

## 4.2 TUNNEL DIODE

A Tunnel diode is a heavily doped p-n junction diode in which the electric current decreases as the voltage increases. In tunnel diode, electric current is caused by “Tunneling”. The tunnel diode is used as a very fast switching device in computers. It is also used in high-frequency oscillators and amplifiers.

### Symbol of Tunnel Diode

The circuit symbol of tunnel diode is shown in the below figure. In tunnel diode, the p-type semiconductor act as an anode and the n-type semiconductor act as a cathode.

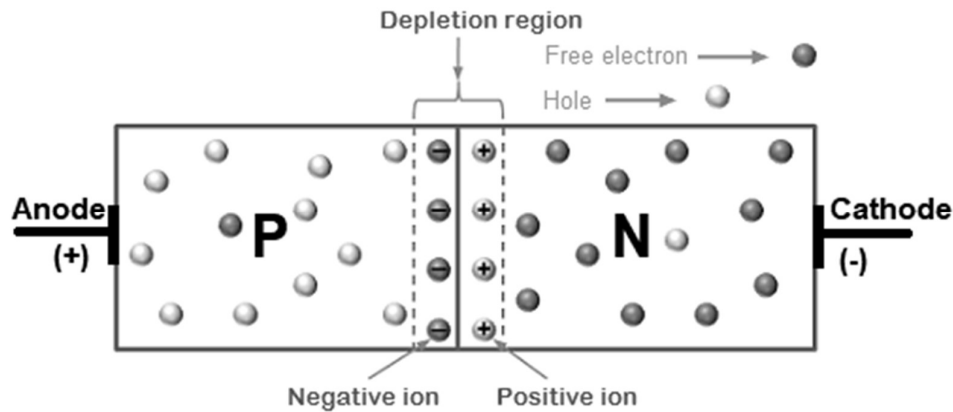


**Fig:4.2.1 Symbol of Tunnel Diode**

The anode is a positively charged electrode which attracts electrons whereas cathode is a negatively charged electrode which emits electrons. In tunnel diode, n-type semiconductor emits or produces electrons so it is referred to as the cathode. On the other hand, p-type semiconductor attracts electrons emitted from the n-type semiconductor so p-type semiconductor is referred to as the anode.

Leo Esaki observed that if a semiconductor diode is heavily doped with impurities, it will exhibit negative resistance. Negative resistance means the current across the tunnel diode decreases when the voltage increases. In 1973 Leo Esaki received the Nobel Prize in physics for discovering the electron tunneling effect used in these diodes.

A tunnel diode is also known as Esaki diode which is named after Leo Esaki for his work on the tunneling effect. The operation of tunnel diode depends on the quantum mechanics principle known as “Tunneling”. In electronics, tunneling means a direct flow of electrons across the small depletion region from n-side conduction band into the p-side valence band.

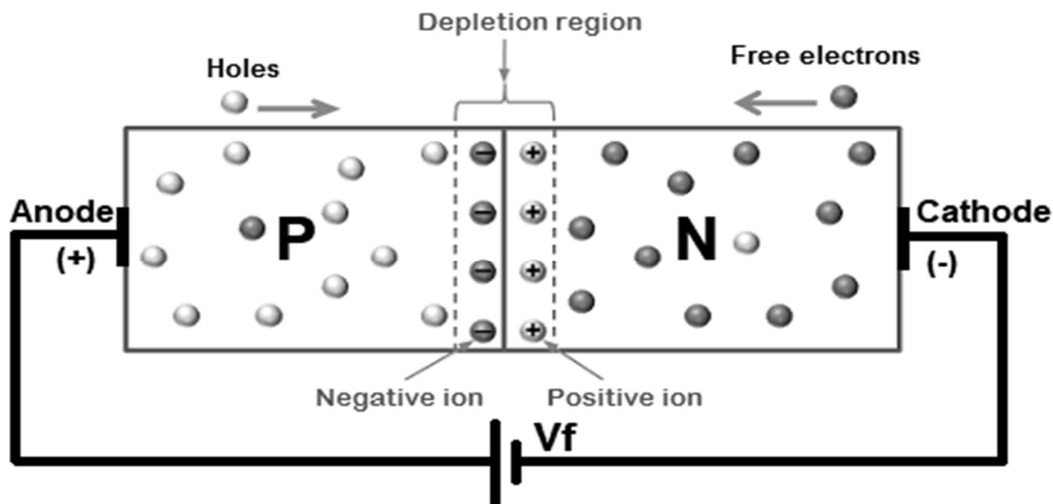


**Fig:4.2.2 Construction of Tunnel Diode**

The germanium material is commonly used to make the tunnel diodes. 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 in a p-n junction diode where mobile charge carriers (free electrons and holes) are absent. Depletion region acts like a barrier that opposes the flow of electrons from the n-type semiconductor and holes from the p-type semiconductor.



**Fig:4.2.3 Working of Tunnel Diode**

The width of a depletion region depends on the number of impurities added. Impurities are the atoms introduced into the p-type and n-type semiconductor to increase electrical conductivity.

If a small number of impurities are added to the p-n junction diode (p-type and n-type semiconductor), a wide depletion region is formed. On the other hand, if large number of impurities are added to the p-n junction diode, a narrow depletion region is formed.

In tunnel diode, the p-type and n-type semiconductor is heavily doped which means a large number of impurities are introduced into the p-type and n-type semiconductor. This heavy doping process produces an extremely narrow depletion region. The concentration of impurities in tunnel diode is 1000 times greater than the normal p-n junction diode.

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

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.

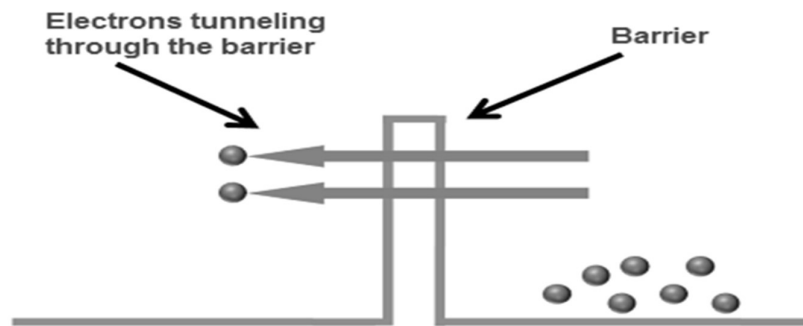
### **Tunneling**

The depletion region or depletion layer in a p-n junction diode is made up of positive ions and negative ions. Because of these positive and negative ions, there exists a built-in potential or electric field in the depletion region. This electric field in the depletion region exerts electric force in a direction opposite to that of the external electric field (voltage). Another thing need to remember is that the valence band and conduction band energy levels in the n-type semiconductor are slightly lower than the valence band and conduction band energy levels in the p-type semiconductor. This difference in energy levels is due to the differences in the energy levels of the dopant atoms (donor or acceptor atoms) used to form the n-type and p-type semiconductor.

### **Electric current in tunnel diode**

In tunnel diode, the valence band and conduction band energy levels in the n-type semiconductor are lower than the valence band and conduction band energy 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 in energy levels, the conduction band of the n-type material overlaps with the valence band of the p-type material.



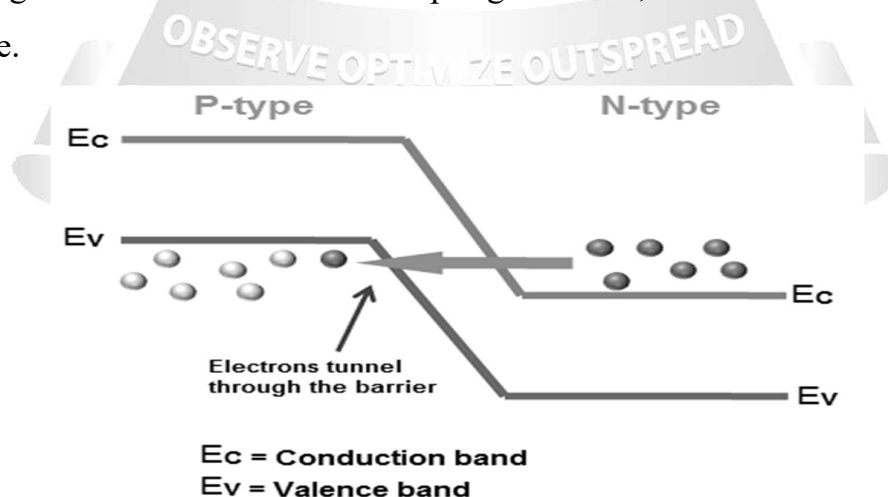
**Fig:4.2.4 Tunneling**

Quantum mechanics says that the electrons will 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 the small depletion region 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.

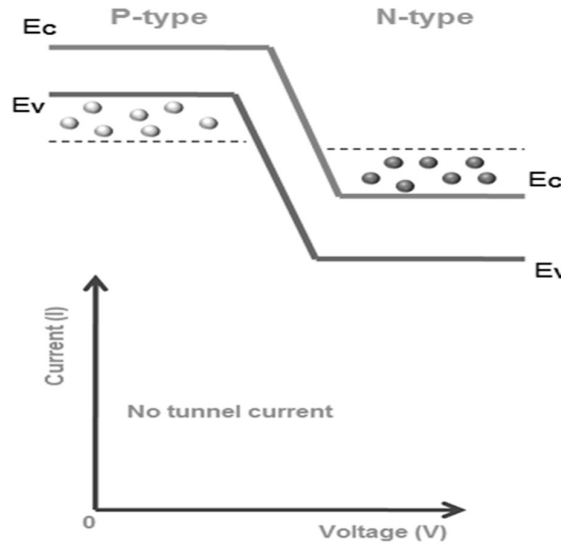
In tunnel diodes, the electrons need not overcome the opposing force from the depletion layer to produce electric current. The electrons can directly tunnel from the conduction band of n-region into the valence band of p-region. Thus, electric current is produced in tunnel diode.



**Fig:4.2.5 Energy Band Diagram of Tunnel Diode**

### 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.



**Fig:4.2.6 Unbiased Tunnel Diode**

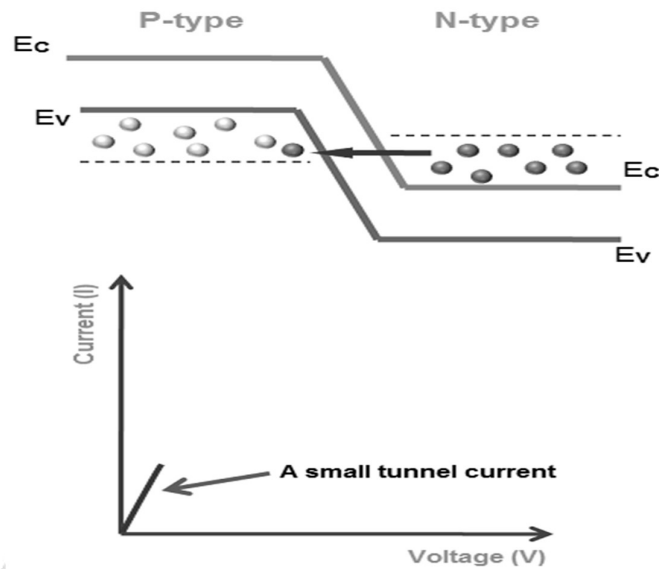
Because of this overlapping, the conduction band electrons at n-side and valence band holes at p-side are nearly at the same energy level. So when the temperature increases, some electrons tunnel from the conduction band of n-region to the valence band of p-region. In a similar way, holes tunnel from the valence band of p-region to the conduction band of n-region.

However, the net current flow will be zero because an equal number of charge carriers (free electrons and holes) flow in opposite directions.

### 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.

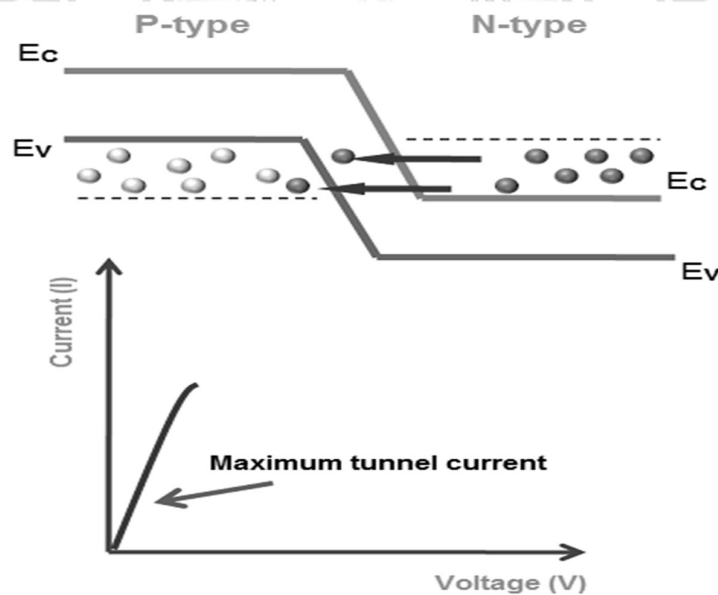
However, a small number of electrons in the conduction band of the n-region will tunnel to the empty states of the valence band in p-region. This will create a small forward bias tunnel current. Thus, tunnel current starts flowing with a small application of voltage.



**Fig:4.2.7 Small Forward Voltage**

**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.

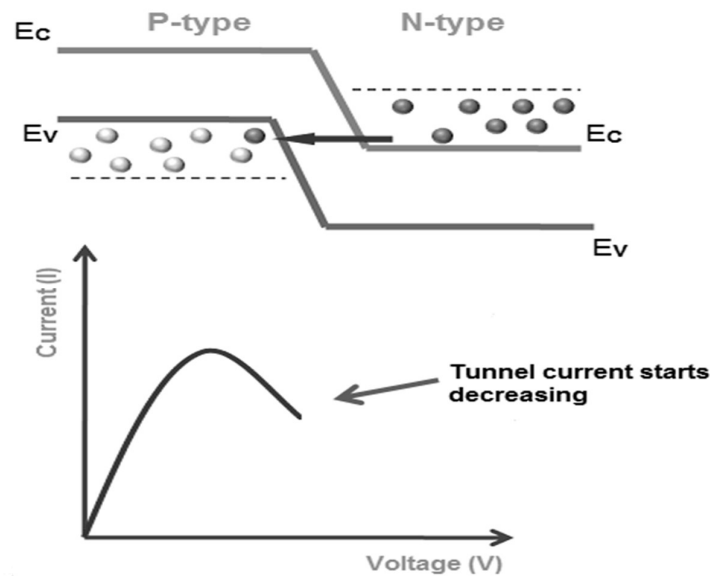


**Fig:4.2.8 Maximum Forward Voltage**

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.

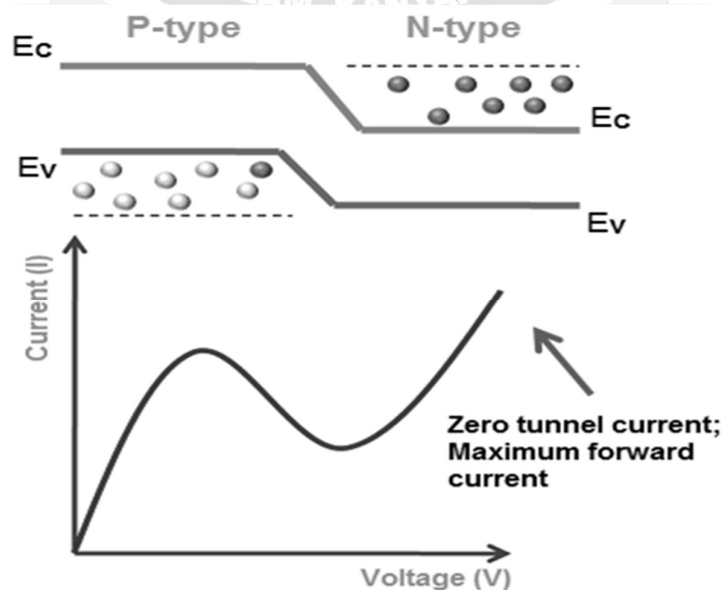


**Fig:4.2.9 Applied voltage is further increased**

Since the conduction band of the n-type material and the valence band of the p-type material still 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.



**Fig:4.2.8 Applied voltage is largely increased**

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.

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**

- Long life
- High-speed operation
- Low noise
- Low power consumption

#### **Disadvantages of tunnel diodes**

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

#### **Applications of tunnel diodes**

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

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