Semiconductor Devices: An Overview

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ABSTRACT

Before the advent of semiconductor devices, vacuum tubes served as the primary tools for signal enhancement, exchange, and various applications. However, despite their usefulness, vacuum tubes were bulky, required high operating voltages, and were inefficient. With the introduction of semiconductor devices such as transistors, a new era began in electronic hardware. Semiconductors are materials that possess characteristics between conductors and insulators, enabling them to conduct electrical current to a certain extent. The most widely used semiconductor material in the hardware industry is silicon. Initially, germanium was extensively utilized during the early stages of semiconductor development. However, due to its instability at high temperatures, silicon became the preferred choice. In this section, we will delve into the details of semiconductors, their types, and devices associated with them.

Keywords: Semiconductor, PN device, LED, Schottky diode, V-I Characteristics

I. BASICS OF SEMICONDUCTORS

Semiconductor materials possess two types of current carriers: free electrons and holes. In a natural semiconductor material, free electrons are generated when the material attains sufficient atomic energy, causing valence electrons in the valence band to transition to the conduction band, thus becoming free electrons. When valence electrons move to the conduction band, they leave behind vacancies in the valence band known as holes. In an undoped, intrinsic semiconductor material, the number of holes in the valence band is equal to the number of free electrons in the conduction band. However, these materials do not conduct current well in their natural state due to the limited number of free electrons and holes.

To enhance the conductivity of a semiconductor material, it must undergo a process called doping. Doping involves introducing impurities into the semiconductor, which increases the number of charge carriers. These impurities can introduce either additional free electrons or additional holes to the intrinsic semiconductor material.

To increase the number of free electrons, pentavalent impurity particles are added during the doping process. These particles, such as arsenic, phosphorus, bismuth, or antimony, have five valence electrons. For instance, during doping, antimony atoms covalently bond with four adjacent silicon atoms. The antimony utilizes four of its valence electrons to form covalent bonds with the silicon atoms, leaving an extra electron that becomes a free electron. By introducing pentavalent impurity particles into a natural semiconductor material, both the number of free electrons and the conductivity of the material can be increased. Semiconductors doped with pentavalent impurities are referred to as n-type semiconductors, as the majority of their charge carriers are electrons. The addition of these impurities transforms an intrinsic semiconductor into an extrinsic semiconductor.

To increase the number of holes in an intrinsic semiconductor material, trivalent impurity particles are used during doping. These particles, such as boron, indium, and gallium, have three valence electrons in their outer shell. For example, when a boron atom covalently bonds with four adjacent silicon atoms, a hole is created. This occurs because the four silicon atoms require one electron each from the boron atom, but the boron atom only has three valence electrons. By introducing more trivalent impurity particles into a natural semiconductor material, the number of holes can be increased, thereby influencing the material's conductivity. Semiconductors doped with trivalent impurities are known as p-type semiconductors, as the majority of their charge carriers are holes.

The doping process transforms an intrinsic semiconductor material into an extrinsic semiconductor, resulting in either an n-type or a p-type semiconductor material. When n-type and p-type semiconductor materials are combined, it forms a p-n junction. This p-n junction serves as the foundation for various commonly used semiconductor devices, including diodes, transistors, and thyristors.

A semiconductor is a substance whose resistivity lies between the guides and protectors. The property of resistivity is not the one specifically that picks a material as a semiconductor, yet it has relatively few properties as follows.

- Semiconductors have the resistivity which is not as much as protectors and more than guides.
- Semiconductors have negative temperature co-effective. The obstruction in semiconductors, increments with the lessening in temperature as well as the other way around.
- The Leading properties of a Semiconductor changes, when a reasonable metallic pollution is added to it, which is a vital property.

Semiconductor contraptions are extensively used in the field of equipment. The semiconductor has displaced the huge vacuum tubes, from which the size and cost of the contraptions got lessened and this insurrection has kept on building its speed provoking the new developments like composed equipment. The going with portrayal shows the gathering of semiconductors.

A. Conduction in Semiconductors

The uttermost shell has the valence electrons which are around joined profoundly. Such a molecule, having valence electrons when conveyed close to the next particle, the valence electrons of both these particles combine to outline "Electron matches". This holding is not exactly outstandingly great and subsequently it is a Covalent bond. For example, a germanium bit has 32 electrons. 2 electrons in first circle, 8 in second circle, 18 in third circle, while 4 in last circle. These 4 electrons are valence electrons of germanium particles. These electrons will by and large get together with valence electrons of associating particles, to shape the electron matches, as shown in the going with model (fig.1).

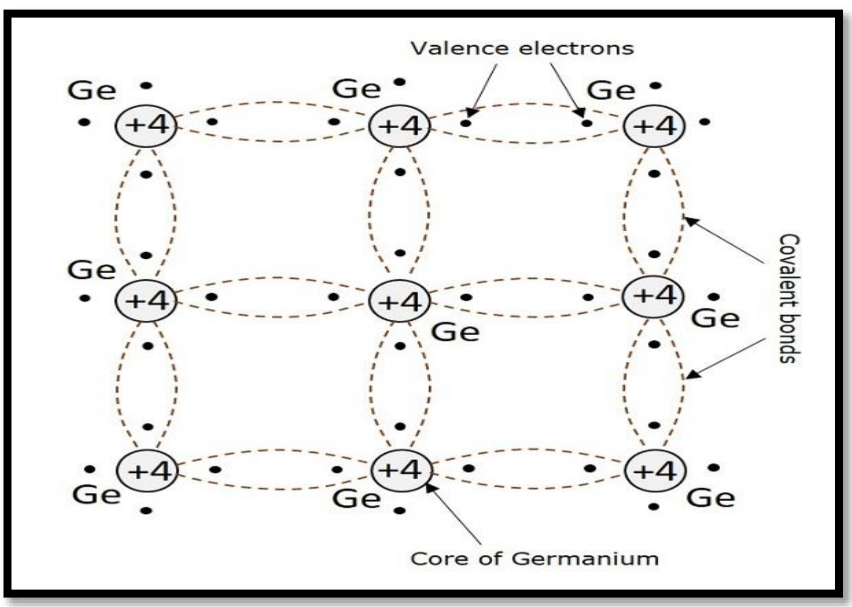

Fig. 1. Covalent Bonding of Germanium (Ge) Atoms

B. Creation of Hole

When a diamond is subjected to atomic energy, some electrons are dislodged from their positions, causing the covalent bonds to break. These broken covalent bonds result in the formation of free electrons that move without a specific path. Simultaneously, the displaced electrons create vacancies, known as holes, in their original positions. These holes represent the absence of an electron and can be seen as unit positive charges, while the electrons themselves are considered unit negative charges. While the liberated electrons move randomly, when an external electric field is applied, they move in the opposite direction to the applied field. Conversely, the holes created due to the lack of electrons move towards the applied field.

C. Hole Current

At the point when a covalent bond is broken, an opening is made. Indeed, there is solid areas for an of semiconductor valuable stone to shape a covalent bond. Hence, an opening does not will regularly exist in a valuable stone. This can be better gotten a handle on by the going with figure, showing a semiconductor germanium cross segment.

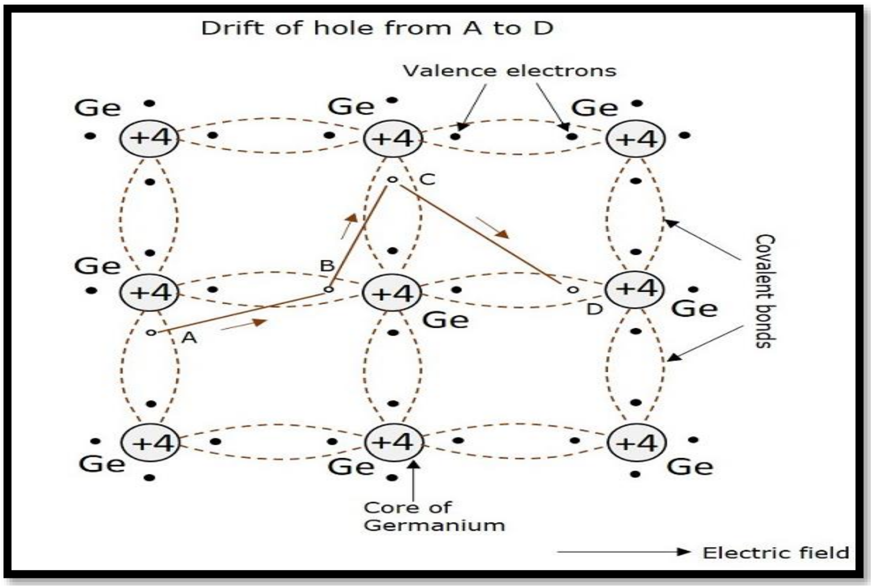

Fig. 2. Creation of Holes in Germanium (Ge) Atoms

When an electron is displaced from point A, it creates a hole in its original position. To restore the covalent bond at point A, an electron from point B moves to fill the hole (fig.2). This process continues, forming a path. The generation of holes with minimal applied field is remarkable. However, when an electric field is applied, the holes move in the direction of the field, resulting in hole current. This should be distinguished from electron current, as it is the movement of holes that contributes to the overall current flow. Electrons and holes, while moving randomly, can encounter each other and form pairs through recombination. This recombination results in the breaking of another covalent bond. As the temperature increases, the velocity of electrons and holes also increases, leading to a higher recombination rate. Consequently, the densities of electrons and holes increase. This leads to an increase in semiconductor conductivity, a decrease in resistivity, and a negative temperature coefficient.

II. INTRINSIC SEMICONDUCTORS

An intrinsic semiconductor refers to a semiconductor in its purest form, without any intentional doping. The properties of an intrinsic semiconductor are as follows:

- ❖ The electrons and openings are exclusively made by warm excitation.
- ❖ The quantity of free electrons is equivalent to the quantity of openings.
- ❖ The conduction ability is little at room temperature.

To grow the conduction capacity of trademark semiconductor, it is smarter to add a couple of pollutions. This course of adding corruptions is called as Doping. By and by, this doped trademark semiconductor is called as an extraneous Semiconductor.

A. Doping

The process of addition of impurities to the semiconductor materials is named as doping. The impurities added, are for the most part trivalent and pentavalent impurities.

B. Pentavalent Impurities

- ❖ The pentavalent impurities have 5 valence electrons in the outer most shell. Example: Bismuth, Antimony, Arsenic, Phosphorus
- ❖ The pentavalent atom (have 5 valence electrons) is called as a donor atom because it donates one electron to the conduction band of pure semiconductor atom.

C. Trivalent Impurities

- ❖ The trivalent impurities have 3 valence electrons in the outer most shell. Example: Gallium, Indium, Aluminum, Boron
- ❖ The trivalent (have 3 valance electrons) atom is called as an acceptor atom because it accepts one electron from the semiconductor atom.

III. EXTRINSIC SEMICONDUCTOR

An impure form of a semiconductor, obtained by introducing dopants into a pure semiconductor, is known as an extrinsic semiconductor. Extrinsic semiconductors can be classified into two types based on the type of dopants added. These types are N-type extrinsic semiconductors and P-type extrinsic semiconductors.

A. N-Type Extrinsic Semiconductor

To create an N-type extrinsic semiconductor, a small quantity of pentavalent impurity (fig.3) is introduced into a pure semiconductor. This impurity contains five valence electrons that are available as free electrons.

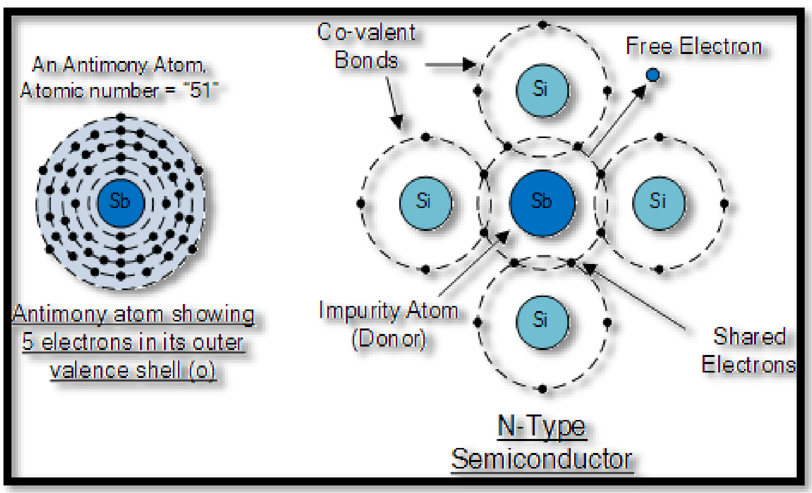

Fig.3. N – Type Extrinsic Semiconductor with Impurity Atoms

For example, if Arsenic atom is added to the germanium atom, four of the valence electrons get attached with the Ge atoms while one electron remains as a free electron. This is as shown in the following model (fig. 4).

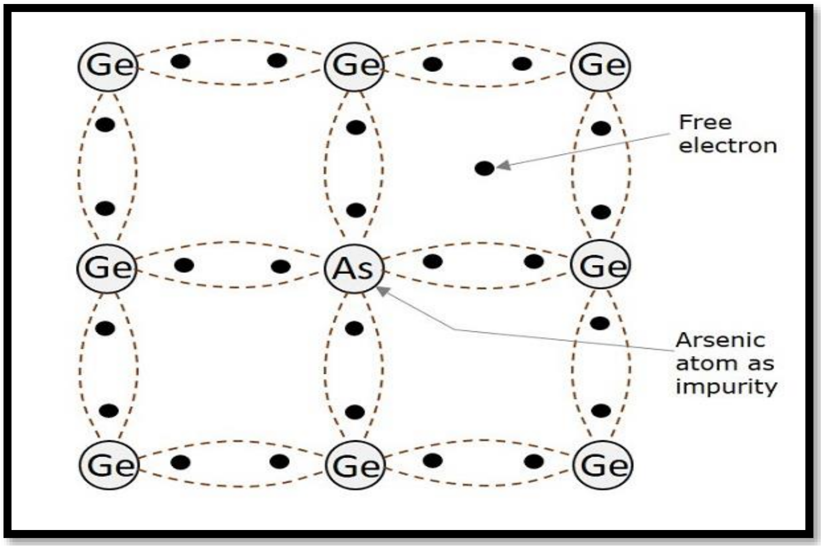

Fig.4. Covalent Bonding of N – Type Extrinsic Semiconductor

The presence of these free electrons in an N-type extrinsic semiconductor contributes to electron current, as they are the majority carriers in this type of semiconductor. When a pentavalent impurity is added to a pure semiconductor, it provides additional electrons for conduction.

- In an N-type extrinsic semiconductor, the conduction occurs predominantly through the movement of electrons, making them the majority carriers, while the holes serve as minority carriers.
- Since there is no net increase in positive or negative charges, the presence of free electrons in the N-type semiconductor results in electrical neutrality.
- When an electric field is applied to an N-type semiconductor that contains a pentavalent impurity, the free electrons move towards the positive terminal. This type of conductivity is referred to as negative or N-type conductivity.

B. P-Type Extrinsic Semiconductor

To create a P-type extrinsic semiconductor, a small amount of trivalent impurity is introduced into a pure semiconductor. The impurity added has three valence electrons. For instance, if a Boron atom is added to a germanium atom, three of the valence electrons of Boron bond with the germanium atoms, forming three covalent bonds. However, one electron in the germanium remains unpaired and does not form a bond. Since the Boron atom lacks an extra electron to form a complete covalent bond, this unpaired space is considered a hole. This can be observed in the following (fig.5).

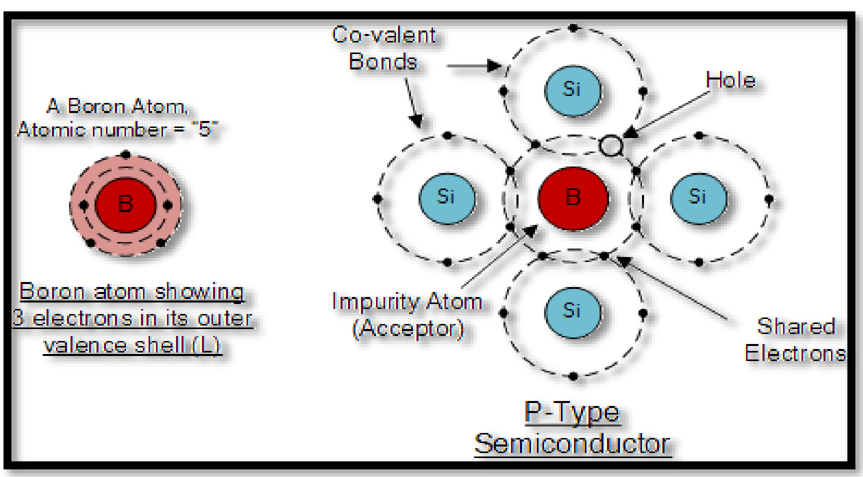

Fig.5. P – Type Extrinsic Semiconductor with Impurity Atoms

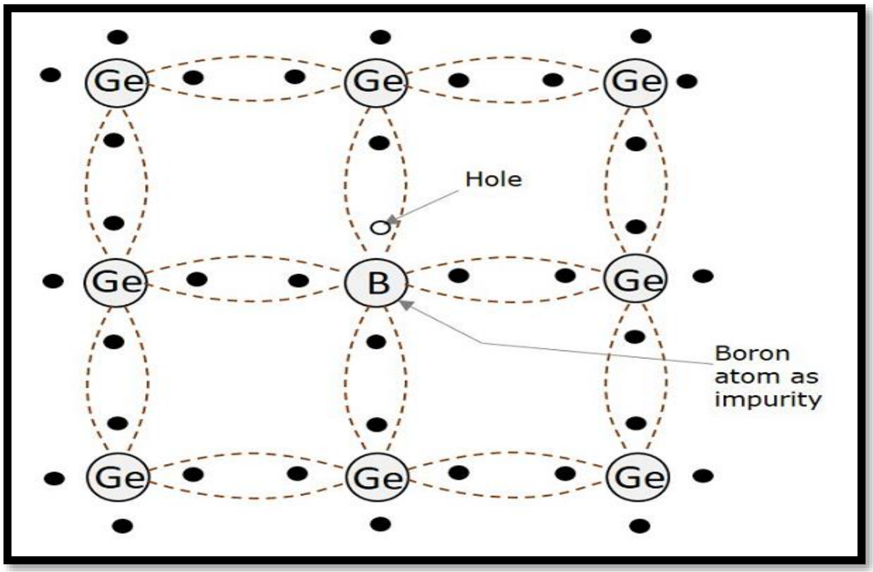

Fig.6. Covalent Bonding of P – Type Extrinsic Semiconductor

When a small amount of boron impurity (fig.6) is introduced, it creates multiple holes that contribute to conduction. These holes constitute hole current.

- In a P-type extrinsic semiconductor, the conduction primarily occurs through the movement of holes, making them the majority carriers, while the electrons act as minority carriers.
- The introduced impurity, known as acceptors, provides additional holes by accepting electrons from the germanium atoms.
- As the number of available holes remains equivalent to the number of acceptors, the P-type semiconductor maintains electrical neutrality.
- When an electric field is applied to a P-type semiconductor that contains a trivalent impurity, the holes move towards the negative cathode, albeit at a slower speed than electrons. This is referred to as P-type conductivity.
- In this type of P-type conductivity, the valence electrons move from one covalent bond to another, unlike in N-type conductivity.

Silicon (fig.7) is preferred in semiconductor technology over other materials like germanium due to several reasons. Among these materials, silicon (Si) is the most widely used material for manufacturing various electronic components.

The preference for silicon over germanium is based on the following factors:

- The energy band gap in silicon is 0.7 eV, while in germanium (Ge), it is 0.2 eV. The larger energy band gap in silicon makes it better suited for electronic applications.
- Silicon exhibits a lower thermal generation rate compared to germanium. This means that silicon is less prone to generating excess heat when current flows through it.
- The formation of a silicon dioxide (SiO_2) layer is relatively easier compared to germanium, making it more conducive for large-scale production and integration technologies.
- Silicon is abundantly available in nature compared to germanium, which makes it more accessible and cost-effective for semiconductor manufacturing.
- Components made of silicon (Si) have lower noise levels compared to germanium (Ge), resulting in improved overall performance and reliability.

These advantages contribute to the widespread utilization of silicon as the preferred material in semiconductor devices and electronic components.

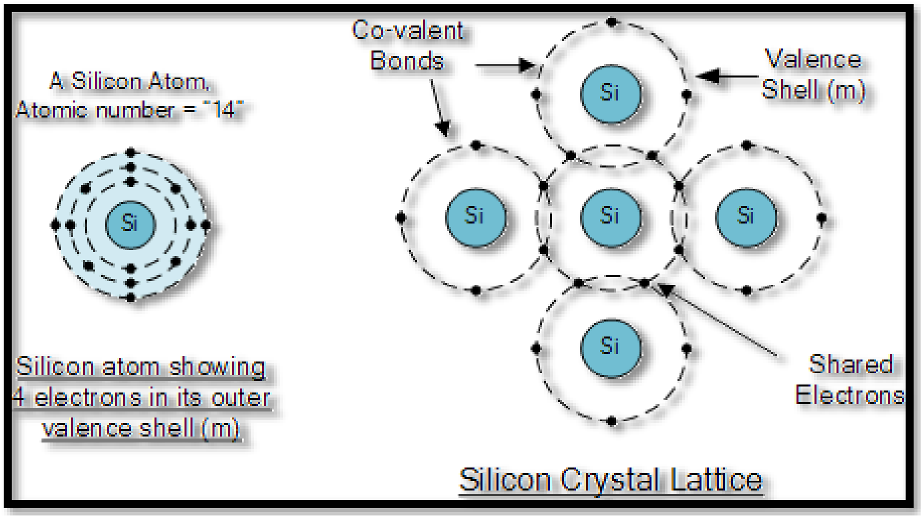

Fig.7. Covalent Bonding of Silicon (Si) Atoms

As a result, silicon is extensively employed in the production of a wide range of electronic components used for constructing diverse circuits with specific functionalities. Each component possesses unique properties and serves distinct purposes.

IV. PN JUNCTION THEORY

PN combination hypothesis shows that when silicon is doped with genuine measures of Antimony, a N-type semiconductor material is illustrated, and when a similar silicon material is doped with limited measures of Boron, a P-type semiconductor material is shaped. In any case, these actually doped N-type and P-type semiconductor materials do basically no disengaged as they are electrically unbiased. Regardless, expecting it join (or wire) these two semiconductor materials together they act in an extremely astonishing manner as they merge conveying what is for the most part known as a "PN Crossing point" permitting us to zero in on the impact of PN combination hypothesis.

Whenever the P-type semiconductor and N-type semiconductor materials are first joined an extraordinarily monster thickness incline exists between the various sides of the PN combination. The result is that a part of the free electrons from the provider defilement particles begin to get across this as of late formed convergence to finish off the openings in the P-type material conveying negative particles. Anyway, because the electrons have gotten across the PN convergence from the N-type silicon to the P-type silicon, they leave insistently charged benefactor particles (ND) on the negative side and as of now the openings from the acceptor corruption get across the convergence the alternate way into the district where there are enormous amounts of free electrons. Accordingly, the charge thickness of the P-type along the convergence is stacked up with antagonistically charged acceptor particles (NA), and the charge thickness of the N-type along the crossing point becomes positive. This charge get of electrons and openings across the PN convergence is known as dispersal.

This interaction goes on to and fro until the quantity of electrons which have crossed the intersection have a sufficiently huge electrical charge to repulse or keep any additional charge transporters from getting over the intersection. In the long run a condition of balance (electrically impartial circumstance) will happen delivering a "possible obstruction" zone around the region of the intersection as the contributor iotas repulse the openings and the acceptor particles repulse the electrons. Since no free charge transporters can rest in a position where there is a likely boundary, the districts on either side of the intersection currently become totally drained of any freer transporters in contrast with the N and P type materials further away from the intersection. This region around the PN Intersection is currently called the Consumption Layer.

A. The PN junction

As the N-type material has lost electrons and the P-type has lost openings, the N-type material has become positive with respect to the P-type. Then, at that point, the presence of debasement particles on the two sides of the intersection makes an electric field be laid out across this locale with the N-side at a positive voltage comparative with the P-side (fig.8). The issue currently is that a free charge requires an additional energy to defeat the obstruction that presently exists for it to have the option to cross the consumption locale intersection. A reasonable positive voltage (forward inclination) applied between the two closures of the PN intersection can supply the free electrons and openings with the additional energy.

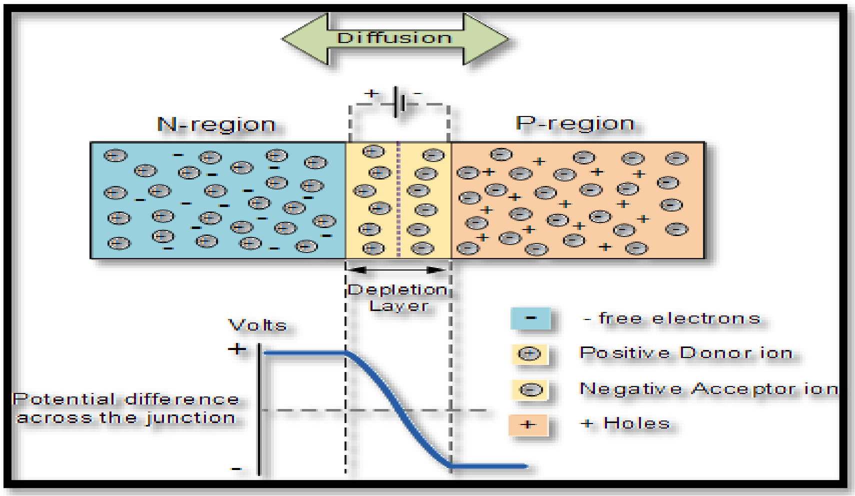

Fig. 8. PN Junction Device

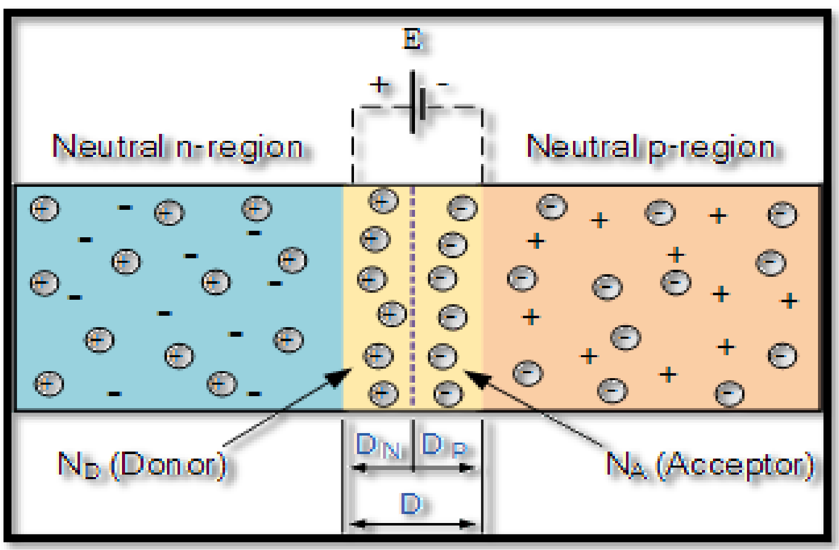

Fig. 9. Depletion Layer Distance

The outside voltage expected to beat this potential deterrent that by and by exists is a lot of wards upon the sort of semiconductor material utilized and its genuine temperature. Routinely at room temperature the voltage across the consumption layer for silicon is around 0.6 volts to 0.7 volts and for germanium is around 0.3 volts to 0.35 volts. This potential obstacle will continually exist whether the gadget isn't connected with any outer power source, as found in diodes (fig.9). The significance of this fundamental expected across the intersection point, is that it clashes with both the development of openings and electrons across the combination and is the clarification it is known as far as possible.

The PN intersection is framed inside a solitary gem of material as opposed to just consolidating or melding two separate pieces. The consequence of this cycle is that the PN intersection has correcting voltage – current (VI or

V-I) attributes. Electrical contacts are joined onto either side of the semiconductor to engage an electrical relationship with be made to an external circuit. The subsequent electronic gadget that has been made is regularly called a PN intersection Diode or essentially Signal Diode. PN intersections can be made by consolidating or diffusing contrastingly doped semiconductor materials to deliver an electronic gadget called a diode which can be utilized as the fundamental semiconductor design of rectifiers, a wide range of semiconductors, LED's, sun-based cells, and a lot more such strong state gadgets.

B. PN Junction Diode

The PN convergence diode involves a p-region and n-locale secluded by a utilization locale where charge is taken care of. The effect depicted in the past educational activity is achieved with basically no external voltage being applied to the certified PN crossing point achieving the convergence being in a state of equilibrium. However, when electrical connections are established at the terminals of both the N-type and P-type materials, and they are subsequently connected to a battery source, an additional energy source emerges that surpasses the potential difference.

The presence of this additional energy source allows free electrons to overcome the depletion region and move from one side to the other. A PN Junction Diode, one of the simplest semiconductor devices, exhibits the electrical property of allowing current flow in only one direction. In any case, not the least bit like a resistor, a diode does not act straightly concerning the applied voltage. All things considered, it has a dramatic current-voltage (I-V) relationship and accordingly it cannot portray its activity by essentially utilizing a condition like Ohm's regulation. In case a sensible positive voltage (forward tendency) is applied between the two terminations of the PN convergence, it can supply free electrons and openings with the extra energy they hope to get through the intersection as the width of the utilization layer around the PN crossing point is lessened. By applying a negative voltage (switch predisposition) bring about the free charges being pulled away from the intersection bringing about the exhaustion layer width being expanded.

This action alters the effective resistance of the PN junction, either allowing or impeding the flow of current through the diode. As a result, the depletion layer expands when a reverse voltage is applied and contracts when a forward voltage is applied. These changes occur due to the variations in electrical properties on either side of the PN junction, leading to physical modifications. One of the outcomes of these changes is observed in the static I-V (current-voltage) characteristics of PN junction diodes. The modification is manifested by an asymmetric current flow when the bias voltage polarity is adjusted, as depicted below.

C. Junction Diode Symbol and Static V-I Characteristics

To utilize the PN junction (fig.10) as a functional device or as needed, it is first necessary to bias the junction. This involves applying a voltage potential across it. In the voltage diagram provided, "Bias Voltage" refers to an external voltage potential that increases the potential barrier. On the other hand, an external voltage that decreases the potential barrier is referred to as "Forward Bias."

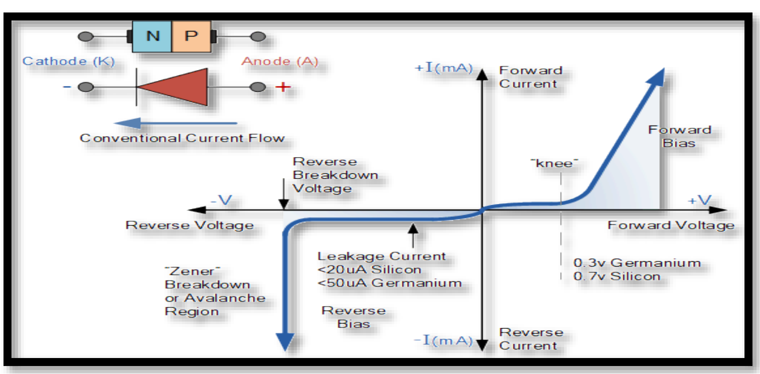

Fig.10. Junction diode and Voltage – Current (VI) characteristics

Different biasing conditions include:

- ❖ Zero Bias: In this condition, no external voltage potential is applied to the PN junction diode.
- ❖ Reverse Bias: The potential is applied in a negative direction to the P-type material and in a positive direction to the N-type material across the diode. This increases the width of the PN junction diode.
- ❖ Forward Bias: The potential is applied in a positive direction to the P-type material and in a negative direction to the N-type material across the diode. This decreases the width of the PN junction diode.

D. Zero Biased Junction Diode

When a diode is connected in a zero-bias condition, no external potential energy is applied to the PN junction. Even if the diode's terminals are shorted together, some majority carriers (holes) in the P-type material, possessing sufficient energy, are able to cross the junction against its barrier potential. This flow of carriers is known as "Forward Current." Additionally, minority carriers (electrons) generated in the N-type material successfully cross the junction in the opposite direction, which is referred to as "Reverse Current" or IR. This exchange of electrons and holes across the PN junction is known as diffusion, as illustrated below.

However, the potential barrier restricts the diffusion of any additional majority carriers across the junction. Nevertheless, the potential barrier allows minority carriers (few free electrons in the P-region and few holes in the N-region) to drift across the junction. As a result, a "Quiescent" or equilibrium state is established when the majority carriers are equal and moving in opposite directions, resulting in no net current flow in the circuit. This condition indicates that the junction is in a state of "Dynamic Equilibrium." The generation of minority carriers is continuously maintained due to thermal energy. However, this equilibrium state can be disrupted by increasing the temperature of the PN junction (fig.11), which leads to an increase in the generation of minority carriers, subsequently causing an increase in leakage current. However, no electric current can flow since no circuit has been connected to the PN junction.

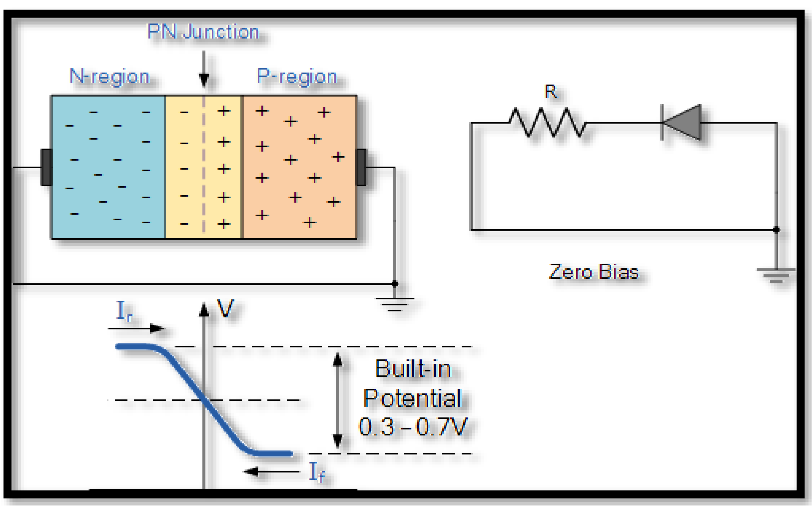

Fig.11. Zero biased PN junction diode

E. 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, while a negative voltage is applied to the P-type material (fig.12). The positive voltage applied to the N-type material attracts electrons towards the positive cathode and away from the junction. Similarly, the positive voltage repels the holes in the P-type material away from the junction and towards the negative anode. As a result, the depletion region widens due to the lack of electrons and holes, creating a high impedance pathway and establishing a significant potential barrier across the junction. This barrier prevents current from flowing through the semiconductor material.

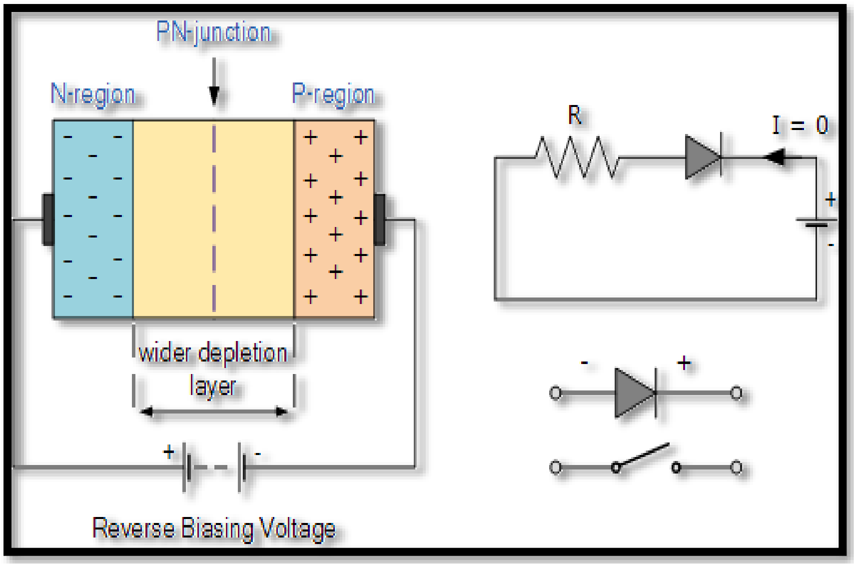

Fig.12. Increase In the Depletion Layer Due to Reverse Bias

This condition corresponds to a high resistance value across the PN junction, resulting in virtually no current flowing through the diode as the reverse bias voltage increases. However, a small reverse leakage current, typically measured in microamperes (µA), still flows through the junction. It is important to note that if the reverse bias voltage (Vr) applied to the diode is increased to a sufficiently high value, it can cause the diode's PN junction to overheat and fail due to the avalanche effect. This can result in a short circuit condition, leading to the maximum current flow through the diode. This characteristic is represented by a steep downward slope in the reverse static characteristics curve, as shown below.

F. Reverse Characteristics Curve for a Junction Diode

Occasionally, the avalanche effect has practical applications in voltage stabilizing circuits. In such circuits, a series current-limiting resistor is employed with the diode to restrict the reverse breakdown current to a predetermined maximum value. This configuration ensures a desired voltage output across the diode, as illustrated in (fig. 13).

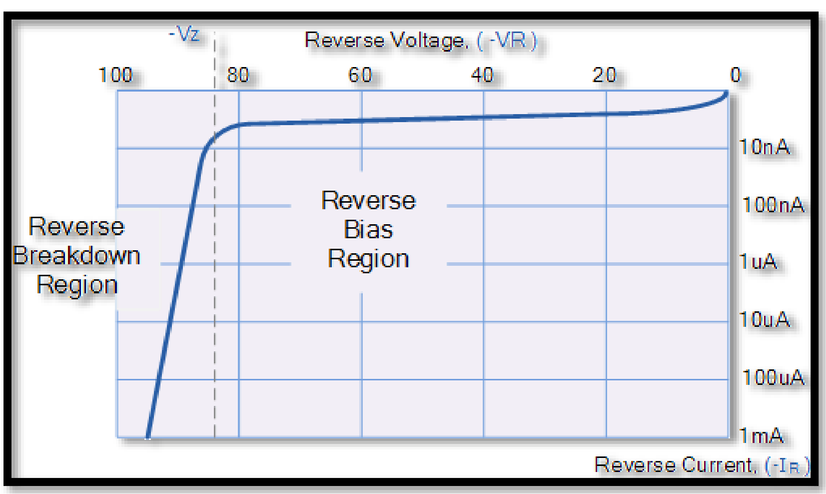

Fig. 13. Reverse Characteristics Curve for a Junction Diode

G. 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, while a positive voltage is applied to the P-type material (fig.14). If this external voltage exceeds the value of the potential barrier, which is approximately 0.7 volts for silicon and 0.3 volts for germanium, the resistance of the potential barrier is overcome, and current starts to flow. This occurs because the negative voltage attracts electrons towards the junction, providing them with enough energy to overcome the barrier and combine with the holes that are being pushed towards the junction by the positive voltage. As a result, the characteristic curve shows zero current flow up to this voltage point, referred to as the "knee" on the static curves, and then a significant increase in current flow through the diode with only a small increase in the external voltage, as illustrated below.

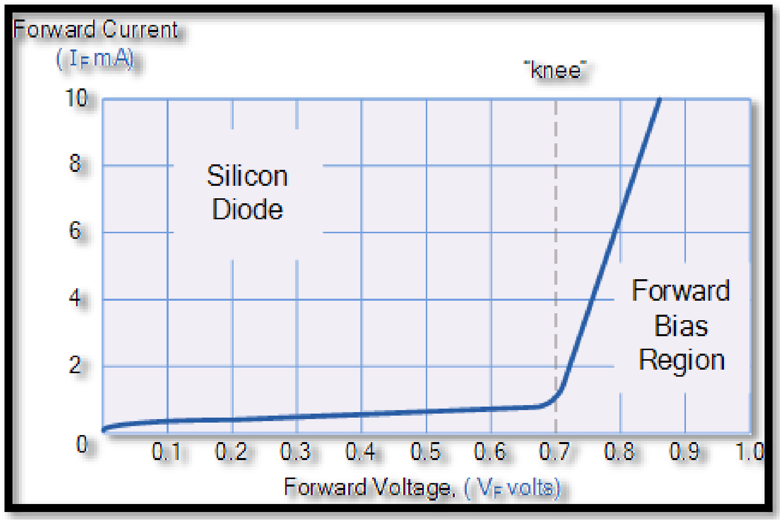

Fig.14. Forward Characteristics Curve for a Junction Diode

Applying a forward bias voltage (fig.15) to the junction diode results in the depletion layer becoming extremely thin and narrow. This creates a low impedance path through the junction, allowing high currents to flow. The point on the static I-V characteristics curve where this sudden increase in current occurs is known as the "knee" point.

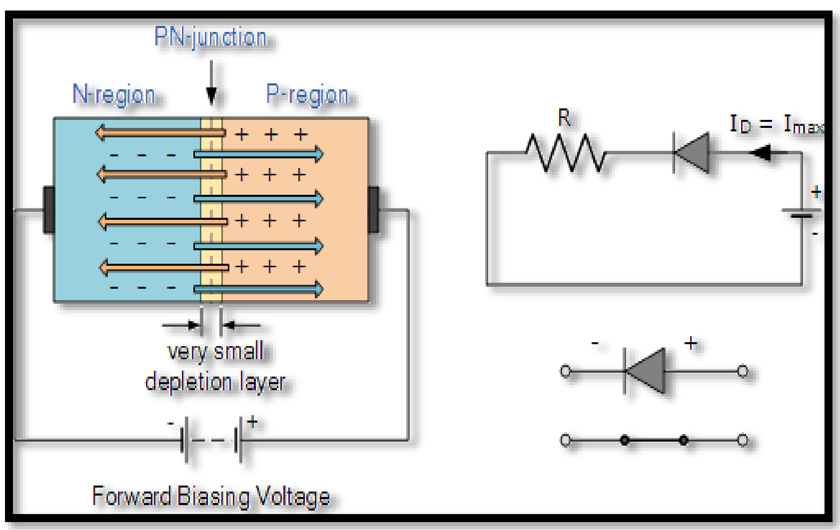

Fig. 15. Reduction of Depletion Layer due to Forward Bias

In this condition, the PN junction provides a low resistance path, allowing significantly large currents to pass through the diode with only a slight increase in forward voltage. The actual voltage drops across the junction, or diode, is maintained at a relatively constant value, approximately 0.3V for germanium and around 0.7V for silicon diodes. Since the diode can conduct "unlimited" current beyond this knee point, effectively behaving like a short circuit, resistors are utilized in series with the diode to limit its continuous flow. Exceeding the maximum forward current specification of the device causes it to dissipate more power than it was designed for, leading to rapid device failure.

V. THE LIGHT EMITTING DIODE (LED)

The Light Emitting Diode (LED) (fig.16) is a widely recognized type of semiconductor diode. It emits a narrow range of light, such as visible light at various colored frequencies, infrared light for remote control applications, or laser-like light, when a forward current is passed through it. The LED, also known as a Light Emitting Diode, shares similar electrical characteristics with a PN junction diode. This means that an LED allows current to flow in its forward direction but blocks the flow of current in the reverse direction.

LEDs are manufactured using an extremely thin layer of moderately heavily doped semiconductor material. Depending on the type of semiconductor material used and the level of doping, when the LED is forward biased, it emits light at a specific spectral frequency. Electrons from the semiconductor's conduction band recombine with holes from the valence band, releasing energy in the form of photons. These photons generate monochromatic (single-colored) light. Due to the thin layer construction, a significant number of these photons can escape the junction and be emitted as visible light.

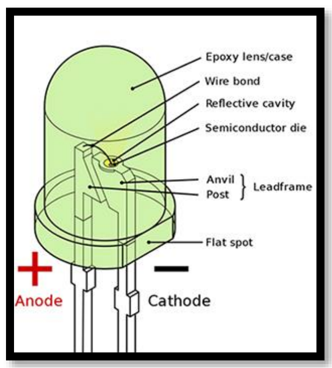

Fig. 16. LED Structure

A. LED Construction

When operated in a forward biased direction, Light Emitting Diodes (LEDs) are semiconductor devices that convert electrical energy into light energy. The construction of an LED differs significantly from that of a conventional signal diode. An LED's PN junction is encapsulated within a clear, hard plastic epoxy resin hemispherical shell or body, providing protection against vibration and shock. In particular, an LED junction does not inherently emit a significant amount of light, so the epoxy resin body is designed to reflect the photons of light generated by the junction away from the underlying substrate base to which the diode is attached. The emitted light is then focused upward through the domed top of the LED, which acts as a lens, concentrating the light. As a result, the emitted light appears particularly bright at the top of the LED.

However, not all LEDs are manufactured with a hemispherical-shaped epoxy shell. Some signal LEDs have a rectangular or round shape, and their body may be flat on top or formed into a bar or arrow shape. In most cases, LEDs have two leads protruding from the bottom of the body. Additionally, modern light emitting diodes often feature a cathode (-ve) terminal, which can be identified by a notch or flat spot on the body, or by having a shorter cathode lead compared to the longer anode (+ve) lead. Unlike traditional incandescent lights and bulbs that emit a significant amount of heat when illuminated, LEDs produce a "cool" type of light, which results in higher efficiency as most of the generated energy is emitted within the visible range. As solid-state devices, LEDs can be compact, durable, and have significantly longer lifespans compared to conventional light sources.

B. Light Emitting Diode Colors

A light emitting diode (LED) obtains its color through a different mechanism. Unlike typical signal diodes, which are designed for display or power rectification and manufactured using either Germanium or Silicon semiconductor materials, LEDs are created using specialized semiconductor compounds. These compounds include Gallium Arsenide (GaAs), Gallium Phosphide (Ga P), Gallium Arsenide Phosphide (Ga As P), Silicon Carbide (Si C), or Gallium Indium

Nitride (Ga In N), combined in varying proportions to achieve specific wavelength emissions. Different LEDs emit light in specific regions of the visible light spectrum and produce varying levels of power. The specific choice of semiconductor material determines the overall wavelength of the emitted photons, which, in turn, determines the resulting color of the light produced.

Table 1. Light Emitting Diode (LED) and its Characteristics

Semiconductor Materials	**Wave length range**	**Color**	**Forward Voltage at 20 mA**
Ga As	850nm - 940nm	Infra-Red	1.2 v
Ga As P	630nm - 660nm	Red	1.8 v
Ga As P	605nm - 620nm	Amber	2.0 v
Ga As P N	585nm - 595nm	Yellow	2.2 v
Al Ga P	550nm - 570nm	Green	3.5 v
Si C	430nm - 505nm	Blue	3.6 v
Ga In N	450nm	White	4.0 v

The actual color of a light emitted by an LED is primarily determined by the frequency of the light generated, which is influenced by the specific semiconductor compound used in the formation of the PN junction during manufacturing. The plastic body of the LED does not permanently determine its color, although it may be tinted to enhance the light output and indicate its color when not illuminated. LED devices are available in a wide range of colors, with the most common being red, blue, yellow, and green. They are widely used as visual indicators and in moving light displays. Additionally, blue and white LEDs have been developed, but they tend to be more expensive than standard colors due to the complexities involved in precisely combining multiple semiconductor compounds and introducing nitrogen particles during the doping process.

The main P-type dopant used in the production of Light Emitting Diodes is Gallium (Ga, atomic number 31), while the primary N-type dopant is Arsenic (As, atomic number 33), resulting in the compound Gallium Arsenide (GaAs) crystalline structure (table.1). However, Gallium Arsenide alone emits a significant amount of low-intensity infrared radiation (approximately 850nm-940nm) when a forward current is applied. While this level of infrared light is suitable for TV remotes, it is not particularly useful if the LED is intended for visible light emission. To address this, Phosphorus (P, atomic number 15) is added as a third dopant, reducing the overall frequency of the emitted radiation to below 680nm, resulting in visible red light to the human eye. Further advancements in the doping process of the PN junction have allowed for a wide range of color options, covering visible light as well as infrared and ultraviolet frequencies. By combining different semiconductor, metal, and gas compounds, a diverse range of LEDs can be created.

C. Types of Light Emitting Diodes (LEDs)

The color ranges of various semiconductor compounds used in LEDs are as follows:

- ❖ Gallium Arsenide (GaAs): Infrared
- ❖ Gallium Arsenide Phosphide (GaAsP): Red to infrared, orange
- ❖ Aluminum Gallium Arsenide Phosphide (AlGaAsP): Bright red, orange-red, orange, and yellow
- ❖ Gallium Phosphide (GaP): Red, yellow, and green
- ❖ Aluminum 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
- ❖ Aluminum Gallium Nitride (AlGaN): Ultraviolet

Similar to standard PN junction diodes, light emitting diodes (LEDs) are current-dependent devices with a forward voltage drop (VF) that varies based on the semiconductor compound and the forward current. The forward operating voltage and forward current requirements vary depending on the semiconductor material used. Typically, the forward voltage for common LEDs ranges from around 1.2 to 3.6 volts. The specific voltage values depend on the manufacturer and the specific dopant materials and frequencies utilized. For example, a standard red LED has a forward voltage drop of around 1.2V, while a blue LED typically has a forward voltage drop of around 3.6V. The actual voltage drops across the LED at a given current, such as 20mA, will also depend on the specific conduction characteristics of the LED. Since an LED is a diode, its current-voltage characteristics can be represented by plotted curves for each color, as shown below.

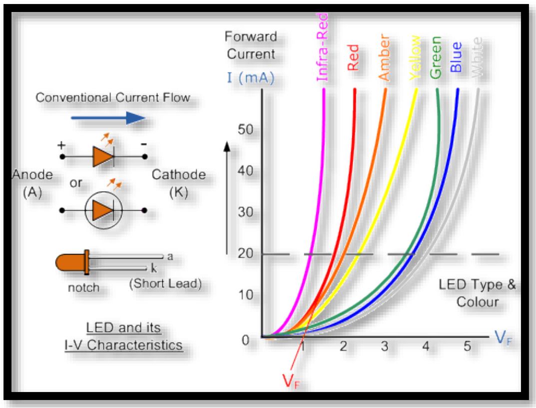

Fig.17. Light Emitting Diode (LED) V-I Characteristics

The schematic diagram and V-I (Voltage-Current) characteristics curves of a Light Emitting Diode (LED) illustrate the available colors (fig.17). To emit light, an LED requires a current to flow through it since its light intensity is directly proportional to the forward current passing through the LED. When connecting the LED to a power supply in a forward bias condition, it is important to limit the current using a series resistor. This resistor ensures that excessive current does not flow through the LED, which could cause it to fail prematurely. It is never advisable to directly connect an LED to a battery or power supply without a current-limiting resistor.

From the information provided in table.1, it is evident that each LED color has its specific forward voltage drop across the PN junction. This voltage drop is determined by the semiconductor material used and is typically specified for a certain forward conduction current, commonly around 20mA. LEDs are typically operated with a low-voltage DC supply, and a series resistor (RS) is employed to maintain the forward current at a safe value, ranging from approximately 5mA for a simple LED indicator to 30mA or higher for applications requiring high brightness light output.

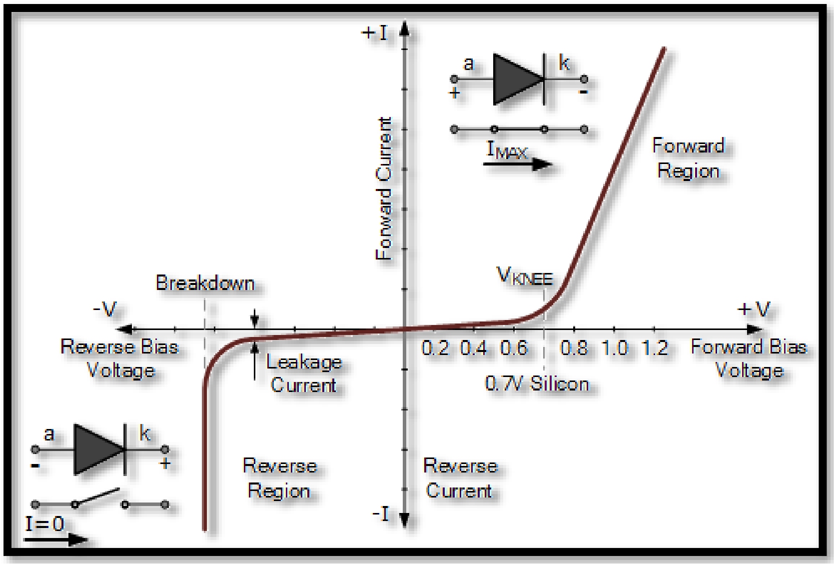

Fig. 18. PN-junction Diode V-I Characteristics

In practical silicon junction diodes, the voltage at the knee point can range from approximately 0.6 to 0.9 volts, depending on the specific doping used during the manufacturing process and whether the device is a small signal diode or a larger power diode (fig.18). In comparison, the knee voltage for a standard germanium diode is typically lower, around 0.3 volts, making it more suitable for low-level signal applications. However, there is another type of diode known as a Schottky Barrier Diode, or simply a "Schottky Diode," which not only has a lower knee voltage but also exhibits a fast-switching speed. Schottky diodes can be used in various applications similar to conventional PN junction diodes and have specific advantages, especially in digital logic, power electronics, and solar charger applications.

VI. THE SCHOTTKY DIODE

The Schottky Diode is another type of semiconductor diode that can be used in various applications, similar to other junction diodes. One of the main advantages of the Schottky Diode is its lower forward voltage drop compared to the standard silicon PN junction diode, which is typically around 0.7 volts. Schottky diodes find significant applications in rectification, signal modulation, switching, as well as TTL and CMOS logic gates, primarily due to their low power consumption and fast switching speeds. TTL Schottky logic gates are identified by the letters LS appearing in their logic gate circuit code, such as 74LS00.

Unlike a standard PN junction diode, which is formed by combining a p-type and an n-type semiconductor material, Schottky Diodes are made by connecting a metal electrode to an n-type semiconductor. Because they consist of a metal-semiconductor junction instead of a p-n junction, Schottky diodes do not have a depletion layer and are classified as unipolar devices, unlike conventional bipolar PN junction diodes. The most commonly used contact metal for Schottky diode fabrication is "Silicide," which is a highly conductive silicon-metal compound. The silicide metal-silicon contact exhibits relatively low ohmic resistance, allowing more current to flow and resulting in a lower forward voltage drop of around $Vf < 0.4V$ under normal operating conditions. Different metal combinations will yield different forward voltage drops, typically ranging between 0.3 and 0.5 volts.

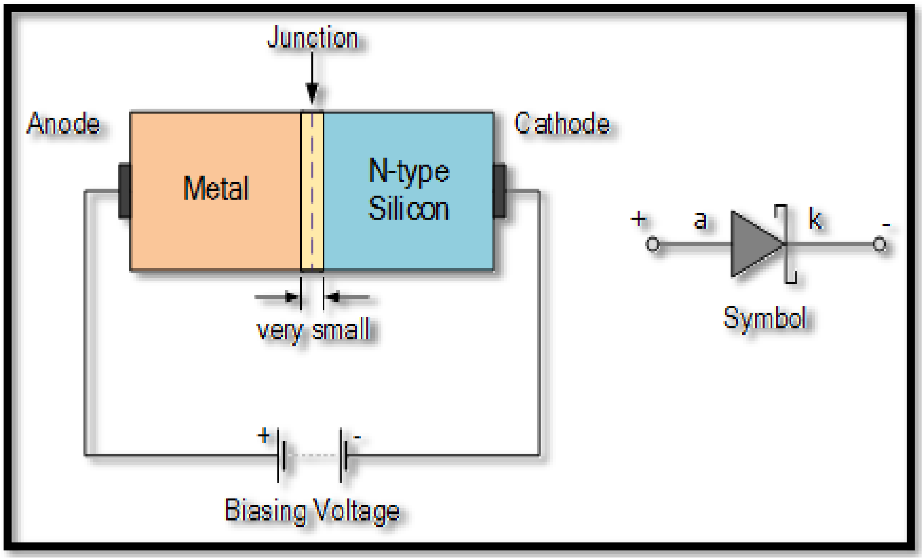

Fig. 19. Schottky Diode Symbol and Construction

The diagram in (fig. 19) illustrates an improved representation of a Schottky diode. It consists of a lightly doped n-type silicon semiconductor combined with a metal electrode, forming a "metal-semiconductor junction." The width and electrical characteristics of this metal-semiconductor junction depend on the specific metal compound and semiconductor material used in its fabrication. When the diode is forward-biased, electrons flow from the n-type material to the metal electrode, allowing current to pass through. Therefore, the conduction in a Schottky diode is primarily due to the movement of majority carriers. Since there is no p-type semiconductor material and therefore no minority carriers (holes), when reverse-biased, the diode quickly ceases conduction and transitions to a high-resistance state, similar to a conventional PN junction diode. As a result, a Schottky diode exhibits a very fast response to changes in bias and demonstrates the characteristics of an ideal diode. As discussed earlier, the knee voltage at which a Schottky diode turns "ON" and begins conducting is much lower than its PN junction counterpart, as shown in the accompanying V-I characteristics curve.

The overall shape of the V-I characteristics curve for a metal-semiconductor Schottky diode (fig.20) is similar to that of a standard PN junction diode, except for the knee voltage at which the MS junction diode begins to conduct, which is much lower at around 0.4 volts. Due to this lower value, the forward current of a silicon Schottky diode can be significantly higher than that of a standard PN junction diode, depending on the metal electrode used. It is important to note that according to Ohm's law, power is equal to the product of voltage and current (P = V x I), so a lower forward voltage drop for a given diode current, ID, results in lower power dissipation across the junction. This lower power dissipation makes the Schottky diode a suitable choice for low-voltage and high-current applications, such as solar photovoltaic panels, where the forward voltage drop across a standard PN junction diode would lead to excessive heating. However, it should be noted that the reverse leakage current for a Schottky diode is generally higher than that of a PN junction diode.

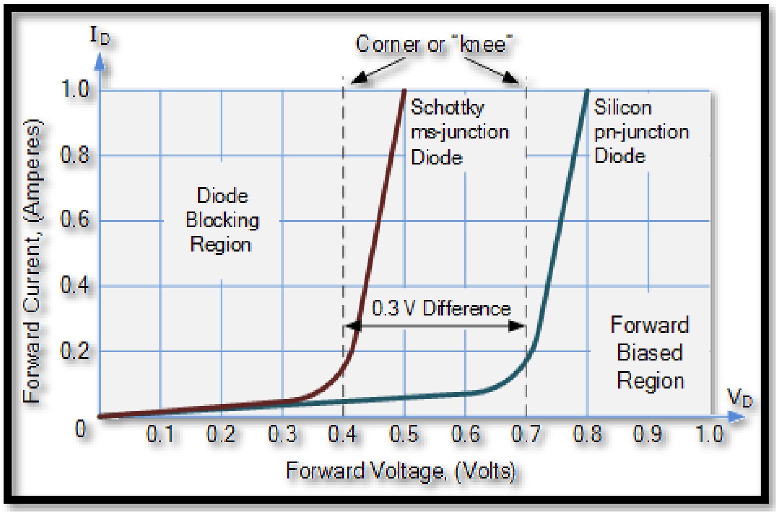

Fig. 20. Schottky Diode V-I Characteristics

If the V-I characteristics curve of a diode shows a linear and non-saturating behavior, it indicates that the diode has an ohmic contact. Ohmic contacts are commonly used to connect semiconductor wafers and chips to external connector pins or system components. For example, they are used to connect the semiconductor wafer of a typical logic gate to the pins of its plastic dual in-line package.

However, Schottky diodes, being made with a metal-to-semiconductor junction, tend to be slightly more expensive than standard PN junction silicon diodes with similar voltage and current ratings. For instance, the 1.0 Ampere 1N58XX Schottky series can be compared to the widely popular 1N400X series of diodes.

A. Schottky Diodes in Logic Gates

The Schottky diode finds extensive use in electronic circuits, particularly in Schottky transistor-transistor logic (TTL) high-level logic gates and circuits. This is due to their superior performance in terms of higher frequency response, reduced switching times, and lower power consumption. When fast switching is required, Schottky-based TTL is the preferred choice.

There are three main series of TTL logic gates that utilize Schottky diodes in their design:

- Schottky Diode Clamped TTL (S series): The Schottky "S" series TTL (74SXX) is an improved version of the original diode-semiconductor diode-transistor logic (DTL) and 74 series TTL logic gates and circuits. Schottky diodes are placed across the base-emitter junction of the switching transistors to prevent them from saturating and causing delay in operation, resulting in faster performance.
- Low-Power Schottky (LS series): The 74LSXX series TTL offers better switching speed, stability, and power dissipation compared to the previous 74SXX series. Along with higher switching speed, the low-power Schottky TTL family consumes less power, making it a suitable choice for specific applications.
- Advanced Low-Power Schottky (ALS series): The 74ALSXX series features further improvements in diode junction materials, resulting in reduced propagation delay and significantly lower power dissipation compared to the 74LSXX and 74LS series. However, being a newer and more advanced design, the ALS series is slightly more expensive.

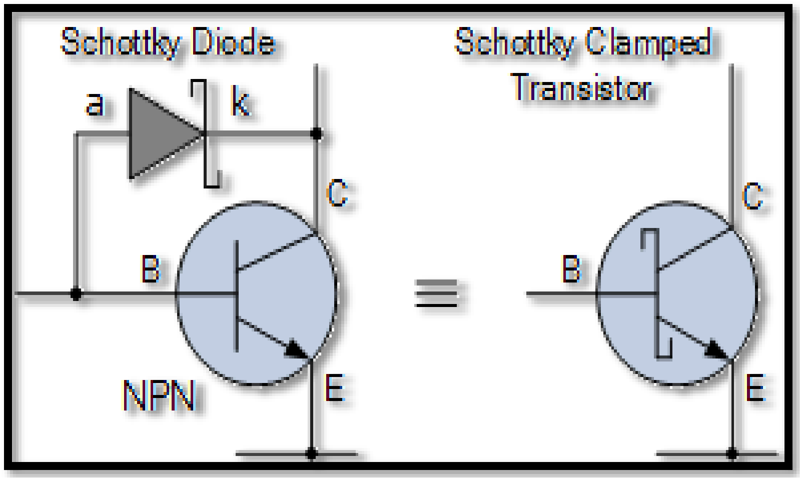

Fig. 21. Schottky Clamped Transistor

The previous Schottky TTL gates and circuits incorporate a Schottky-guarded semiconductor to protect them from excessive saturation. In this configuration, a Schottky diode is connected in parallel across the base-emitter junction of a standard bipolar junction semiconductor. When the semiconductor operates in the active region of its characteristic's curves, the base-emitter junction is reverse biased, allowing the semiconductor to function as a regular NPN transistor (fig.21). However, as the semiconductor approaches saturation, the Schottky diode becomes forward biased and maintains the power base junction at its 0.4-volt knee value, preventing the semiconductor from entering deep saturation by diverting any excess base current through the diode. This prevents the switching transistors in the logic circuits from saturating heavily, reducing their propagation delay and making Schottky TTL circuits ideal for use in counters, oscillators, and memory chips.

VII. APPLICATION OF SEMICONDUCTOR IN DAILY LIFE

- Semiconductors play a crucial role in solar technology.
- They are utilized in 3D printing machines.
- Temperature sensors used in air conditioning systems are made with semiconductor devices.
- Semiconductor control technology allows rice cookers to cook perfectly by maintaining precise temperature control.
- Semiconductors are essential for the operation of bank ATMs, trains, the internet, communications, and other aspects of the social infrastructure, including healthcare systems for the elderly, among other things.
- They are used in self-driving vehicles.
- Semiconductor devices are employed in computers, calculators, solar panels, and other electronic devices.
- CPUs, which are used in various electronic devices such as computers and mobile phones, rely on semiconductor technology. Semiconductors form the building blocks of logic gates.

VIII. ADVANTAGES OF SEMICONDUCTORS

- Unlike vacuum tubes, semiconductors do not require filament heating, making them suitable for a wide range of applications.
- Semiconductor devices are solid-state devices, making them resistant to shocks and vibrations.
- Their small size makes semiconductor devices highly portable and easy to integrate into various systems.
- Semiconductors are more cost-effective compared to vacuum tubes.
- Semiconductor devices require lower input power for operation, resulting in energy efficiency.
- Semiconductor devices operate silently, producing no noise during their operation.
- Semiconductor materials have a longer lifespan and can potentially have an almost infinite lifespan.

IX. INDUSTRIAL USES OF SEMICONDUCTORS

Semiconductors possess unique physical and chemical properties that make them ideal for driving technological advancements in various fields. They play a crucial role in the development of computer chips, semiconductors, LEDs, solar cells, and more. The utilization of semiconductors extends even to critical applications such as controlling the operations of spacecraft, trains, and robots, where they are integrated into CPUs and other control devices, all of which rely on the capabilities provided by semiconductor materials.

CONCLUSION

Semiconductors possess a unique combination of properties, such as controlled conduction of electric current, compact size, and low cost, making them highly versatile for various applications in different devices and systems. They play a crucial role in the development of diodes, photosensors, microcontrollers, integrated circuits, and more.
Semiconductors are a class of materials that exhibit electrical conductivity between that of conductors and insulators. They can be chemically manipulated to regulate the flow and control of electric current. Intrinsic semiconductors, such as silicon, germanium, and gallium arsenide, have high chemical purity but poor conductivity. Extrinsic semiconductors, on the other hand, contain impurities that significantly enhance their conductivity through a process called doping.

Advancements in semiconductor technology have been closely linked to the rapid progress in computing. They are widely used in nearly all electronic devices, as they provide a balance between the conductive and insulating properties, allowing controlled flow of electricity. These devices are prevalent in communication systems, circuitry, and are cost-effective and compact, making them popular in both domestic and industrial applications. Semiconductor devices can be classified into two-terminal and three-terminal configurations, each with their own specific properties and applications.

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