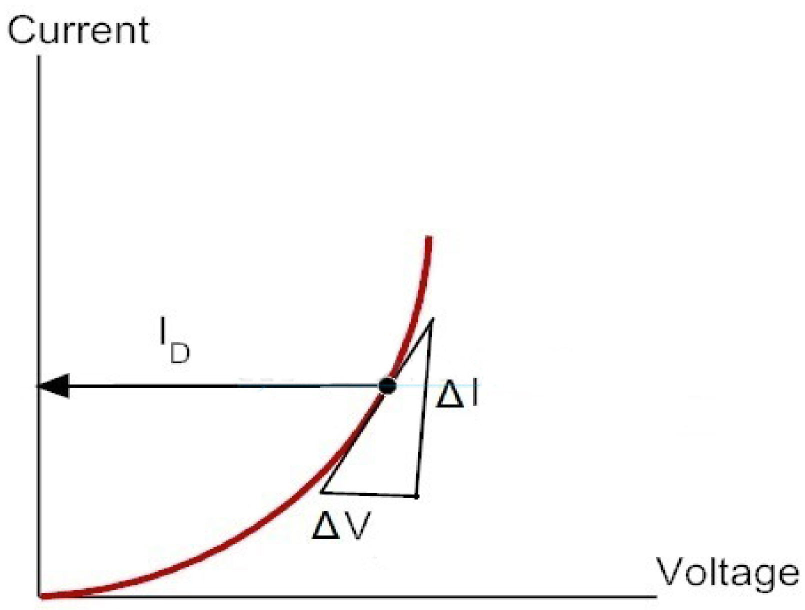
$$R_F = \frac{OA}{OB}$$

Dynamic or AC Forward Resistance

The opposition offered by a diode to the changing current flow I forward bias condition is known as its **AC Forward Resistance**. It is measured by a ratio of change in voltage across the diode to the resulting change in current through it. From the figure A above it is clear that for an operating point P the AC forward resistance is determined by varying the forward voltage (CE) on both the sides of the operating point equally and measuring the corresponding forward current (DF).

The Dynamic or AC Forward Resistance is represented as

$$r_f = \frac{CE}{DF} = \frac{\Delta V}{\Delta I}$$



The value of the forward resistance of a crystal diode is very small, ranging from 1 to 25 Ohms.

II. Reverse Resistance (R_R)

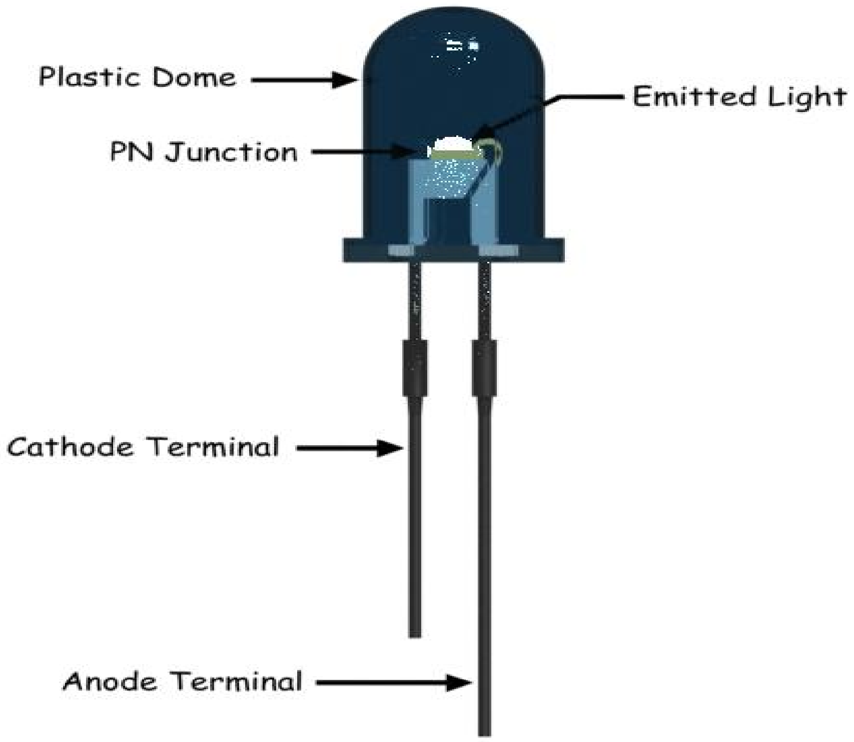
Under the Reverse biasing condition, the opposition offered by the diode to the reverse current is known as **Reverse Resistance**. Ideally, the reverse resistance of a diode is considered to be infinite. However, in actual practice the reverse resistance is not infinite because diode conducts a small leakage current (due to minority carriers) when reverse biased.

The value of reverse resistance is very large as compared to forward resistance. The ratio of reverse to forward resistance is 100000 : 1 for silicon diodes, whereas it is 40000 : 1 for germanium diode.

V. Light Emitting Diode (LED)

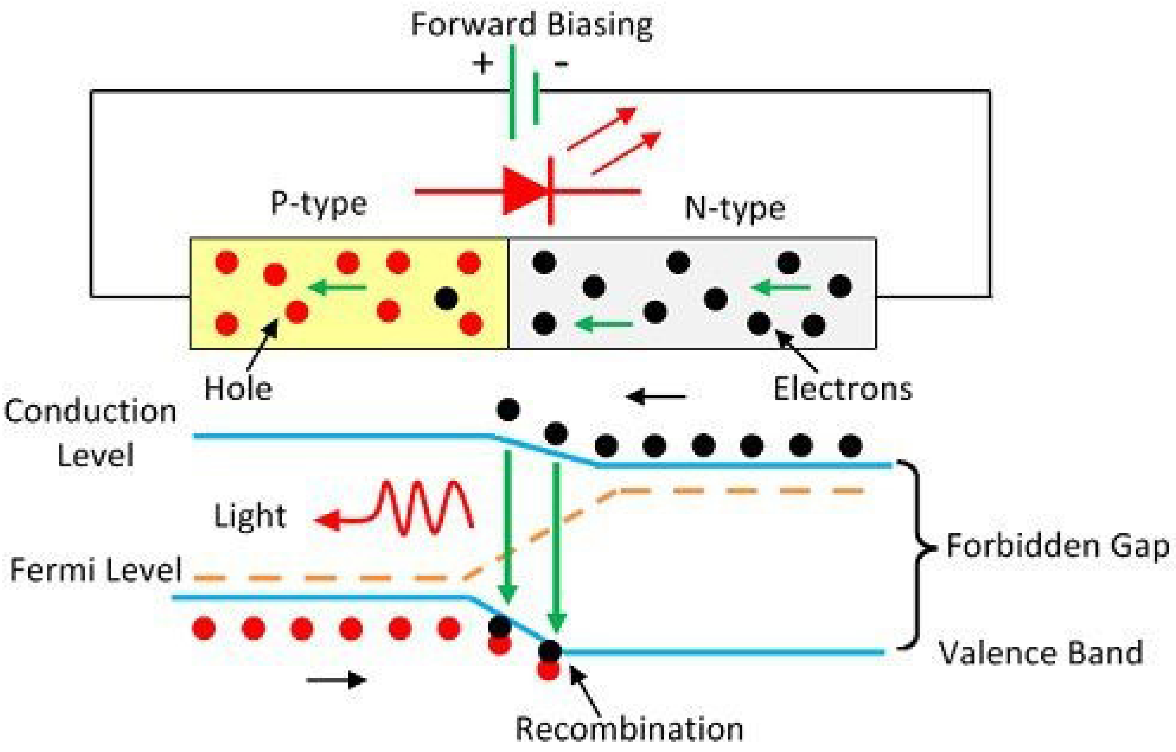
The lighting emitting diode is a p-n junction diode. It is a specially doped diode and made up of a special type of semiconductors. When the light emits in the forward biased, then it is called as a light emitting diode.

A. Physical Structure of LED



B. Working of LED

The working of the LED depends on the quantum theory. The quantum theory states that when the energy of electrons decreases from the higher level to lower level, it emits energy in the form of photons. The energy of the photons is equal to the gap between the higher and lower level.



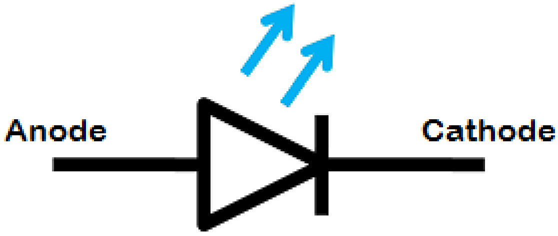
The LED is connected in the forward biased, which allows the current to flows in the forward direction. The flow of current is because of the movement of electrons in the opposite direction. The recombination shows that the electrons move from the conduction band to valence band and they emits electromagnetic energy in the form of photons. The energy of photons is equal to the gap between the valence and the conduction band.

C. Types of Light Emitting Diodes

There are different types of light emitting diodes present and some of them are mentioned below.

- Gallium Arsenide (GaAs) – infra-red
- Gallium Arsenide Phosphide (GaAsP) – red to infra-red, orange
- Aluminium Gallium Arsenide Phosphide (AlGaAsP) – high-brightness red, orange-red, orange, and yellow
- Gallium Phosphide (GaP) – red, yellow and green
- Aluminium Gallium Phosphide (AlGaP) – green
- Gallium Nitride (GaN) – green, emerald green
- Gallium Indium Nitride (GaInN) – near ultraviolet, bluish-green and blue
- Silicon Carbide (SiC) – blue as a substrate
- Zinc Selenide (ZnSe) – blue
- Aluminium Gallium Nitride (AlGaN) – ultraviolet

D. Symbol of LED

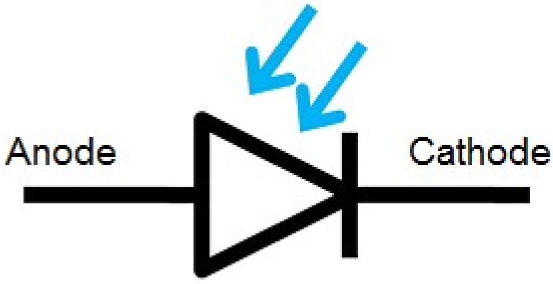


LED symbol

VI. Photodiode

Photodiode is a two terminal electronic device which, when exposed to light the current starts flowing in the diode. It is operated in reverse biased mode only. It converts **light energy** into **electrical energy.** When the ordinary diode is reverse biased the reverse current starts increasing with reverse voltage the same can be applied to the photodiode.

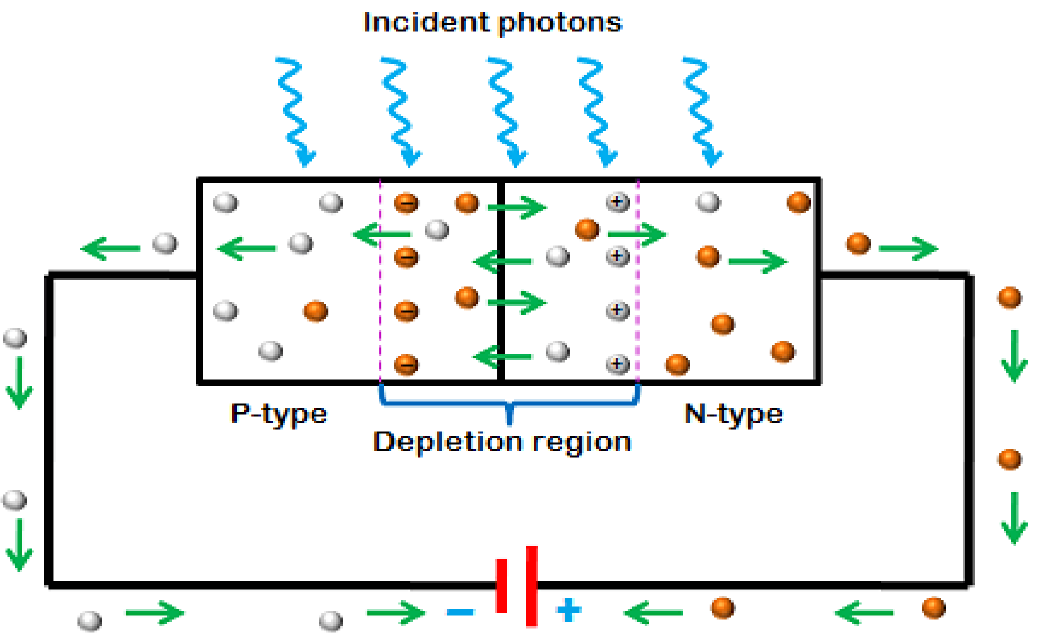
A. Symbol of Photodiode



Photodiode symbol

B. Working of Photodiode

When photons of energy greater than 1.1 eV hit the diode, electron-hole pairs are created. The intensity of photon absorption depends on the energy of photons – the lower the energy of photons, the deeper the absorption is. This process is known as the inner photoelectric effect.



PN Junction photodiode

If a photon of sufficient energy enters a depleted region of a diode, it could hit an atom with enough energy to release said electron from the atomic structure, thus creating a free electron and a hole ie an atom with an electron space. The electron has a negative charge, and the hole a positive charge. These electron-hole pairs drift apart and are swept from the junction - due to the built-in electric field of the depletion region. As a result, the holes move toward the anode and the electrons move toward the cathode, thereby producing photocurrent.

The sum of photocurrents and dark currents, which flow with or without light, is the total current passing through the photodiode. The sensitivity of the device can be increased by minimizing the dark current.

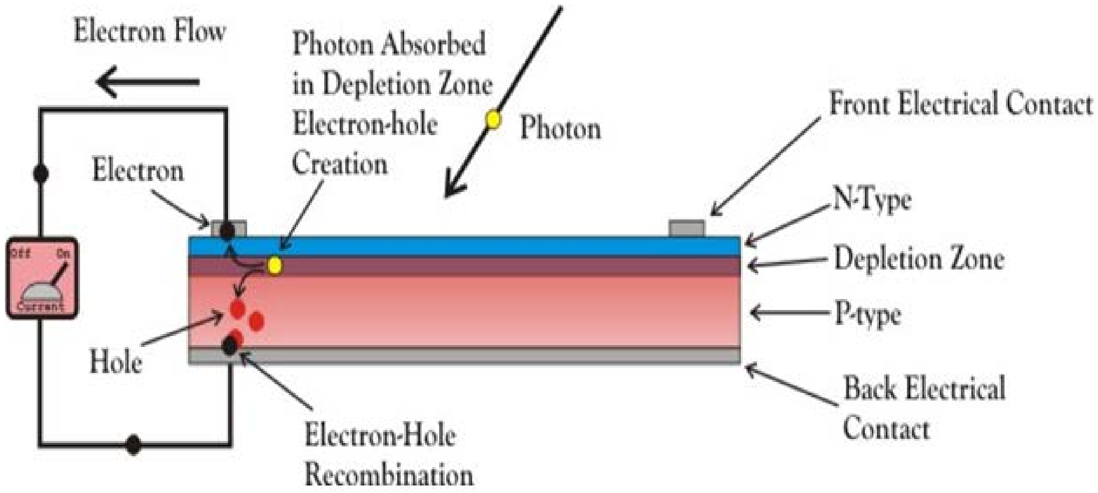
The current which flows in photodiode before light rays are incident on it is called **dark current.** As leakage current flows in the conventional diode, similarly the **dark current** flows in the photodiode.

VII. Solar Cell

A **solar cell** (also known as a photovoltaic cell or PV cell) is defined as an electrical device that converts light energy into electrical energy through the photovoltaic effect. A solar cell is basically a p-n junction diode. Solar cells are a form of photoelectric cell, defined as a device whose electrical characteristics – such as current, voltage, or resistance – vary when exposed to light.
Individual solar cells can be combined to form modules commonly known as solar panels. The common single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 to 0.6 volts. By itself this isn't much – but remember these solar cells are tiny. When combined into a large solar panel, considerable amounts of renewable energy can be generated.

A. Working Principle of Solar Cell

When light reaches the p-n junction, the light photons can easily enter in the junction, through very thin p-type layer. The light energy, in the form of photons, supplies sufficient energy to the junction to create a number of electron-hole pairs. The incident light breaks the thermal equilibrium condition of the junction. The free electrons in the depletion region can quickly come to the n-type side of the junction.



Similarly, the holes in the depletion can quickly come to the p-type side of the junction. Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction.

Similarly, the newly created holes once come to the p-type side cannot further cross the junction became of same barrier potential of the junction. As the concentration of electrons becomes higher in one side, i.e. n-type side of the junction and concentration of holes becomes more in another side, i.e. the p-type side of the junction, the p-n junction will behave like a small battery cell. A voltage is set up which is known as photo voltage. If we connect a small load across the junction, there will be a tiny current flowing through it.