Digital Electronics and Logic Design (EC 106)

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In this topic we will learn

- Semiconductor theory
- Introduction to PN diode
- Zener diode

Semiconductor Materials

Conductor: The term conductor is used for any material that will support a generous flow of charge when the volatge is applied across its terminals.

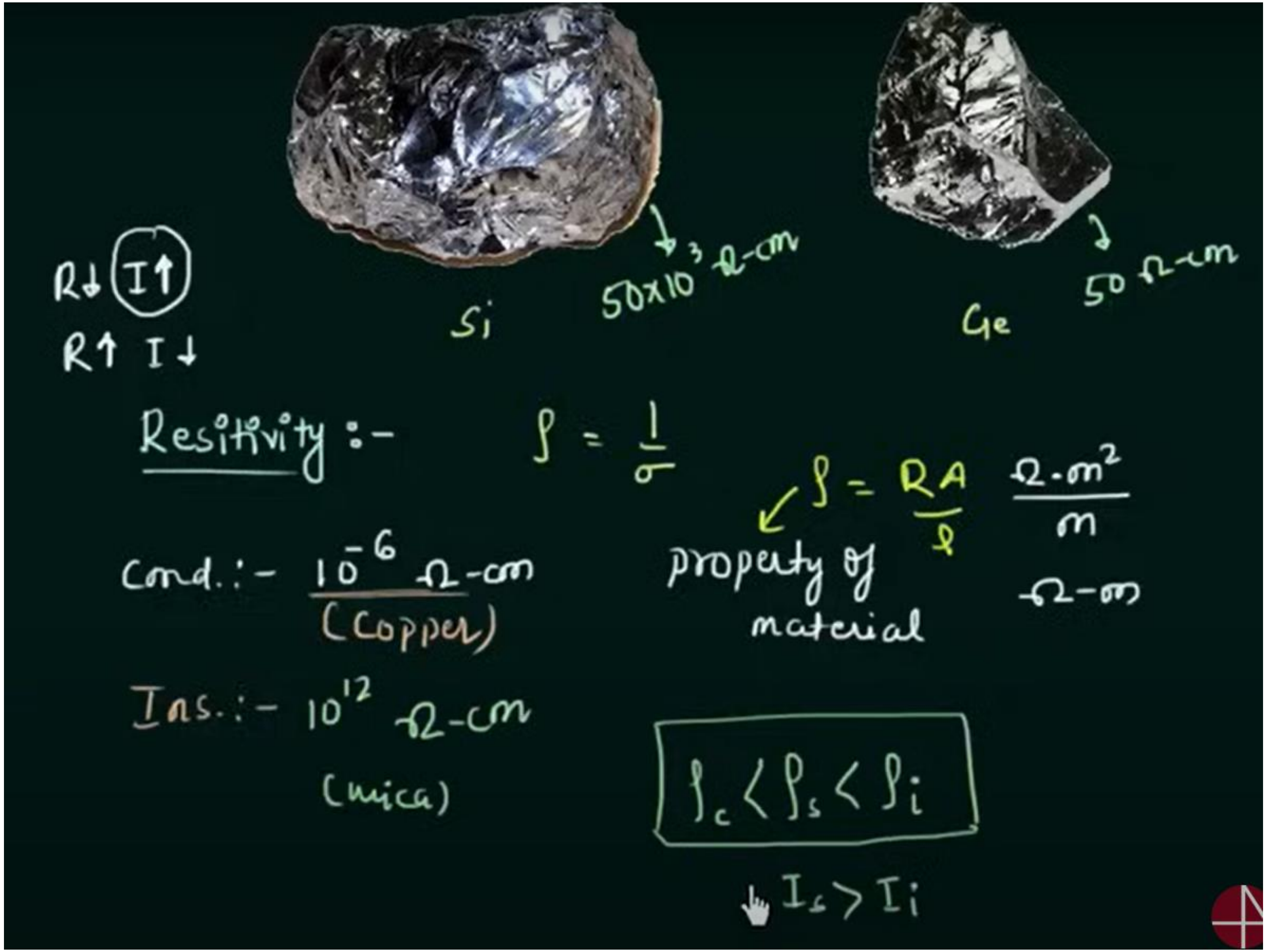
ex :

Semiconductor: It is a material that has conducti
but less than conductor.

Insulator: An insulator is a material that offers very low conductivity when voltage is applied.

ex :

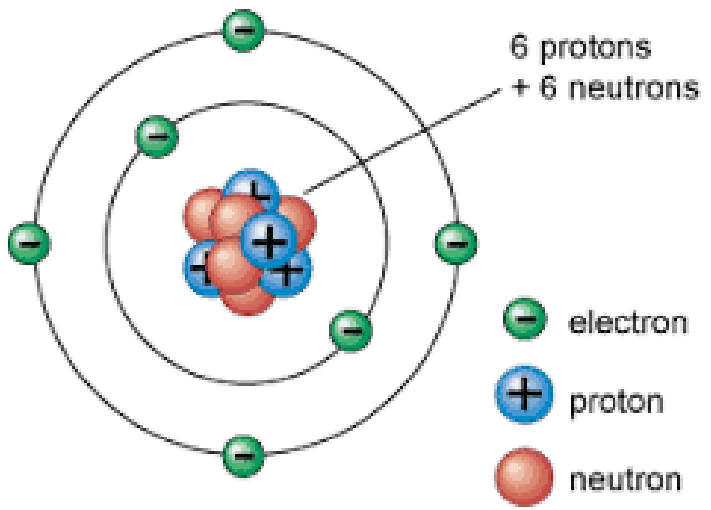
Crystalline structure of Silicon (Si) and Germanium (Ge)



Importance of Resistivity and Conductivity

Important points to be refreshed

- Atomic structure
  - Nucleus and its orbits
  - Structure of the elements
  - Atomic weight = no. of protons + no. of neutrons
  - Atomic number = no. of electrons in an atom

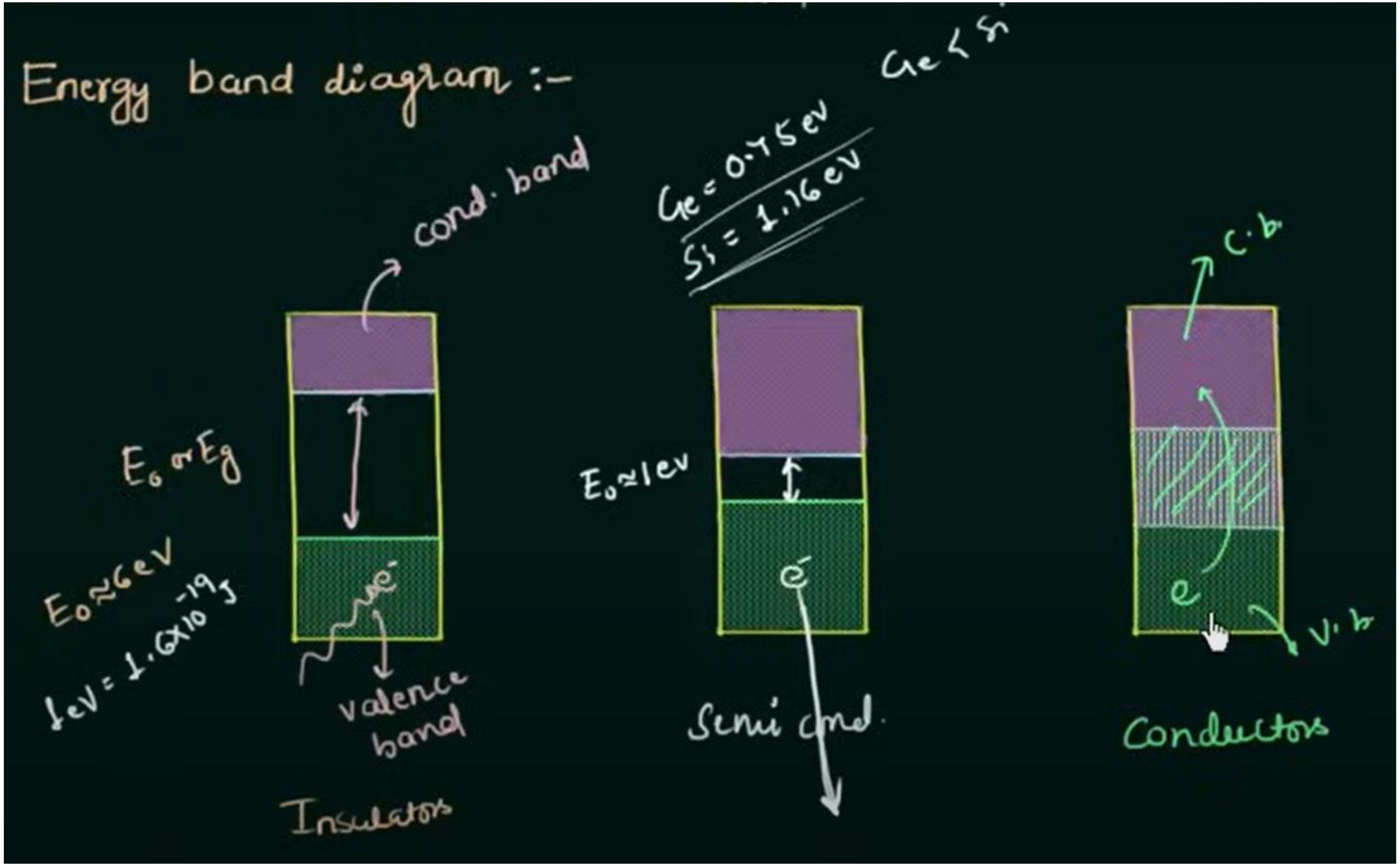


Carbon atom

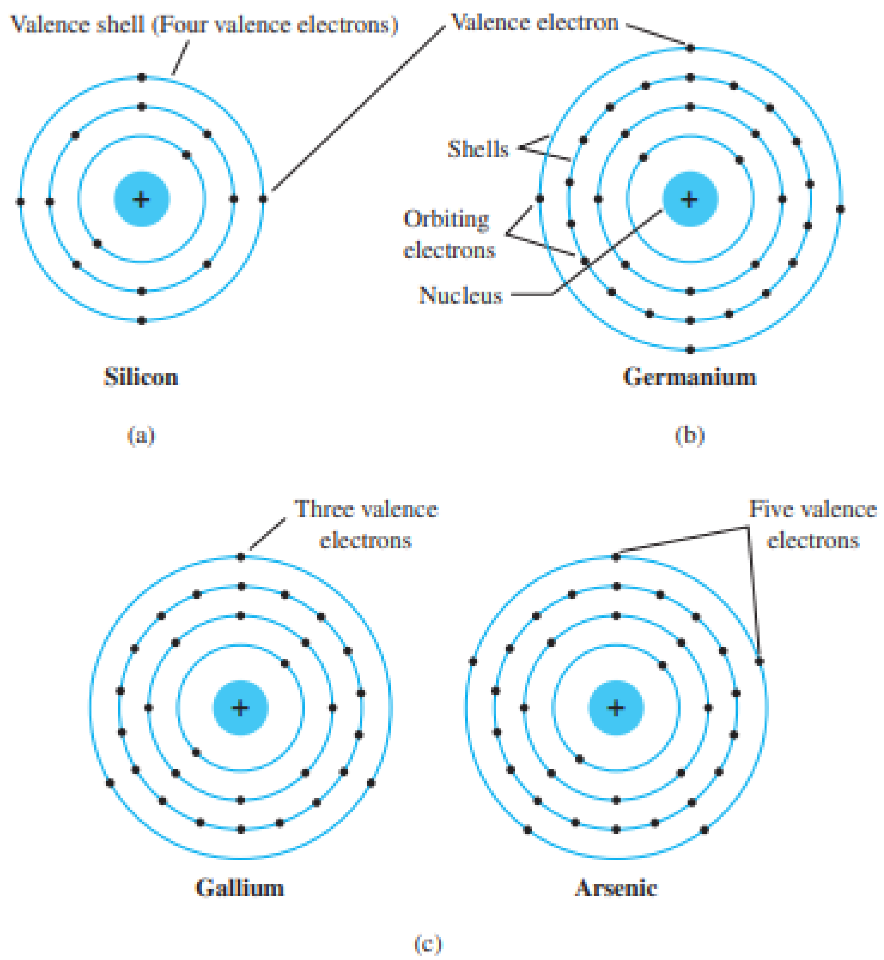
- The Electrons

Charge of an electron = 1.6×10^{-19} Coulomb
Mass of an electron = 9×10^{-31} kg

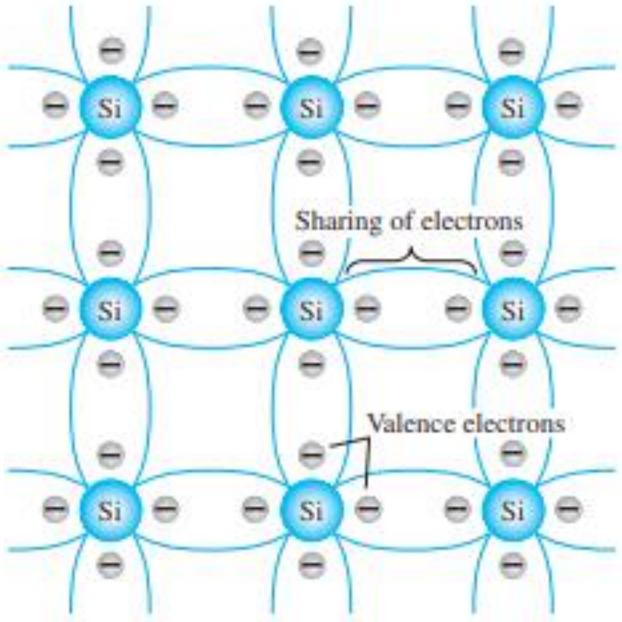
They are mobile in nature due to less mass



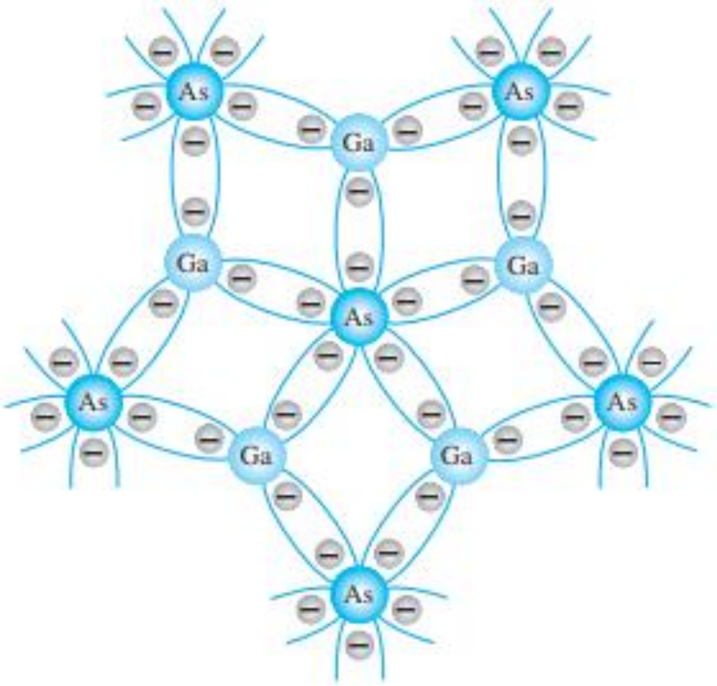
Energy Band Diagram



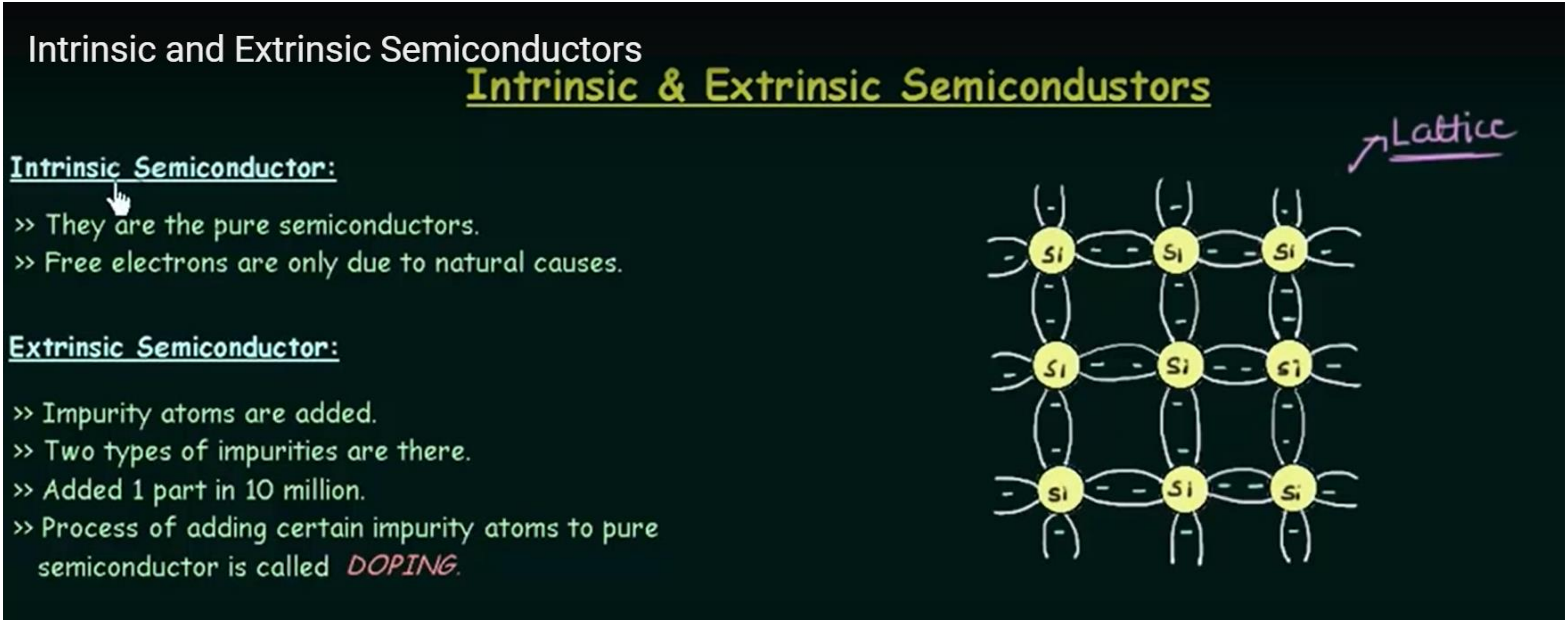
Atomic structure of Si, Ge, Ga and As



Covalent bonding of Si atom



GaAs is a compound structure and they together act as a good semiconductor



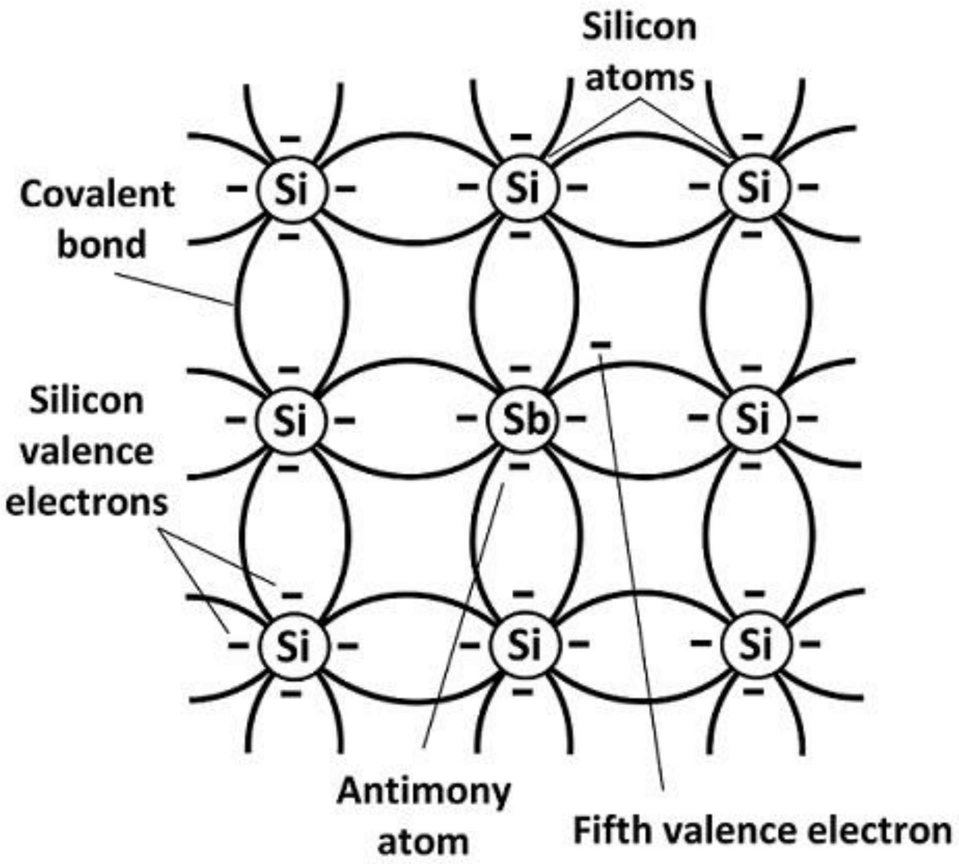
- Semiconductors have negative temperature coefficient.
- This means that as the temperature increases, the resistance decreases. The electrons in the valence band gets energy and breaks the covalent bond and is available for conduction.
- This phenomenon is opposite in conductors.

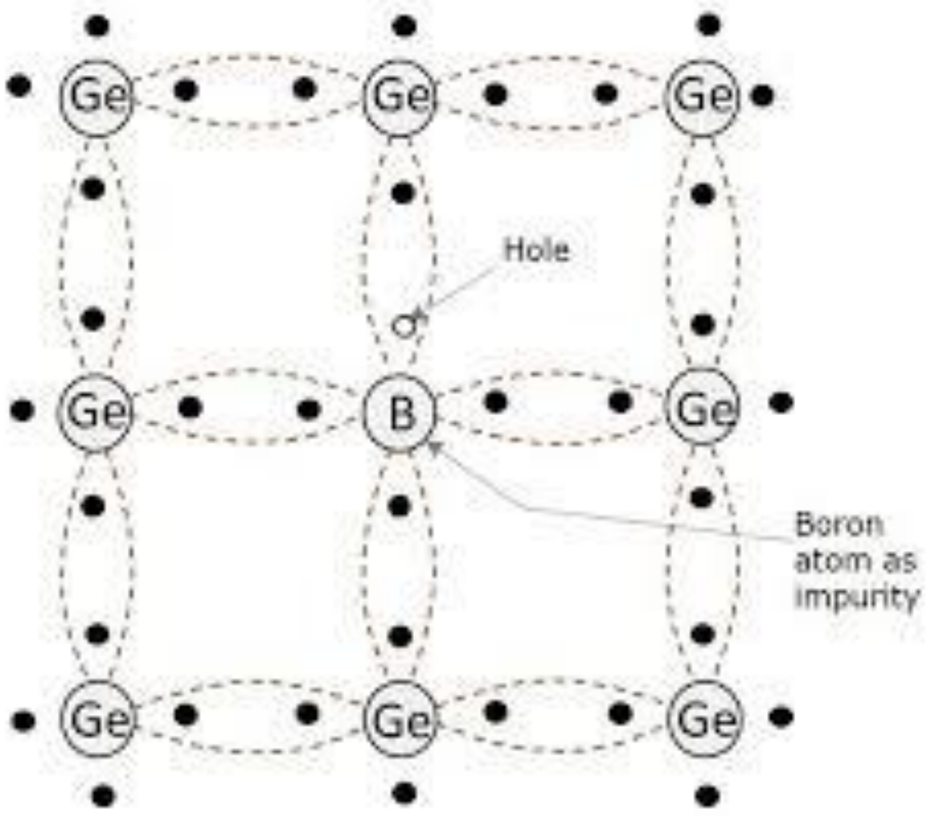
Extrinsic semiconductors are impure materials.

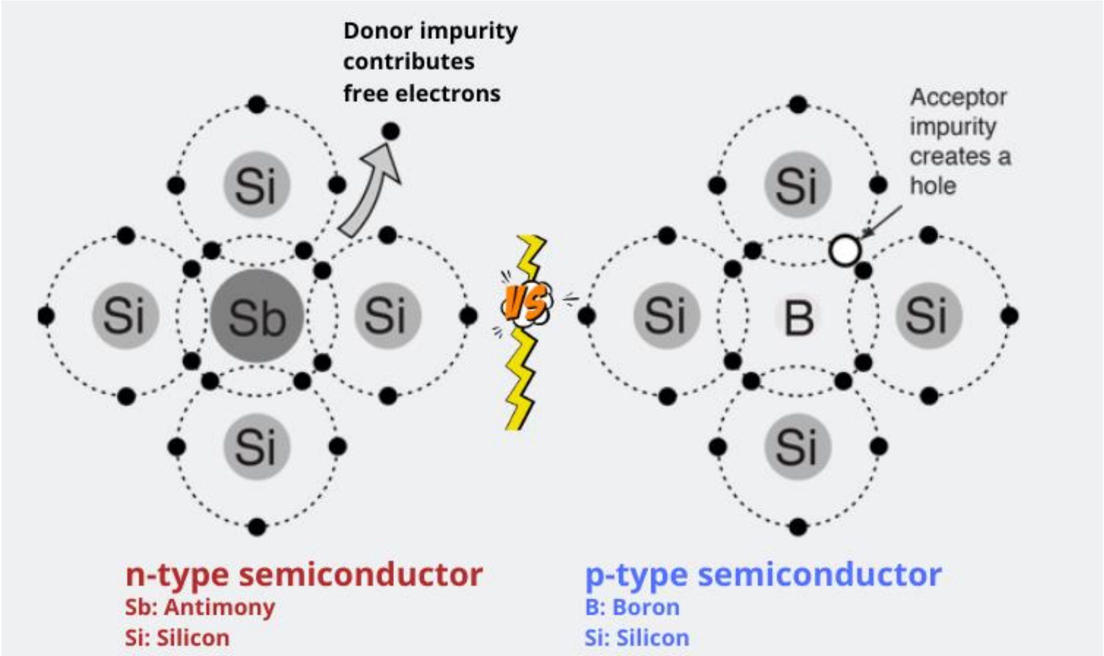
There are two types of impurities that are added to intrinsic semiconductors

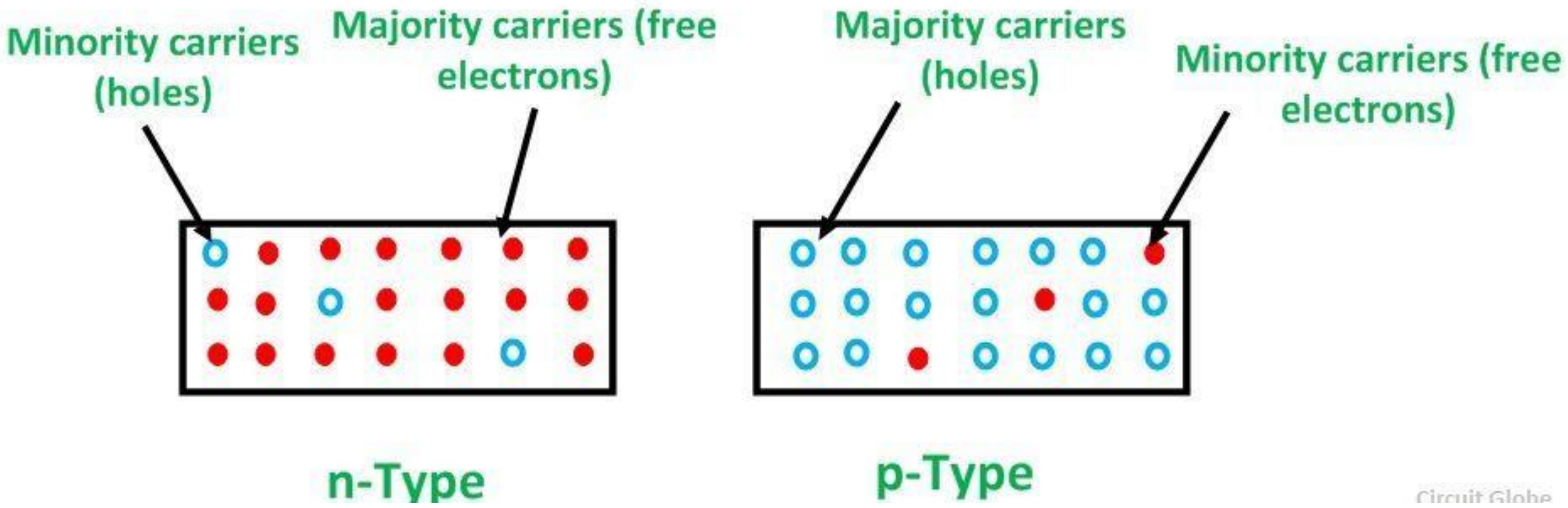
- Trivalent : Belongs to III group of elements. Ex.: Boron, Gallium, Indium, Aluminum
- Pentavalent: Belongs to V group of elements. Ex.: Antimony, Phosphorous, Arsenic
- For 10 millions pure semiconductor atoms, 1 impurity atom is added.

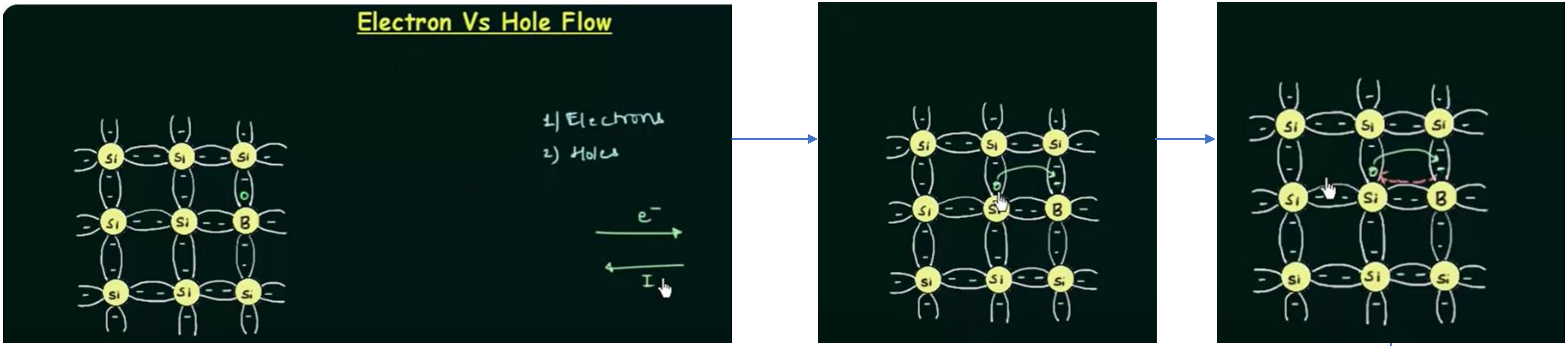
- Thus we have two types of extrinsic semiconductors
- P-type (with trivalent)
- N-type (with pentavalent)

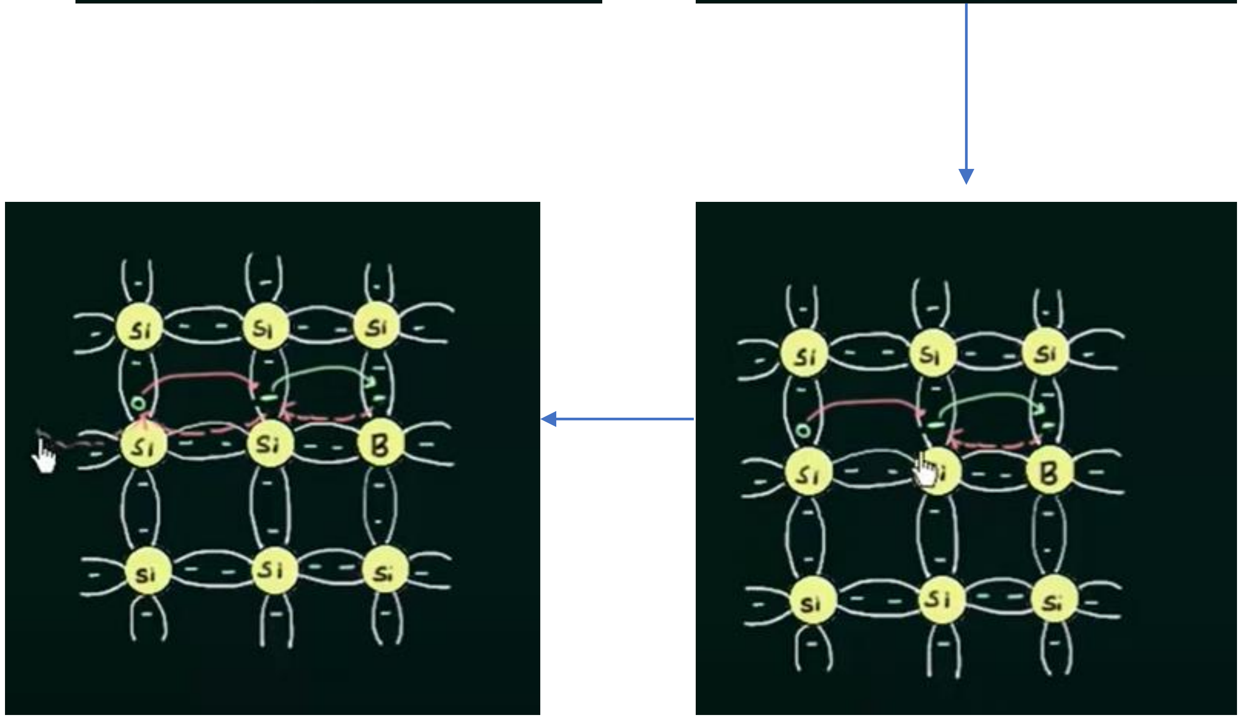

Silicon
atoms
Covalent
bond
Silicon
valence
electrons
Si
Sb
Antimony
atom
Fifth valence electron


Ge
B
Hole
Boron
atom as
impurity


Donor impurity
contributes
free electrons
Si
Si
Sb
Si
Si
VS
Acceptor
impurity
creates a
hole
Si
Si
B
Si
Si
n-type semiconductor
Sb: Antimony
Si: Silicon
p-type semiconductor
B: Boron
Si: Silicon


Minority carriers
(holes)
Majority carriers (free
electrons)
Majority carriers
(holes)
Minority carriers (free
electrons)
n-Type
p-Type
Circuit Globe





There are two types of current: Natural current and Conventional current.
Conventional current flows opposite to the direction of flow of charge carriers (hole or e^-)

The holes are treated as positive charge carriers. They are moving from right to left
This direction is same as of natural current which is same as the direction of flow of charge carriers (hole or e^-)

» Properties of Silicon and Germanium at 300 K.

	Silicon	Germanium
Energy gap (ev)	1.1	0.7
Electron mobility (m^2/Vs)	0.135	0.39
Hole mobility (m^2/Vs)	0.048	0.19
Intrinsic carrier density (n_i)	1.5×10^{16}	2.4×10^{19}
Intrinsic resistivity	2300	0.46
Density (g/m^3)	2.33×10^{6}	3.32×10^{6}

Important values to remember

The law of mass action states that the product of number of electrons in the conduction band and the number of holes in the valence band is constant at a fixed temperature and is independent of amount of donor and acceptor impurity added.
Mathematically it is represented as

$$np = n_i^2 = \text{constant}$$

The law of mass action is applied for both intrinsic and extrinsic semiconductors.

For extrinsic semiconductor the law of mass action states that the product of majority carriers and minority carriers is constant at fixed temperature and is independent of amount of donor and acceptor impurity added.

Law of mass action for n-type semiconductor

The law of mass action for n-type semiconductor is mathematically written as

$$n_n \, p_n = n_i^2 = \text{constant}$$

Where n_n= number of electrons in n-type semiconductor
p_n = number of holes in n-type semiconductor

The electrons are the majority carriers and holes are the minority carriers in n-type semiconductor.

The law of mass action for p-type semiconductor is mathematically written as

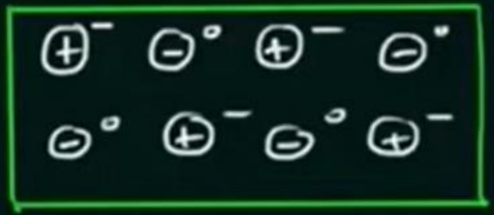
$$p_p \, n_p = n_i^2 = \text{constant}$$

Where p_p = number of holes in p-type semiconductor
n_p = number of electrons in p-type semiconductor

The holes are the majority carriers and electrons are the minority carriers in p-type semiconductor.

Proof of Mass action Law

Electrical Neutrality is sat. by Semi cond. also



$N_D \rightarrow$ conc. of donor atoms

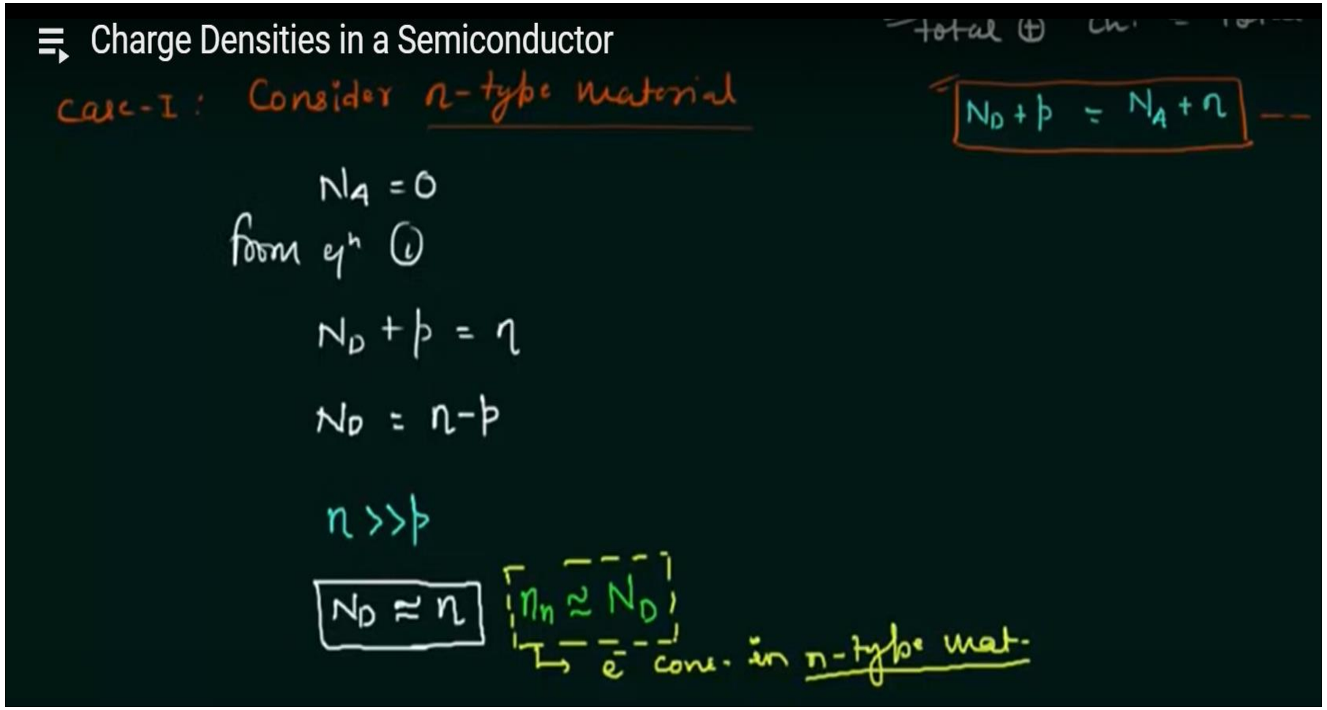
$N_A \rightarrow$ conc. of acc. atoms

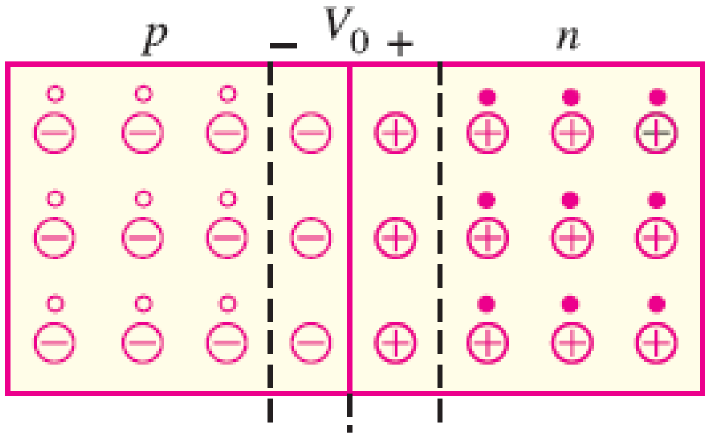
$p \rightarrow$ hole conc.

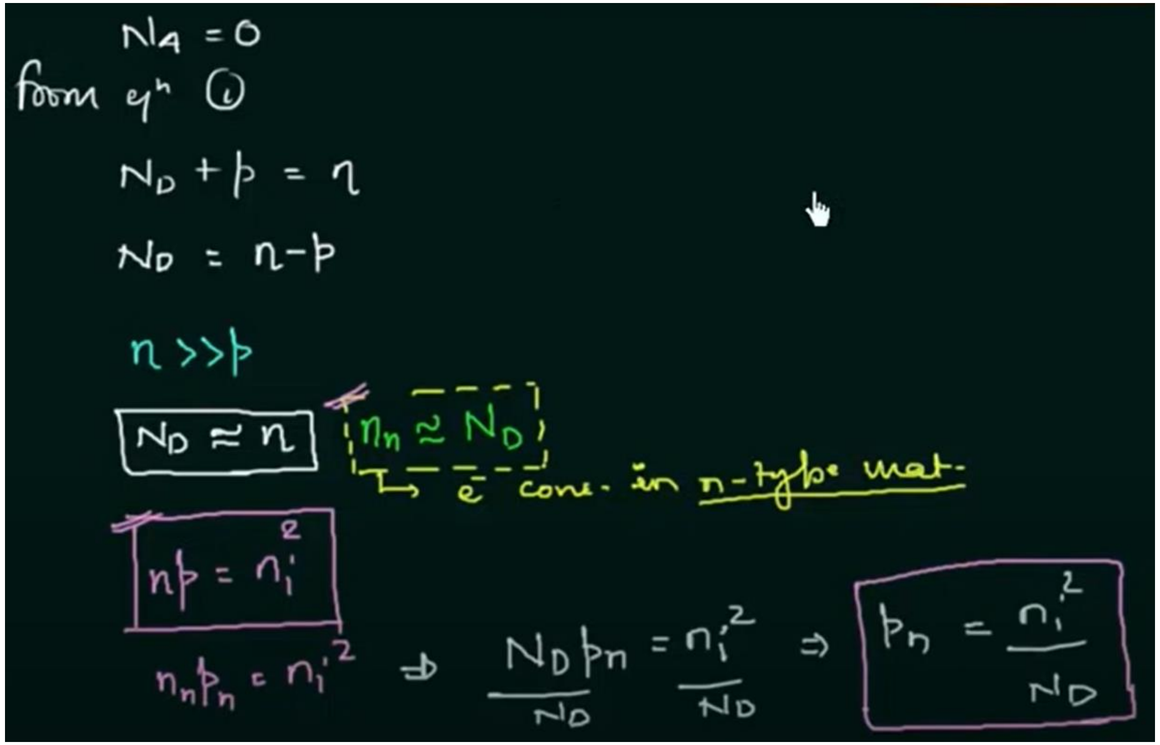
$n \rightarrow e^-$ conc.

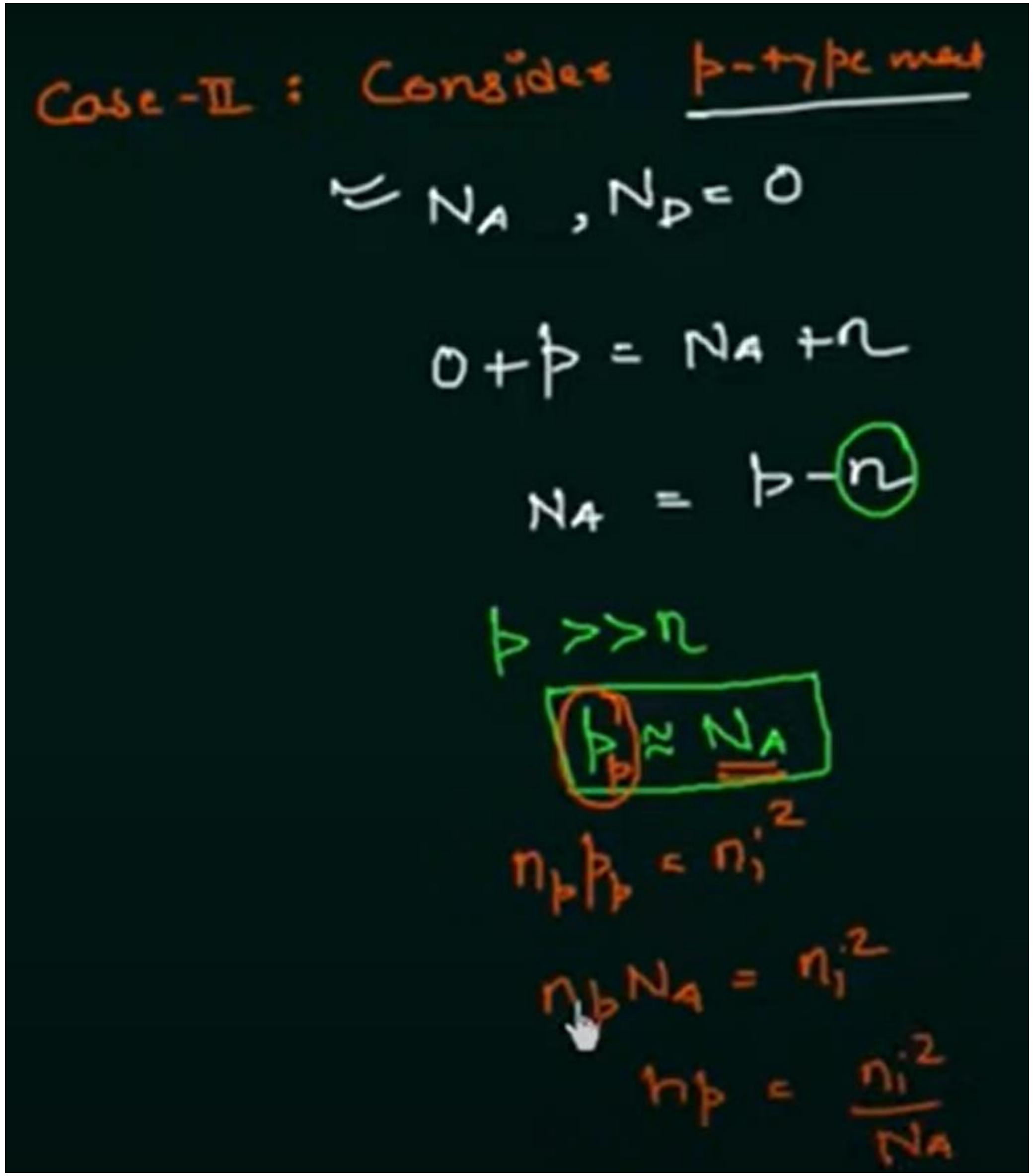
= total $\oplus^{ve}$ ch. = total $\ominus^{ve}$ charge.

$$\boxed{N_D + p = N_A + n}$$


Charge Densities in a Semiconductor
case-I : Consider n-type material
$N_D + p = N_A + n$
$N_A = 0$
from eqn (i)
$N_D + p = n$
$N_D = n - p$
$n >> p$
$N_D \approx n$
$n_n \approx N_D$
e^- conc. in n-type mat.


p
$-$ V_0 $+$
n

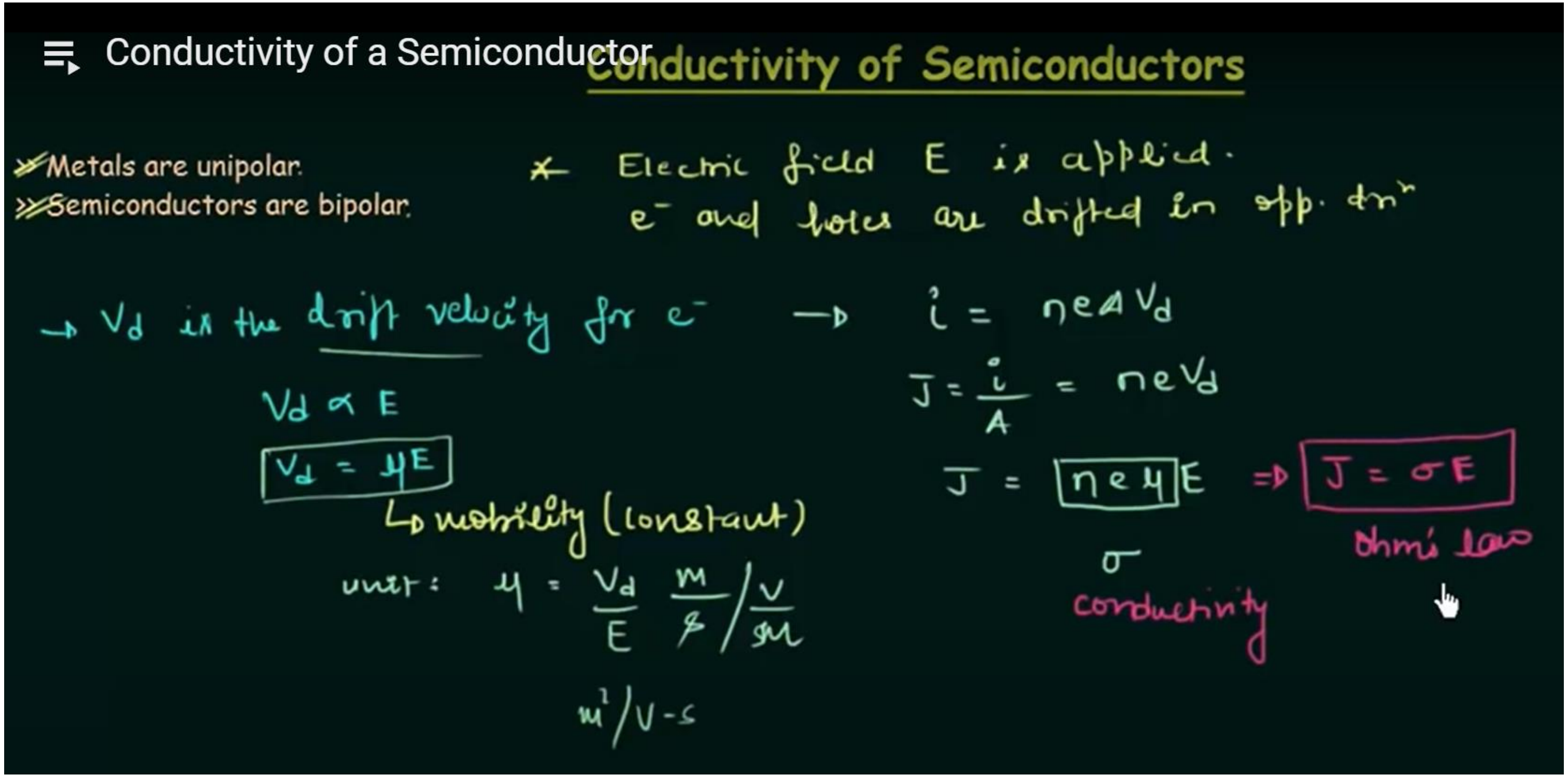

$N_A = 0$
from eqn (i)
$N_D + p = n$
$N_D = n - p$
$n >> p$
$N_D \approx n$
$n_n \approx N_D$
e^- conc. in n-type mat.
$np = n_i^2$
$n_n p_n = n_i^2 \Rightarrow \frac{N_D p_n}{N_D} = \frac{n_i^2}{N_D} \Rightarrow p_n = \frac{n_i^2}{N_D}$



The generation in a doped intrinsic semiconductor remains unaffected

The product of the concentrations of free electrons and free holes in a semiconductor is equal to the square of the intrinsic carrier concentration, which is constant due to the generation and recombination of charge carriers.

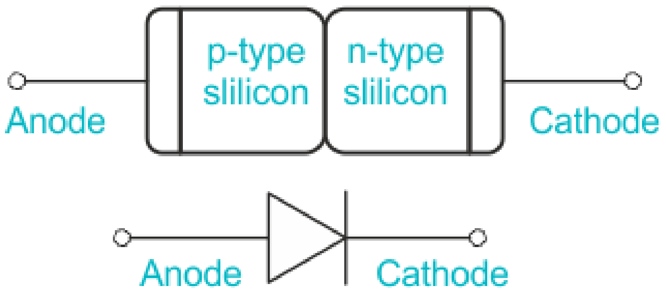
Recombination is directly proportional to the concentration of electrons and holes, as more electrons or holes increase the chances of recombination occurring.

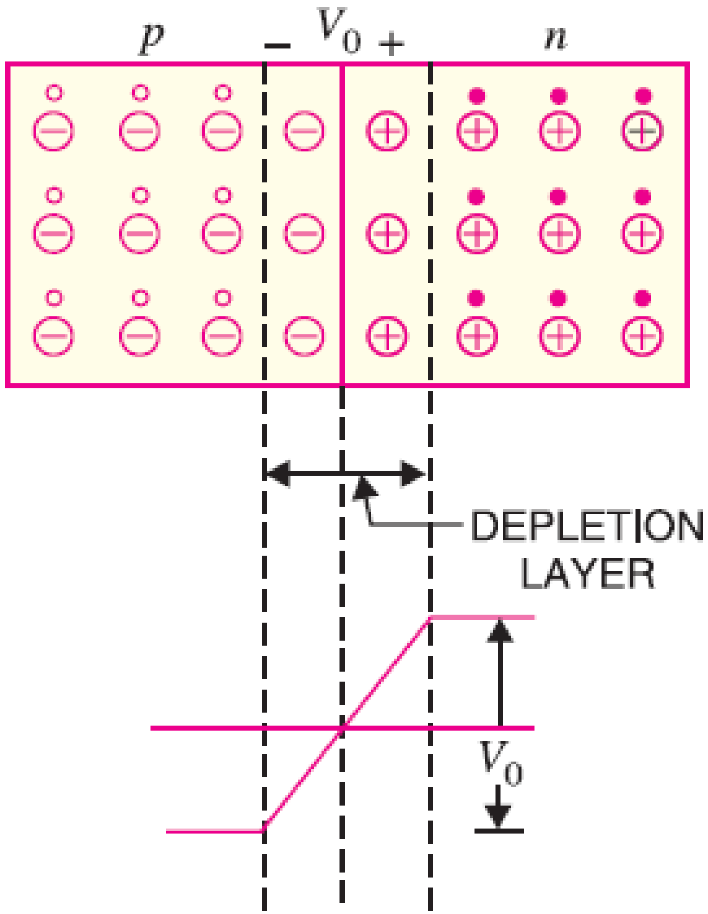


J = σE where σ is the conductivity

For semiconductors, there is a combination of holes and electrons. Therefore, $\sigma = e\,(n_e\mu_e + n_h\mu_h)$

The mobility of holes is lesser than that of electrons. This is because they have high mass density. So σ_h is < σ_e





Formation of PN Junction Diode

- In a PN junction diode, an ionized donor is left behind on the N-side when an electron diffuses from the N-side to the P-side
- Moreover, a layer of positive charge develops on the N-side of the junction.

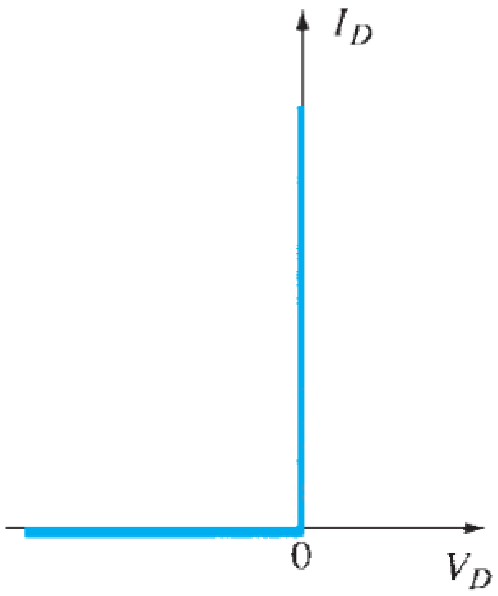
- When a hole moves from the P-side to the N-side, an ionized acceptor is left behind on the P-side, causing a layer of negative charges to accumulate on the P-side of the junction.

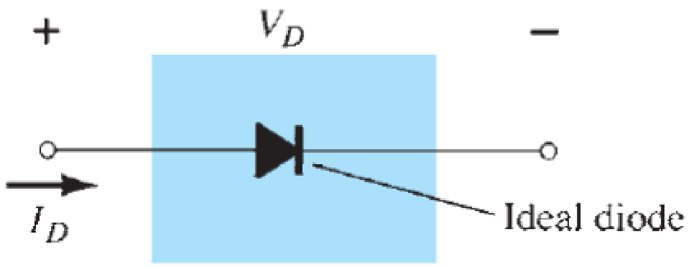
- The depletion area is defined as a region of positive and negative charge on each side of the junction.

- An electric field with a direction from a positive charge to a negative charge develops on either side of the junction.

Ideal Diode

Diode will behave as short circuit as soon as the voltage across it becomes greater than zero





- The electric potential between P and N-regions changes when an external potential is supplied to the PN junction terminals.
- As a result, the flow of the majority of carriers is altered, allowing electrons and holes to diffuse through the PN junction.

- if the applied voltage reduces the width of the depletion layer, the diode is said to be in the forward bias state.
- In reverse bias, the applied voltage increases the width of the depletion layer.
- The diode is said to be in the zero bias or unbias state if the breadth of the depletion layer remains unchanged

Current Flow in PN Junction Diode

- As the voltage applied to the PN junction increases, electrons from the n-side are driven towards the p-side.
- Simultaneously, holes from the p-side migrate towards the n-side. This movement of charge carriers creates a concentration gradient across the junction.
- Due to this gradient, charge carriers diffuse from regions of higher concentration to regions of lower concentration, resulting in a current flow within the PN junction.

V-I Characteristics of PN Junction

The V-I characteristics of the PN junction can be explained in three cases:

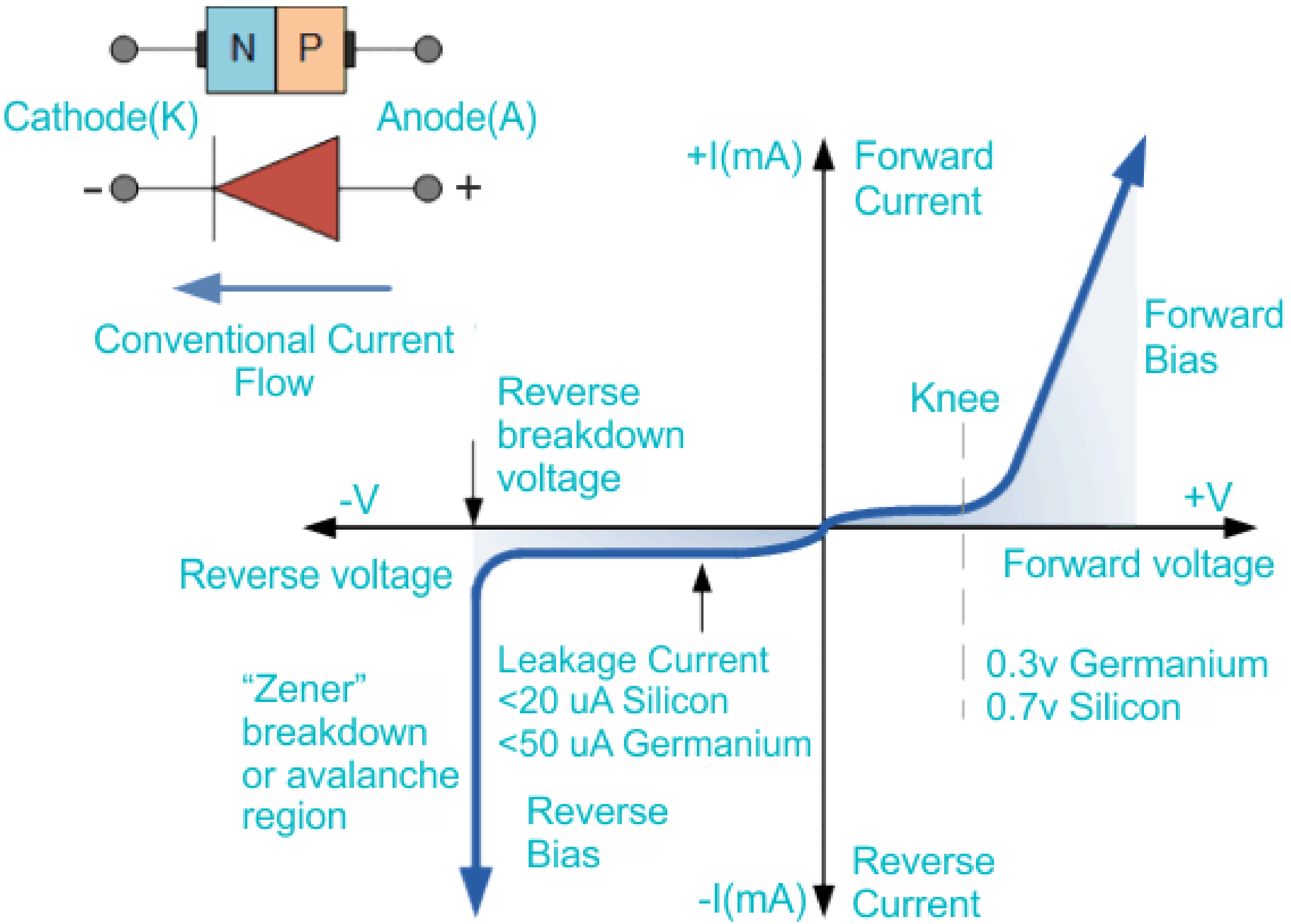
- Zero bias or unbias
- Forward bias
- Reverse bias

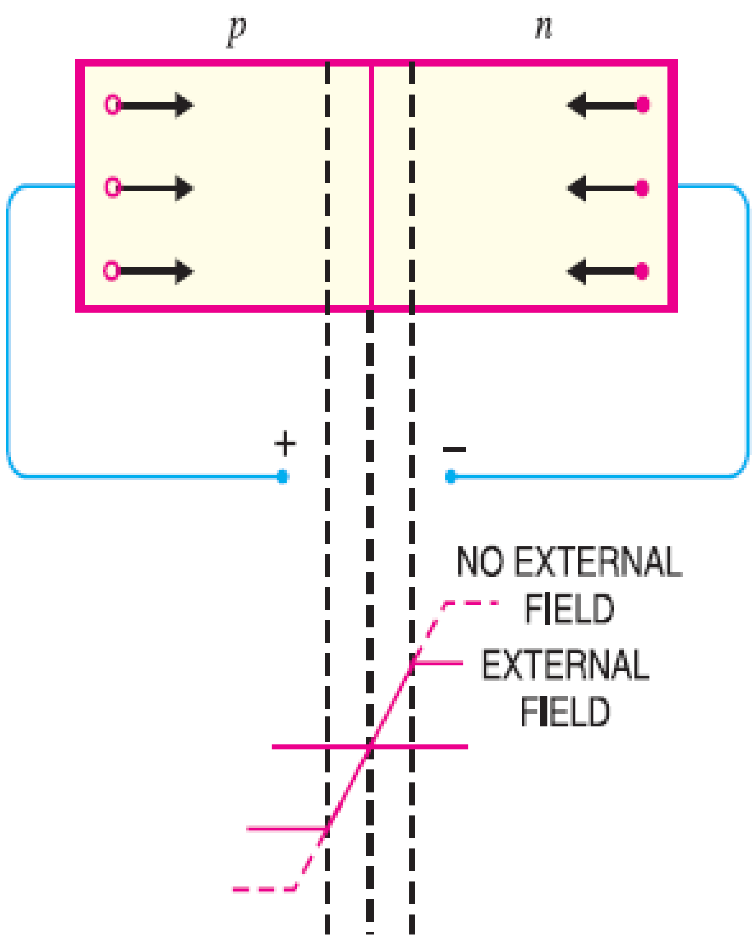
- No movement of holes or electrons occurs at zero bias state as no potential is applied externally which prevents the passage of electric current to flow in the diode.

- When the PN junction diode is in the forward bias, the P-type is linked to the positive terminal of the external voltage, while the N-type is connected to the negative terminal. This arrangement of diodes reduces the potential barrier. When the voltage is 0.7 V for silicon diodes and 0.3 V for germanium diodes, the potential barriers diminish, and current flows.

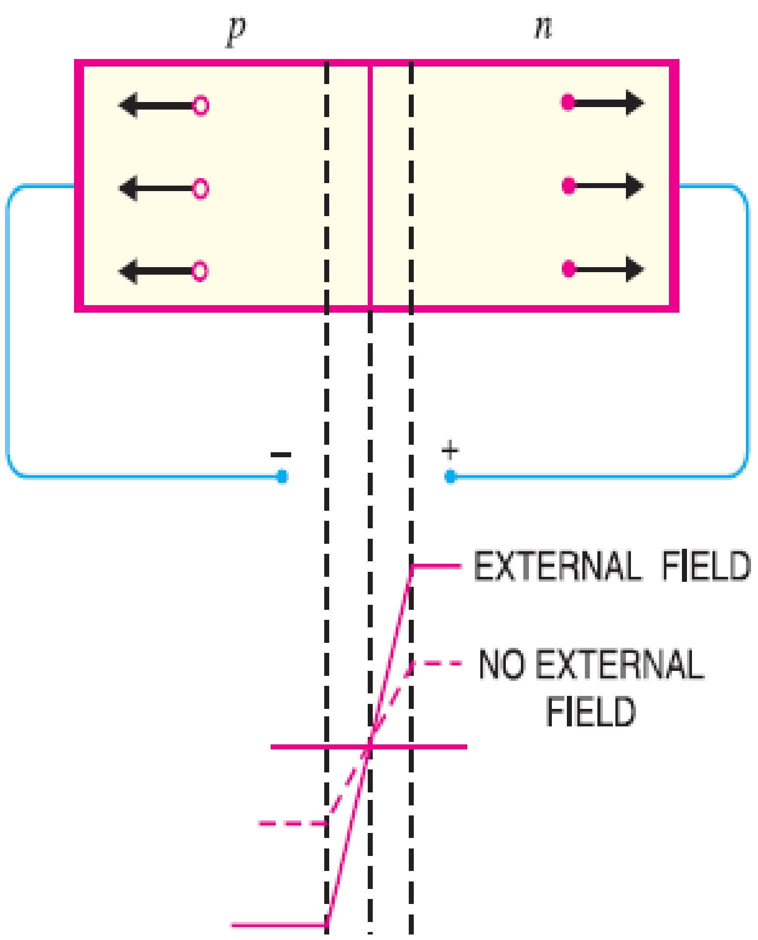
- The current grows slowly while the diode is in the forward bias, and the curve formed is non-linear because the voltage supplied to the diode surpasses the potential barrier. Once the diode has broken over the potential barrier, it operates normally, and the curve climbs steeply as the external voltage rises, yielding a linear curve.

- When the PN junction diode is in negative bias, the P-type is linked to the negative terminal of the external voltage, while the N-type is connected to the positive terminal which leads to the higher potential barrier. Because minority carriers are present at the junction, a reverse saturation current occurs at first.


N
P
Cathode(K)
Anode(A)
-
+
Conventional Current Flow
+I(mA)
Forward Current
Forward Bias
Knee
Reverse breakdown voltage
-V
+V
Reverse voltage
Forward voltage
Leakage Current
<20 uA Silicon
<50 uA Germanium
0.3v Germanium
0.7v Silicon
“Zener” breakdown or avalanche region
Reverse Bias
-I(mA)
Reverse Current

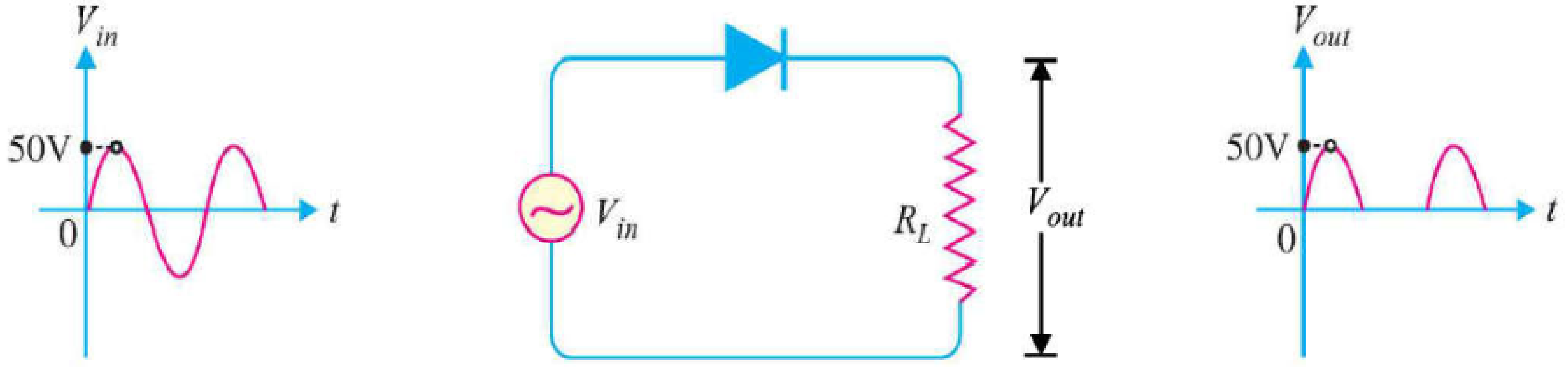


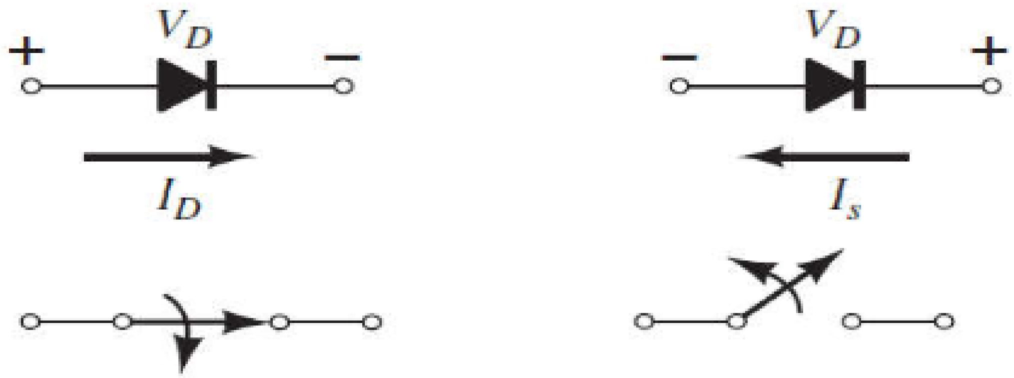
Forward bias Condition



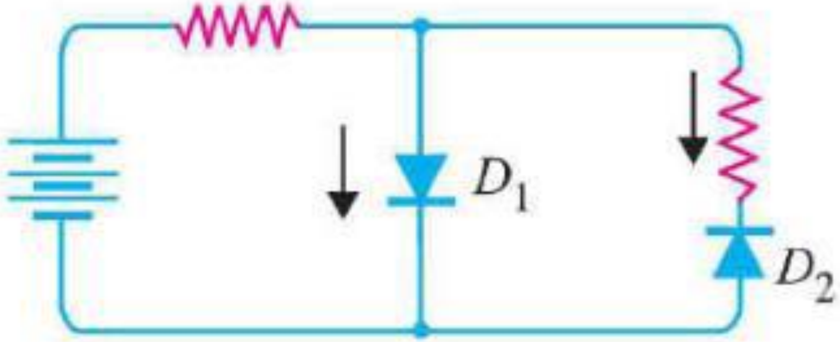
Reverse bias Condition

- Diode behaves as a switch
- Forward Biased – Closed Switch, connects AC Supply to load
- Reverse Biased – Open Switch, disconnects AC with load

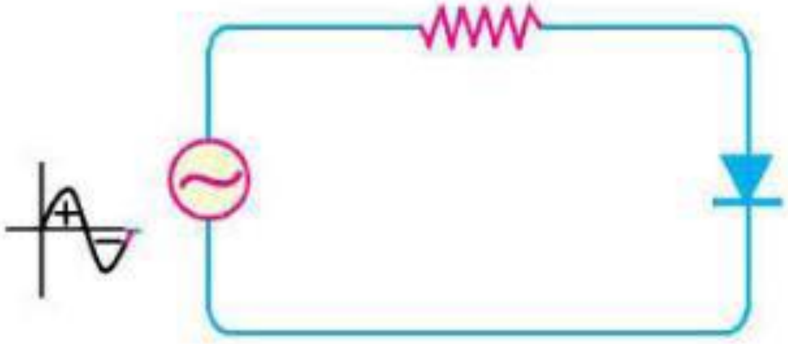




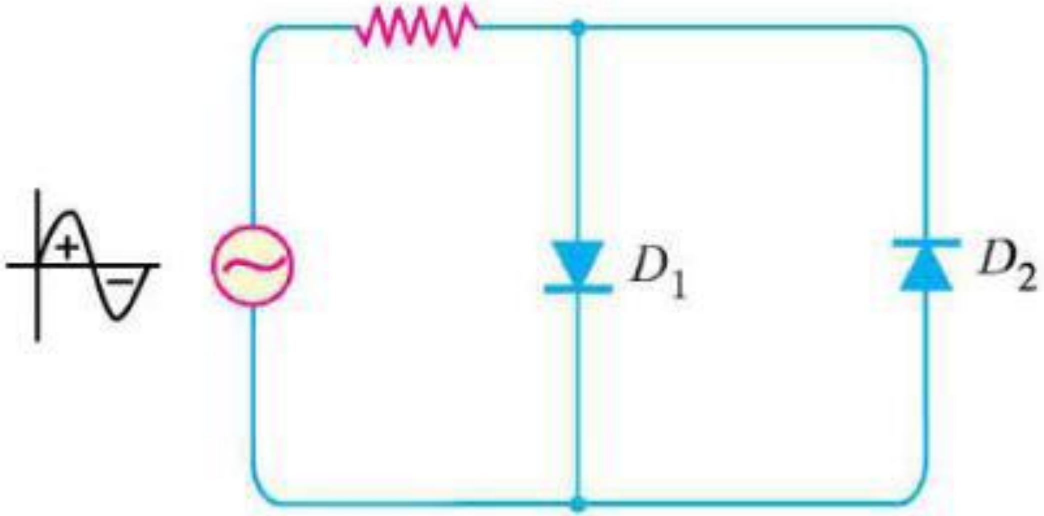
Identify whether the diode/diodes is/are forward or reverse biased?



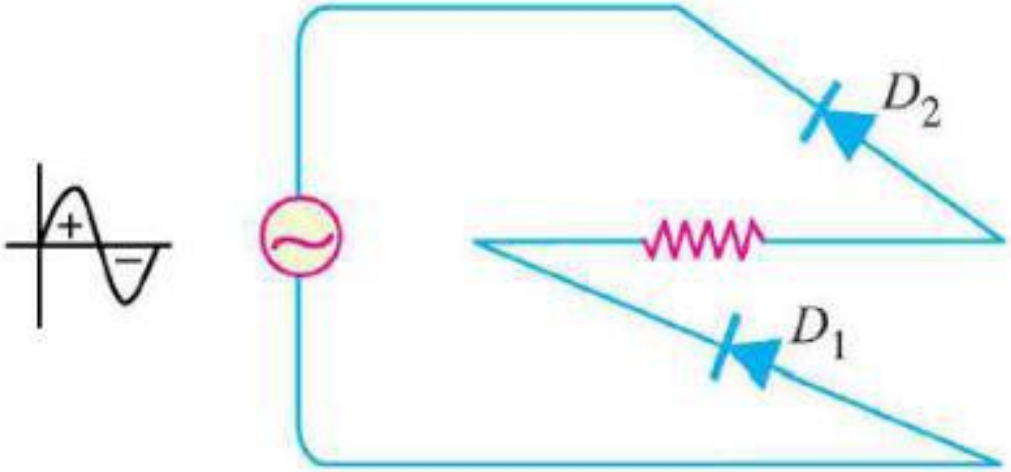
(i)



(ii)

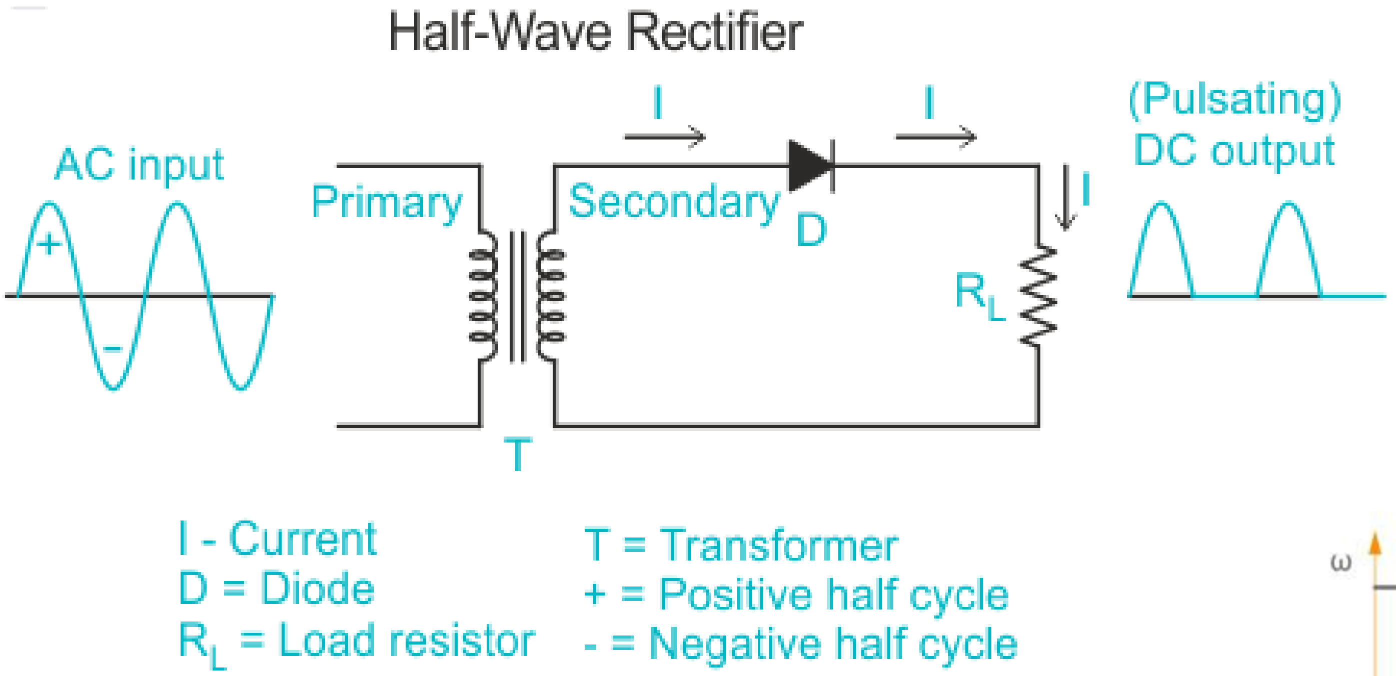


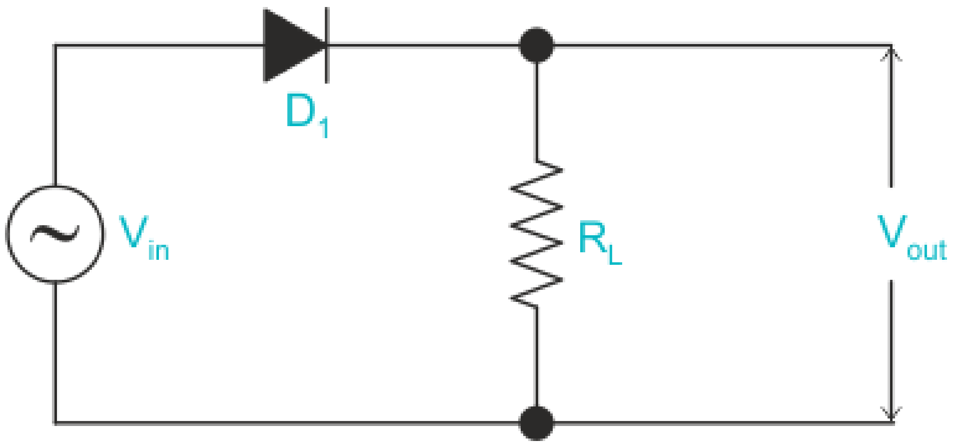
(iii)

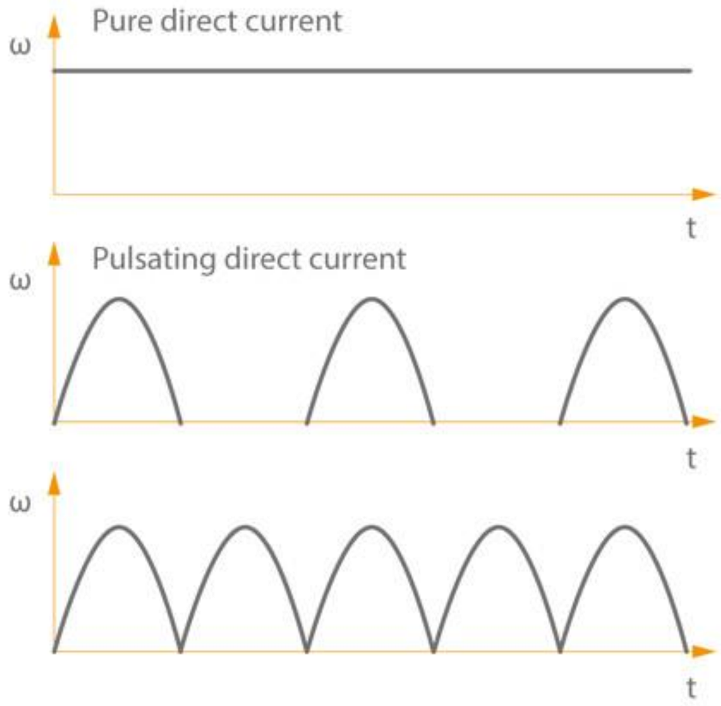


(iv)

RECTIFIERS


Half-Wave Rectifier
AC input
+
-
Primary
Secondary
T
I
I
I
D
R_L
(Pulsating)
DC output
I - Current
D = Diode
R_L = Load resistor
T = Transformer
+ = Positive half cycle
- = Negative half cycle


D_1
V_{in}
R_L
V_{out}


Pure direct current
ω
t
Pulsating direct current
ω
t
ω
t

A half-wave rectifier produces pulsing direct current (DC) rather than pure DC. We may see ripples in the output pulsating DC signal.

Filters such as capacitors and inductors help decrease the ripples in the output DC signal. The ripple factor indicates how many ripples there are in the output DC signal.

A strong pulsing DC signal is indicated by a big ripple factor, and a low pulsating DC signal is indicated by a low ripple factor.

The ripple factor is defined as the ratio of RMS value of AC output voltage to that of dc output voltage.

$$\frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}}$$

The efficiency of the HWR is given by

$$\eta = P_{dc}/P_{ac}$$

Advantages and Disadvantages of Half Wave Rectifier

The major advantages of half wave rectifier is that they are:

- Low cost
- Easy circuit construction
- Usage of few components

The major disadvantages are:

- As the half wave rectifier allows only one cycle, there’s loss of power in the output.
- DC from the rectifier circuit is pulsating direct current
- Output voltage is low

Example 1: A half wave rectifier's input AC power is 200 watts and the obtained dc output power is 20 watts. What is the efficiency of rectification?

Example 2: Two diodes are used in a full-wave rectifier, and the resistance value of each diode can be assumed to be constant at 30Ω. The RMS secondary voltage on the transformer is 60 V from the center tap to every end of the secondary, and the load resistance is 900 Ω. Find the mean load current and the RMS value of load current.

Solution: The maximum AC voltage V_m and maximum load current I_m is given by:

$$V_m = 60 \times \sqrt{2} = 84.8V$$

$$I_m = \frac{V_m}{r_f + R_L} = \frac{84.8V}{(30 + 900)\Omega} = 91.1mA$$

The mean load current,

$$I_{DC} = \frac{2I_m}{\pi} = \frac{2 \times 91.1}{\pi} = 58mA$$

The RMS value of load current,

$$I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{91.1}{\sqrt{2}} = 64.4mA$$

Example 6.13. *An a.c. supply of 230 V is applied to a half-wave rectifier circuit through a transformer of turn ratio 10 : 1. Find (i) the output d.c. voltage and (ii) the peak inverse voltage. Assume the diode to be ideal.*

Solution.

Primary to secondary turns is

$$\frac{N_1}{N_2} = 10$$

R.M.S. primary voltage

$$= 230 \text{ V}$$

∴ Max. primary voltage is

$$V_{pm} = (\sqrt{2}) \times \text{r.m.s. primary voltage}$$

$$= (\sqrt{2}) \times 230 = 325.3 \text{ V}$$

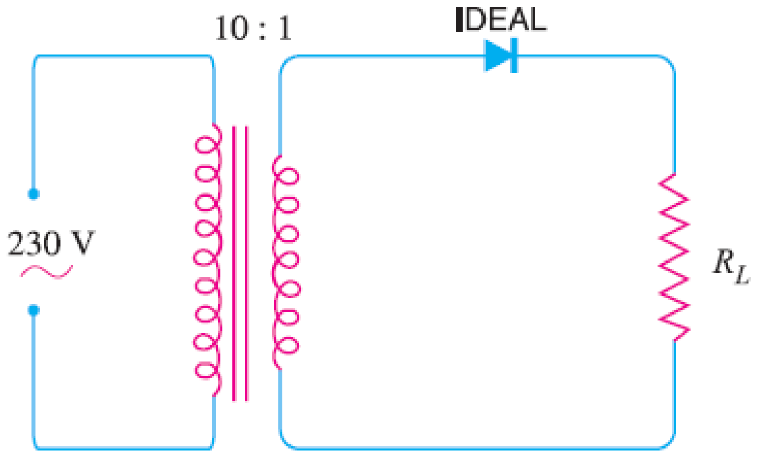


Fig. 6.23

Max. secondary voltage is

$$V_{sm} = V_{pm} \times \frac{N_2}{N_1} = 325.3 \times \frac{1}{10} = 32.53 \text{ V}$$

(i)
$$I_{d.c.} = \frac{I_m}{\pi}$$

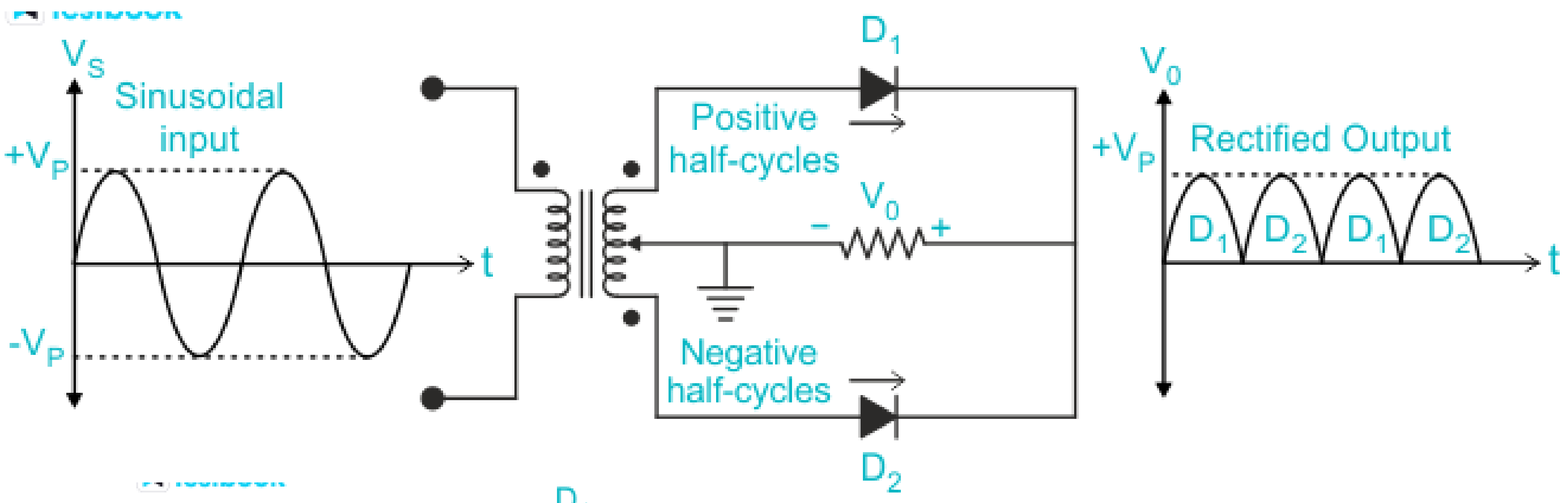
∴
$$V_{dc} = \frac{I_m}{\pi} \times R_L = \frac{V_{sm}}{\pi} = \frac{32.53}{\pi} = \mathbf{10.36\ V}$$

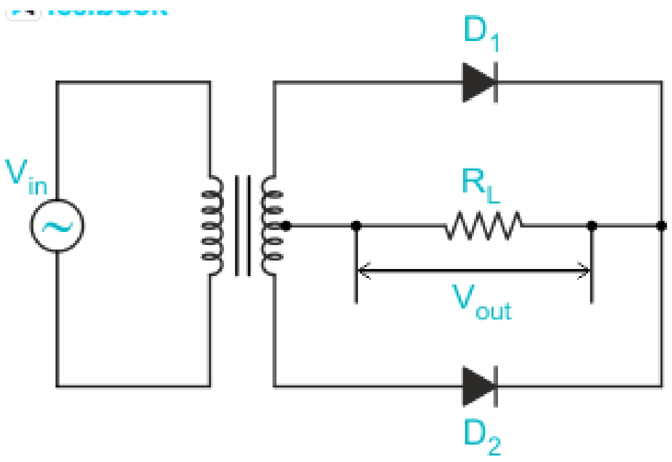
(ii) During the negative half-cycle of a.c. supply, the diode is reverse biased and hence conducts no current. Therefore, the maximum secondary voltage appears across the diode.

∴ Peak inverse voltage = **32.53 V**

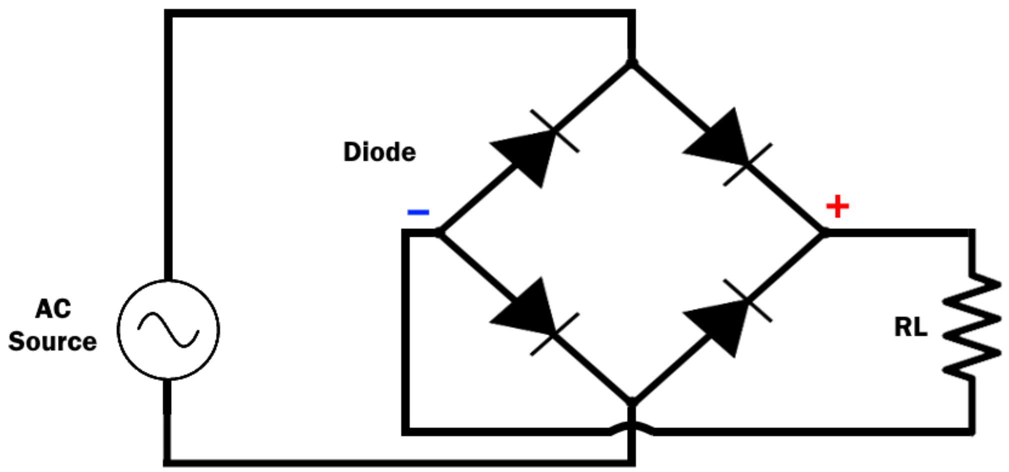
Full-Wave Rectifier

Full-Wave Rectifiers are rectifier electric circuits that convert both half cycles of an alternating current (AC) into direct current (DC).

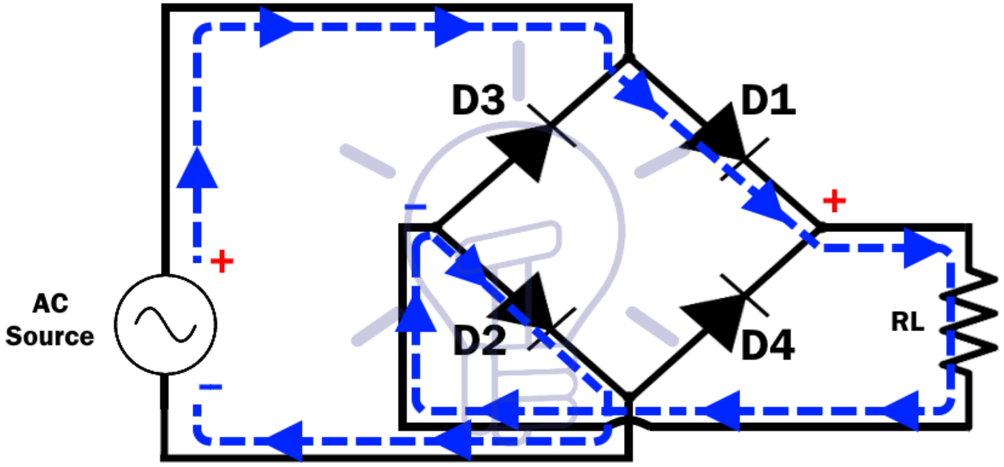




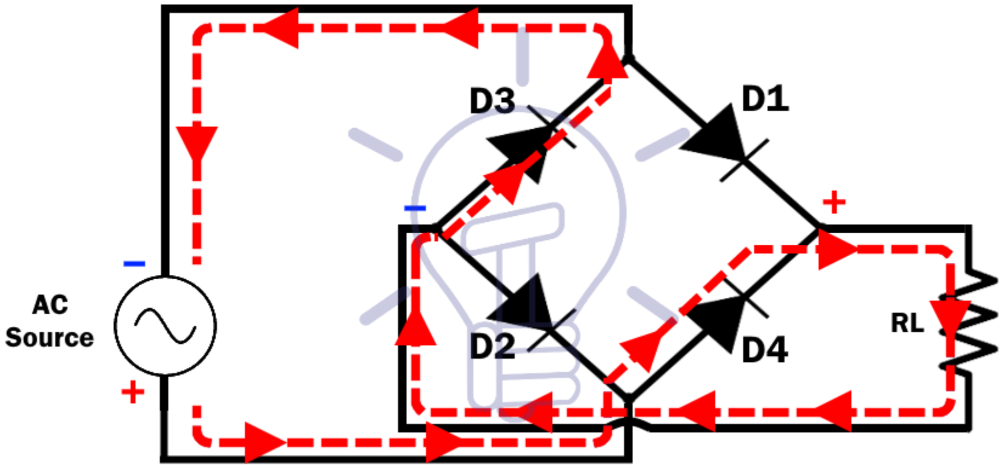
Center tapped circuit



Bridge Rectifier



Bridge Rectifier During Positive Cycle



Bridge Rectifier During Negative Cycle

Advantages

- The need for centre-tapped transformer is eliminated.
- The output is twice that of the centre-tap circuit for the same secondary voltage.
- The PIV is one-half that of the centre-tap circuit (for same d.c. output).

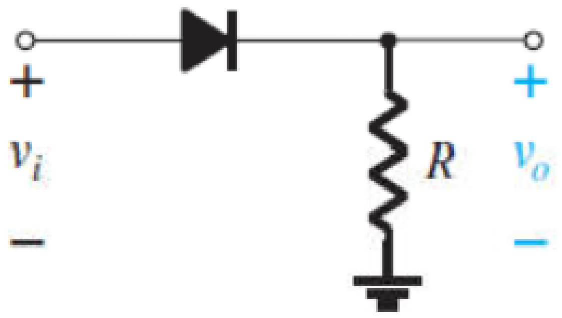
Disadvantages

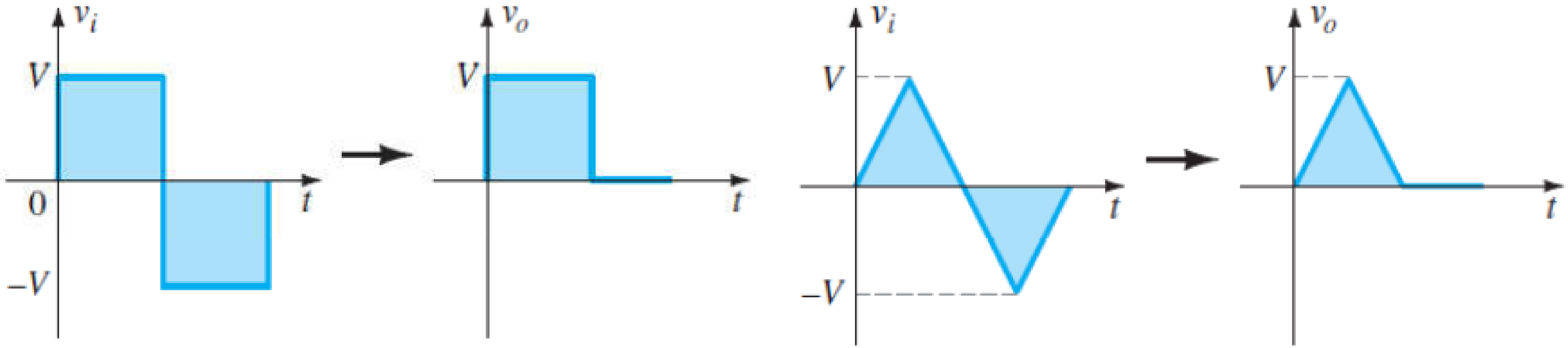
- It requires four diodes.

Parameters	**Half-Wave Rectifier**	**Full-Wave Rectifier**
Number of diodes	1	2 or 4
Efficiency	40.6%	81.2%
Ripple frequency	f	2f
Ripple factor	High	Low
Voltage regulation	Good	Better than Half wave

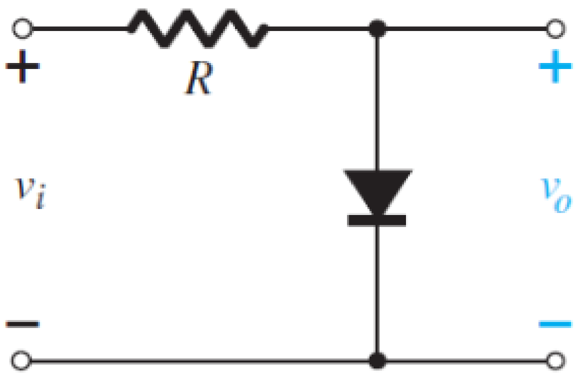
DIODE AS A CLIPPER – SERIES CONFIGURATION

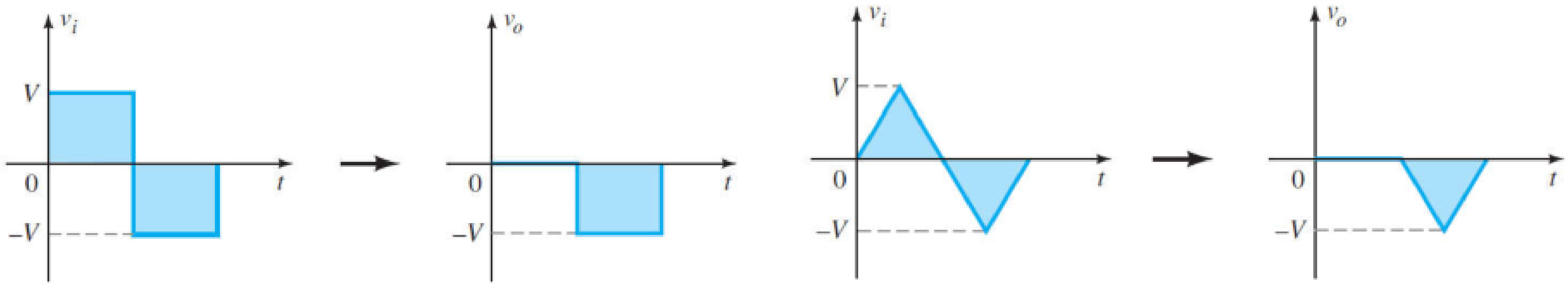
Clipping a portion of an input signal without distorting the remaining part of the waveform

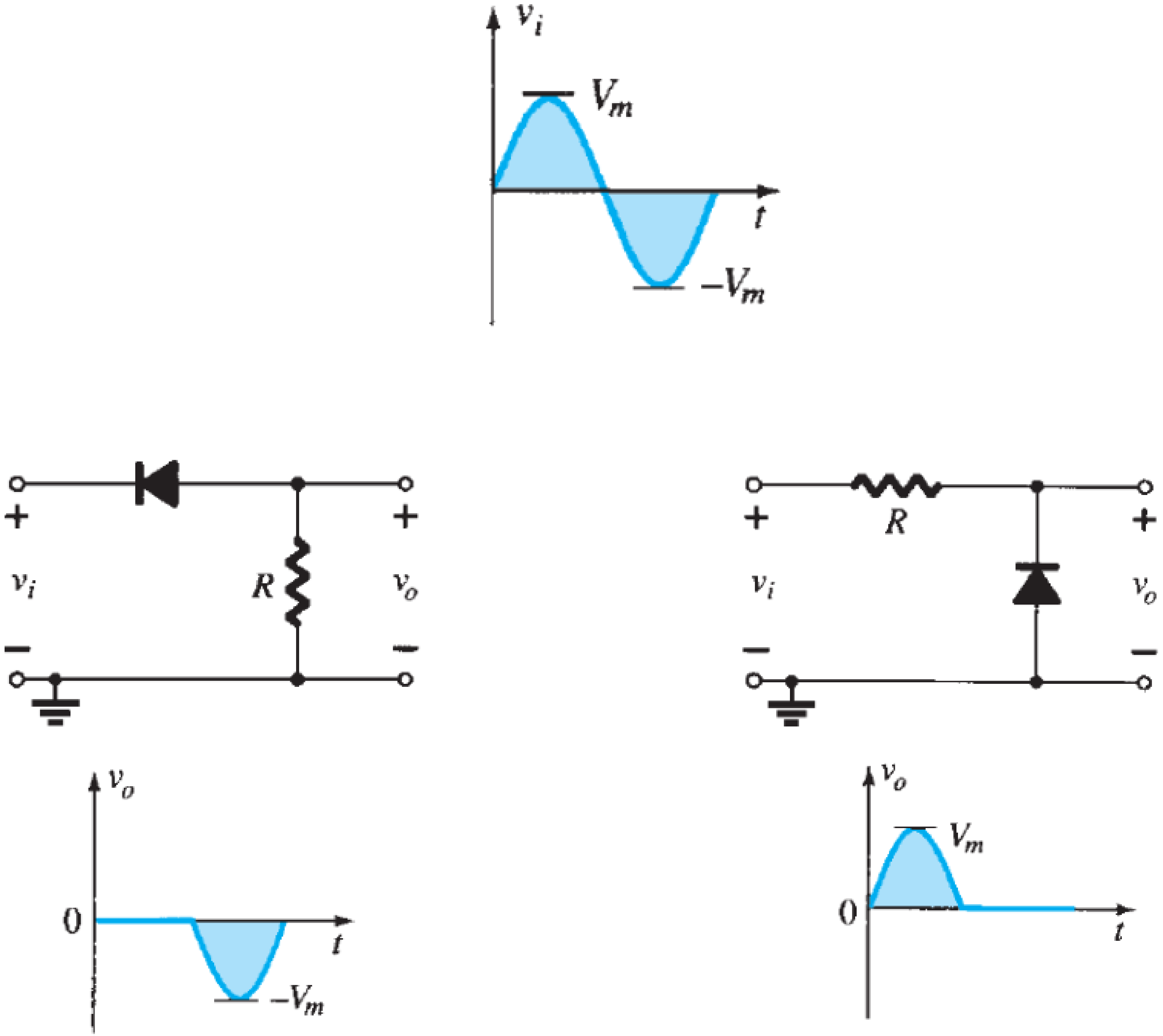




DIODE AS A CLIPPER – PARALLEL CONFIGURATION







v_i
V_m
t
$-V_m$
+
v_i
−
R
+
v_o
−
v_o
0
t
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v_o
V_m
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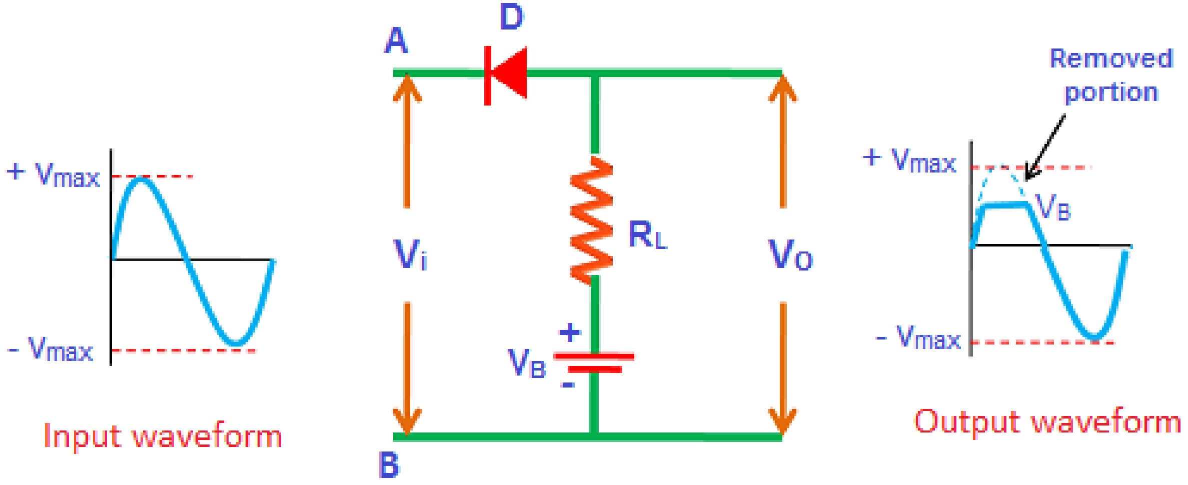
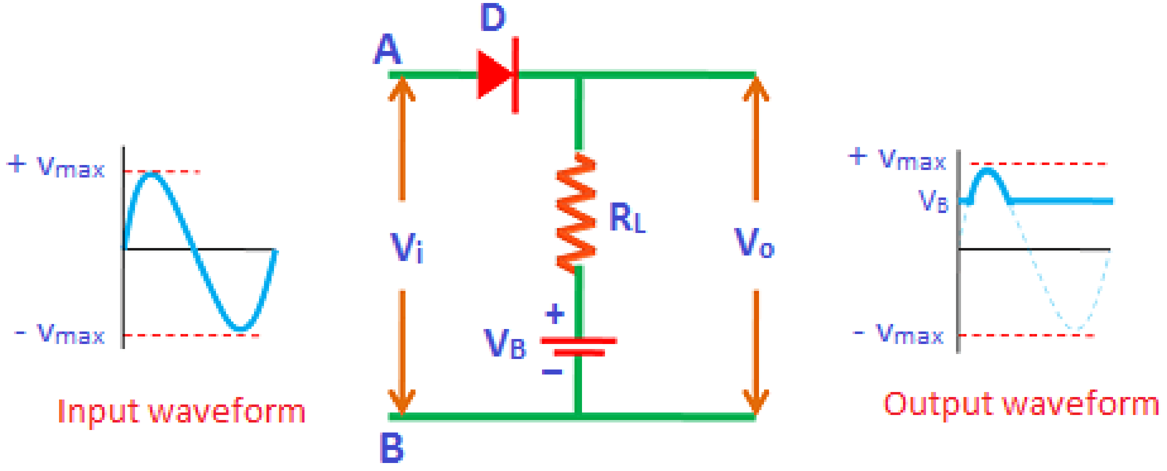
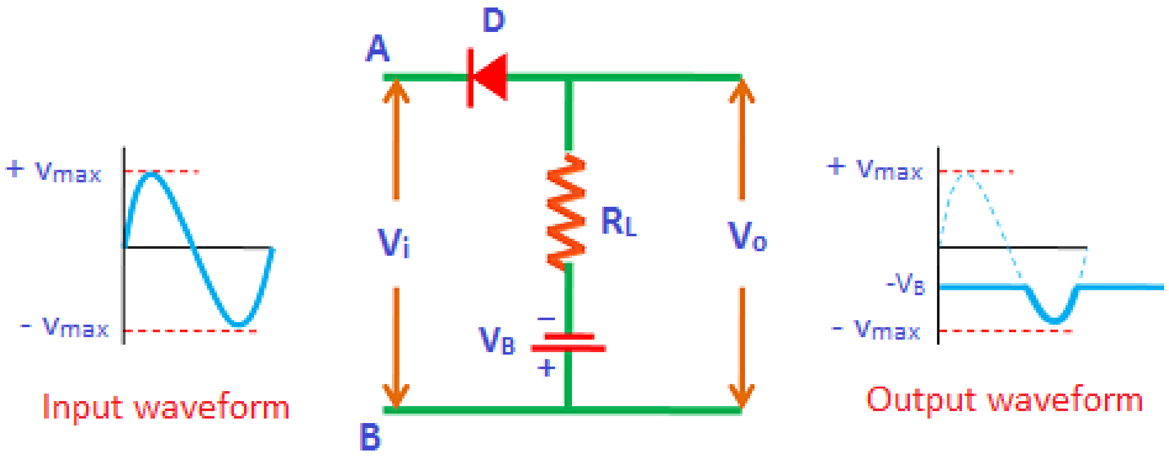


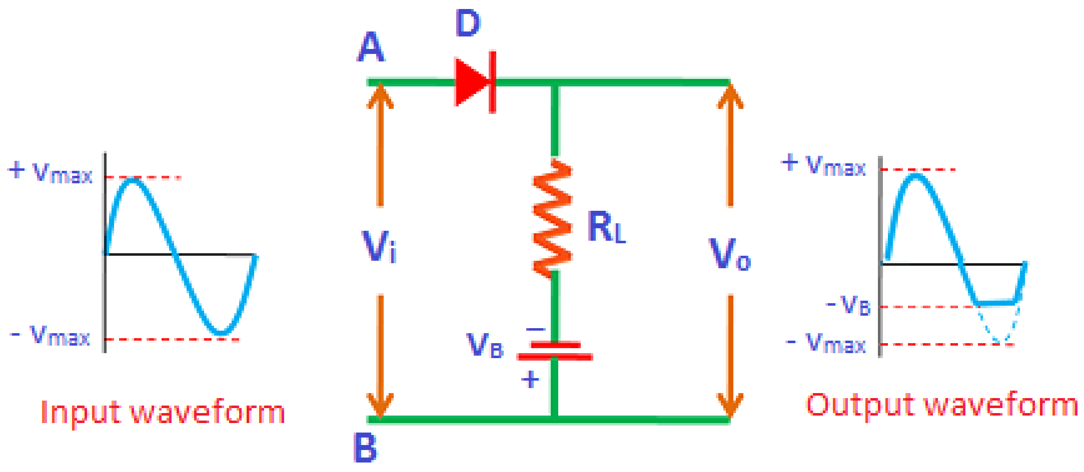
Series positive clipper with positive bias



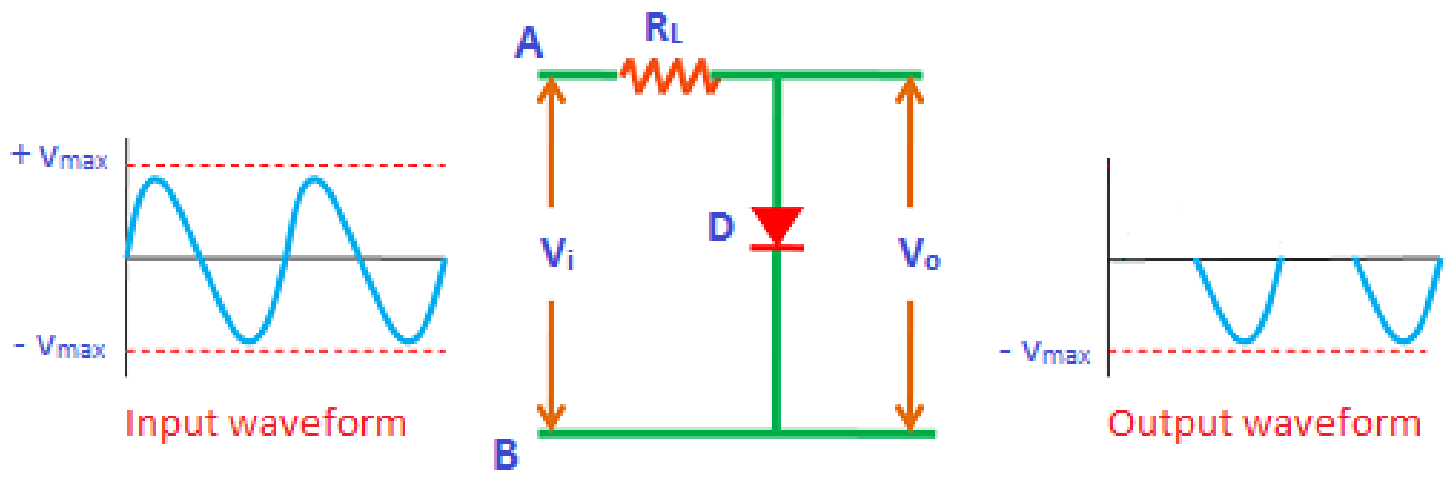
Series negative clipper with positive bias



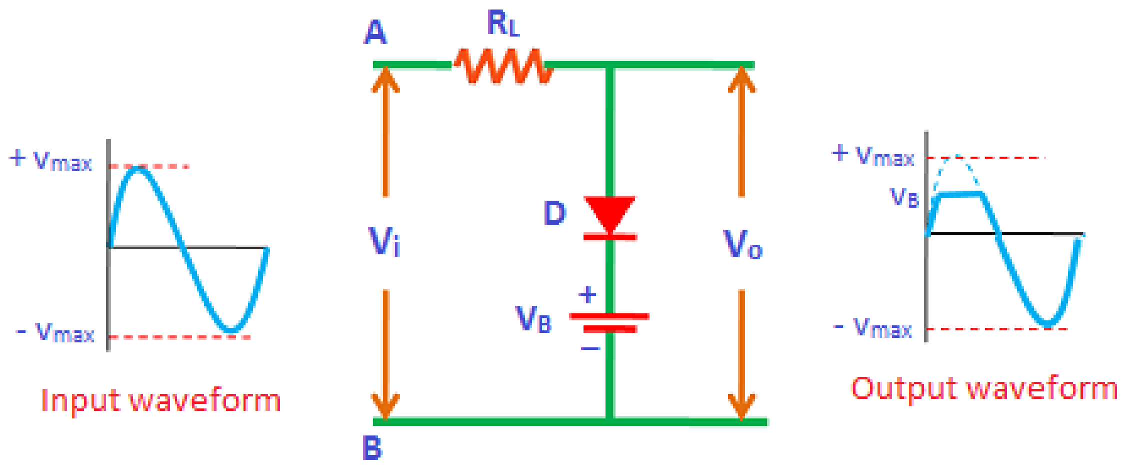
Series positive clipper with negative bias



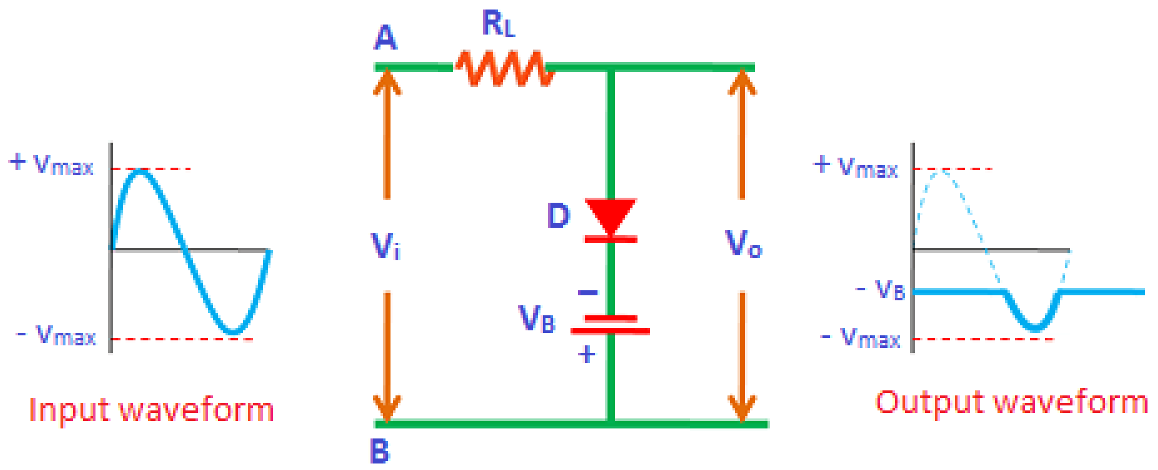
Series negative clipper with negative bias



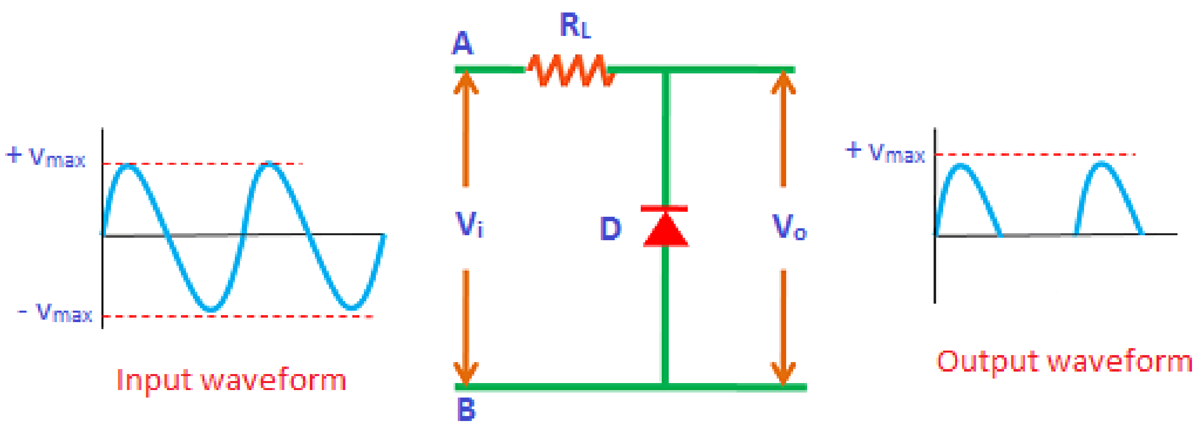
Shunt positive clipper



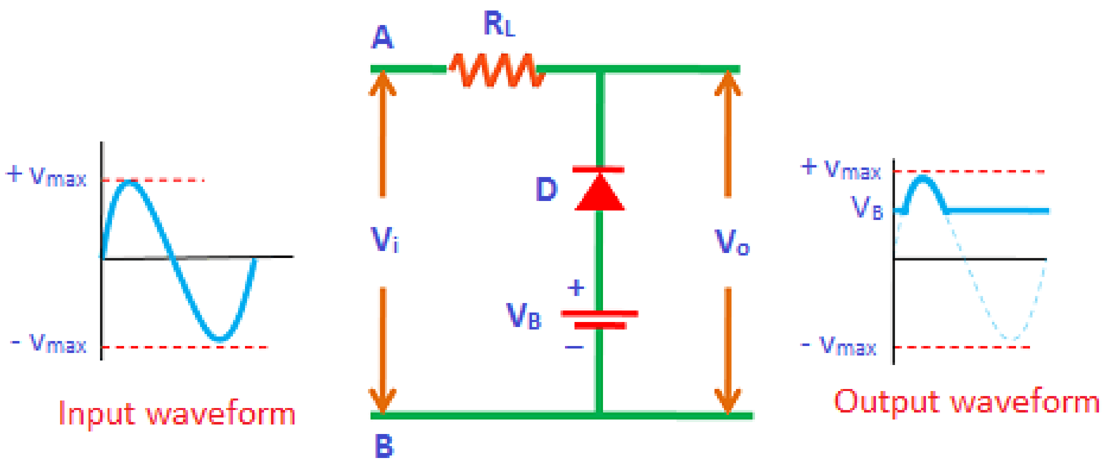
Shunt positive clipper with positive bias



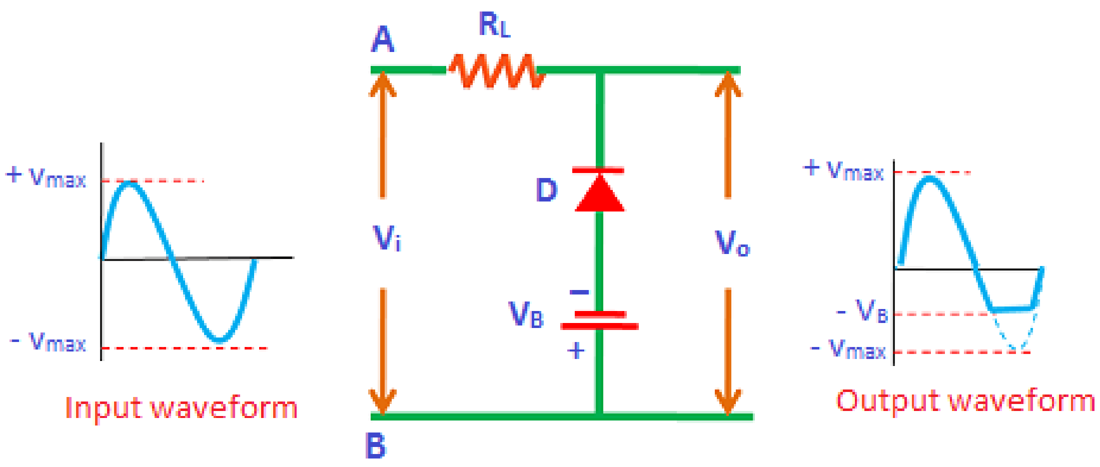
Shunt positive clipper with negative bias



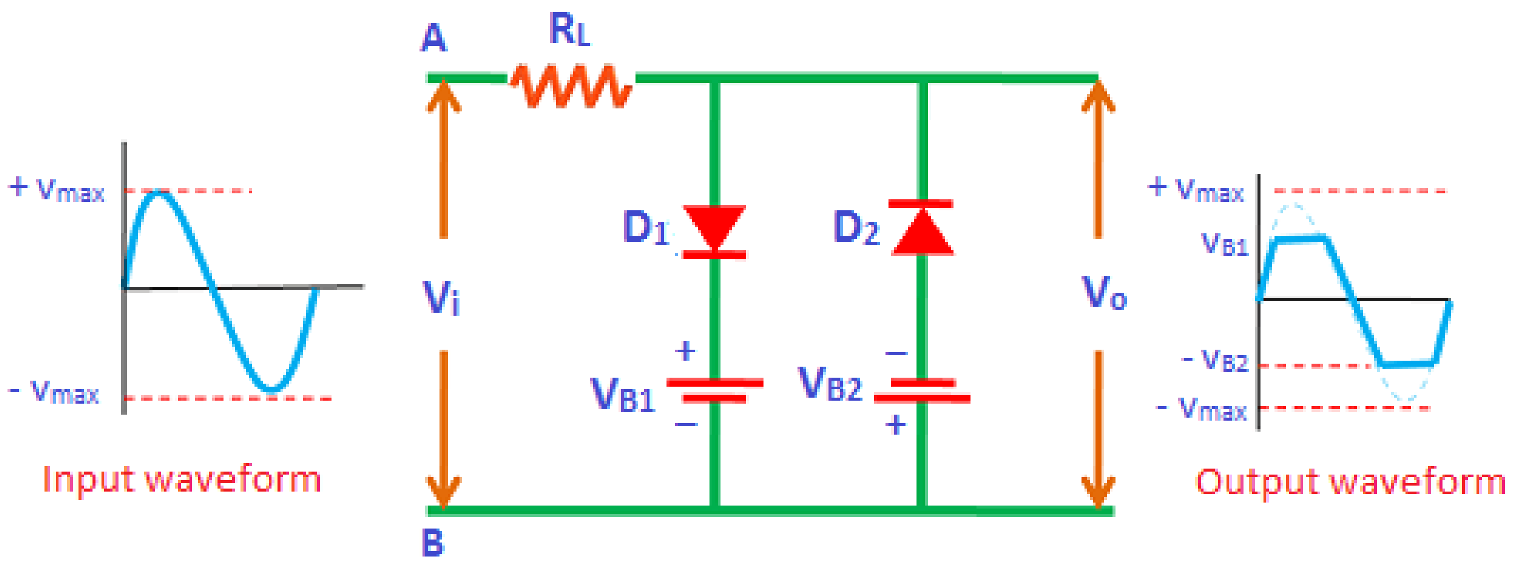
Shunt negative clipper



Shunt negative clipper with positive bias



Shunt negative clipper with negative bias



Dual (Combination) clipper

Applications:

•Clippers are commonly used in power supplies.

•Used in TV transmitters and Receivers

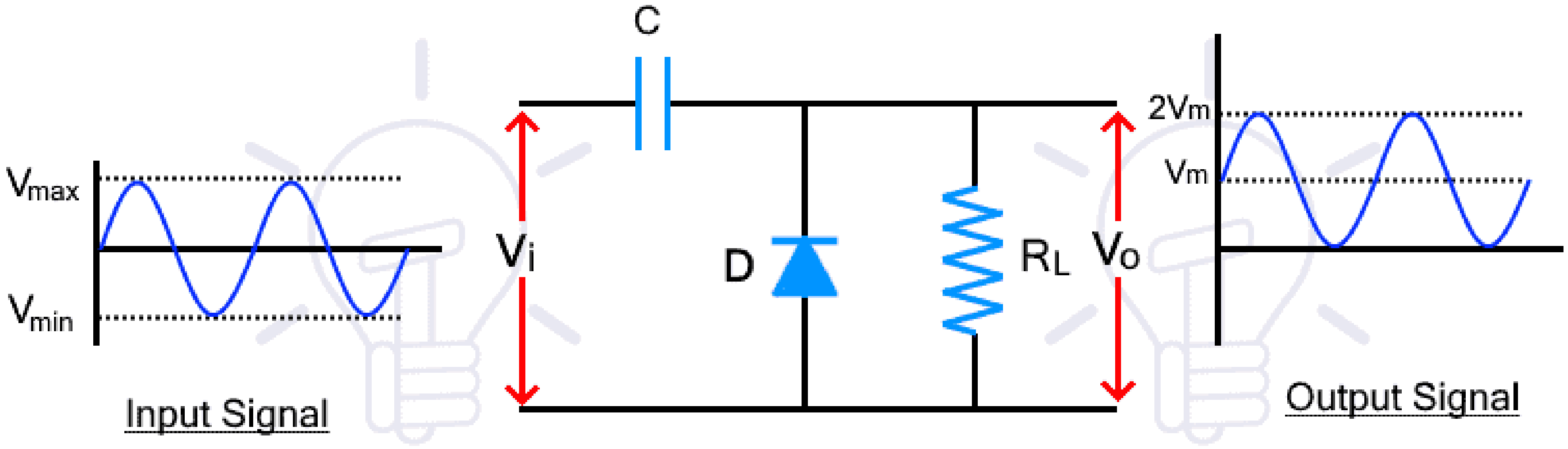
•They are employed for different wave generation such as square, rectangular, or trapezoidal waves.

•Series clippers are used as noise limiters in FM transmitters.

Positive Clamper:

The positive clamper is made up of a voltage source V_i, capacitor C, diode D, and load resistor R_L. In the below circuit diagram, the diode is connected in parallel with the output load.

So the positive clamper passes the input signal to the output load when the diode is reverse biased and blocks the input signal when the diode is forward biased.



Positive Clamper

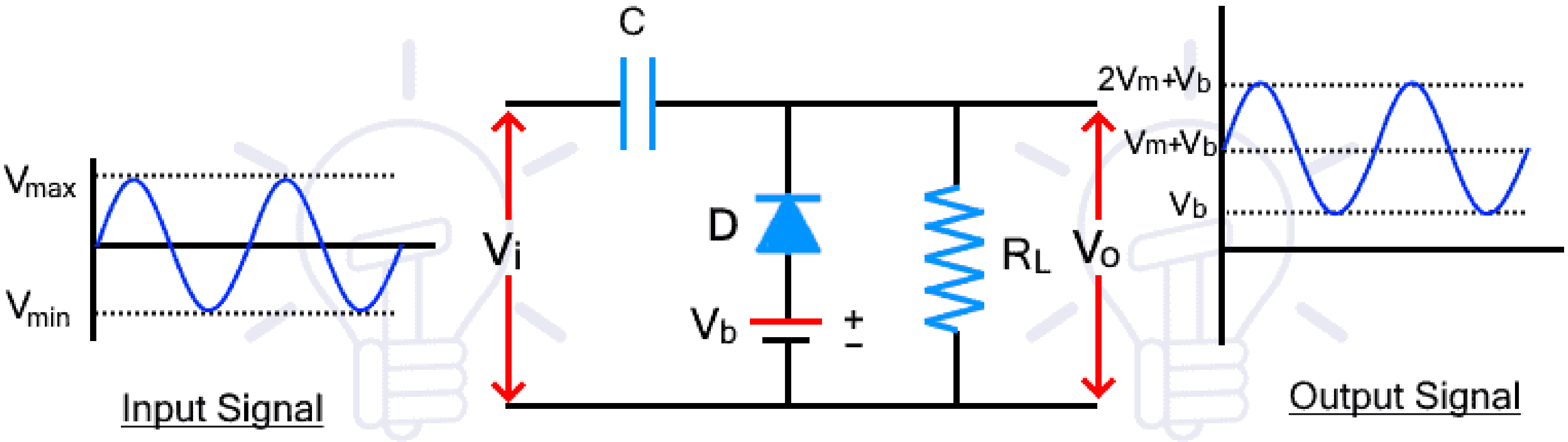
During the positive half cycle, the diode is reverse biased, therefore, therefore, the input signal appears at the output as it is. At this point, the capacitor is not charged and there is no clamping. Therefore, the output at this half cycle is not considered.

During the next negative half cycle, the diode becomes forward biased and it starts to conduct, at this half cycle, the capacitor charges up to the peak input voltage V_M with inverse polarity.

During the next positive half cycle, the diode is reverse biased and it does not conduct. Due to this, the capacitor starts to discharge. The capacitor discharge adds to the input signal which appears at the output as the summation of both voltages which reaches up to $2V_M$. This is how the signal level is shifted above the 0v line.

Positive Clamper with Positive Biasing

During positive biasing a positive voltage source is added in series with the diode as shown in the figure below.



Positive Clamper with Positive Bias

During the positive half cycle, the diode is reverse biased for the input signal but forward biased for the battery voltage.

Therefore, the diode conducts until the input voltage exceeds the battery. During the conduction, the capacitor is charged with the battery voltage V_B.

The diode stops conduction once the input voltage exceeds.

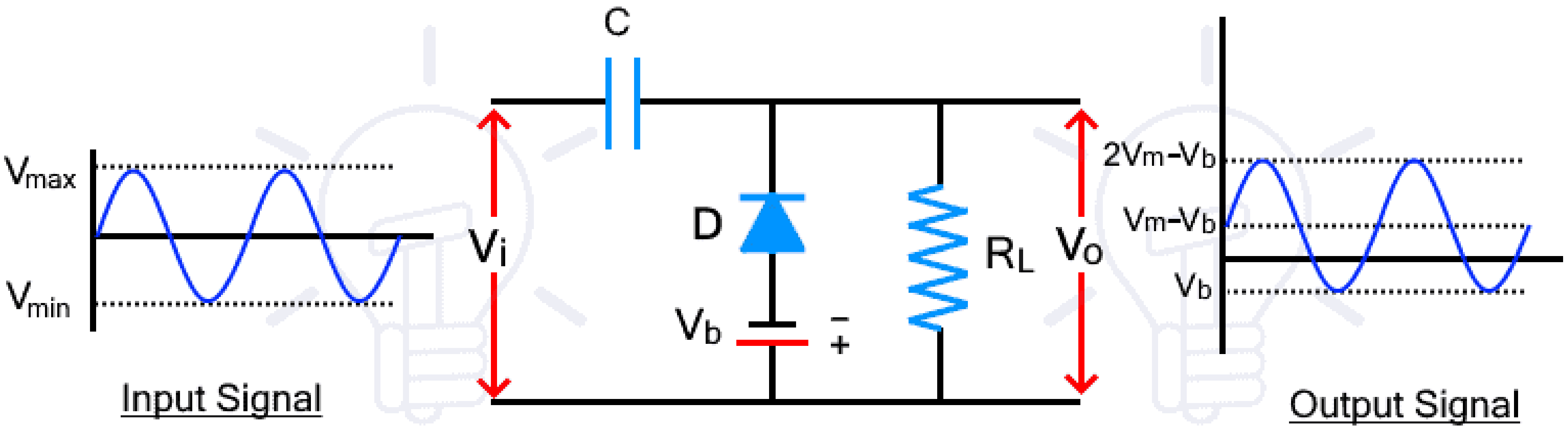
During the negative half cycle, the diode is forward biased for both input and battery voltage.

Thus the diode conducts to charge the capacitor with both the input and battery voltage V_M+V_B.

During the next positive half cycle, the capacitor is discharged that adds to the input signal waveform as explained in the positive clamper circuit.

Positive Clamper with Negative Biasing

The negative biased positive clamper has the same operation as a positive biased clamper except the waveform is shifted down by the amount of the battery voltage V_B



Positive Clamper with Negative Bias

During the positive half cycle, the diode is reverse biased due to both input voltage and the battery voltage. The diode does not conduct and the capacitor does not charge.

During the negative half cycle, the diode is forward biased for input voltage but it is reversed biased for battery voltage V_B.

Therefore, the diode does not conduct unless the input voltage exceeds the battery voltage and when the diode conducts, the capacitor charges. Due to this, the charging voltage of the capacitor is reduced to $V_m – V_B$.

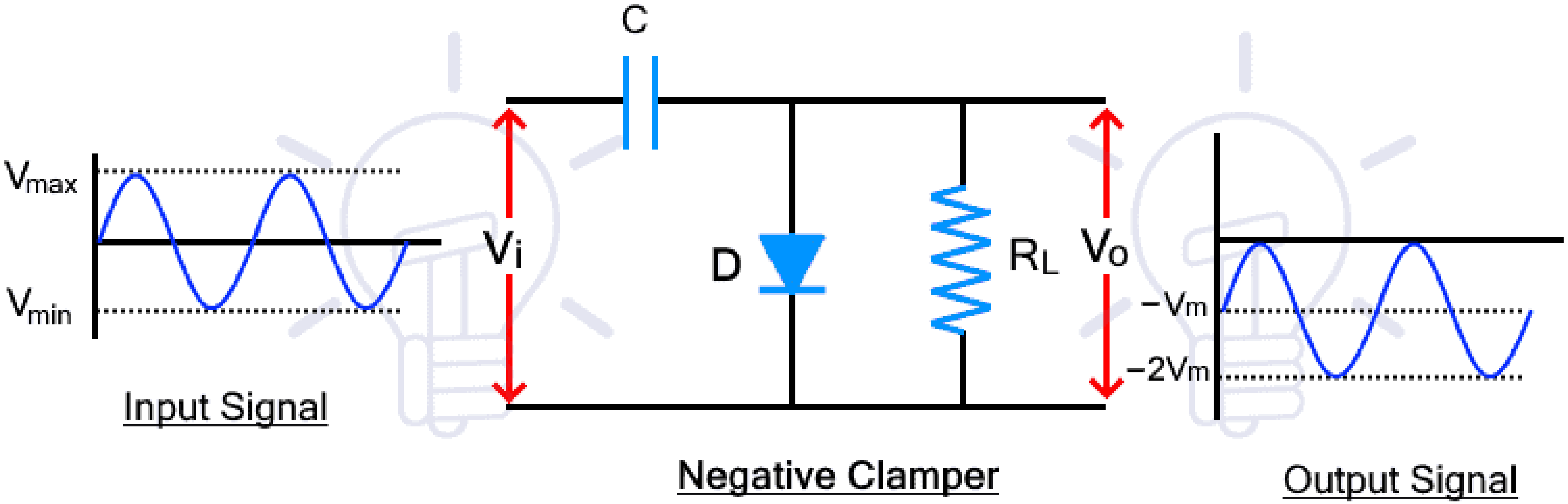
During the next positive cycle, the diode does not conduct, thus the capacitor is discharge and the waveform is shifted upward by $V_M – V_B$ (the capacitor voltage).

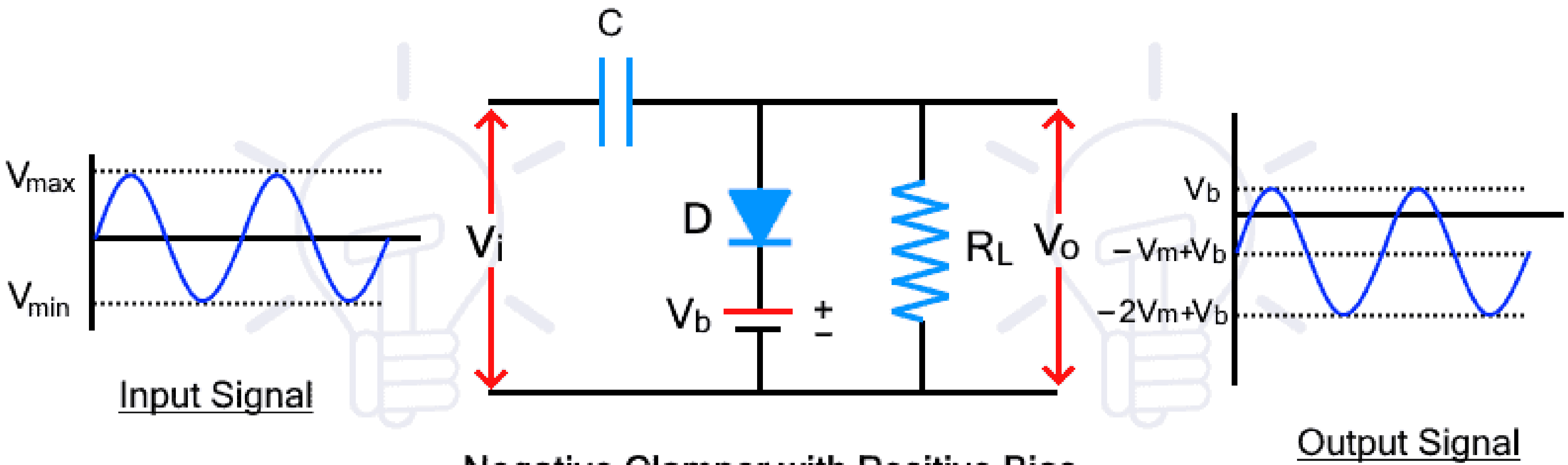
The biasing voltage shifts the waveform down by the amount of V_B of a positive clamper.

Negative Clamper:

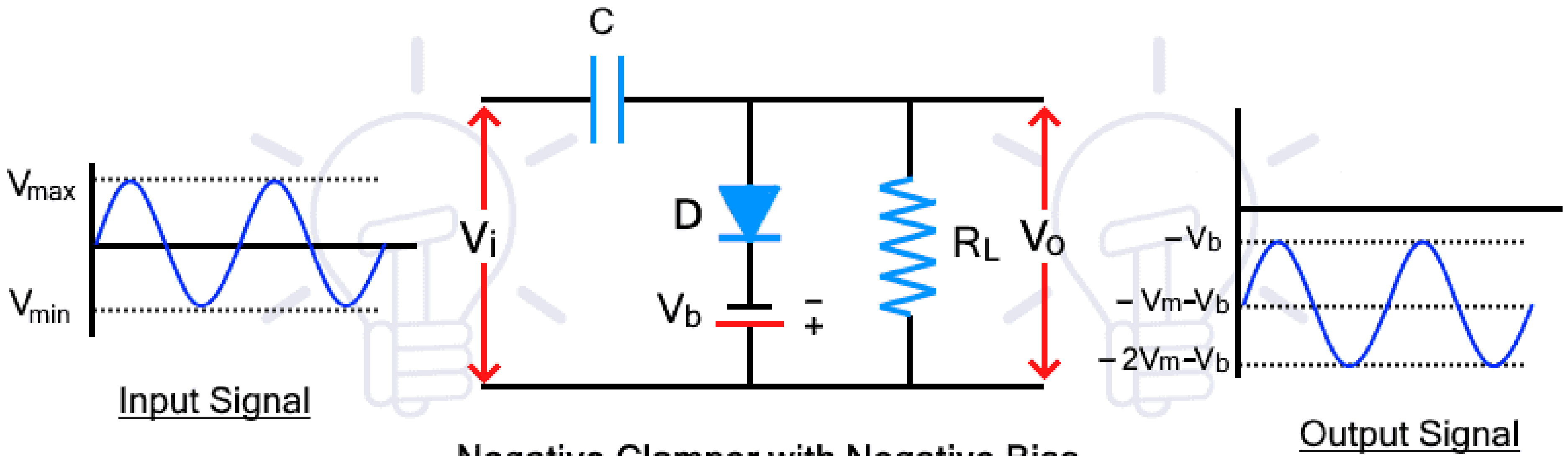
During the positive half cycle, the diode is forward-biased. Therefore, it conducts and charges the capacitor with inverse polarity up to the peak input voltage -V_M. There is no output during this half cycle.

During the negative half cycle, the diode is reverse biased and it does not conduct. Therefore, the capacitor discharges which adds with the input waveform. The addition of both voltages shifts the whole waveform furthermore up to -2V_M. This is how the input signal is shifted downward.





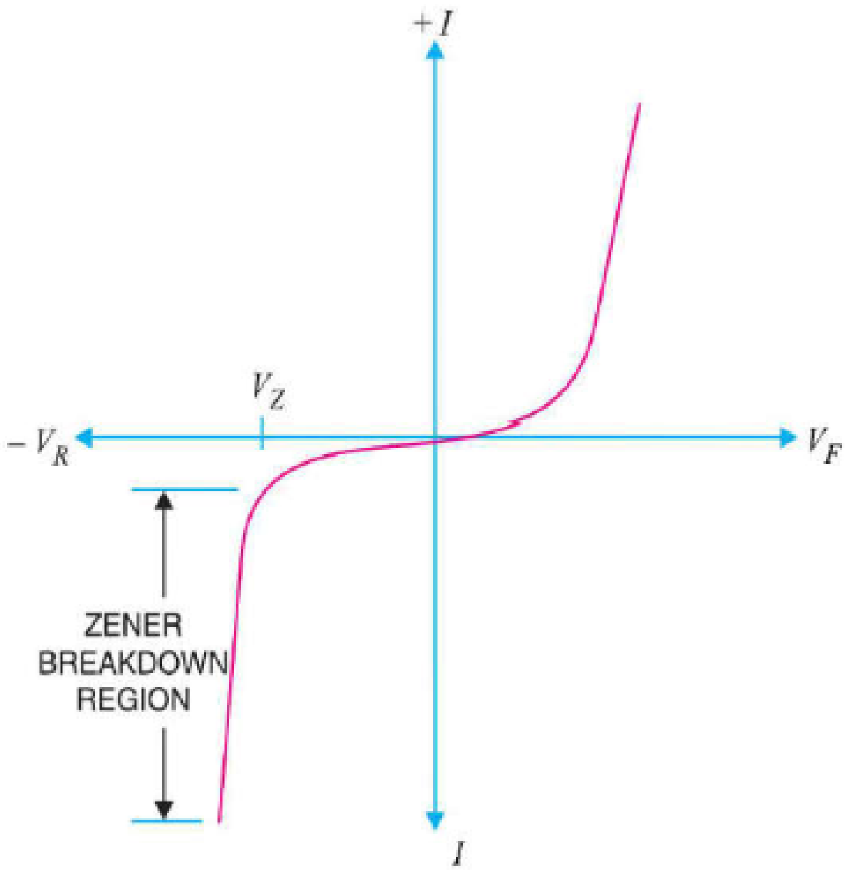
Negative Clamper with Positive Bias



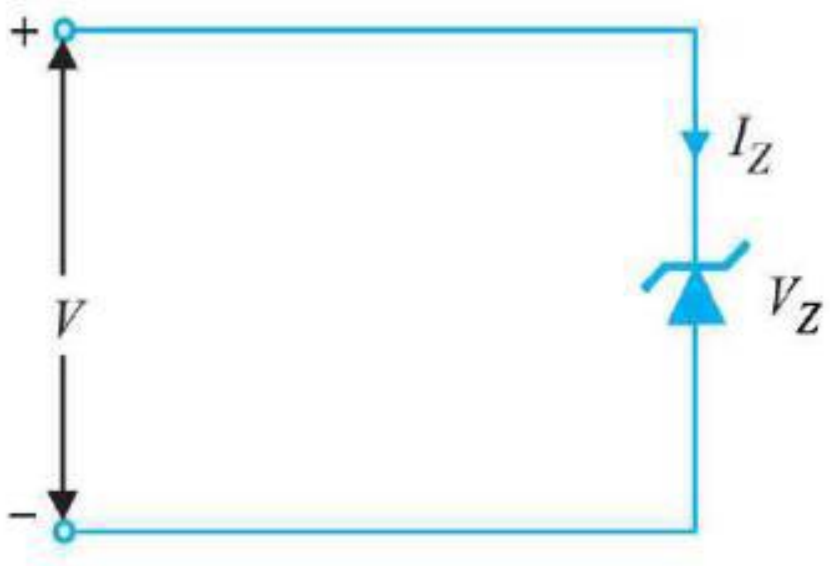
Negative Clamper with Negative Bias

ZENER DIODE

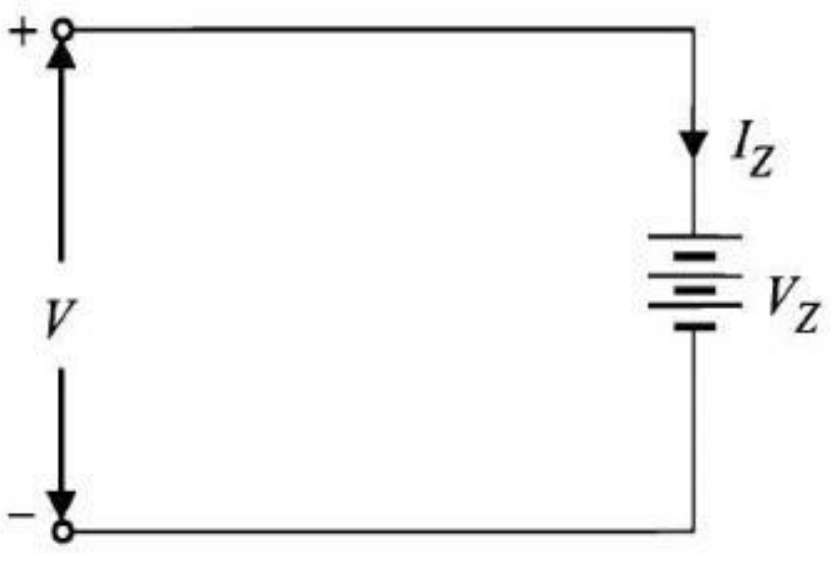
- A special diode designed to operate in reverse breakdown region
- An ordinary diode will get damaged due to excessive current
- A zener diode is heavily doped to reduce the breakdown voltage as well as depletion layer width
- As a result the diode has a **sharp** reverse breakdown voltage
- Characteristics show two imp points
    - After breakdown, the diode current increases rapidly
    - The reverse voltage across the diode remains constant.
    - This phenomenon of voltage remaining constant helps us to use Zener diode in voltage regulation.



- Always operated in reverse bias
- When forward biased, will behave as a normal diode
- When the reverse voltage across the diode is greater than or equal to the breakdown voltage, it can be replaced by a battery e qual to the Vz (Zener Voltage or Breakdown Voltage)

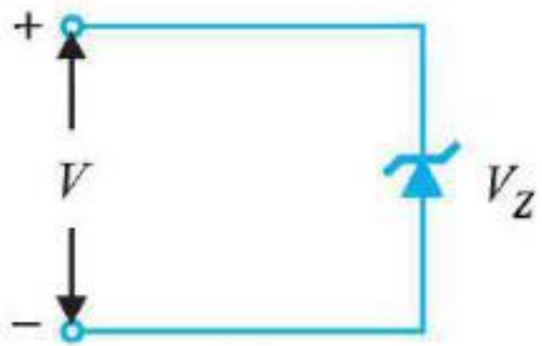


(i)
$V \geq V_Z$



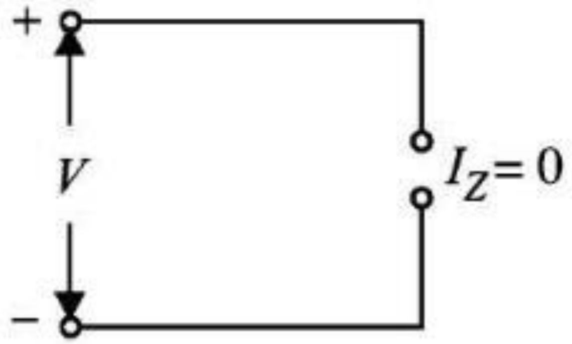
(ii)
Equivalent circuit of zener for "on" state

❑ However if the reverse voltage is less than the breakdown voltage, it will work as open circuit as shown below.



(i)

$V_Z > V > 0$

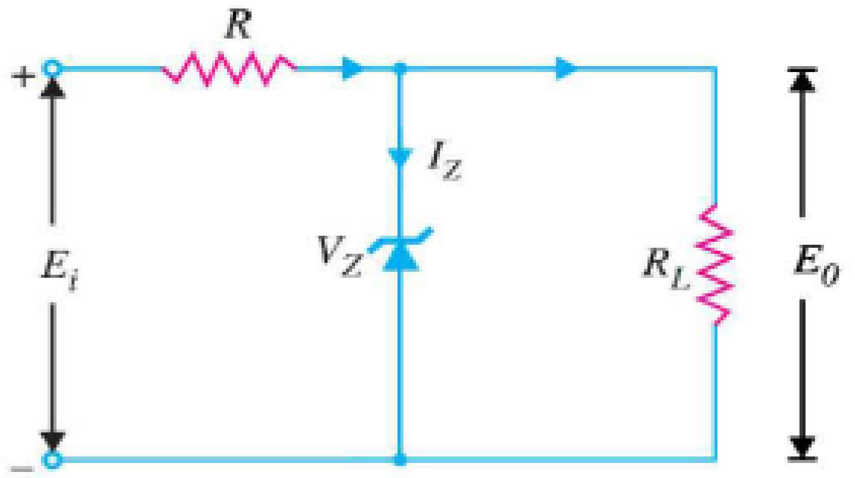


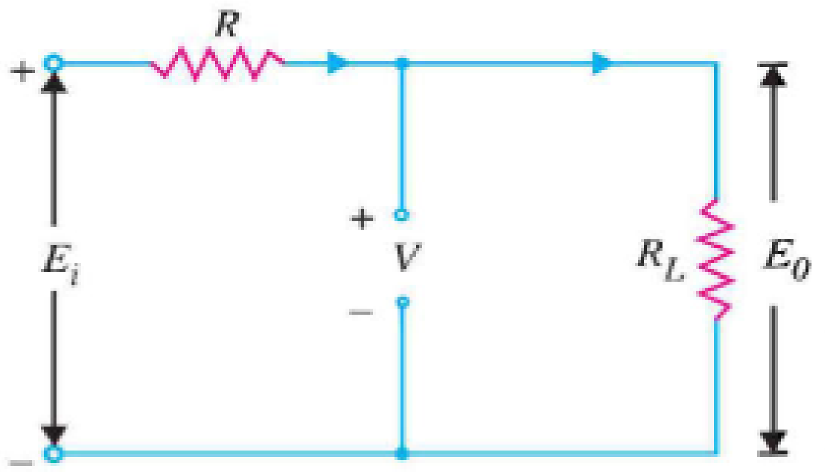
(ii)

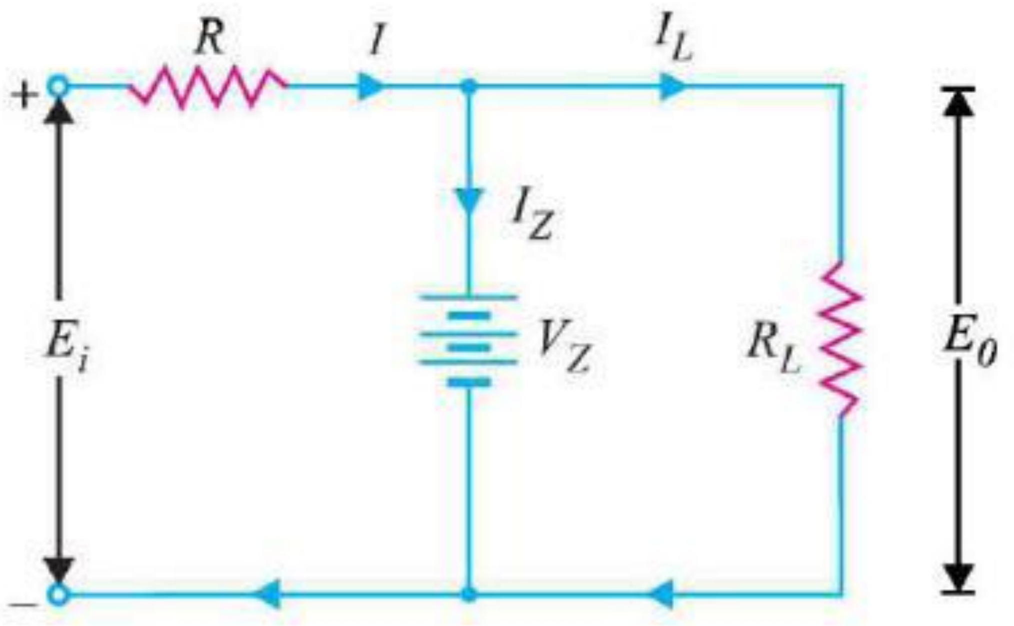
Equivalent circuit of zener for ''off'' state

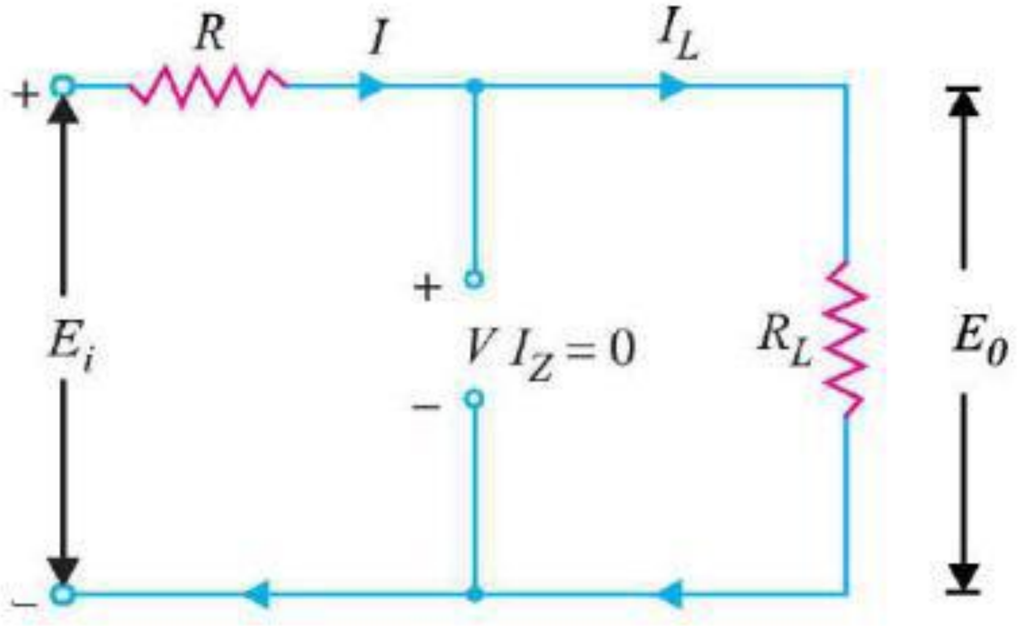
- Try to find the state of the zener diode (Off, Forward Biased, Reverse Biased, Reverse Biased and in Breakdown)
- Remove the diode and find the voltage across Load Resistance
- If above voltage is greater than specified breakdown voltage of zener diode than replace it by a battey of Vz. The voltage now across both diode as well as the Load resistance will remain constant at Vz.
- If it less, then the replace it by an open circuit. In this case there is no regulation and the voltage across the load fluctuates as per the variations in the input power supply.

$$V = E_0 = \frac{R_L E_i}{R + R_L}$$









- $V > V_Z$: $E_0 = V_Z$, $I_Z = I - I_L$, $P_Z = V_Z$, $I_L = V_Z/R_L$
- $V < V_Z$: $I = I_L$, $I_Z = 0$, $P_Z = 0$ $(P_Z = V_Z I_Z)$ $I_L = E_i/(R+R_L)$

When the circuit is properly designed, the load voltage E_0 remains essentially constant (equal to V_Z) even though the input voltage *Ei* and load resistance R_L may vary over a wide range.

Suppose the input voltage increases. Since the Zener is in the breakdown region, the Zener diode is equivalent to a battery V_Z as shown in Fig. It is clear that output voltage remains constant at V_Z (= E_0).

The excess voltage is dropped across the series resistance *R*. This will cause an increase in the value of total current *I*.

The Zener will conduct the increase of current in *I* while the load current remains constant.

Hence, output voltage V_Z remains constant irrespective of the changes in the input voltage *Ei*.

Now suppose that input voltage is constant but the load resistance R_L decreases. This will cause an increase in load current.

The extra current cannot come from the source because drop in R (and hence source current I) will not change as the Zener is within its regulating range.

The additional load current will come from a decrease in Zener current I_Z. Consequently, the output voltage stays at constant value.

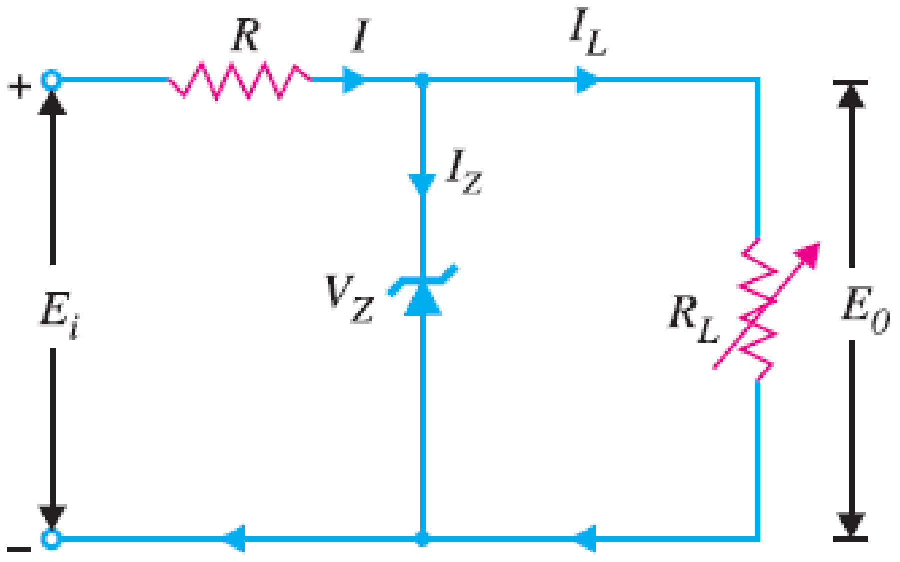
$$\text{Voltage drop across } R = E_i - E_0$$
$$\text{Current through } R, I = I_Z + I_L$$

Applying Ohm's law, we have, $$R = \frac{E_i - E_0}{I_Z + I_L}$$

Fixed Ei and Variable R_L

This case is shown in Fig. below. Here the applied voltage (E_i fixed while load resistance R_L (and hence load current I_L) changes.

Note that there is a definite range of R_L values (and hence I_L values) which will ensure the Zener diode to be in "on" state. Let us calculate that range of values.

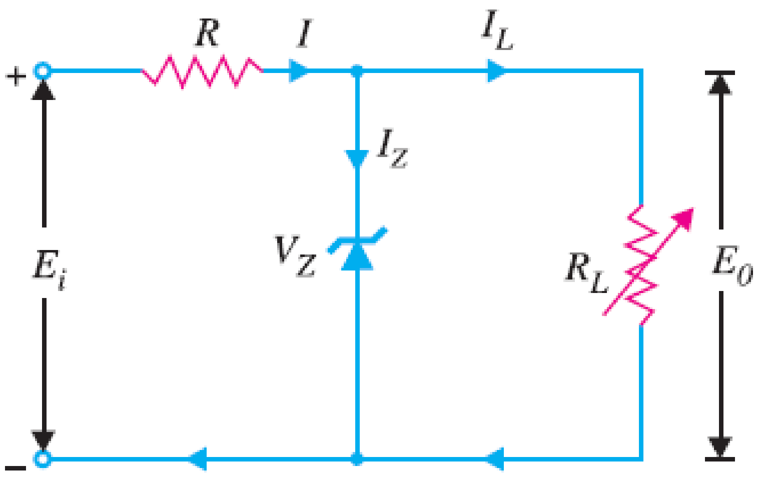


(i) R_{Lmin} and I_{lmax}

Once the Zener is in the "on" state, load voltage E_0 (= V_Z) is constant.

As a result, when load resistance is minimum (*i.e.*, R_{Lmin}), load current will be maximum ($I_L = E_0 / R_L$).

In order to find the minimum load resistance that will turn the Zener on, we simply calculate the value of R_L that will result in $E_0 = V_Z$ *i.e.*,



$$E_0 = V_Z = \frac{R_L E_i}{R + R_L}$$

$$R_{Lmin} = \frac{R V_Z}{E_i - V_Z} \qquad I_{Lmax} = \frac{E_0}{R_{Lmin}} = \frac{V_Z}{R_{Lmin}}$$

(*ii*) I_{Lmin} and R_{Lmax}

It is easy to see that when load resistance is maximum, load current is minimum. Now, Zener current, $I_Z = I - I_L$

When the Zener is in the "on" state, I remains fixed. This means that when I_L is maximum, I_Z will be minimum.

On the other hand, when I_L is minimum, I_Z is maximum.

If the maximum current that a Zener can carry safely is I_{ZM}, then

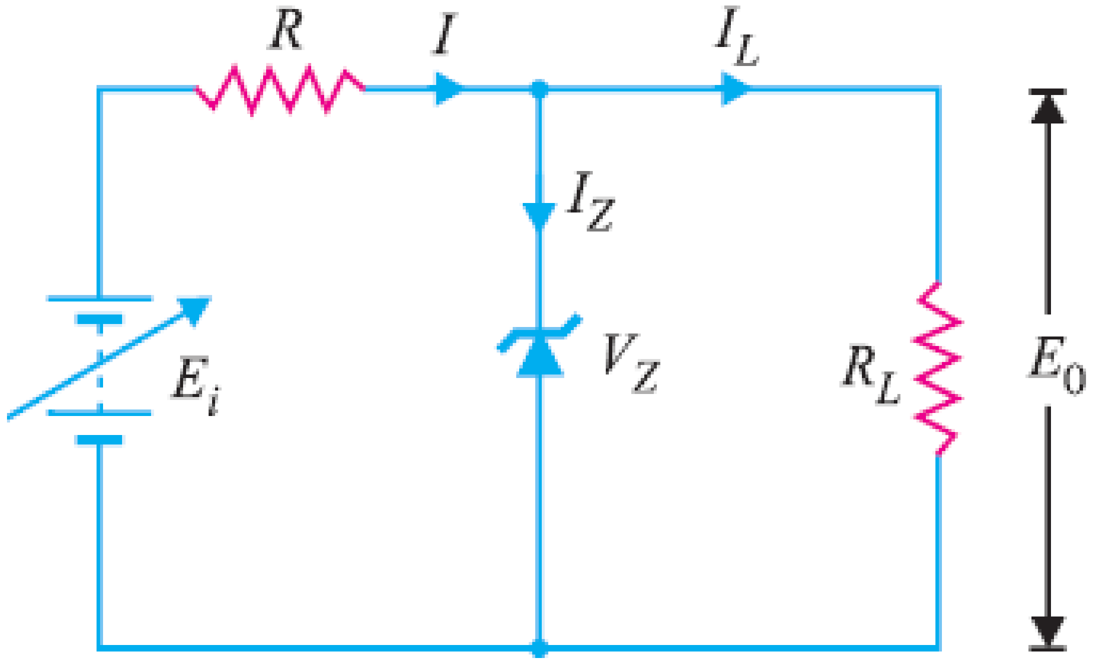
$$I_{Lmin} = I - I_{ZM}$$

$$R_{Lmax} = \frac{E_0}{I_{Lmin}} = \frac{V_Z}{I_{Lmin}}$$

If the load resistance exceeds this limiting value, the current through Zener will exceed I_{ZM} and the device may burn out.

Fixed R_L and Variable Ei. This case is shown in Fig. below. Here the load resistance *RL* is fixed while the applied voltage (*Ei*) changes.

Note that there is a definite range of *Ei* values that will ensure that zener diode is in the "on" state. Let us calculate that range of values.



(i) Ei (*min*)

To determine the minimum applied voltage that will turn the Zener on, simply calculate the value of *Ei* that will result in load voltage $E_0 = V_Z$

$$E_0 = V_Z = \frac{R_L\ E_i}{R + R_L}$$

$$E_{i\,(min)} = \frac{(R + R_L)\,V_Z}{R_L}$$

(*ii*) Ei (*max*)

Now, current through R, $I = I_Z + I_L$

Since I_L $(= E_0 / R_L = V_Z / R_L)$ is fixed, the value of I will be maximum when Zener current is maximum

$$I_{max} = I_{ZM} + I_L$$

$$E_i = I\,R + E_0$$

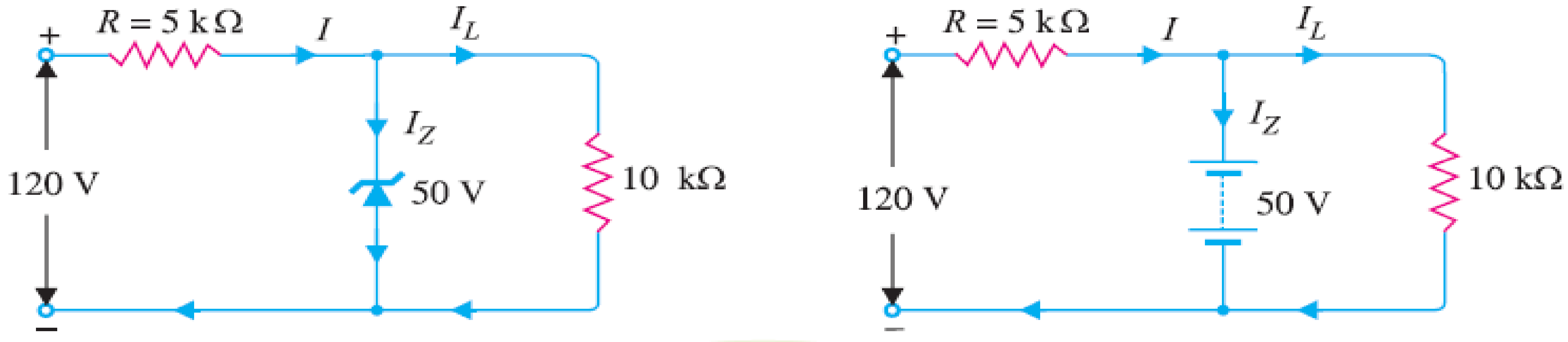
Since E_0 (= V_Z) is constant, the input voltage will be maximum when I is maximum.

$$E_{i\,(max)} = I_{max}\,R + V_Z$$

Example 6.25. *For the circuit shown in Fig. 6.61 (i), find :*

(i) the output voltage *(ii) the voltage drop across series resistance*

(iii) the current through zener diode.



Solution. If you remove the zener diode in Fig. 6.61 (*i*), the voltage V across the open-circuit is given by :

$$V = \frac{R_L\ E_i}{R + R_L} = \frac{10 \times 120}{5 + 10} = 80\ \text{V}$$

Since voltage across zener diode is greater than V_Z (= 50 V), the zener is in the "on" state. It can, therefore, be represented by a battery of 50 V as shown in Fig. 6.61 (*ii*).

(*i*) Referring to Fig. 6.61 (*ii*),

$$\text{Output voltage} = V_Z = \mathbf{50\ V}$$

(*ii*) $$\text{Voltage drop across } R = \text{Input voltage} - V_Z = 120 - 50 = \mathbf{70\ V}$$

(*iii*) $$\text{Load current, } I_L = V_Z/R_L = 50\ \text{V}/10\ \text{k}\Omega = 5\ \text{mA}$$

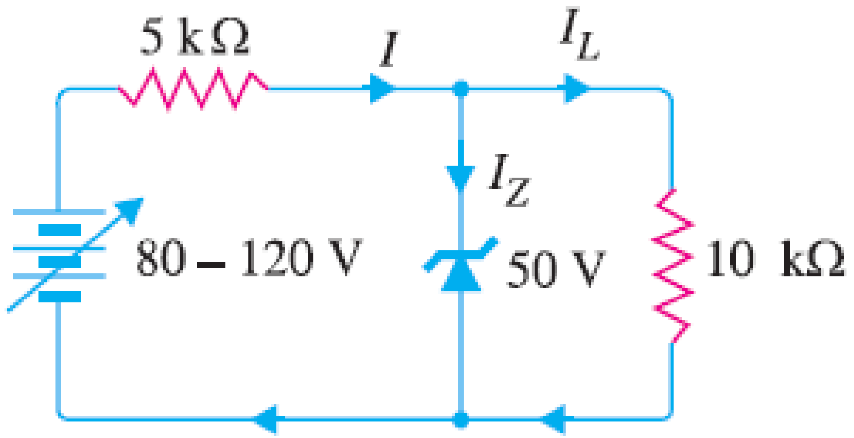
$$\text{Current through } R,\ I = \frac{70\ \text{V}}{5\ \text{k}\Omega} = 14\ \text{mA}$$

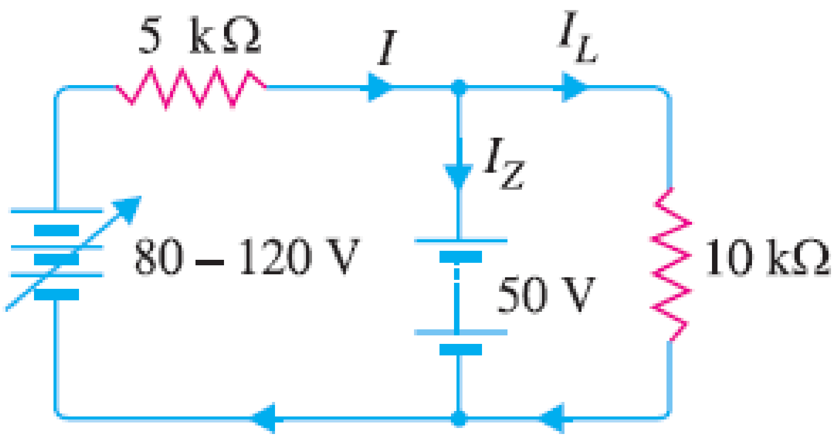
$$\text{Applying Kirchhoff's first law, } I = I_L + I_Z$$

$$\therefore \quad \text{Zener current, } I_Z = I - I_L = 14 - 5 = \mathbf{9\ mA}$$

Example 6.26. *For the circuit shown in Fig. 6.62 (i), find the maximum and minimum values of zener diode current.*

Solution. The first step is to determine the state of the zener diode. It is easy to see that for the given range of voltages (80 – 120 V), the voltage across the zener is greater than V_Z (= 50 V). Hence the zener diode will be in the "on" state for this range of applied voltages. Consequently, it can be replaced by a battery of 50 V as shown in Fig. 6.62 (*ii*).





Maximum zener current. The zener will conduct *maximum current when the input voltage is maximum *i.e.* 120 V. Under such conditions :

$$\text{Voltage across } 5\text{ k}\Omega = 120 - 50 = 70\text{ V}$$

$$\text{Current through } 5\text{ k}\Omega,\ I = \frac{70\text{ V}}{5\text{ k}\Omega} = 14\text{ mA}$$

$$\text{Load current, } I_L = \frac{50\text{ V}}{10\text{ k}\Omega} = 5\text{ mA}$$

$$\text{Applying Kirchhoff's first law, } I = I_L + I_Z$$

$$\therefore \quad \text{Zener current, } I_Z = I - I_L = 14 - 5 = \mathbf{9\text{ mA}}$$

Minimum Zener current. The zener will conduct minimum current when the input voltage is minimum *i.e.* 80 V. Under such conditions, we have,

$$\text{Voltage across } 5\text{ k}\Omega = 80 - 50 = 30\text{ V}$$

$$\text{Current through } 5\text{ k}\Omega,\ I = \frac{30\text{ V}}{5\text{ k}\Omega} = 6\text{ mA}$$

$$\text{Load current, } I_L = 5\text{ mA}$$

$$\therefore \quad \text{Zener current, } I_Z = I - I_L = 6 - 5 = \mathbf{1\text{ mA}}$$