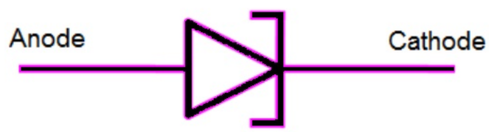
Tunnel Diode

A Tunnel diode is a heavily doped p-n junction diode which displays a negative resistance behaviour in a specific region in its characteristic curve. By Negative resistance we mean that in that region, the current flowing through the diode decreases as the voltage is increased. As the voltage is increased from zero, the current through the diode increases, then it decreases, and then it again increases. The initial increase of current (before its decrease) is attributed to a phenomenon called "Quantum Tunnelling". This is the reason for the particular name of this device. The tunnel diode is used as a fast switching device in computers as well as in high frequency oscillators and amplifiers.

Symbol of Tunnel Diode

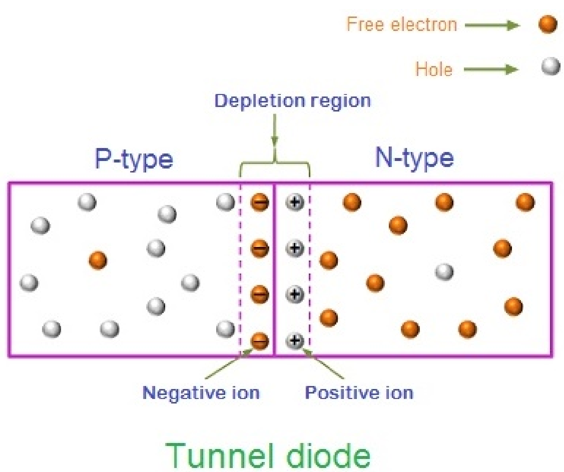
The symbol for Tunnel Diode is shown in the figure below.



An anode is a positively charged electrode that attracts electrons. The Cathode is a negatively charged electrode that emits electrons. In a tunnel diode, the anode is connected to p-type semiconductor while the cathode is connected to n-type semiconductor.

What is a Tunnel Diode

The Tunnel diode was invented by Leo Esaki in 1958. This is why it is also known as Esaki diode. Esaki observed that if a semiconductor is heavily doped with impurities, it exhibits a negative dynamic resistance. This means that the current through the device decreases as the voltage across it is increased. Leo Esaki got the Nobel Prize in 1973 for discovering the quantum tunnelling effect causes this behavior in these diodes. Quantum tunnelling refers to a direct flow of electrons across a thin depletion region from the n-side conduction band to the p-side valence band.



Tunnel Diodes are generally constructed from Germanium. But they are also made from other types of materials such as gallium arsenide, gallium antimonide, and silicon.

Width of the depletion region in tunnel diode

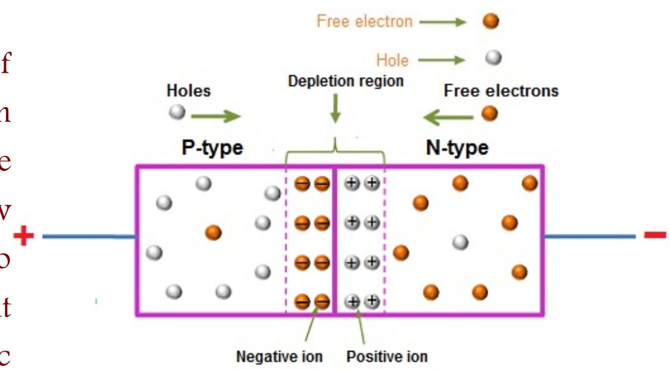
The depletion region is a region that exists on both sides of a p-n junction which is devoid of mobile charge carriers (Free electrons and Holes). This region acts as a potential barrier that opposes the flow of electrons from the n-side to p-side and of holes from the p-side to n-side. Only those very few charge carriers whose kinetic energy is more than the barrier height can cross the depletion region.

The width of the depletion region depends on the concentration of the impurity atoms. We call those specific atoms as impurities which have been introduced into the semiconductor in a very small amount to give them the characteristic properties that make them either p-type or n-type. If only a small number of impurity atoms are present, both on the n-side and the p-side (This is known as light doping) of the p-n junction diode, a wide depletion region is formed. On the other hand, if large number of impurities are added during the construction of the p-n junction diode, a narrow depletion region is formed.

In a Tunnel diode, the p-type and n-type semiconductors that form the junction are both heavily doped. This means that there is a very large concentration of impurity atoms on both sides of the p-n junction. The concentration of impurities in tunnel diode is nearly a thousand times greater than that in the normal p-n junction diode. This heavy doping produces an extremely narrow depletion region.

Forward biased normal p-n junction diode:

In a normal p-n junction diode, the width of the depletion region is large as compared to the width of depletion region the tunnel diode. This wide depletion layer in the normal diode opposes the flow of current. Hence, depletion layer acts as a barrier. To overcome this barrier, we need to apply sufficient voltage. When sufficient voltage is applied, electric current starts flowing through the diode.



Forward bias p-n junction diode

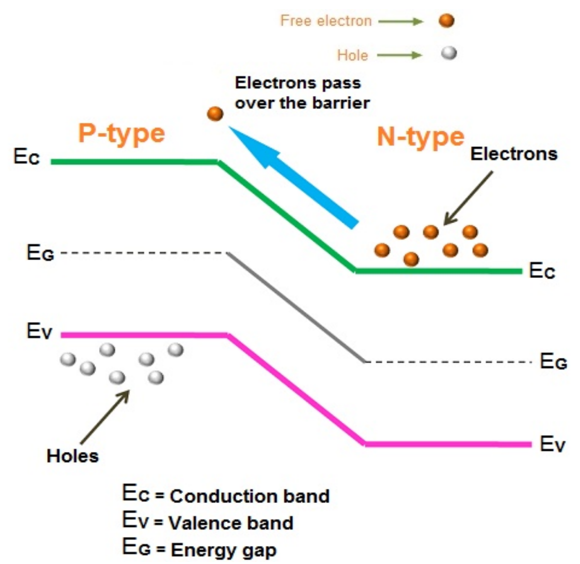
Forward biased tunnel diode: Unlike the normal p-n junction diode, the width of a depletion layer in tunnel diode is extremely narrow. So applying a small voltage is enough to produce electric current due to the quantum tunnelling effect. Quantum tunnelling is explained below.

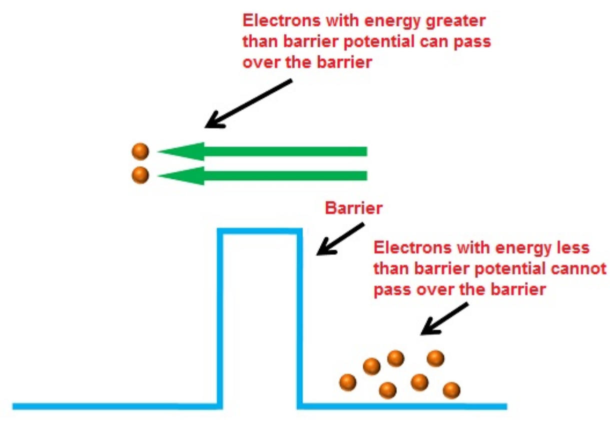
Tunnel diodes are capable of remaining stable for a long duration of time than the ordinary p-n junction diodes. They are also capable of high-speed operations.

Concept of tunneling

The depletion region in a p-n junction diode contains positive and negative ions embedded in the crystal lattice. These positive and negative ions create a potential gradient or electric field in the depletion region. This electric field exerts an electric force in a direction opposite to the externally applied electric field that is produced due to biasing. Now, energy levels of the valence band and conduction band in the n-type semiconductor are slightly lower than corresponding energy levels in the p-type semiconductor. This is because trivalent impurities exert lower forces on the outer-shell electrons and lower forces mean that the electron orbits are slightly larger and have greater energy.

When a forward bias voltage is applied to the ordinary p-n junction diode, the width of depletion region decreases and at the same time the barrier height also decreases. However, the electrons in the n-type semiconductor cannot penetrate through the depletion layer because the built-in voltage of depletion layer opposes the flow of electrons. If the applied voltage is greater than the built-in voltage of depletion layer, the electrons from n-side overcome the opposing force from depletion layer and they enters into p-side. In simple words, the electrons can pass over the barrier (depletion layer) if the energy of the electrons is greater than the barrier height or barrier potential. Therefore, an ordinary p-n junction diode produces electric current only if the applied voltage is greater than the built-in voltage of the depletion region.





Ordinary p-n junction diode

Electric current in a p-n junction diode:

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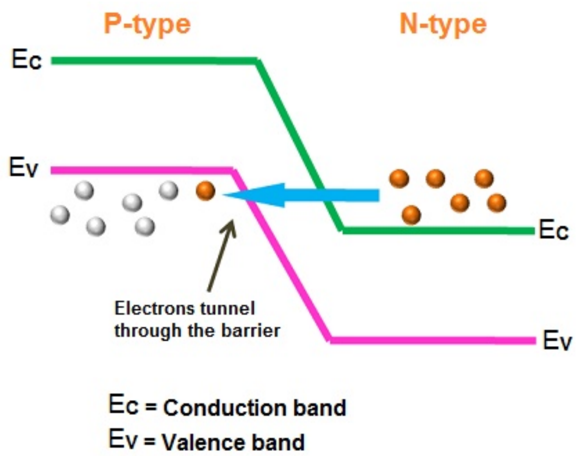
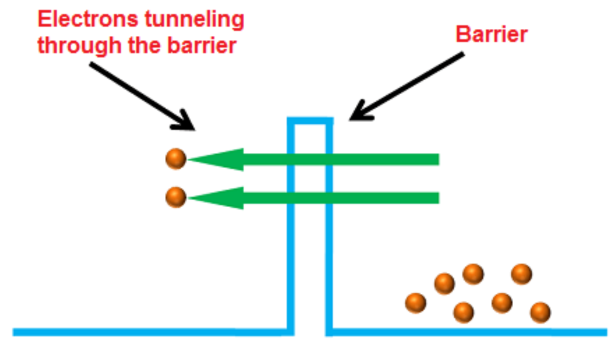
Electric current in a tunnel diode:

In tunnel diode, the valence band and conduction band energy levels in the n-type semiconductor are lower than the corresponding levels in the p-type semiconductor. Unlike the ordinary p-n junction diode, the difference in energy levels is very high in tunnel diode. Because of this high difference, the conduction band of the n-type material overlaps with the valence band of the p-type material.





Tunnel diode

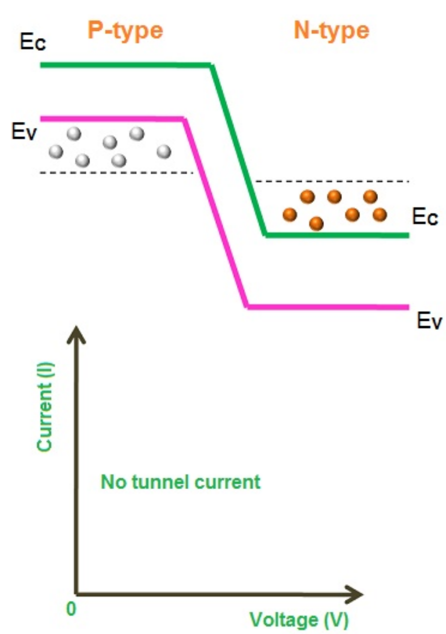
According to Quantum mechanics, the electrons directly penetrate through the depletion layer or barrier if the depletion width is very small. The depletion layer of tunnel diode is very small. It is in nanometers. So the electrons can directly tunnel across it from n-side conduction band into the p-side valence band.

In ordinary diodes, current is produced when the applied voltage is greater than the built-in voltage of the depletion region. But in tunnel diodes, a small voltage which is less than the built-in voltage of depletion region is enough to produce electric current.

In tunnel diodes, the electrons need not overcome the opposing force from the depletion layer to produce electric current. The electrons can directly tunnel from the conduction band of n-region into the valence band of p-region. Thus, electric current is produced in tunnel diode.

Tunnel Diode Chracteristics:

Step 1: Unbiased tunnel diode – When no voltage is applied to the tunnel diode, it is said to be an unbiased tunnel diode. In tunnel diode, the conduction band of the n-type material overlaps with the valence band of the p-type material because of the heavy doping. Because of this overlapping, the conduction band electrons at n-side and valence band holes at p-side are nearly at the same energy level. So when the temperature increases, some electrons tunnel from the conduction band of n-region to the valence band of p-region. In a similar way, holes tunnel from the valence band of p-region to the conduction band of n-region. The net current flow is zero because an equal number of charge carriers (free electrons and holes) flow in opposite directions.

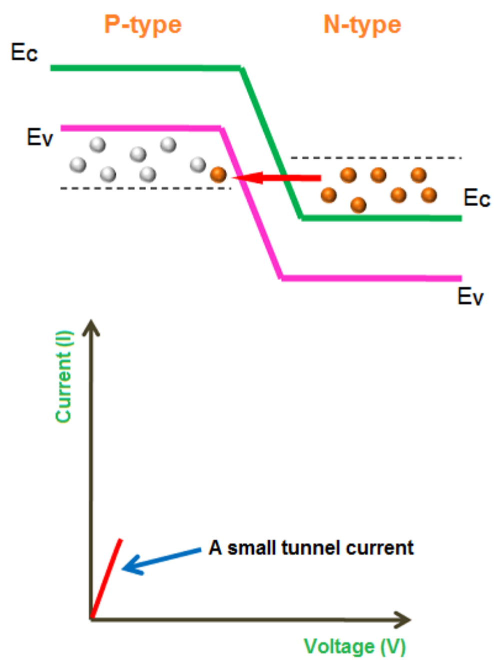


Unbiased tunnel diode

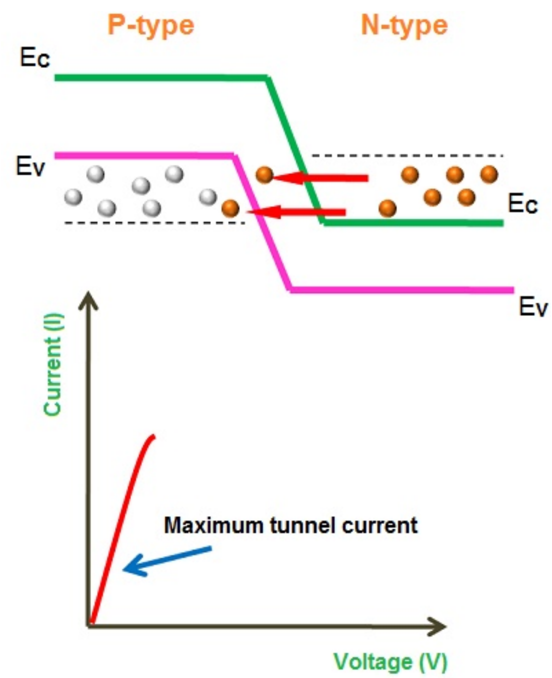
Step 2: Small voltage applied to the tunnel diode

When a small voltage is applied to the tunnel diode which is less than the built-in voltage of the depletion layer, no forward current flows through the junction.

However, a small number of electrons in the conduction band of the n-region will tunnel to the empty states of the valence band in p-region. This will create a small forward bias tunnel current. Thus, tunnel current starts flowing with a small application of voltage.



Small tunnel current



Maximum tunnel current

Step 3: Applied voltage is slightly increased

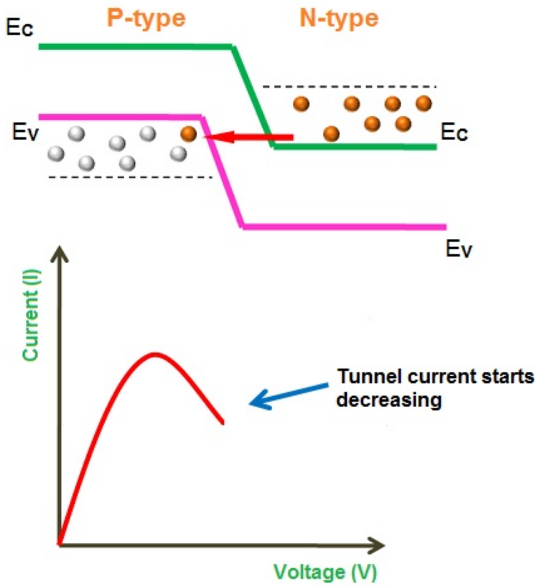
When the voltage applied to the tunnel diode is slightly increased, a large number of free electrons at n-side and holes at p-side are generated. Because of the increase in voltage, the overlapping of the conduction band and valence band is increased. In simple words, the energy level of an n-side conduction band becomes exactly equal to the energy level of a p-side valence band. As a result, maximum tunnel current flows.

Step 4: Applied voltage is further increased

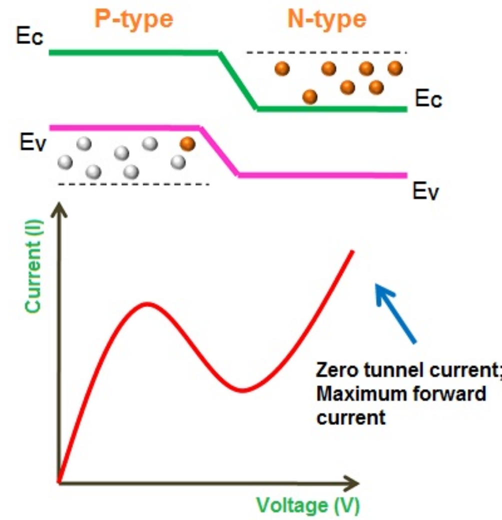
If the applied voltage is further increased, a slight misalign of the conduction band and valence band takes place. Since the conduction band of the n-type material and the valence band of the p-type material sill overlap. The electrons tunnel from the conduction band of n-region to the valence band of p-region and cause a small current flow. Thus, the tunneling current starts decreasing.

Step 5: Applied voltage is largely increased

If the applied voltage is largely increased, the tunneling current drops to zero. At this point, the conduction band and valence band no longer overlap and the tunnel diode operates in the same manner as a normal p-n junction diode. If this applied voltage is greater than the built-in potential of the depletion layer, the regular forward current starts flowing through the tunnel diode.



Tunnel current starts decreasing



Zero tunnel current; maximum forward current

The portion of the curve in which current decreases as the voltage increases is the negative resistance region of the tunnel diode. The negative resistance region is the most important and most widely used characteristic of the tunnel diode. A tunnel diode operating in the negative resistance region can be used as an amplifier or an oscillator.

Advantages of tunnel diodes

Tunnel diodes have the following advantageous features.

1. Long life
2. High-speed operation
3. Low noise
4. Low power consumption

Disadvantages of tunnel diodes

1. Tunnel diodes cannot be fabricated in large numbers
2. Being a two terminal device, the input and output are not isolated from one another.

Applications of tunnel diodes

1. Tunnel diodes are used as logic memory storage devices.
2. Tunnel diodes are used in relaxation oscillator circuits.
3. Tunnel diode is used as an ultra high-speed switch.
4. Tunnel diodes are used in FM receivers.

Reference: https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/semiconductor-diodes/tunneldiode-howitworks.html