## Module – 1 Semiconductor Diodes and Applications

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## 1.1 PN Junction Diode

When P-type and N-type semiconductors are joined together, at that instant PN junction is formed. This is also called as PN junction diode. Diode is a two terminal device which allows current to flow only in one direction, offering less resistance. The structure and the circuit symbol are as shown in the fig.1.1.

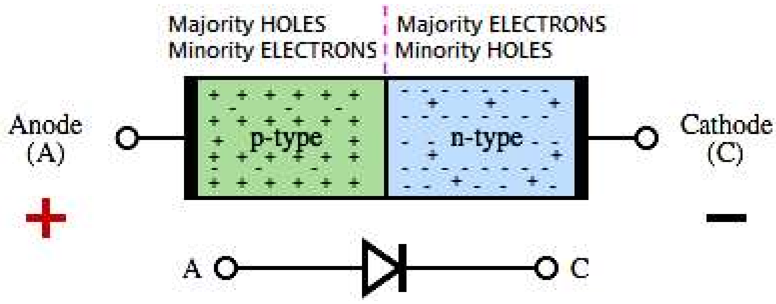



**Fig.1.1 structure and circuit symbol of the PN junction Diode**

Diode has an arrow head symbol (►) indicating the conventional direction of current flow in Forward Bias condition.

**Unbiased Diode :** When no external DC voltage is applied between Anode and Cathode, it is said to be unbiased Diode. The instant, P-type and N-type semiconductors are joined; the following phenomenon takes place immediately.

(i) The majority electrons from N-side diffuse (spread) into P-side and the majority holes from P-side diffuse into N-side. It is as shown in the fig.1.2 (a).

(ii) The free electron – hole recombination creates a pair of ions. Fixed positive ions on N-side and fixed negative ions on P-side. It is as shown in the fig.1.2 (b).

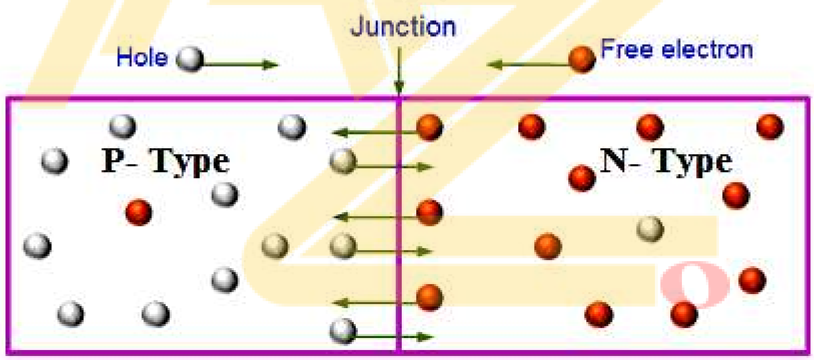



**Fig.1.2 (a) Holes from P-Type diffuse into N-Type and Electrons from N-Type diffuse into P-Type**

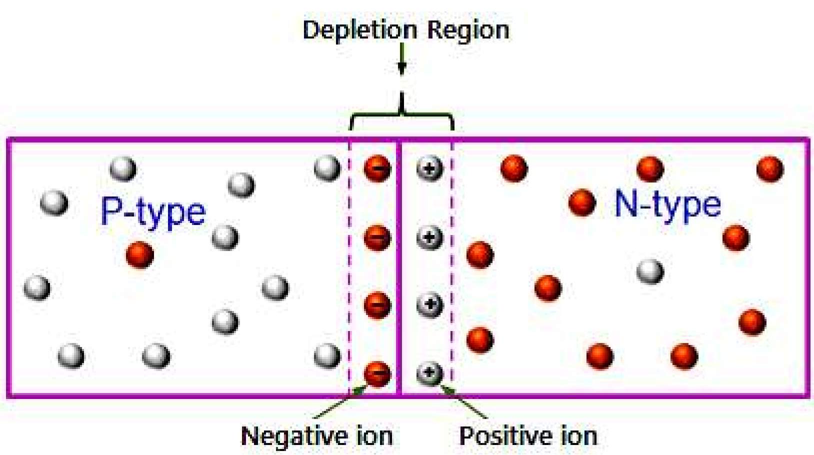



**Fig.1.2 (b) Holes and electrons recombined across the PN junction causes depletion region**

The region of positive ions on N-side and negative ions on P-side at the junction is called the depletion region.

(iii) An electric potential is developed due to the immobile positive and negative ions (known as barrier potential, $V_B$) that stops further re-combination of electrons and holes.

(iv) This barrier potential, $V_B$, causes the movement of minority charge carriers in opposite direction. This is called drift current (very small in magnitude in terms of µA or ηA).

(v) In equilibrium state, the net current across the junction is zero.

## Types of Diode Biasing

*Biasing* is the process of applying external DC voltage across the device to bring it into the operating condition. There are two types of biasing:

1. Forward Biasing (FB) and
2. Reverse Biasing (RB)

**Forward Biasing:** Diode is said to be Forward Biasing, if P-side is connected to positive (+) and N-side is connected to negative (-) of the battery, $V_F$ as shown in the fig.1.3.

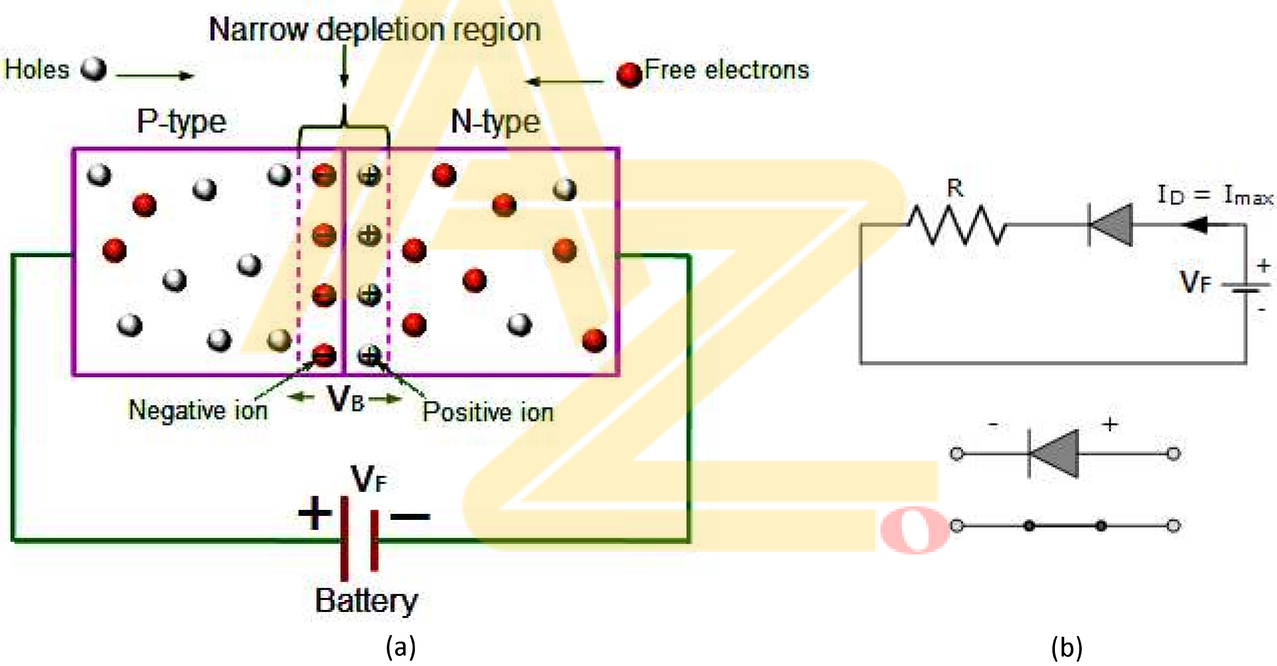



**Fig.1.3 (a) Diode under Forward Biasing condition (depletion width decreases)**
**(b) Practical diode circuit acts like a closed switch**

Let $V_F$ be the forward voltage applied across the terminals of the diode D and $V_B$ be the barrier potential developed across the PN junction. When FB is applied across the diode; the following points are observed.

(i) If $V_F < V_B$, diode does not conduct and no current flows through the diode (i.e, $I_D = 0$). Because, the depletion width will not decrease. That means, electrons cannot gain enough energy to cross over the depletion region and move towards P-region. Same applies to holes in the opposite.

(ii) If $V_F > V_B$, diode conducts and current flows in the circuit. This is because, holes of P-region are repelled by (+) and electrons of N-region are repelled by (-) of the battery, $V_F$. As a result, depletion width reduces. It is as shown in the fig.1.3 (a).

(iii) If $V_F >> V_B$ and since, forward biased diode offers less resistance, current rises sharply. It is desired an external series resistance R, to limit the diode current $I_D$, as shown in fig. 1.3(b).

**Example 1:** Find the value of series resistance R, required to driving a forward current of 1.25mA through a Germanium diode from a 4.5V battery. Write the circuit diagram showing all the values.

**VTU (14ELN15/25) June/July 2015**

**Solution**: Given $I_F = 1.25mA$,

$V = 4.5V$,

$V_D = 0.3V$

Using Ohm's law, $V = I_F R$ and from fig Ex 1

$$(4.5 - 0.3) = 1.25 \times 10^{-3} R$$

$$R = 4.2 / (1.25 \times 10^{-3}) = 3.36 K\,\Omega$$

$$\boxed{R = 3.36K\,\Omega}$$

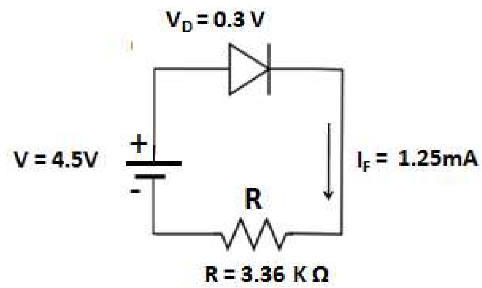
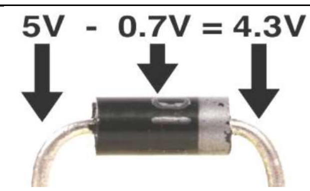



**Fig. Ex 1**

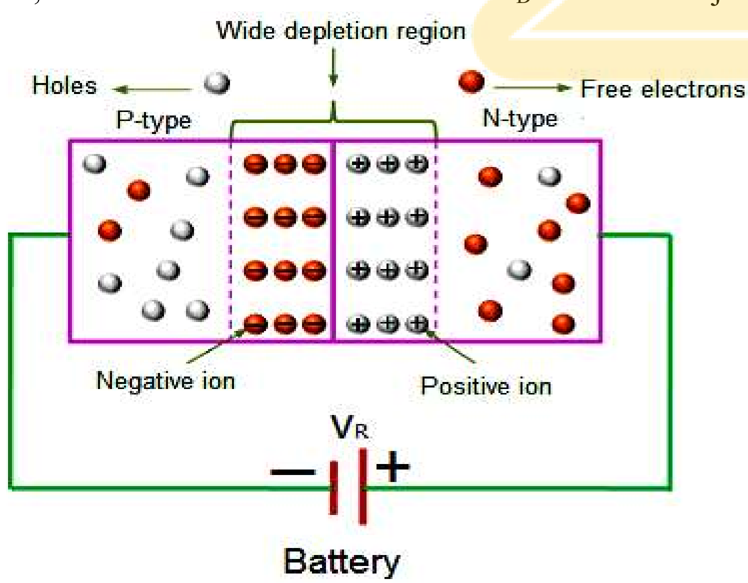
[NOTE: The amount of energy required by electrons to cross the junction is equal to the barrier potential, $V_B$ (0.3V for Germanium diode and 0.7V for Silicon). This means, when diode is FB, voltage drop across the diode ≡ 0.7V for (Si) and 0.3V for (Ge)]



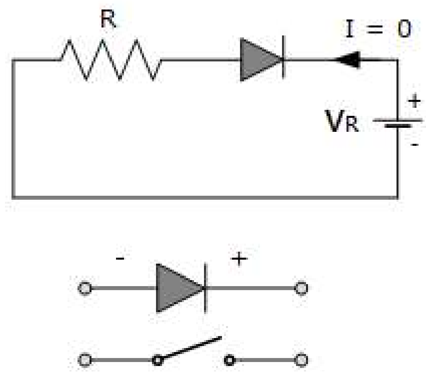

**Reverse Biasing:** Diode is said to be reverse biasing, if P-side is connected to negative (-) and N-side is connected to positive (+) of the battery, $V_R$ as shown in the fig. 1.4(a).

When RB is applied across the diode; the following phenomena occur.

(i) Quickly, electronics of N-side are attracted towards the positive (+) and holes of P-side are attracted towards the negative (-) of the battery. This reduces the number of majority carriers on either side of the regions and depletion width increases. It is as shown in the fig.1.4 (a). Additional more positive and negative immobile ions are created across the junction. This increases the resistance of the crystal. As a result, diode does not conduct and current $I_D$ due to the majority carriers is zero ($I_D = 0$).




(a)




(b)

**Fig.1.4 (a) Diode under Reverse Bias condition (increase in the depletion width).**
**(b) Practical diode circuit acts like a open switch.**

(ii) Electrons of P- region and holes of N-region (*minority charge carriers*) are pushed towards the PN junction by the respective battery terminals. This constitutes a very small reverse current called *reverse saturation current* $I_S$. The magnitude is in terms of µA or ηA.

## V I – Characteristics of Diode

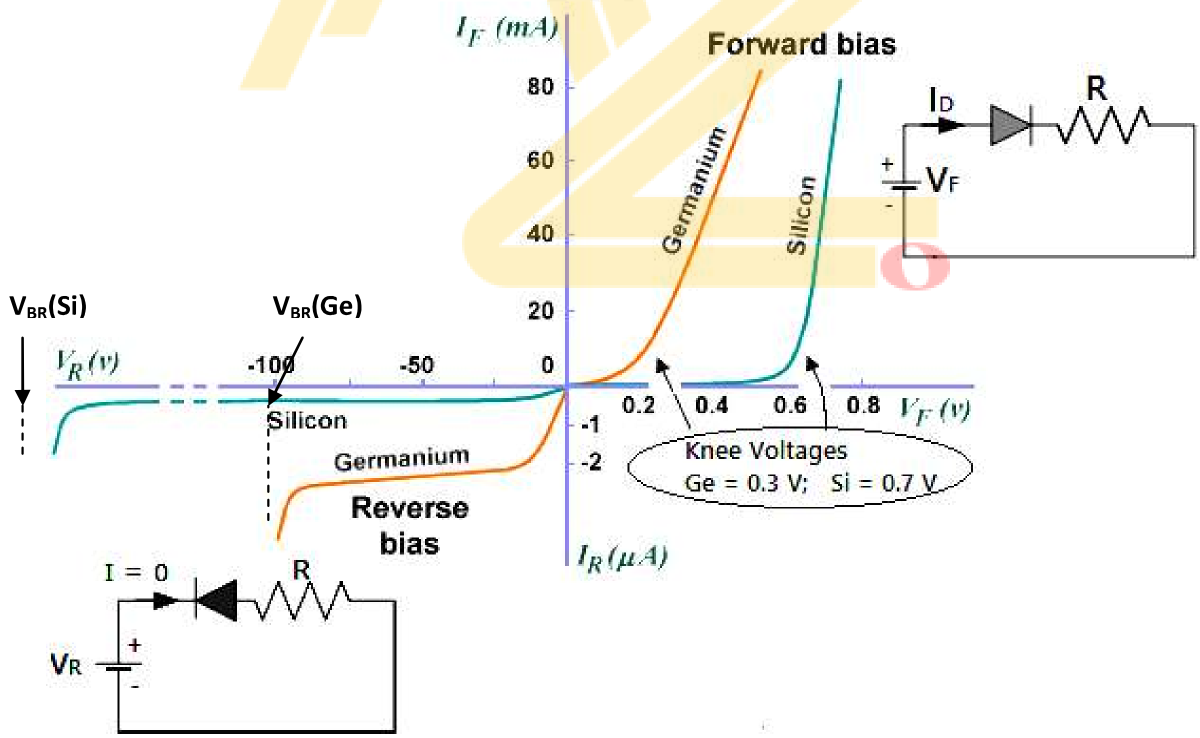
V I means, Volt – Ampere, is an experimental study to analyze graphically the electrical behavior (relationship between voltage and current) of the device. V I – Characteristics of the Diode (shown in fig.1.5) is non-linear (not straight line), because its resistance is not constant.

## 1. Forward Characteristics

This is ON mode of diode. P-side is connected to positive (+) and N-side is connected to negative (-) of the battery. From the fig. 1.5(a) the following point are observed.

(i) The current in this mode is called *forward current,* $I_F$, only due to majority carriers.
(ii) At $V_F = 0$, diode does not conduct, hence there is no forward current (i.e., $I_F = 0$).
(iii) With gradual increase in the forward voltage $V_F$, forward current $I_F$ increases.
(iv) Continuing increase of $V_F$, causes rapid increase of $I_F$, because diode offers less resistance.
(vi) The *knee voltage*, at which diode current starts to increase rapidly (0.3V for Germanium diode and 0.7V for Silicon). Above knee voltage, the diode current is almost exponential growth.

(vii) Dynamic resistance of the diode, $r_D = \frac{small\ change\ in\ diode\ forward\ voltage}{respective\ change\ in\ its\ forward\ current} = \frac{\Delta V}{\Delta I}\ \Omega$




(a) (b)

**Fig.1.5 V-I characteristics of diode: (a) Forward Biased characteristics (b) Reverse Biased characteristics of Silicon and Germanium diodes**

**Comparison of VI characteristics between Silicon and Germanium diode is illustrated in the fig. 1.5.**

| Parameter | Silicon (Si) | Germanium (Ge) |
|---|---|---|
| 1. $I_{CBO}$ at 25°C | 0.01 µA to 1µA | 2 to 15 µA. |
| 2. variation of $I_{CBO}$ with temperature | $I_{CBO} \cong$ doubles with each 8 to 10°C rise | $I_{CBO} \cong$ doubles with each 12°C rise |
| 3. working temperature | operated up to 150°C | operated up to 70°C |
| 4. potential barrier | 0.7V | 0.3V |
| 5. PIV ratings | 1000V | close to 400V |

**Example 2:** The incremental change in the voltage and the current is found to be 0.19 V and 37.6 mA respectively from the forward characteristics of the diode. Determine the AC resistance of the junction. **VTU (11ELN15/25) Jan 2013**

**Solution**: Given $\Delta I_F = 37.6$ mA,

$\Delta V_F = 0.19$ V

AC resistance = Dynamic resistance of the diode,

$$r_D = \frac{\Delta V_F}{\Delta I_F}\ \Omega$$

i.e., slope of fig Ex 2 $= \frac{1}{r_D} = \frac{1}{\frac{\Delta V_F}{\Delta I_F}} = \frac{\Delta I_F}{\Delta V_F}$

$$r_D = \frac{0.19}{37.6\ x10^{-3}} = 5.05\ \Omega$$

$$\boxed{r_D = 5.05\ \Omega}$$

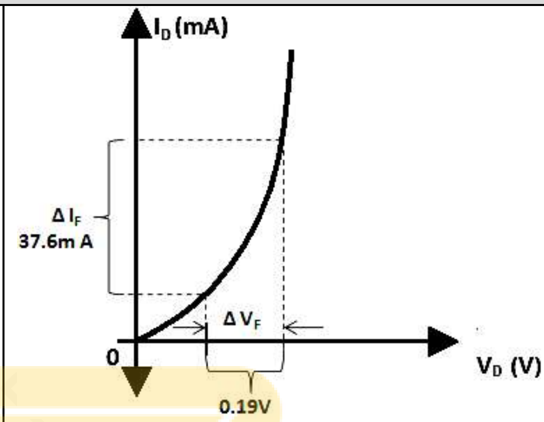



**Fig. Ex 2**

## 2. Reverse Characteristics

This is OFF mode of diode. P-side is connected to positive (+) and N-side is connected to negative (-) of the battery. From the fig. 1.5 (b), the following points are observed.

(i) The majority carrier current is blocked, but very small reverse current called *reverse saturation current* $I_S$ flows due to minority charge carriers (see fig. 1.5 (b)).

(ii) At a point called *break down voltage*, $V_{BR}$, reverse current $I_R$ sharply increases. This is not normal mode of operation. That means, if $I_R$ exceeds the maximum rating, diode will get damage.

(iii) Break down voltage depends on doping level, set by the manufacturer.

## Diode parameters or Specifications

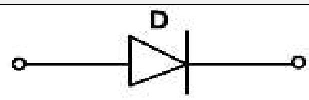
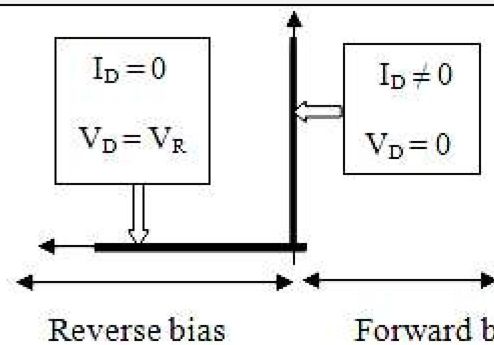
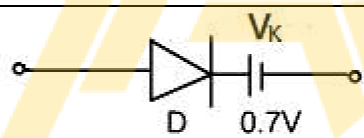
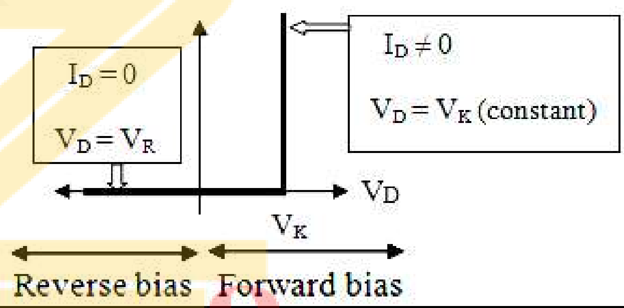
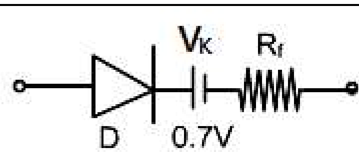
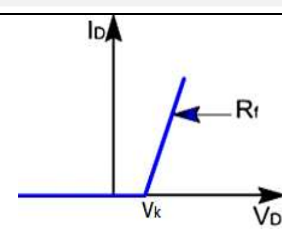
Diode specifications are the ratings of diodes important in circuit design and component selection. The list below provides a summary of some of the more widely used diode specifications, with their meanings.

1. **Forward Voltage ($V_F$):** Forward voltage is the voltage drop across a PN junction diode during forward biased condition. It is due to the majority carriers, measured in volts.
2. **Forward Current ($I_F$):** It is a current flowing through forward biased diode (due to the majority carriers), measured in milli ampere (mA).
3. **Reverse Current ($I_R$):** It is a current flowing through reverse biased diode (due to the minority carriers), measured in µA or ηA.

4. **Reverse Break down Voltage ($V_{BR}$) or Peak Inverse Voltage (PIV):** It is a maximum reverse voltage that a diode can withstand without damage, measured in volts.
5. **Power Dissipation ($P_D$):** It is the product of diode voltage, $V_D$ and diode current, $I_D$. i.e., $\mathbf{P_D} = V_D I_D$, measured in watts.

## 1.2 Diode Equivalent Circuit

Diode equivalent circuits or approximations describe the behavior of diode circuit. It is useful in the analysis of the device. In the approximation, the equivalent circuit involves voltage cells and resistors. There are three diodes approximations demonstrated below.

<table>
<tr><th>Approximation</th><th>Equivalent circuit</th><th>Characteristics curve</th></tr>
<tr><td>1st Approximation (Ideal diode)<br>Acts like a perfect switch with zero resistance.</td><td>
<br>Observation: Diode starts conducting instantly without any voltage drop, when it is forward biased.</td><td>
</td></tr>
<tr><td colspan="3">➢ In forward bias, diode is like a closed switch, hence R = 0, in turn conducts heavily even if $V_D = 0$<br>➢ In reverse bias, diode is like a open switch, hence $R = \infty\ \Omega$, in turn does not conduct ,therefore $I_D = 0$</td></tr>
<tr><td rowspan="2">2nd Approximation (Real or practical diode)<br>Assume the diode drop voltage, $V_K$.</td><td>
<br>Battery $V_K$ (0.7V for Si) indicates voltage drop across diode.</td><td>
</td></tr>
<tr><td colspan="2">Observation: Diode starts conducting well after voltage drop $V_K$, when it is forward biased.</td></tr>
<tr><td colspan="3">➢ In forward bias, diode starts conducting well after voltage drop $V_K$ offering R = 0<br>➢ In reverse bias, diode offers $R = \infty\ \Omega$, in turn does not conduct, therefore $I_D = 0$</td></tr>
<tr><td>3rd Approximation (Piece wise linear)<br>Assume the diode drop voltage, $V_K$ and bulk resistance $R_D$.</td><td>
<br>$R_f$ = dynamic resistance<br>$= \frac{\Delta V_R}{\Delta I_D}\ \Omega$<br>$\mathbf{V_D = V_K + I_D R_f}$ (linear equation)</td><td>
<br>Observation: Curve is formed by two straight lines. One, along x-axis, indicates diode does not conduct up to $V_K$ . Two, slope $= \frac{1}{R_f} = \frac{\Delta I_D}{\Delta V_R}$</td></tr>
<tr><td colspan="3">➢ In forward bias, diode starts conducting well after voltage drop $V_K$ offering low resistance, $R_f$<br>➢ In reverse bias, diode offers very high resistance, but $R \neq \infty\ \Omega$.</td></tr>
</table>

## Diode Relationship

The current and the voltage relationship of the PN-junction diode is exponential. It is described by Shockley's ideal diode equation, mathematically expressed as,

$$I_D = I_S\left(e^{\frac{qV_D}{nKT}} - 1\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Where,

$I_D$ and $V_D$ are the diode current and voltage, respectively

q = charge on the electron, $1.602 \times 10^{-19}$ C

n = ideality factor or emission coefficient n = 1 for Si, n = 2 for Ge

K = Boltzmann's constant, $1.38 \times 10^{-23}$ J / K

T = temperature in Kelvin, KT/q is also known as the *thermal voltage*. At 300K (room temperature), KT/q = 25.9 mV

Eqn (1) is applicable for unbiased, forward biased and reverse biased condition of the diode.

1. **For Unbiased Diode:**

Diode voltage $V_D = 0$

$$I_D = I_S\left(e^{\frac{qV_D}{nKT}} - 1\right)$$

$$I_D = I_S(e^0 - 1) = 0$$

2. **Forward biased Diode:**

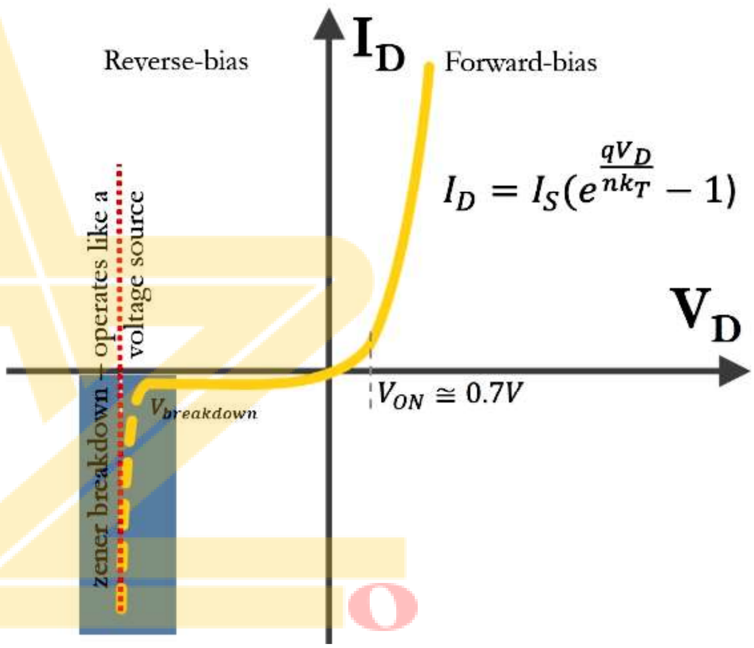
Diode voltage $V_D = + V_F$

$$I_D = I_S\left(e^{\frac{V_F}{nKT}} - 1\right) = I_F \ \ \mathbf{mA}$$

3. **Revesse biased Diode:**

Diode voltage $V_D = - V_R$

$$I_D = I_S\left(e^{\frac{-V_R}{nKT}} - 1\right) = -I_S \ \ \mathbf{\mu A}$$




**NOTE**: 1) Eqn (1) is applicable for unbiased, forward biased and reverse biased condition of the diode but not applicable for $V_D > V_{Breakdown}$

2) Ideal Forward curve passes through the origin.

3) $I_s$ increases as $T$ increases; the rise is 7%/ºC for both Si and Ge and approximately doubles for every 10ºC rise in temperature.

4) Barrier voltage ($V_B$) is also dependent on temperature it decreases by 2mV/ºC for Ge and Si.

**Example 3**: A Germanium diode is used in a rectifier circuit and is operating at a temperature of 25°C with a reverse saturation current of 100 µA. Calculate the value of forward current, if it is forward biased by 0.22 V. Assume n = 1. **VTU - Feb 2005**

***Solution***: Given, $I_S$ = 100 µA, $V_F$ = 0.22 V, T = 25 + 273K = 298 °K, n = 1,

K = $1.38 \times 10^{-23}$ J/K, q = $1.602 \times 10^{-19}$ C

Diode current equation is given by, $I_D = I_S\left(e^{\frac{qV_D}{nKT}} - 1\right)$

Let, $V_T = KT/q = (1.38 \times 10^{-23} \times 298)/1.602 \times 10^{-19}$

$\mathbf{V_T = 25mV,}$

Then above eqn, is written as,

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

$$= 100 \times 10^{-6}\left(e^{\frac{0.22}{1 \times 25 \times 10^{-3}}} - 1\right)$$

$I_D = 0.6633A$

$\boxed{\mathbf{I_D = 0.6633\ A}}$

## Applications of Diodes

- Voltage regulators, Signal rectifiers and Clippers and clampers

**Example-4 : Determine the output $V_o$ of the circuit given in the fig. Ex-4.**

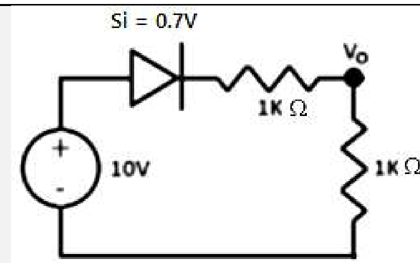


Fig.Ex-4

***Solution:*** Given Si =0.7V, $V_i$ =10V, $R_1 = R_2 = 1K\Omega$.

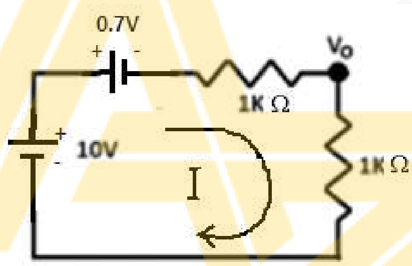
Modifying the given circuit

Apply KVL to find current, I.

$V_i = V_D + I(R_1 + R_2)$

$10V = 0.7 + I(1K+1K)$

$I = 9.3/2 \times 10^3 =$ **4.65mA**




Output $V_o$ is determined as:

Current flowing through $R_2$

$V_o = I R_2 = 4.65 \times 10^{-3} \times 1 \times 10^3$

$\mathbf{V_o = 4.65V}$

## 1.3 Zener Diode

Zener diode is a highly doped PN junction diode, designed to operate in Zener Breakdown Voltage ($V_z$) in the reverse biased condition. In the forward bias direction, the zener diode behaves like an ordinary diode. In the reverse bias direction, there is practically no reverse current flow until $V_z$ is reached. When $V_z$ occurs there is a sharp increase in reverse current ($I_z$). Varying amount of reverse current ($I_R$) can pass through the zener diode without damaging it. The breakdown voltage or zener voltage ($V_z$) across the diode remains relatively constant. The maximum $I_R$ is limited, by the wattage rating of the diode.

The depletion region formed in the zener diode is very thin (< 1 μm) and the electric field is very high (about 500 kV/m) even for a small reverse bias voltage of about 5 V, allowing electrons to tunnel from the valence band of the p-type material to the conduction band of the n-type material.

Circuit symbol and approximated model of zener diode is shown in fig. 1.6.

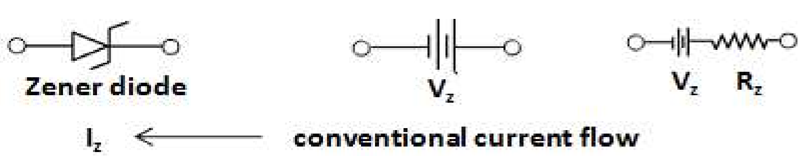



**Fig.1.6 Circuit symbol, Ideal and Practical Approximated models of zener diode**

## PN Junction Breakdown

Electrical break down of any material (say metal, conductor, semiconductor or even insulator) can occur due to two different phenomena.

**1) Zener breakdown** and
**2) Avalanche breakdown**

**Differences between Zener breakdown and Avalanche breakdown**

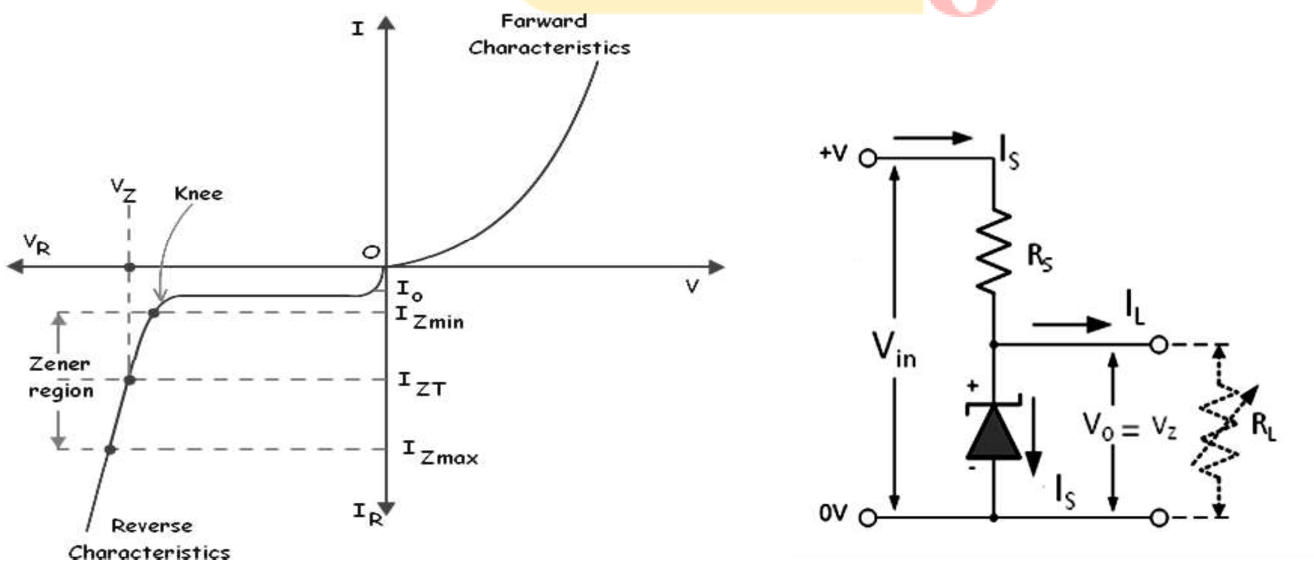
| Zener breakdown | Avalanche breakdown |
|---|---|
| 1. The Zener breakdown occurs in heavy doping & thin junction diodes. | 1. The avalanche breakdown occurs in low doping diodes. |
| 2. Depletion layer is narrow. | 2. Depletion layer is large. |
| 3. A strong electric field is produced. | 3. Electric field is not so strong. |
| 4. $V_z$ occurs earlier than $V_{BR}$. | 4. $V_{BR}$ occurs later than $V_z$. |
| 5. Electron-hole pairs acquire energy from the electric field generated by depletion region. | 5. Electron-hole pairs acquire energy from the applied potential. |
| 6. Temperature coefficient is negative; therefore, $V_z$ decreases as junction temperature increases. | 6. Temperature coefficient is positive; therefore, $V_{BR}$ increases as junction temperature increases |
| 7. V I characteristics is very sharp | 7. V I characteristics is not so sharp |

## V I characteristics of Zener diode

Typical V I characteristics of Zener diode is shown in fig. 1.7 (a).

Observations from the graph:

1. In the forward bias condition, the zener diode behaves like an ordinary diode.




(a) (b)

**Fig.1.7 (a) VI characteristics of zener diode (b) Zener diode as voltage regulator**

2. In the reverse bias condition, there is practically no reverse current flow until the breakdown voltage ($V_Z$) is reached. When $V_Z$ occurs there is a sharp increase in reverse current ($I_Z$).
3. For voltages $V_R < V_Z$, zener diode acts as an open switch, except a negligible leakage current called reverse saturation current ($I_o$).
4. For voltages $V_R > V_Z$, zener diode acts as a constant voltage regulator between $I_{Z(min)}$ and $I_{Z(max)}$.
5. Since, the zener reverse characteristics is not exactly vertical, it possess resistance called zener resistance $R_Z$. It is given by $R_Z = \frac{\Delta V_Z}{\Delta I_Z}$ Ω. $R_Z$ defines how $V_Z$ varies with respect to $I_Z$.

## 1.4 Zener diode as voltage regulator

The circuit diagram of the zener diode as a simple voltage regulator is shown in fig. 1.8. The resistor, $R_S$ is connected in the circuit to limit the current flow through the zener diode with the input voltage source, $V_{in}$. The stabilized output voltage $V_o$ ( = $V_z$) is taken from across the zener diode. The zener diode is operating in the breakdown region when it is reverse biased by connecting with its cathode terminal to the positive of the supply $V_{in}$.

- As long as $V_{in} > V_Z$, the zener operates in the breakdown region and maintains constant voltage across the load, irrespective changes in load current or input voltage.

**Case 1) : Under No load condition**

- Load current $I_L = 0$
- $I_S$ passes through $R_S$ and the zener diode which in turn dissipates its maximum power
- $P_{D(max)} = V_Z I_{z\,(max)}$
- Zener diode works as voltage regulator as long as $I_z < I_{z\,(max)}$.

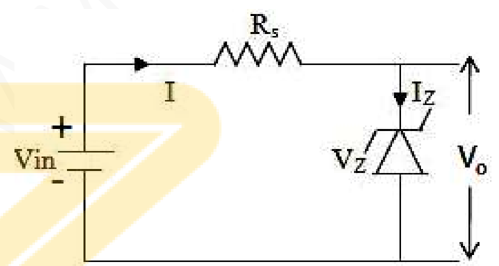
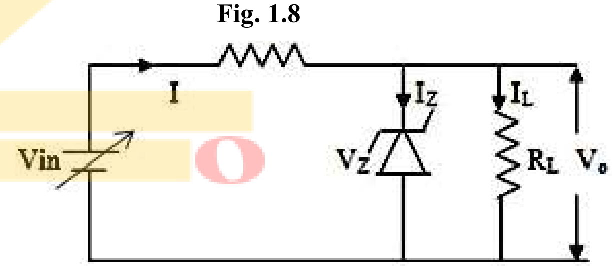



Fig. 1.8

**Case 2) : Under load condition**

(a) Line regulation

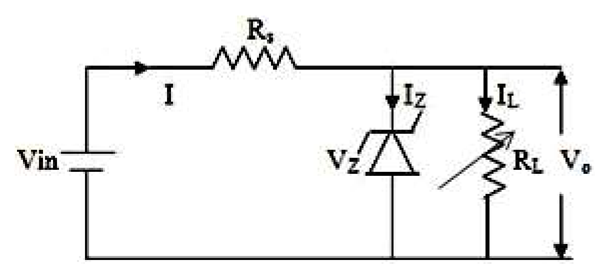
- $R_S$ and $R_L$ are fixed
- Only input voltage $V_{in}$ ( > desired $V_o$) is varied
- As current I varies, the voltage drop across $R_S$ and $I_z$ varies, but output voltage ($V_o = V_z$) would remain constant as long as $V_{in}$ is maintained above a minimum value.




$V_o = Vin – I\,R_S$

(b) Load regulation

- $V_{in}$ (must be > desired $V_o$) and $R_S$ are fixed
- Only $R_L$ is varied
- As $I_L$ varies, $I_z$ varies and $I_S$ is constant, but output voltage ($V_o = V_z$) would remain constant as long as $R_L$ is maintained above a minimum value.




- Maximum current is $I_{Z(max)} = P_Z / V_Z$.
- Zener diodes are available from 2.4 to 200 volts as voltage regulators, with power ratings of 0.25, 0.4, 0.5, 1, 2, 3, and 5 watts.

**Conditions for proper operation of Zener regulator**

1. The zener must operate in the breakdown region or regulating region, i.e. between $I_Z(max)$ and $I_Z(min)$.
2. The zener should not be allowed to exceed maximum dissipation power otherwise it will be destroyed due to excessive heat.

**Applications for Zener Diodes:**

1. Voltage stabilizers or regulators (in shunt mode)
2. Surge suppressors for device protection
3. Peak clippers
4. Switching operations
5. Reference elements and in meter protection applications

**Design:** If the voltage across the Zener diode exceeds a certain value it would draw excessive current from the supply. The series resistor $R_S$ value is designed so that when the input voltage is at $V_{INmin}$ and the load current is at $I_{Lmax}$ that the current through the Zener diode is at least $I_{Zmin}$ . That means, to fix the current through the Zener diode, $R_s$ is introduced whose value is chosen from the following equation

Series Resistor value (ohms) = $(V_i - V_z)$ / (Zener current + load current).

$$R_{min} = \frac{V_{i(max)} - V_z}{I_{L(min)} + I_{z(max)}} \qquad R_{max} = \frac{V_{i(min)} - V_z}{I_{L(max)} + I_{z(min)}}$$

Then for all other combinations of input voltage, $V_i$ and load current, $I_L$, the Zener diode conducts the excess current ($I_{z\,(max)}$) thus maintaining a constant output voltage $V_o$, across the load. The Zener diode conducts the least current ($I_{z\,(min)}$) when the load current ($I_L$) is the highest and it conducts the most current when the load current is the lowest. The power dissipation of Zener diode is described as:

$$P_z = V_z I_{z(max)}$$

Total current I is calculated from the input loop, $V_i = IR_s + V_z$ or from KCL, $I = I_z + I_L$

**Example-5: In a zener regulator output is maintained at 5V, 20mA. Assume $I_{z\,(min)}$ and $I_{z\,(max)}$ are 5mA and 80mA, respectively. Design a zener regulator if input DC is 10V$\pm$ 20%. VTU Mar 1999**

***Solution:*** Given data

$V_o = V_z = 5V$

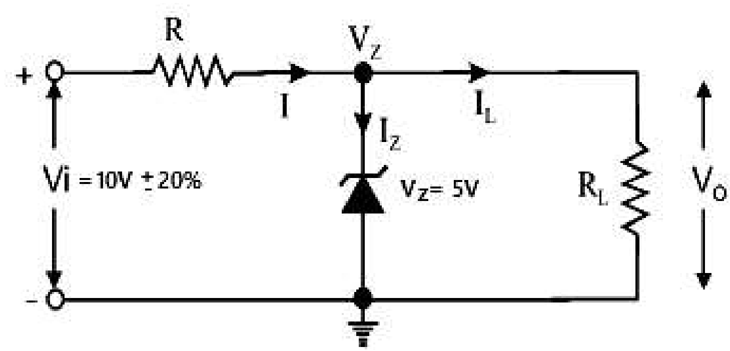
$I_o = I_L = 20$ mA

$V_i = 10V \mp 20\%$

$V_{i(min)} = 10 - 2$ (- 20%) = 8V

$V_{i(max)} = 10 + 2$ (-+20%) = 12V

$\therefore V_i$ = (8V to 12V)




**(i) To find $R_L$:**

$$\frac{V_L}{I_L} = \frac{5}{20x10^{-3}} = 250\Omega$$

**(ii) To find $R_{(min)}$ and $R_{(max)}$:**

$$R_{min} = \frac{V_{i(max)} - V_z}{I_{L(min)} + I_{z(max)}} = \frac{12-5}{20x10^{-3} + 80x10^{-3}} = 70\Omega$$

$$R_{max} = \frac{V_{i(min)} - V_z}{I_{L(max)} + I_{z(min)}} = \frac{8-5}{20x10^{-3} + 5x10^{-3}} = 120\Omega$$

**$R_L = 250\ \Omega$**

**$R_{min} = 70\ \Omega$**

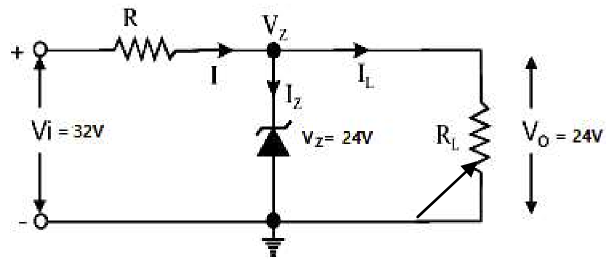
**$R_{max} = 120\ \Omega$**

**Example-6: A 24V, 600mW zener diode is used for providing a 24 V stabilized supply to a variable load. If the input is 32V, calculate (i) the series resistance required (ii) diode current when the load is 1.2KΩ.**

***Solution:*** Given data

$V_o = V_z = 24V$, $V_i = 32V$

Note that load is variable: $I_L$




$$P_z = V_z I_{z(max)}$$

$$I_{z(max)} = \frac{P_z}{V_z} = \frac{600x10^{-3}}{24} = 25\ mA$$

$$R_{min} = \frac{V_i - V_z}{I_{L(min)} + I_{z(max)}} = \frac{32-24}{0 + 25x10^{-3}} = 320\Omega$$

$If\ load\ resistance\ \mathbf{R_L} = \mathbf{1.2K}\Omega,$

$$I_L = \frac{V_o}{R_L} = \frac{24}{1.2x10^3} = 20\ mA$$

Total current I is determined by applying KVL to the input loop, $V_i = IR + V_z$

$$I = \frac{V_i - V_z}{R} = \frac{32-24}{320} = 25\ mA$$

$I_{z(min)} = I - I_L \rightarrow I_{z(min)} = 25 - 20 = 5\ mA$

**$I_{z(min)} = 5\ mA$** **$I_{z\ (max)} = 25\ mA$**

**$R_{s(min)} = 320\ \Omega$**

**Silicon Vs Germanium**

| Parameter | Silicon (Si) | Germanium (Ge) |
|---|---|---|
| 1. $I_S$ at 25°C | 0.01 μA to 1μA | 2 to 15 μA. |
| 2. variation of $I_S$ with temperature | $I_S \cong$ doubles with each 8 to 10°C rise | $I_S \cong$ doubles with each 12°C rise |
| 3. working temperature | operated up to 150°C | operated up to 70°C |
| 4. potential barrier, $V_B$ | 0.7V | 0.3V |
| 5. PIV ratings ($V_{BR}$) | 50V to 1000V | 100V to 400V |

## 1.5 Rectification

Many electronic types of equipments need DC voltage. Therefore, AC is required to convert into DC. The process of converting AC to DC (rippled) is called rectification. The following are the common types of rectifier circuits.

1. *Half-wave rectifier* – uses only one diode and ordinary power transformer.
2. *Full-wave rectifier* – there are two types:
    - *Center Tapped full wave rectifier* - uses two diodes and center tapped power transformer.
    - *Bridge full wave rectifier* - uses four diodes and ordinary power transformer.

## 1.5.1 Half-wave rectifier

Half wave rectification is carried out by a step-down transformer and a diode as shown in fig. 1.9(a).

During **positive half cycle** of the secondary voltage $\mathbf{V_m}$:

- Diode is forward biased and offers low resistance $R_F$, hence it acts like a closed switch.
- Therefore, it conducts for $0 \leq t \leq \pi$. See fig. 1.9(b).
- Then, diode current $I_D$ flows through the load resistance $R_L$. Therefore, output voltage $V_o = I_D R_L$.

During **negative half cycle** of the secondary voltage $\mathbf{V_m}$:

- Diode is reverse biased and offers very high resistance $R_r$, acts like a open switch.
- Therefore, it does not conduct for $\pi \leq t \leq 2\pi$.
- Then, diode current $I_D = 0$. Therefore, output voltage $V_o = 0$.
- The cycle repeats over time axis.

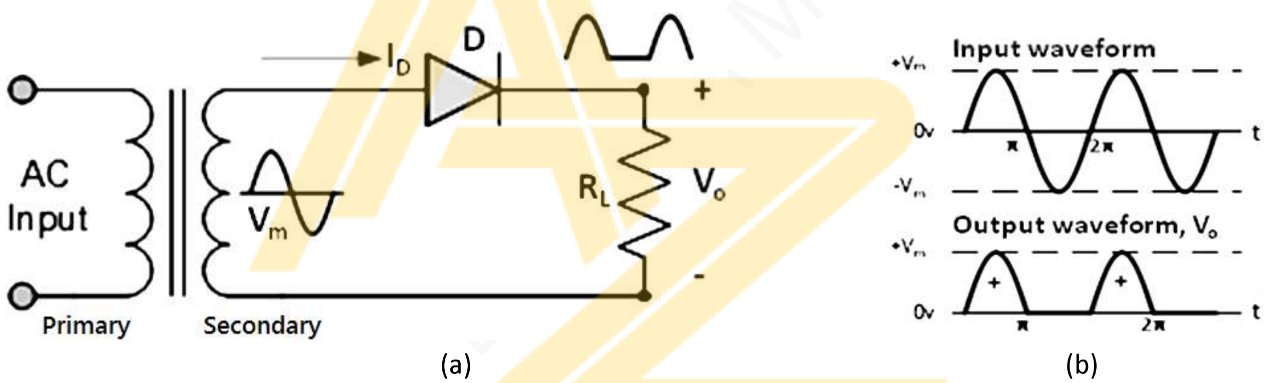



**Fig. 1.9 (a) Half wave rectifier circuit (b) input-output voltage wave forms**

A half wave rectifier is rarely used in practice, because it conducts only for positive half cycle of the input signal. It is never preferred as the power supply of an audio circuit due to its high ripple factor.

**Advantage**: Half wave rectifier is cheap, simple and easy to construct.
**Disadvantage**:

1. Ripple factor is high at the output.
2. Rectification efficiency is quite low, that means, power is delivered only during one half cycle of the input alternating voltage.
3. Transformer utilization factor is low.

| **Example 7: A diode with $V_F = 0.7V$ is connected as a half wave rectifier, the load resistance is 600 Ω and AC input is 24V(r m s). Determine (i) output voltage, (ii) load current and diode peak reverse voltage.** |
|---|
| ***Solution***: Given $V_F = 0.7V$, |

$R_L = 600\ \Omega$,

$V_{rms} = 24V$

To find $V_m$ : $V_m = \sqrt{2} \times 24 = 33.94V$

**(i)** Output voltage, $V_{dc} = \frac{V_m}{\pi} = \frac{33.94}{\pi} =$ **10.8 V**

**(ii)** Load current, $I_L = \frac{V_L}{R_L}$

i.e., $V_L = V_m - V_F$, since, $V_F = 0.7V$,

$\therefore V_L = 33.94 - 0.7 = 33.24V$

$I_L = \frac{V_m}{R_L} = \frac{33.24}{600} =$ **0.0554A**

**(iii)** Diode peak reverse voltage = PIV = $V_m$ = 33.94V

**$V_{dc}$ = 10.8 V**
**$I_L$ = 0.0554A**
**PIV = 33.94V**

## 1.5.2 Center tapped full-wave rectifier

Two diodes $D_1$ and $D_2$ are used in this circuit. They feed a common load resistor $R_L$, with the help of a center tapped transformer as shown in the fig. 1.10.

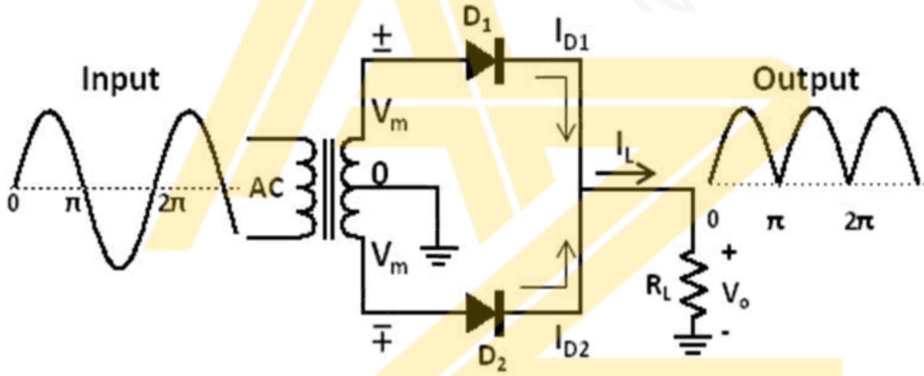



**Fig.1. 10 Center tapped full wave rectifier circuit**

During **+ve half cycle** of upper secondary voltage **$V_m$** / **-ve half cycle** of lower secondary voltage **$V_m$** :

- Diode $D_1$ is forward biased; it offers low resistance $R_{F1}$, acts like a closed switch.
- Hence, it conducts for $0 \leq t \leq \pi$. Then, diode current $I_{D1}$ flows through the load resistance $R_L$. Therefore, output voltage $V_o = I_{D1} R_L = I_L R_L$
- While, Diode $D_2$ is reverse biased, it offers very high resistance $R_r$, acts like a open switch.
- Hence, it does not conduct for $0 \leq t \leq \pi$. Therefore, diode current $I_{D2} = 0$. But, $V_o = I_{D1} R_L = I_L R_L$.

During **-ve half cycle** of upper secondary voltage **$V_m$** / **+ve half cycle** of lower secondary voltage **$V_m$** :

- Diode $D_2$ is forward biased, it offers low resistance $R_{F2}$, acts like a closed switch.
- Hence, it conducts for $\pi \leq t \leq 2\pi$. Thern, diode current $I_{D2}$ flows through the load resistance $R_L$. Therefore, output voltage $V_o = I_{D2} R_L = I_L R_L$
- While, Diode $D_1$ is reverse biased, it offers very high resistance $R_r$, acts like a open switch.
- Hence, $D_1$ does not conduct for $\pi \leq t \leq 2\pi$. Therefore, diode current $I_{D1} = 0$. But, $V_o = I_{D2} R_L = I_L R_L$.

The cycle repeats. The complete input-output waveform of the Center tapped full-wave rectifier is shown in fig.1.11.

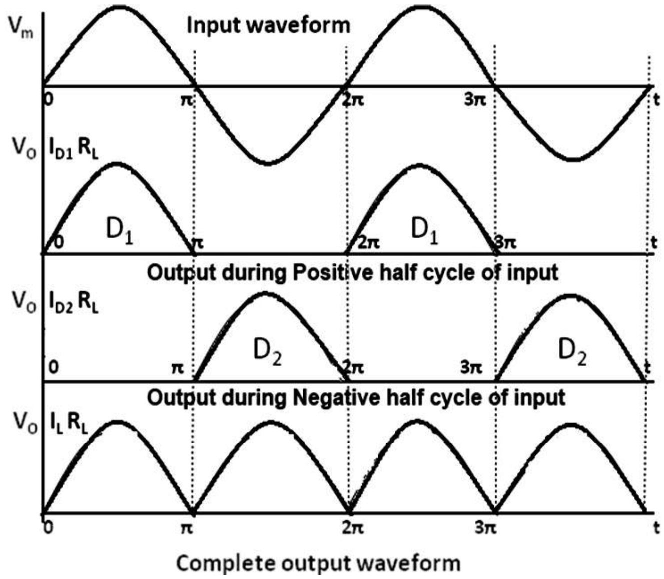



**Fig. 1.11 The complete input-output waveform of center tapped full wave rectifier**

[ **NOTE**: Output voltage $V_o = I_D R_L$, flows in the same direction for both (+ ve) and (- ve) half cycles.]

**Disadvantages**

- Since, each diode uses only one-half of the transformers secondary voltage, the DC output is comparatively small.
- It is difficult to construct and locate the center-tap on secondary winding of the transformer.
- The diodes used must have high PIV.

## 1.5.3 Bridge full-wave rectifier

Bridge full wave rectifier employs four diodes, but the center tapped transformer is not required. It is as shown in fig. 1.12(a).

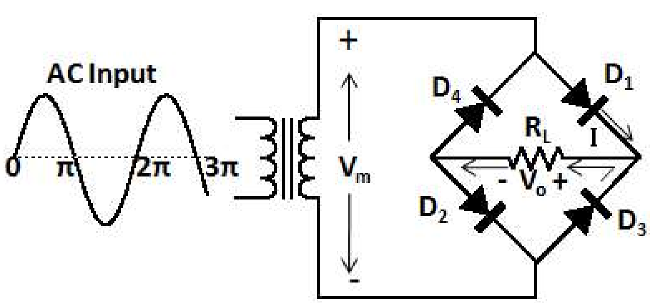
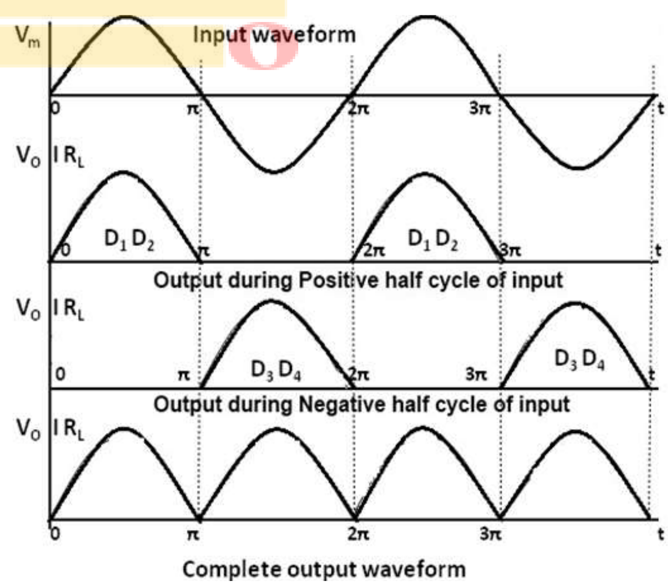



**Fig.1. 12. (a) Bridge full wave rectifier circuit**




**(b) The complete input-output voltage waveform of Bridge full wave rectifier**

During **positive half cycle** of the secondary voltage $\mathbf{V_m}$:

- Diodes $D_1D_2$ are forward biased, they offer low resistance, and hence, they conduct for $0 \leq t \leq \pi$. Then, current I flows through the load resistance $R_L$. Therefore, $V_o = I\,R_L$.
- While, Diodes $D_3D_4$ are reverse biased, they offer very high resistance, and hence, they do not conduct for $0 \leq t \leq \pi$. Therefore, no current I flows through the load resistance $R_L$. But, $V_o = I\,R_L$

During **negative half cycle** of the secondary voltage $\mathbf{V_m}$:

- Diodes $D_3D_4$ are forward biased, they offer low resistance, and hence, they conduct for $\pi \leq t \leq 2\pi$. Then, current I flows through the load resistance $R_L$. Therefore, $V_o = I\,R_L$.
- While, Diodes $D_1D_2$ are reverse biased, they offer very high resistance, and hence, they do not conduct for $\pi \leq t \leq 2\pi$.

The complete input-output voltage waveform of the Bridge full wave rectifier is shown in fig. 1.12(b).

**Advantages:**

1. Need for center-taped transformer is eliminated.
2. Output is twice when compared to center-tapped full wave rectifier for the same secondary voltage.
3. The PIV is one-half (1/2) compared to center-tapped full wave rectifier

**Disadvantage:**

It requires four diodes, the use of two extra diodes cause an additional voltage drop thereby reducing the output voltage.

## 1.5.4 Performance measures of rectifiers

The following are the important performance measures of the rectifiers

1. Output current or DC current or Average current ($I_{dc}$)/ DC output voltage ($V_{dc}$)
2. Root Mean Square (RMS) value of current and output voltage ($I_{rms}$) / ($V_{rms}$)
3. Ripple Factor ($\gamma$)
4. Rectification Efficiency ($\eta$)
5. Peak Inverse Voltage (PIV)

## Performance measures of Half Wave rectifier

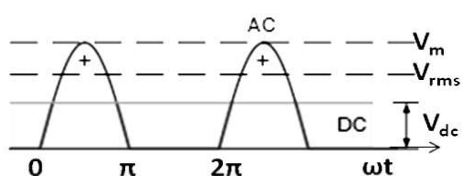



**Fig. 1.13 Output voltage wave forms of half wave rectifier for one complete cycle**

It is observed from the fig.1.13 that the output voltage waveform of a half wave rectifier for one complete cycle (from 0 to $2\pi$) is

$$I_L = I_m \sin\omega t \quad \text{for } 0 \leq \omega t \leq \pi \quad \ldots\ldots (2)$$

$$I_L = 0 \quad \text{for } \pi \leq \omega t \leq 2\pi$$

That means, only one (+ve) half cycle is present between $0 \leq \omega t \leq \pi$ and the signal is absent between $\pi \leq \omega t \leq 2\pi$. This cycle repeats for the next cycle. Positive (+) half cycle at the output contains AC and DC components. This variation is called *ripple*.

## 1. Average current ($I_{dc}$)/ DC Output Voltage ($V_{dc}$)

To obtain only DC value, the signal is to be integrated over one complete cycle ($0 \le \omega t \le 2\pi$). Where $\omega$ (= $2\pi f = 2\pi/T$) is the angular frequency in radian/sec.
Sine wave as current or voltage signal is mathematically represented and DC current (or load current) through the load resistance is evaluated by,

$$I_{dc} = \frac{\text{area under the curve}}{\text{length of the base}}\ (\text{of one cycle}) = \frac{\int_0^{2\pi} i_L\, d\omega t}{2\pi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$I_{dc} = \frac{1}{2\pi}\left\{\underbrace{\int_0^{\pi} I_m \sin\omega t\ \ d\omega t}_{\substack{\text{Presence of signal}\\ \text{between } 0 \text{ and } \pi}} + \underbrace{\int_{\pi}^{2\pi} 0\cdot d\omega t}_{\substack{\text{Absence of signal}\\ \text{between } \pi \text{ and } 2\pi}}\right\}$$

$$I_{dc} = \frac{I_m}{2\pi}\ \{-\cos\omega t\}_0^{\pi} = \frac{I_m}{2\pi}\{-\ (\cos\pi - \cos 0)\} = \frac{I_m}{2\pi}\{-\ (-1 - 1)\} = \frac{I_m}{2\pi}\{2\} = \frac{I_m}{\pi}$$

Using Ohm's law

$$I_m = \frac{V_m}{R_{total}} = \frac{V_m}{R_L + R_S + R_f}$$

where, $R_L$ = Resistance of the load,
$R_S$ = Resistance of secondary windings of transformer and
$R_f$ = forward resistance of the diode.

Therefore, $V_{dc} = I_{dc} \cdot R_L$

$$V_{dc} = \frac{I_m}{\pi} \cdot R_L$$

| Average current of HWR |
|---|
| $\mathbf{I_{dc} = \frac{I_m}{\pi}}$ |
| $V_{dc} = \frac{I_m}{\pi} \cdot (R_L + R_S + R_f)$ For precise measurements |

## 2. RMS Value of Load Current ($I_{rms}$) / Voltage ($V_{rms}$)

RMS voltage at the load resistance can be calculated as $I_{rms} = \sqrt{(\text{mean value})^2}$. By definition, it is the area of one full cycle which represents the square of the function, divide by the base.

Mathematically,

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} i_L^2\ d\omega t + \underbrace{\int_{\pi}^{2\pi} i_L^2\ d\omega t}_{0\ (\text{signal is absent})}}$$

$$= \sqrt{\frac{1}{2\pi}\int_0^{\pi} (I_m \sin\omega t)^2 d\omega t}$$

$$= \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2\omega t\, d\omega t}$$

$$= \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \left(\frac{1-\cos 2\omega t}{2}\right) d\omega t}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) d\omega t}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\left\{\int_0^{\pi} 1.\, d\omega t - \int_0^{\pi} \cos 2\omega t\right\} d\omega t}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\{(\pi - 0) - 0\}} = \sqrt{\frac{I_m^2}{2\cdot 2\,\pi}(\pi)} = I_{rms} = \frac{I_m}{2}$$

| RMS Value (current) of Half wave rectifier $\mathbf{I_{rms} = \frac{I_m}{2}}$ |
|---|

| RMS Value (voltage) of Half wave rectifier $\mathbf{V_{rms} = \frac{V_m}{2}}$ |
|---|

## 3. Ripple Factor (γ)

Ripple factor is a measure of varying components at the output of the rectifier. The pulsating output of a rectifier consists of DC and AC component (known as ripples) as denoted in the fig. 13. It is defined as the ratio of RMS value of AC component to the DC component in the output.

$$\gamma = \frac{\text{RMS value of AC component}}{\text{DC component in the output}} = \frac{I_{ac}}{I_{dc}}$$

We know that, $I_{rms}^2 = I_{ac}^2 + I_{dc}^2$ or $I_{ac}^2 = I_{rms}^2 - I_{dc}^2$ or $I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$

$$\gamma = \frac{I_{ac}}{I_{dc}} = \frac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}} = \sqrt{\frac{I_{rms}^2}{I_{dc}^2} - \frac{I_{dc}^2}{I_{dc}^2}} = \sqrt{\frac{I_{rms}^2}{I_{dc}^2} - 1} \qquad \left(\text{where, } I_{rms} = \frac{I_m}{2} \text{ and } I_{dc} = \frac{I_m}{\pi}\right)$$

$$\gamma = \sqrt{\left(\frac{\frac{I_m}{2}}{\frac{I_m}{\pi}}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{2}\right)^2 - 1} = 1.21$$

Ripple factor of Half wave rectifier $\gamma = \mathbf{1.21}$

## 4. Rectification Efficiency (η)

Rectifier efficiency is a measure that indicates amount of input power converted into the DC output power supplied to the circuit. It is defined as the ratio of output dc power to the total amount of input

$$\text{x } 100\ \% = \frac{I_{dc}^2 R_L}{I_{rms}^2 (R_L + R_S + R_f)} \text{ x } 100\ \% = \frac{\left(\frac{I_m}{\pi}\right)^2}{\left(\frac{I_m}{2}\right)^2} \frac{R_L}{(R_L + R_S + R_f)} \text{ x } 100\ \%$$

Maximum rectifier efficiency,

$$\eta = \frac{40.6\ \%}{1 + \left(\frac{R_S + R_f}{R_L}\right)}$$

That means, in the half wave rectifier only **40.6%** AC power gets converted into DC power in the load.

## 5. Peak Inverse Voltage (PIV)

The maximum reverse voltage across the diode is called peak inverse voltage (PIV). Half wave rectifier consists of one diode and in reverse bias the total peak voltage $V_m$ will be dropped across this diode. So, PIV of the half wave rectifier is $V_m$.

$\mathbf{PIV = V_m}$

## 1.5.5 Performance measures of Full Wave rectifier

Full wave rectification reduces the ripple factor and increases the output DC voltage level. In this process the phase of the second half of the input wave is reversed, hence a series of positive half waves are present. The analysis is same for both the Center Tapped and the Bridge Full Wave Rectifiers.

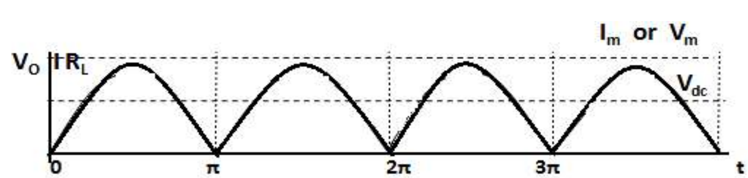



**Fig.1. 14 Output voltage wave forms of full wave rectifier**

It is observed from the fig.1.14 that the output voltage waveform of a full wave rectifier for one complete cycle (from 0 to 2π) is

$$V_o = V_m \sin\omega t \qquad \text{for } 0 \le \omega t \le \pi$$

$$V_o = V_m \sin\omega t \qquad \text{for } \pi \le \omega t \le 2\pi \qquad \ldots\ldots\ldots\ldots \quad (4)$$

## 1. Average current ($I_{dc}$)/ DC Output Voltage ($V_{dc}$)

From the equation (4), it is seen that $V_o$ = twice the $V_m$ over one full cycle ($0 \le \omega t \le 2\pi$)

Therefore, $V_{dc} = 2 \times \frac{V_m}{\pi}$ (double that of the half wave)

Similarly, $I_{dc} = \frac{2I_m}{\pi}$ where, $I_m = \frac{V_m}{R_L}$

Average current or output voltage of Full wave Rectifier $\boxed{I_{dc} = \frac{2I_m}{\pi}}$

## 2. RMS Value of Load Current ($I_{rms}$) / Voltage ($V_{rms}$)

Since, $0 \le \omega t \le \pi$ and $\pi \le \omega t \le 2\pi$ durations in the fig. 14 have identical pulses; $I_{rms}$ becomes,

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} i_L^2 \, d\omega t + \int_{\pi}^{2\pi} i_L^2 \, d\omega t} \Rightarrow \sqrt{\frac{2}{2\pi}\int_0^{\pi}(I_m \sin\omega t)^2 d\omega t} \Rightarrow \sqrt{\frac{2}{2\pi}\int_0^{\pi} I_m^2 \sin^2\omega t \, d\omega t}$$

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \left(\frac{1-\cos 2\omega t}{2}\right) d\omega t} \Rightarrow \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) d\omega t} \Rightarrow \sqrt{\frac{I_m^2}{2\pi}\left\{\int_0^{\pi} 1.\, d\omega t - \int_0^{\pi}\cos 2\omega t\right\} d\omega t}$$

$$I_{rms} = \sqrt{\frac{I_m^2}{2\pi}\{(\pi - 0) - 0\}} \Rightarrow \sqrt{\frac{I_m^2}{2\pi}(\pi)} \Rightarrow \frac{I_m}{\sqrt{2}}$$

**RMS value of of Full wave Rectifier** $\boxed{I_{rms} = \frac{I_m}{\sqrt{2}} \text{ and } V_{rms} = \frac{V_m}{\sqrt{2}}}$

## 3. Ripple Factor (γ)

$$\gamma = \frac{I_{ac}}{I_{dc}} = \frac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}} = \sqrt{\frac{I_{rms}^2}{I_{dc}^2}} - 1 = \sqrt{\left(\frac{\frac{I_m}{\sqrt{2}}}{\frac{2I_m}{\pi}}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1} = 0.48$$

**Ripple factor of Full wave Rectifier** $\boxed{\gamma = 0.48}$

## 4. Rectification Efficiency (η)

$$\eta = \frac{P_{dc}}{P_{ac}} \times 100\,\% = \frac{I_{dc}^2 R_L}{I_{rms}^2 (R_L + R_S + R_f)} \times 100\,\% = \frac{\left(\frac{2I_m}{\pi}\right)^2}{\left(\frac{I_m}{\sqrt{2}}\right)^2} \frac{R_L}{(R_L + R_S + R_f)} \times 100\,\%$$

Maximum rectifier efficiency,

$$\eta = \left(\frac{2\sqrt{2}}{\pi}\right)^2 \frac{R_L}{(R_L + R_S + R_f)} \times 100\% \qquad \eta = \frac{81.2\,\%}{1 + \left(\frac{R_S + R_f}{R_L}\right)}$$

**That means, in the full wave rectifier 81.2 % AC power gets converted into DC power in the load.**

## 5. Peak Inverse Voltage (PIV)

| Type of FWR | PIV | Reason |
|---|---|---|
| **Center Tapped** | **$2V_m$** | The secondary voltage $V_m$ and voltage across the load ($= 2V_m$) appears across the non-conducting diode. |
| **Bridge** | **$V_m$** | Sum of secondary voltage and voltage across the load = $2V_m$. Since, two diodes conduct during each half cycle this voltage is sharing by two diodes. i.e., PIV= 2 $V_m$/2 = $V_m$ |

## 1.5.6 Rectifier with Filter

Filters are employed in rectifier circuits for smoothing the DC output voltage, so that the undesirable AC components (the ripples), can be minimized. Capacitor C can be used as a filtering element which converts the rippled output of the rectifier into a smooth DC output voltage.

## 1. Half wave Rectifier with Capacitor Filter

Half wave rectifier with capacitor filter is as depicted in the fig. 1.15.

i) When diode D conducts for (+) half cycle in the half wave rectifier, capacitor C charges quickly to the maximum level through the forward resistances of the diodes $R_F$. The charge time of the capacitor C is from $t_1$ to $t_2 = R_F C$.

ii) When the rectified voltage starts to decrease, diode does not conduct. Capacitor C discharges slowly through the load $R_L$, until the next (+) half cycle is met. That means, charge stored in the capacitor is supplied to the load during fall in the voltage cycle.

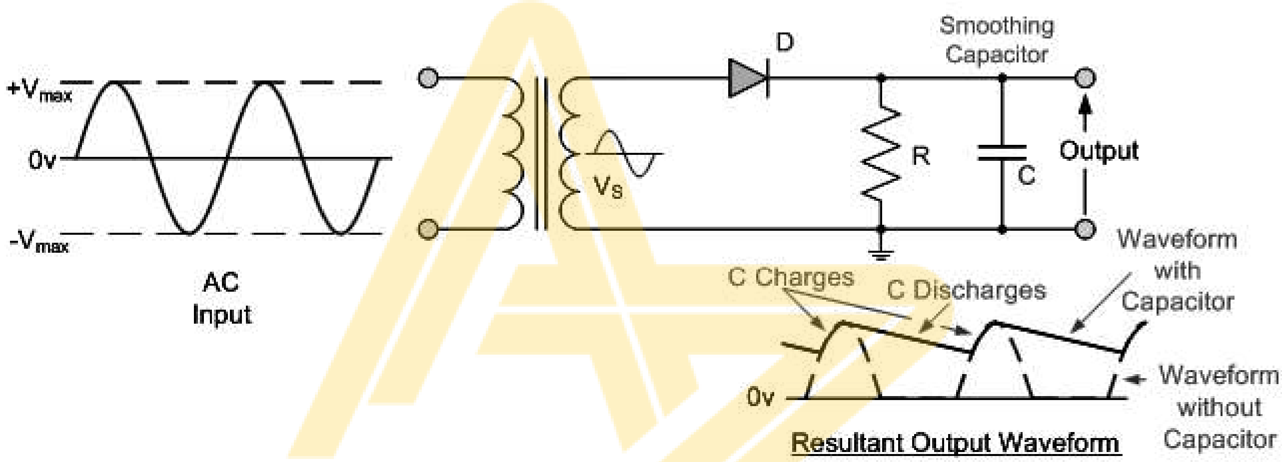



**Fig. 1.15 Half wave rectifier with capacitor filter and filtered output voltage wave form**

- ➢ The discharge time of the capacitor C is from $t_2$ to $t_3 = R_L C$. It is shown in the fig. 1.16.
- ➢ This repeats for the remaining cycles.

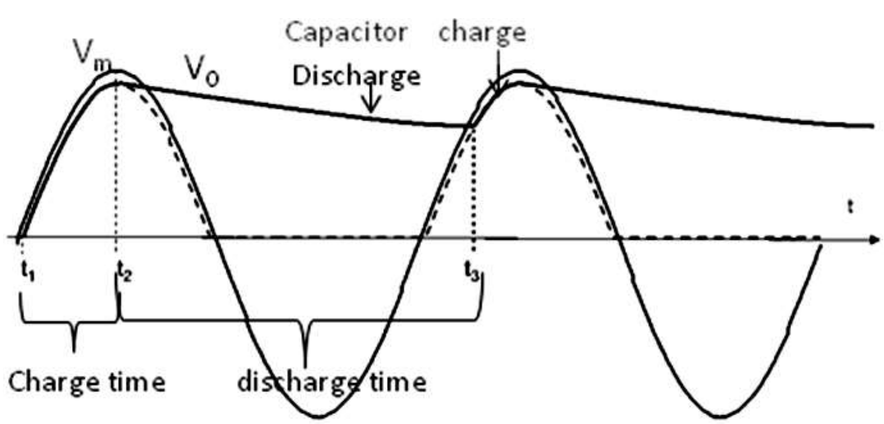



**Fig. 1.16 Filtered output voltage wave form of Half Wave Rectifier**

## 1.6 PHOTODIODE

A photodiode is a PN junction semiconductor device that consumes light energy to generate electric current. It is also sometimes referred as photo-detector, photo-sensor, or light detector. Photodiodes are specially designed to operate in reverse bias condition.

PIN (p-type, intrinsic and n-type) structure is mostly used for constructing the photodiode instead of p-n (p-type and n-type) junction structure because PIN structure provide fast response time, used in high-speed applications.

A photodiode has two terminals: a cathode and an anode. The symbol of photodiode is shown in the fig.1.17 (a), contains arrows striking the diode representing the light or photons. Fig.1.17 (b) depicts its construction.

**Working:** When an external light energy is supplied to the photodiode, the valence electrons in the depletion region gains energy. Due to which the electrons from valence band jump into the conduction band and contribute to current. In this way, the photodiode converts light energy into electrical energy.

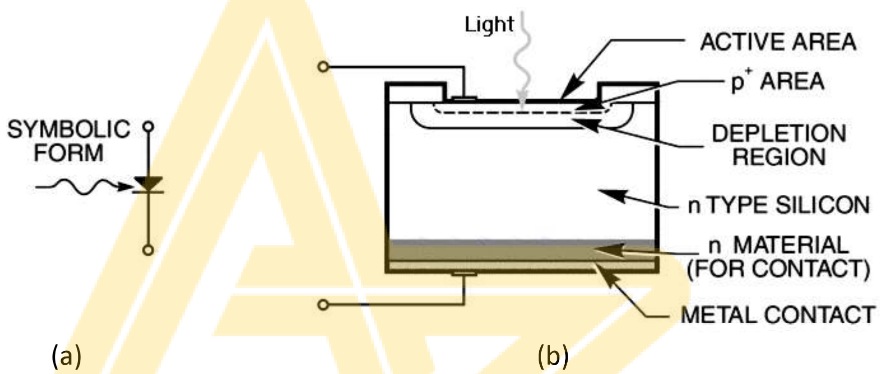



**Fig.1.17 Photodiode (a) Symbol (b) Construction**

The materials used for photodiode and its electromagnetic wavelength range is given in the table – I.

**Table I - Materials used for photodiode and its electromagnetic wavelength range**

| Sl no. | Material used | EM wavelength range |
|---|---|---|
| 1 | Silicon | (190-1100) nm |
| 2 | Germanium | (400-1700) nm |
| 3 | Indium gallium arsenide | (800-2600) nm |
| 4 | Mercury, cadmium Telluride | (400-14000) nm |

**Types of photodiodes**

1. PN junction photodiode
2. PIN photodiode
3. Avalanche photodiode

Among all the three photodiodes, PN junction and PIN photodiodes are most widely used.

**Advantages**

- Low resistance

- Better frequency response
- Linear
- Less Noisy
- It can be used as variable resistance device.
- It is highly sensitive to the light.
- The speed of operation is very high.

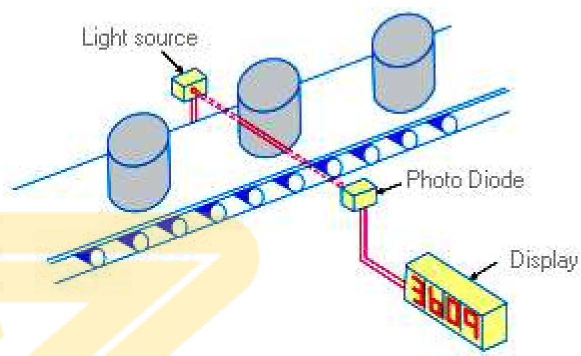
**Disadvantages**

- Small active area (Should not exceed the working temperature limit specified by the manufactures)
- Rapid increase in dark current and it depends on temperature.
- Require amplification at low illumination level.
- Photodiode characteristics are temperature dependent
- Poor temperature stability.

**Applications**

1. Light detector
2. Demodulators
3. Encoders
4. Optical communication system
5. High speed counting and switching circuits
6. Computer punching cards and tapes
7. Light operated switches
8. Sound track films
9. Electronic control circuits

**Example:** High speed counting




## 1.7 Light Emitting Diode (LED)

LED is a semiconductor light source, that emits light when an electric current is passed through it. They operate on low voltage and power. LEDs are one of the most common electronic components and are mostly used as indicators in circuits. They are also used for luminance and optoelectronic applications.

**Working Principle**:

When the device is forward-biased, electrons cross the *pn* junction from the *n*-type material and recombine with holes in the *p*-type material. When recombination takes place, the recombining electrons release energy in the form of *photons.*

**Working:**

When a suitable forward biasing voltage is applied to the leads of LED, electron-holes are recombining within the device, releasing energy in the form of photons.

LED has two terminals: a Cathode and an Anode. The symbol of LED shown in the fig.1.18 (a), contains arrows o the diode representing the light emitting. Fig.1.18 (b) depicts its simple construction. The light emitted from LEDs varies from visible to infrared and ultraviolet regions and LED materials are given as in the table-II.

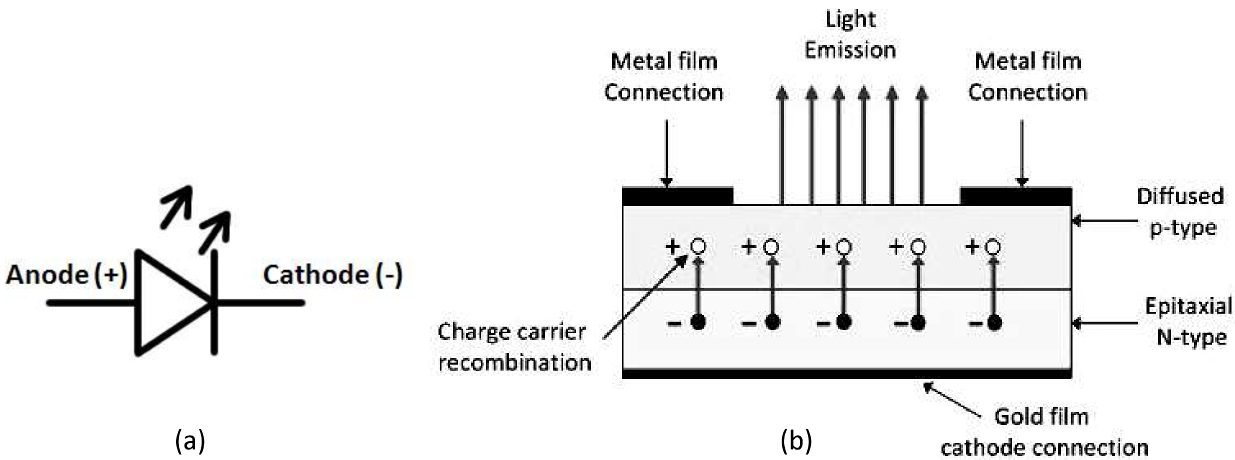



**Fig.1.18 Light Emitting Diode (a) Symbol (b) Construction**

**Table-II: EM wavelength range for different LED materials**

| Sl no. | Material used | EM wavelength range |
|---|---|---|
| 1 | Indium gallium nitride (InGaN) | blue, green and ultraviolet |
| 2 | Aluminum gallium indium phosphide (AlGaInP): | yellow, orange and red |
| 3 | Aluminum gallium arsenide (AlGaAs | red and infrared |
| 4 | Gallium phosphide (GaP): | yellow and green |

### Advantages

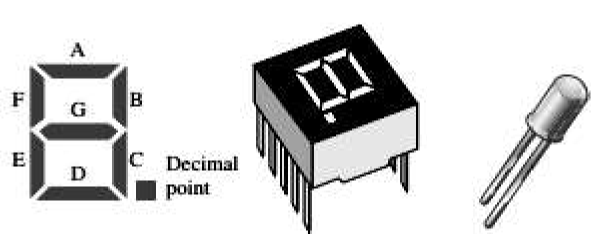
- Energy efficient source of light for short distances and small areas.
- The typical LED requires only 30-60 mW to operate
- Durable and shockproof unlike glass bulb lamp types
- Reducing stray light pollution on street lights

### Disadvantages

- Semiconductors are sensitive to being damaged by heat, so large heat sinks must be employed to keep powerful arrays cool. This increases the cost.
- Shock proof requires unlike glass bulb lamp types.

### Applications

- Indication lights on devices
- As small and large lamps
- Traffic lights
- Large video screens
- Street lighting (although this is still not widespread)



## 1.8 Photo-Coupler

**Photo-coupler**, or optical isolator, is a component that transfers electrical signals between two isolated circuits by using light. Opto-isolators prevent high voltages from affecting the system receiving the signal.

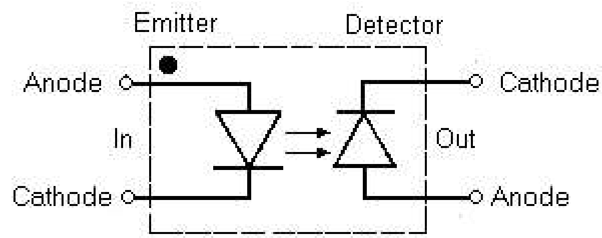



**Fig.1.19 Schematic diagram of photocoupler**

Photo-coupler contains an LED and a photodiode in a single package is shown in fig.1.19. It has a LED on the input side and a *photo-detector* diode on the output side. When the current is set up in the LED, light energy impinges on the photo-detector, and this sets up a reverse current in the output circuit. The light detector can be a photodiode or a phototransistor.

**Applications:**

1. Monitor high voltage
2. Output voltage sampling for regulation
3. Micro system control for power ON/OFF
4. Signal isolation. It provides complete isolation because its input side is not electrically connected to the output side.

## 1.8 78XX and 7805 based Fixed IC voltage regulator

Different parts of a robot require different DC voltage levels. Motors usually run on high voltages, like 12V or 36V. Microcontrollers run on 3.3V or 5V. Electromagnets work on even greater voltages and currents. That means, using 78xx ICs, would decrease weight and save a lot of space, in turn, conveniently step down to a specific voltage output.

The 78XX ICs have 3 pins (input, ground and output) and these regulators are referred to positive voltages as shown in the fig.1.20.

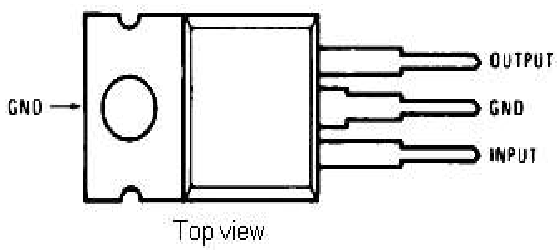
Ex: 7805 chip, XX = 05 (see fig.1.20). So, the chip maintains a constant 5V across the output terminal. The capacitors in the circuit decrease the amount of voltage fluctuations. If there is an increase in the voltage the capacitors store it. If there is a decrease, they release their energy to maintain a constant voltage across the output. Note that the input voltage must be greater than the required output voltage.

**Illustration**: Heat generated = (input voltage – 5V) x output current.

If we have a system with input 12 volts and output current required is 0.5 amperes. We have: (12 – 5) x 0.5 = 7 × 0.5 = 3.5 W; that means, 3.5W energy is being wasted as heat, hence an appropriate *heat sink* is required to disperse this heat. On the other hand, energy actually being used is: (5 x 0.5Amp) = 2.5W. So, 1W energy, that is actually utilized but it is wasted.

Below table describes significant details of IC 7805.

| 7805 IC Pin No | Function | Rating |
|---|---|---|
| 1 | Input voltage | Input voltage range 7V- 35V |
| 2 | Ground (0V) | Current rating $I_c = 1A$ |
| 3 | Regulated output | Output voltage range $V_{Max} = 5.2V$ , $V_{Min} = 4.8V$ |



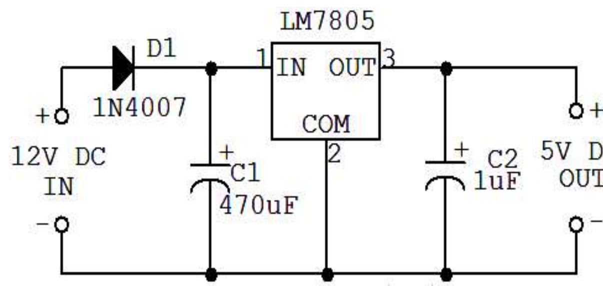




**Fig.1.20 7805 IC is a fixed positive voltage regulator provides a constant 5 volts output**.

## Solved Examples

**Example 1**: Calculate the reverse saturation current for Silicon diode which passes a current of 10 mA at 27°C for a forward bias of 700mV. **VTU - June/July 2012**

***Solution***: Given, $I_F = 10$ mA,

$V_D = 700$ mV,

$T = 27 + 273K = 300\ ^oK$,

n = 2 (Si),

$K = 1.38 \times 10^{-23}$ J/K,

$q = 1.602 \times 10^{-19}$ C

Diode current equation is given by, $I_D = I_S\left(e^{\frac{qV_D}{nKT}} - 1\right)$ ……………………………………(1)

Let, $V_T = KT/q = (1.38 \times 10^{-23} \times 300)/1.602 \times 10^{-19} \approx 26mV$,

Then eqn(1), is written as,

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

$$10 \times 10^{-3} = I_S\left(e^{\frac{0.7}{2 \times 0.26}} - 1\right)$$

$$I_S = \frac{10 \times 10^{-3}}{701893} = 0.014247\mu A$$

$$\boxed{\mathbf{I_S = 14.24\ \eta A}}$$

**Example 2: A half wave rectifier is driven by a sinusoidal voltage *v* = 200 sin 250t volts. Treating the diode as ideal and load resistance is 2 K Ω. Find (i) output voltage, (ii) output current (iii) rms current (iv) ripple factor (vi) efficiency.**

***Solution:*** Given *v* = 200 sin 250t is compared with general sinusoidal voltage $v = V_m \sin \omega t$

$V_m = 200$ V $\omega = 250$ rad/sec $R_L = 2\ K\ \Omega$,

To find $I_m$ : $I_m = \frac{V_m}{R_L + R_F} = \frac{200}{2000} = 0.1A$

**(i)** Output voltage, $V_{dc} = \frac{V_m}{\pi} = \frac{200}{\pi} = 63.66$ V

**(ii)** Output current, $I_{dc}$ or $I_L = \frac{V_L}{R_L} = \frac{V_m}{R_L} = \frac{63.66}{2000} = 0.0318$ A

**(iii)** RMS current $I_{rms} = \frac{I_m}{2} = \frac{I_m}{2} = \frac{0.1}{2} = 0.05A$

**(iv)** Ripple factor $\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{0.05}{0.0318}\right)^2 - 1} = 1.21$

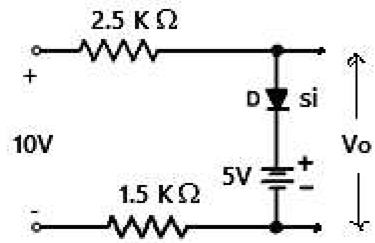
**(v)** **Efficiency** $\eta = \frac{I_{dc}^2 R_L}{I_{rms}^2 (R_L + R_F)} \times 100\% = 40.44\%$

## Exercise

1. What is a PN junction Diode?
2. Explain the formation of depletion layer in PN junction Diode.
3. Discuss the behavior of PN junction Diode under:
   (i) No bias (ii) Forward Bias and (iii) Reverse Bias conditions.
4. Draw and explain V-I characteristics of Silicon and Germanium diodes.
5. Define the following PN junction Diode parameters:
   (i) Forward Voltage ($V_F$) (ii) Forward Current ($I_F$) (iii) Reverse Current ($I_R$)
   (iv) Reverse Break down Voltage ($V_{BR}$) or Peak Inverse Voltage (PIV)
   (v) Power Dissipation ($P_D$) (vi) Dynamic Resistance ($r_D$) (vii) Knee voltage ($V_K$)
6. With appropriate diagrams discuss diode approximations.
7. What is a rectifier? Briefly discuss the common types of rectifier circuits.
8. With neat circuit diagram and waveforms explain half wave rectifier; center tapped full wave rectifier and full wave bridge rectifiers.
9. Show that $\gamma = 1.21$, $\eta = 40.6\%$ of a half wave rectifier. And
11. Show that $\gamma = 0.48$, $\eta = 81\%$ of a full wave rectifier.
12. Deduce the following:
    (i) $I_{av}$ or $I_{DC}$ (ii) $I_{rms}$ / $V_{rms}$ for half wave rectifier and full wave rectifier.
13. Discuss the need of filter circuit. Explain the operation of C – filter for half wave rectifier.
14. With neat circuit diagram and waveforms explain the operation of C – filter for full wave rectifier.
15. Explain how zener diode works as a voltage regulator.
16. Write a note on: (i) Photodiode (ii) LED (iii) Photocoupler
17. With neat circuit explain 7805 based fixed IC voltage regulator.

## Tutorial Questions

1. Determine the output $V_o$ for the circuit given in the fig.1.




2. A zener diode has a breakdown voltage of 10V. It is supplied from voltage source varying between 20V – 40V in series with resistance of 820Ω using an ideal zener diode model obtain minimum and maximum zener currents.
3. Design a zener diode voltage regulator to meet the following specifications: DC $V_{in}$ =18V, $V_o$=10V, load current=20mA, $I_{z(min)}$and $I_{z(max)}$ are 10mA and 100mA, respectively.
4. A full wave rectifier is driving a load resistance of 500Ω. It is driven by a source voltage of 240V, 50Hz. Neglecting the diode resistances, determine (i) average DC voltage, (ii) average DC and (iii) frequency of output waveform.

## Multiple Choice Questions

1. In a PN junction with no external voltage, the electric field between acceptor and donor ions is called

A. Peak
B. Barrier
C. Threshold
D. Path

2. In a P-N junction the potential barrier is due to the charges on either side of the junction, these charges are

A. Majority carriers
B. Minority carriers
C. Both (a) and (b)
D. Fixed donor and acceptor ions

3. In an unbiased PN junction

A. The junction current at equilibrium is zero as equal but opposite carriers are crossing the junction
B. The junction current is due to minority carriers only
C. The junction current reduces with rise in temperature
D. The junction current at equilibrium is zero as charges do not cross the junction

4. A forward potential of 10V is applied to a Si diode. A resistance of 1 KΩ is also in series with the diode.

A. 10 mA
B. 9.3 mA
C. 0.7 mA
D. 0

5. For a P-N junction diode, the current in reverse bias may be

A. Few milliamperes
B. Between 0.2 A and 15 A
C. Few micro or nano amperes
D. Few amperes

6. When P-N junction is in forward bias, by increasing the battery voltage

A. Circuit resistance increases
B. Current through P-N junction increases
C. Current through P-N junction decreases
D. None of the above happens

7. In a PN junction when the applied voltage overcomes the ........ potential, the diode current is large, which is known as .............

A. Barrier, forward bias
B. Reverse, reverse bias
C. Resistance, reverse bias
D. Depletion, negative bias

8. As a PN junction is forward biased

A. The depletion region decreases
B. Holes as well as electrons tend to drift away from the junction
C. The barrier tends to breakdown
D. None of the above

9. The main reason why electrons can tunnel through a PN junction is that

A. Barrier potential is very low
B. They have high energy
C. Impurity level is low
D. Depletion layer is extremely thin

10. A reverse-biased PN junctions has

A. A net electron current
B. A net hole current
C. negligible current
D. A very narrow depletion layer

11. The depletion layer of a PN junction diode has

A. Only free mobile holes
B. Neither free mobile electrons nor holes
C. Both free mobile holes as well as electrons
D. Only free mobile electrons

12. Barrier potential in a PN junction is caused by

A. Flow of drift current
B. Diffusion of majority carriers across the junction
C. Migration of minority carriers across the junction
D. Thermally-generated electrons and holes

13. The diode is used in

A. Digital circuits
B. Detectors
C. Rectifiers
D. All of the above

14. The static VI characteristics of a junction diode can be described by the equation called

A. Child's three half-power law
B. Boltzmann diode equation
C. Einstein's photoelectric equation
D. Richardson-Dushman equation

15. The reverse saturation current in junction diode is independent of

A. Potential barrier
B. Junction area
C. Doping of 'P' and 'N' type region
D. Temperature

16. Depletion region behaves as

A. An insulator
B. Semiconductor
C. Conductor
D. High resistance

17. A crystal diode has forward resistance of the order of ……………

A. kΩ
B. MΩ
C. Ω
D. none of the above

18. The forward voltage drop across a silicon diode is about …………………

A. 0.5 V
B. 0.3 V
C. 1.0 V
D. 0.7 V

19. If the doping level of a crystal diode is increased, the breakdown voltage…………
A. remains the same
B. is decreased
C. is increased
D. none of the above

20. The current in a Zener diode is controlled by
A. Zener diode resistance
B. Potential barrier
C. Reverse bias voltage
D. External circuits

21. In a zener diode
A. Negative resistance characteristic exists
B. Forward voltage rating is high
C. Sharp breakdown occurs at low reverse voltage
D. All of the above

22. In the breakdown region, a zener diode behaves like a …………… source.
A. constant voltage
B. constant current
C. constant resistance
D. none of the above

23. If the a.c. input to a half-wave rectifier is an r.m.s value of 400/√2 volts, then diode PIV rating is
A. 400/√2 V
B. 400 V
C. 400 x √2 V
D. none of the above

24. The ripple factor of a half-wave rectifier is …………………
A. 2
B. 1.21
C. 2.5
D. 0.48

25. If the PIV rating of a diode is exceeded , ………………
A. the diode is destroyed poorly
B. the diode conducts
C. the diode behaves like a zener diode
D. none of the above

26. The maximum efficiency of a full-wave rectifier is ………………..
A. 40.6 %
B. 46.4%
C. 82.1 %
D. 81.2 %

27. The most widely used rectifier is ……………….
A. half-wave rectifier
B. centre-tap full-wave rectifier
C. bridge full-wave rectifier
D. none of the above

28. Forward voltage drop of an LED is greater than
A. 0.5 V
B. 1.2 V
C. 2.4 V
D. 5 V

29. In photodiode, when there is no incident light, the reverse current is almost negligible and is called
A. Zener current
B. PIN current
C. photo current
D. dark current

30. What is the possible range of current limiting resistor essential for lightening the LED in certain applications after switched it ON?

A. 25- 55 Ω
C. 110-220 Ω

B. 55-110 Ω

D. 220- 330 Ω

31. Which among the following are regarded as three-pin voltage regulator ICs?

A. Fixed voltage regulators

B. Adjustable voltage regulators

C. Both A and B

D. None of the above

32. The 7812 regulator IC provides

A. 5 V

B. –5 V

C. 12 V

D. –12 V

33. To get a maximum output current, IC regulation is provided with

A. Radiation source

B. Heat sink

C. Peak detector

D. None of the mentioned

34. The change in output voltage for the corresponding change in load current in a 7805 IC regulator is defined as

A. All of the mentioned

B. Line regulation

C. Load regulation

D. Input regulation

35. Color of light emitted by LED depends on

A. its forward bias

B. its reverse bias

C. forward current

D. semiconductor material

## Answers for Multiple choice Questions

**1. B, 2. D, 3. A, 4. B, 5. C, 6. B, 7. A, 8. A, 9. D, 10. C, 11. B, 12. B, 13. D, 14. B, 15. B, 16. A, 17. C, 18. D, 19.B, 20.D, 21.C, 22. A, 23.B, 24. B, 25. A, 26.C, 27.C, 28.B, 29.D, 30.D, 31.A, 32.C, 33.B, 34.C, 35.D**