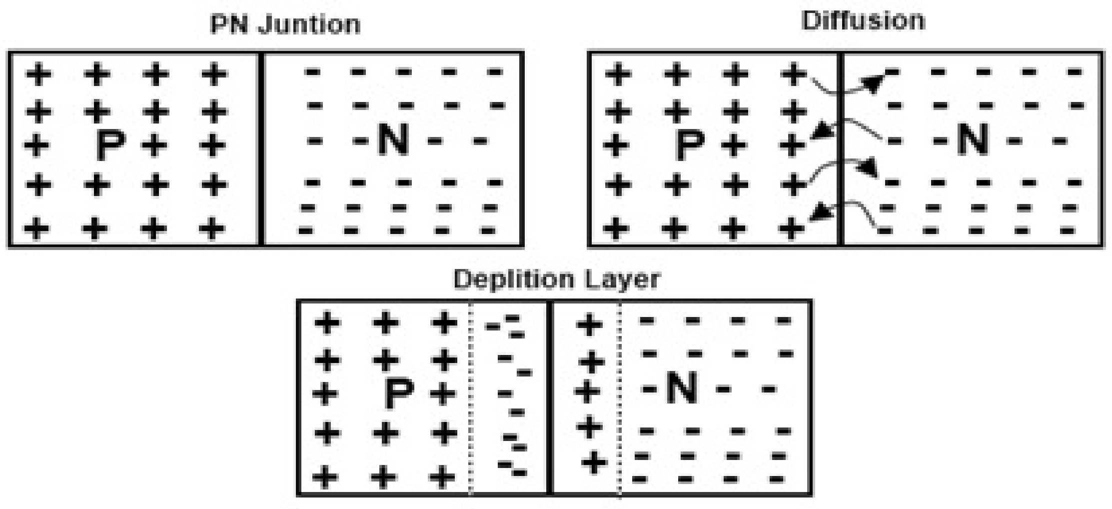
Semi - Conductor Devices

Module 3 Part A QB Solutions

@ Vishnu Nadella

1. Illustrate how the potential barrier prevents the diffusion of electrons and holes across the junction.

> **Barrier Potential:** 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. The barrier potential of a P-N 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.



2. Explain the terms charge carrier generation and recombination in semiconductors.

> **Carrier Generation:**
> Carrier generation describes processes by which electrons gain energy and move from the valence band to the conduction band, producing two mobile carriers.
> **Recombination:**
> Recombination describes processes by which a conduction band electron loses energy and re-occupies the energy state of an electron-hole in the valence band.

3. List the materials used to fabricate direct and indirect band gaps semiconductors.

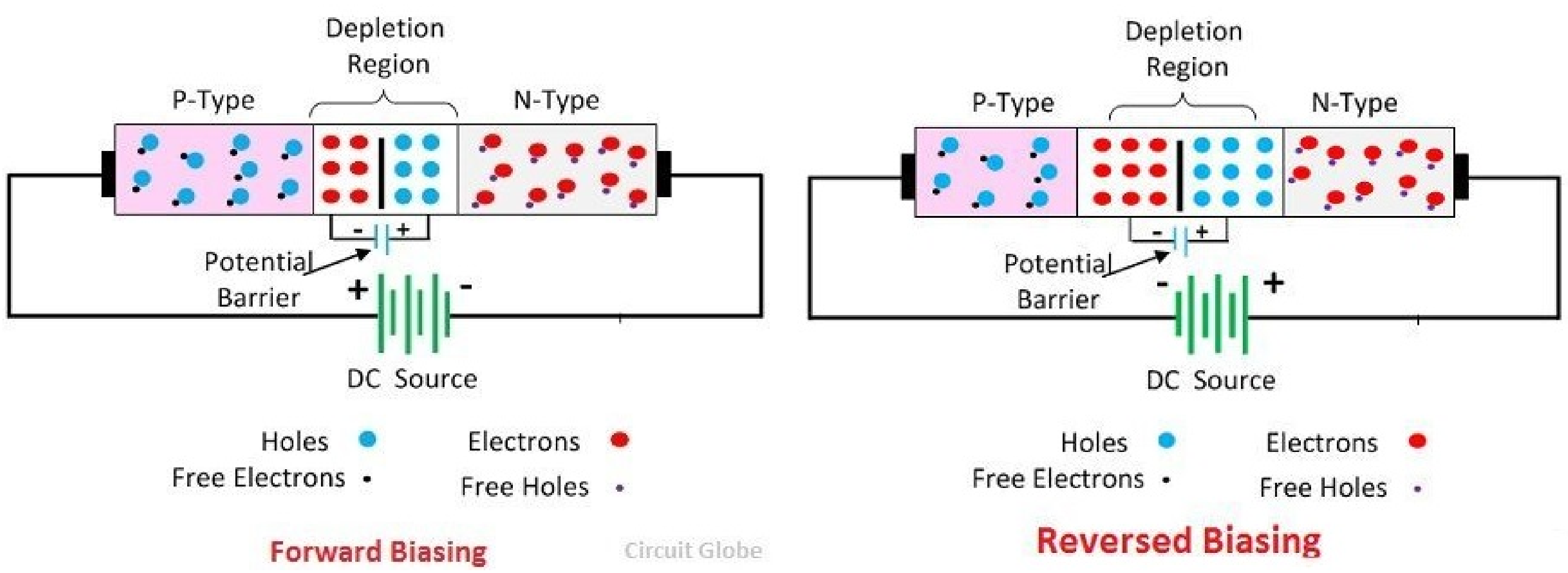
> **Direct bandgap semiconductor:**
> ⇒ These are impure or extrinsic or compound semiconductors.
> ⇒ InP (Indium Phosphide), GaAs (Gallium Arsenide), GaAsP (Gallium Arsenide Phosphide) are the materials or compounds used for Direct bandgap semiconductors.
>
> **Indirect bandgap semiconductor:**

⇒ These are pure or intrinsic or elemental semiconductors.
⇒ Ge (Germanium), Si (Silicon) are the materials or compounds used for Indirect bandgap semiconductors.

4. Explain biasing of a semiconductor material. Show how they are connected in forward and reverse biasing.

Biasing semiconductor material
When an external source of energy is applied to a P-N junction it is called a bias voltage or simply biasing. This method either increases or decreases the barrier potential of the junction.
Forward biasing means putting a voltage across a diode that allows current to flow easily, while reverse biasing means putting a voltage across a diode in the opposite direction.

NOTE: *(Below diagrams are for reference only)*



5. List the applications of direct and indirect band gap semiconductors.

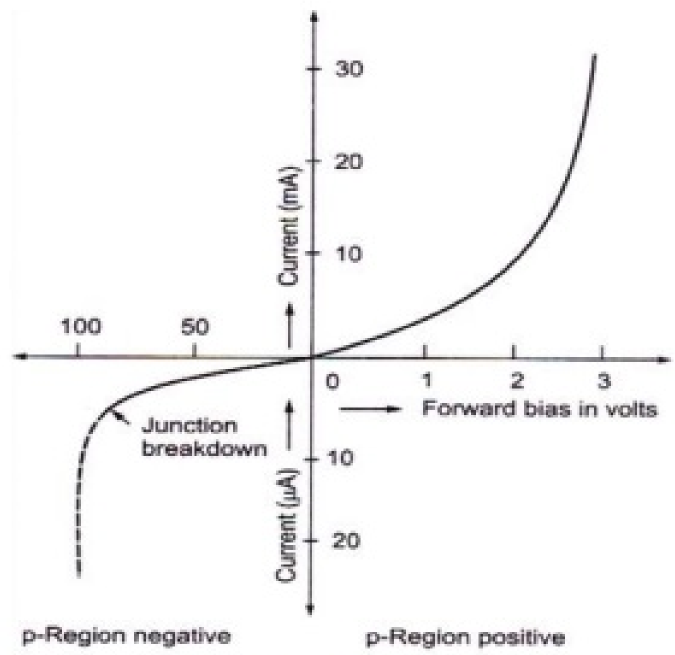
⇒ **Direct Band-Gap:**
They are used to fabricate LEDs, Laser Diodes, etc.
⇒ **Indirect Band-Gap:**
They are used to amplify the signals in electronic devices like rectifiers, transistors, amplifiers, etc..

6. Recall different techniques used for the formation P-N junction diode

In practice a P-N junction diode may be obtained in any of the following three methods:
1) Grown junction type
2) Fused (or alloyed) junction type and
3) Diffused junction type

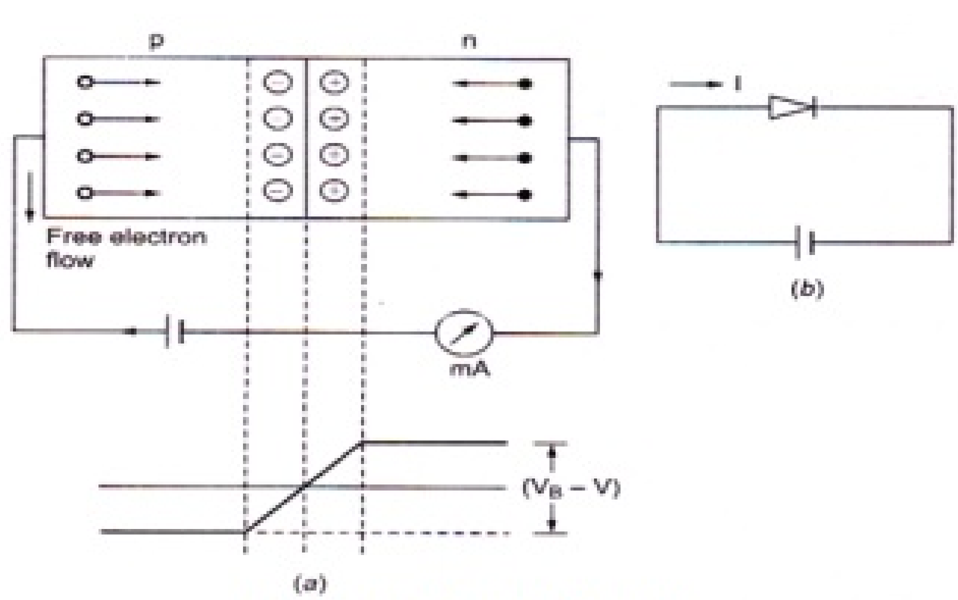
7. Define the Depletion layer formed in a P-N junction diode. Draw the V-I characteristics of the diode.

A depletion region or depletion layer is a region in a P-N junction diode, where no mobile charge carriers are present. The depletion layer acts like a barrier that opposes the flow of electrons from the n-side and holes from the p-side. It is usually caused by the diffusion of charges, producing a narrow region at the junction.
The V-I characteristics of the P-N diode can be expressed using the following graph:



V-I curve of p-n diode

8. Draw the circuit of a forward biased P-N junction diode.



Forward Biased Circuit

9. What are elemental and compound semiconductors? Give two examples.

Elemental:
Indirect band-gap or intrinsic or pure semiconductors are known as elemental semiconductors.
Ex: Ge (Germanium), Si (Silicon).

Compound:
Direct band-gap or Extrinsic or impure semiconductors are known as Compound semiconductors.
Ex: InP (Indium Phosphide), GaAs (Gallium Arsenide), GaAsP (Gallium Arsenide phosphide).

10. Why is Zener diode used as a voltage regulator?

> Zener diode is a silicon semiconductor with a p-n junction that is specifically designed to work in the reverse biased condition. When forward biased, it behaves like a normal signal diode, but when the reverse voltage is applied to it, the voltage remains constant for a wide range of currents. Due to this feature, it is used as a voltage regulator in d.c. circuit.

Module 3 Part B QB Solutions

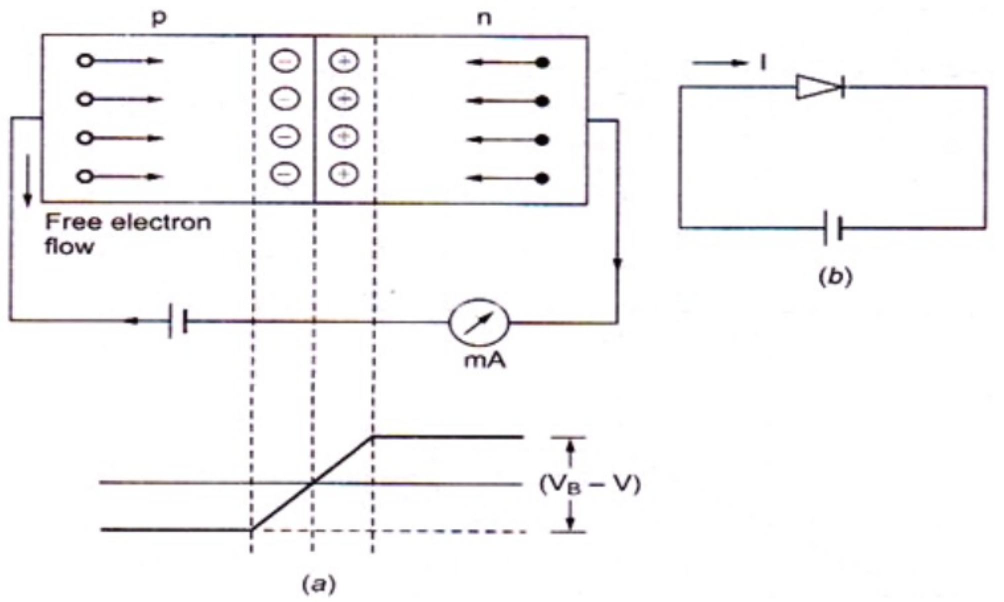
1. Write notes on direct and indirect band gap semiconductors.

> **Direct Band Gap:**
> ⇒ These are impure or extrinsic or compound semiconductors
> ⇒ Ex: InP (Indium Phosphide), GaAs (Gallium Arsenide), GaAsP (Gallium Arsenide phosphide), etc.
> ⇒ The minimum energy of the Conduction band(CB) and maximum energy of the Valence Band (VB) has the same value as the wave vector. ($k_1 = k_2$)
> ⇒ Here an electron from CB can recombine with a hole in VB directly by emitting light of photon of energy = hϑ
> ⇒ They are used to fabricate LEDs, Laser Diodes, etc.
> ⇒ Emission of light has energy gap is $E_g = \frac{hC}{\lambda} eV$
>
> **Indirect Band Gap:**
> ⇒ These are pure or intrinsic or elemental semiconductors
> ⇒ Ex: Ge (Germanium), Si (Silicon).
> ⇒ The minimum energy of Conduction Band (CB) and maximum energy Valence Band (VB) have the different values of the wave vector, i.e. $k_1 \neq k_2$
> ⇒ Here an electron from CB cannot recombine directly with holes in VB. But can recombine through traps by emitting light without emissions of photon or light.
> ⇒ They are used to amplify the signals in electronic devices like rectifiers, transistors, amplifiers, etc.
> ⇒ No emission of light. It conducts only electricity

2. What is forward biasing of a P-N junction? Draw the circuit diagram and explain.

> **Forward Biased Circuit:**
> ⇒ When the positive terminal of the battery is connected to p-type and negative to n-type, the function is said to be forward-biased.
> ⇒ Since the potential barrier height is very small $(0.2V)$, when the applied voltage exceeds that value.
> ⇒ The junction resistance becomes almost zero and a low resistance path is established. Hence even for a small increase of applied voltage, we observe a large increase in circuit current such a current is called forward bias current and the current is called forward current.
> ⇒ When the applied voltage is above the barrier potential the forward current(in (MA) is

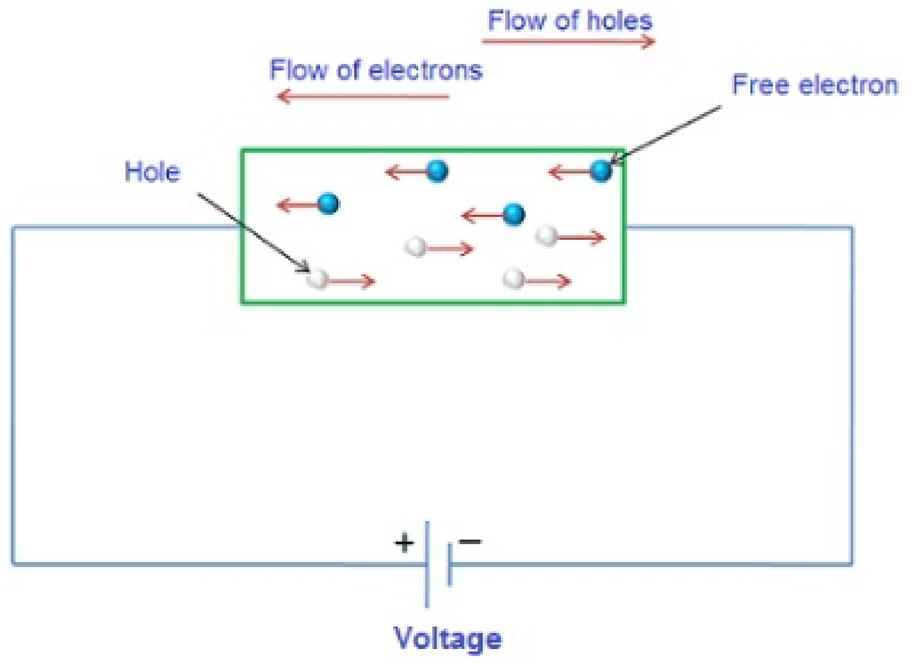
> found to increase linearly with the applied voltage, under forwarding bias, the D. C. resistance is about 100Ω for Ge diode)



Forward Biased Circuit

3. Describe the drift and diffusion currents in a semiconductor.

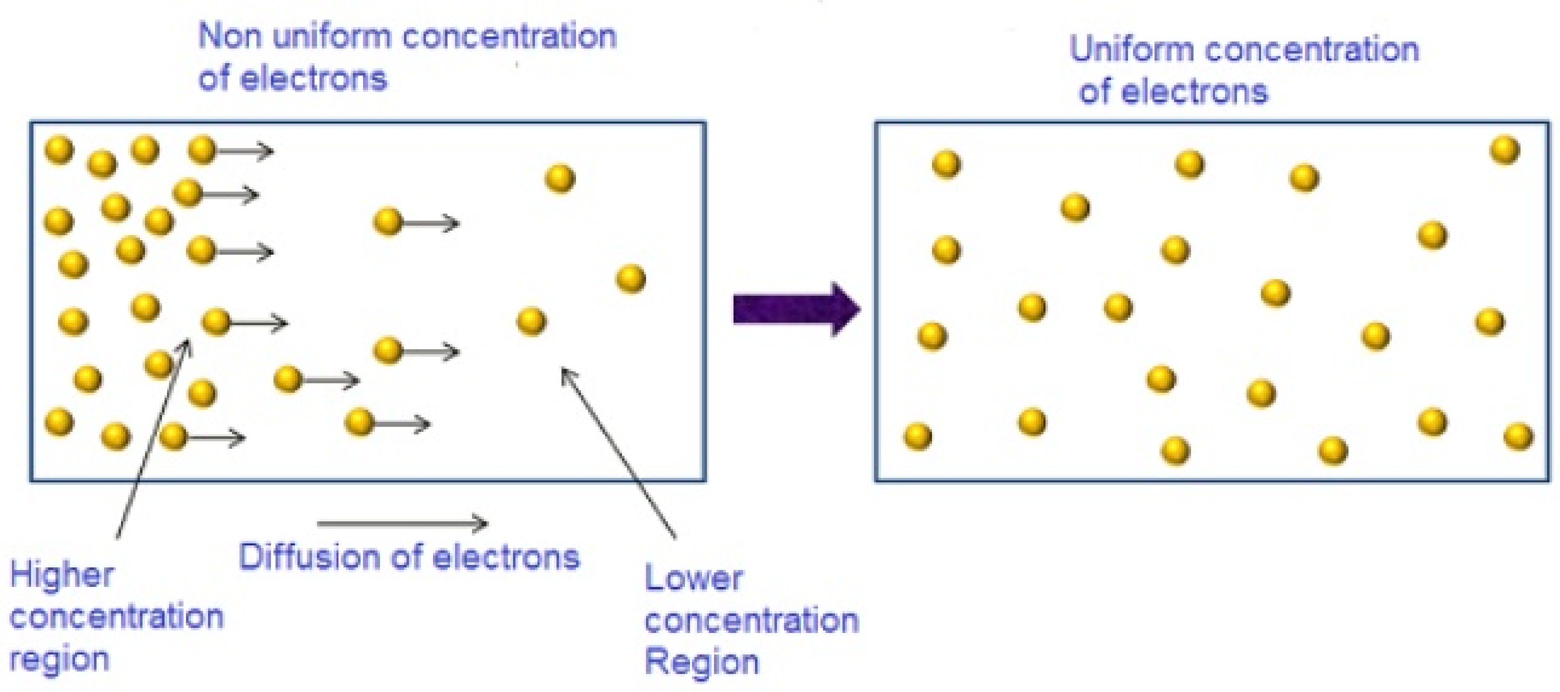
> **Drift currents in Semiconductor:**
> The flow of charge carriers, which is due to an applied voltage or electric field is called drift current.
> In a semiconductor, there are two types of charge carriers, they are electrons and holes. When the voltage is applied to a semiconductor, the free electrons move towards the positive terminal of a battery and holes move towards the negative terminal of the battery.
> **NOTE:** *(below diagrams are for reference only)*



> **Diffusion currents in Semiconductors:**
> The process by which, charge carriers (electrons or holes) in a semiconductor move from a region of higher concentration to a region of lower concentration is called diffusion.
> The region in which more number of electrons is present is called the higher concentration region and the region in which less number of electrons is present is called the lower concentration region. Current produced due to the motion of charge carriers from a region of higher concentration to a region of lower concentration is called

diffusion current. The diffusion process occurs in a semiconductor that is non-uniformly doped.

NOTE: *(below diagrams are for reference only)*



4. Discuss in detail about formation of a P-N junction diode

⇒ When a layer of P-type semiconductor material is placed with a layer of N-type semiconducting material in such a way, that the atoms of P-type combine with the atoms of N-type across the surface of contact form a surface junction where the combination has occurred are known as P-N junction.

⇒ Combined P-type and N-type semiconductors with P-N junction formation are known as junction diode of P-N diode.

⇒ In practice, a P-N junction diode may be obtained in any of the following three methods.

1) Grown junction type
2) Fused (or alloyed) junction type
3) Diffused junction type

1) Grown junction type:

When an extrinsic semiconductor is grown from the melt, during the middle of the growth process, impurities of the opposite kind are added to the melt so that the opposite type of crystal grows further.

Ex: N-type Silicon Crystal and P-type SIlicon with a trivalent impurity (Boron)

2) Fused (or alloyed) junction type:

In this type P-type and N-type materials are kept in contact and fused together by proper heat treatment to form the junction.

Ex: N-type Germanium Water and P-type Indium

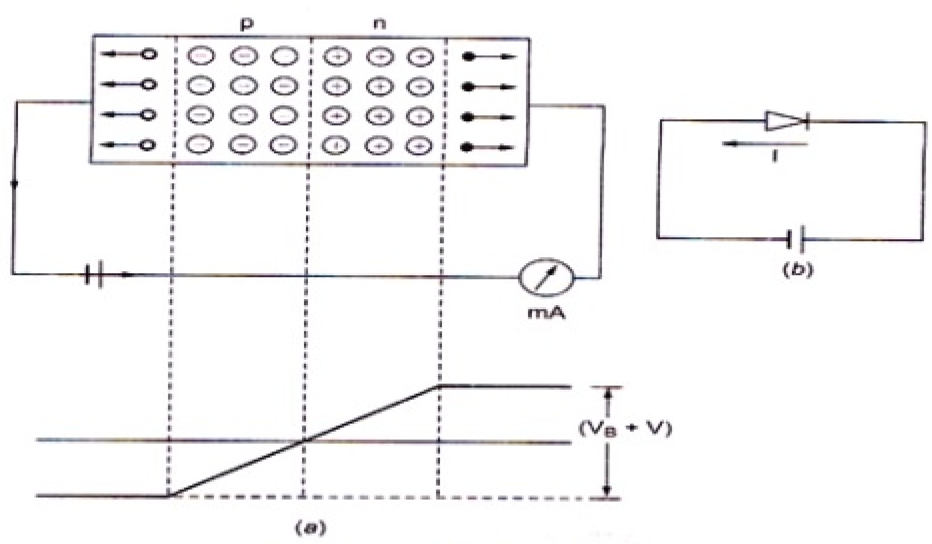
3) Diffused Junction type:

Diffused junctions are formed by the impurity diffusion technique. The diffusion process employs either the gas diffusion method or the solid diffusion method.

Ex: N-type Silicon and P-type Indium

5. What is reverse biasing of a P-N junction diode? Draw the circuit diagram and explain.

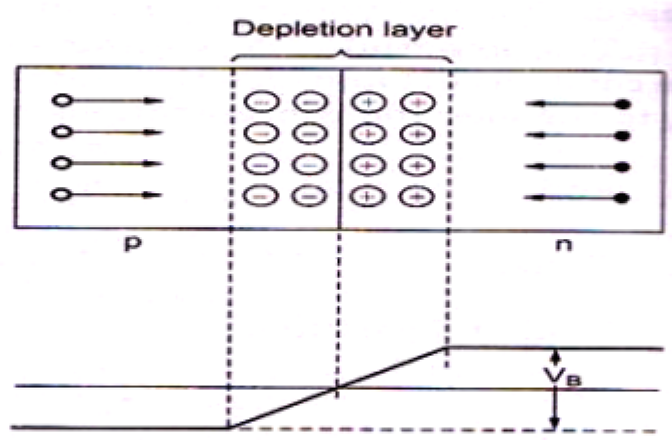
> ⇒ The process by which, a P-N junction diode blocks the electric current in the presence of applied voltage is called reverse-biased PN junction diode. These positive ions at the P-N junction (n-side) oppose the flow of positive charge carriers (holes) from the p-side.
> ⇒ When reverse biased, a slight reverse current (in micro Amps) flows in the circuit. Even for a large increase in bias voltage (say $20V$), there is negligible reverse current.
> ⇒ When the applied reverse voltage is high enough to break the covalent bonds of the crystal, the current rises suddenly in the reverse direction.
> ⇒ The breakdown reverse bias is called breakdown voltage or Zener voltage. For Ge(Germanium) diode reverse resistance is around $1M\Omega$.



Reverse Biased Circuit

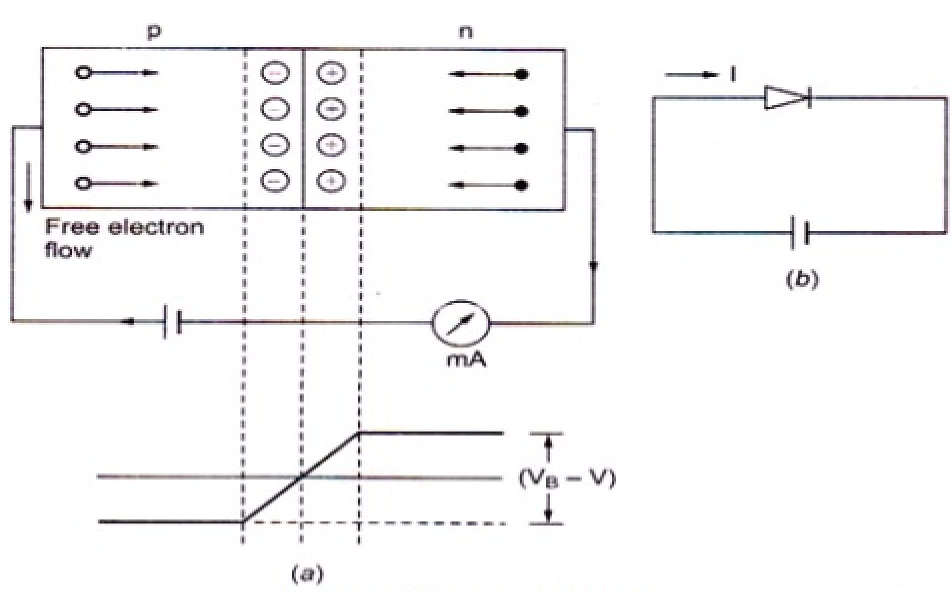
6. Draw the graphic symbol of the crystal diode and explain its significance. How will you determine the V-I characteristics of a P-N diode?

> Volt-ampere (V-I) characteristics of a PN junction or semiconductor diode are the curve between the voltage across the junction and the current through the circuit.
> Normally the voltage is taken along the x-axis and current along the y-axis.
> The characteristics can be explained under three cases, such as :
> ⇒ Zero bias or unbiased
> ⇒ Forward bias
> ⇒ Reverse bias
>
> **1) Zero bias or Unbiased:**
> → When the function is not connected to any voltage source, it is said to be unbiased and due to barrier potential across the junction, there is no flow of charge carriers and hence there is no current flow through the junction.



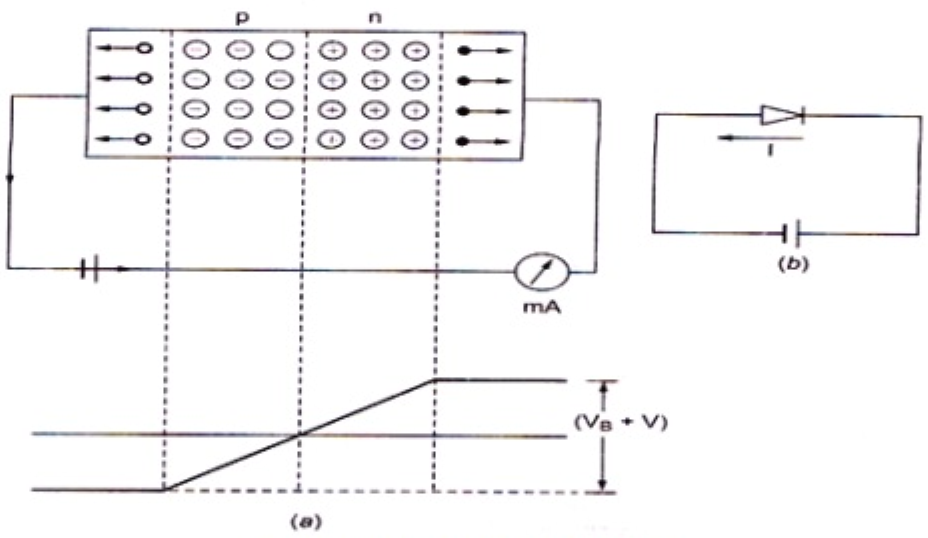
Unbiased p-n junction

2) Forward Biased Circuit:
→In forward biased condition, the P-type of the PN junction is connected to the positive terminal and the N-type is connected to the negative terminal of the external voltage. This results in a reduced potential barrier.
→Since the potential barrier height is very small (0.2V), when the applied voltage exceeds that value. The junction resistance becomes almost zero and a low resistance path is established. Hence even for a small increase of applied voltage, we observe a large increase in circuit current such a circuit is called a forward bias circuit and the current is called forward current.
→When the applied voltage is above the barrier potential the forward current (in MA) is found to increase linearly with the applied voltage, under forwarding bias, the D. C. resistance is about 100 Ω for Ge (Germanium) diode.



Forward Biased Circuit

3) Reverse Biased Circuit:
→ In reverse bias condition, the P-type of the PN junction is connected to the negative terminal and the N-type is connected to the positive terminal of the external voltage. This results in an increased potential barrier at the junction.
→ When reverse biased, a slight reverse current (in micro Amps) flows in the circuit. Even for a large increase in bias voltage (in micro Amps) flows in the circuit. Even for a large increase in bias voltage (say $20V$), there is negligible reverse current.
→ When the applied reverse voltage is high enough to break the covalent bonds of the crystal, the current rises suddenly in the reverse direction.
→ The breakdown reverse bias is called breakdown voltage or Zener voltage. For Ge(Germanium) diode reverse resistance is around $1M\Omega$.



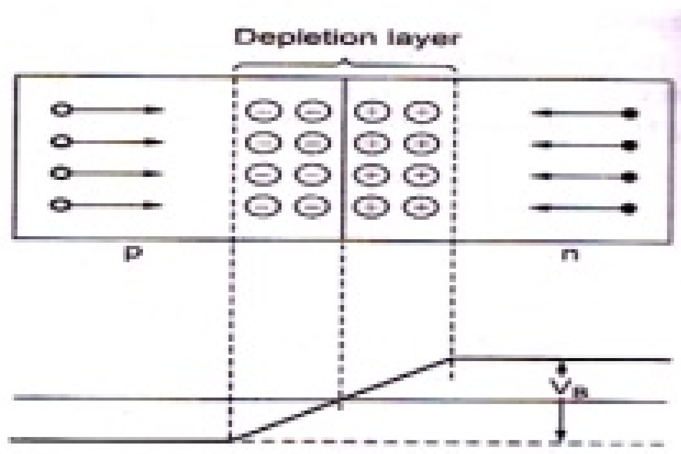
Reverse Biased Circuit

7. Write a short note on Zener diode. Explain how Zener diode maintains constant voltage across the load.

> A Zener diode which is also known as the reverse-biased diode is a special type of diode designed to reliably allow the current to flow "backward" when a certain amount of voltage is passed, then it is known as the Zener voltage. This kind of behavior is observed because during reverse bias the depletion layer will get thicker and makes it impossible for electrons to flow through and after certain voltage (Since voltage increases the amount of work done increases and power increases) electrons will pass through the depletion layer and this voltage is known as Zener Voltage.
>
> Zener diodes are widely used in electronic equipment of all kinds and are one of the basic building blocks of electronic circuits. They are also used to protect circuits from overvoltage, especially electrostatic discharge (ESD).

8. Draw and explain the energy band diagram for a p-n junction diode in an unbiased condition.

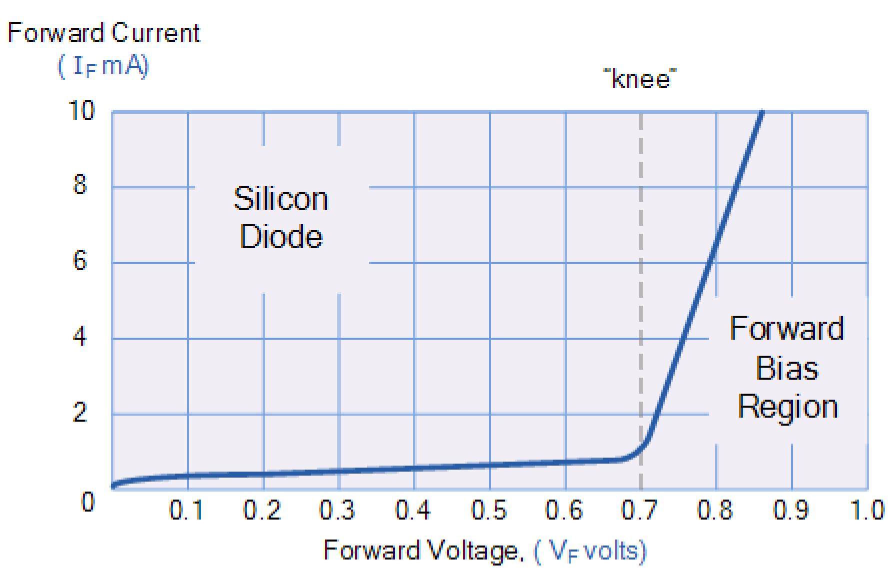
> When the function is not connected to any voltage source, it is said to be unbiased, and due to the barrier of the potential across the junction, there is no flow of charge carriers and hence there is no current flow through the junction.
> Explanation - The potential barrier that now exists discourages the diffusion of any more majority carriers across the junction. However, the potential barrier helps minority carriers (few free electrons in the P-region and few holes in the N-region) to drift across the junction.
> Then an “Equilibrium” or balance will be established when the majority carriers are equal and both moving in opposite directions so that the net result is zero current flowing in the circuit. When this occurs the junction is said to be in a state of "Dynamic Equilibrium".



Unbiased p-n junction

9. Show that the application of forwarding bias voltage across p-n junction causes an exponential increase in the number of charge carriers in opposite regions.

> 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.
> 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 conduction across the p-n junction takes place due to the migration of the majority carriers from one region to another. The resistance of the p-n junction becomes low when forward-biased. The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve below as the "knee" point.
> **NOTE:** *(The below V-I graph is for reference only)*



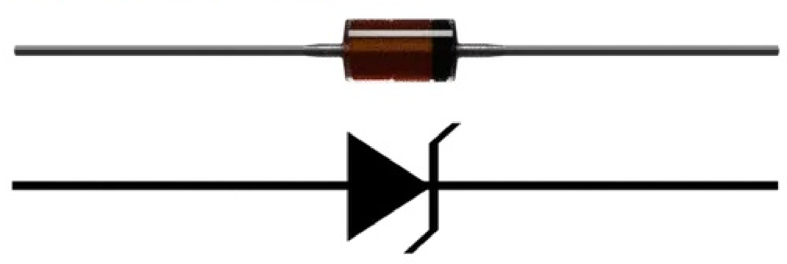
10. What is Zener voltage or breakdown voltage in a PN junction diode?

> The Zener breakdown voltage is the reverse bias voltage after which a significant amount of current starts flowing through the Zener diode. Here in the diagram, VZ refers to the Zener breakdown voltage. Until the voltage reaches the Zener breakdown level, a tiny amount of current flows through the diode. Once the reverse bias voltage becomes more than the Zener breakdown voltage, a significant amount of current starts flowing through the diode due to Zener breakdown. The voltage remains at the Zener breakdown voltage value, but the current through the diode increases when the input voltage gets increased. Due to the unique property of the Zener diode, the depletion region regains

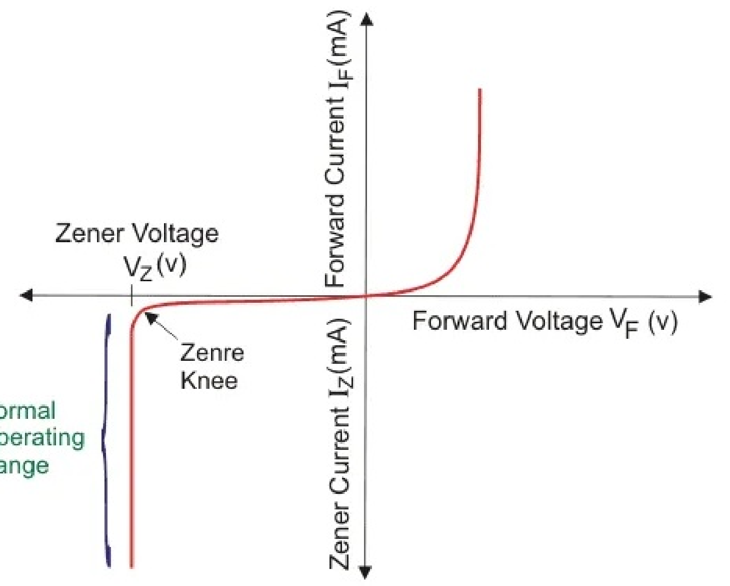
its original position when the reverse voltage gets removed.

The Zener diode doesn't get damaged despite this massive amount of current flowing through it. This unique functionality makes it very useful for many applications.
As the voltage remains at the Zener breakdown voltage, we use Zener diodes for voltage regulation. We use them in voltage stabilizers and various other protection circuits. We also use them in clipping circuits and clamping circuits. They provide a low-cost solution for voltage regulation.
NOTE: *(The below diagram and graph is for additional information)*

Here is the Zener diode symbol



Let us now look at the **Zener diode characteristic:**



Module 3 Part C QB Solutions

1. Calculate the value of applied forward voltage for a P-N junction diode, if $Is = 50\mu A$, $I = 2A$ and $\frac{e}{kT} = 40$.

$I = 2A$ (net current in diode)
$Is = 50\mu A$ (saturation current)
e/KT = 40
$I = Is(exp^{(ev/KT)} - 1)$

$2/50 * 10^{-6} = exp(40 * v) - 1$
$40000 + 1 = exp(40 * v)$
$40001 = exp(40 * v)$

Applying natural log (ln) on both sides
$ln(40001) = ln(exp(40 \times v))10.597 = 40 \times v$
NOTE: ($ln(40001)$ = 10.597 and $ln(exp(40 \times v)) = 40 \times v$)
$v = 10.597/40$

> $v = 0.265V$
> Therefore forward voltage is $0.265V$

2. The current in a p-n junction at $27^{\circ}C$ is $0.18\mu A$ when a large reverse bias voltage is applied. Estimate the current when a forward bias of $0.98V$ is applied.

> **Forward Bias:**
> $V = 0.98V$
> $i =?$(to be found)
>
> **Reverse Bias:**
> $i = 0.18 * 10^{-6}A$
> $T = 27^{\circ}C$
>
> So, now to find Terminal Voltage,
> $V_T = KT/q$
> (K is Boltzmann Constant, q is Charge and T is the temperature in $^{\circ}$Kelvin)
> $V_T = \frac{(27+273.15)}{11600}$
>
> $V_T = \frac{300.15}{11600} = 0.025875V$
>
> $I = I_o(e^{\frac{v}{\eta * V_T}} - 1)$
> $I = 0.18 * 10^{-6}(e^{\frac{0.98}{1\times0.0258}} - 1)$
>
> NOTE: $(e^{\frac{0.98}{1\times0.0258}}) = 3.13 \times 10^{16}$
> $I = 0.18 \times 10^{-6}(3.136 \times 10^{16} - 1)$
>
> $I = 0.18 \times 10^{-6} \times 3.136 \times 10^{16}$
>
> $I = 56448 \times 10^5$
> Therefore the required Current value is $I = 56448 \times 10^5$

3. Evaluate the forward bias current of a Si diode when forward bias voltage of $0.4V$ is applied, the reverse saturation current is $1.17 \times 10^{-9}A$ and the thermal voltage is $25.2mV$

> **Given**:
> $I = I_O \times (e^{\frac{V}{\eta \times V_T}} - 1)$
> where $I_O = 1.17 \times 10^{-9}$ (A reverse saturation current)
> $\eta =$ ideality factor
> $V_T = 25.2mA = 0.0252A$ (thermal voltage)
> $V = 0.4V$ (applied voltage)
>
> Since in this question ideality factor is not mentioned it can be taken as one.
> $\eta = 1$
> Therefore, $I = 1.17 \times 10^{-9} \times (e^{\frac{0.4}{0.0252}} - 1) = 9.156mA$

NOTE: $(e^{\frac{0.4}{0.0252}}) = 7826420.982$
The forward bias current of the Si diode is $9.156mA$.

4. Obtain the reverse saturation current of a diode if the current at $0.2V$ forward bias is $0.1mA$ at a temperature of $25^{\circ}C$ and the ideality factor is 1.5.

Explanation: Equation for diode current
$I = I_O \times (e^{\frac{V}{\eta V_T}} - 1)$ where $I_O =$ reverse saturation current
$\eta =$ ideality factor
$V_T =$ thermal voltage
$V =$ applied voltage
Here, $I = 0.1mA, \eta = 1.5, V = 0.2V$, $V_T = \frac{T \times K}{11600}$
Therefore,
So, now to find Terminal Voltage,
$V_T = \frac{KT}{q}$
(K is Boltzmann Constant, q is Charge and T is temperature in $^{\circ}K$)
$V_T = \frac{(25+273.15)}{11600}$

$V_T = \frac{298.15}{11600} = 0.0257V$
Now,
$I = I_O \times (e^{\frac{V}{\eta \times V_T}} - 1)$

$0.1 \times 10^{-3} = I_O \times (e^{\frac{0.2}{1.5 \times 0.0257}} - 1)$
$0.1 \times 10^{-3} = I_O \times (179.122 - 1)$

$I_O = \frac{0.1 \times 10^{-3}}{178.122}$
$I_O = 5.61 \times 10^{-7}\ Amps$
Therefore reverse saturation current is $I_O = 5.16 \times 10^{-7} Amps$

5. Find the applied voltage on a forward-biased diode if the current is $1mA$ and the reverse saturation current is 10^{-10}. Given temperature is $25^{\circ}C$ and ideality factor as 1.5

Explanation: Equation for diode current
$I = I_O \times (e^{\frac{V}{\eta \times V_T}} - 1)$ where $I_O =$ reverse saturation current
$\eta =$ ideality factor
$V_T =$ thermal voltage
$V =$ applied voltage

$V_T = \frac{K \times T}{q}$ here K is Boltzmann constant and T is temperature in Kelvin and q is charge
$T = (25 + 273)^{\circ}K = 298^{\circ}K$
$V_T = \frac{298}{11600} = 0.0257V$
$\eta = 1.5$

$I = 1mA$
$I_O = 10^{-10}A$
$I = I_O \times (e^{\frac{V}{\eta \times V_T}} - 1)$

$\frac{I}{I_O} + 1 = e^{\frac{V}{\eta \times V_T}}$

Applying natural logarithm on both sides $ln((\frac{I}{I_O}) + 1) = ln(e^{\frac{V}{\eta \times V_T}})ln((\frac{10^{-3}}{10^{-10}}) + 1) = \frac{V}{\eta \times V_T}ln(10^7 + 1) = \frac{V}{1.5 \times 0.0256} = \frac{V}{0.0384}$
$16.12 \times 0.0384 = V$

$V = 0.619V$
Therefore, applied voltage on forward bias is $V = 0.619V$