P-N Junction diode and Zener Diode

- Introduction to Semiconductors
- PN Junction
- PN Junction Diode

  → Construction

  → Thermal Equilibrium
- IV characteristics of PN Junction Diode

  → Forward Bias

  → Reverse Bias

  1. Avalanche Breakdown 2. Zener Breakdown
- Zener Diode
- IV characteristics of Zener Diode
- Zener Diode as Voltage Regulator

Classification of Materials

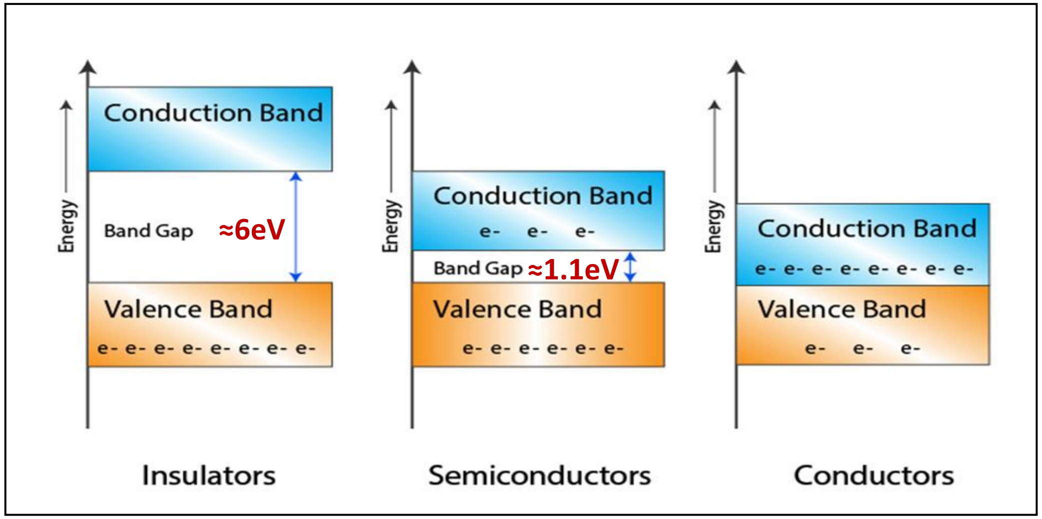
→ **Based on Electrical Conductivity**

Parameter	Conductor (e.g. Copper, Aluminium, Silver, Gold)	Semiconductor e.g. Germanium, Silicon GaAs	Insulators e.g. Paper, Mica, glass, quartz
Resistivity	10^{-4} to 10^{-6} Ω-cm.	10^{1} to 10^{4} Ω-cm.	10^{10} to 10^{12} Ω-cm.

Classification of Materials..

→ Energy band diagrams insulator, semiconductor and conductor

Band structure of a material defines the band of energy levels that an electron can occupy.



- The electrons in the outermost shell are known as valence electrons. These valence electrons contain a series of energy levels and form an energy band known as valence band. The valence band has the highest occupied energy.

- The valence electrons can leave the outermost orbit even at room temperature and become free electrons. The free electrons conduct current in conductors and are therefore known as conduction electrons.
- The conduction band is one that contains conduction electrons and has the lowest occupied energy levels.
- **The gap between the valence band and the conduction band is referred to as forbidden gap. As the name suggests, the forbidden gap doesn't have any energy and no electrons stay in this band.**

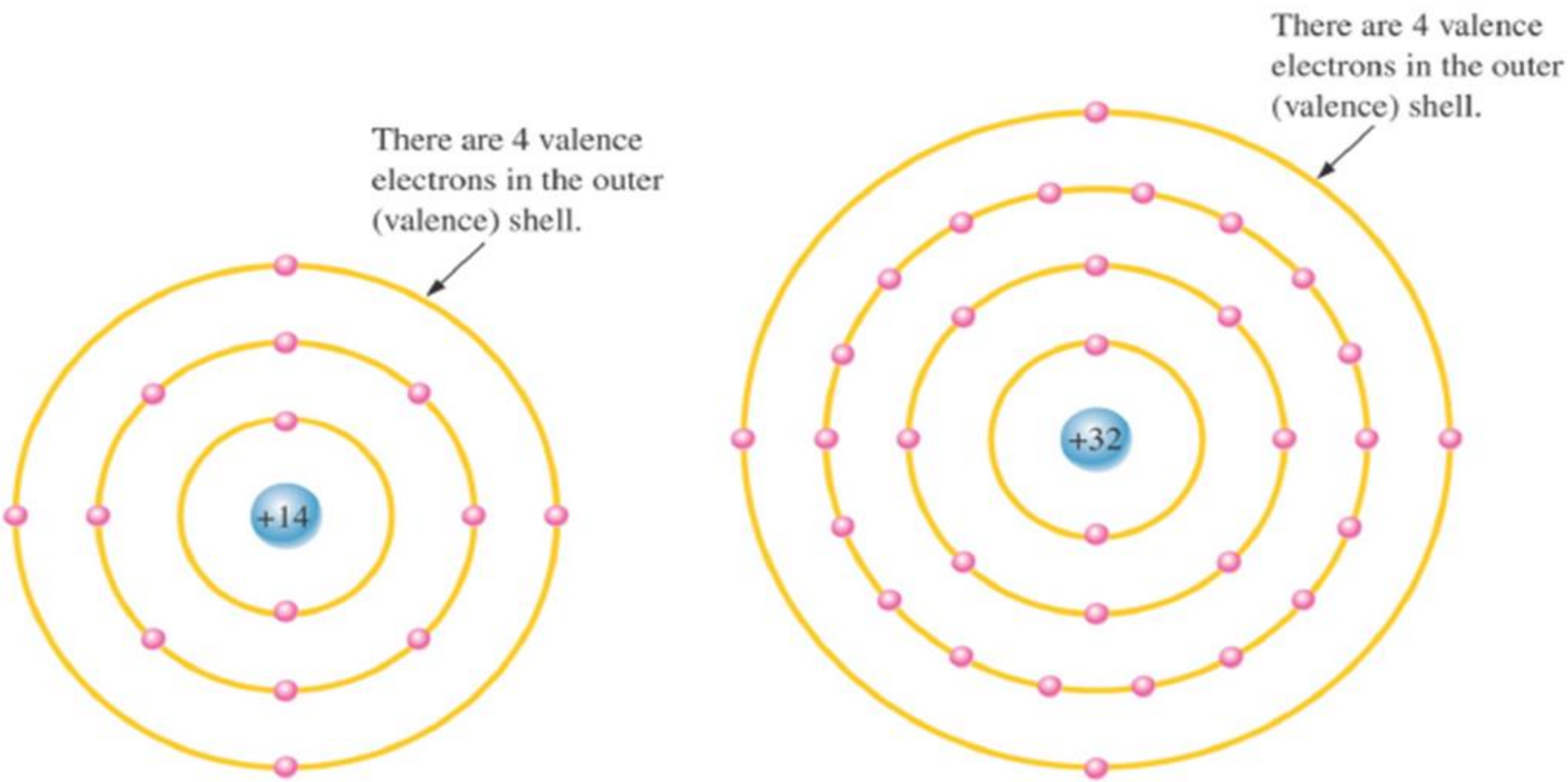
Semiconductor Materials

- **Two types of semiconducting materials : silicon and germanium**

→both have four valance electrons

→ atoms within the crystal structure are held together by covalent bonds (atoms share valence electrons)

→**An intrinsic crystal is one that has no impurities**

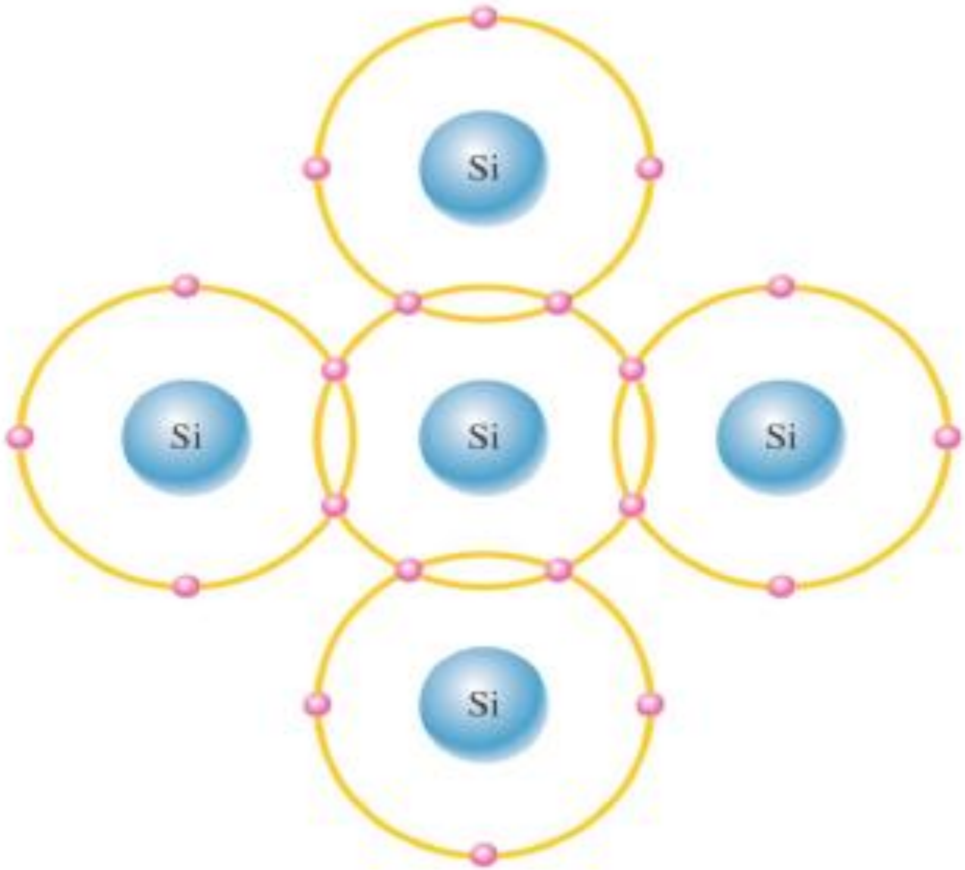


(a) Silicon atom

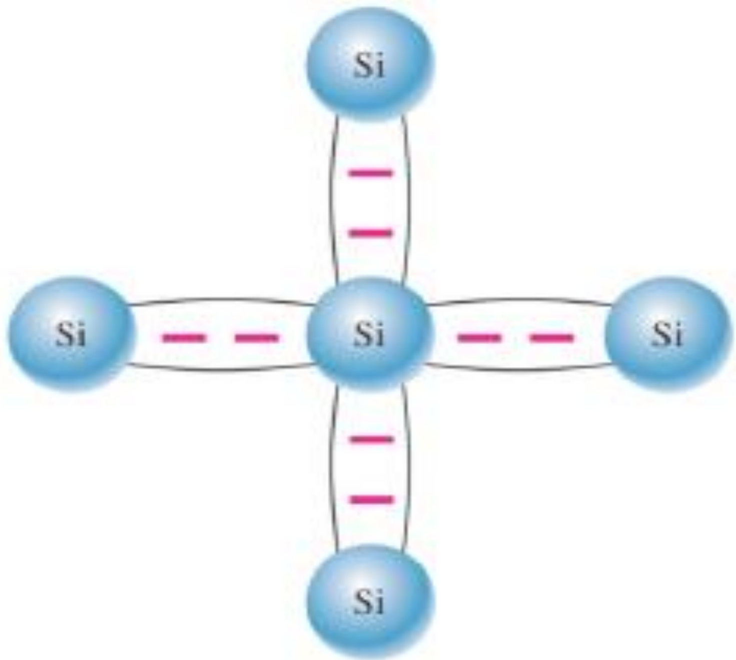
(b) Germanium atom

Semiconductor Materials..

Covalent bonds in a silicon crystal. The actual crystal is 3-dimensional.



(a) The center atom shares an electron with each of the four surrounding atoms creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.



(b) Bonding diagram. The red negative signs represent the shared valence electrons.

Modified Semiconductor Materials

- **Doping is the process of adding impurities to intrinsic semiconducting materials to increase and control conductivity within the material.**

→ ***n*-type material is formed by adding pentavalent (5 valence electrons) impurity atoms** (**Pentavalent impurities : Phosphorous , Arsenic, Antimony**)

-- electrons are called majority carriers in *n*-type material

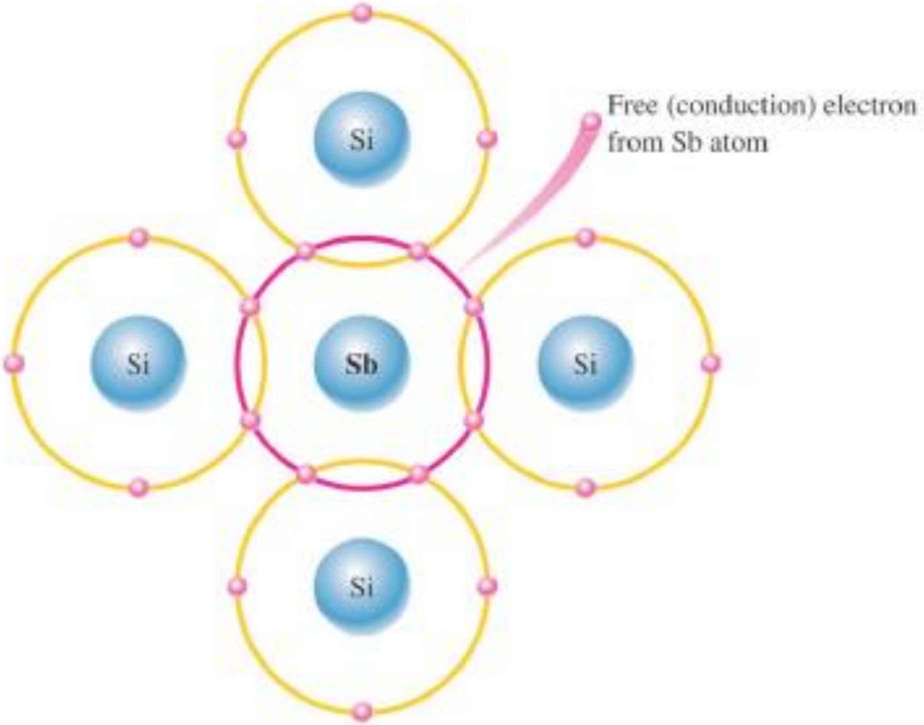
-- holes are called minority carriers in *n*-type material

→ ***p*-type material is formed by adding trivalent (3 valence electrons) impurity atoms (Tri-valent impurities : Boron (B), Gallium (G), Indium(In), Aluminium(Al)**)

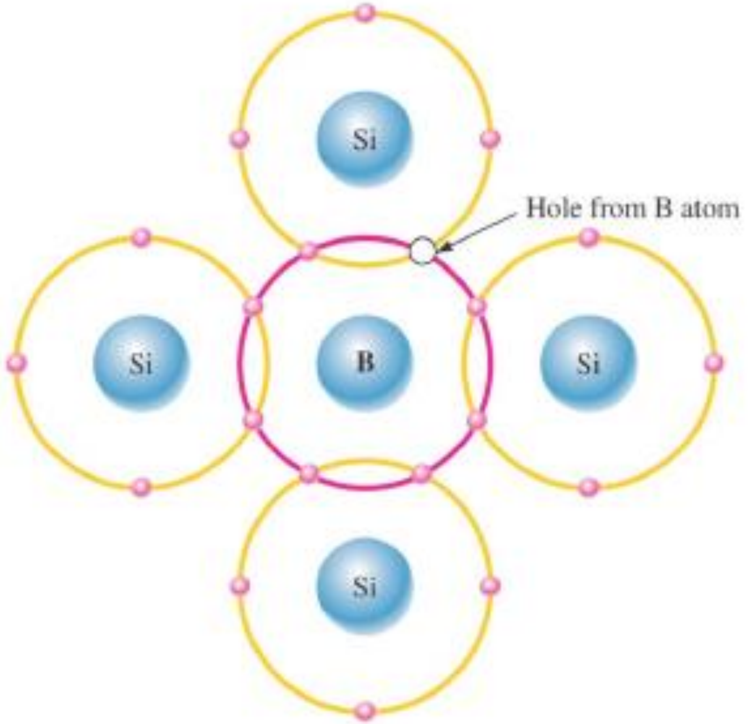
-- holes are called majority carriers in *p*-type material

-- electrons are called minority carriers in *p*-type material

Modified Semiconductor Materials



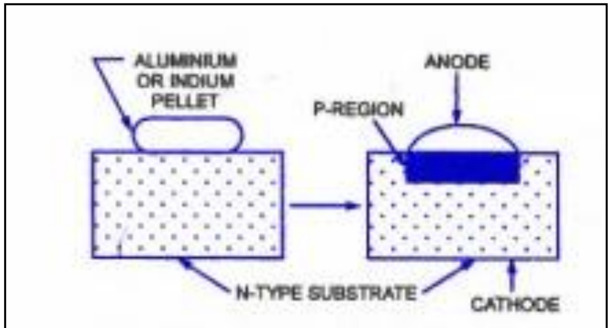
(a) Pentavalent impurity atom in a silicon crystal. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.



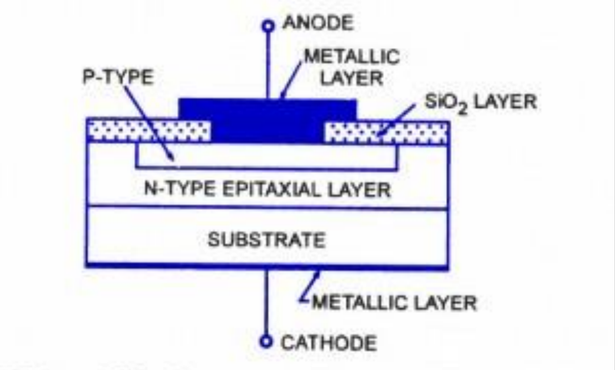
(b) Trivalent impurity atom in a silicon crystal. A boron (B) impurity atom is shown in the center.

P-N Junction

- A **p-n junction** is formed by joining p-type and n-type semiconductors together in very close contact. The term junction refers to the boundary interface where the two regions of the semiconductor meet.
- p-n junctions are created in a single crystal of semiconductor by doping, for example, by ion implantation, diffusion of dopants, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant)



Alloy Type or Fused Junction Diode

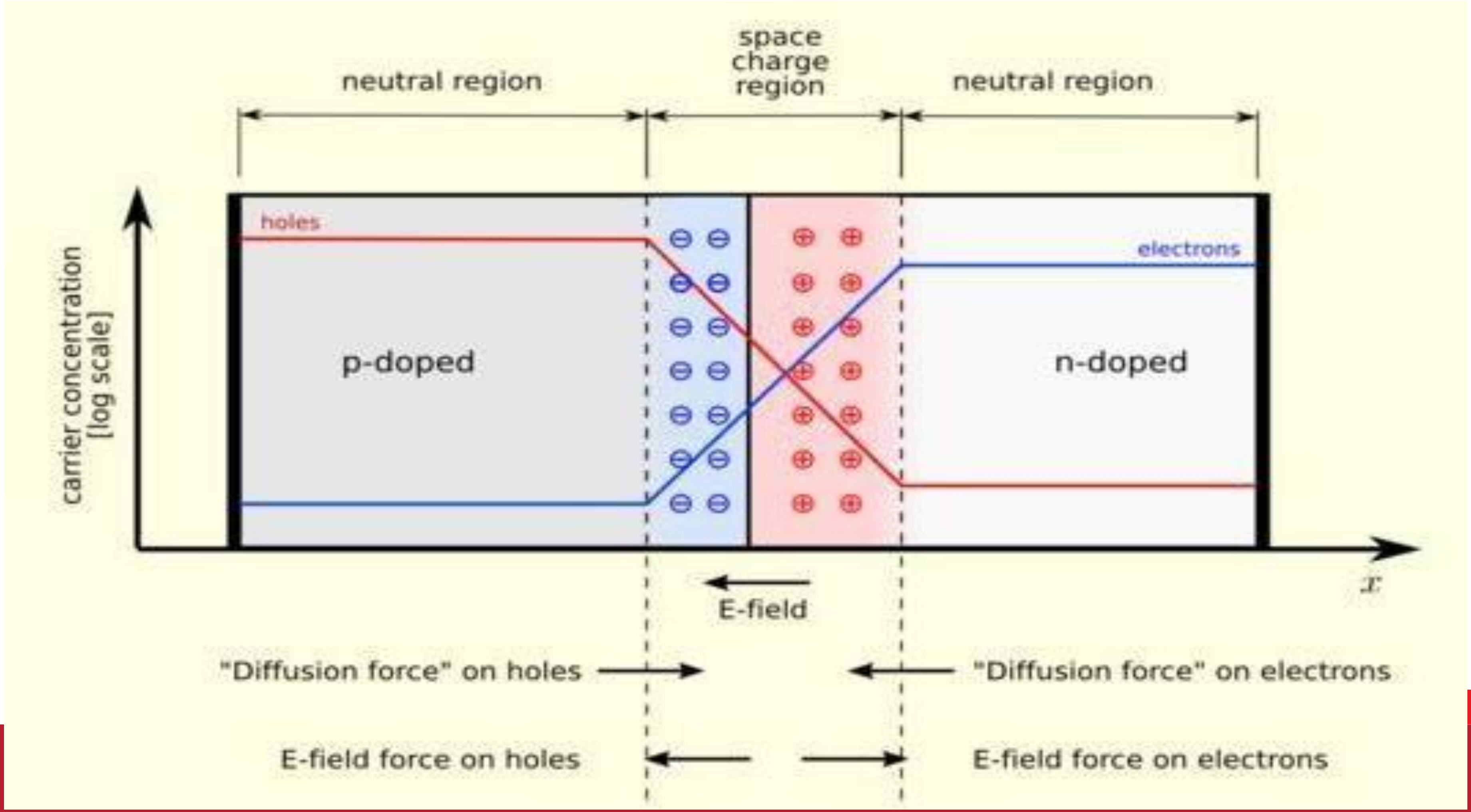


Epitaxially Grown or Planar Diffused Diode

- p-n junctions are elementary “building blocks” of almost all semiconductor electronic devices such as diodes, transistors, solar cells, LEDs, and integrated circuits; they are the active sites where the electronic action of the device takes place.

p-n junction in thermal equilibrium: with zero bias voltage applied

- The regions nearby the p-n interfaces lose their neutrality and become charged, forming the space charge region or depletion layer.



p-n junction in thermal equilibrium: with zero bias voltage applied

- The electric field created by the space charge region opposes the diffusion process for both electrons and holes.

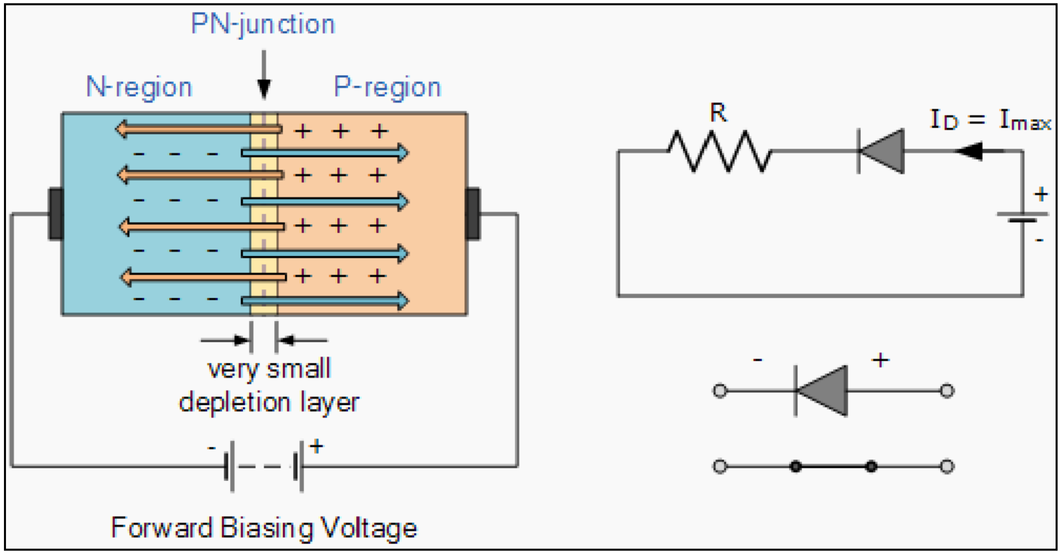
- There are two concurrent phenomena: the diffusion process that tends to generate more space charge, and the electric field generated by the space charge that tends to counteract the diffusion.

- The space charge region is a zone with a net charge provided by the fixed ions (donors or acceptors) that have been left uncovered by majority carrier diffusion.
- When equilibrium is reached, the charge density is approximated by the displayed step function.

- The region is completely depleted of majority carriers (leaving a charge density equal to the net doping level), and the edge between the space charge region and the neutral region is quite sharp.

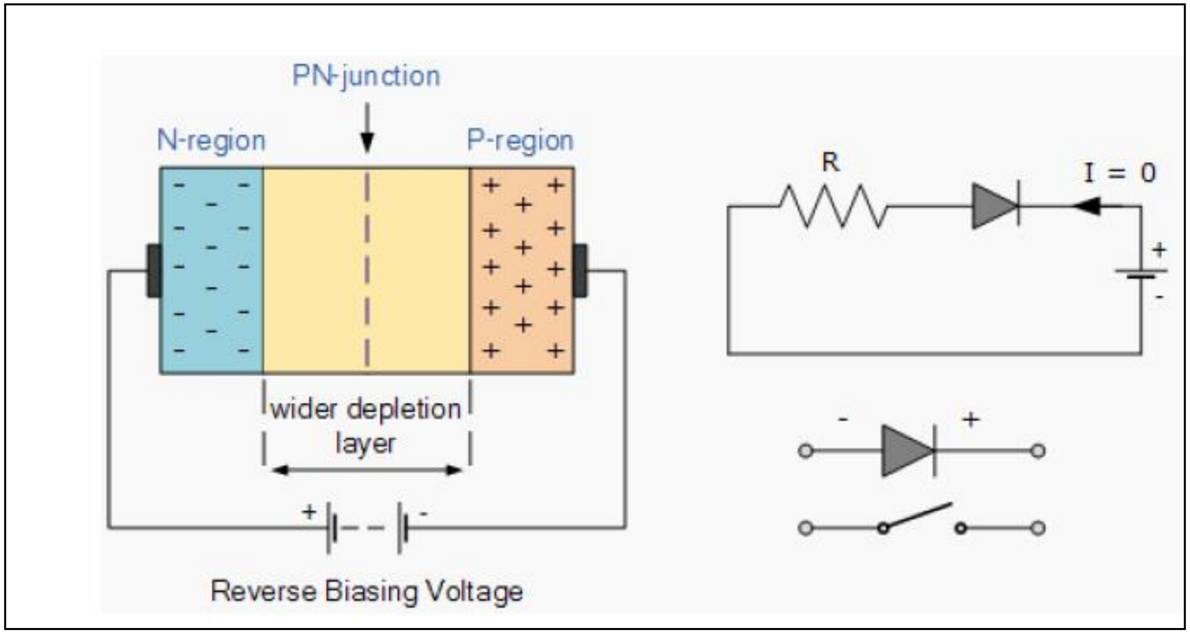
- The space charge region has the same charge on both sides of the p-n interfaces, thus it extends farther on the less doped side.

Forward biasing of p-n junction



- The applied forward potential establishes the electric field which acts against the field due to potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junction.
- Since the potential barrier voltage is very small, a small forward voltage is sufficient to completely eliminate the barrier.
- Once the potential barrier is eliminated by the forward voltage, junction resistance becomes almost zero and a low resistance path is established for the entire circuit. Therefore, current flows in the circuit. This is called *forward current*.

Reverse biasing of *p-n* junction

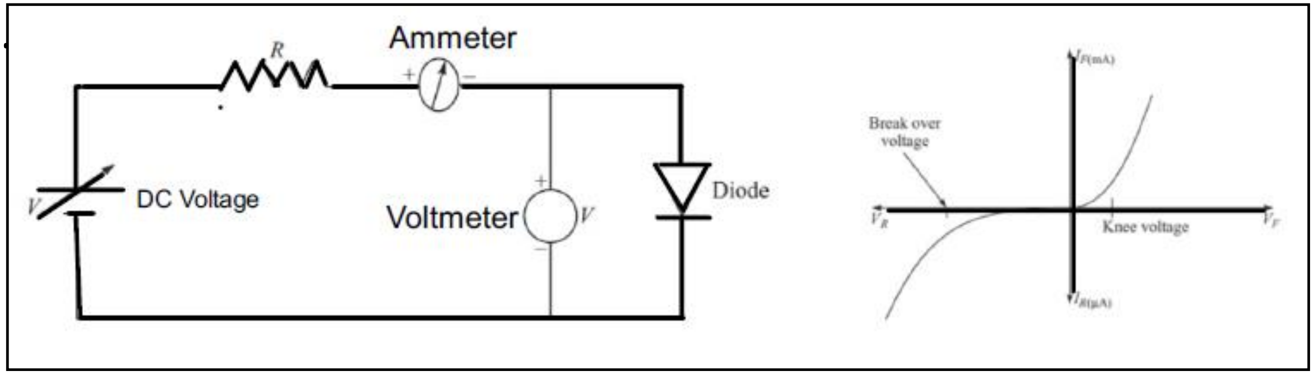


- The applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore, the resultant field at the junction is strengthened and the barrier height is increased.

- The increased potential barrier prevents the flow of charge carriers across the junction. Thus, a high resistance path is established for the entire circuit and hence current does not flow.

VOLT-AMPERE (*V-I*) CHARACTERISTICS OF *P-N* JUNCTION DIODE

- The *V-I* characteristics of a semiconductor diode can be obtained with the help of the circuit



- The supply voltage *V* is a regulated power supply, the diode is forward biased in the circuit shown. The resistor *R* is a current limiting resistor.
- By varying the supply voltage different sets of voltage and currents are obtained.
- By plotting these values on a graph, the forward characteristics can be obtained. It can be noted from the graph the current remains zero till the diode voltage attains the barrier potential.
- For silicon diode, the barrier potential is 0.7 V and for germanium diode, it is 0.3 V.

  The barrier potential is also called *knee voltage* or *cut-in voltage*.
- The reverse characteristics can be obtained by reverse biasing the diode. It can be noted that at a particular reverse voltage, the reverse current increases rapidly. This voltage is called *breakdown voltage*.

DIODE CURRENT EQUATION

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

- I_D is the total diode current
- I_s reverse saturation current
- V_D applied voltage across the diode
- η an ideality factor, value between 1&2.
- V_T thermal voltage:

$$V_T = \frac{kT}{q}$$

where k = 1.38 x 10^{-23} J/K , Boltzmann constant

q = 1.6x10^{-19} C , charge of electrons

T= temperature in ^{o}K

At room temperature 27^{o}C , T= 273+27= 300^{o}K

Thermal Voltage $V_T \approx$ 26mV

DIODE CURRENT EQUATION

→ **With Zero Voltage:** $V_D = 0, \ \because I_D = I_s\left(e^{V_D/nV_T} - 1\right) = I_s\left(e^0 - 1\right) = 0$

→ **Under forward-biased condition,**

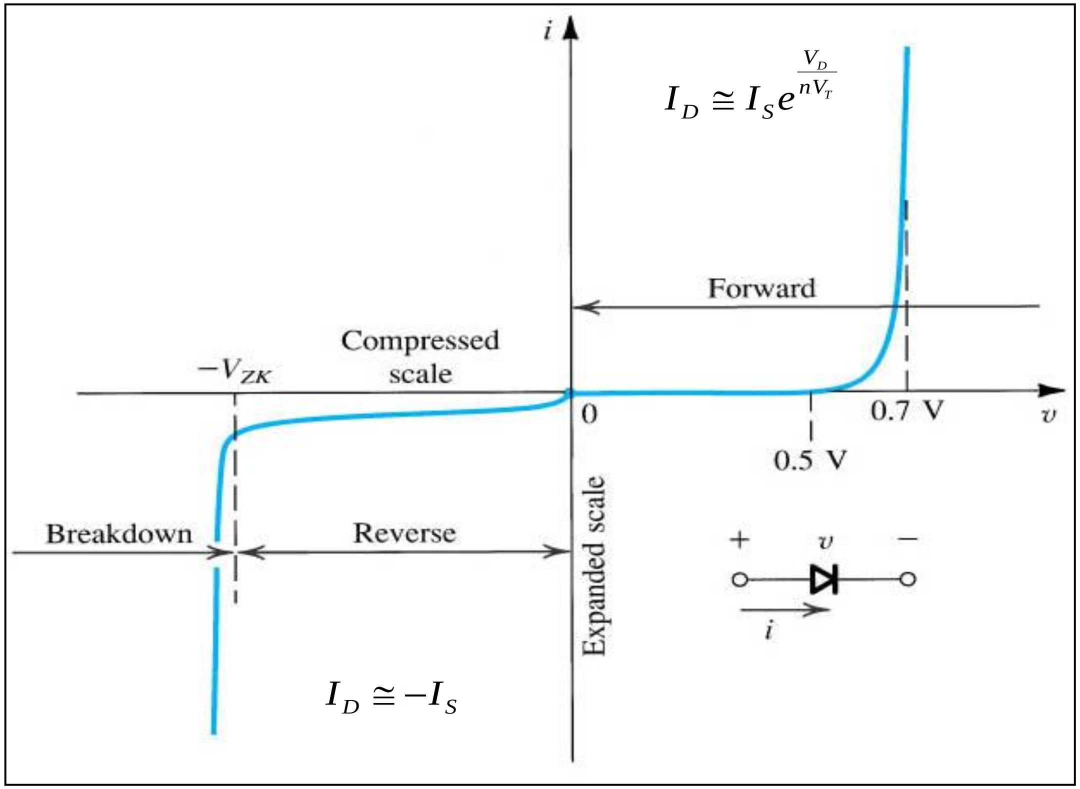
$V_D > 0$ So $V_D >> \eta V_T$, then $e^{\frac{V_D}{nV_T}} >> 1$ and $I_D \cong I_S e^{\frac{V_D}{nV_T}}$

→ **Under Reversed-biased Condition**

$V_D < 0$ So $V_D << \eta V_T$, then $e^{\frac{V_D}{nV_T}} << 1$ and $I_D \cong -I_S$

I-V Characteristics

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



When $V_D < V_{ZK}$, the diode enters the breakdown region, the reverse current increases sharply. V_{ZK} is known as the zener knee voltage.

Basic Definitions

- ***Knee Voltage or Cut-in Voltage***

  It is the forward voltage at which the diode starts conducting.

- **Breakdown Voltage**

  It is the reverse voltage at which the diode (p-n junction) breaks down with a sudden rise in reverse current.

- **Peak-inverse Voltage (PIV)**

  It is the maximum reverse voltage that can be applied to a p-n junction without causing damage to the junction. If the reverse voltage across the junction exceeds its peak inverse voltage, then the junction exceeds its peak-inverse voltage, and the junction gets destroyed because of excessive heat. In rectification, care should be taken that reverse voltage across the diode during –ve half cycle of ac doesn't exceed the peak-inverse voltage of the diode.

  and the voltage across the junction.

Basic Definitions

- **Maximum Forward Current**

  It is the maximum instantaneous forward current that a p-n junction can conduct without damaging the junction. If the forward current is more than the specified rating then the junction gets destroyed due to overheating.

- **Maximum Power Rating**

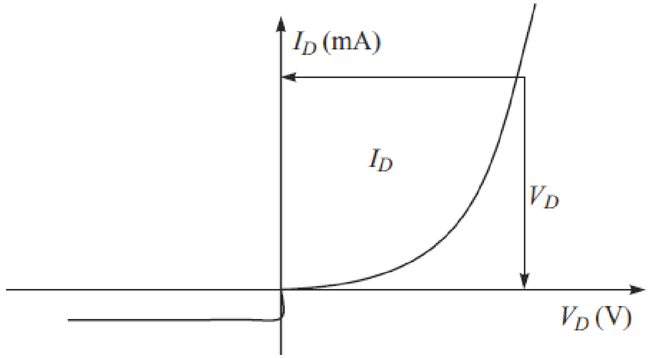
  It is the maximum power that can be dissipated at the junction without damaging it.The power dissipated across the junction is equal to the product of junction current and the voltage across the junction.

STATIC AND DYNAMIC RESISTANCE OF A DIODE

DC or Static Resistance

$$R_F = \frac{V_D}{I_D}$$

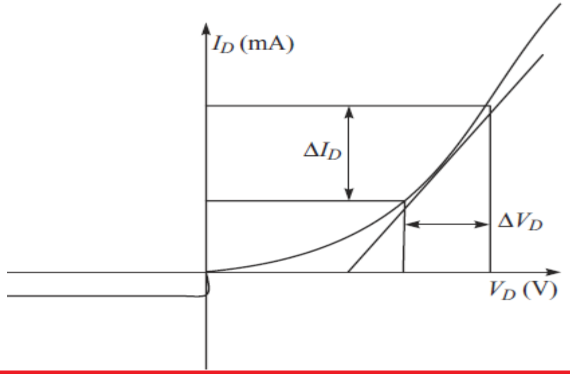
When diode is forward biased, it offers a definite resistance in the circuit. This resistance is known as dc resistance or static resistance (*RF*). It is simply the ratio of the dc voltage (*VD*) across the diode to the dc current (*ID*) flowing through it.



AC or Dynamic Resistance

$$r_f = \frac{\Delta V_D}{\Delta I_D}$$

The ac or dynamic resistance of a diode, at a particular dc voltage, is equal to the reciprocal of the slope of the characteristics at that point



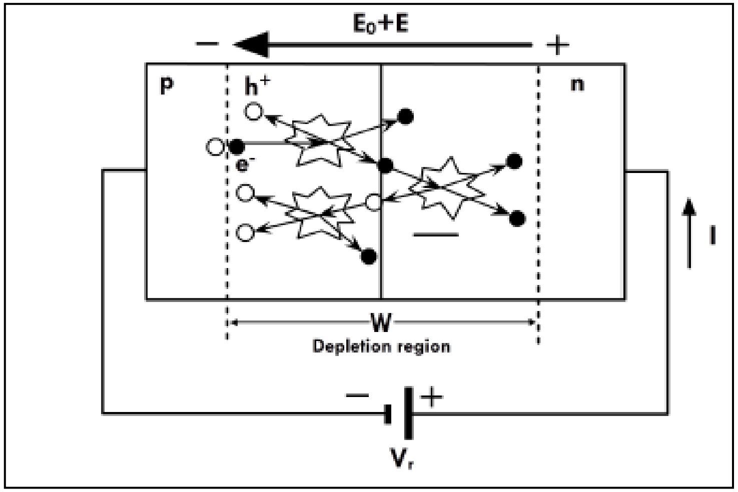
BREAK DOWN Mechanisms In PN Junction

- Reverse bias voltage, at which the breakdown of a P-N junction diode occurs is called the *breakdown voltage.*

- The breakdown voltage depends on the width of the depletion region, which, in turn, depends on the doping level.

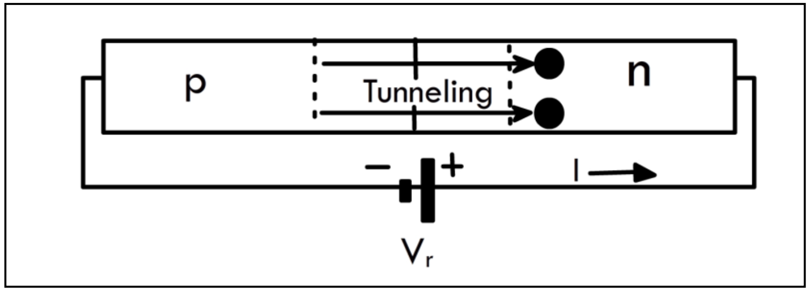
- There are two mechanisms by which breakdown can occur at a reverse biased P-N junction
  1. avalanche break down
  2. Zener breakdown.

Avalanche breakdown

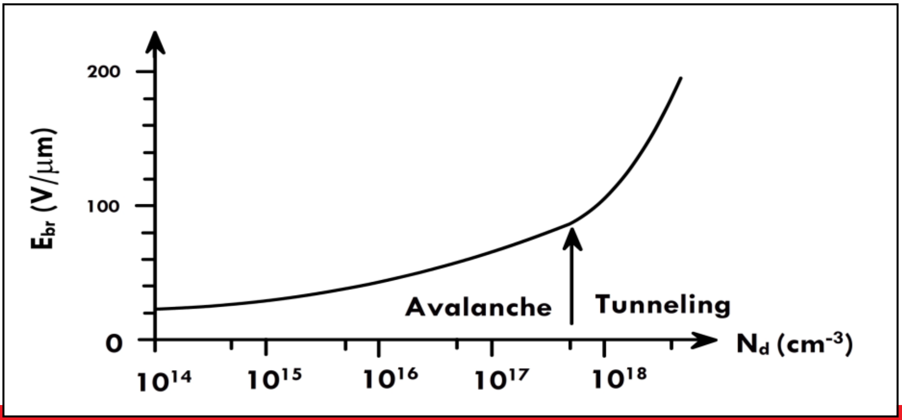


- Avalanche breakdown occurs in moderately and lightly doped PN junctions with a wide depletion region.
- Electron hole pairs thermally generated in the depletion region are accelerated by the external reverse bias. Electrons are accelerated towards the n side and holes towards the p side.
- These electron can interact with other Si atoms and if they have sufficient energy can knock out electrons from these Si atoms. This process is called impact ionization and leads to production of a large number of electrons.
- This causes the rapid rise in current. The breakdown voltage decreases with increase in dopant concentration.
- The breakdown region is the knee of the characteristic curve. After breakdown the current is not controlled by the junction voltage but rather by the external circuit.

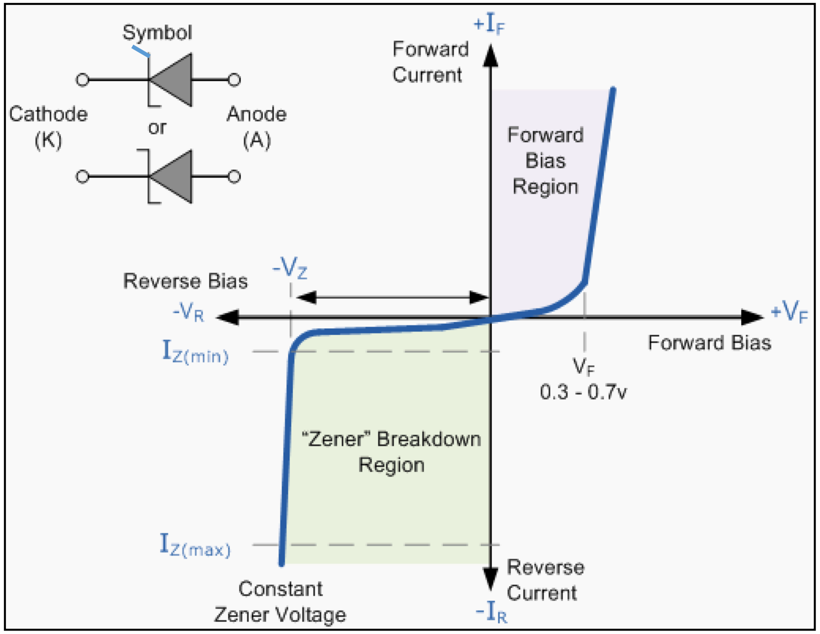
Zener breakdown



- With increase in doping concentration the breakdown mechanism, changes from Avalanche to a tunnelling mechanism. This is called a Zener breakdown.
- The depletion width decreases with dopant concentration.
- It is possible for carriers to tunnel across the narrow depletion region.
- The electrons tunnel from the valence band on the p side to the conduction band on the n side, driven by the externally applied reverse bias. Tunnelling also leads to a large increase in current.
- The transition from avalanche to Zener as the primary breakdown mechanism with dopant concentration is shown.



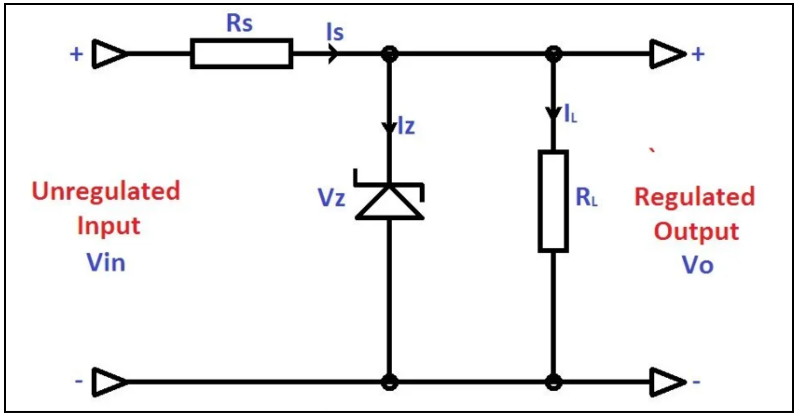
Zener Diode



- The Zener diode is like a general-purpose signal diode consisting of a silicon PN junction. When biased in the forward direction it behaves just like a normal signal diode passing the rated current.
- A reverse voltage applied across the Zener diode exceeds the rated voltage of the device, the diodes breakdown and high current flows through diode.

- Zener diodes are primarily used as surge protectors in circuits, since there is a rapid increase in current with a small change in voltage. Prior to breakdown there is a high resistance small reverse saturation current but after breakdown the resistance is very small.
- Zener diode is used as voltage regulators in circuits.

Zener Diode as Voltage Regulator

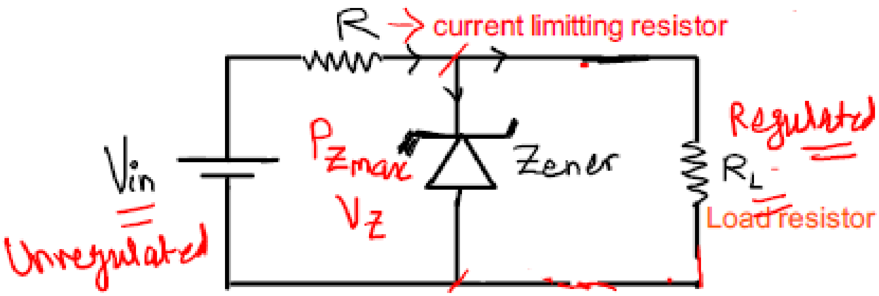


- Zener Diodes are widely used as Shunt Voltage Regulators to regulate voltage across small loads.
- Zener Diodes have a sharp reverse breakdown voltage and breakdown voltage will be constant for a wide rang of currents. Thus Zener diode parallel to the load such that the applied voltage will reverse bias it.
- If the reverse bias voltage across the Zener diode exceeds the knee voltage, the voltage across the load will be constant.
- The value of Rs must be small enough to keep the Zener Diode in reverse breakdown region. The minimum current required for a Zener Diode to keep it in reverse breakdown region will be given in its datasheet. For example, a 5.6 V, 0.5 W Zener diode has a recommended reverse current of 5 mA. If the reverse current is less than this value, the output voltage Vo will be unregulated.
- The value of Rs must be large enough that the current through the zener diode should not destroy it. That is the maximum power dissipation Pmax should be less than IzVz.

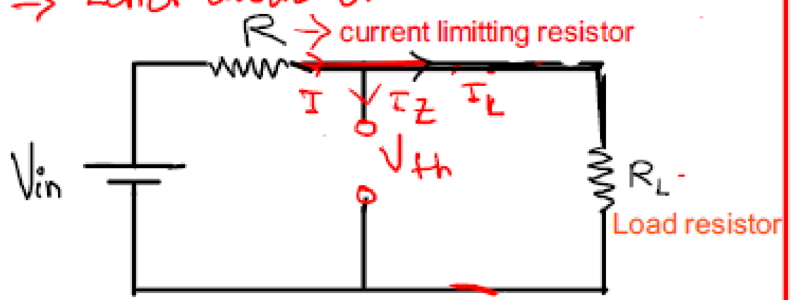
Zener Diode as Voltage Regulator

Zener diode as voltage regulator

1. If input voltage Vin and R_L are constant



⇒ Zener diode OFF $|V_Z$



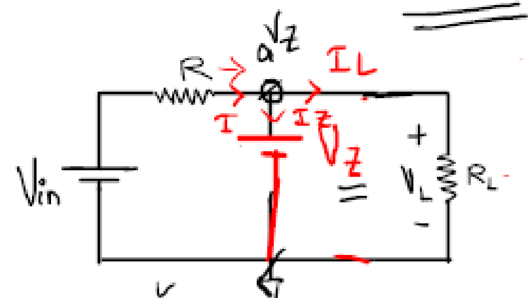
$$V_{th} = \frac{R_L \times V_{in}}{R + R_L}$$

$$|V_{th}| < V_Z$$

$$I_Z = 0$$

$$I = I_L = \frac{V_{in}}{R + R_L}$$

→ Zener ON $|V_{th}| > V_Z$



$$I = I_L + I_Z$$

$$I_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L}$$

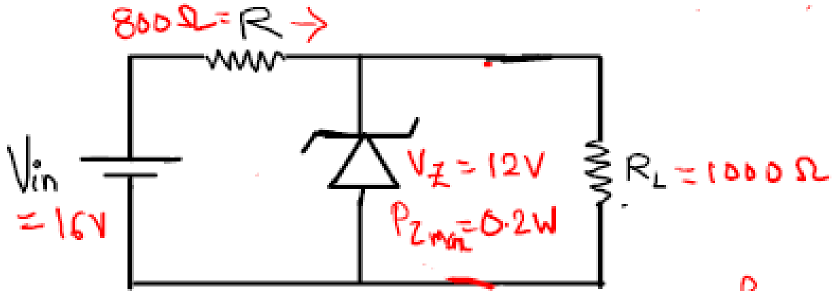
$$I = \frac{V_{in} - V_Z}{R}$$

$$\boxed{I_Z = I - I_L}$$

Zener Diode as Voltage Regulator..

Zener diode as voltage regulator

numerical 1. If input voltage Vin and RL are constant



Zener off
$$V_{th} = \frac{R_L \times V_{in}}{R + R_L}$$
Zener on
$$V_{th} = V_Z$$

$$\Rightarrow V_{th} = \frac{16 \times 1000}{800 + 1000}$$

$$V_{th} = \frac{16000}{1800} = 8.8V$$

$$|V_{th}| < (V_Z = 12)$$

So Zener off

$I_Z = 0$, $I = I_L = \frac{16}{1800}$

$I_L = 8.8mA$

So for $V_{th} \geq V_Z$ to ensure Zener breakdown

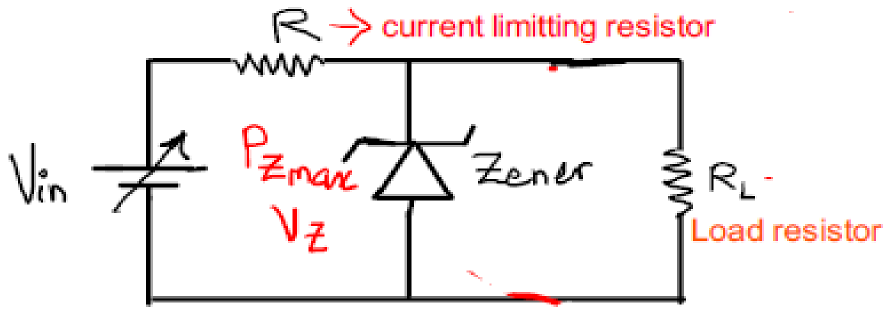
to find R
$$12 = \frac{1000 \times 16}{R + 1000} \qquad V_{th} = \frac{R_L \times V_{in}}{R + R_L}$$

So
$R \simeq 333\ \Omega$

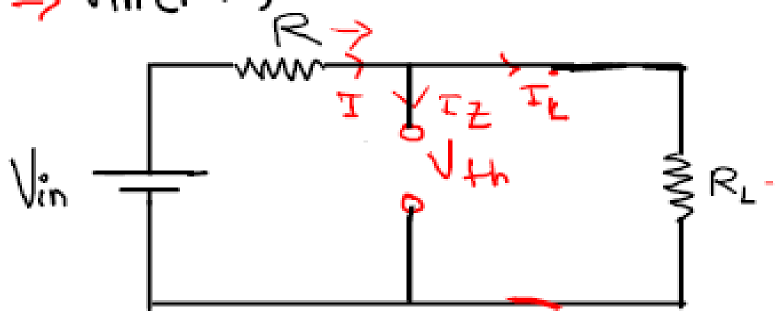
$V_L = 12V$

Zener Diode as Voltage Regulator..

2. If input voltage Vin variable and RL is constant



⇒ $V_{in(min)} = ?$

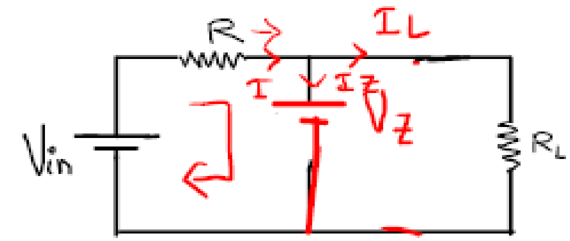


$$V_{th} = \frac{R_L \times V_{in}}{R + R_L}$$

$$|V_{th}| \geq V_Z$$

$$V_{in(min)} = \frac{(R+R_L) \times V_Z}{R_L}$$

→ $V_{in(max)} = ?$



Maximum current through Zener diode will Limit

$$I = I_Z + I_L$$

$$I = I_{Zmax} + I_L \quad \text{--- (1)}$$

$$I_{Zmax} = \frac{P_{Zmax}}{V_Z} \quad \& \quad I_L = \frac{V_Z}{R_L}$$

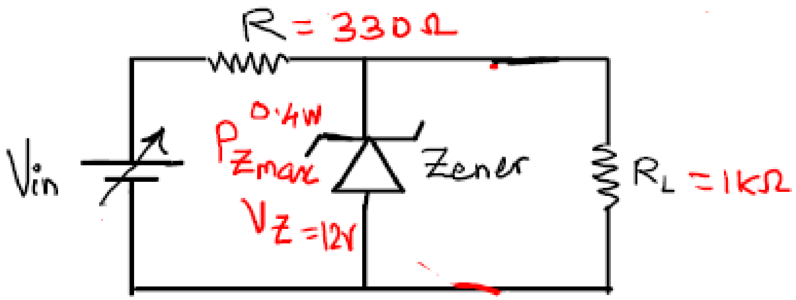
KVL to mesh (I)

$$V_{in(max)} - IR - V_Z = 0$$

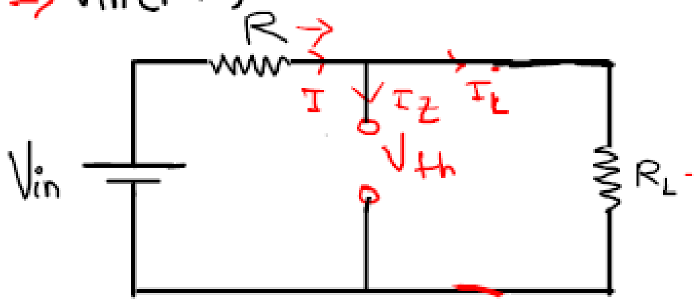
$$V_{in(max)} = IR + V_Z$$

Zener Diode as Voltage Regulator..

Numerical 2. If input voltage Vin variable and RL is constant



$\Rightarrow V_{in(min)} = ?$



$$V_{th} = \frac{R_L \times V_{in}}{R + R_L}$$

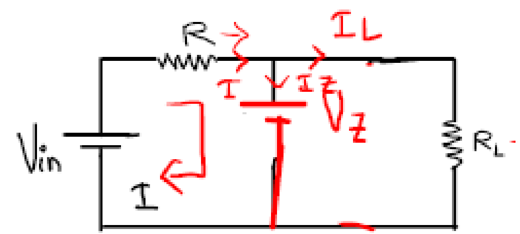
$$|V_{th}| \geq V_Z$$

$$V_{in(min)} = \frac{(R + R_L) \times V_Z}{R_L}$$

$$V_{in(min)} = \frac{(330 + 1000) \times 12}{1000}$$

So $\boxed{V_{in(min)} = 15.6V}$

$\Rightarrow V_{in(max)} = ?$



$$I_{Zmax} = \frac{P_{Zmax}}{V_Z} = \frac{0.4}{12} = 33.3mA$$

$$I_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L} = \frac{12}{1000} = 12mA$$

$$I = I_{Zmax} + I_L = 45.3mA$$

KVL to mesh (I)

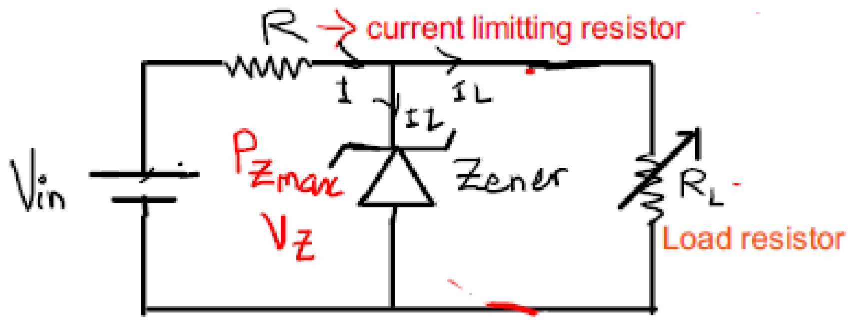
$$V_{in(max)} = I \cdot R + V_Z$$

$$V_{in(max)} = (45.3 \times 330) + 12$$

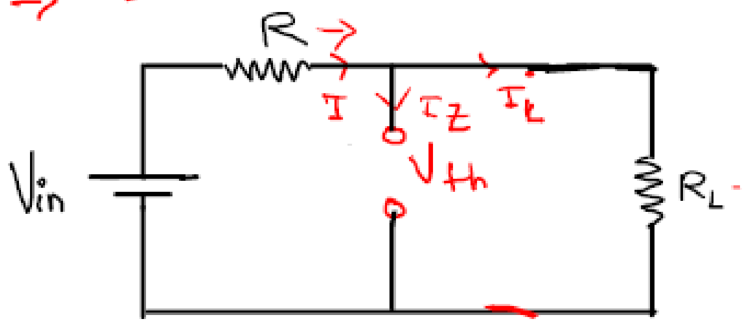
$$\boxed{V_{in(max)} = 26.9V}$$

Zener diode as voltage regulator

3. If input voltage Vin fixed and RL variable



$\Rightarrow R_L(min) = ?$



$$V_Z = \frac{R_L \times V_{in}}{R + R_L}$$

$$|V_{th}| \geq V_Z$$

$$V_Z R + V_Z R_L = R_L V_{in}$$

$$V_Z R = R_L (V_{in} - V_Z)$$

$$R_L(min) = \frac{V_Z \times R}{(V_{in} - V_Z)}$$

$\Rightarrow R_L(max) = ?$

$$P_{Zmax} = V_Z \cdot I_{Zmax}$$

$$I_{Zmax} = \frac{P_{Zmax}}{V_Z}$$

$$I = I_{Zmax} + I_{Lmin}$$

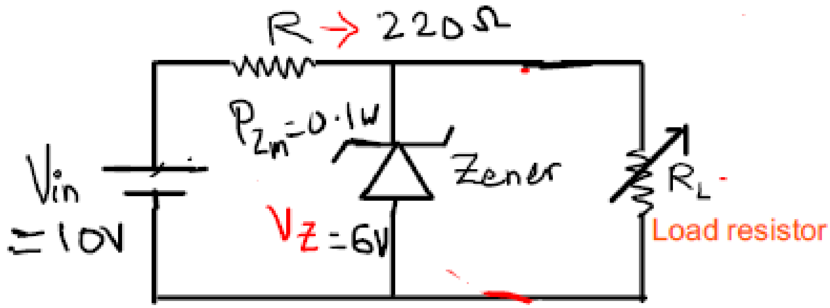
$$I_{Lmin} = I - I_{Zmax}$$

$$I_{L(min)} = \frac{V_{in} - V_Z}{R} - \frac{P_{Zmax}}{V_Z}$$

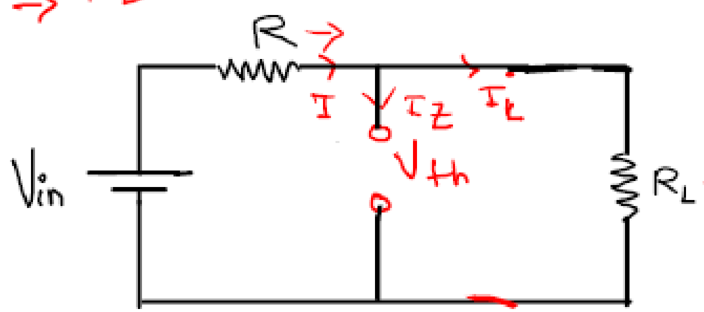
$$R_{L(max)} = \frac{V_Z}{I_{Lmin}}$$

Zener diode as voltage regulator

Example 3. If input voltage Vin fixed and RL variable



⇒ $R_L(min) = ?$



$$R_L(min) = \frac{R V_Z}{(V_{in} - V_Z)} = \frac{220 \times 6}{10 - 6} = 330\,\Omega$$

→ $R_L(max) = ?$

$$P_{Zmax} = V_Z \cdot I_{Zmax}$$

$$I_{Zmax} = \frac{P_{Zmax}}{V_Z}$$

$$I = I_{Zmax} + I_{Lmin}$$

$$I_{Lmin} = I - I_{Zmax}$$

$$I_{L(min)} = \frac{V_{in} - V_Z}{R} - \frac{P_{Zmax}}{V_Z}$$

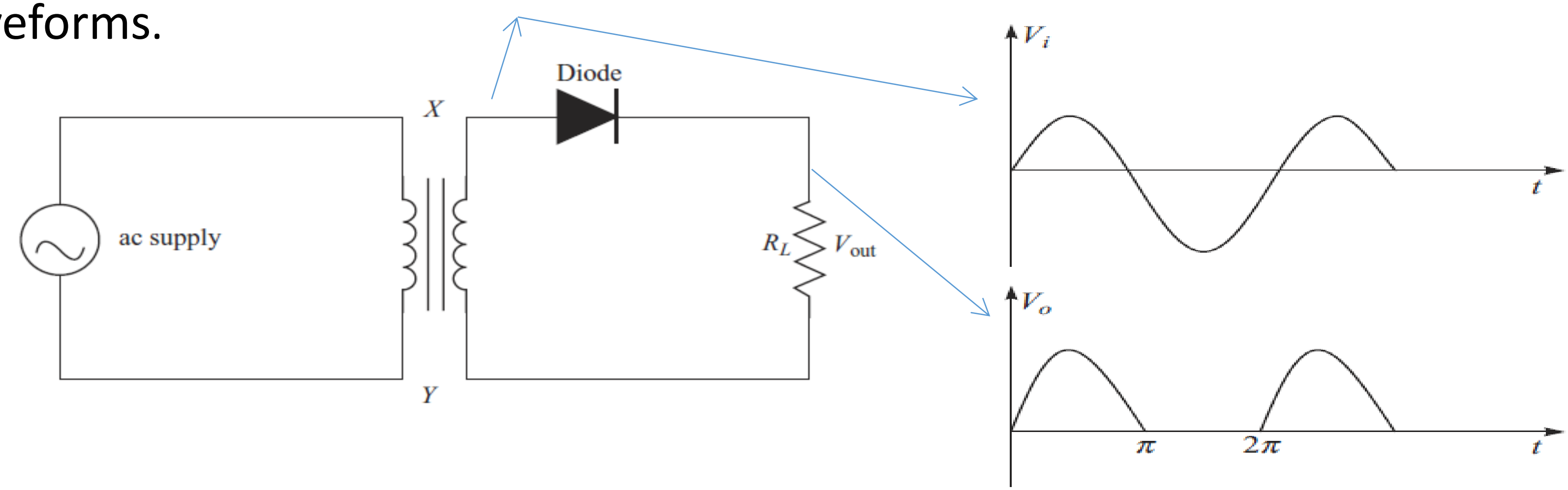
$$I_L(min) = \frac{10-6}{220} - \frac{0.1}{6} = 1.51\,mA$$

$$R_L(max) = \frac{V_Z}{I_{Lmin}}$$

$$R_L(max) = \frac{6}{1.5\,mA} \simeq 3.9\,K\Omega$$

HALF-WAVE RECTIFIER

The circuit diagram of a half-wave rectifier is shown along with the I/P and O/P Waveforms.



- The transformer is employed in order to step-down the supply voltage.
- The diode is used to rectify the ac signal while the pulsating dc is taken across the load resistor RL. During the +ve half-cycle, the end X of the secondary is +ve and end Y is –ve. Thus, forward biasing the diode.
- As the diode is forward biased, the current flows through the load RL and a voltage is developed across it.
- During the –ve half-cycle the end Y is +ve and end X is –ve thus, reverse biasing the diode. As the diode is reverse biased there is no flow of current through RL thereby the output voltage is zero.

Efficiency of a Half wave Rectifier

$$\text{Rectifier efficiency } \eta = \frac{\text{dc power output}}{\text{input ac power}}$$

Let $V = V_m \sin\theta$ be the voltage across the secondary winding

r_f = diode resistance
R_L = load resistance

dc Power

$$I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i \cdot d\theta = \frac{1}{2\pi}\int_0^{\pi} \frac{V_m \sin\theta}{r_L + R_L} d\theta$$

$$= \frac{V_m}{2\pi(r_f + R_L)}\int_0^{\pi} \sin\theta\, d\theta$$

$$= \frac{2V_m}{2\pi(r_f + R_L)} = \frac{I_m}{\pi}$$

$$P_{dc} = I_{dc}^2 \times R_L$$

$$= \left(\frac{I_m}{\pi}\right)^2 \times R_L$$

ac Power Input

$$P_{ac} = I_{rms}^2 (r_f + R_L)$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2 d\theta}$$

$$I_{rms}^2 = \frac{1}{2\pi}\int_0^{2\pi} i^2 d\theta$$

But $i = I_m \sin\theta$

$$I_{rms}^2 = \frac{1}{2\pi}\int_0^{\pi} (I_m \sin\theta)^2 d\theta$$

$$I_{rms}^2 = \frac{I_m^2}{4}$$

$$I_{rms} = \frac{I_m}{2}$$

$$P_{ac} = \left(\frac{I_m}{2}\right)^2 (r_f + R_L)$$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{\left(\frac{I_m}{\pi}\right)^2}{\left(\frac{I_m}{2}\right)^2} \times \frac{R_L}{(r_f + R_L)}$$

$$\eta = \frac{0.406}{1 + \frac{r_f}{R_L}}$$

The efficiency is maximum if *rf* is negligible as compared to *RL*.
Therefore, maximum rectifier efficiency = 40.6%

Ripple Factor

- The pulsating output of a rectifier consists of dc component and ac component (also known as ripple). The ac component is undesirable and accounts for the pulsations in the rectifier output. The effectiveness of a rectifier depends on the magnitude of ac component in the output : the smaller this component, the more effective is the rectifier. " The ratio of rms value of ac component to the dc component in the rectifier output is known as ripple factor".

Ripple Factor for Half-wave Rectification

$$r = \frac{I_{ac}}{I_{dc}}$$

$$I_{rms} = \sqrt{I_{ac}^2 + I_{dc}^2}$$ OR $$I_{ac} = \sqrt{I^2{}_{rms} - I^2{}_{dc}}$$

$$r = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

Divide both RHS and LHS by I_{dc}, we get

we have $I_{rms} = \frac{I_m}{2}$

$$\frac{I_{ac}}{I_{dc}} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2}$$

$$I_{dc} = \frac{I_m}{\pi}$$

ripple factor $r = 1.21$

It is clear that ac component exceeds dc component in the output of a half-wave rectifier.

Transformer utilization factor

Transformer utilization factor is a quantitative indication of the utilization of VA Rating of Transformer. The more the value of TUF, the more will be the utilization. In other words, the VA rating of required transformer will be less if TUF is more and vice versa.

Transformer Utilization Factor (TUF)

$$= \frac{\text{DC Power Output}}{\text{Effective VA Rating of Transformer}}$$

$$= \frac{\text{Pdc}}{\text{Effective VA Rating of Transformer}}$$

where Pdc is the dc power output

Effective VA Rating of Transformer is the average value of transformer primary and secondary VAs.

DC Power Output, Pdc = Average Current x Average Voltage

Transformer Utilization Factor (TUF) of Half Wave Rectifier

- **DC Power Output, Pdc = Average Current x Average Voltage**

$$P_{dc} = \frac{V_m}{\pi} X \frac{I_m}{\pi} \quad \text{....................(1)}$$

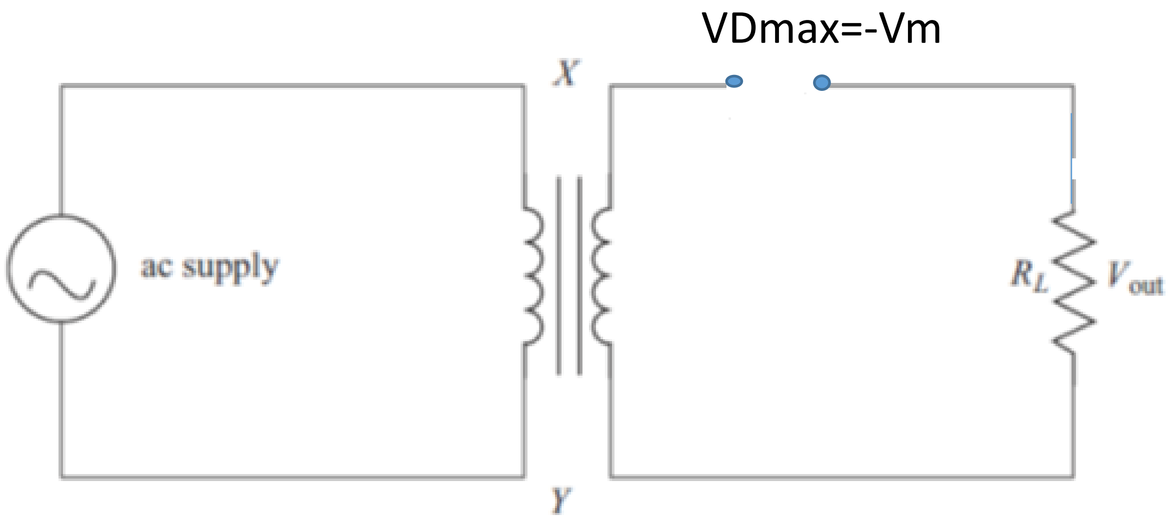
- **VA rating of Transformer**
- The voltage of source is sinusoidal, therefore its rms value will be equal to (Vm/√2).
- The rms value of the source current will be equal to the rms value of the load current. As the rms value of load current for half wave rectifier is equal to (Im/2), therefore the rms value of source current will also be equal to (Im/2).

$$VA_{rating} = \frac{V_m}{\sqrt{2}} X \frac{I_m}{2} \quad \text{....................(2)}$$

From equation (1) and (2) $TUF = \frac{2\sqrt{2}}{\pi^2}$ **= 0.285**

Peak Inverse Voltage

During Negative Half cycle Diode D is Reverse biased shown by open circuit so Voltage across is –Vm.



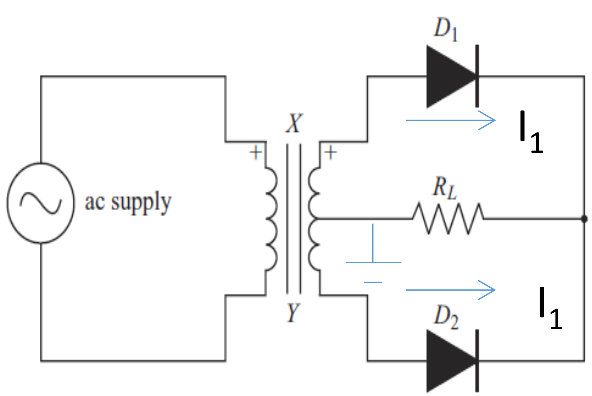
So PIV= Vm

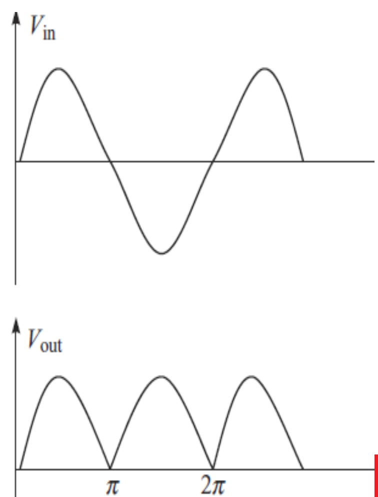
FULL-WAVE RECTIFIER

Full-wave rectifiers are of two types:
1. Centre tapped full-wave rectifier 2. Bridge rectifier

Centre Tapped Full-wave Rectifier

- It employs two diodes and a centre tap transformer. The ac signal to be rectified is applied to the primary of the transformer and the dc output is taken across the load, *RL*.
- During the +ve half-cycle end *X* is +ve and end *Y* is –ve. This makes diode *D*1 forward biased and thus a current *i*1 flows through it and load resistor *RL*. Diode *D*2 is reverse biased and the current *i*2 is zero.
- During the –ve half-cycle end *Y* is +ve and end *X* is –ve. Now diode *D*2 is forward biased and thus a current *i*2 flows through it and load resistor *RL*. Diode *D*1 is reversed and the current *i*1 = 0.

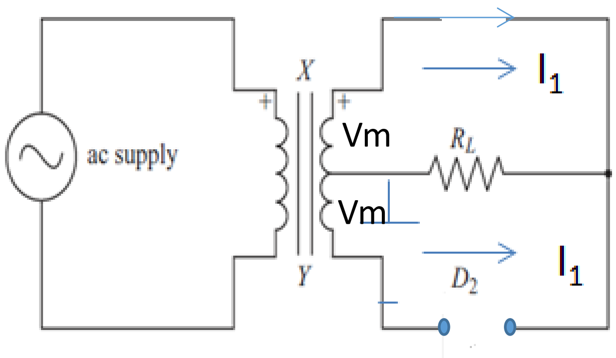




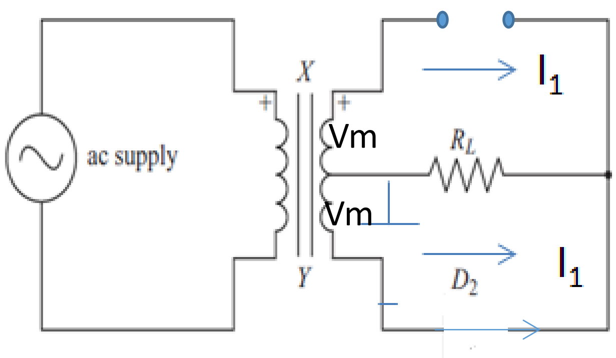
Disadvantages

- Since each diode uses only one-half of the transformer secondary voltage the dc output is comparatively small.
- It is difficult to locate the centre-tap on secondary winding of the transformer.
- The diodes used must have high peak-inverse voltage

Peak Inverse Voltage



During Positive half cycle D1 conducts (Short circuit) and D2 off (open circuit) so V_{D2max}= 2Vm

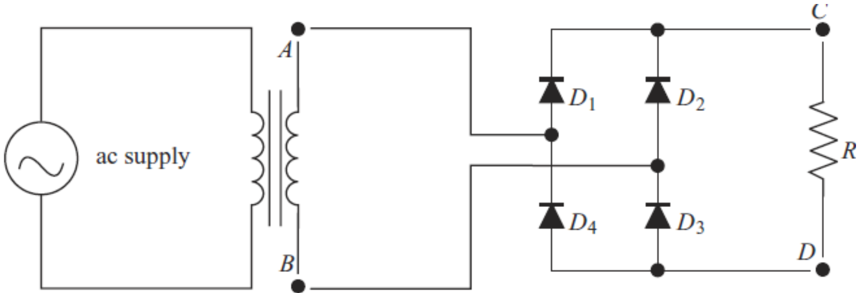


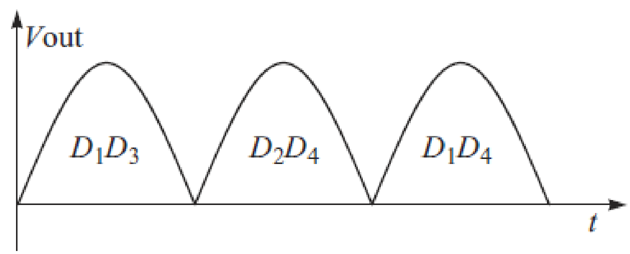
During negative half cycle D2 conducts (Short circuit) and D1 off (open circuit) so V_{D1max}= 2Vm

So PIV= 2Vm

Full-wave Bridge Rectifier

- It uses four diodes and one transformer.
- During the +ve half-cycle, end *A* is +ve and end *B* is –ve thus diodes *D*1 and *D*3 are forward bias while diodes *D*2 and *D*4 are reverse biased thus a current flows through diode *D*1, load *RL* (*C* to *D*) and diode *D*3.
- During the –ve half-cycle, end *B* is +ve and end *A* is –ve thus diodes *D*2 and *D*4 are forward biased while the diodes *D*1 and *D*3 are reverse biased. Now the flow of current is through diode *D*4 load *RL* (*D* to *C*) and diode *D*2. Thus, the waveform is same as in the case of centre-tapped full-wave rectifier.





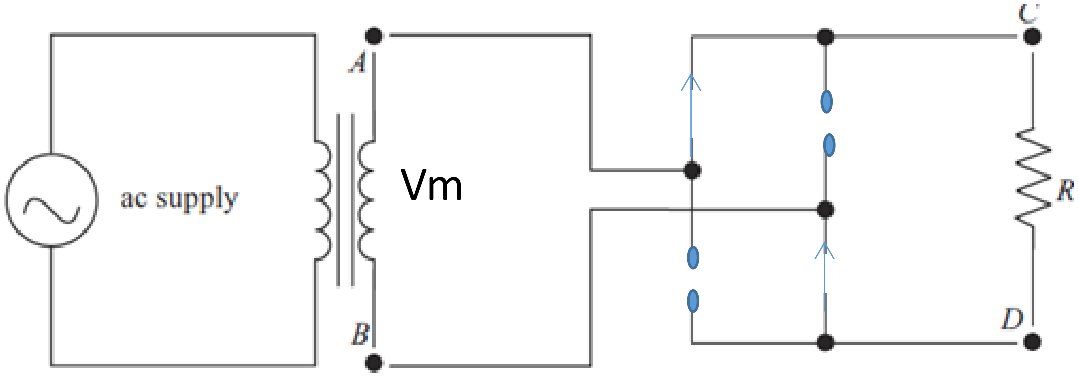
Advantages

- The need for centre-tapped transformer is eliminated.
- The output is twice when compared to centre-tapped full-wave rectifier, for the same secondary voltage.
- The peak inverse voltage is one-half (1/2) compared to centre-tapped full-wave rectifier.
- Can be used where large amount of power is required.

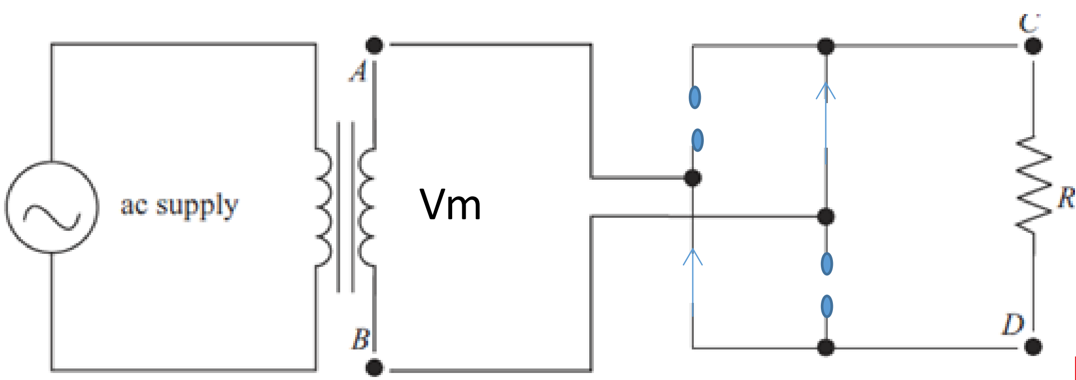
Disadvantages: • It requires four diodes. • The use of two extra diodes causes an additional voltage drop thereby reducing the output voltage.

Peak Inverse Voltage

During the +ve half-cycle, end *A* is +ve and end *B* is –ve thus diodes *D*1 and *D*3 are forward bias (Short circuit) while diodes *D*2 and *D*4 are reverse biased (open circuit)



During the -ve half-cycle, end *B* is +ve and end *A* is –ve thus diodes *D*2 and *D*4 are forward bias (Short circuit) while diodes *D*1 and *D*3 are reverse biased (open circuit)



So PIV= Vm

Efficiency of Full-wave Rectifier

$V = V_m \sin\theta$ be the voltage across the secondary winding

$I = I_m \sin\theta$ be the current flowing in secondary circuit

r_f = diode resistance

R_L = load resistance

dc power output

$$P_{dc} = I_{dc}^2 R_L$$

$$I_{dc} = I_{av} = 2\frac{1}{2\pi}\int_0^{\pi} i \cdot d\theta$$

$$I_{av} = 2\frac{1}{2\pi}\int_0^{\pi} I_m \sin\theta \cdot d\theta$$

$$I_{av} = \frac{2I_m}{\pi}$$

$$P_{dc} = \left(\frac{2I_m}{\pi}\right)^2 R_L$$

ac power output

$$P_{ac} = I_{rms}^2 (r_f + R_L)$$

$$I_{rms} = \sqrt{2\frac{1}{2\pi}\int_0^{\pi} i^2 d\theta}$$

$$I_{rms}^2 = \frac{1}{\pi}\int_0^{\pi} i^2 d\theta$$

$$I_{rms}^2 = \frac{1}{\pi}\int_0^{\pi} (I_m \sin\theta)^2 d\theta$$

$$I_{rms}^2 = \frac{I_m^2}{2}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}}$$

$$P_{ac} = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)$$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{\left(\frac{2I_m}{\pi}\right)^2}{\left(\frac{I_m}{\sqrt{2}}\right)^2} \times \frac{R_L}{(r_f + R_L)}$$

$$\eta = \frac{0.812}{1 + \frac{r_f}{R_L}}$$

The efficiency will be maximum if rf is negligible as compared to RL. Hence, maximum efficiency = 81.2%. This is double the efficiency due to half-wave rectifier. Therefore, a full-wave rectifier is twice as effective as a half-wave rectifier.

Ripple Factor for Full-wave Rectification

$$r = \sqrt{\left(\frac{I_{\text{rms}}}{I_{\text{dc}}}\right)^2 - 1}$$

For full-wave rectification, we have $I_{\text{rms}} = \dfrac{I_m}{\sqrt{2}}$

$$I_{\text{dc}} = \frac{2I_m}{\pi}$$

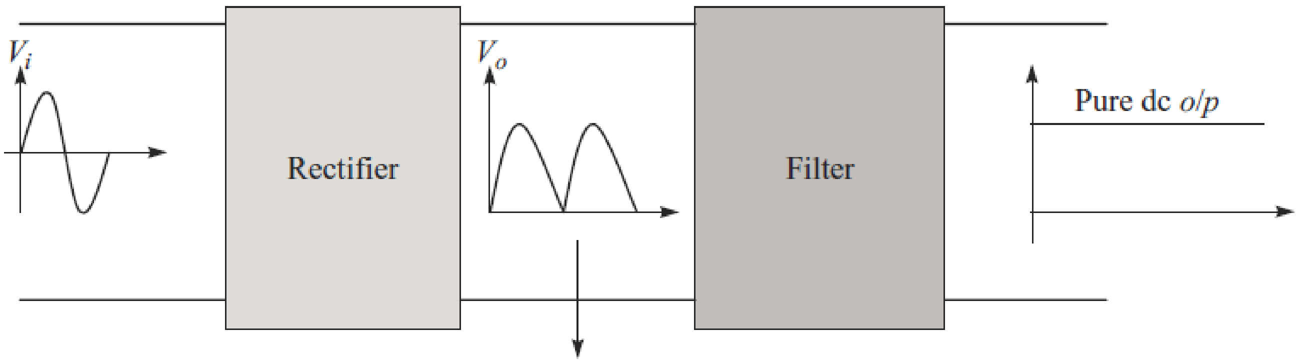
Ripple factor $r = 0.48$

Comparison of Rectifiers

Particulars	Half-wave rectifier	Centre-tapped full-wave rectifier	Bridge rectifier
1. No. of diodes	1	2	4
2. I_{dc}	I_m/Π	$2I_m/\Pi$	$2I_m/\Pi$
3. V_{dc}	V_m/Π	$2V_m/\Pi$	$2V_m/\Pi$
4. I_{rms}	$I_m/2$	$I_m/\sqrt{2}$	$I_m/\sqrt{2}$
5. Efficiency	40.6%	81.2%	81.2%
6. PIV	V_m	$2V_m$	V_m
7. Ripple factor	1.21	0.48	0.48
8. TUF	0.285	0.672	0.810

FILTERS

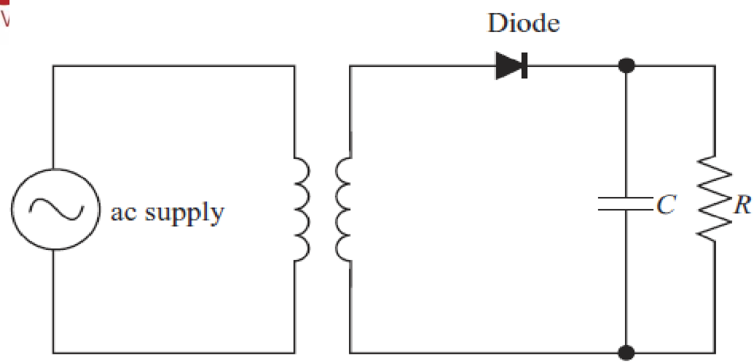
- The output of the rectifier is pulsating dc, i.e., the output obtained by the rectifier is not pure dc but it contains some ac components along with the dc o/p. These ac components are called ripples, which are undesirable or unwanted.
- To minimize the ripples in the rectifier output filter circuits are used. These circuits are normally connected between the rectifier and load

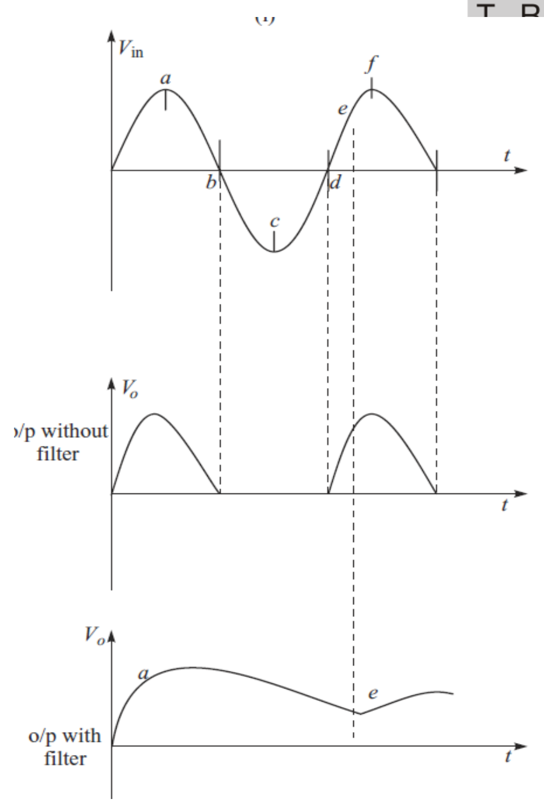


- Filter is a circuit which converts pulsating dc output from a rectifier to a steady dc output. In other words, filters are used to reduce the amplitudes of the unwanted ac components in the rectifier.
- Types of Filters

1. Capacitor filter (C-filter)   2. Inductor filter
3. Choke input filter (LC-filter)   4. Capacitor input filter (Π filter)

Capacitor Filter(C -Filter)





- When the input signal rises from o to a the diode is forward biased therefore it starts conducting since the capacitor acts as a short circuit for ac signal. It gets charged up to the peak of the input signal and the dc component flows through the load, *RL*.
- When the input signal falls from a to b the diode gets reverse biased. This is mainly because of the voltage across the capacitor obtained during the period o to a is more when compared to Vi. Therefore, there is no conduction of current through the diode.
- The charged capacitor acts as a battery and it starts discharging through the load, RL. Meanwhile the input signal passes through b, c, d sections. When the signal reaches the point d the diode is still reverse biased since the capacitor voltage is more than the input voltage. At e the input voltage can be expected to be more than the capacitor voltage. When the input signal moves from e to f the capacitor gets charged to its peak value again. The diode gets reverse biased and the capacitor starts discharging.

Ripple factor for the rectifiers with C-filter

The ripple factor for a half-wave rectifier with C-filter is given by

$$r = 1/2\sqrt{3}\, f_C R_L$$

f = the line frequency (Hz)
C = capacitance (F)
R_L = load resistance (Ω)

Ripple factor for full-wave rectifier with C-filter is given by $r = 1/4\sqrt{3}\, f_C R_L$