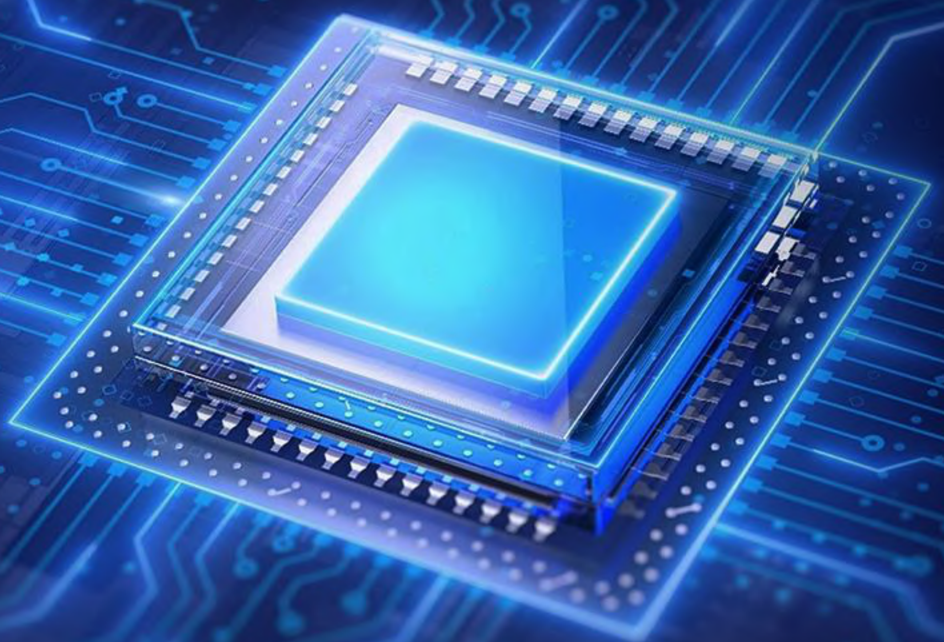
Welcome to

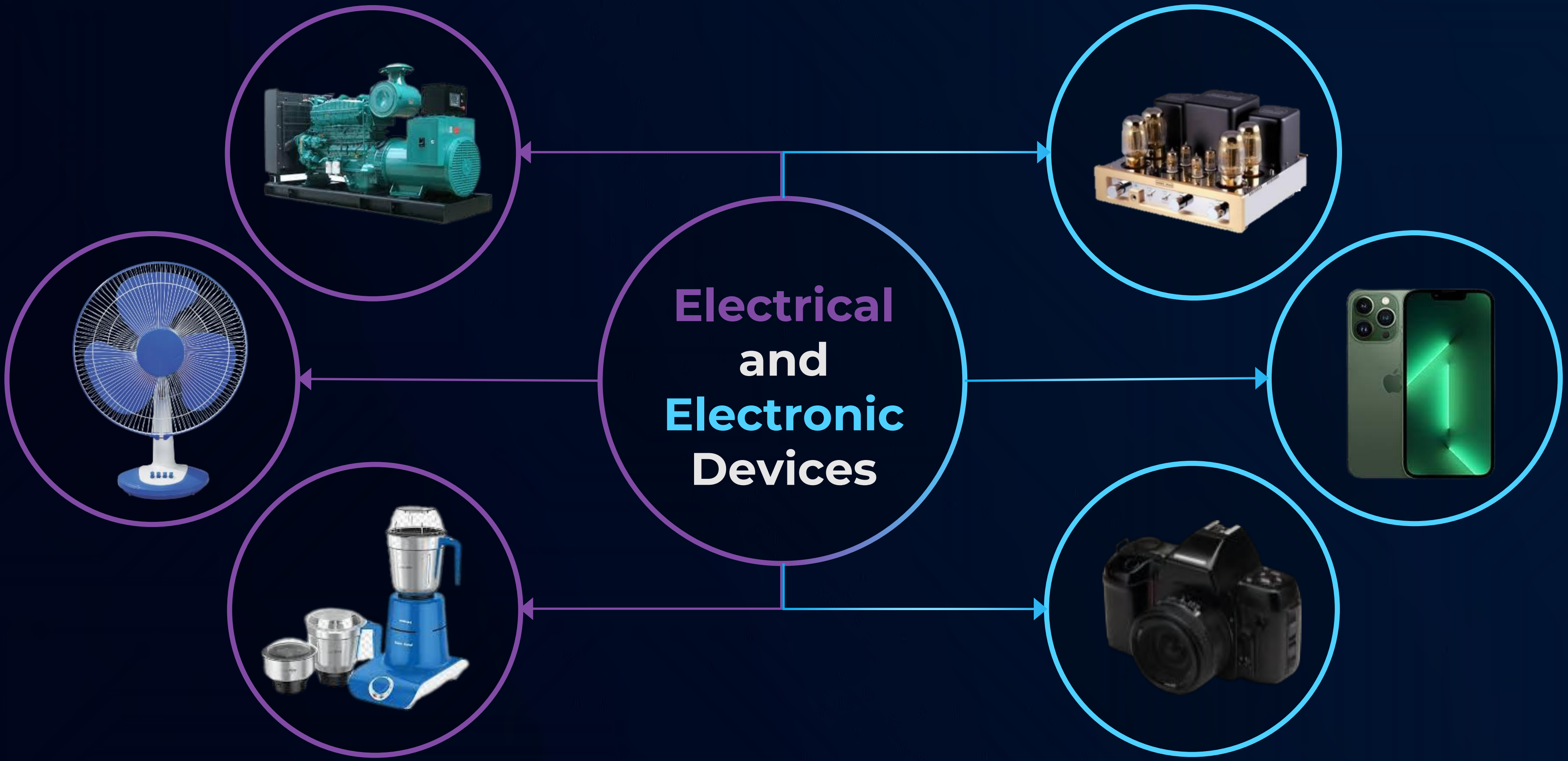
Aakash + BYJU'S NOTES

Semiconductors



Electrical Devices

Electrical Devices: The devices which convert the electrical energy into other forms of energy to perform a task.



Electronic Devices: The devices which can control the flow of electrons, thereby controlling the flow of energy.

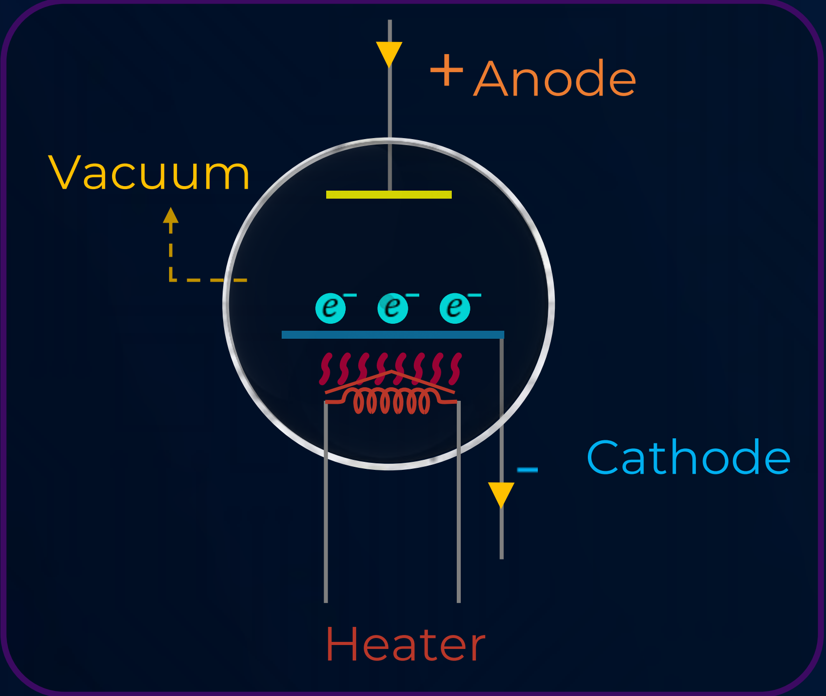
Vacuum Tube

Vacuum Tube

- Number of e^- can be controlled by varying voltage between the anode and the cathode.
- Electrons can flow only in one direction.

  Cathode $\longrightarrow$ Anode

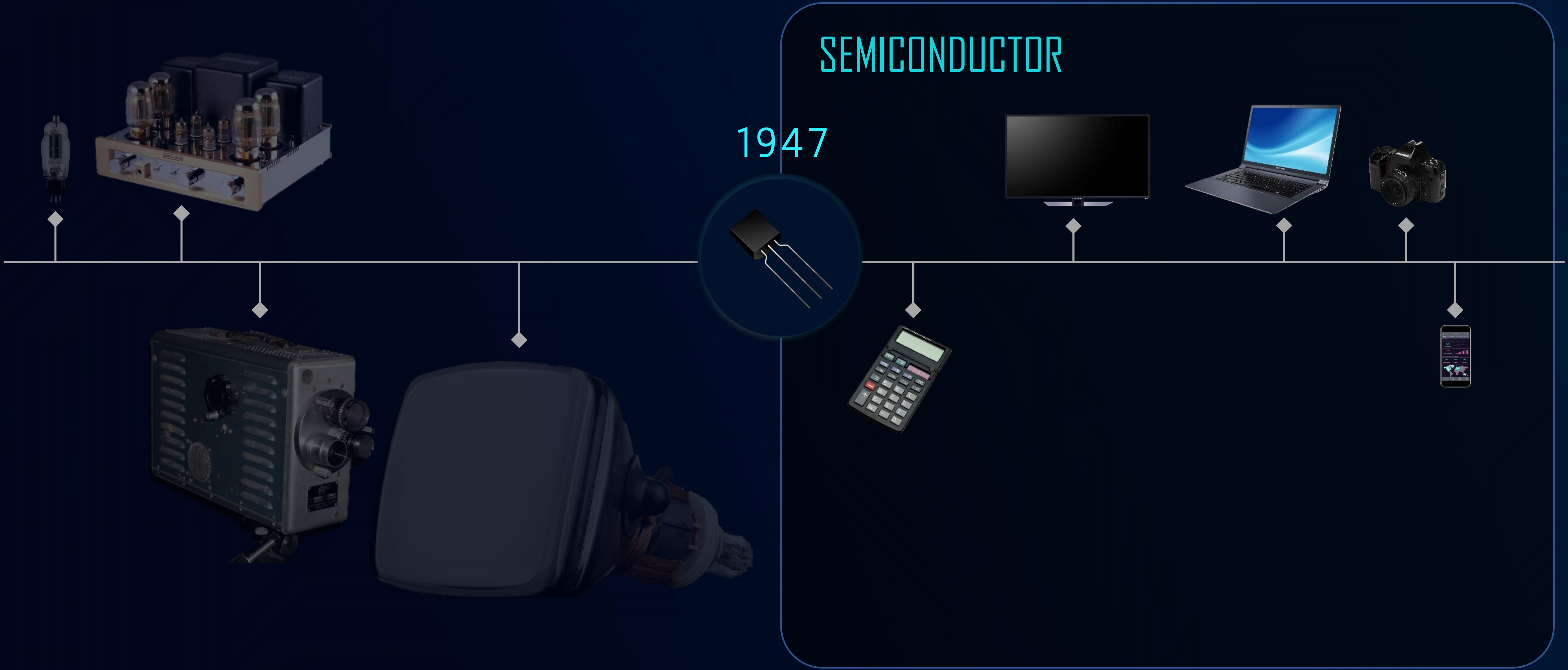
- Vacuum is created because e^- can collide with air molecules and lose energy.



Disadvantage:

- Bulky in size
- Vacuum creation is challenging
- Operates at high power
- Operates at high voltage $(100\ V)$
- Low life
- Less reliability

Journey of Development of Electronic Devices



Semiconductor: Properties

- The flow of charge carriers (electrons and holes) can be controlled with a high degree of precision → Conductivity can be controlled

- It can give unidirectional current.

- Conductivity of semiconductors increases with increase in temperature.

Advantage:

- Small in size
- No Vacuum or heating is required
- Operates at low power and low voltage
- Long life
- High reliability

Semiconductors

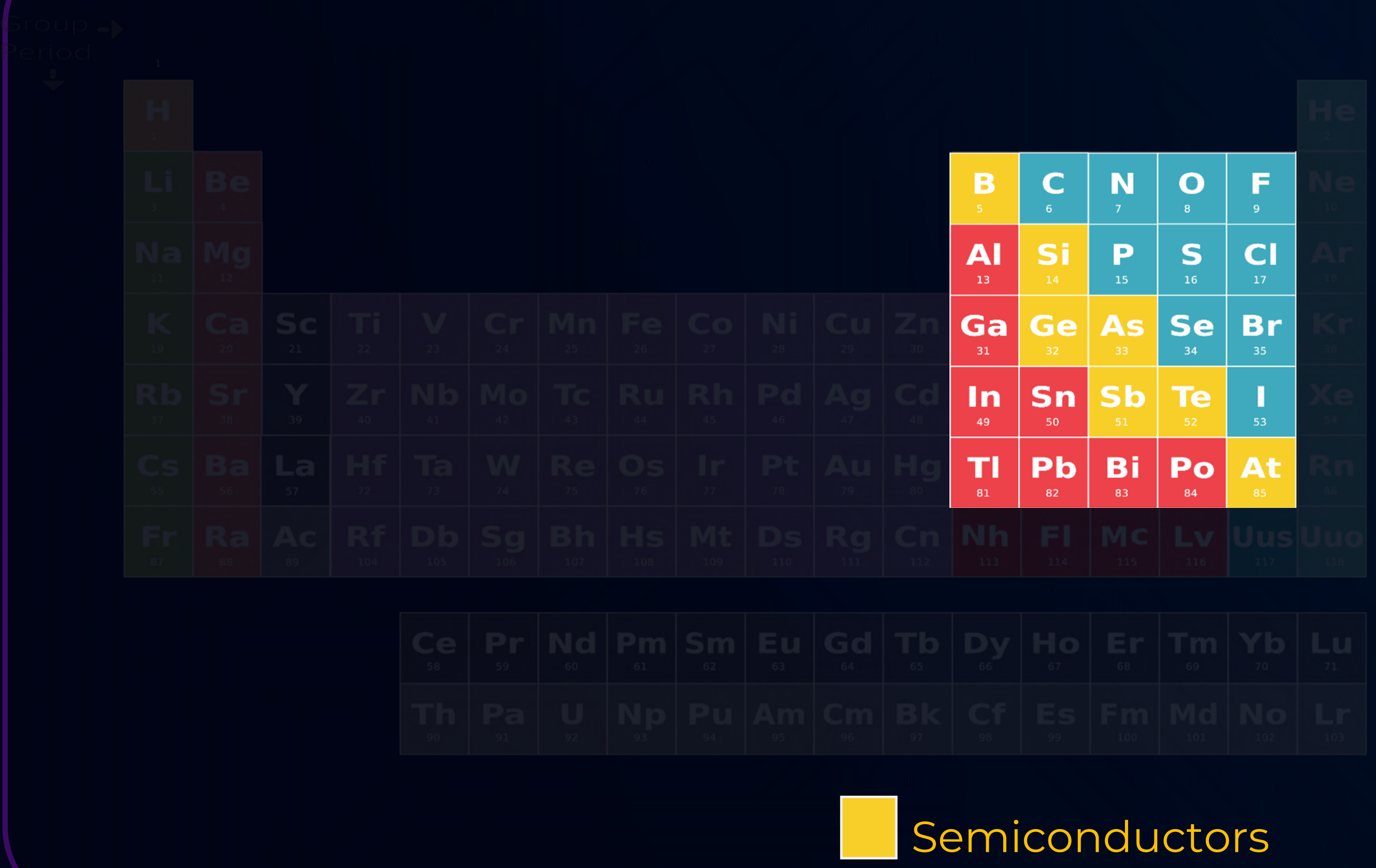
Semiconductors are materials which have conductivity between conductors (Silver, Copper etc..) and insulators (Diamond, Glass etc...).

Material	Resistivity (ρ)	Conductivity $(\sigma = 1/\rho)$
Conductors	$10^{-2} - 10^{-8}\ \Omega m$	$10^{2} - 10^{8}\ S/m$
Semiconductors	$10^{-5} - 10^{6}\ \Omega m$	$10^{-6} - 10^{5}\ S/m$
Insulators	$10^{11} - 10^{19}\ \Omega m$	$10^{-19} - 10^{-11}\ S/m$

Examples:

- Elemental semiconductors:
  Silicon (Si) , Germanium (Ge)
- Compound semiconductors:
  $GaAs, InP, CdS$, Anthracene, Doped phthalocyanines
  Polypyrrole, Polyaniline, Polythiophene

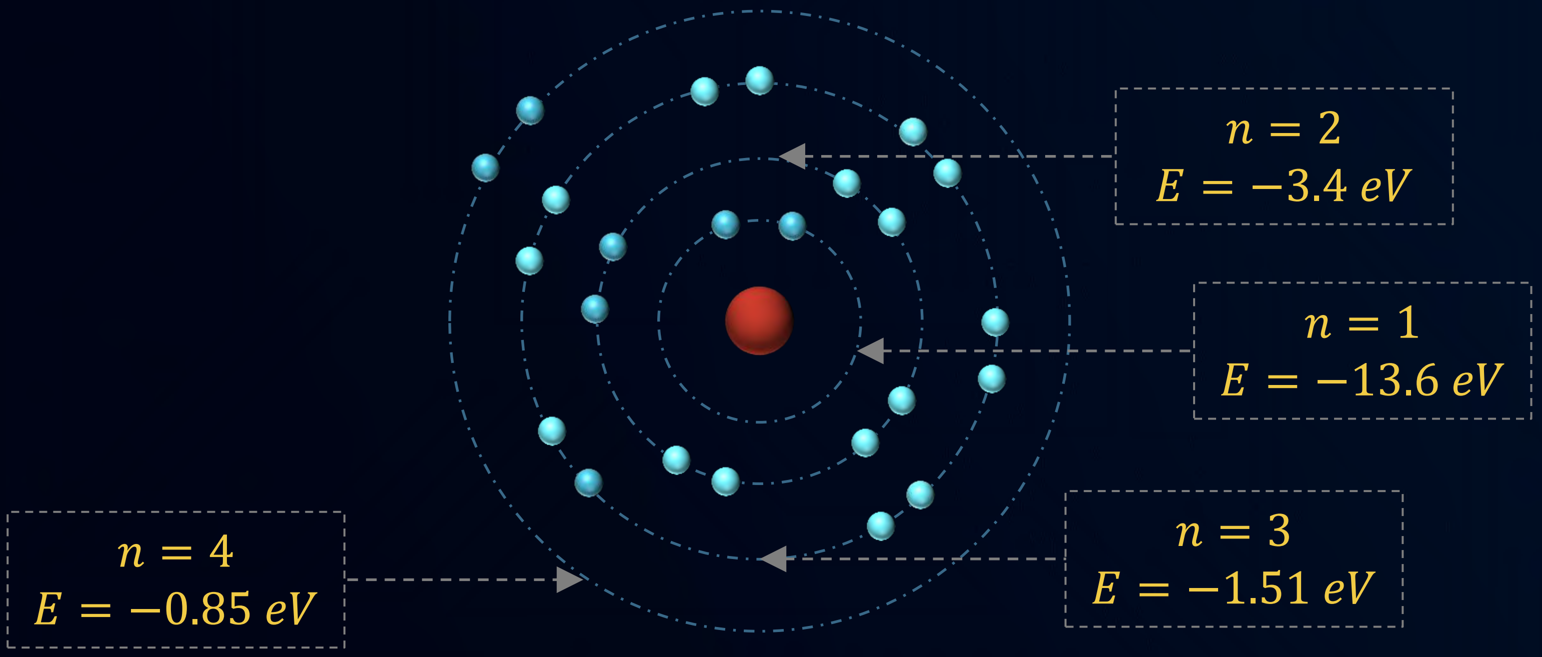
Semiconductors in Periodic Table



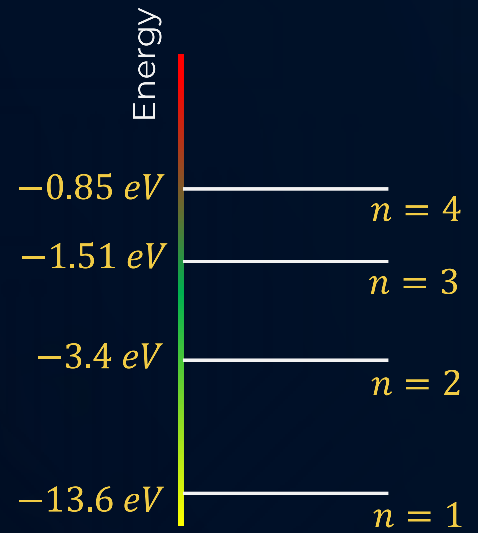
- *Si* and *Ge* are semiconductors in elemental form and others are not in elemental form.

Energy states in an Isolated Atom

- In an isolated atom, each electron has definite energy as per its quantum state. Also, electrons in the same quantum state will have the same energy in all isolated atoms.



Bohr's model



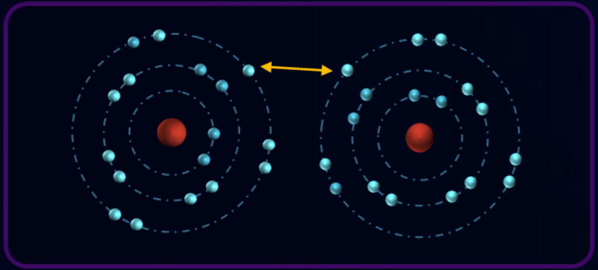
Energy of Isolated Atom

- In an isolated atom, discrete energy levels are present.

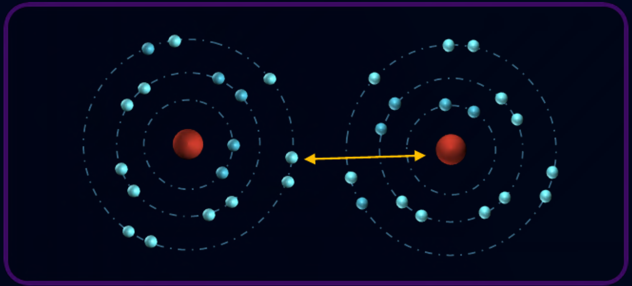
Energy Band in Crystal

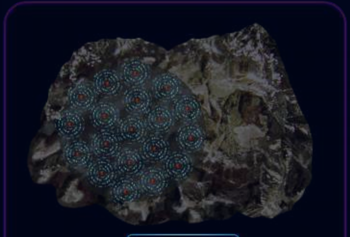
In a crystal, atoms come close (2 Å to 3 Å), and the electrons have some new interactions:

- With electrons of neighbouring atoms



- With nucleus of neighbouring atoms





Crystal

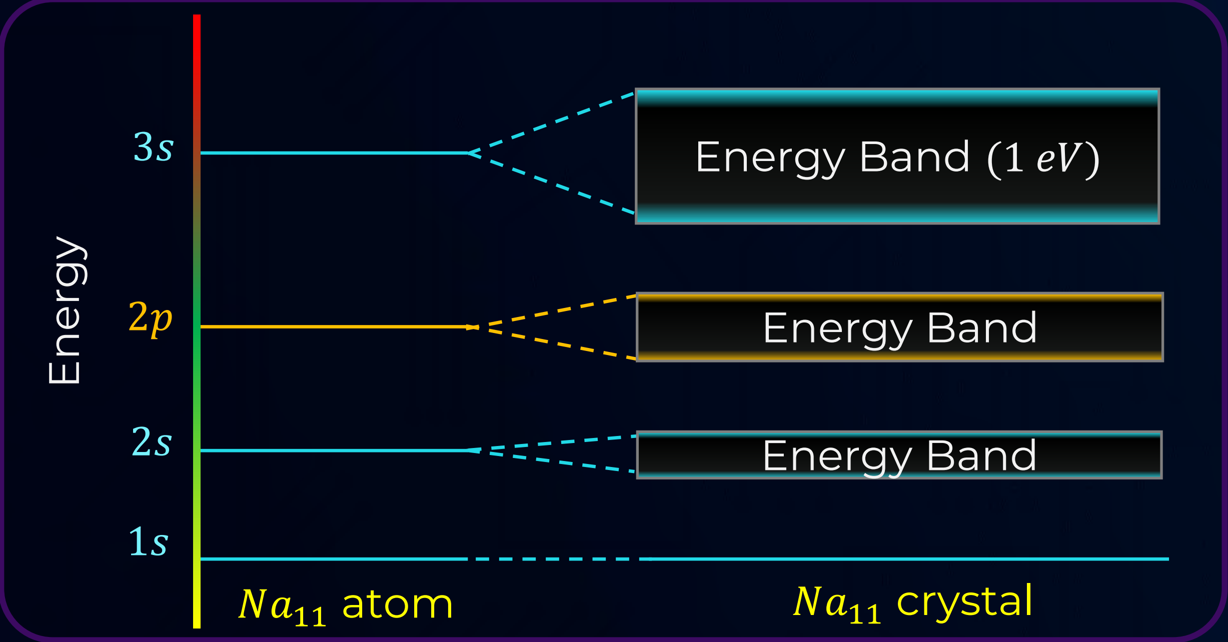
Each atom has unique position

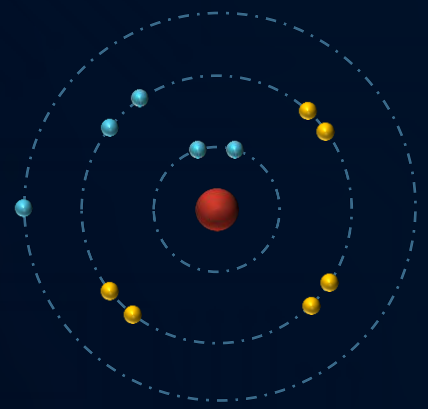
Each e^- has unique interaction

Each e^- has different energy levels even when they belong to same subshell of isolated atom

Conclusion: Their energies are slightly greater or smaller than their original energies in Isolated state.

Energy Bands in Na Crystal





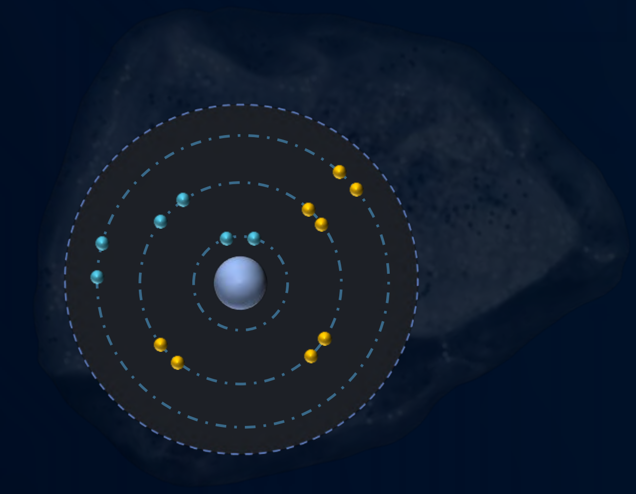
$Na_{11} = 1s^2\ 2s^2 2p^6\ 3s^1$

- If we take N isolated atoms of Na, then all the N number of $3s^1$ electrons will have the same energy. Therefore, their energy state can be represented by a straight line as shown above.
- But, when these isolated atoms are brought closer in a crystal lattice, no two electrons will have same energy due to interatomic interactions and hence, an energy band is created.
- Width of energy band is greatest for valence electrons (For Na, it is 3s electrons).
- The Inner e^- nearly remain unaffected by neighbouring atoms.

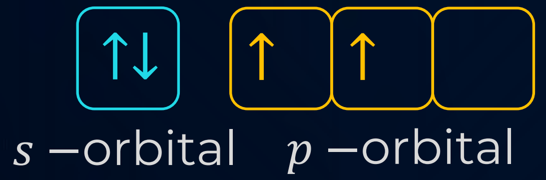
Silicon Semiconductor

Assumption: Si crystal contains $'N'$ atoms of Si.

- $4\ e^-$ in outer orbit of each Si atom $\Rightarrow 4N$ electrons in outer orbit of Si crystal.
- e^-_{max} in s-orbital : $2\ e^-$.
- e^-_{max} in p-orbital : $6\ e^-$.



$$Si_{14} = 1s^2\ \ 2s^2 2p^6\ \ 3s^2 3p^2$$

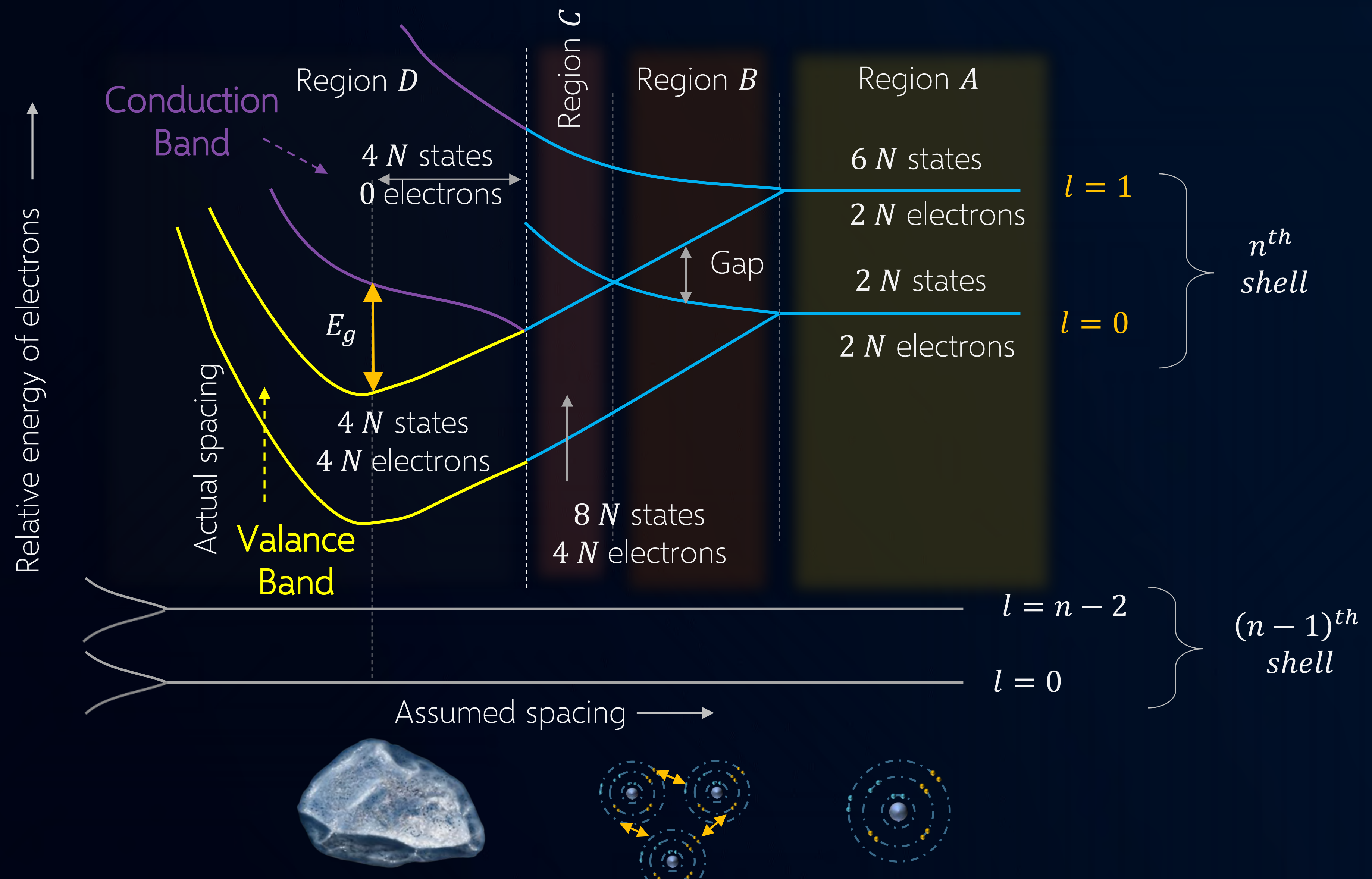


Conclusions:

- $8N(2Ns + 6Np)$ outer energy levels are available in Si crystal.
- At Zero Kelvin,

$8N$ energy levels
- $4N$ are vacant
- $4N$ are filled with e^-

Energy Levels of Silicon Semiconductor



Energy Levels of Silicon Semiconductor

In region A, as the atoms are in isolated states, therefore,

- p orbital → $6N$ states → same energy level → $2N$ states among them are filled with electrons.
- s orbital → $2N$ states → same energy level → all of them are filled with electrons.

In region B, the atoms are brought closer than that in region A and the splitting of energy levels commences. It is noticeable that a gap is formed between two energy bands and electrons can have energy anywhere in the energy band created.

In region C, the atoms are further brought closer and it is seen that all the energy levels start intermixing. Some of the $6N$ states go below the $2N$ states.

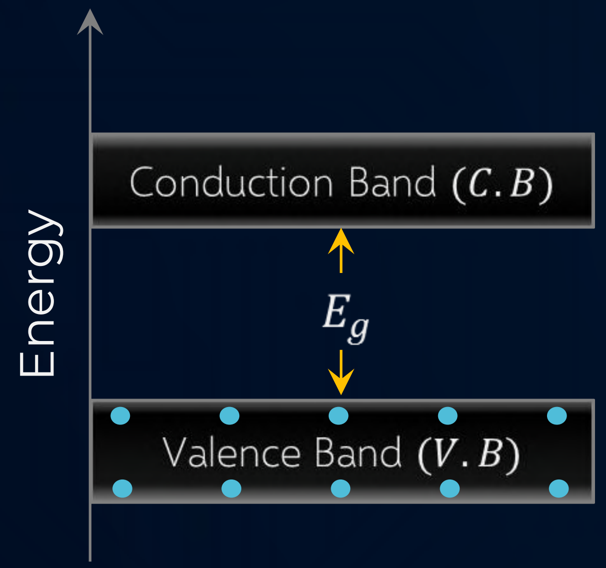
In region D, the spacing is taken very close of the order of 2 to 3 Å, and then the $8N$ states are split equally into two energy bands. There is an energy gap (Eg) between the Conduction band and Valence band.

- At $0\ K$, all the $4N$ electrons lie in the energy band having lower energy (i.e., Valence band) while the energy band having higher energy (i.e., Conduction band) is empty.

Energy Band

Valence Band $(V.B.)$ Energy band containing valence electrons.

- Range of energies possessed by valence electrons in a crystal.
- These $V.B.$ electrons do not participate in electrical conductivity.



Conduction Band $(C.B.)$

- The band above valence band is called conduction band.
- Electrons may or may not exist in $C.B$.
- Range of energies possessed by free electrons in a $C.B$.
- $C.B$ electrons are responsible for electrical conductivity.

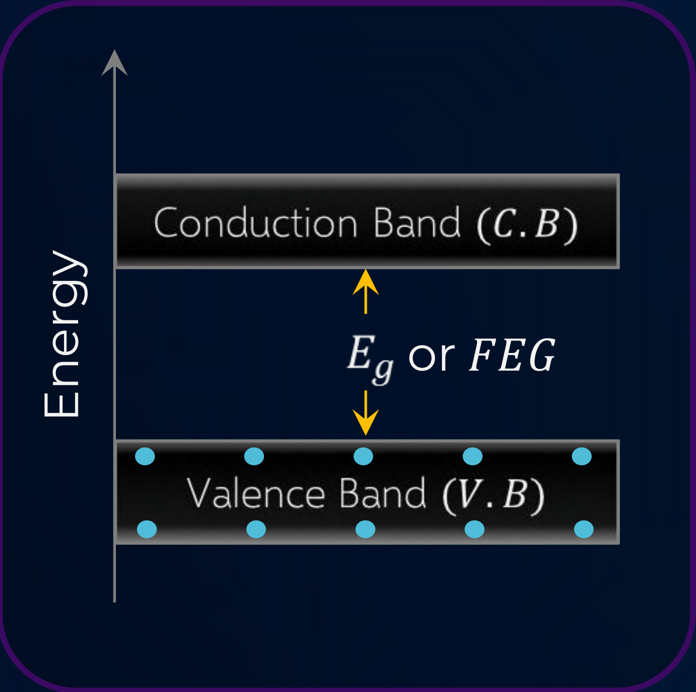
Forbidden Energy Gap (FEG)

Energy Gap (E_g)

Electrons in $V.B$ may gain energy and transit to $C.B$. These electrons cannot be found in the region between $V.B$ & $C.B$. The energies lying in between $V.B$ & $C.B$ are forbidden (restricted, prohibited) for electrons. Thus, there is an Energy Gap E_g also known as the Forbidden Energy Gap FEG.

$$E_g = (C.B)_{min} - (V.B)_{max}$$

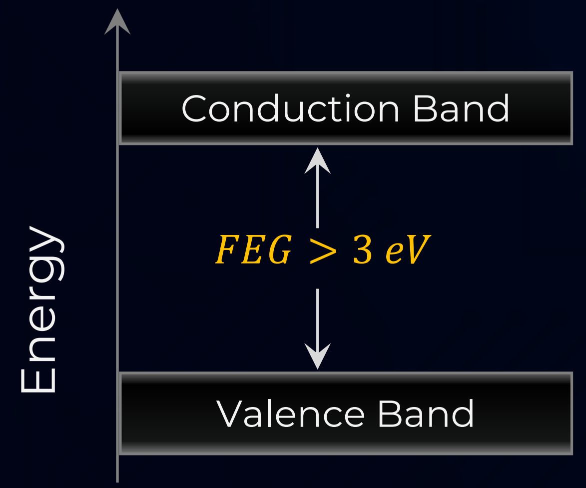
$$E_g = E_c - E_v$$



- When energy equal to E_g is provided, the electrons from the valence band jump into the conduction band leaving behind the holes in the valence band.

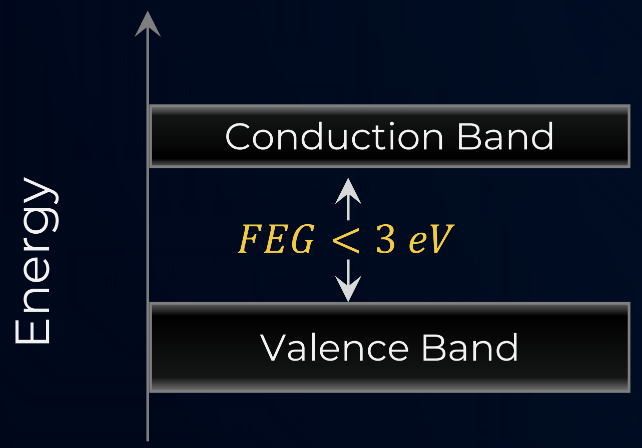
Energy Band in different type of Materials

Insulators



- e^- requires high temperature to jump from Valance Band to Conduction Band.
- No electrical conductivity

Semi-Conductors

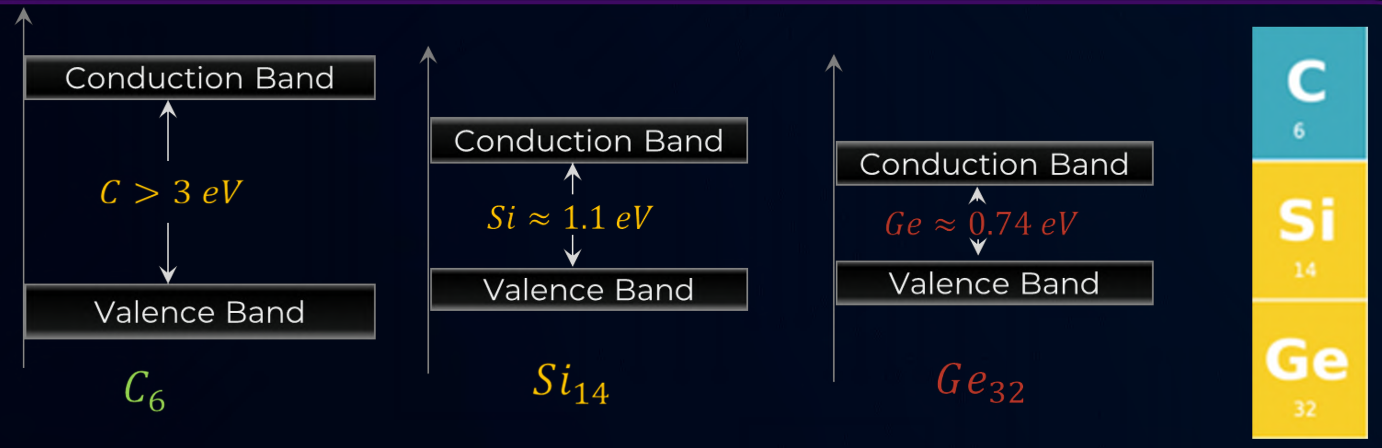


- e^- requires high temperature to jump from Valance Band to Conduction Band.
- Low electrical conductivity

Conductors

- e^- requires low temperature to jump from Valance Band to Conduction Band.
- High electrical conductivity

Carbon, silicon and germanium have energy band gap respectively equal to $(Eg)_C$, $(Eg)_{Si}$ and $(Eg)_{Ge}$. Which of the following statement is true?



As the size of the atom increases, the distance between valence electrons and the nucleus increases which means the influence of the nucleus on electrons will be less, and hence, a small amount of energy will be required to ionize them.

It implies that larger the size of the atom, lesser will be the energy band gap.

A $(Eg)_{Si} < (Eg)_{Ge} < (Eg)_C$

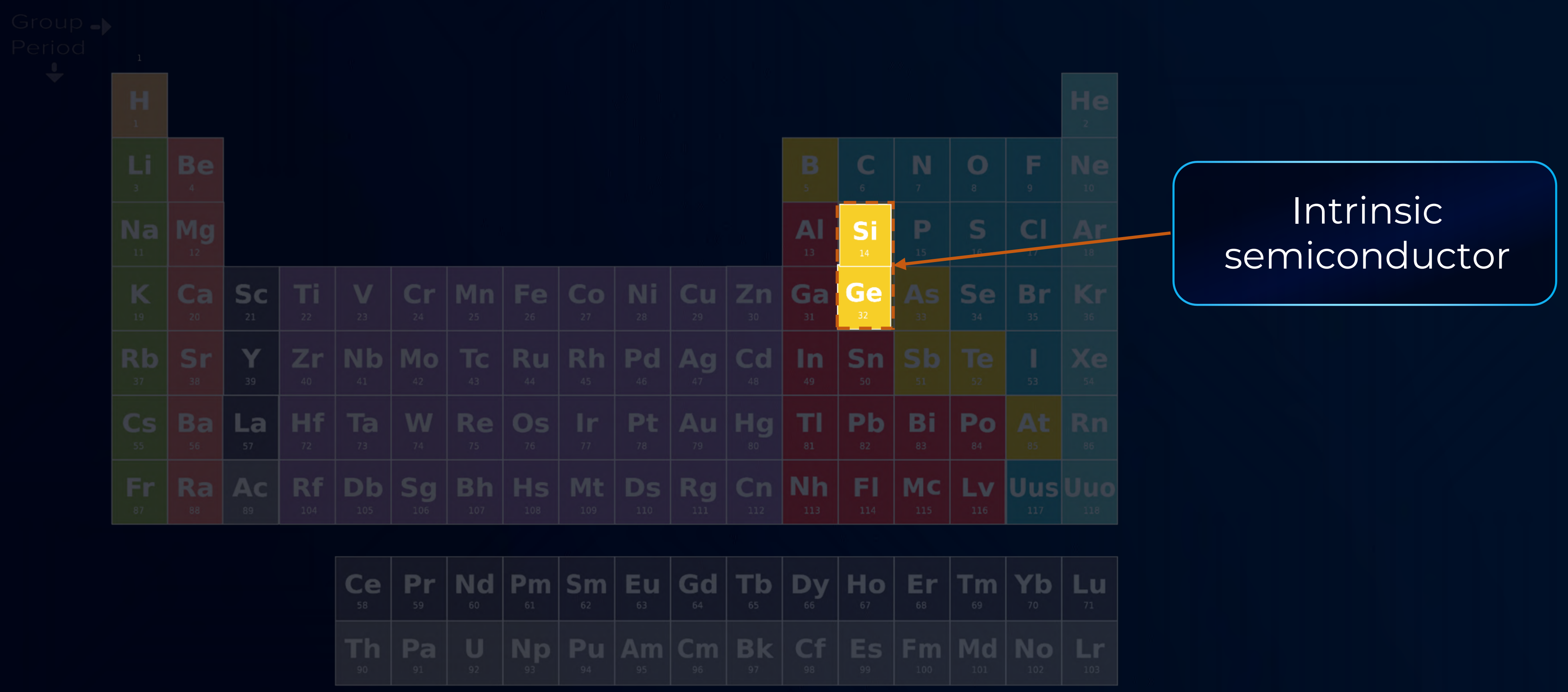
C $(Eg)_C < (Eg)_{Ge} > (Eg)_{Si}$

B $(Eg)_C > (Eg)_{Si} > (Eg)_{Ge}$

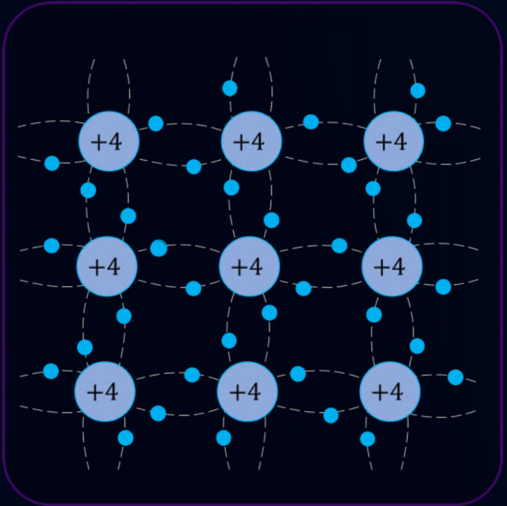
D $(Eg)_{Si} = (Eg)_{Ge} = (Eg)_C$

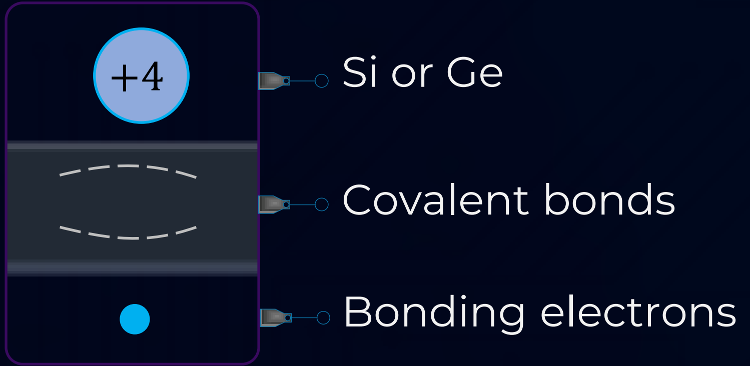
Intrinsic Semiconductor

A semiconductor that is chemically pure or free from impurities is known as an intrinsic semiconductor.

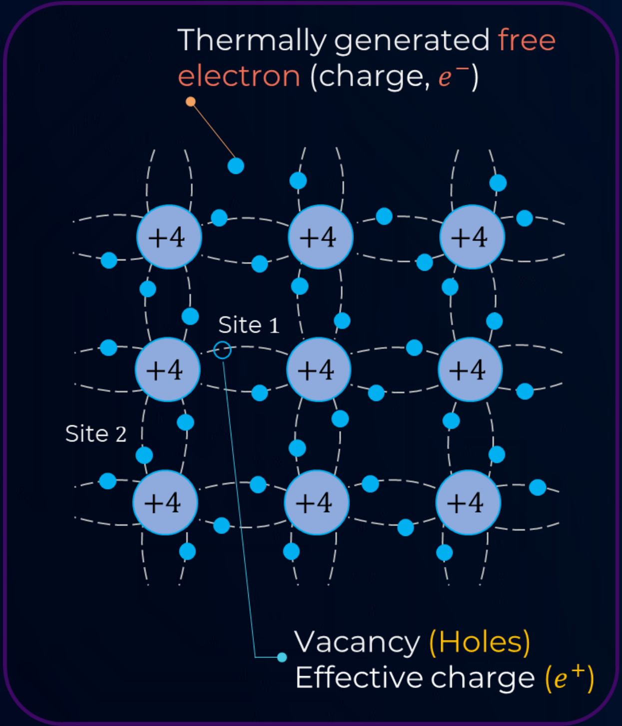


Intrinsic Semiconductor





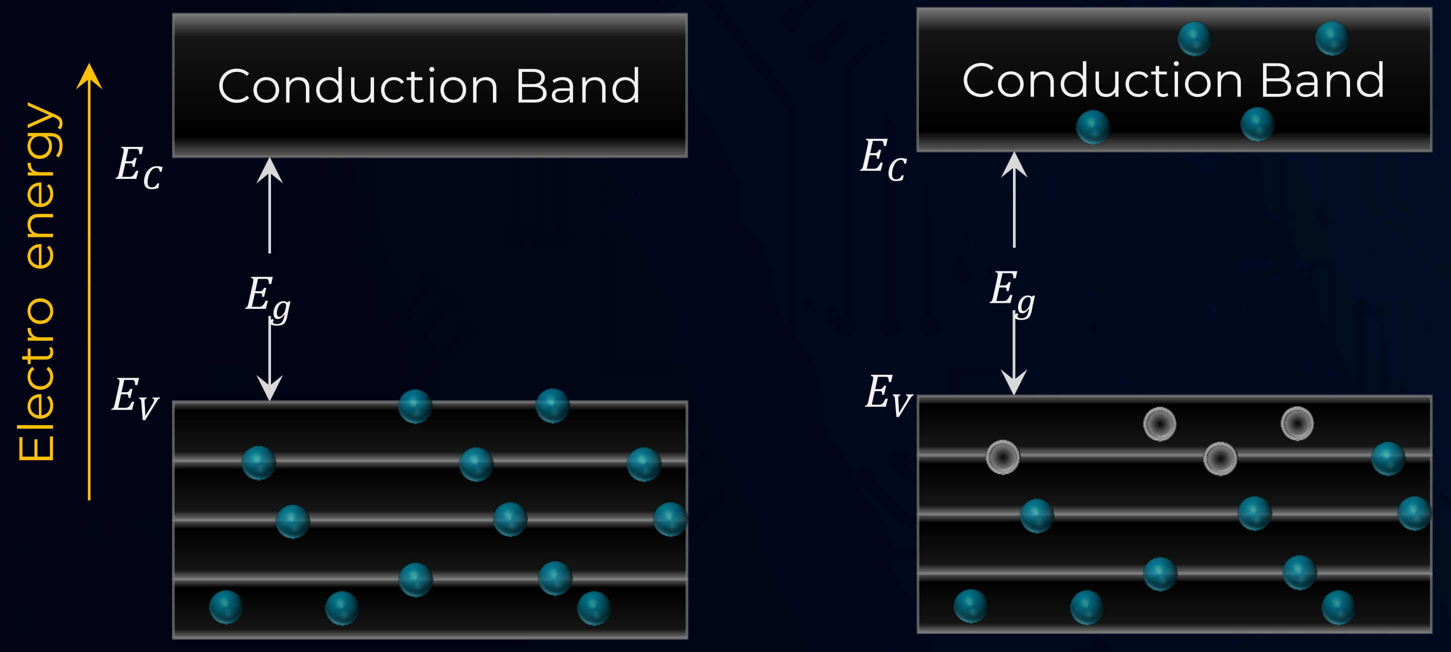
- Si and Ge have four valence electrons each.
- Si and Ge share one of its four valence electrons with each of its four nearest neighbour atoms. These shared electron pairs form covalent bond.



- This free electron will generate a vacancy. This vacancy with effective positive charge is called hole.
- It is possible that another bonded electron may try to fill this vacancy while creating a hole at its present site.
- In this way, the electrons keep on creating holes as they keep on filling the vacancies at other sites. This will seem as if the holes themselves are moving from one site to another.
- Electrons and holes are the energy/charge carriers:
- Current flowing in a semiconductor is due to both free electrons and holes.

$$\text{Total current} = I_e + I_h$$

Intrinsic Semiconductor (Si and Ge)

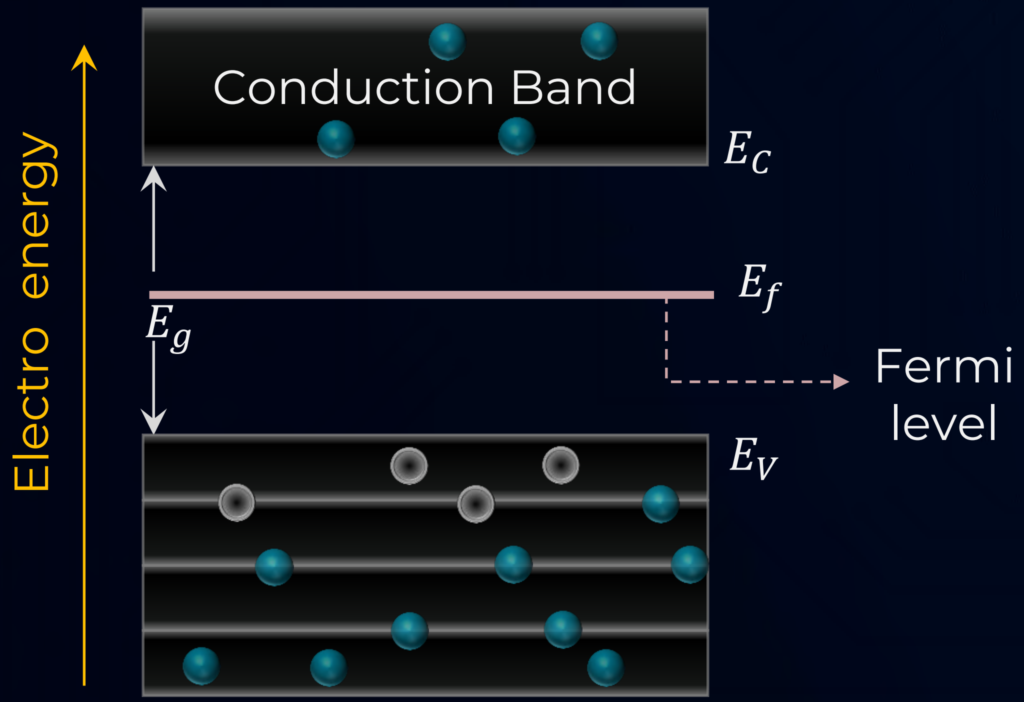


Intrinsic Semiconductor $@\, T = 0\ K$

Intrinsic Semiconductor $@\, T > 0\ K$

- Electron movement in $C.B.$ gives electron current(I_e)
- Hole movement in $V.B.$ gives hole current (I_h)

Fermi level of Intrinsic Semiconductor

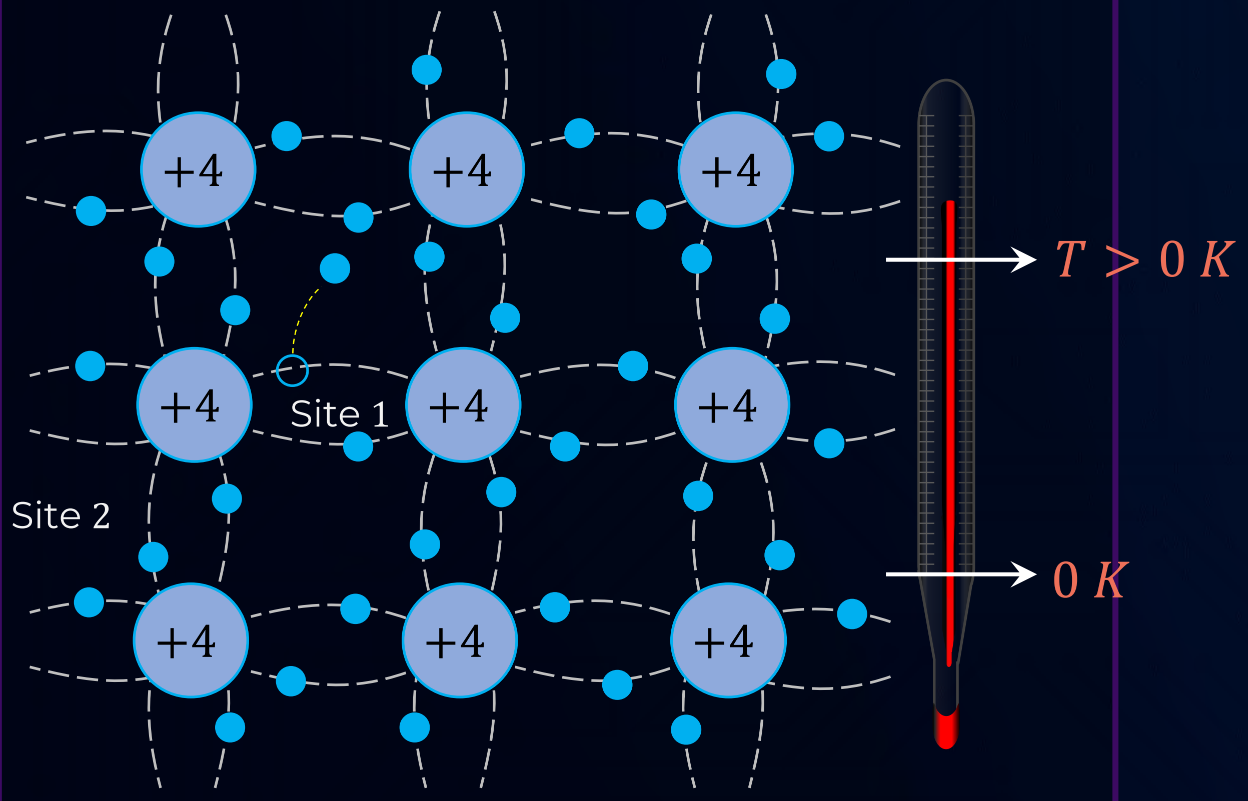


Intrinsic Semiconductor $@\ T > 0\ K$

- The highest energy level that an electron can occupy at the absolute zero temperature is known as the Fermi Level.

- In intrinsic semiconductors, the n_h in the valence band is equal to the n_e in the conduction band. Hence, the probability of occupation of energy levels in the conduction band and valence band are equal. Therefore, the Fermi level for the intrinsic semiconductor lies in the middle of the band gap.

Intrinsic Semiconductor



- In the case of intrinsic semiconductors, the number density of free electrons is equal to the number density of holes.

$$n_e = n_h = n_i$$

- Apart from the process of generation of conduction electrons and holes, a simultaneous process of recombination occurs in which electrons recombine with the holes. At equilibrium,

Rate of generation = Rate of recombination

Limitations of Intrinsic Semiconductors

- In intrinsic semiconductors, current is controlled by the temperature and not by the user.
- Magnitude of current is very small at normal temperature.

$$i = neAv_d$$

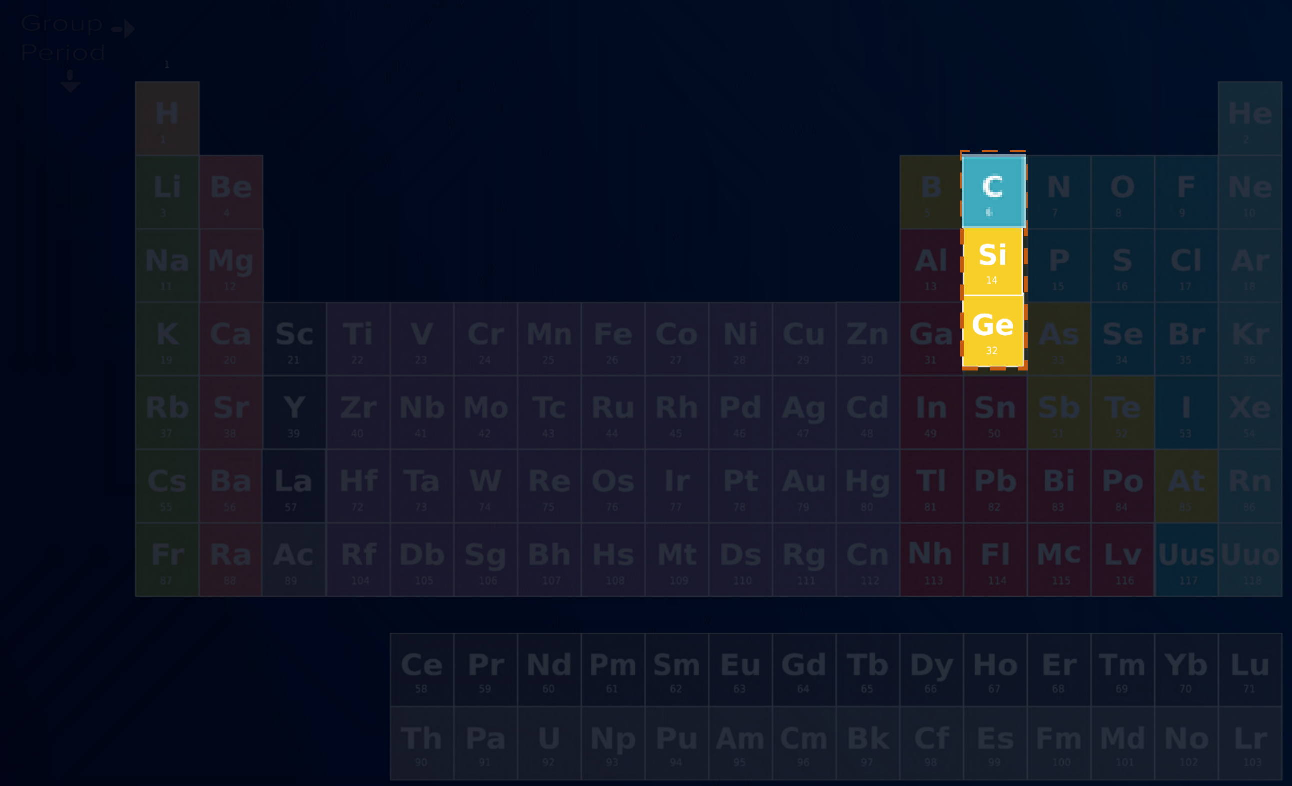
Where,

n = Number of charge carriers per unit volume.
e = Charge on electrons.
A = Cross-sectional area of conductor.
v_d = drift velocity.

- $n_e = n_h$, hence they have poor efficiency.

n_e = Number of free electrons

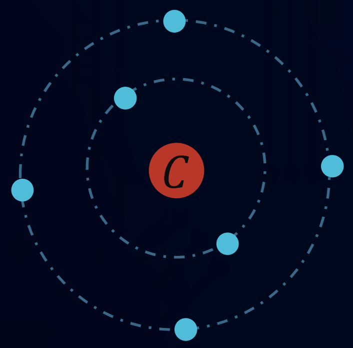
n_h = Number of holes



Why is carbon not an intrinsic semiconductor although it lies in the same group of periodic table as germanium and silicon?

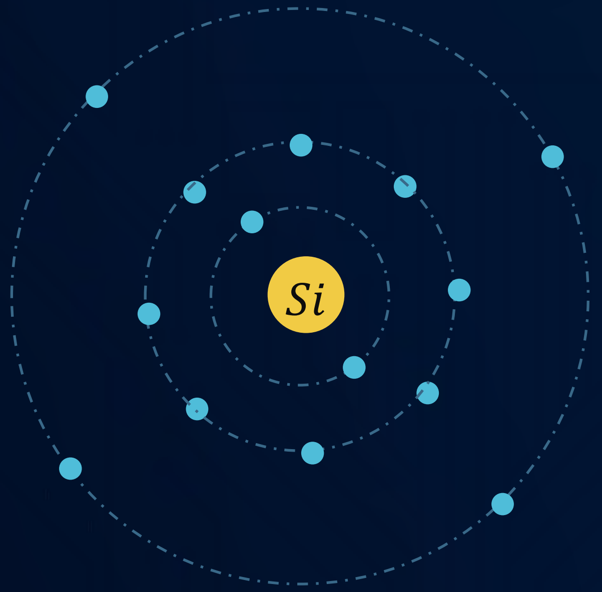
The electronic configuration of carbon (C):

$$C_6^{12} = 1s^2\ 2s^2 2p^2$$



The electronic configuration of Silicon (Si):

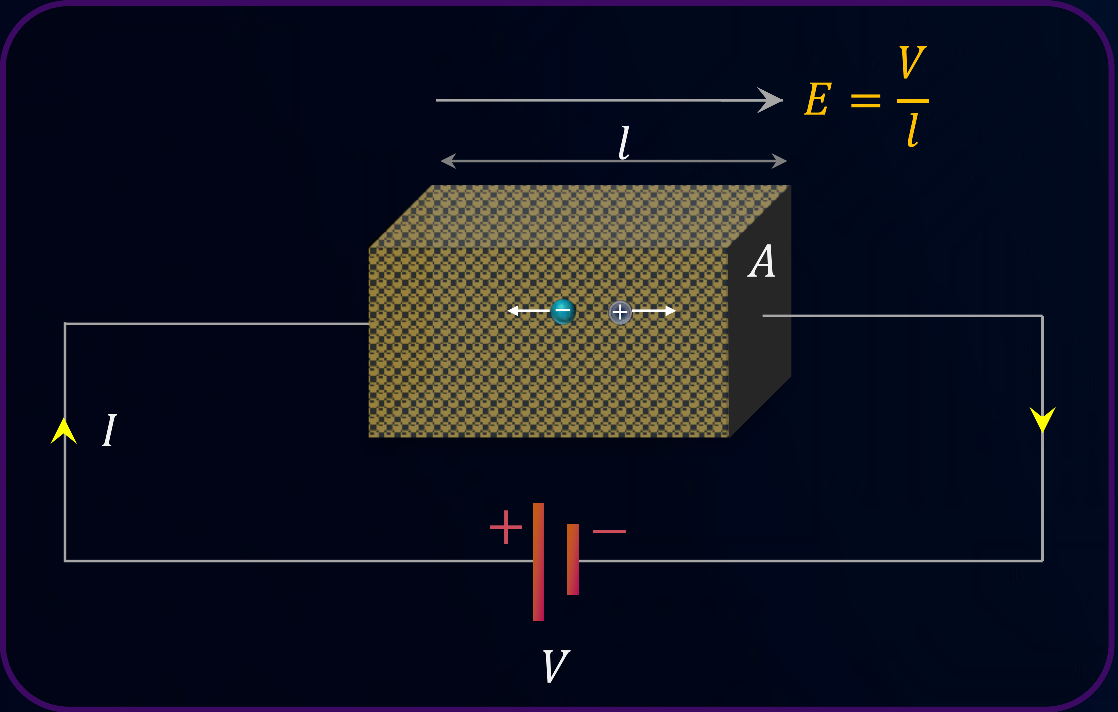
$$Si_{14}^{28} = 1s^2\ 2s^2 2p^6\ 3s^2 3p^2$$



Hence, the four valence electrons are closer to nucleus for C and away from nucleus for Si. So, effect of nucleus on valence electrons is low for Si and high for C.

Energy gap between the conduction band and valence band is least for Ge, followed by Si and highest for C.

Intrinsic Semiconductor: Conductivity (σ)



Let, e = Charge on the electron,
n_h = Number density of holes,
n_e = Number density of electrons,
μ_e = Mobility of electrons,
μ_h = Mobility of holes

We know,

Conductivity $\sigma = \frac{1}{\rho}$ Mobility $\mu = \frac{v_d}{E}$

$V = E.l$ $i = neAv_d$ $R = \rho l/A$

Now,

$$V = iR$$

$$E.l = neAv_d \frac{\rho l}{A}$$

$$\frac{1}{\rho} = ne \frac{v_d}{E} \Rightarrow \boxed{\sigma = ne\mu}$$

For Semiconductor,

$$\sigma = \sigma_{electrons} + \sigma_{holes} = n_e e \mu_e + n_h e \mu_h$$

$$\boxed{\sigma = e(n_e \mu_e + n_h \mu_h)}$$

- Mobility of electrons are more than holes. $(\mu_e > \mu_h)$

Extrinsic Semiconductors

- Extrinsic semiconductors are obtained when a measured and small amount of chemical impurity is added to the intrinsic semiconductors.

- Extrinsic semiconductors are doped intrinsic semiconductors.

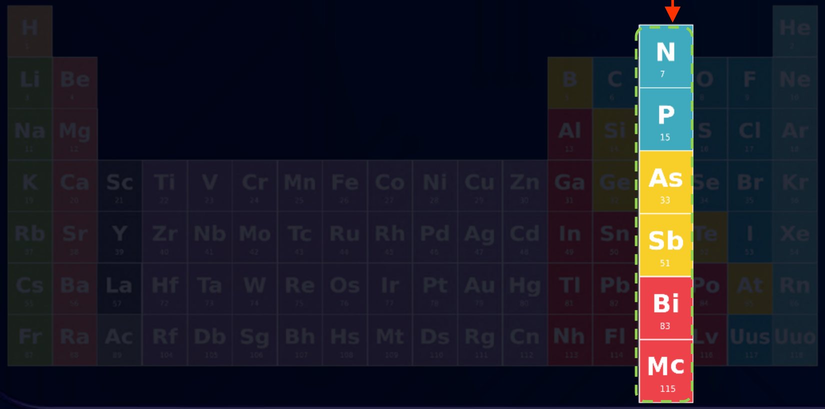
- Doping is a process of replacement of a small number of atoms in the lattice by atoms of neighbouring columns from the periodic table.

- These doped atoms create energy levels within the band gap and therefore alter the conductivity.

Extrinsic Semiconductor

n-type semiconductors

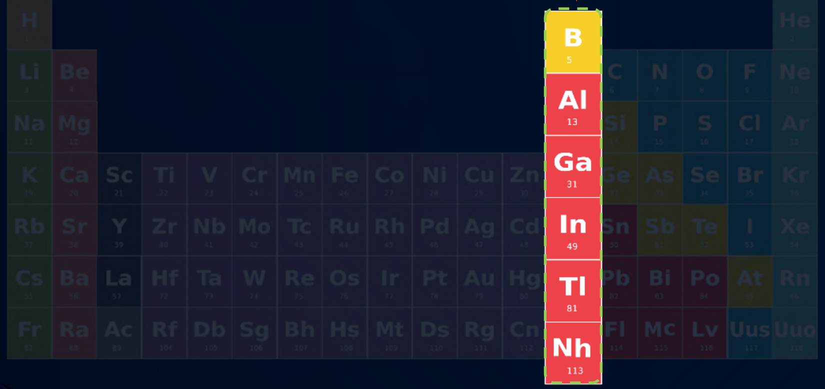
Pentavalent atoms



- Pentavalent atoms – 5 valence electrons.
- It is formed when pentavalent atoms are doped into an intrinsic semiconductor.

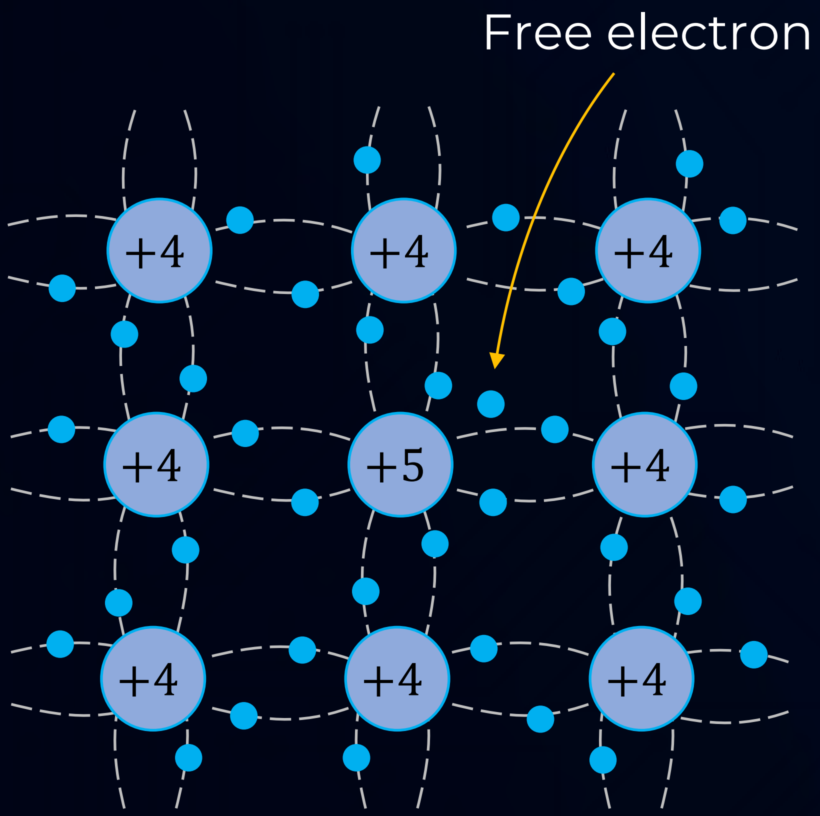
p-type semiconductors

Trivalent atoms



- Trivalent atoms – 3 valence electrons.
- It is formed when trivalent atoms are doped into an intrinsic semiconductor.

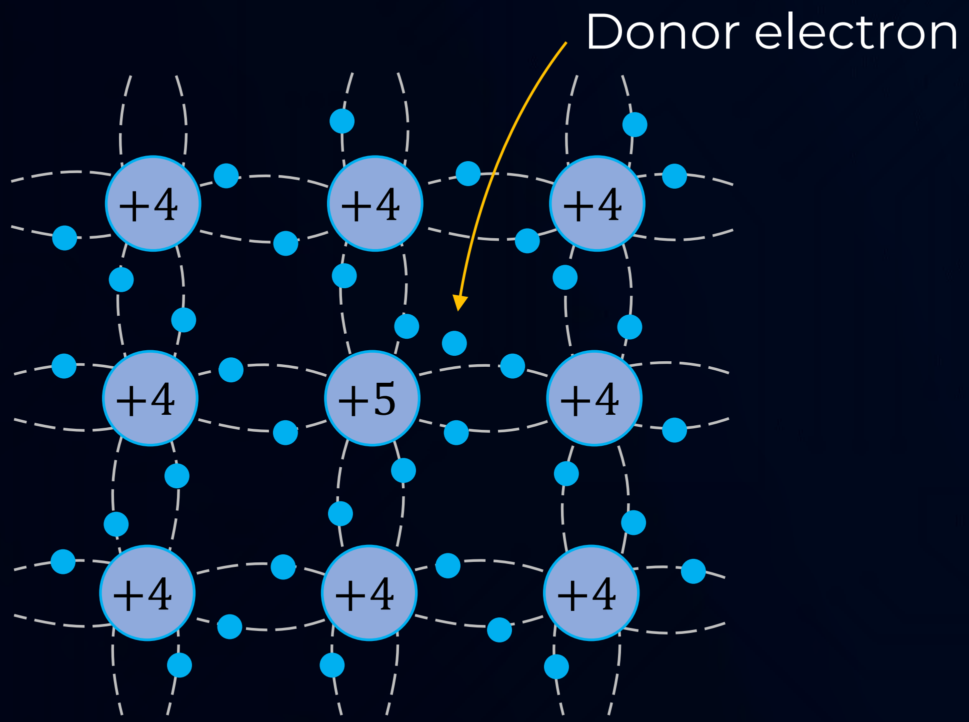
N – type Semiconductor

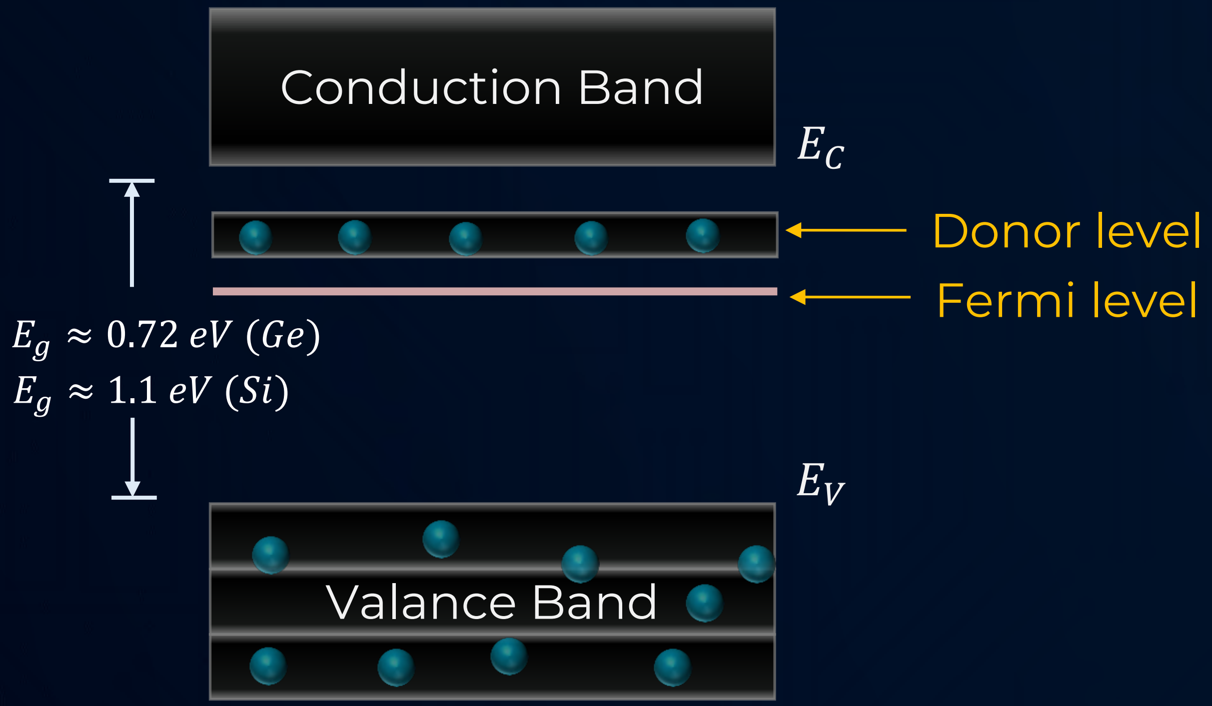


N-type semiconductor

- 5 valence electrons of P form 4 covalent bonds with neighbouring Si atoms; hence, one electron becomes extra in the lattice.
- The ionisation energy required for the 5^{th} valence electron is very low ($0.01\ eV$ for Ge and $0.05\ eV$ for Si) and thus valence electron goes very easily to conduction band.
- The number of $(e - h)$ pair generated will be very less, as more energy is required in breaking a bond and get the pair generated.
- An n-type semiconductor is electrically neutral, not negatively charged.
- Charge carriers
  - Electrons (doping)
  - Electrons & holes ($e - h$ pair generation)
- Free electrons are majority charge carriers.
- Holes are minority charge carriers.
- The pentavalent dopant donates one extra electron for conduction and hence known as donor impurity.
- $n_e \gg n_h$

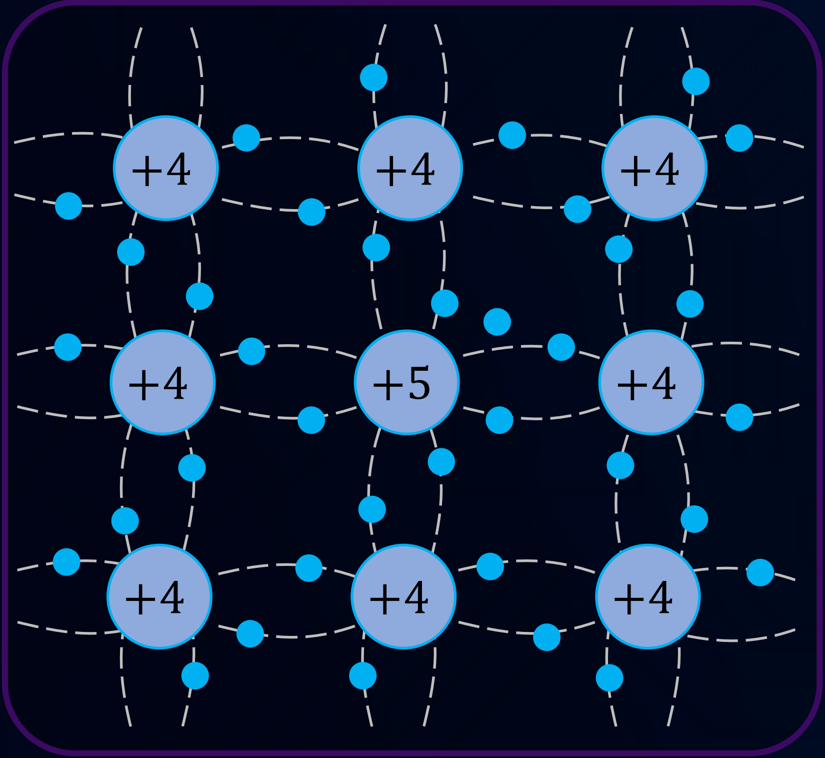
Energy Band for N – Type Semiconductor



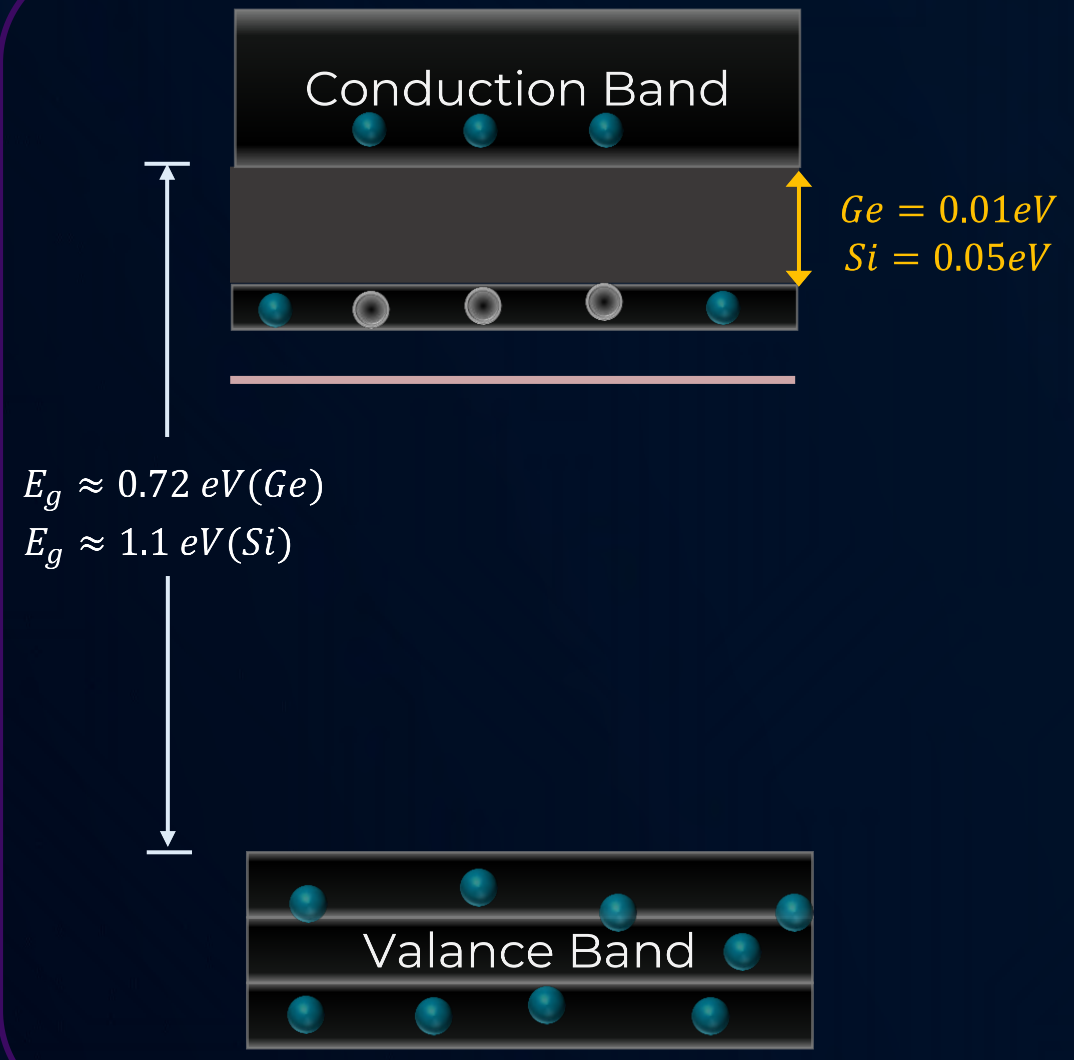


- Fermi level is present near the conduction band and far away from the valence band.
- Energy level of free electron of pentavalent atom which is called a donor electron is very close to the conduction band. So, with small amount of energy electrons will go into the conduction band.
- The energy level of the free electron of a pentavalent atom is called the donor level.

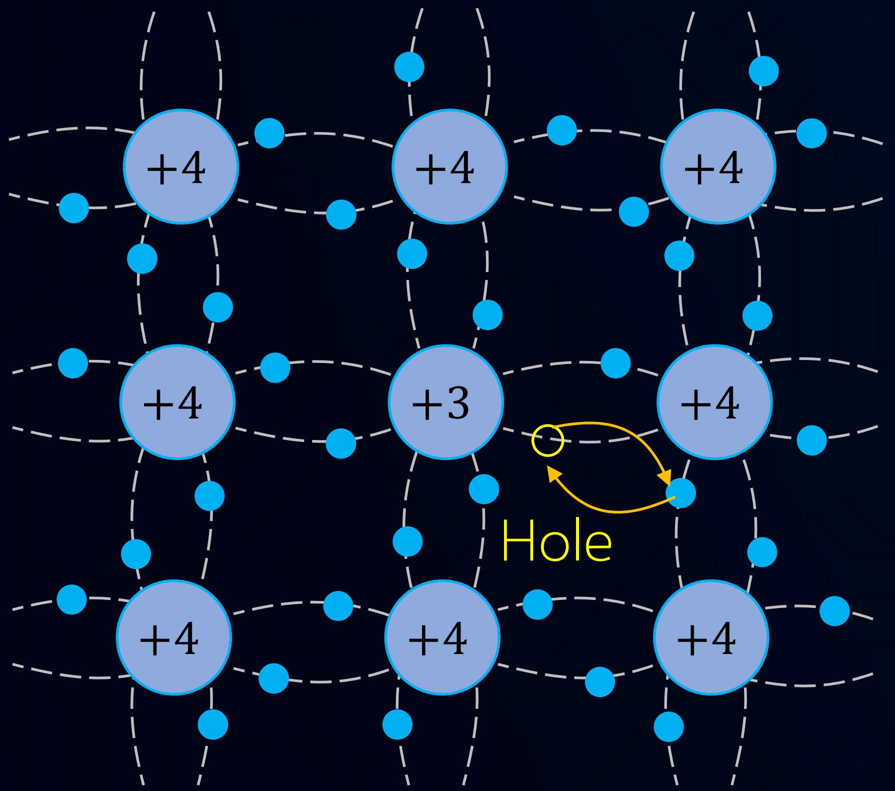
Energy Band for N – Type Semiconductor



- N –type semiconductors are electrically neutral.
- Pentavalent impurity brings one extra electron but also brings one extra proton which makes the semiconductor neutral.



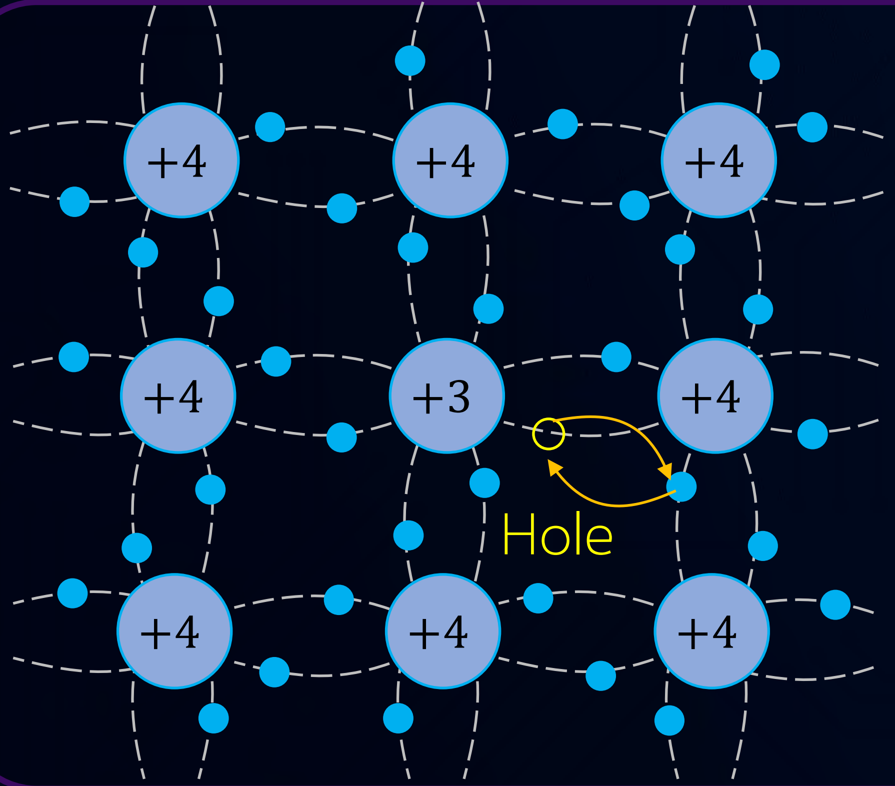
P – type Semiconductor

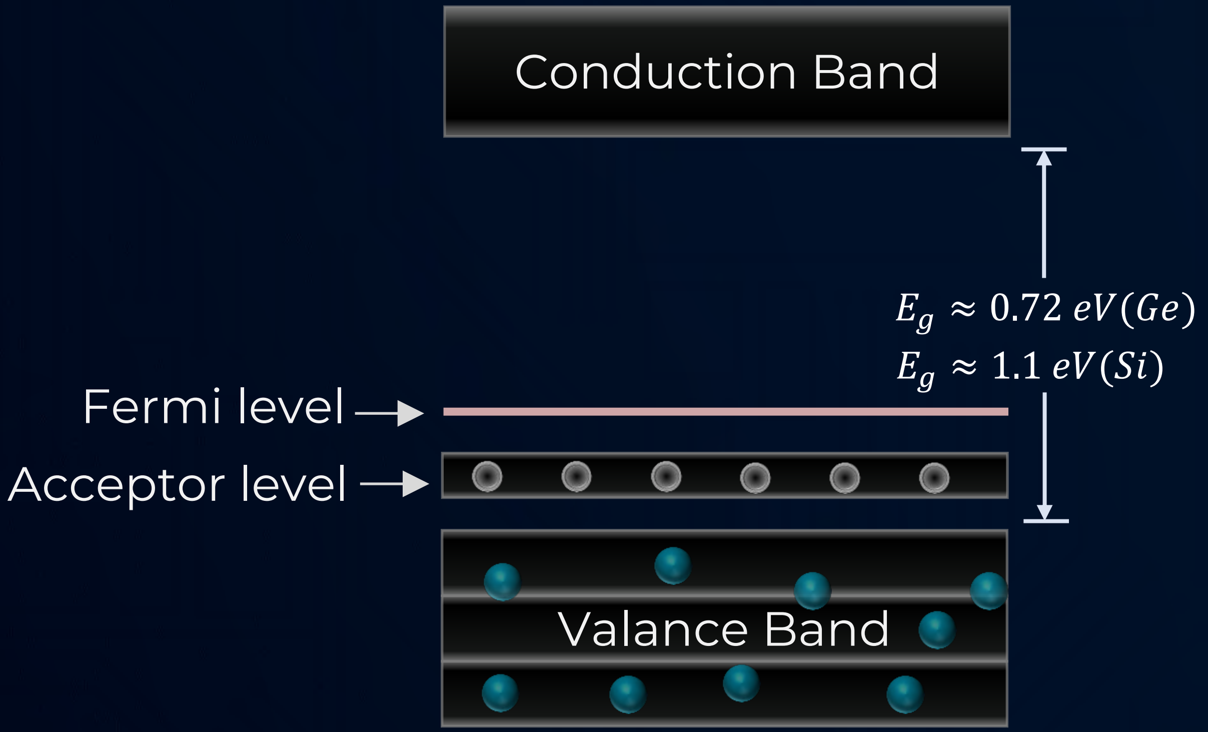


P-type semiconductor

- Since the dopant is trivalent, it has 1 valence e^- less than Si or Ge and hence, a hole is generated.
- An electron from a nearby covalent bond may recombine with a hole and a new hole appears at the site of electron. This way the movement of the hole continues.
- Trivalent impurity accepts an electron from neighbouring atom and hence it is called acceptor impurity.
- Charge carriers
  - Holes (doping)
  - Electrons & holes ($e - h$ pair generation)
- Holes are majority charge carriers.
- Free electrons are minority charge carriers.
- $n_h \gg n_e$

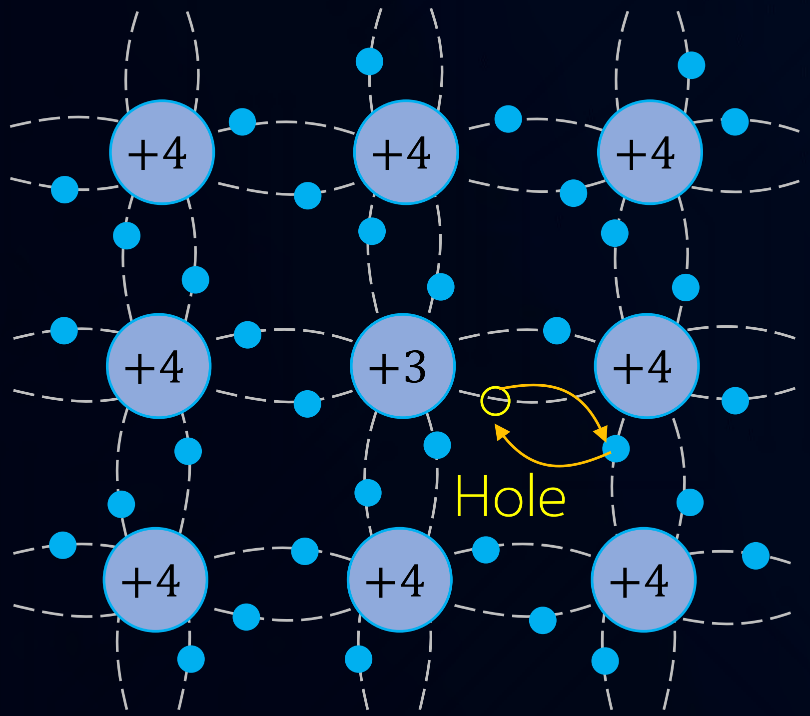
Energy Band P – Type Semiconductor



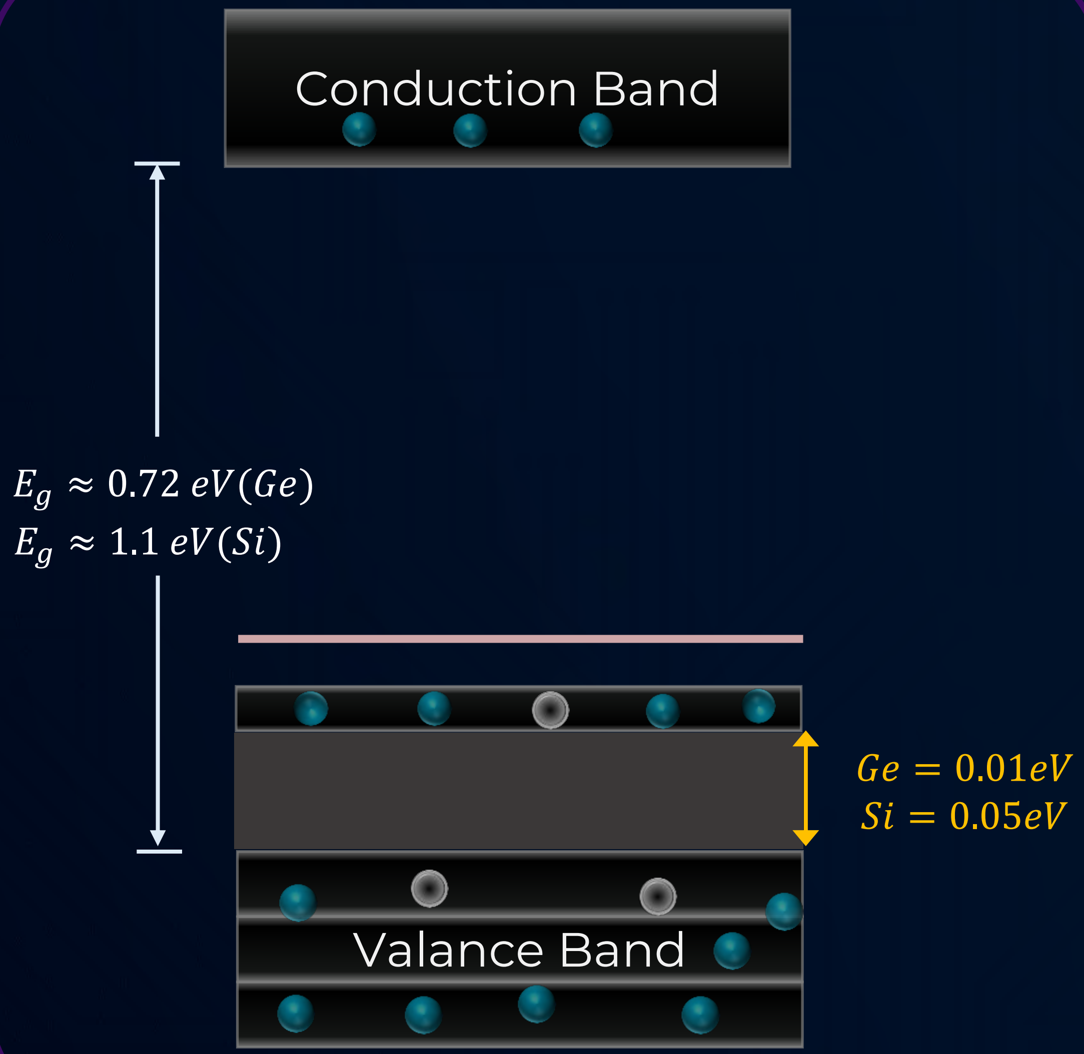


- Fermi level lies above the valence band, and it is closer to the valence band.
- The energy level of the holes created by trivalent atom is called the acceptor level.
- Acceptor level is very close to the valence band. With a small amount of energy, a bonded electron can fill the vacant space created due to a trivalent atom which leads to improved conductivity.

Energy Band P – Type Semiconductor



- *P* –type semiconductors are electrically neutral.
- Trivalent impurity is short of one valence electron, but it is also short of one proton which makes the semiconductor neutral.



Which of the following statement is false?

A. The resistance of intrinsic semiconductor decreases with the increase of temperature.

B. Majority carriers in n – type semiconductors are holes.

C. Pure Si doped with trivalent impurities gives a p – type semiconductor.

D. Minority carriers in a p – type semiconductors are electrons.

Relation between Electron Concentration and Hole Concentration

- For an intrinsic semiconductor, the electron concentration and hole concentration are equal.

  $n_i \rightarrow$ Electron concentration / Hole concentration of an intrinsic semiconductor

- For an extrinsic semiconductor,

  $n_e \rightarrow$ Number of free electrons per unit volume (Electron concentration)

  $n_h \rightarrow$ Number of holes per unit volume (Hole concentration)

- The electron and hole concentration in a semiconductor in thermal equilibrium is given by,

$$n_e n_h = n_i^2$$

A pure silicon crystal has 5×10^{28} atoms per unit volume. It is doped with 1 ppm of pentavalent arsenic. Calculate the number density of holes in the doped silicon crystal. (Intrinsic number density, $n_i = 1.5 \times 10^{16}\ m^{-3}$)

Given: $n = 5 \times 10^{28}\ m^{-3};\ n_i = 1.5 \times 10^{16}\ m^{-3}$

To find: Hole concentration (n_h)

Solution:

1 atom of arsenic is doped in 10^6 atoms of silicon (1 ppm). The free electron concentration in the doped silicon is given by,

$$n_e = \frac{5 \times 10^{28}}{10^6} = 5 \times 10^{22}\ m^{-3}$$

At thermal equilibrium, $n_e n_h = n_i^2$

$$n_h = \frac{(1.5 \times 10^{16})^2}{5 \times 10^{22}} = 4.5 \times 10^9\ m^{-3}$$

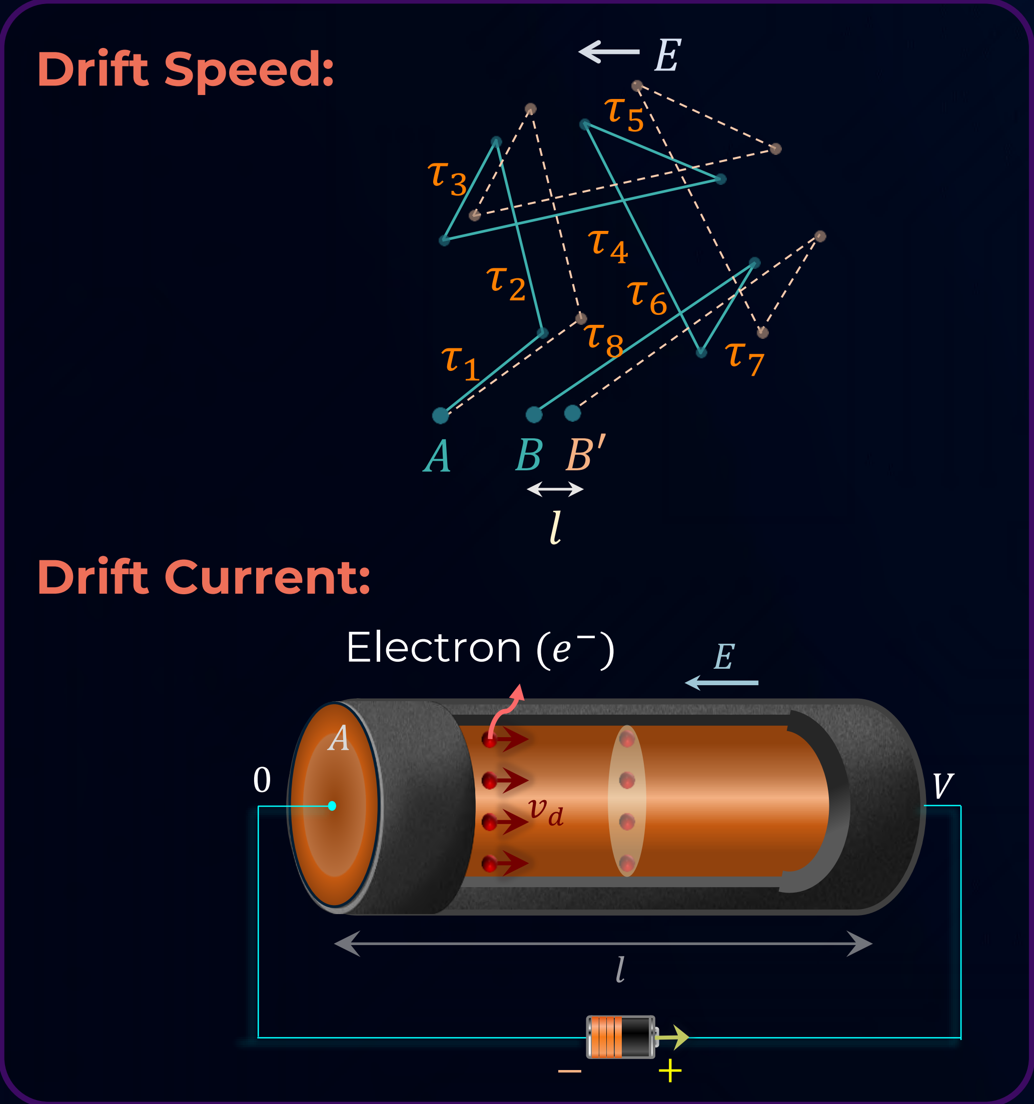
A. $4.5 \times 10^9\ m^{-3}$

B. $8 \times 10^{10}\ m^{-3}$

C. $4 \times 10^{10}\ m^{-3}$

D. $2.5 \times 10^{10}\ m^{-3}$

Drift Speed, Mobility and Drift Current



Drift Speed: The average speed attained by charge carriers (electrons here) in a conductor in a direction opposite to the electric field is:

$$\vec{v_d} = -\frac{e\tau\vec{E}}{m}$$

Mobility: The value of the drift speed per unit of electric field strength. So, the faster the particle moves at a given electric field strength, the larger the mobility.

$$\mu = \frac{|\vec{v_d}|}{E} = \frac{e\tau}{m}$$

$$\mu_h < \mu_e$$

Drift Current: is due to the motion of charge carriers due to the force exerted on them by an electric field:

$$I = neAv_d$$

$$J = \frac{I}{A} = nev_d$$

Mobility of electrons in a semiconductor is defined as the ratio of their drift velocity to the applied electric field. If for an n-type semiconductor, the density of electrons is $10^{19}\ m^{-3}$ and their mobility is 1.6 $\frac{m^2}{V.s}$ then the resistivity of the semiconductor (contribution of holes is ignored) is close to

Given: $n_e = 10^{19}\ m^{-3}$; $\mu_e = 1.6\ m^3/Vs$

Current density,

$J = \sigma E$ also, $J = \frac{I}{A} = nev_d$

$\sigma \rightarrow$ Conductivity

$\rho \rightarrow$ Resistivity

$\sigma E = nev_d \Rightarrow \sigma = ne\frac{v_d}{E} = ne\mu$

$\sigma = e(n_e\mu_e + n_h\mu_h)$

$\sigma = en_e\mu_e$ (contribution of holes is ignored)

$$\rho = \frac{1}{\sigma} = \frac{1}{(1.6 \times 10^{-19})(10^{19})(1.6)}\ \Omega m$$

$$\rho = \frac{1}{2.56} \approx 0.4\ \Omega m$$

A. $0.2\ \Omega m$

B. $2\ \Omega m$

C. $4\ \Omega m$

D. $0.4\ \Omega m$

If the ratio of the concentration of electrons to that of holes in a semiconductor is 7/5 and the ratio of currents is 7/4, then what is the ratio of their drift velocities?

$$\frac{i_e}{i_h} = \frac{7}{4} \qquad \frac{n_e}{n_h} = \frac{7}{5}$$

$$I = neAv_d \Rightarrow v_d \propto \frac{I}{n}$$

$$\frac{(v_d)_e}{(v_d)_h} = \frac{I_e n_h}{n_e I_h} = \frac{7 \times 5}{4 \times 7}$$

$$\frac{(v_d)_e}{(v_d)_h} = \frac{5}{4}$$

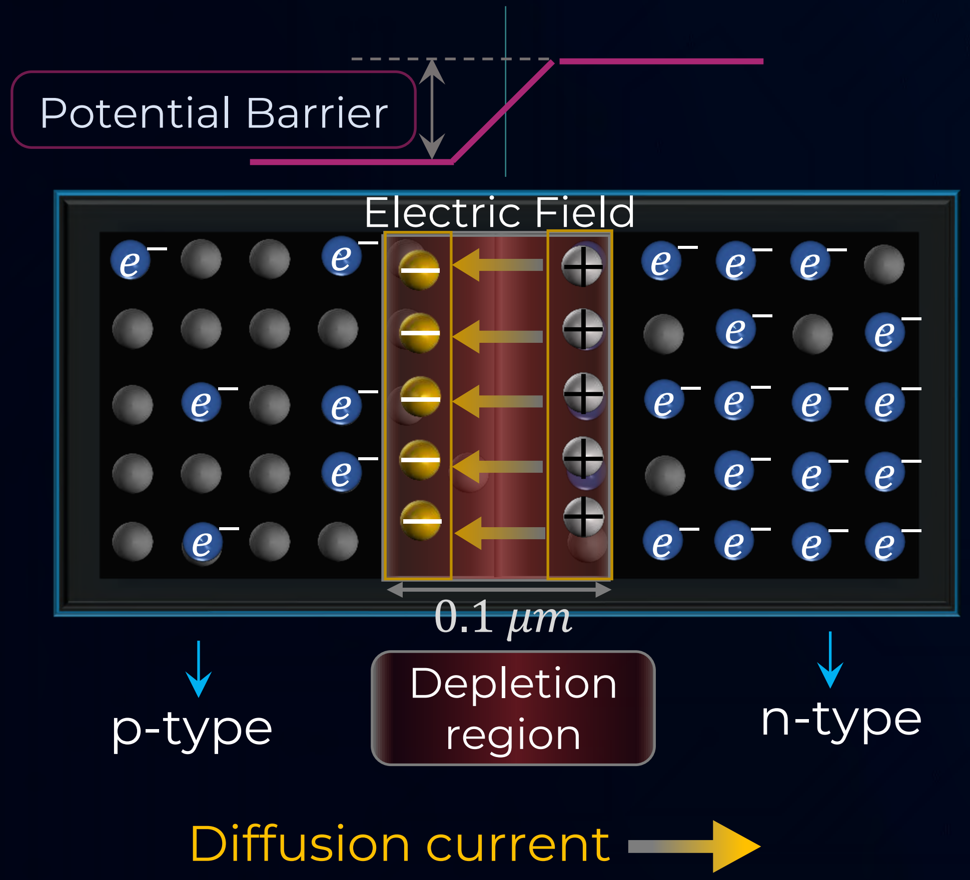
A. 4/7

C. 4/5

B. 5/8

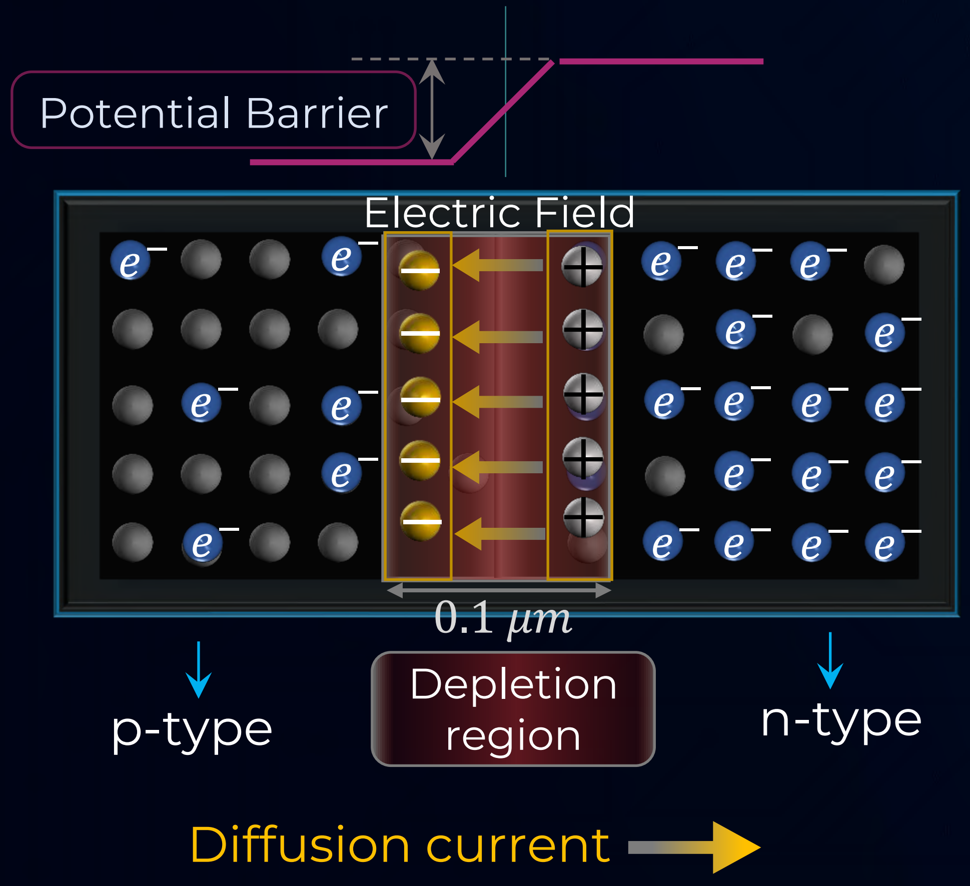
D. 5/4

$P - N$ Junction



- The holes on p side diffuse towards the n side. While the electrons on n side diffuse towards p side.
- Diffusion current is due to the movement of these majority charge carriers.
- The direction of diffusion current is from p side to n side.
- Accumulation of positive charge on n side
  Accumulation of negative charge on p side.
- This region at the junction is called the depletion region.

$P-N$ Junction

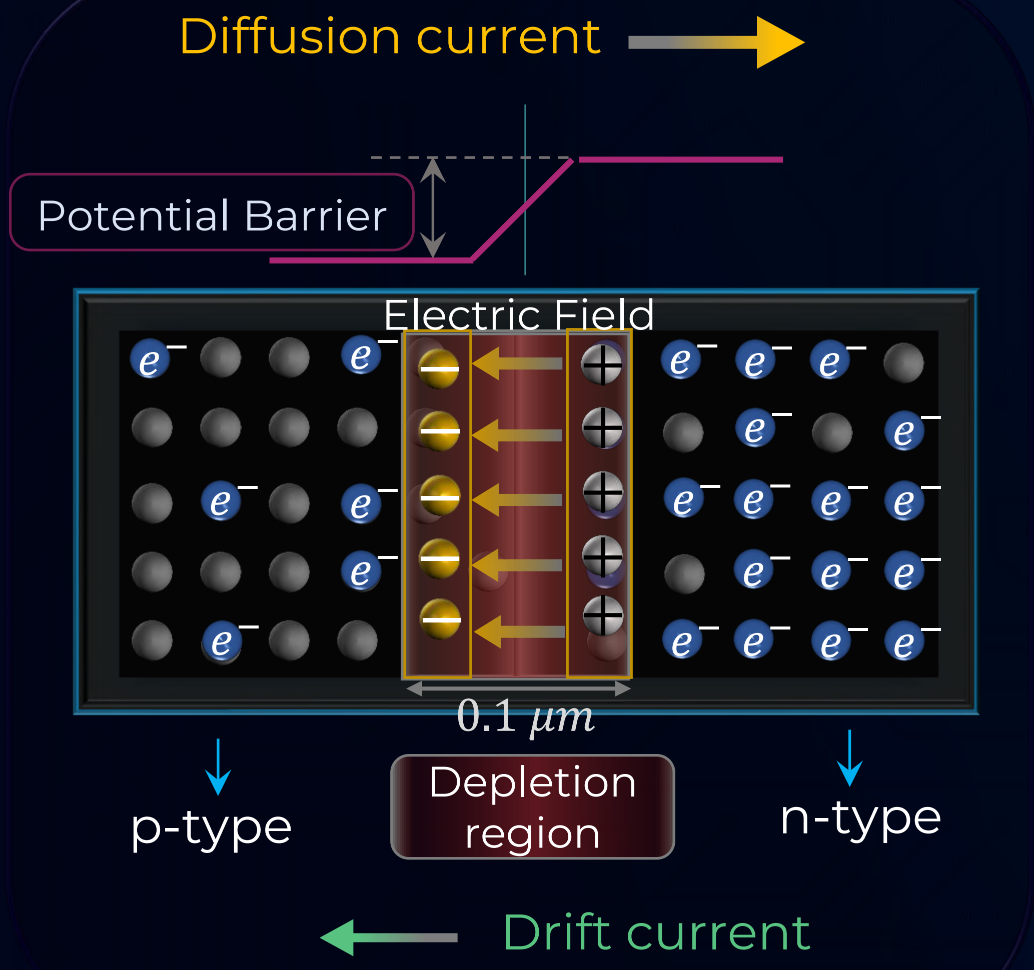


- This accumulation of negative and positive charges at the junction creates an electric field whose direction is from n type to p type semiconductor. This electric field restricts the movement of the majority of charge carriers.

- The electric field creates a sort of potential barrier and any charge carrier either hole or electron has to overcome this barrier to diffuse to the other side of junction.

- The magnitude of diffusion current decreases but, it never becomes zero, as there will be few majority charge carriers which will have enough energy to move to the other side.

$P - N$ Junction

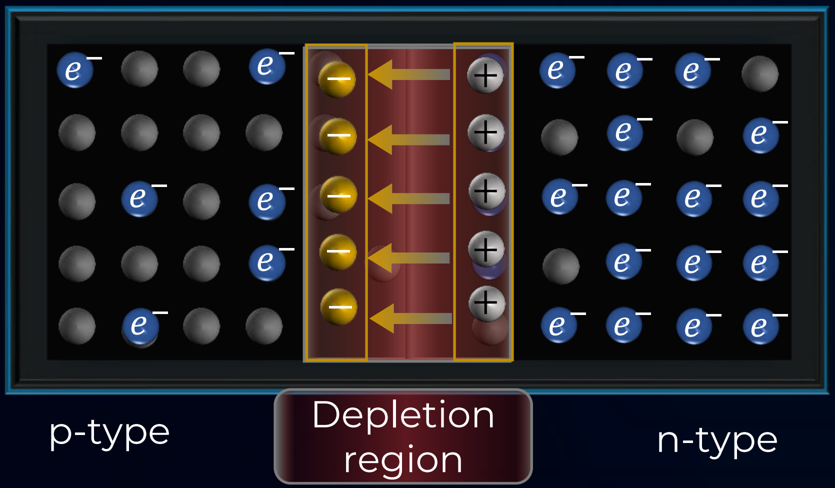


- The electric field will help the minority charge carriers (i.e., the electrons for p type and holes for n type semiconductor) to move to the other side of the junction.
- The current generated due to the movement of minority charge carriers is called the drift current.
- The direction of drift current is from n side to p side.

$P - N$ Junction

Initially,

Only Diffusion current →



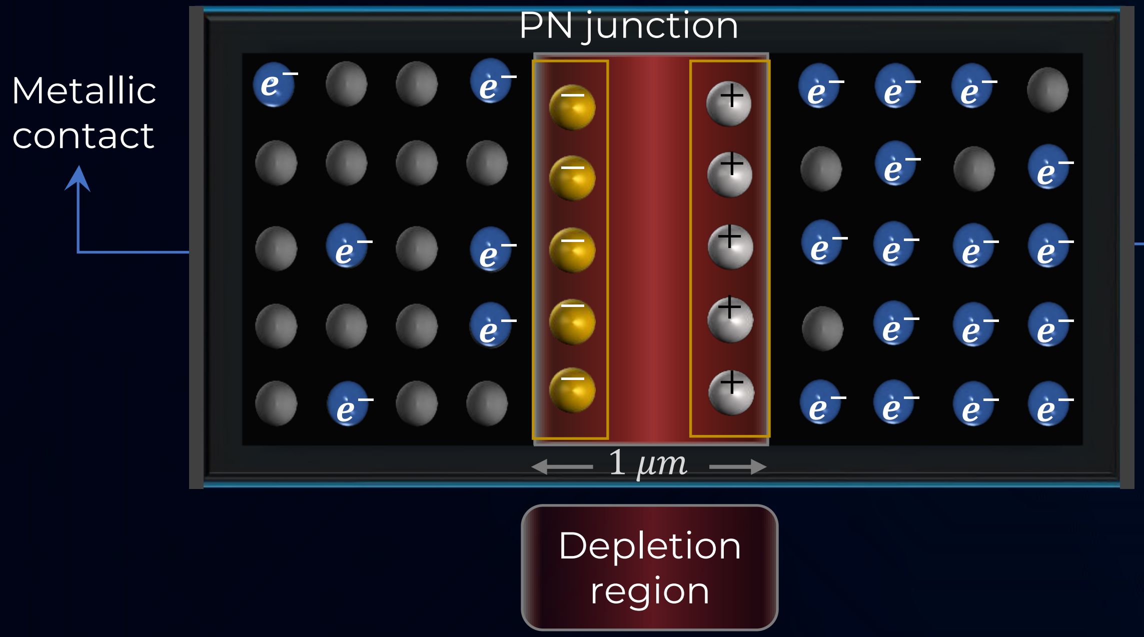
After Depletion region formed,

Diffusion current decreases →

← Drift current increases

$P-N$ Junction (at Steady State)

In equilibrium,

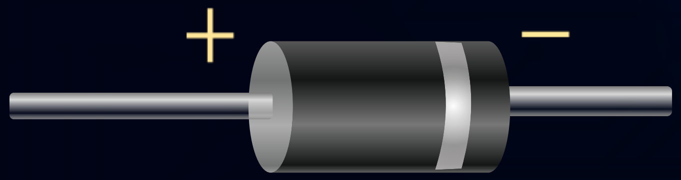


Diffusion current = Drift current

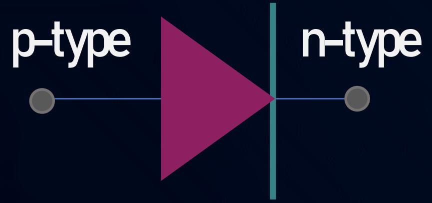
- To use the PN junction in practical circuit, metallic contacts are made at two ends, as shown in figure, and the complete set up is known PN junction diode.
- On changing the polarity of an external battery connected to the diode, the behavior of the diode changes completely.

Diode

- Diode is a two-terminal electronic component that conducts electricity primarily in one direction.
- Diode offers high resistance to flow of current in one direction and low resistance to the flow in opposite direction.
- A diode is basically a junction created by doping both pentavalent atoms and trivalent atoms together in an intrinsic semiconductor.
- Majority charge carriers diffuse from either sides due to the concentration gradient and as a result, when equilibrium is reached, a p-n junction (Diode) is formed.



Diode

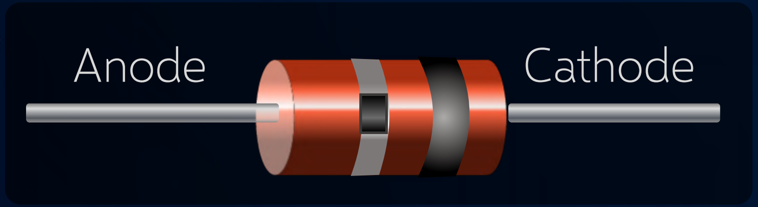


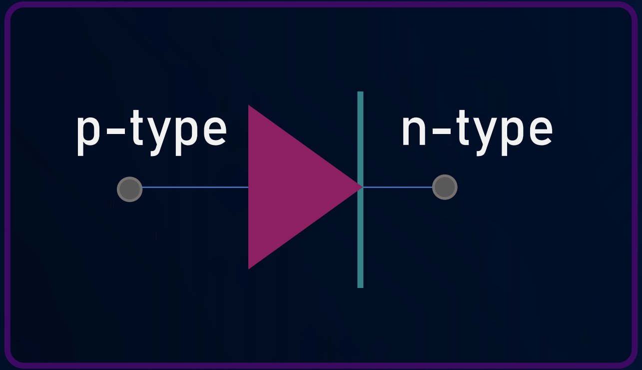
- p-n Junction Diode
- Photo Diode
- Zener Diode
- Light Emitting Diode (LED)

Diode

A semiconductor diode is basically a p-n junction with metallic contacts provided at the ends for the application of an external voltage which can alter the barrier potential.

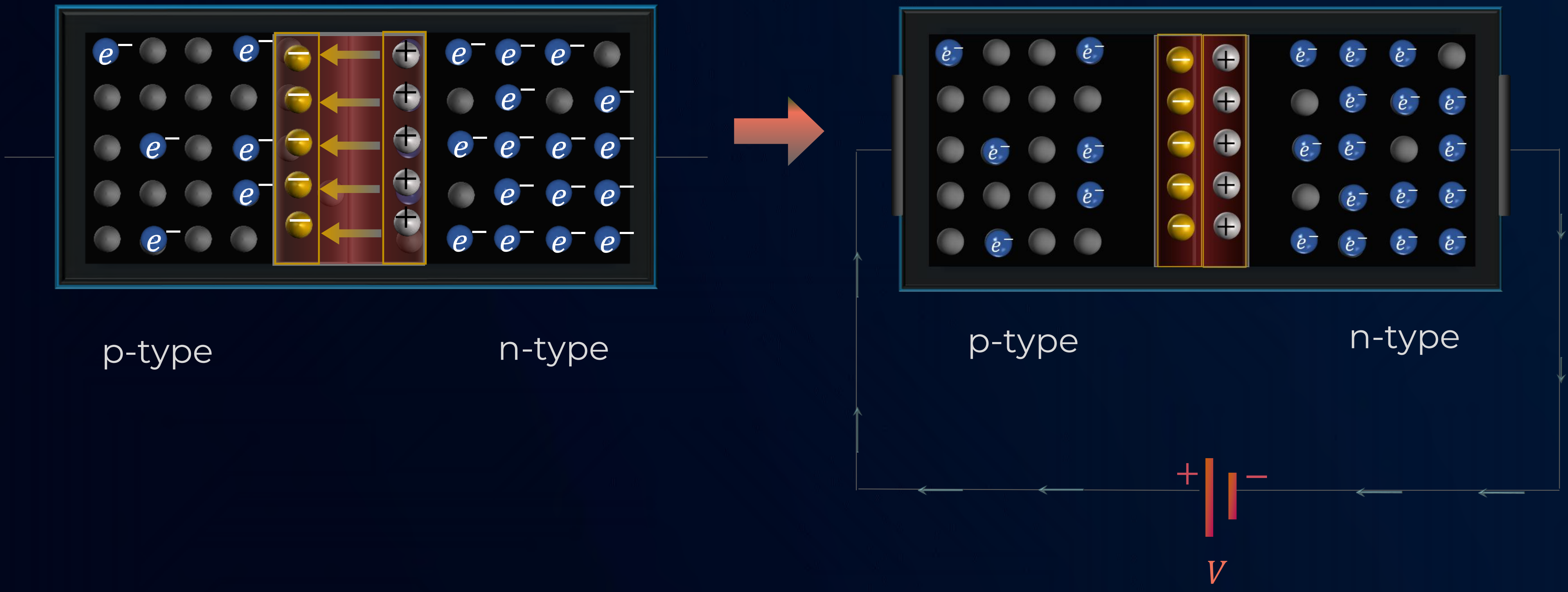
- The direction of arrow indicates the conventional direction of current.
- The equilibrium barrier potential can be altered by applying an external voltage V across the diode.
- Offers low resistance in one direction and high resistance in the other.



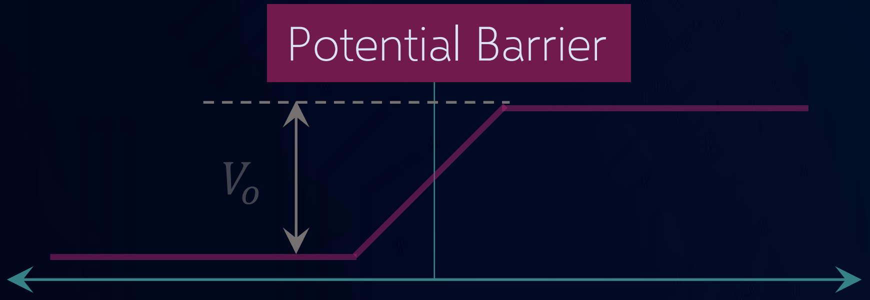


DIODE IN FORWARD BIAS

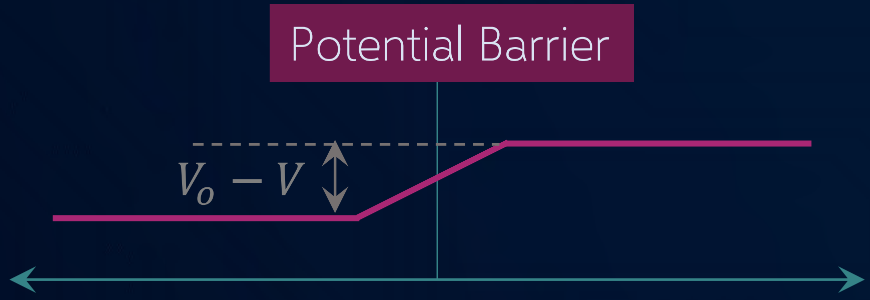
p-n junction forward bias condition: Positive terminal of the battery is connected to the p-side and the negative terminal to the n-side of p-n junction.



DIODE IN FORWARD BIAS



p-n junction



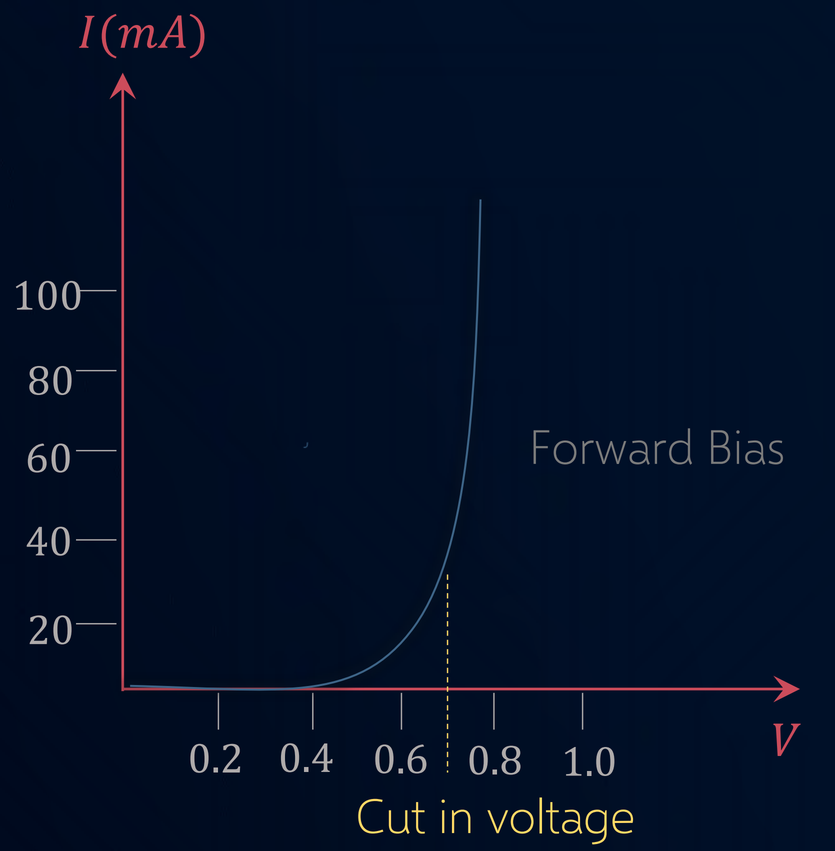
p-n junction-forward bias

- The external potential difference applied by the battery reduces the potential barrier inside the p-n junction as both are opposite in polarity to each other.
- As a result, the electric field decreases and hence, the depletion region shrinks. Due to this, more and more majority charge carriers can cross the depletion region and thus, the diffusion current increases.
- The net current flows from the p-side to the n-side.

Diffusion current $\gg$ Drift current

FORWARD BIAS $I - V$ CHARACTERISTICS

- Initially, on increasing the voltage, the increment in current is almost negligible. But, after a certain value of voltage called the threshold voltage or cut-in voltage, even for a small increase in voltage, the current increases drastically.
- It is because at cut-in voltage, the potential barrier becomes zero and now most of the charge carriers can diffuse to the other side.



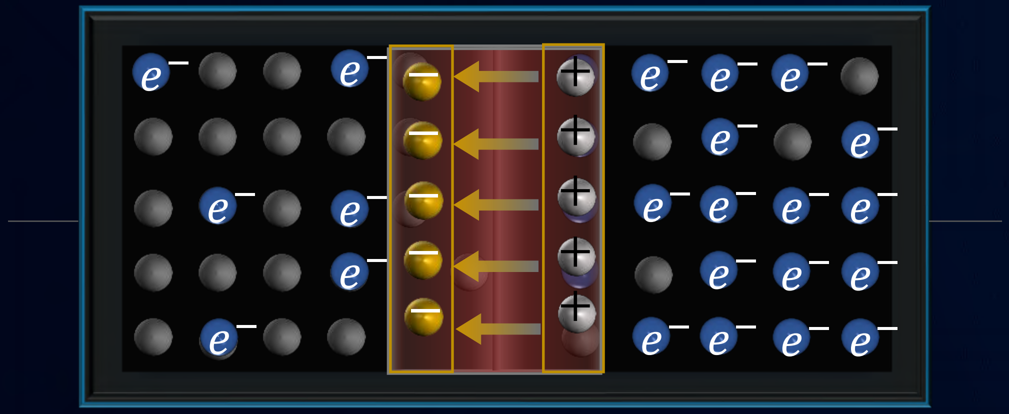
$$\text{Slope} = \frac{\Delta I}{\Delta V} = \frac{1}{R_F}$$

R_F = Forward bias resistance

$R_F \approx 10\ \Omega$ to $100\ \Omega$

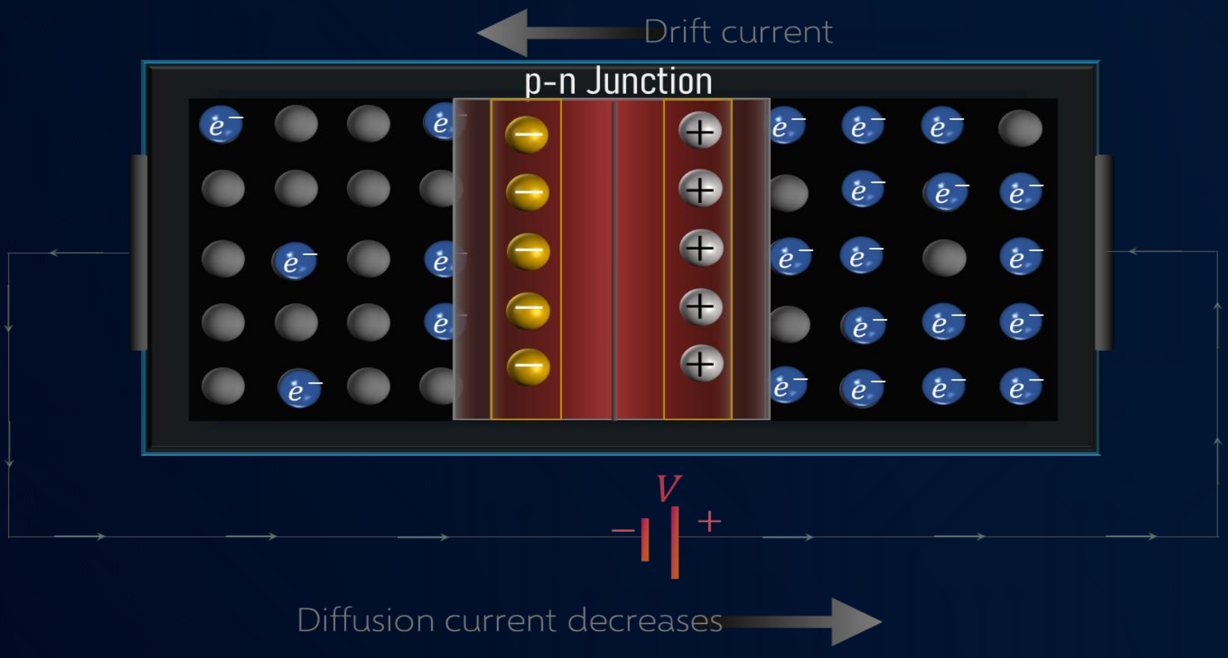
DIODE IN REVERSE BIAS

P-n junction reverse bias condition: Positive terminal of the battery is connected to the $n-$ side and the negative terminal to the $p-$ side of p-n junction

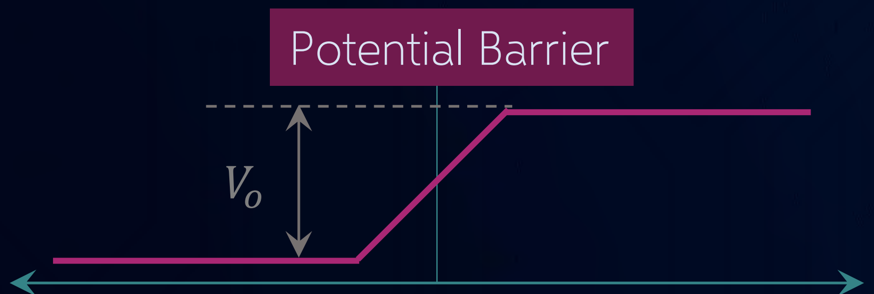


p-type

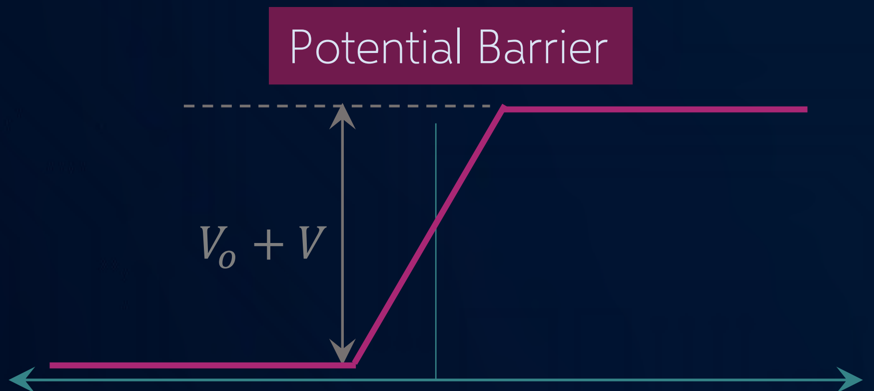
n-type



DIODE IN REVERSE BIAS



p-n junction



p-n junction-reverse bias

- The external potential difference applied by the battery increases the potential barrier inside the $\mathrm{p-n}$ junction.
- As a result, the electric field increases and depletion region expands. The magnitude of diffusion current is still very low. But, even if the electric field supports the migration of the minority charge carriers, the drift current is almost constant.
- This is due to very less concentration of the minority charge carriers. Also, the magnitude of current in reverse bias is very low (of the order of μA).

$I - V$ Characteristics

- Initially, with increase in voltage, the current is very low and is almost constant.
- At breakdown voltage, the current increases sharply due to the avalanche effect.

Avalanche effect:

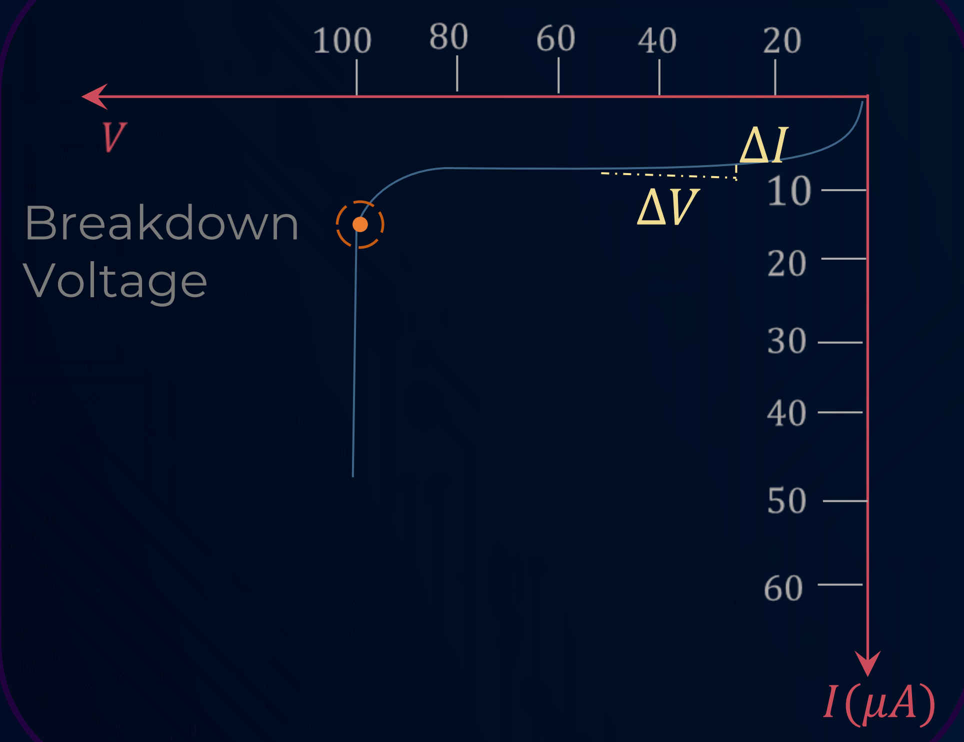
With increase in voltage, the electric field also increases due to which the velocity of the free electrons becomes very high.

This high velocity electron knocks off a bonded electron and then these two free electrons will knock off another two bonded electrons and so the process will go on which results in sharp increase in the current.

$$\text{Slope} = \frac{\Delta I}{\Delta V} = \frac{1}{R_R}$$

R_R = Reverse bias resistance

$R_R \approx 10^6\ \Omega$

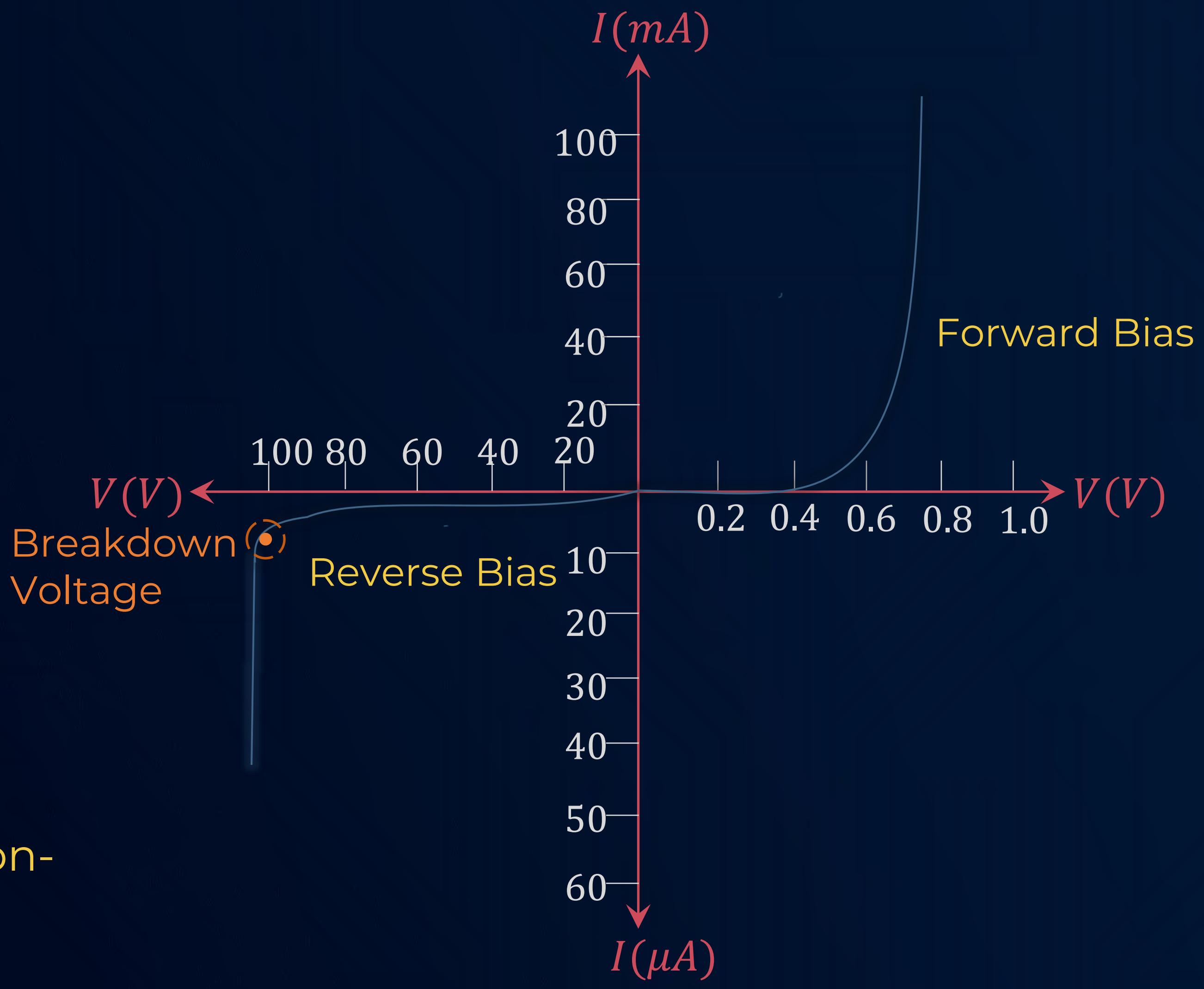


$I - V$ Characteristics

Semiconductors do not follow Ohm's law.

Dynamic resistance:

$$r_d = \frac{\Delta V}{\Delta I}$$



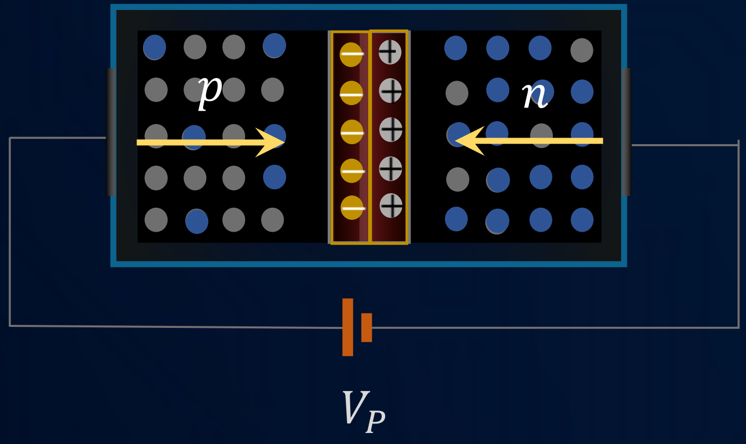
For forward bias, the dynamic resistance is low whereas for reverse bias, the dynamic resistance is very high.

Diode is conducting in forward bias and non-conducting in reverse bias.

In the case of forward biasing of $p-n$ junction, which one of the following figures correctly depicts the direction of flow of carriers.

A

C



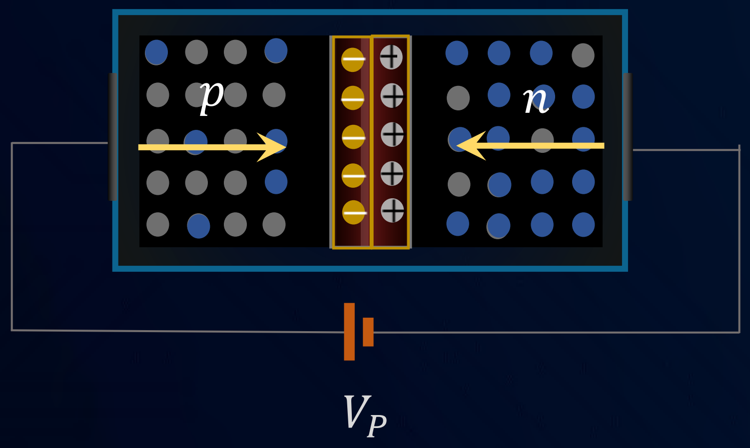
B

D

In the case of forward biasing of p – n junction, which one of the following figures correctly depicts the direction of flow of carriers.

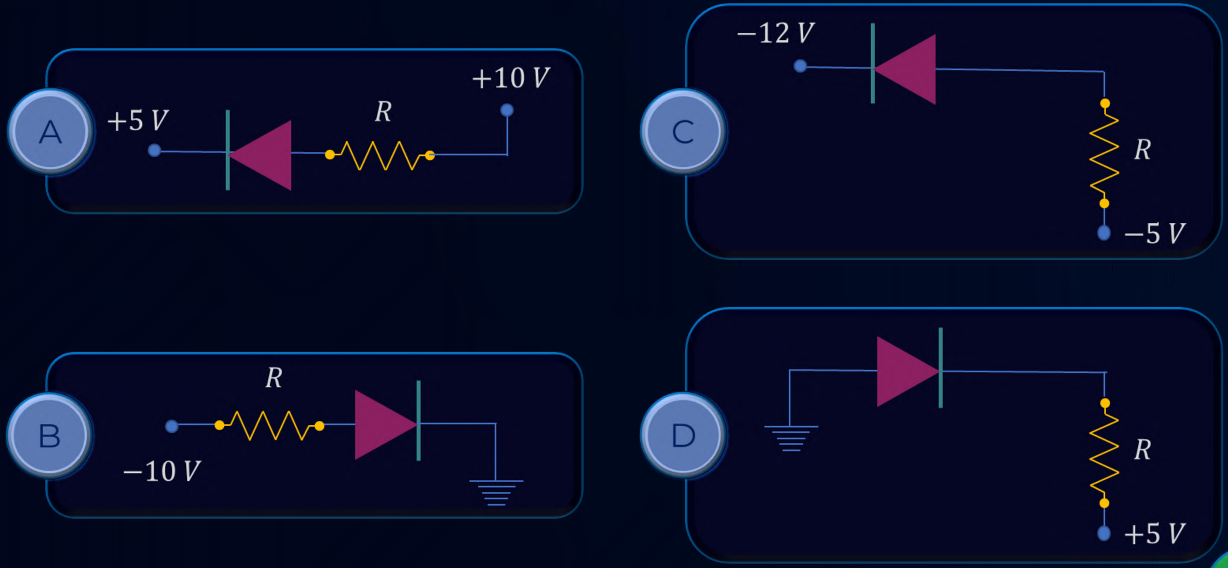
- For p-type, holes are the majority charge carriers whereas for n-type, electrons are the majority charge carriers and in forward bias, diffusion current is dominant.

- The holes diffuse from p-side to n-side and electrons diffuse from n-side to p-side.



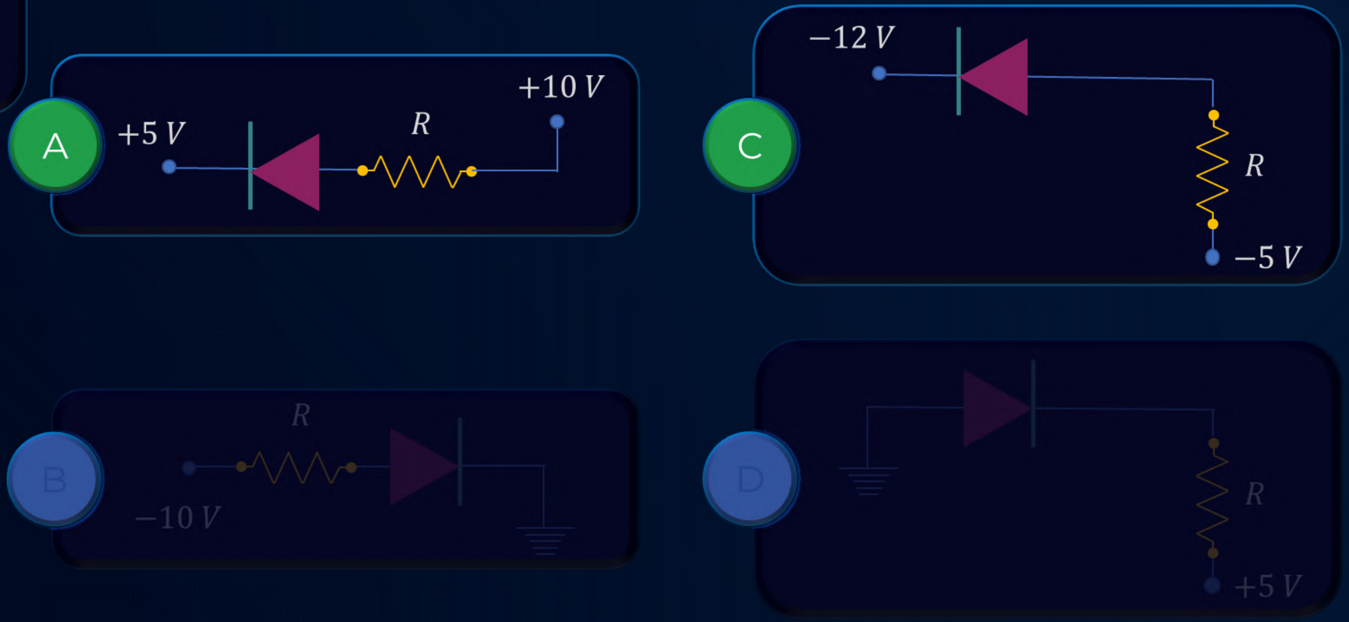
Hence, option (C) is the correct answer.

In the following figure, the diodes which are forward biased is/are:



For forward biasing of diode, p-type of diode should be at higher potential than n-type.

Hence, options (a) and (c) are in forward bias.



Avalanche breakdown is due to

- Avalanche breakdown happens only if the diode is connected in reverse bias. As we increase the reverse bias voltage, the strength of the electric field in depletion region increases. Due to this high electric field, the velocity and hence the kinetic energy of minority electrons also increases. These highly energized electrons knockout the valence electrons from the atoms through collisions. By this way, a large no. of free electrons is generated, and this gives rise to large amount of current.

- Therefore, the avalanche breakdown is due to collision of minority charge carriers.

A. Collision of minority charge carrier

B. Increase in depletion layer thickness

C. Decrease in depletion layer thickness

D. None of these

The dominant mechanism for motion of charge carriers in forward and reverse biased silicon p-n junction are respectively;

A. Drift in forward bias, diffusion in reverse bias

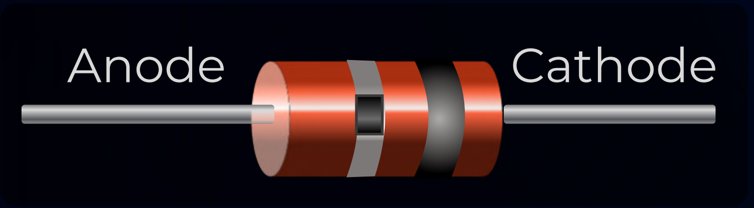
C. Diffusion in forward bias, drift in reverse bias

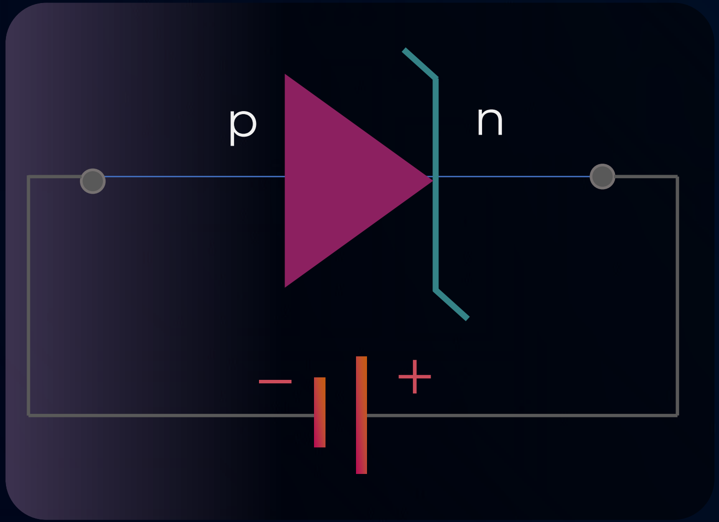
B. Diffusion in both forward and reverse bias

D. Drift in both forward and reverse bias

Zener Diode

Zener diode is a heavily doped semiconductor diode that is designed to operate in the reverse bias condition.





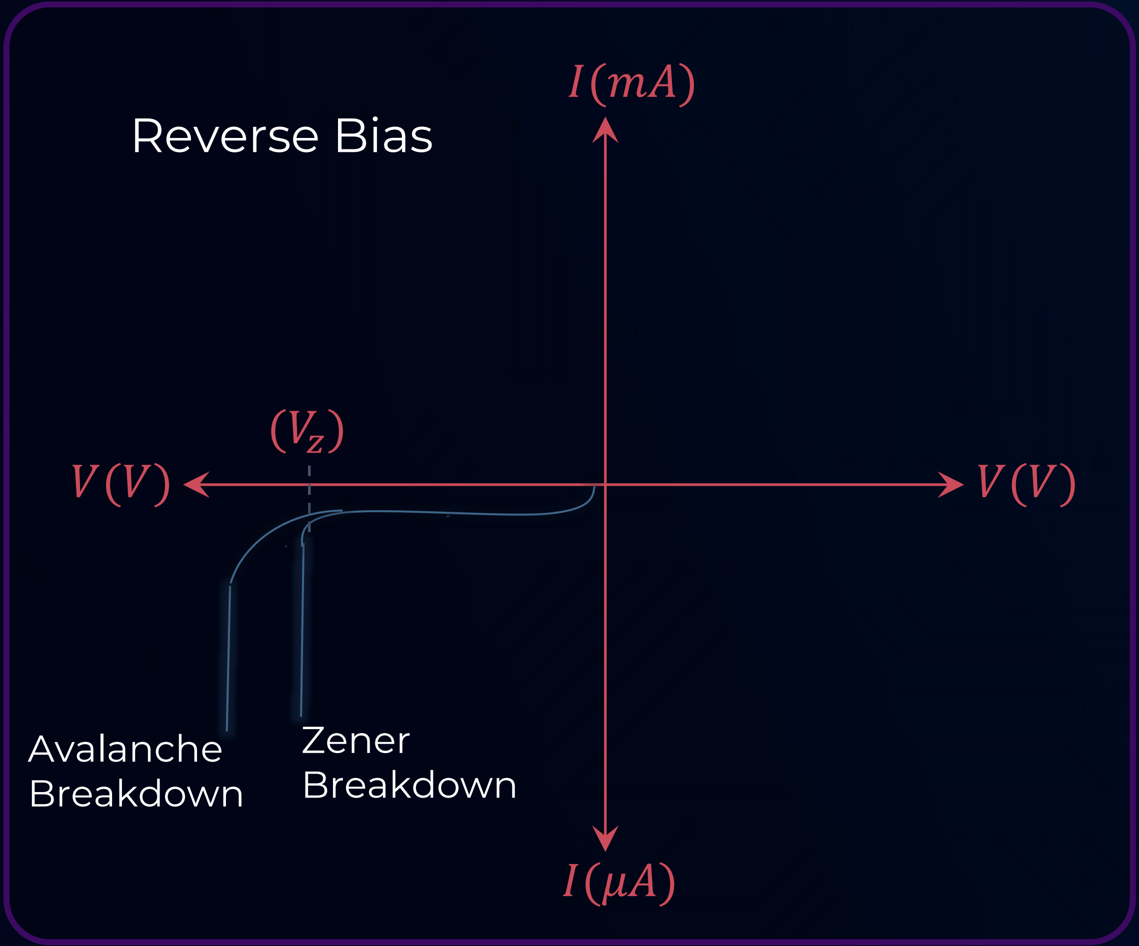
Zener Diode Circuit Symbol

Clarence Melvin Zener

Zener Effect

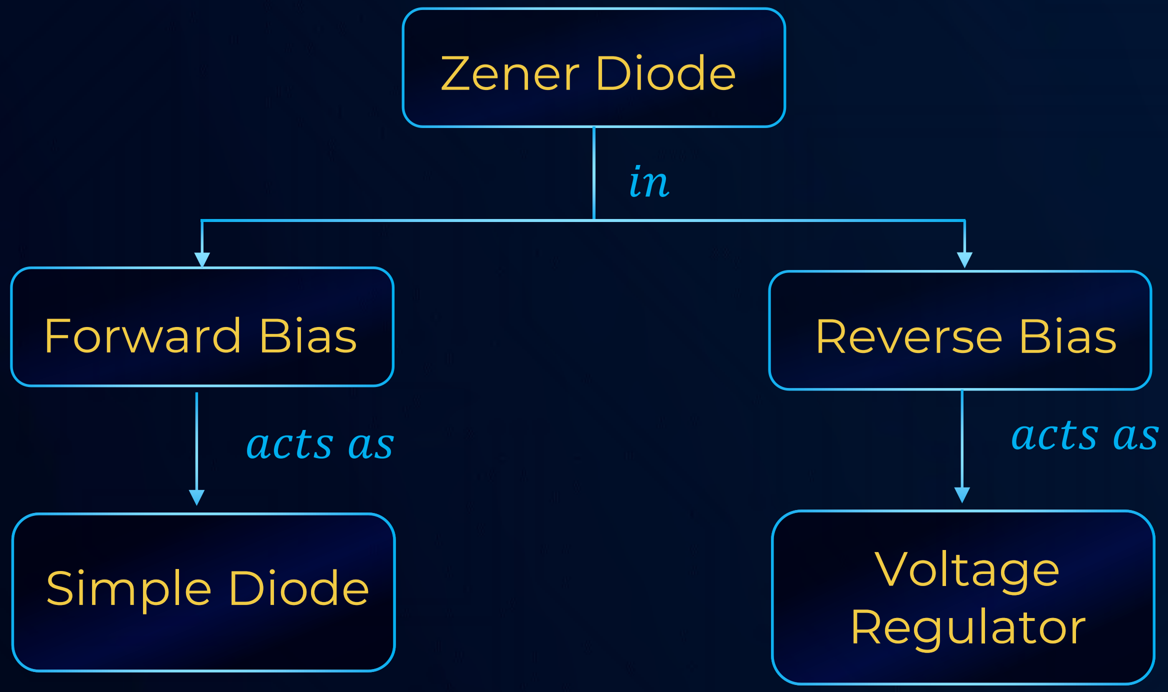
- In Zener diode, impurity (doping) is high on both sides. The depletion layer is also very thin.
- Due to high doping, the concentration of majority charge carriers is very large.
- Hence, a small depletion region will be enough to generate high electric field which can stop the diffusion current.
- Increase in reverse bias voltage causes a high electric field in the depletion region, and this high electric field detaches the valence electrons from the neutral atoms in the depletion region.
- Therefore, a large no. of free electrons are generated. This gives rise to large amount of current.
- This explains the phenomenon of increment in current at Zener voltage in breakdown region.

$I - V$ Characteristics of Zener Diode



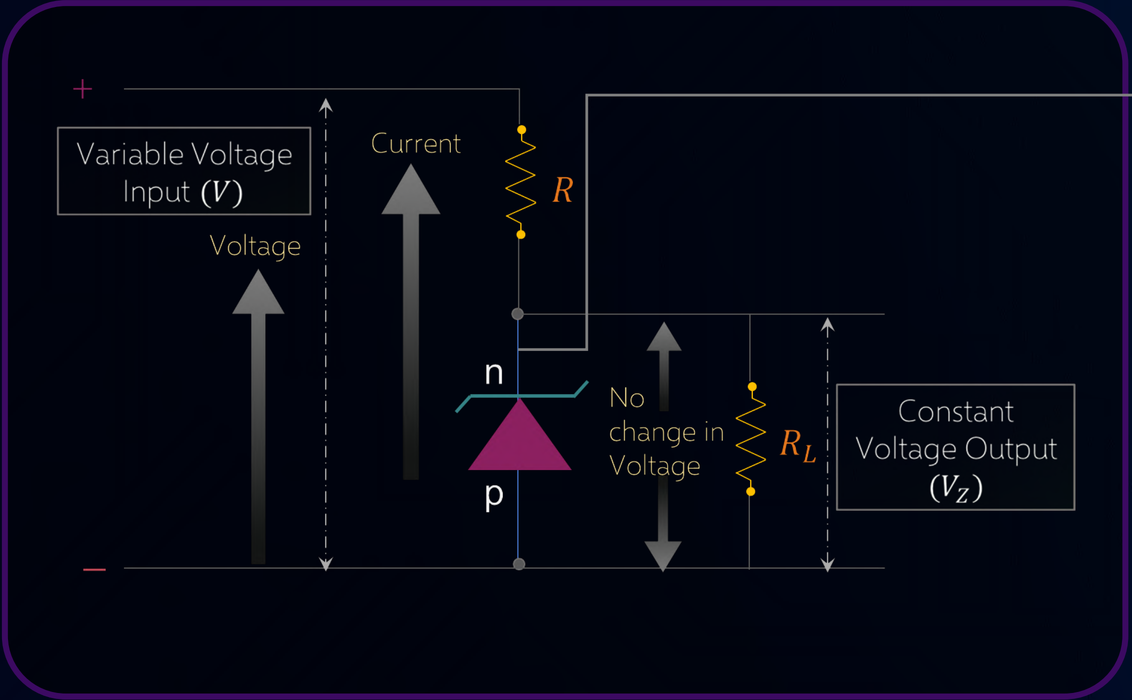
- Works in the breakdown region of reverse bias.
- In breakdown region, the current keeps on increasing while the voltage remains constant.
- The voltage at which this phenomenon happens is known as Zener voltage (V_Z).
- In normal diodes similar phenomenon takes place but, there the mechanism is avalanche breakdown in which free electrons knock off bonded electrons.
- The emission of electrons from the host atoms due to the high electric field (of the order of $10^6\ V/m$) is known as internal field emission or field ionization.

Voltage Regulation using Zener Diode

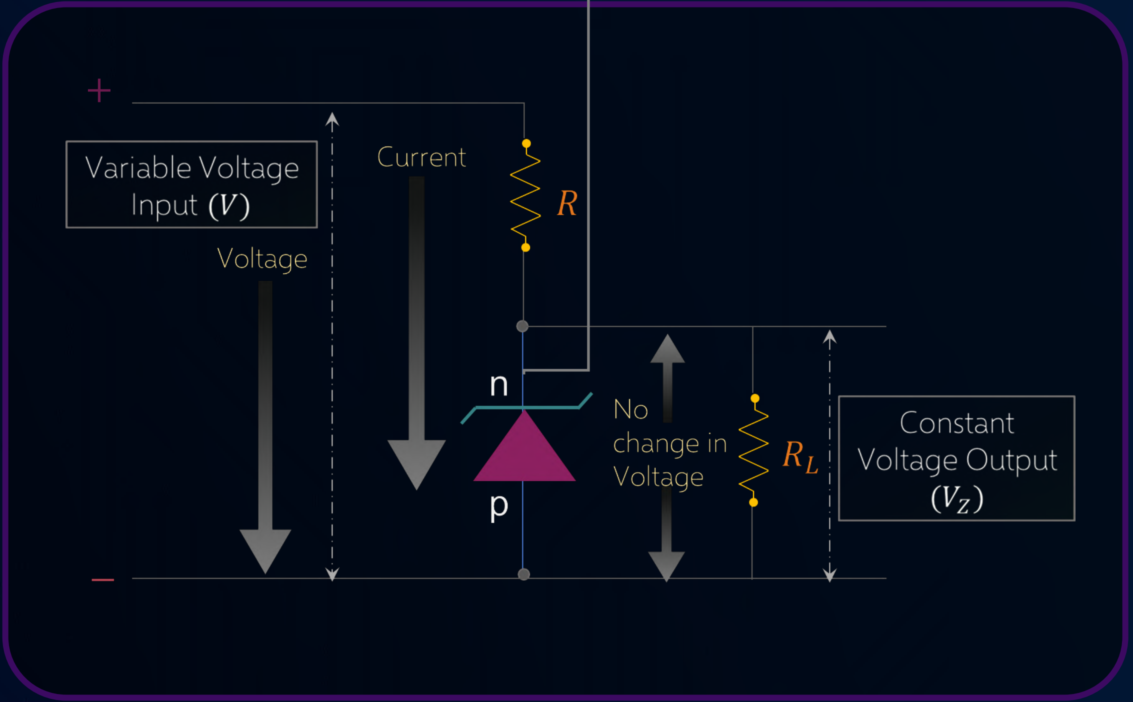


The primary objective of the Zener diode as a voltage regulator is to maintain a constant voltage.

Voltage Regulation using Zener Diode



The current flowing through the Zener diode will change.



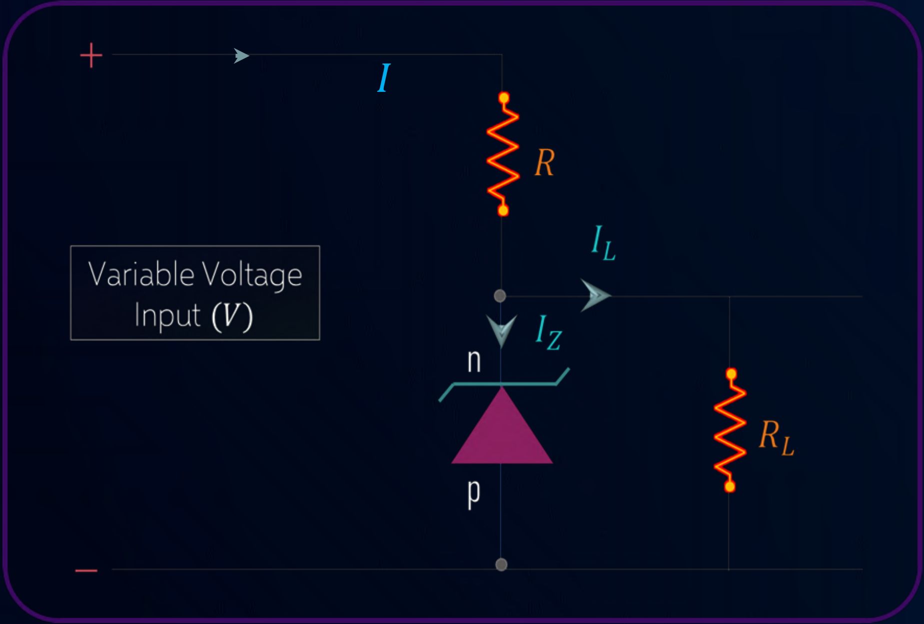
- Any increase or decrease in the input voltage results in increase or decrease of the voltage drop across R without any change in voltage across the Zener diode.

Voltage Regulation of Zener Diode

- For Zener diode to act as a voltage regulator, it must be operated in Breakdown region.

$$I = I_Z + I_L$$

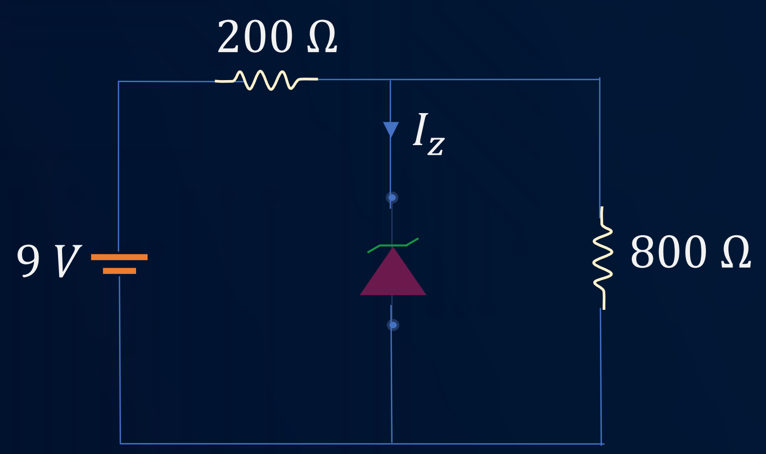
- The series resistance protects the zener diode from damage due to high current flow.



- For good voltage regulation, $I_Z \gg I_L$ so that the Zener diode operates in required region.
- I_Z should be below safe maximum current.

The reverse break down voltage of a Zener Diode is $5.6\ V$ in the given circuit.
The current I_z through the Zener diode is:

Solution:



The current(I_R) through 200 Ω resistor is: $\frac{9-5.6}{200} = \frac{3.4}{200} A$

The current I_z through the Zener is: $I_R - I_L = \frac{3.4}{200} - \frac{5.6}{800} A$

$= 10\ mA$

A) $17\ mA$

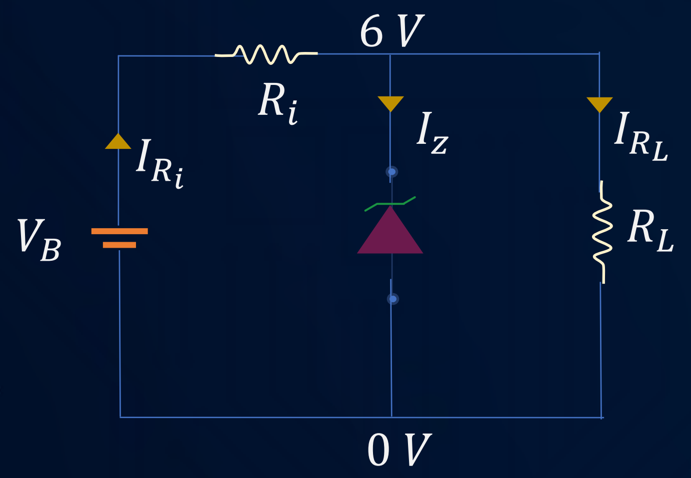
B) $10\ mA$

C) $7\ mA$

D) $15\ mA$

The figure represents a voltage regulator circuit using a Zener diode. The breakdown voltage of the Zener diode is $6\ V$ and the load resistance is $R_L = 4\ K\Omega$. The series resistance of the circuit is $R_i = 1\ K\Omega$. If the battery voltage V_B varies from $8\ V$ to $16\ V$, what are the minimum and maximum values of the current through Zener diode ?

Solution:



For voltage $V_B = 8\ V$

$$I_{R_L} = \frac{6}{R_L} = \frac{6}{4}\ mA \qquad I_{R_i} = \frac{V_B - 6}{R_i} = \frac{8-6}{1}\ mA = 2\ mA$$

$$I_{Z(min)} = \left(2 - \frac{6}{4}\right) mA = 0.5\ mA$$

For voltage $V_B = 16\ V$

$$I_{R_L} = \frac{6}{R_L} = \frac{6}{4}\ mA \qquad I_{R_i} = \frac{V_B - 6}{R_i} = \frac{16-6}{1}\ mA = 10\ mA$$

$$I_{Z(max)} = \left(10 - \frac{6}{4}\right) mA = 8.5\ mA$$

A) $0.5\ mA, 6\ mA$

B) $1\ mA, 8.5\ mA$

C) $0.5\ mA, 8.5\ mA$

D) $1.5\ mA, 8.5\ mA$

RECTIFIER

- A rectifier is a device that converts alternating current (AC), which periodically reverses direction, to direct current (DC).

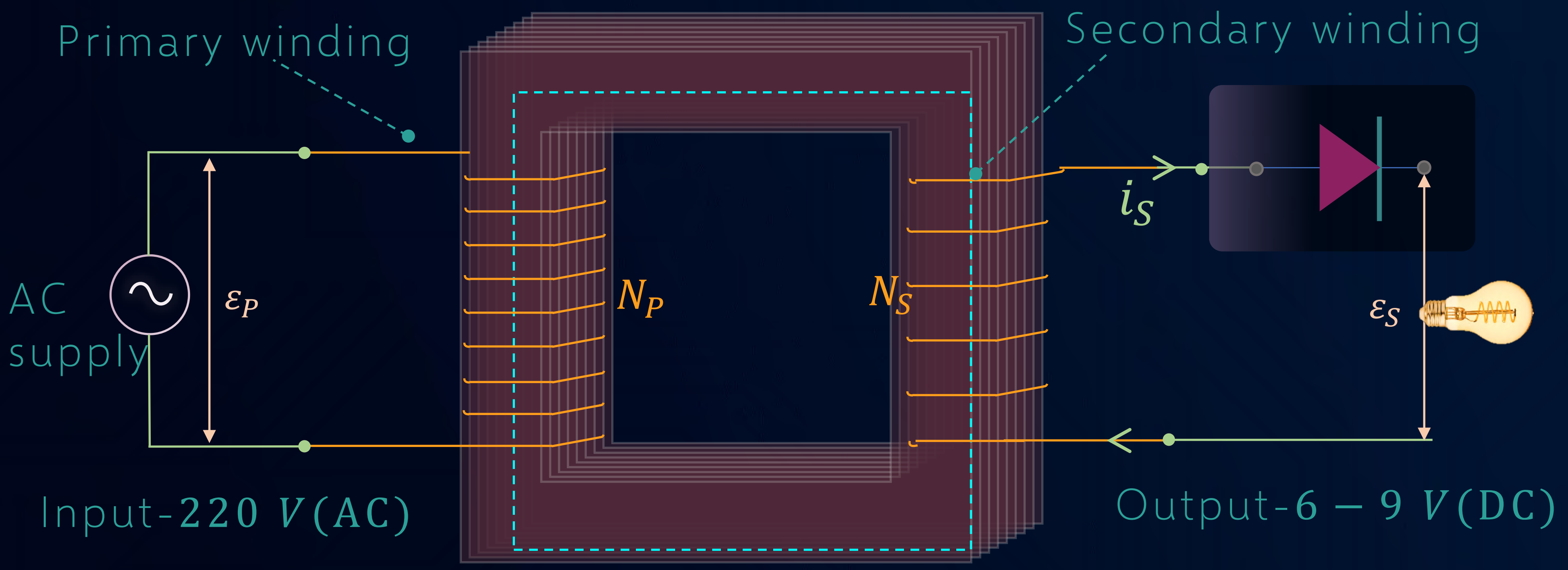
HALF WAVE RECTIFIER

FULL WAVE RECTIFIER

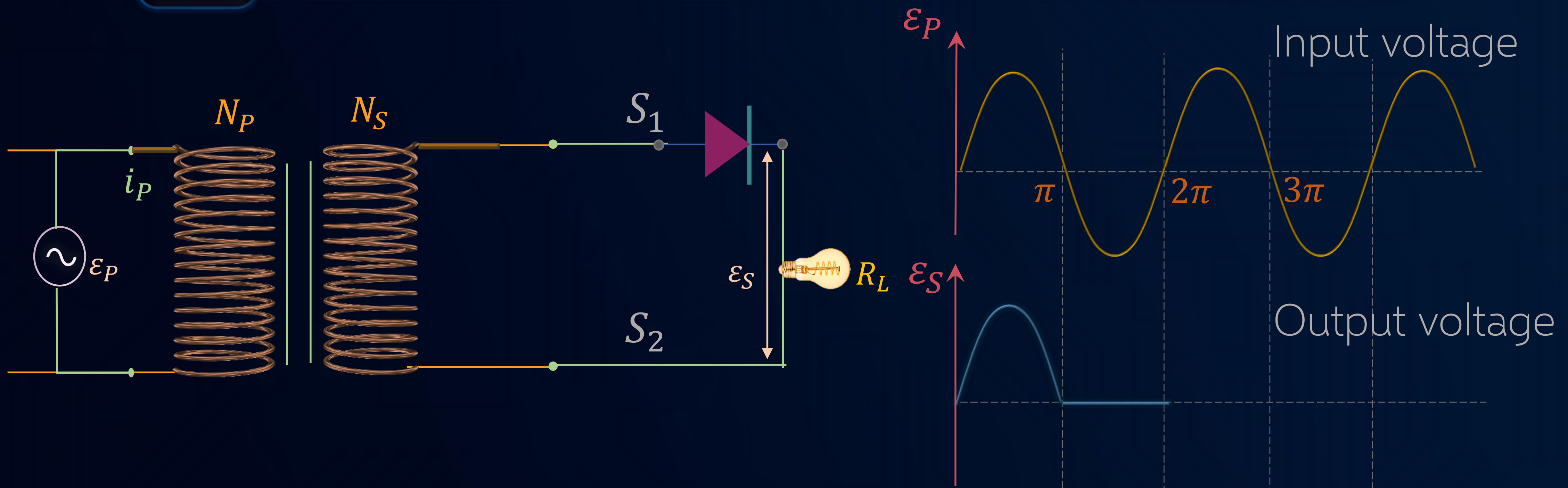
FULL WAVE BRIDGE RECTIFIER

HALF WAVE RECTIFIER

- The diode restricts the current in one direction while allows the current in other direction, thereby, converts the alternating current into direct current.

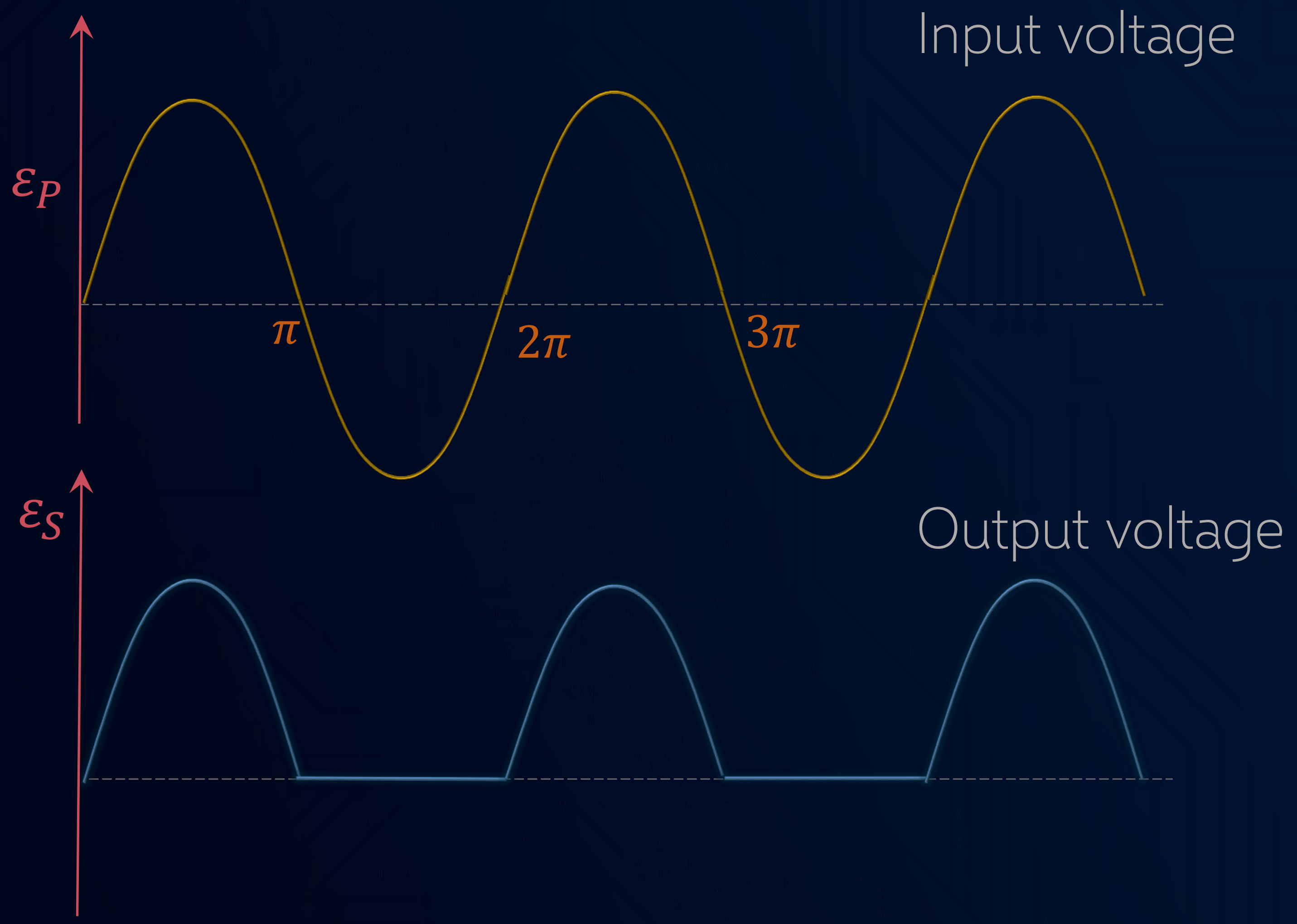


HALF WAVE RECTIFIER

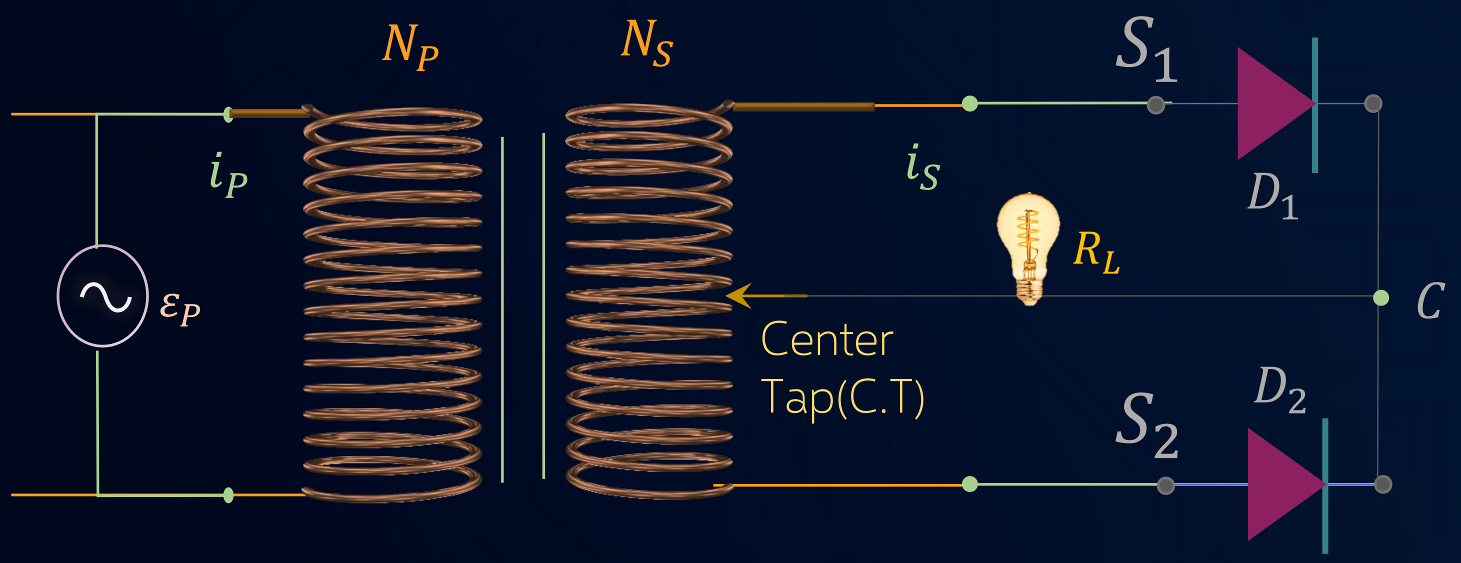


- During the positive half cycle of the input AC, the diode will be in forward bias, and it will allow the current to flow. Therefore, output voltage will be non-zero.
- During the negative half cycle of the input AC, the diode will be in reverse bias, and it will restrict the flow of current. Therefore, the output voltage will be zero in this case.
- The diode allows only positive half cycle of the input. It is known as "Half wave rectifier".

HALF WAVE RECTIFIER

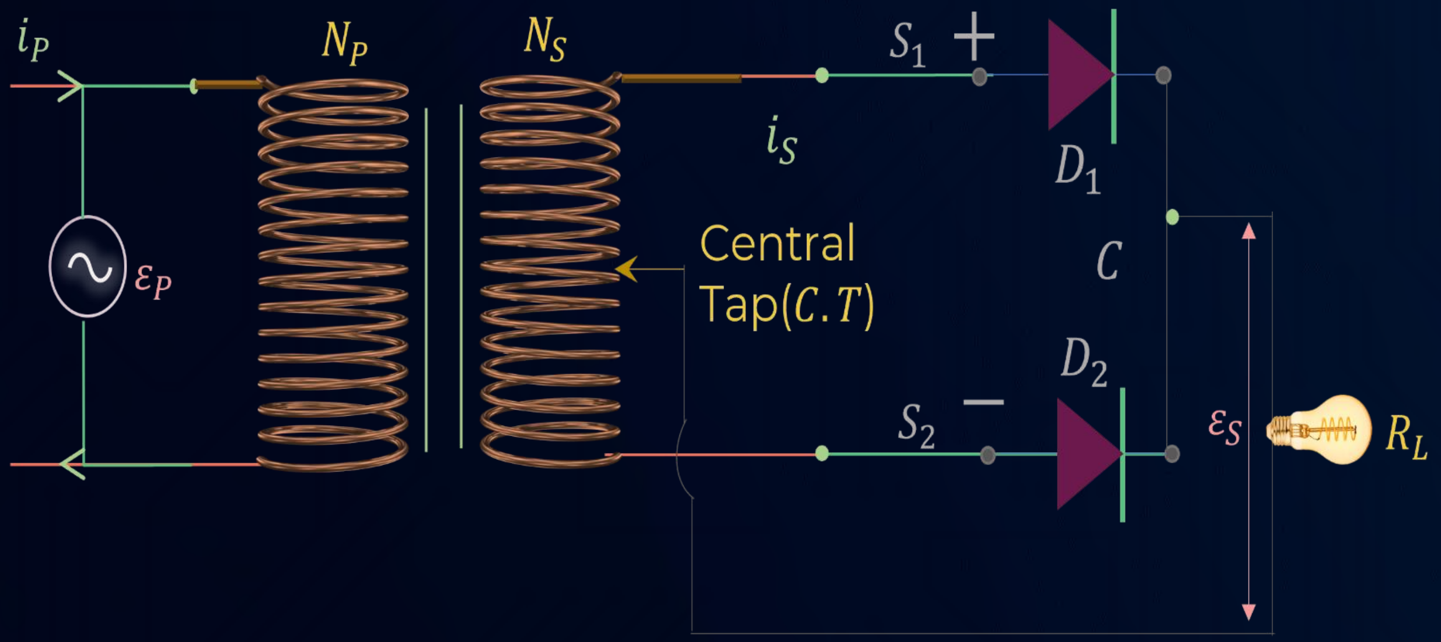


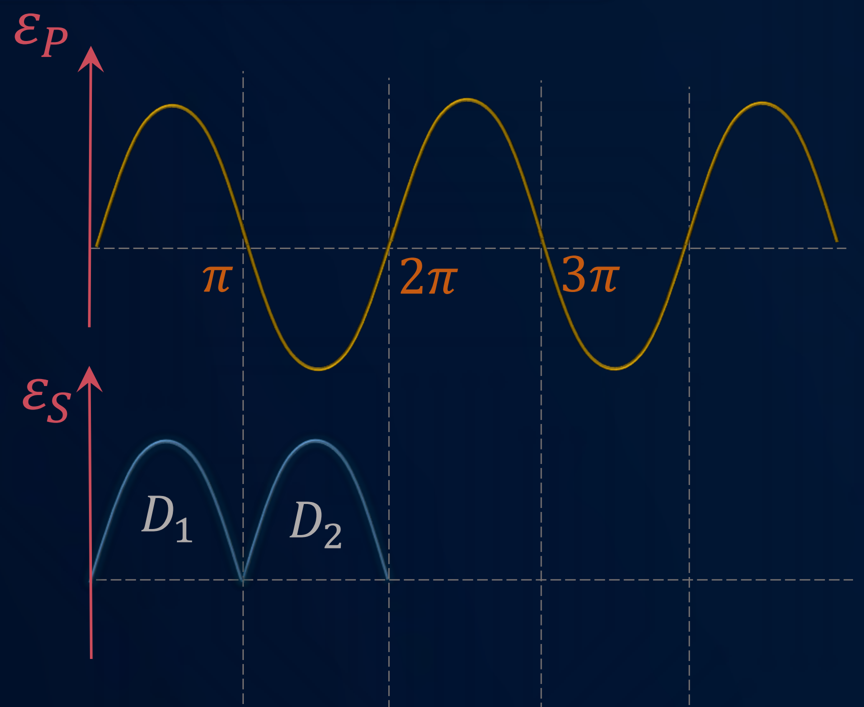
FULL WAVE RECTIFIER



- The central tapped transformer with two diodes are used in Full wave rectifier.

FULL WAVE RECTIFIER



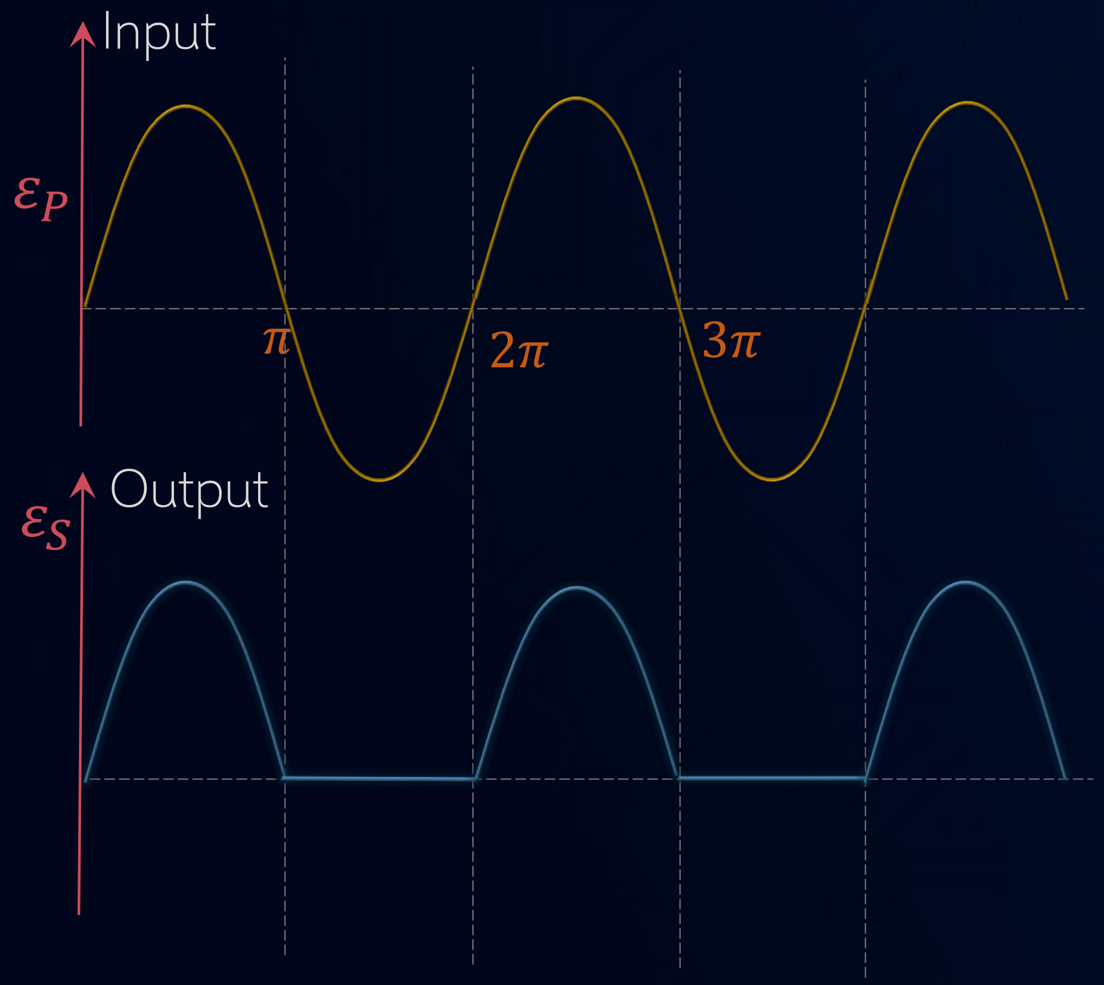


- During the positive half cycle of the input AC, the diode D_1 is forward biased and the diode D_2 is reverse biased. At this situation, point C is at higher potential than the center tap, the output voltage is also positive.

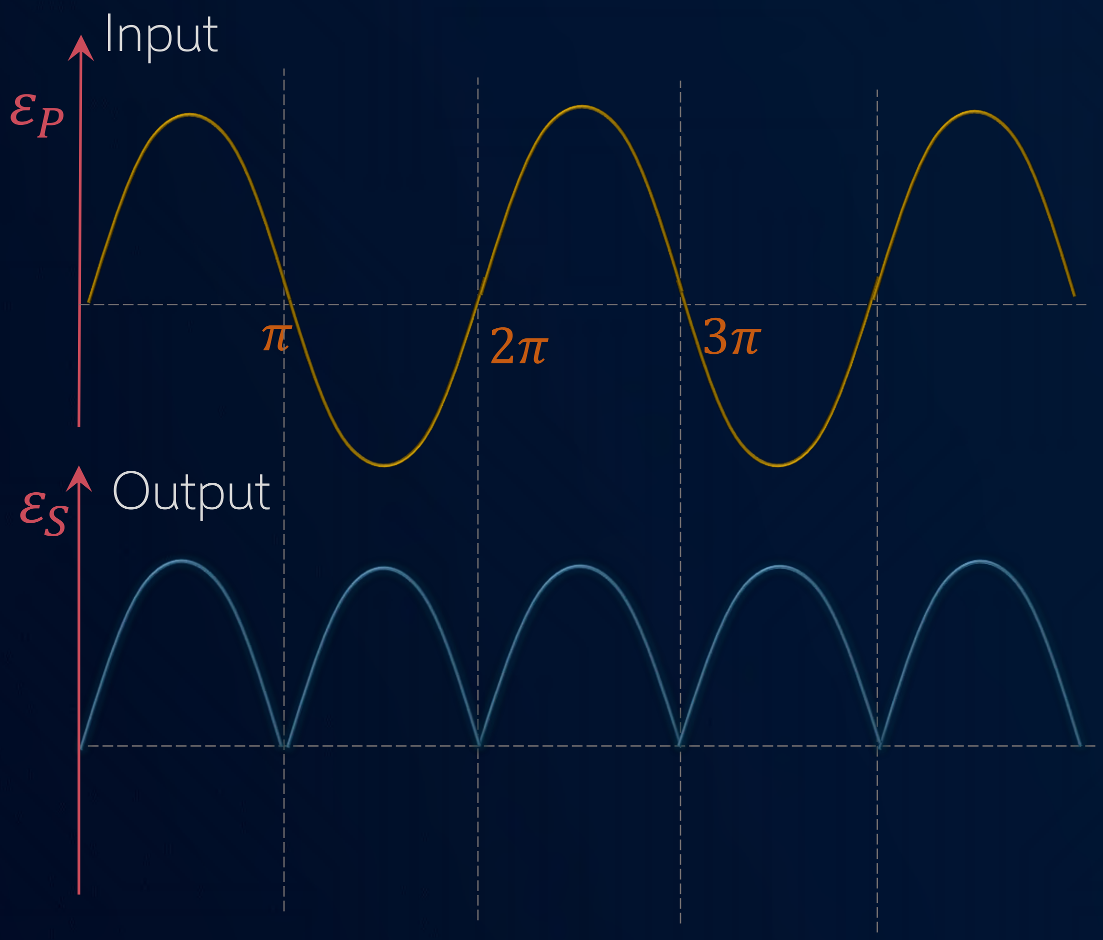
- During the negative half cycle of the input AC, the diode D_1 is reverse biased and the diode D_2 is forward biased. In this case also the point C is at higher potential than the center tap, therefore, the output voltage is positive even though the input voltage is negative.

INPUT vs OUTPUT

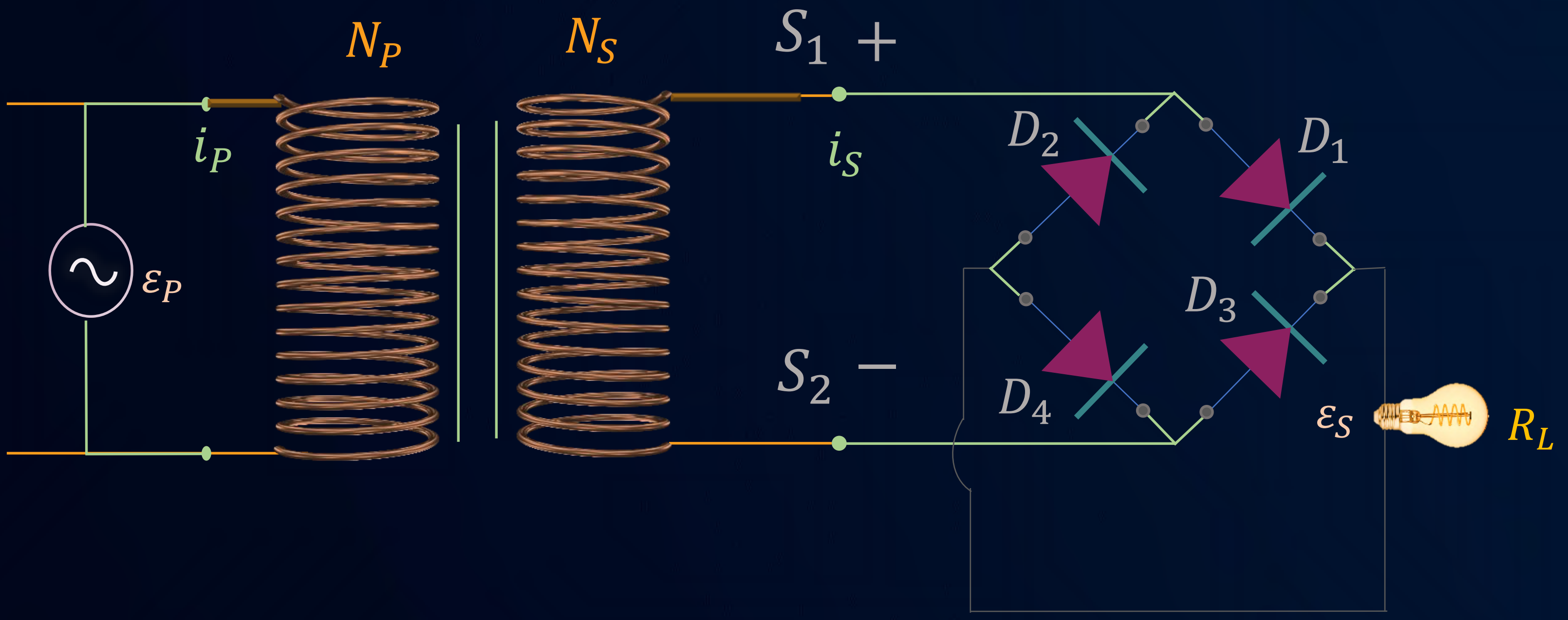
Half wave rectifier



Full wave rectifier

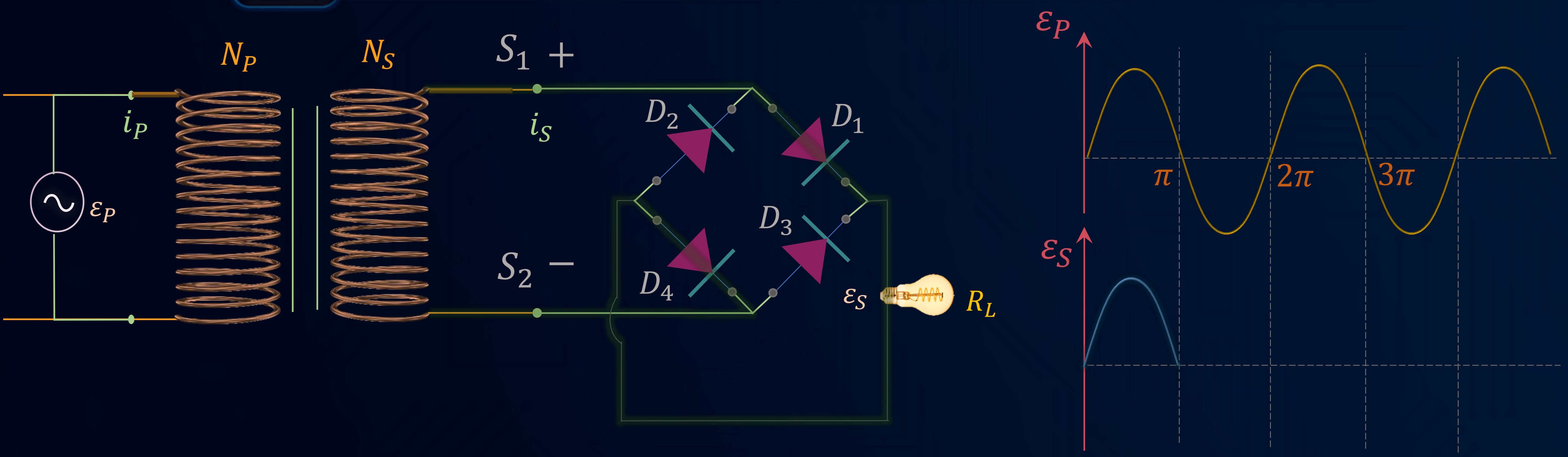


FULL WAVE BRIDGE RECTIFIER



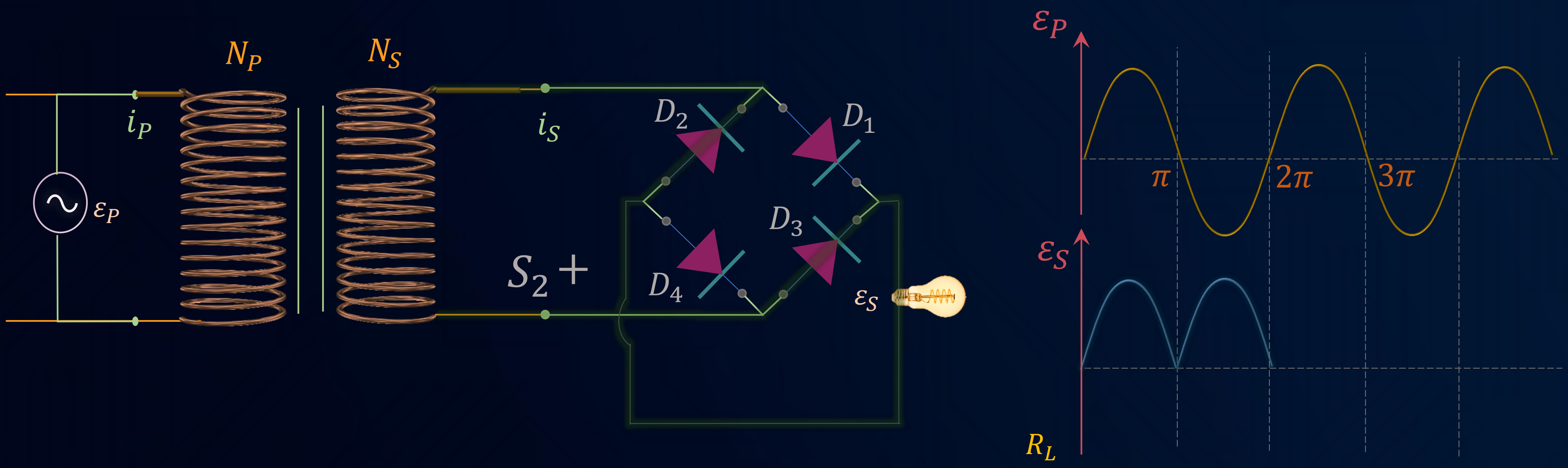
- Uses four or more diodes in a bridge circuit configuration to convert alternating current to a direct current.

FULL WAVE BRIDGE RECTIFIER



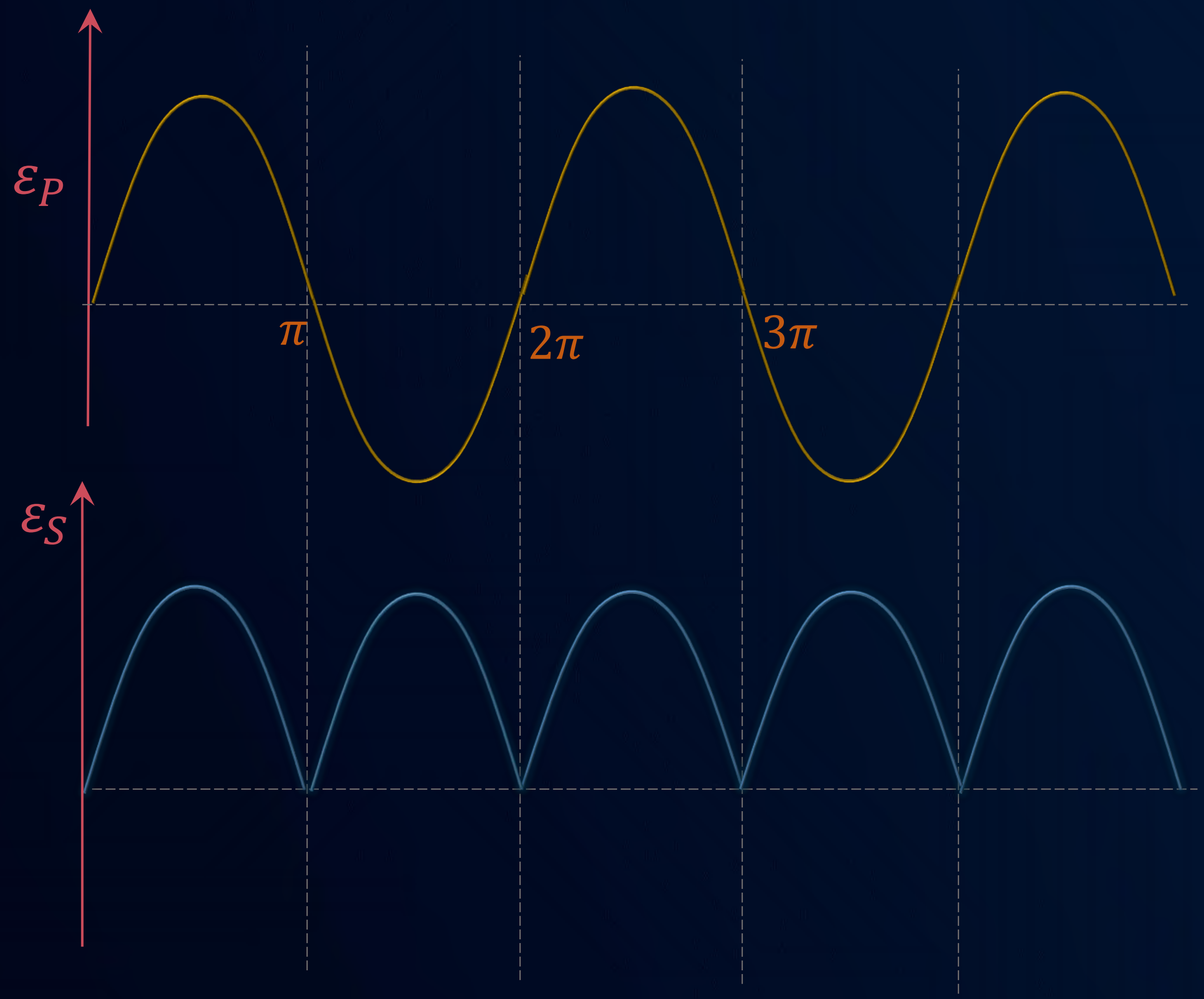
- During the positive half cycle of the input AC, the diodes D_1 and D_4 are forward biased and the diodes D_2 and D_3 are reverse biased. The output voltage is positive.

FULL WAVE BRIDGE RECTIFIER



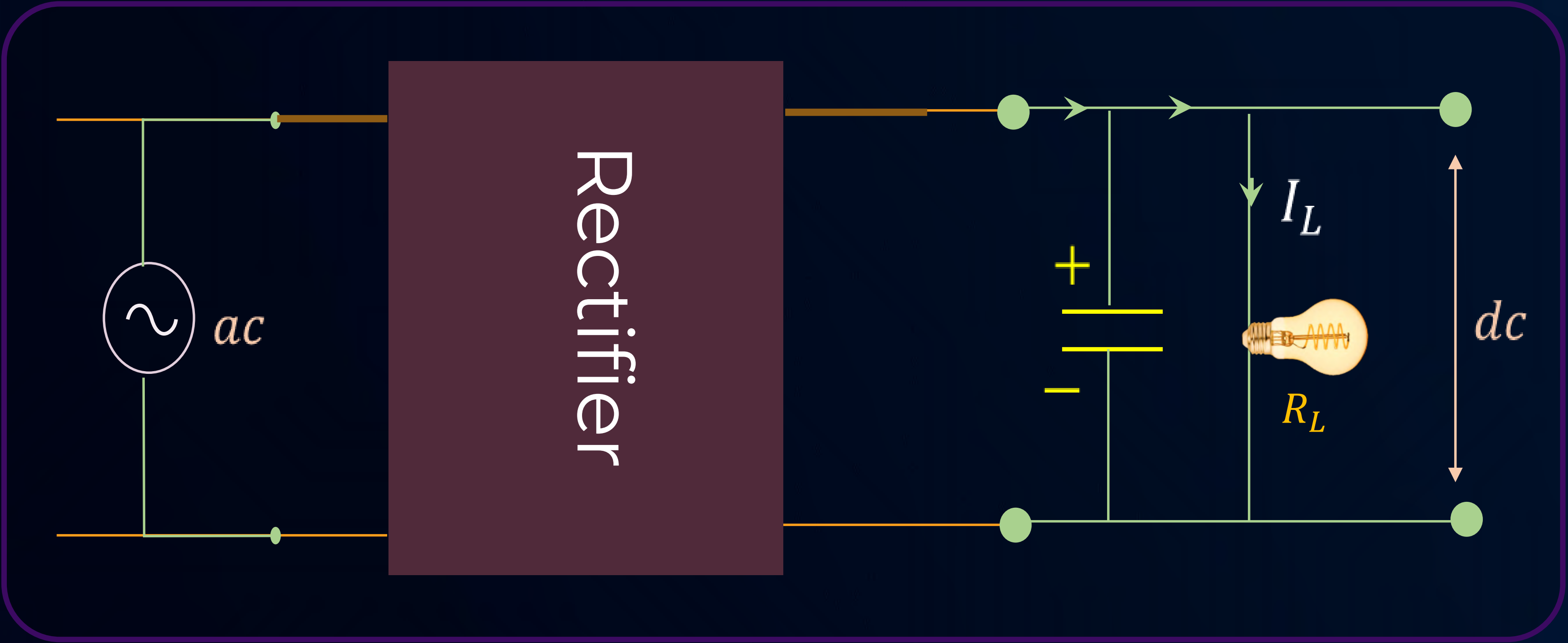
- During the negative half cycle of the input AC, the diodes D_1 and D_4 are reverse biased, and the diodes D_2 and D_3 are forward biased. The output voltage across the load is again positive, even though the input voltage is negative.

FULL WAVE BRIDGE RECTIFIER



Full Wave Rectifier with Capacitor Filter

Capacitor filter is used to filter out the ac ripples and give pure dc voltage.



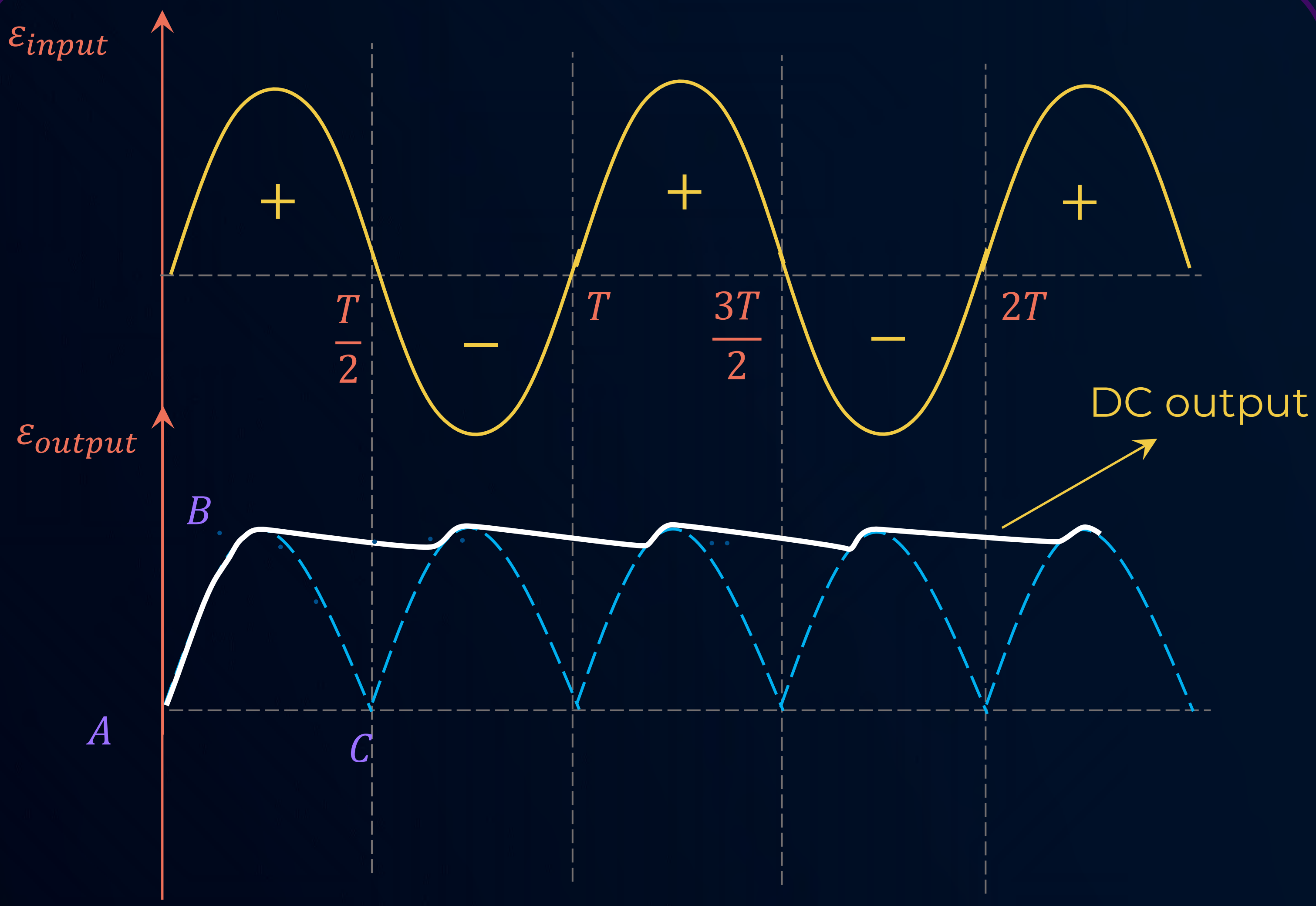
Full Wave Rectifier with Capacitor Filter

$A - B$: Capacitor gets charged.

B: $V_{capacitor} = (\varepsilon_{output})_{max}$

$B - C$: Capacitor gets discharged via R_L.

- Due to the discharging, there is a slight decrease in the capacitor voltage but in the next half cycle as the rectifier output voltage increases, it again start charging and hence, the voltage across the load remains almost constant.



Output

SPECIAL PURPOSE p-n JUNCTION DIODES

Opto-electronic Junction Devices

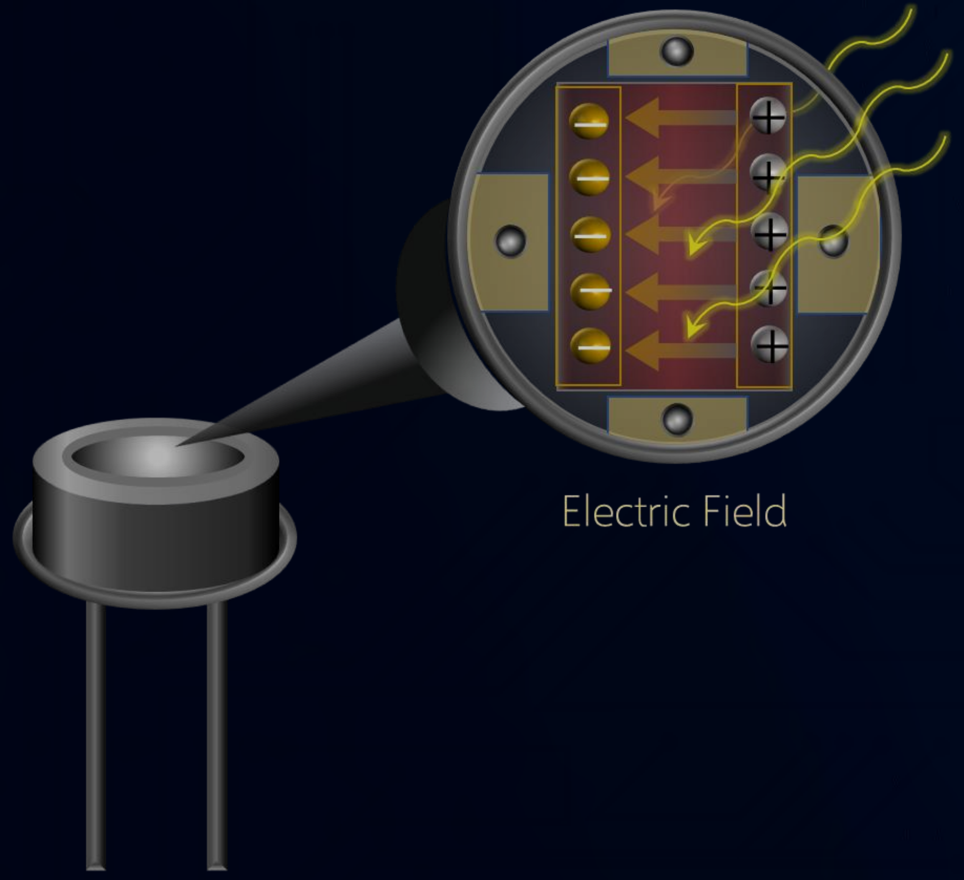
- Optoelectronic junction devices are p-n junction devices in which carriers are generated by photons.

Photo-Diode

LED

Solar Cell

PHOTODIODE



When a photodiode is illuminated by light (photons) of sufficient energy, new electron-hole pairs are generated from the atoms in the depletion region.

Due to the electric field of the junction, the electrons and holes are swept across the depletion region before they can recombine.

Holes move towards p- side and electrons move towards n-side.

Therefore, the direction of current will be from n-side to p-side inside the diode.

PHOTODIODE

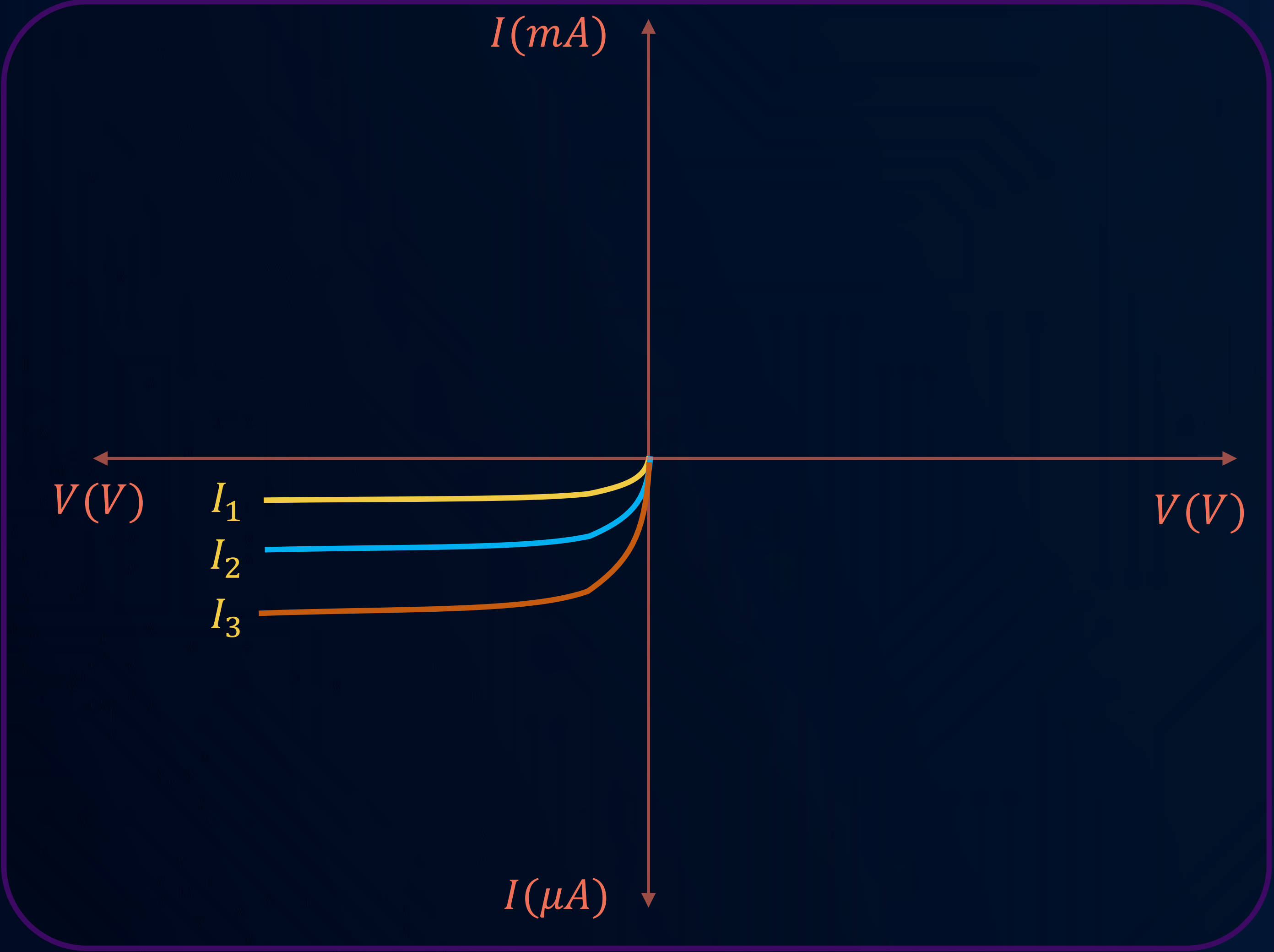
- A photodiode is always used in reverse bias to prevent the recombination of electron-hole pair.

- Thus, the change in the Photocurrent with the change in the intensity of Light can be measured.

I-V CHARACTERISTICS OF PHOTODIODE

- Higher the intensity, higher will be the no. of incident photons, higher the no. of e-h pair generated and hence, higher will be the current.

$$I_3 > I_2 > I_1$$



With increasing biasing voltage of a photodiode, the photocurrent magnitude:

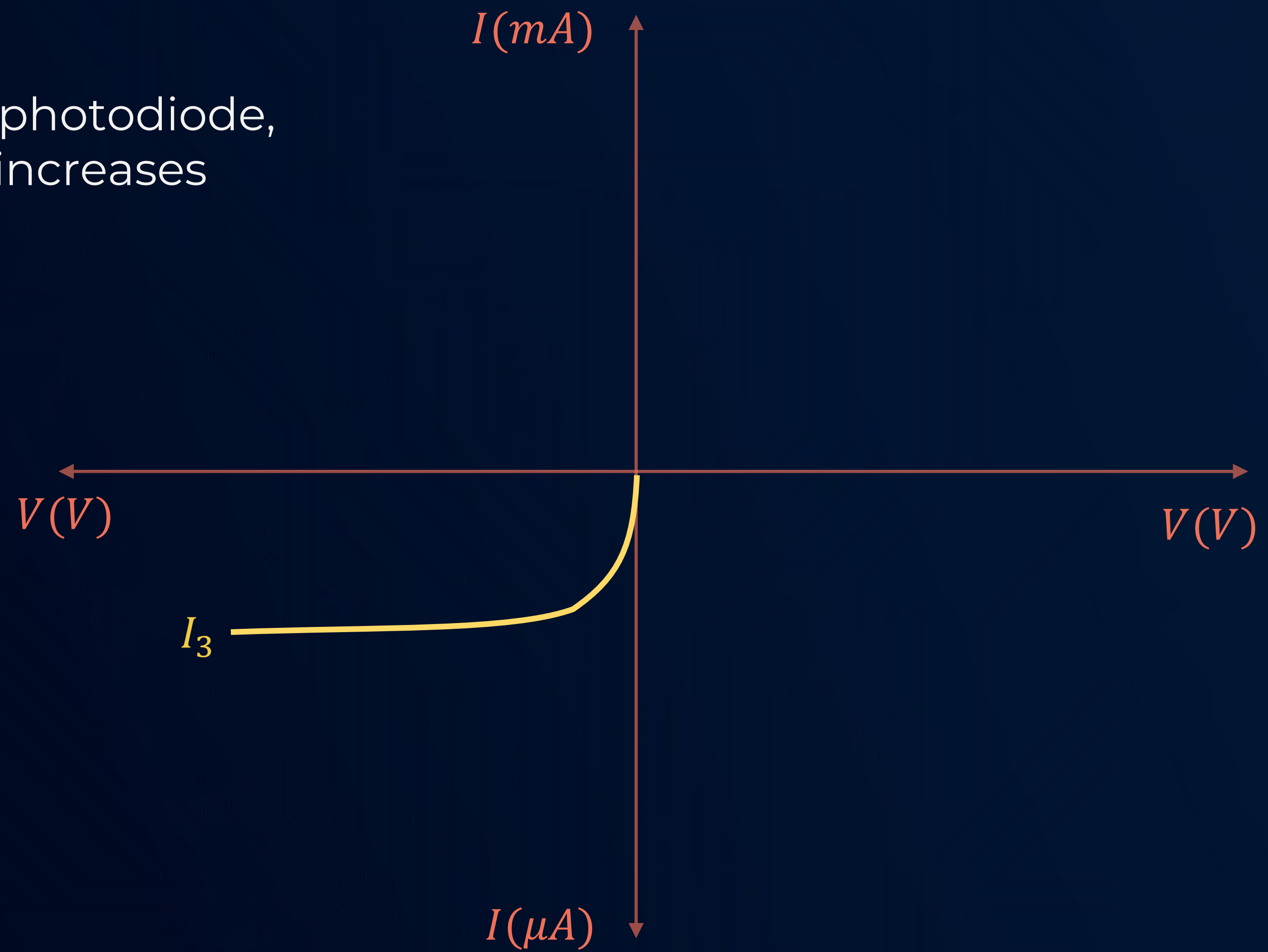
On increasing the biasing voltage of photodiode, the magnitude of photocurrent first increases and then attains a saturation

A. Remains constant

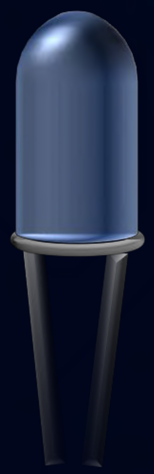
B. Increases initially and after attaining certain value, it decreases

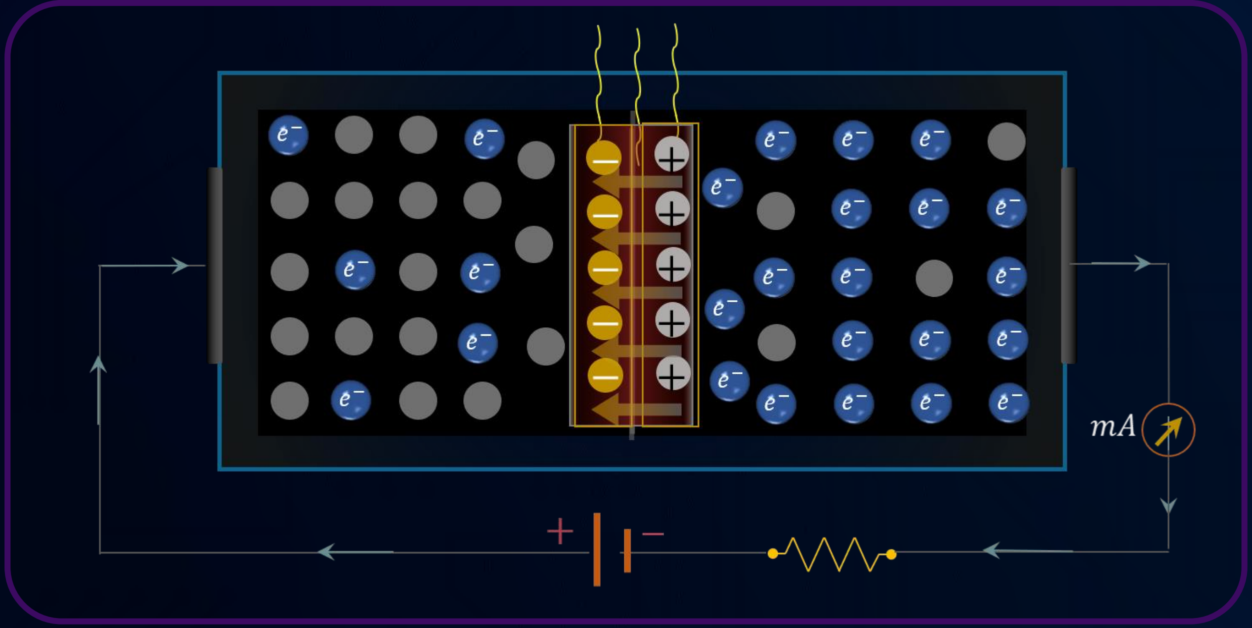
C. Increases linearly

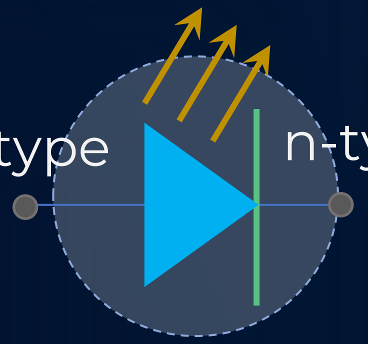
D. Increases initially and saturates finally



LIGHT EMITTING DIODE







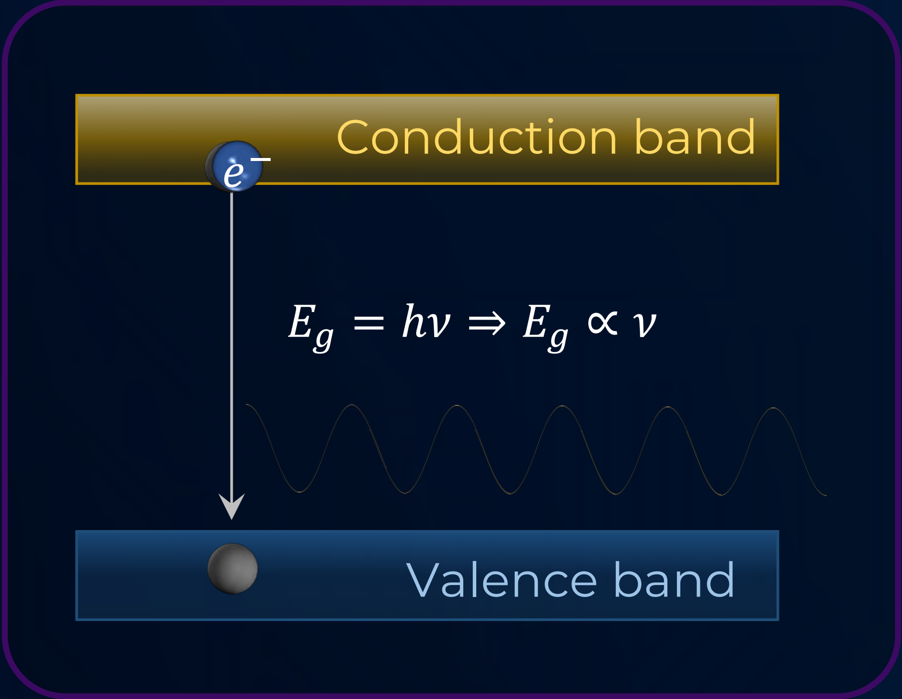
- An LED is a heavily doped p-n junction which operates under forward bias.
- When the diode is forward biased, the majority charge carrier on p-side i.e., holes diffuse towards n-side while the majority charge carrier on n-side i.e., electrons diffuse towards p-side
- Because of the high concentration of majority charge carriers, on p-side, the diffused electrons recombine with holes and on n-side, the diffused holes recombine with electrons. On recombination energy is released in the form of electromagnetic radiation(light).

LIGHT EMITTING DIODE

When Energy E_g is supplied,

The e^- in the valence band takes up the energy and jumps to the conduction band and an electron-hole pair is generated.

On recombination of electron-hole pair (i.e., when an electron in the conduction band jumps back to the valence band) an energy equal to the forbidden gap energy (E_g) is released as EM Radiation.



$$E_g = h\nu$$
$$\Rightarrow E_g \propto \nu$$

- In Si, Ge semiconductors, Infra-red radiation are emitted during recombination, so we can't see it.

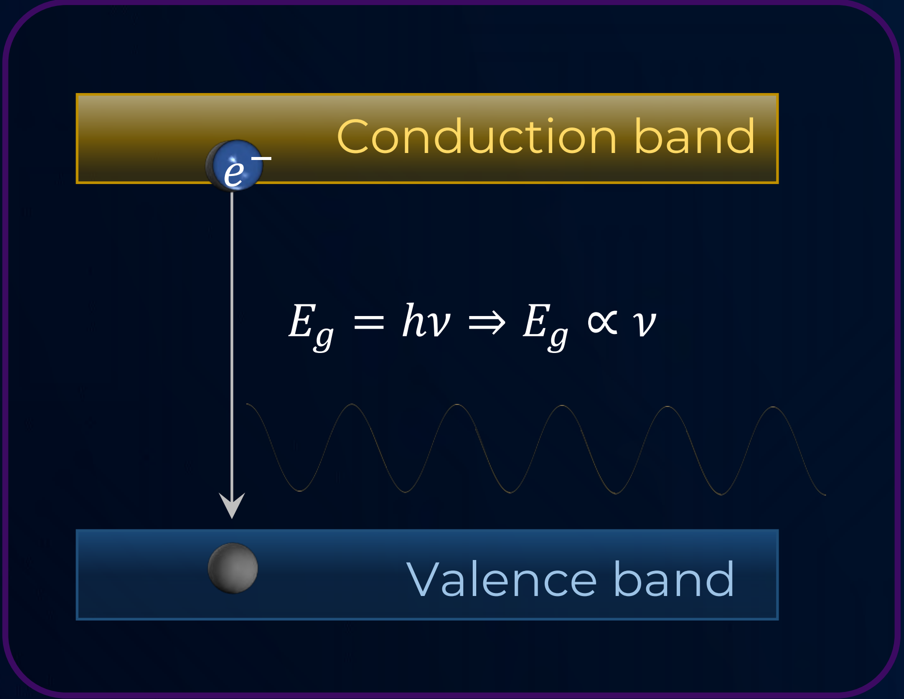
LIGHT EMITTING DIODE

- The semiconductor used for fabrication of visible LEDs must at least have a band gap of $1.8\ eV$ (spectral range of visible light is from about $0.4\ \mu m$ to $0.7\ \mu m$, i.e., from about $1.8\ eV$ to $3\ eV$)

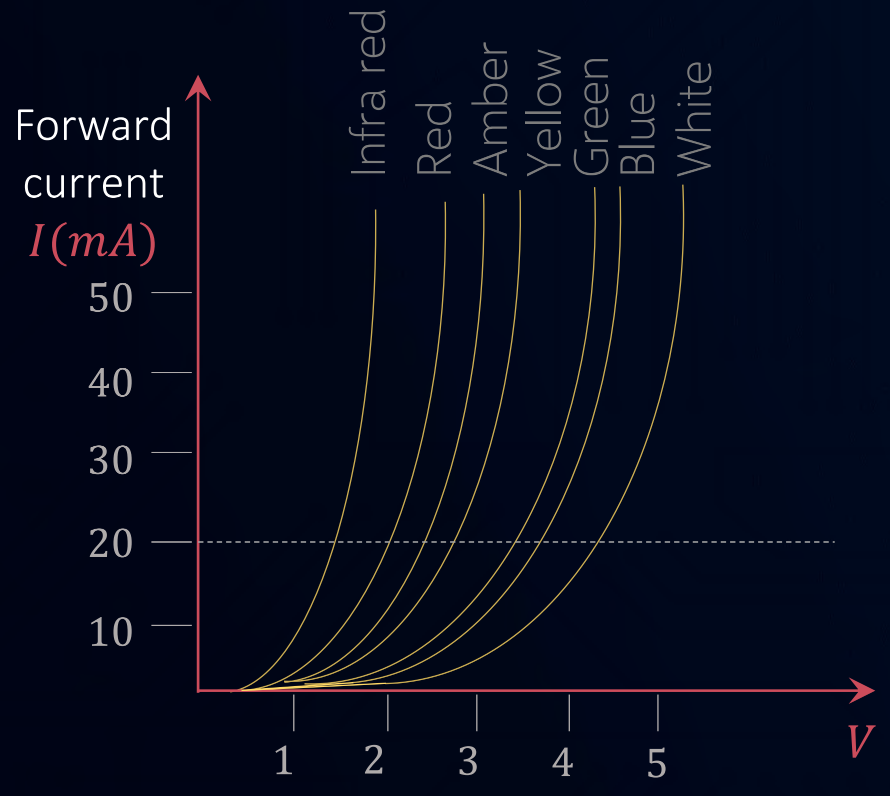
Examples ;

Aluminium Gallium Arsenide $(AlGaAs)$

Gallium Phosphide (GaP)



I-V CHARACTERISTICS OF LIGHT EMITTING DIODE



- Intensity of emitted light is determined by the forward current conducted by the junction.
- Safe value of forward current is around $5\ mA$ for usual LED and go up to $30\ mA$ for LED providing high brightness output.

LIGHT EMITTING DIODE

Advantages of LED(s):

- Low Operational Voltage and Power Consumption
- Instant On-Off switching without warm-up time
- The bandwidth of emitted light is nearly monochromatic.
- Long Life and negligible wear and tear

For LED's to emit light in visible region of electromagnetic light, it should have energy band gap in the range of

$$E_g = \frac{hc}{\lambda}$$

For visible region, $\lambda = 4 \times 10^{-7}\ m - 7 \times 10^{-7}\ m$

$$\frac{6.6 \times 10^{-34} \times 3 \times 10^{8}}{7 \times 10^{-7} \times 1.6 \times 10^{-19}}\ eV \leq E_g \leq \frac{6.6 \times 10^{-34} \times 3 \times 10^{8}}{4 \times 10^{-7} \times 1.6 \times 10^{-19}}\ eV$$

$$E_g \geq 1.75\ eV$$

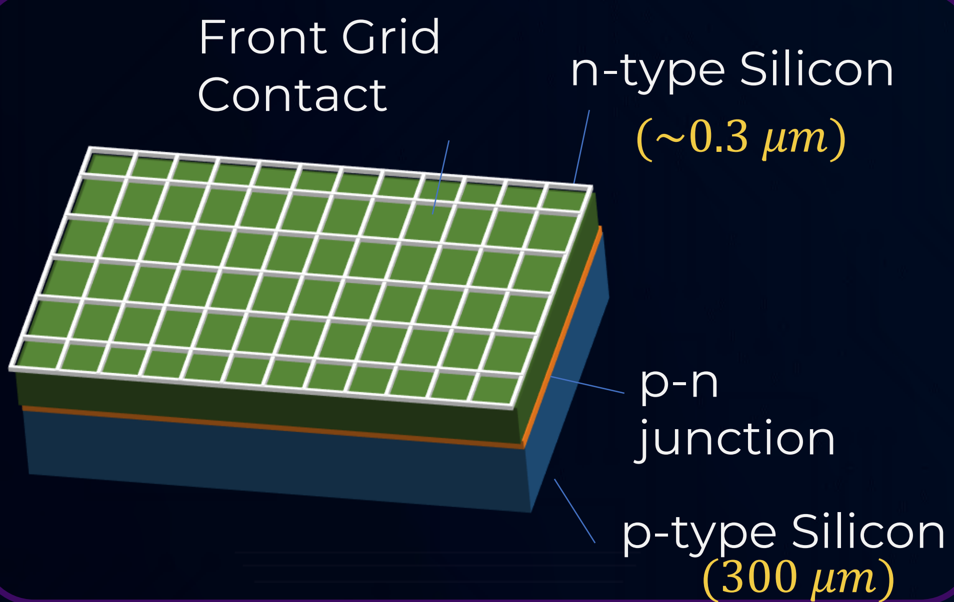
A. $0.1\ eV$ to $0.4\ eV$

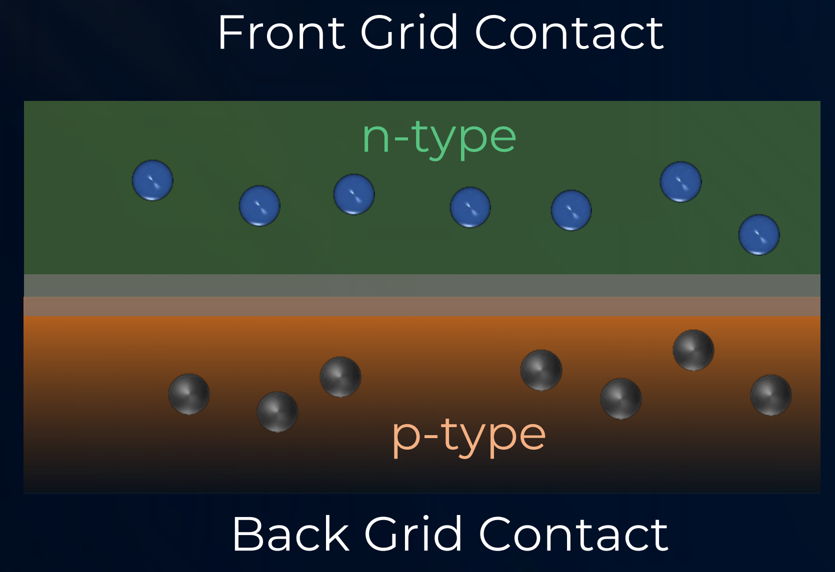
B. $0.5\ eV$ to $0.8\ eV$

C. $0.9\ eV$ to $1.6\ eV$

D. $1.7\ eV$ to $3.0\ eV$

Solar Cell

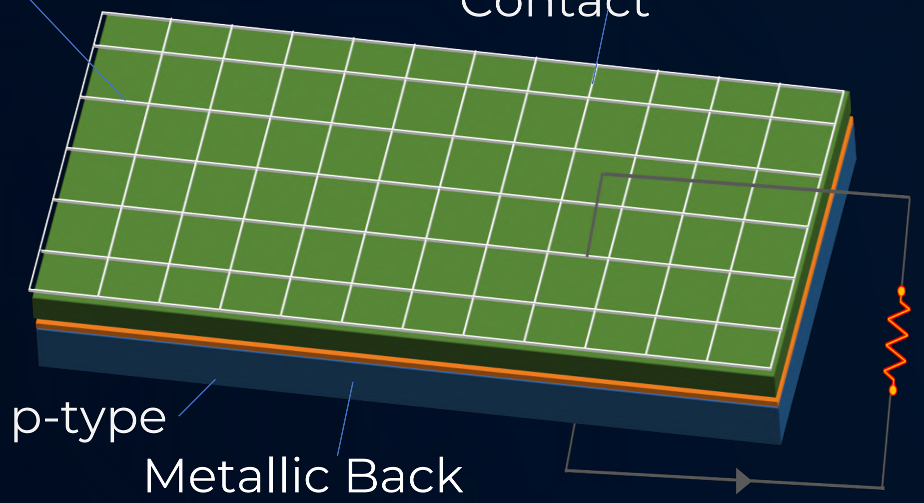




- Back contact, below p-type Si wafer: Metallic.
- Front contact, above n-type Si wafer: Metallic grid, occupies ~15 % of cell area so that light can be incident on the cell from the top.
- Due to the sunlight, electron-hole pairs are generated from the neutral atom at the depletion region and because of the presence of electric field in the depletion region, the electron hole pair get separated.

Solar Cell

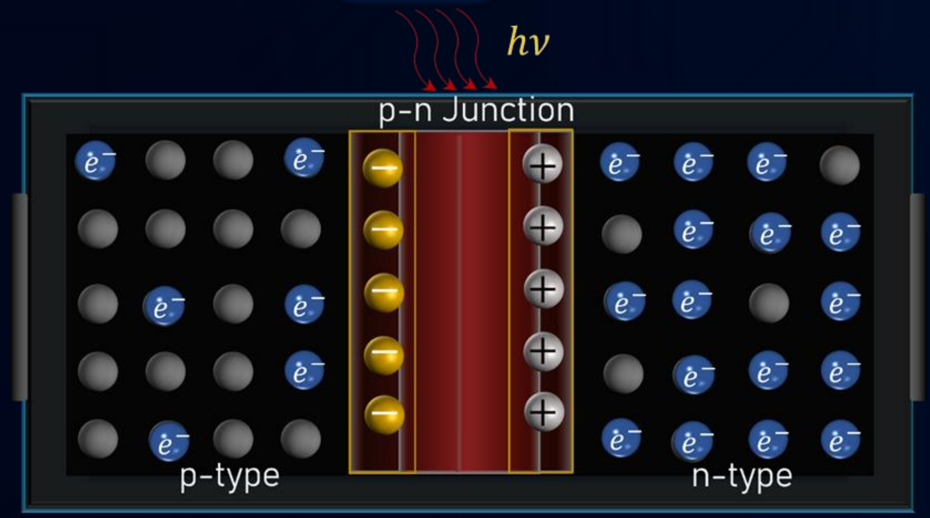
- The separated electron-hole pairs are collected by the front grid contact and the metallic back contact.
- Thus, they give rise to potential difference between front grid contact and metallic back contact.
- When an external load is connected to the cell, currents begins to flow through the load.



Material Selection for solar cell fabrication:

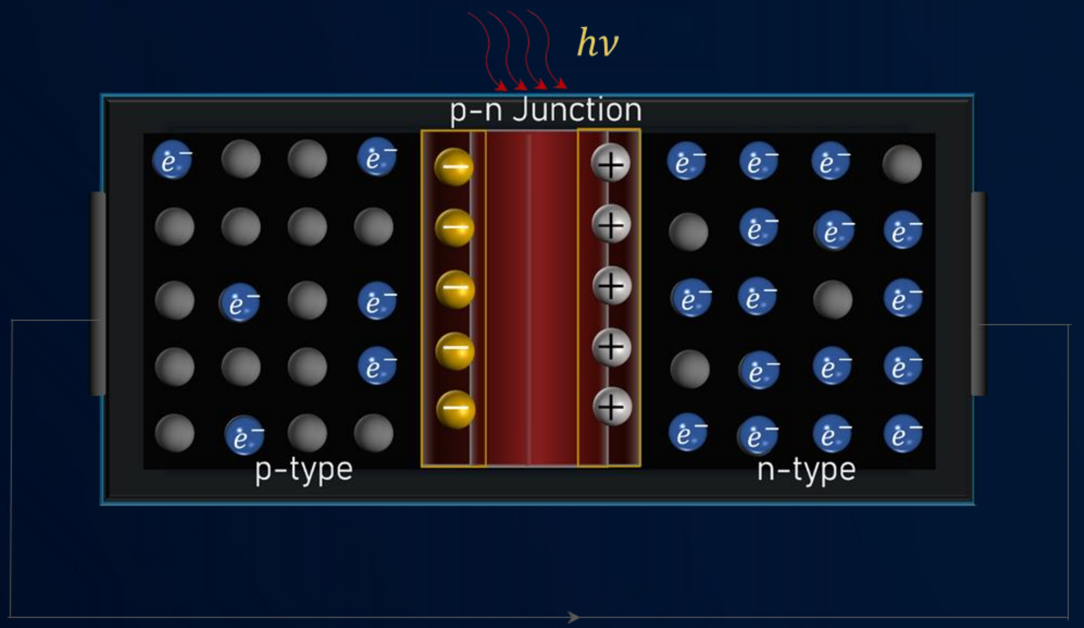
- Band-gap in the range of $1.0\ eV$ to $1.8\ eV$.
- High solar radiation absorption capability.
- Good electrical conductivity.
- Ease of availability and cost.

I-V CHARACTERISTICS OF SOLAR CELL



When the solar cell is not connected to the external circuit

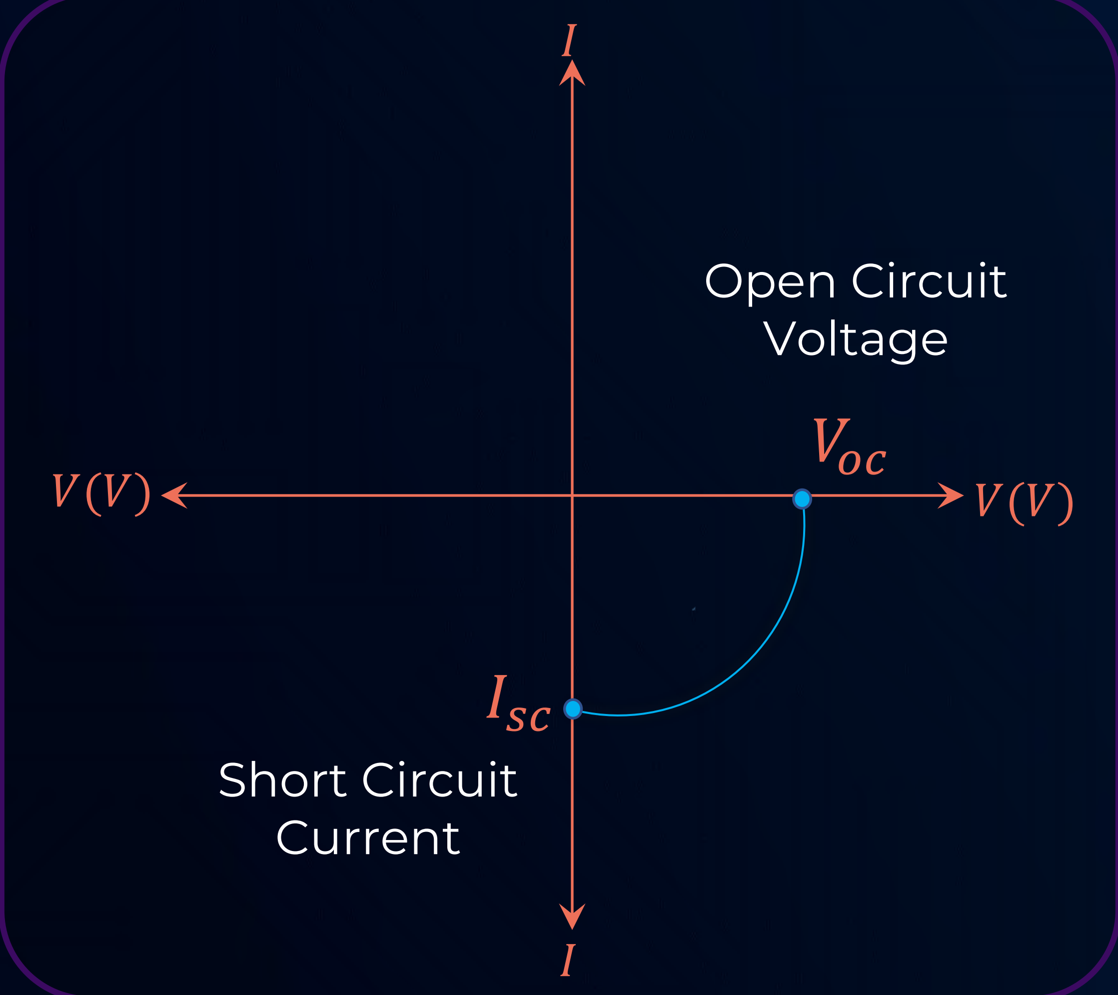
- The accumulation of charges at both ends (i.e., holes on p-side and electrons on n-side) will reach a maximum value at some point of time and this is called saturation. At saturation, the voltage has a maximum value called the open circuit voltage (V_{OC}).



When the ends of the solar cell are connected only by a wire

- The current begins to flow from n-side to p-side inside the p-n junction or p-side to n-side in the external circuit. This current has a maximum value as there is no resistance in the external circuit called the short circuit current (I_{SC}). Since the current is from n-side to p-side inside the p-n junction, it is taken as negative.

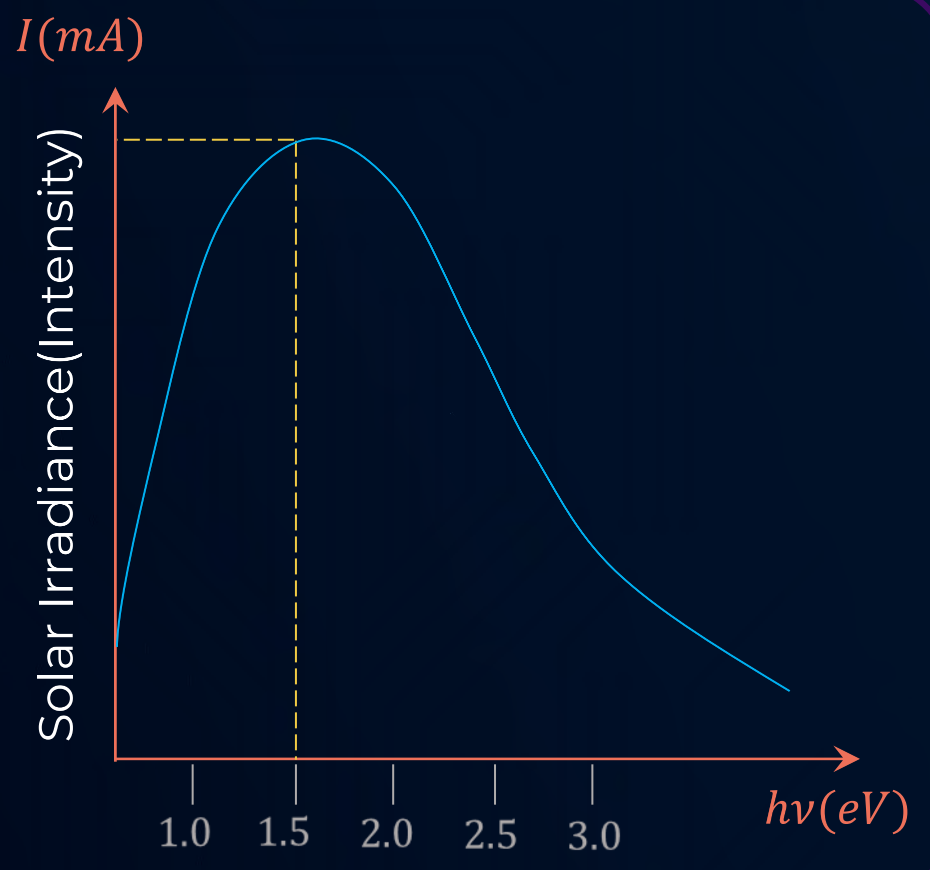
I-V CHARACTERISTICS OF SOLAR CELL



I-V CHARACTERISTICS OF SOLAR CELL

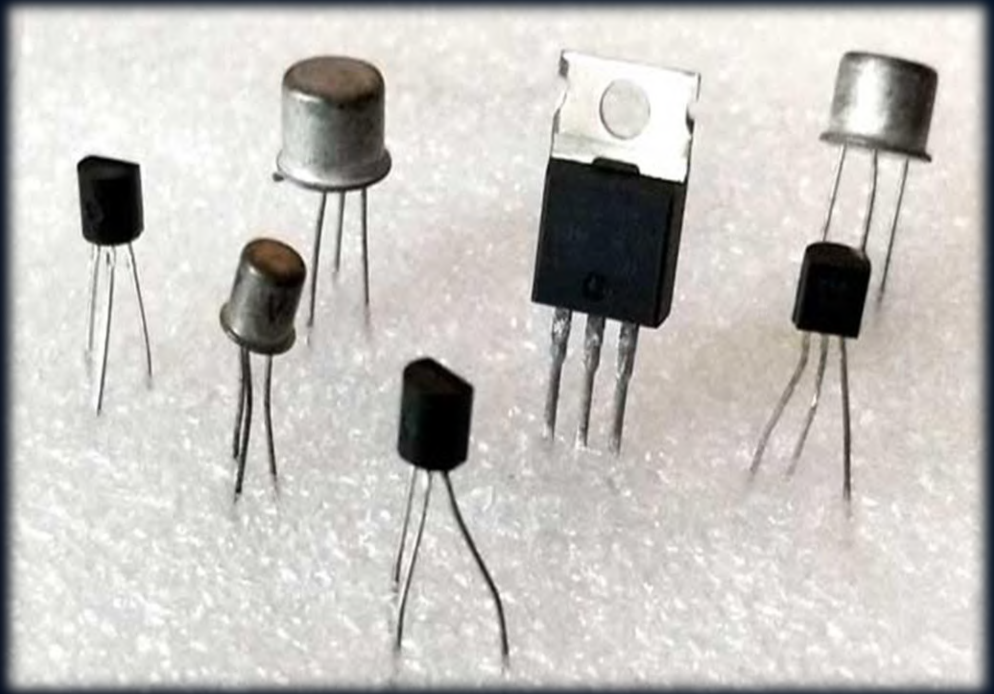
- Maximum number of photons available in sunlight have approximately $1.5\ eV$ energy.
- That means, if we use semiconductor materials with band gap $\sim 1.5\ eV$ or less, then we will get the maximum energy from sunlight.

Semiconductor Material	Formula	Band-gap (eV)
Silicon	Si	1.11
Cupric oxide	CuO	1.20
Gallium arsenide	$GaAs$	1.43
Indium phosphide	InP	1.35



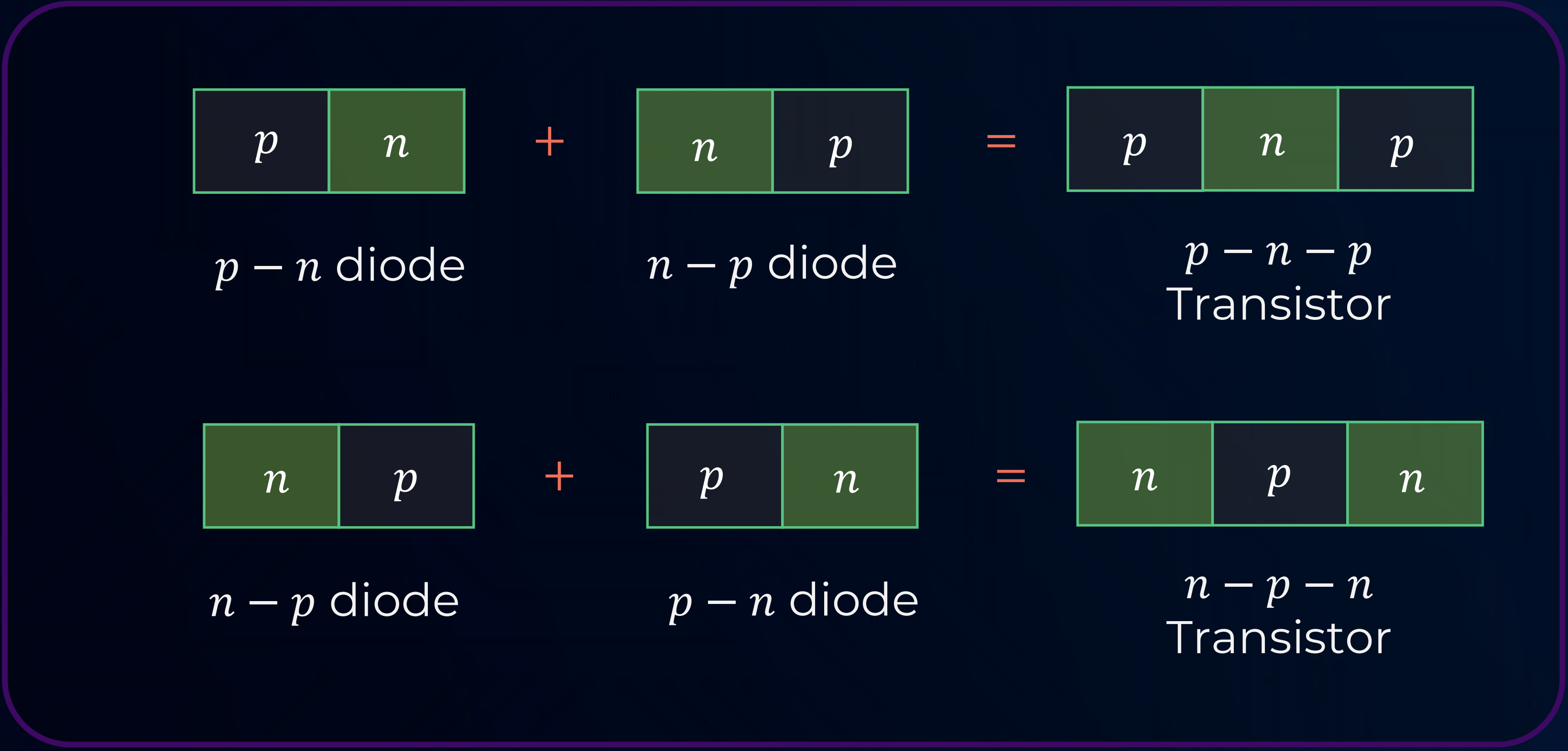
Introduction of Transistors

- Transistors were designed in 1947 by J. Bardeen, William B. Shockley & W. H. Brattain of Bell Telephone Lab, USA.



Junction Transistors

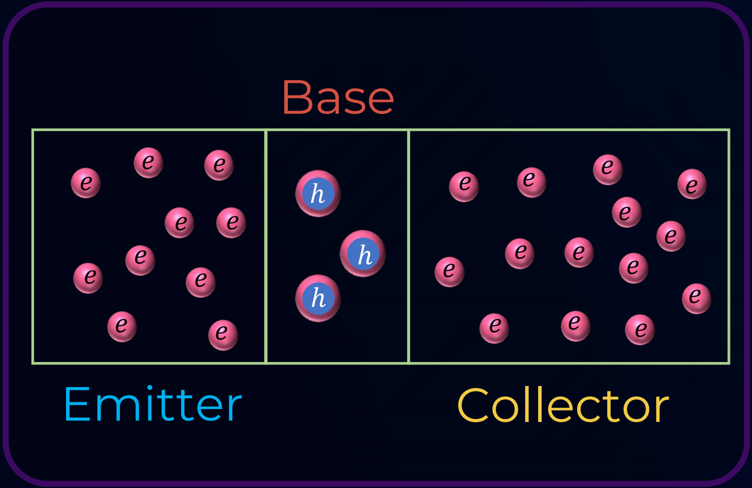
- Transistors are basically combination of two diodes or two junctions.



$n-p-n$ and $p-n-p$ Transistors

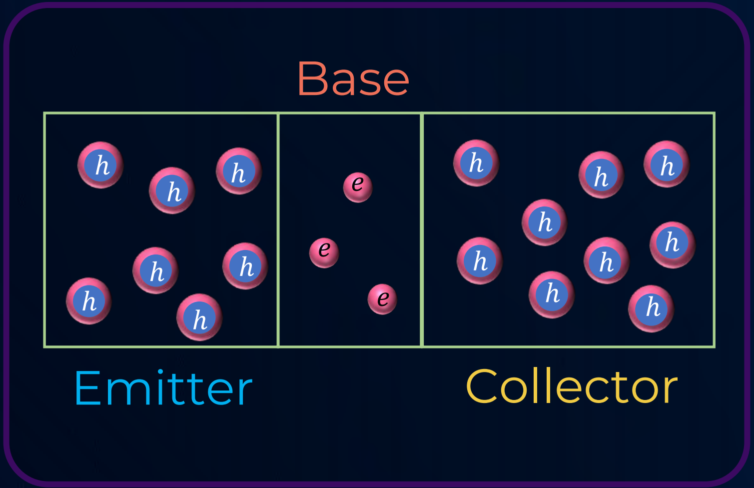
$n-p-n$ Transistor

- A thin layer of p-type semiconductor is sandwiched between two n-type semiconductors.

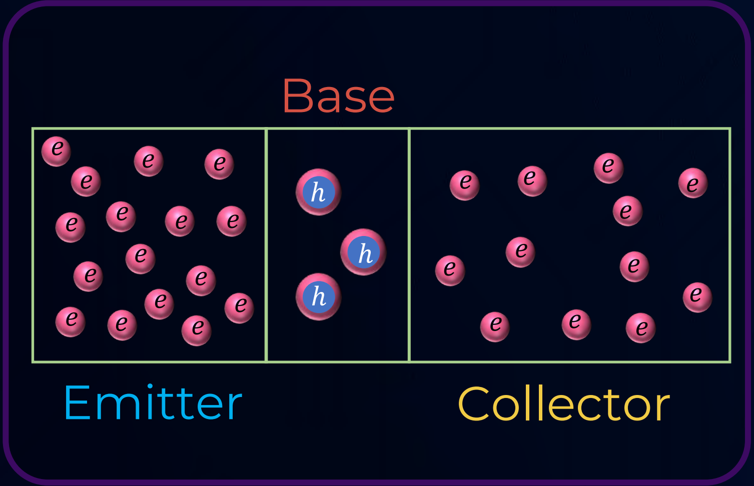


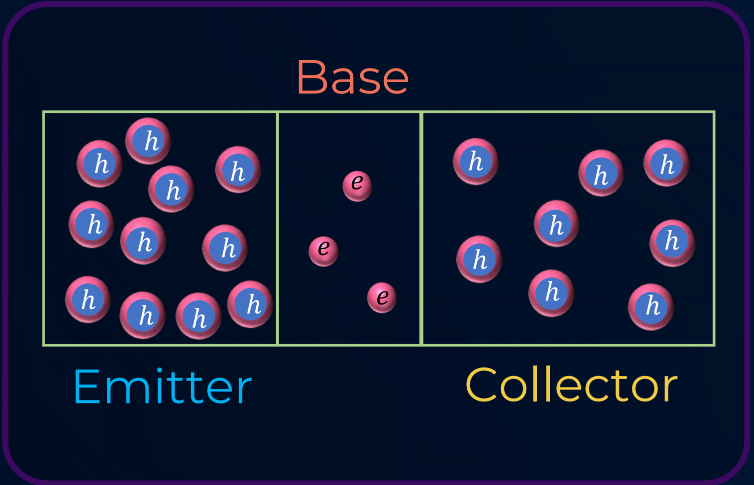
$p-n-p$ Transistor

- A thin layer of n-type semiconductor is sandwiched between two p-type semiconductors.



Structure of Transistors

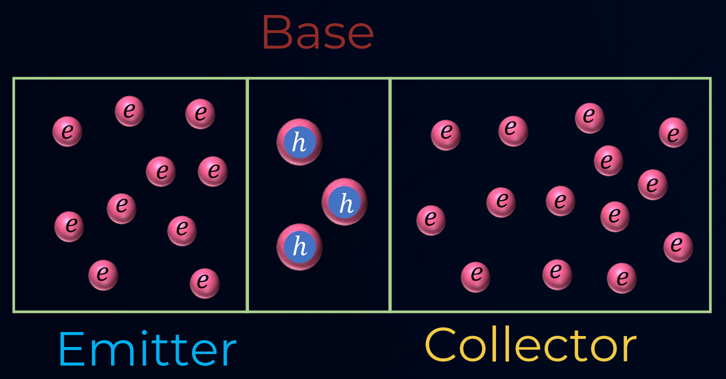




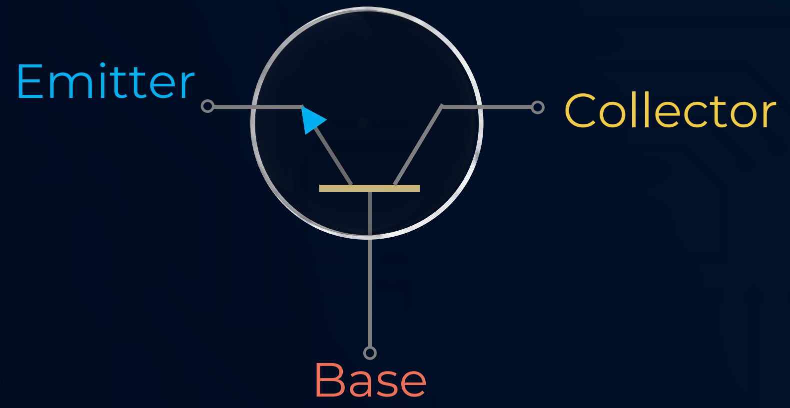
All three segments of a transistor have different thicknesses and doping levels:

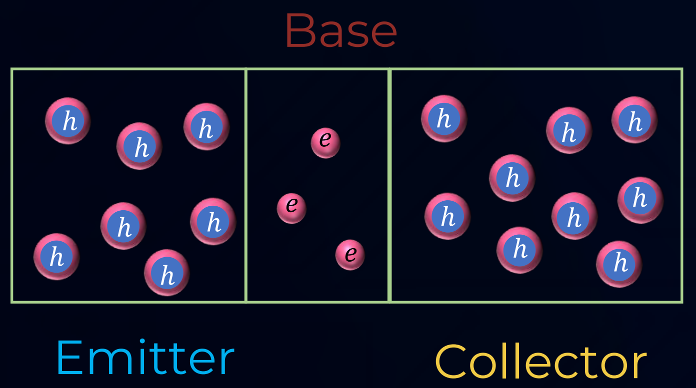
Segment	Size	Doping
Emitter	Moderate	High
Base	Thin	Low
Collector	Large	Moderate

Schematic of Transistors

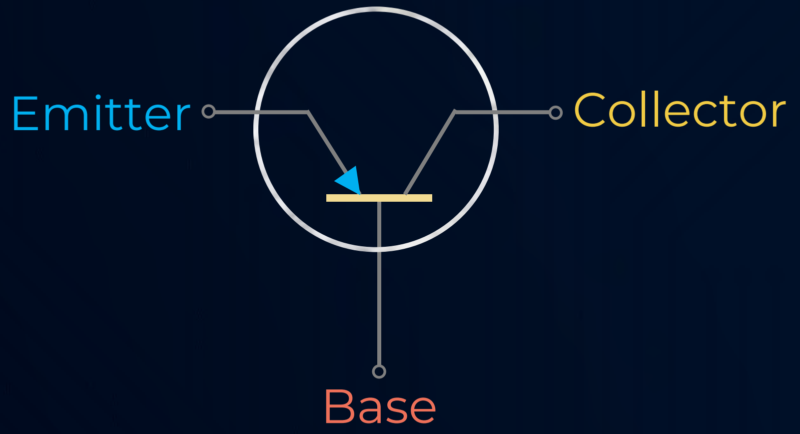


n-*p*-*n* transistor





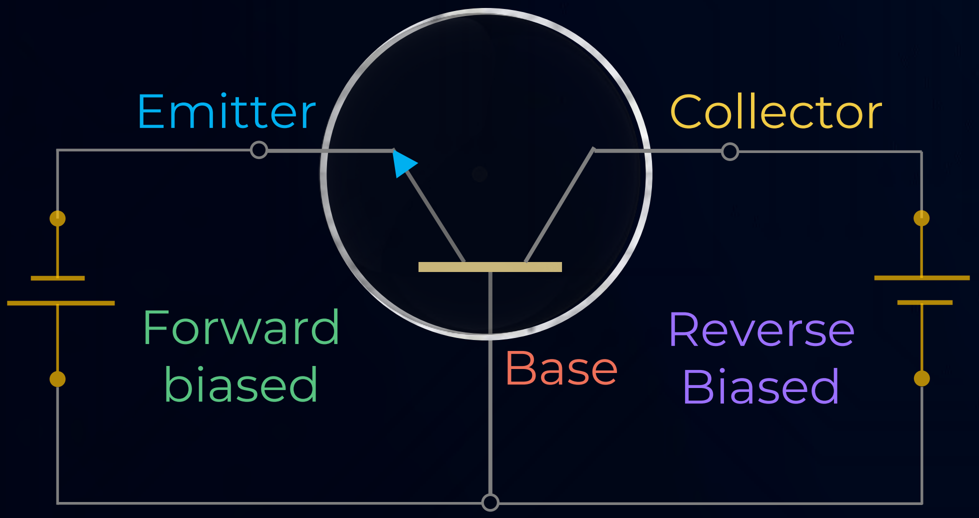
p-*n*-*p* transistor



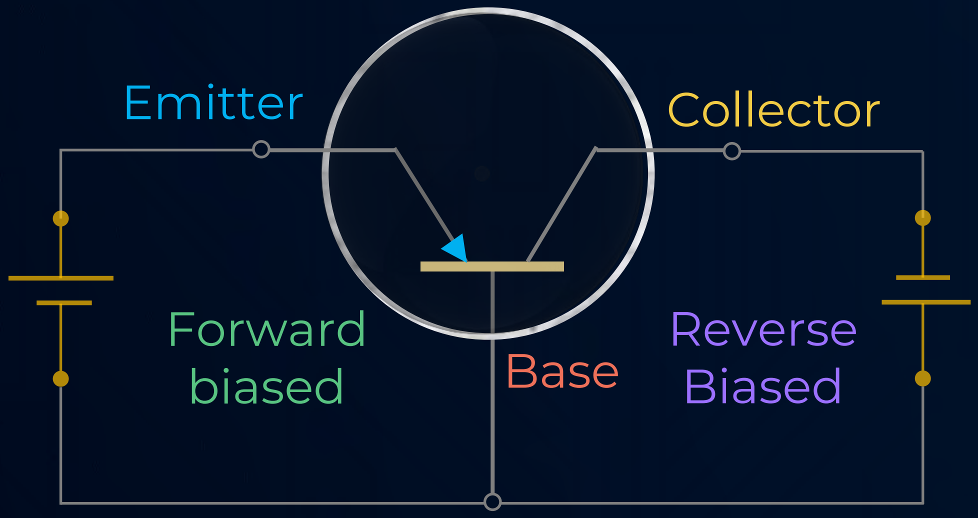
- The arrow on the emitter line shows direction of current through emitter base junction.

Forward Bias and Reverse Bias of Transistors

$n - p - n$ transistor



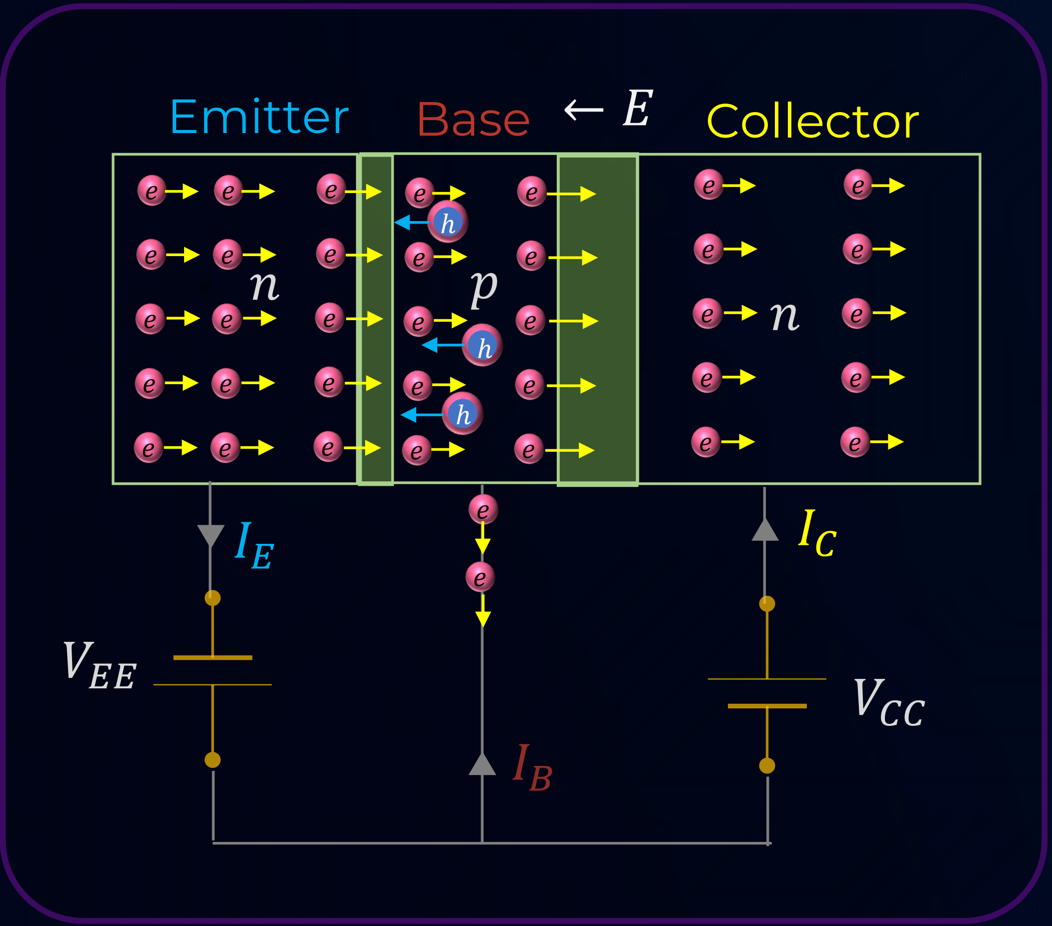
$p - n - p$ transistor



- In normal operation, the emitter-base junction is forward-biased, and the collector-base junction is reverse-biased.

} Active state of the transistor

Working of Transistors (Common Base)



n-p-n transistor in common-base mode

- Emitter-base junction → forward biased → Thin
- Collector-base junction → reverse biased → Thick
- Due to heavily doped emitter, e^- are easily injected to base.
- Most of the injected electrons can easily pass the base-collector junction as the direction of the electric field supports the motion of injected electrons, and the rest of the electrons come out of the base terminal.
- I_E → Emitter current (Coming out of the emitter)
- I_B → Base current (Going into the base)
- I_C → Collector current (Going into the collector)

Working of Transistors (Common Base)

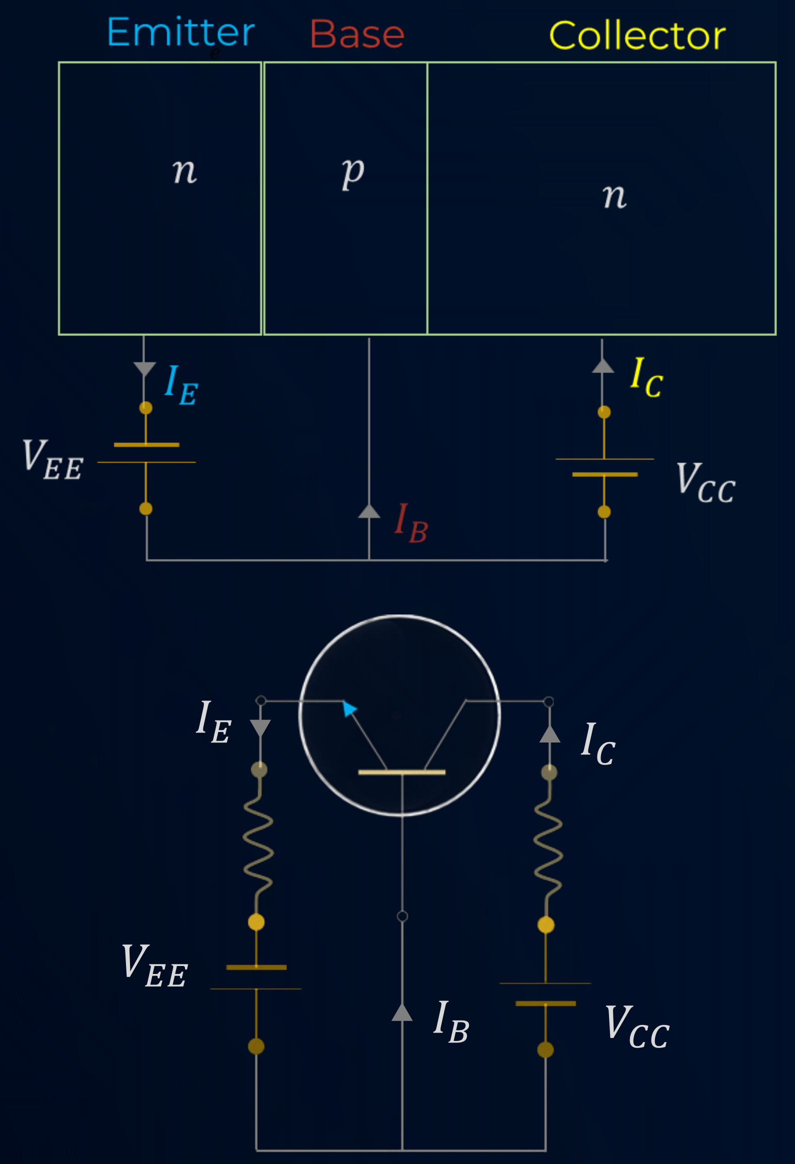
- Using Kirchhoff's law, $I_E = I_B + I_C$
- The physical design of a transistor is such that $I_B \ll I_E$. Typically I_B is 1~5% of I_E.
- α & β parameters for transistors are defined as,

$$\alpha = \frac{I_C}{I_E}$$

$$\beta = \frac{I_C}{I_B}$$ → Current gain (β)

$\alpha \cong 0.95\ to\ 0.99$

$$\beta = \frac{\alpha}{1-\alpha}$$



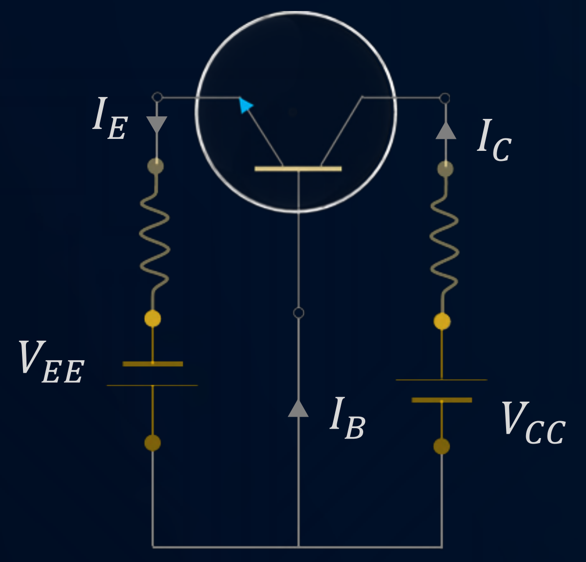
Current Gain (β)

- Current gain (β)

$$\beta = \frac{I_C}{I_B}$$

$\beta \cong 50 \text{ to } 200$

- From the relation $I_C = \beta I_B$, we get I_C which is 50 to 200 times higher than I_B . So, a transistor can also be used as an amplifier.



- For DC Current

$I_C = \beta_{DC} I_B$

- For AC Current

$\Delta I_C = \beta_{AC} \Delta I_B$

It refers to change in current.

- In general, it is seen experimentally that:

$$\beta_{AC} = \beta_{DC} = \beta$$

In a common base mode of a transistor, the collector current is $5.488\ mA$ for an emitter current of $5.60\ mA$. The value of base current amplification factor (β) will be:

Given: $I_C = 5.488\ mA, I_E = 5.60\ mA$

To find: β

Solution: $I_B = I_E - I_c$

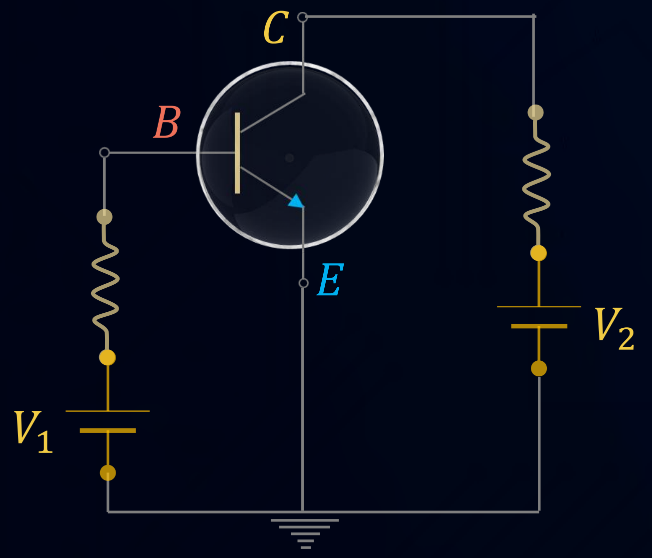
$$I_B = 5.60 - 5.488 = 0.112\ mA$$

$$\beta = \frac{I_C}{I_B} = \frac{5.488}{0.112}$$

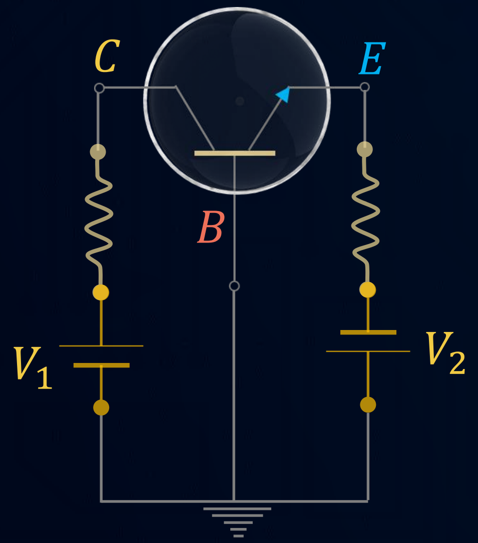
$$\beta = 49$$

Mode of Operation of Transistors

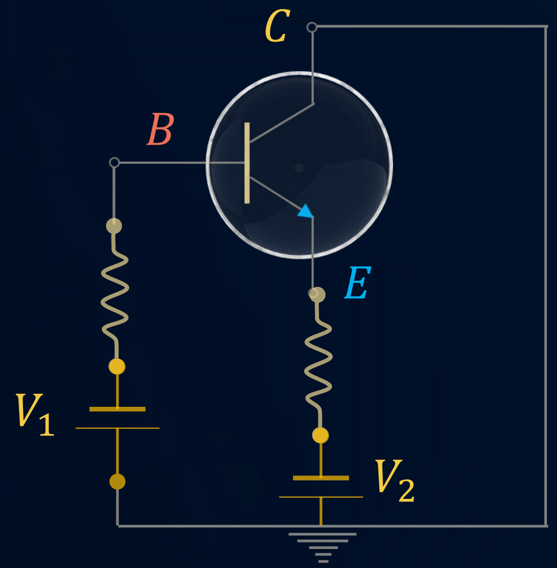
A transistor can be configured in 3 different ways:



Common emitter



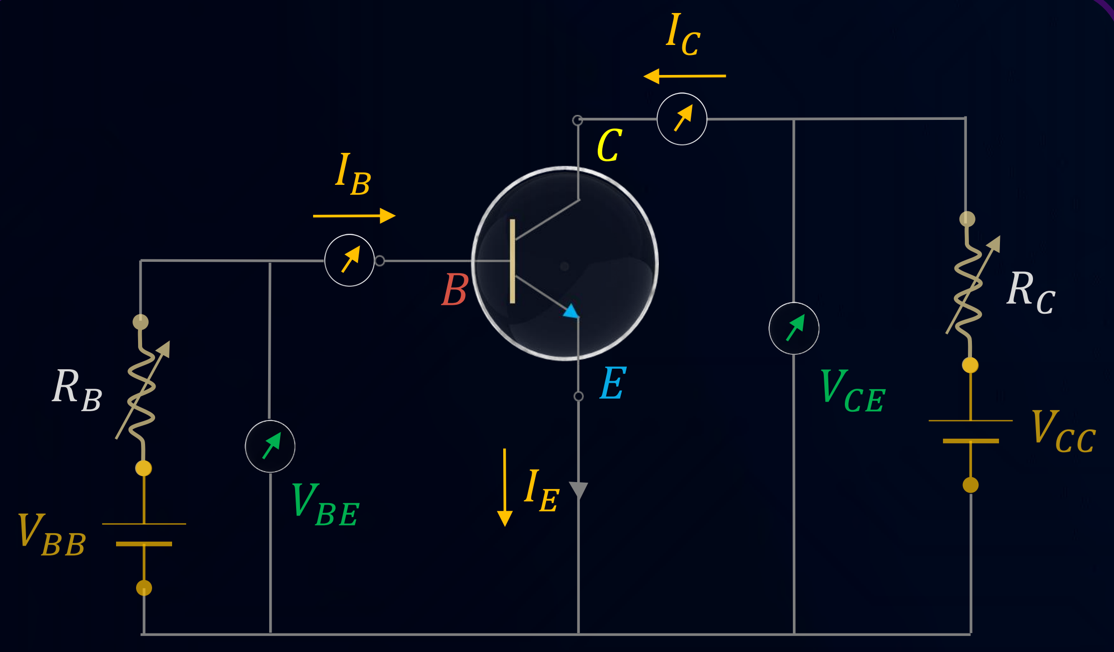
Common base



Common collector

- All three are n-p-n transistors.
- $V_2 > V_1 \Rightarrow$ E-B Junction in forward bias and C-B Junction in reverse bias.
- The transistor is most widely used in common emitter configuration.

Common Emitter Transistor



Common-emitter mode in n-p-n transistor

- The BE junction is forward biased with the help of V_{BB}.
- $V_{CC} > V_{BB} \rightarrow$ CB junction is reverse biased.
- $I_E = I_B + I_C$
- V_{BE} → Potential difference b/w the base and the emitter. } Forward bias Voltage
- V_{CE} → Potential difference b/w the collector and the emitter.
- V_{CE} is only providing the reverse bias voltage so that CB junction becomes reversed biased. V_{CE} itself is not the reverse bias voltage.
- Higher the value of V_{CE}, higher is the reverse bias voltage b/w the collector and the base.

Transistor Characteristics

- Input characteristics: Variation of I_B with V_{BE} keeping V_{CE} fixed.

  Here,

  V_{BE}: Base-Emitter voltage.

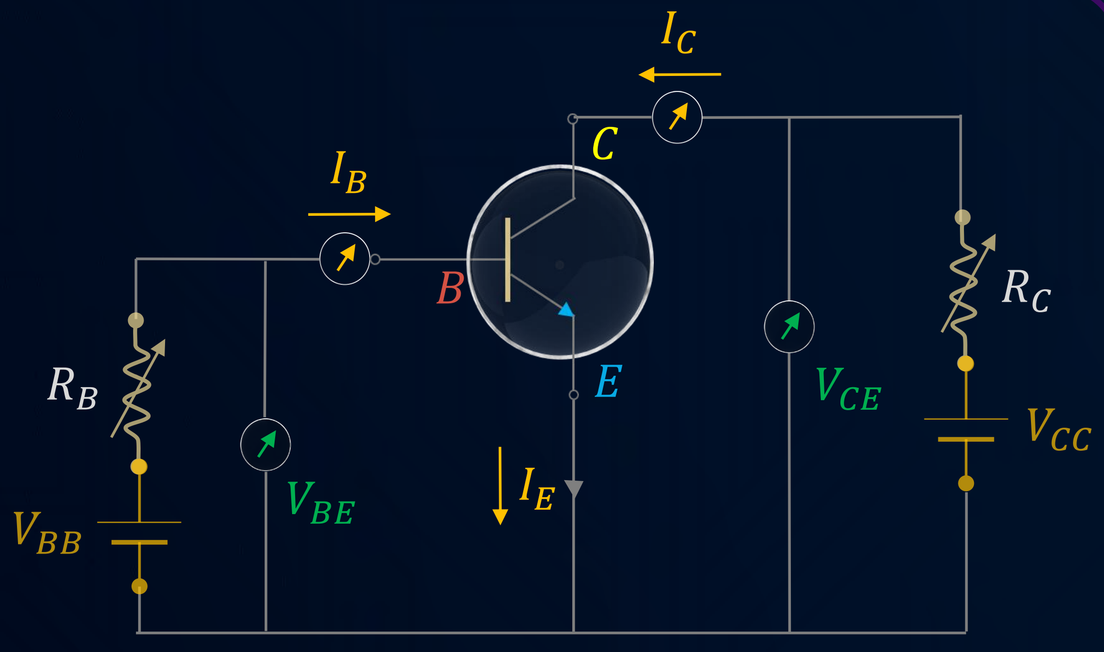
  I_B: Input current.

- Output characteristics: Variation of I_c with V_{CE} keeping I_B fixed.

  Here,

  V_{CE}: Collector-Emitter voltage.

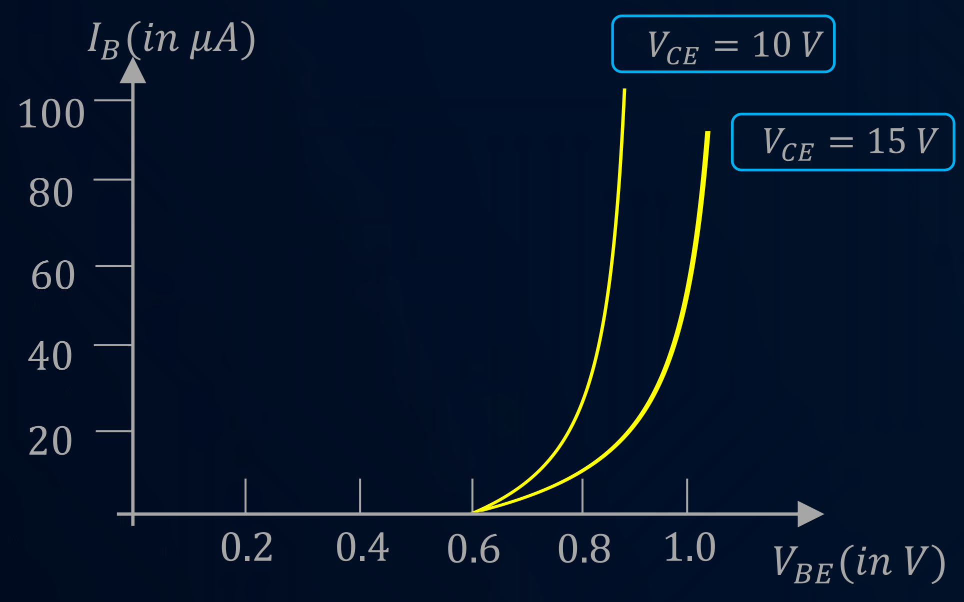
  I_C: Output current.



Input Characteristics of Transistors

V_{BE}

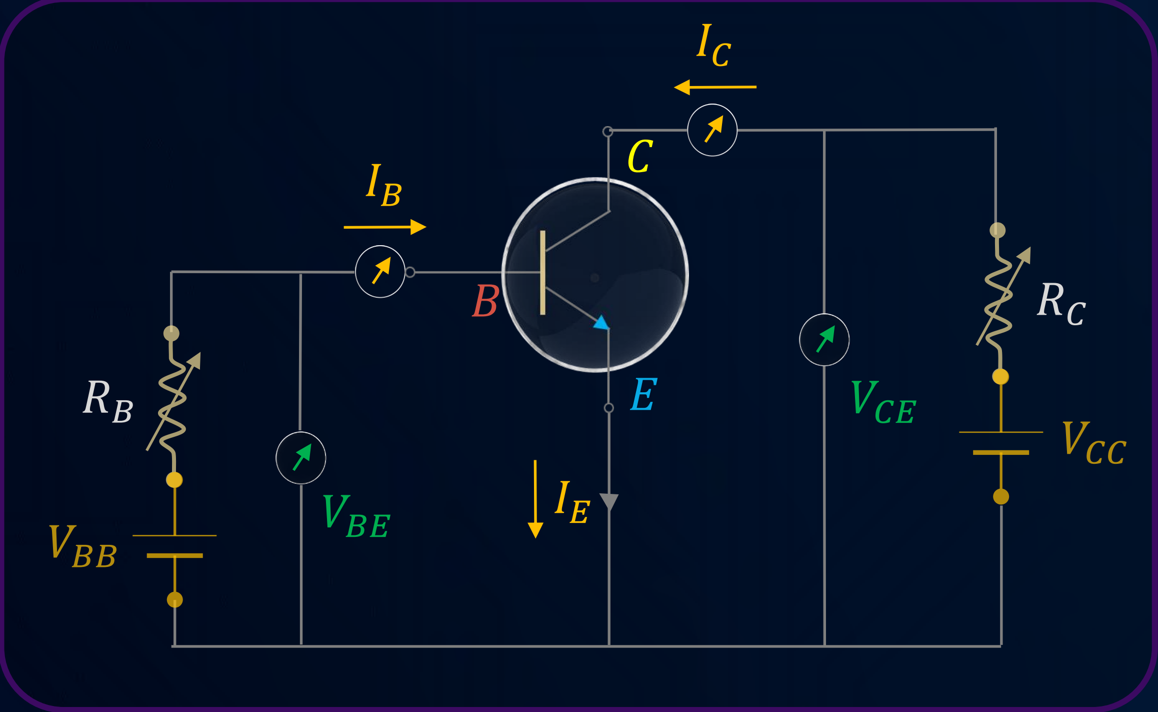
- < Barrier Potential of BE junction → I_B is small
- > Barrier Potential of BE junction → I_B starts growing gradually, and the curve looks similar to that of a forward bias p-n junction.



- With increases of V_{CE} base current (I_B) decreases.

Output Characteristics of Transistors

- For output characteristics, I_B is fixed and dependence of I_C on V_{CE} is studied .

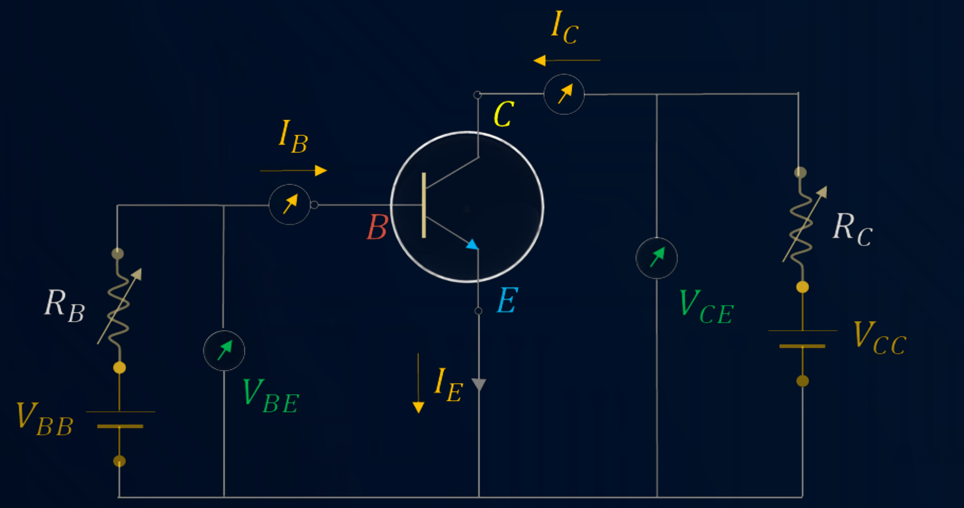


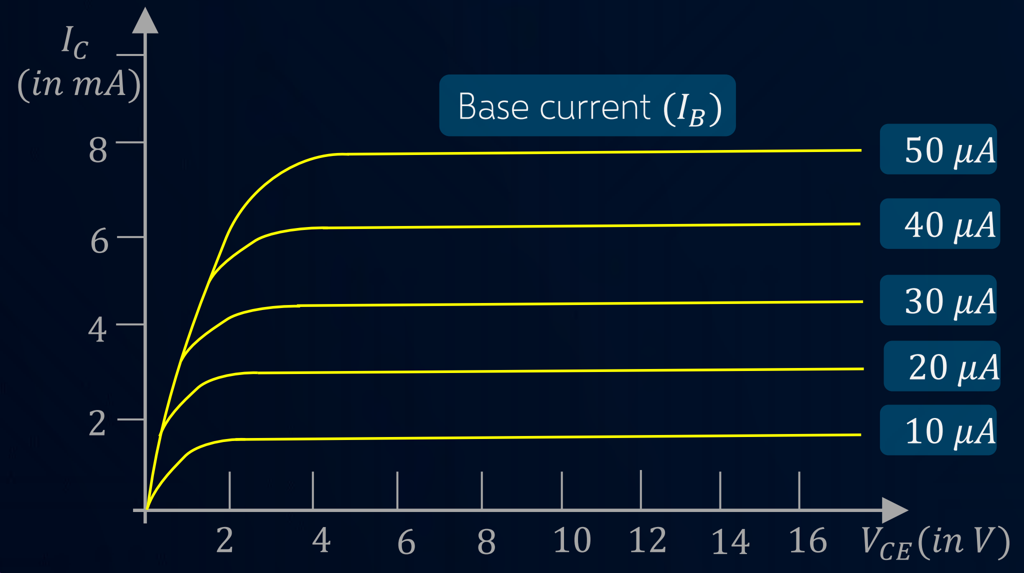
Output Characteristics of Transistors

- When V_{CE} increases. → Increases the strength of electric field. → I_C Increases.

- Since the concentration of electrons is limited at the emitter, it can provide electrons up to a certain limit. Therefore, the I_C can't increase indefinitely with the increase of V_{CE} rather the I_C will reach a constant value.

- Since $I_C = \beta I_B$, I_C increases with increase in I_B.





Transistor Characteristics

- Input resistance (r_i)

$$r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE}}$$

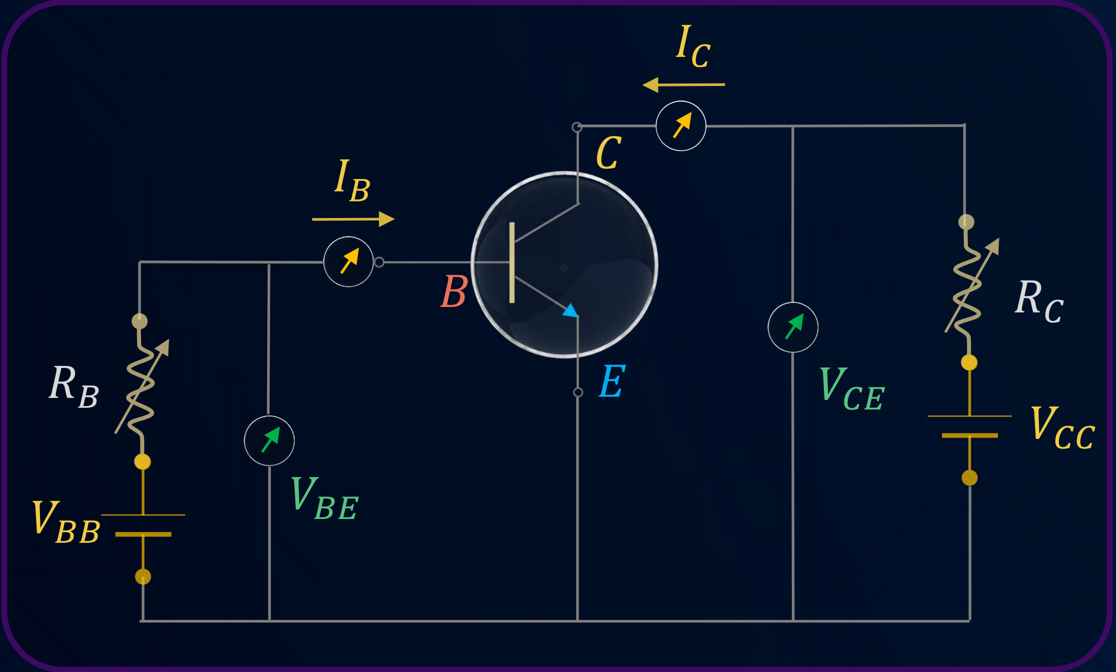
- Output resistance (r_o)

$$r_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B}$$

- Current amplification factor (β)

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$$

$$\beta_{dc} = \frac{I_C}{I_B}$$



- Input and output resistances are dynamic resistance because the voltage and current do not follow linear relation in case transistor.

The output characteristics of a transistor is shown in figure. Find the value of β_{ac} when $V_{CE} = 10\ V$ and $I_C = 4.0\ mA$.

Given: $V_{CE} = 10\ V$ and $I_C = 4.0\ mA$

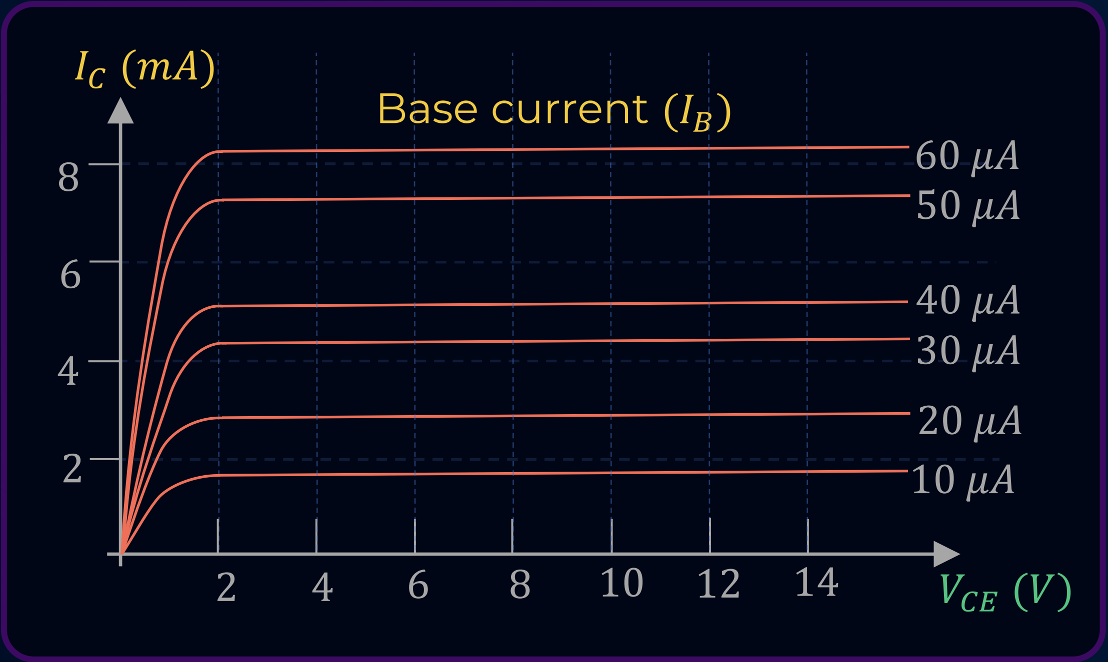
To find: β_{ac}

Solution:

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$$

$$\beta_{ac} = \left(\frac{(4.5-3)mA}{(30-20)\mu A}\right)_{V_{CE}}$$

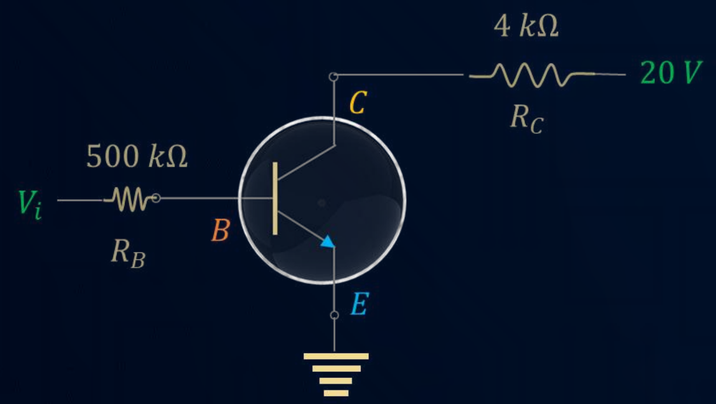
$$\beta_{ac} = 150$$



In the circuit shown in the figure, the input voltage $V_i = 20\ V, V_{BE} = 0\ V$ and $V_{CE} = 0\ V$. Then find the values of I_B, I_C and β.

Given: $V_i = 20\ V, V_{BE} = 0\ V$ and $V_{CE} = 0\ V$

To Find: I_B, I_C and β



Solution: Collector current is calculated as:

$$I_C = \frac{20 - 0}{4 \times 10^3} = 5 \times 10^{-3}\ A$$

$$I_C = 5\ mA$$

We know that input voltage is given by:

$$V_i = V_{BE} + I_B R_B$$

$$V_i = 0 + I_B R_B$$

$$20 = 0 + I_B \times 500 \times 10^3$$

$$I_B = \left(\frac{20}{500 \times 10^3}\right) = 40\ \mu A$$

$$\beta = \frac{I_C}{I_B} = \frac{5 \times 10^{-3}}{40 \times 10^{-6}} = 125$$

A. $I_B = 40\ \mu A, I_C = 10\ mA, \beta = 250$

B. $I_B = 25\ \mu A, I_C = 5\ mA, \beta = 200$

C. $I_B = 20\ \mu A, I_C = 5\ mA, \beta = 250$

D. $I_B = 40\ \mu A, I_C = 5\ mA, \beta = 125$

Transistors as Device

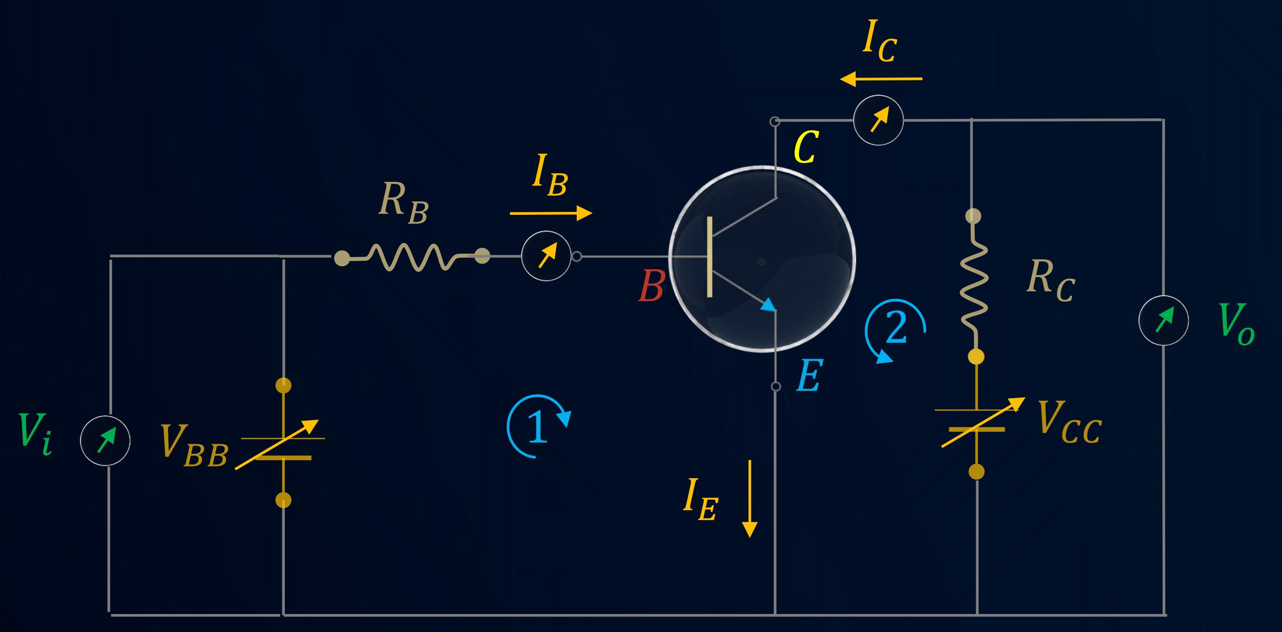
V_i = Input voltage.

V_o = Output voltage which is b/w collector and emitter.

Applying Kirchhoff's Voltage Law in loop 1 & 2:

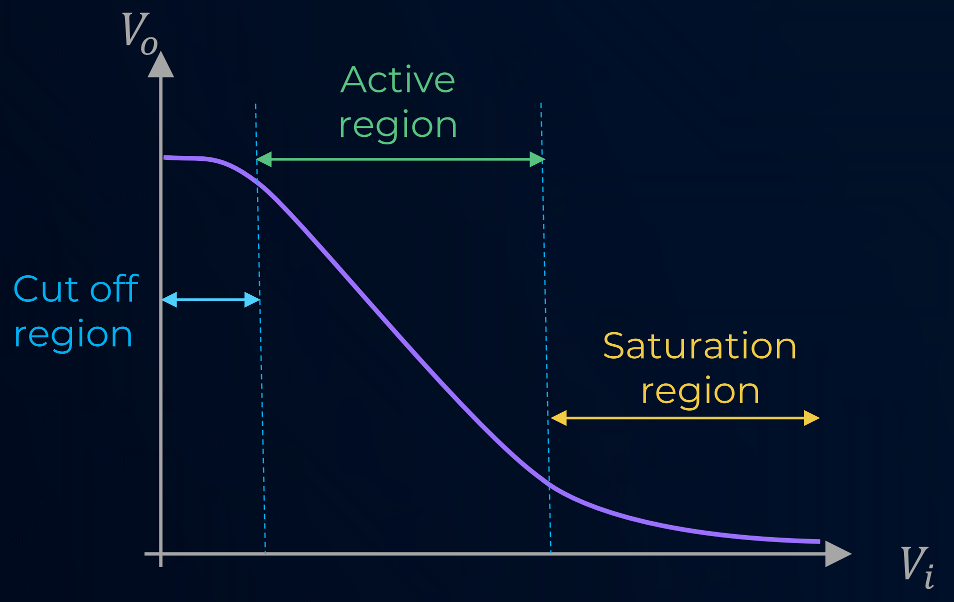
$$V_{BB} = V_i = I_B R_B + V_{BE}$$

$$V_{CE} = V_o = V_{CC} - I_C R_C$$



Transistors as Device

- $V_{BB} = V_i = I_B R_B + V_{BE}$
- $V_{CE} = V_o = V_{CC} - I_C R_C$
- When V_i is low, V_o is high.
- When V_i is high, V_o is low.



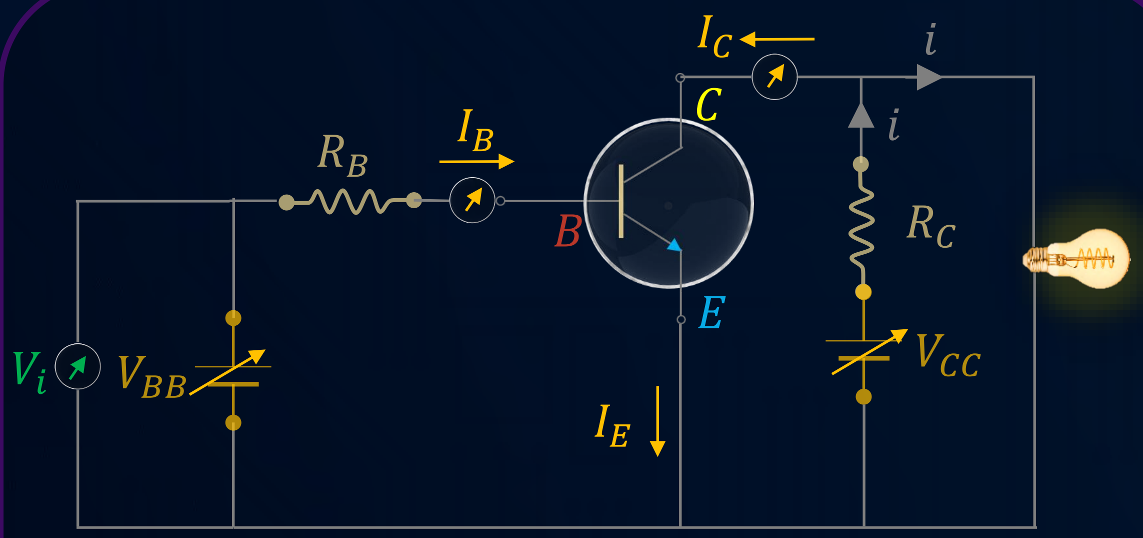
Region	V_i	V_{BE}	I_B	I_C	V_{CE}/V_O
Cut-Off	Low	Low	0	0	V_{CC}
Active	↑	↑	↑	↑	↓
Saturated	High	High	High	High (Saturated)	Low ~ Zero

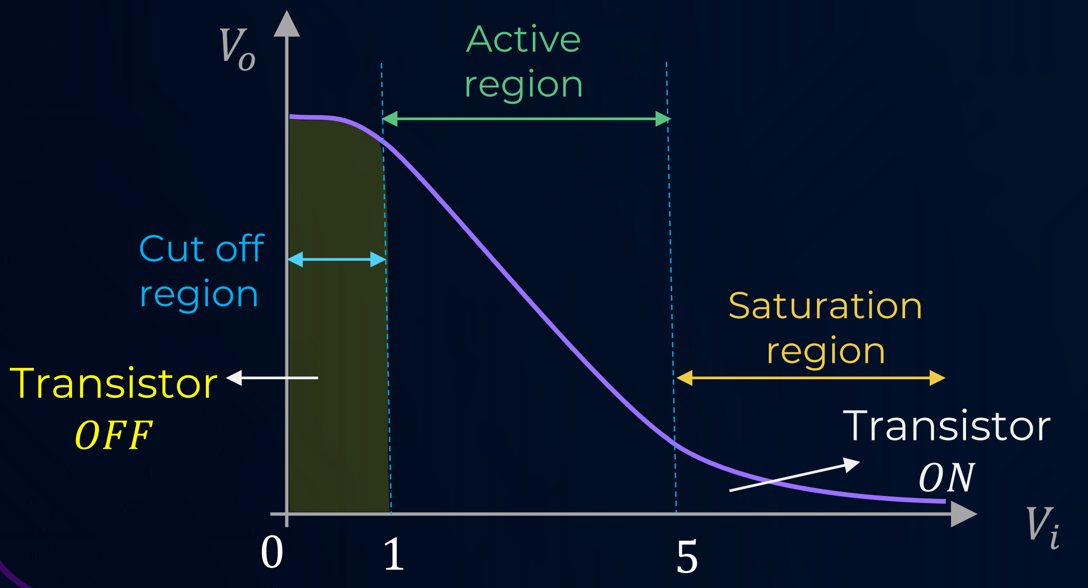
Transistors as Switch

- Transistor can be operated as a switch.
- Let $V_i = (0-1)V$ → Low Input

  $V_i > 5\,V$ → High Input
- Cut off region → Transistor OFF
- Saturation region → Transistor ON

When $V_i < 1\,V$, the transistor goes to the cut-off region. → No current through the transistor ($I_C = 0$) → Output (V_O) $= V_{CC}$ → Bulb glows



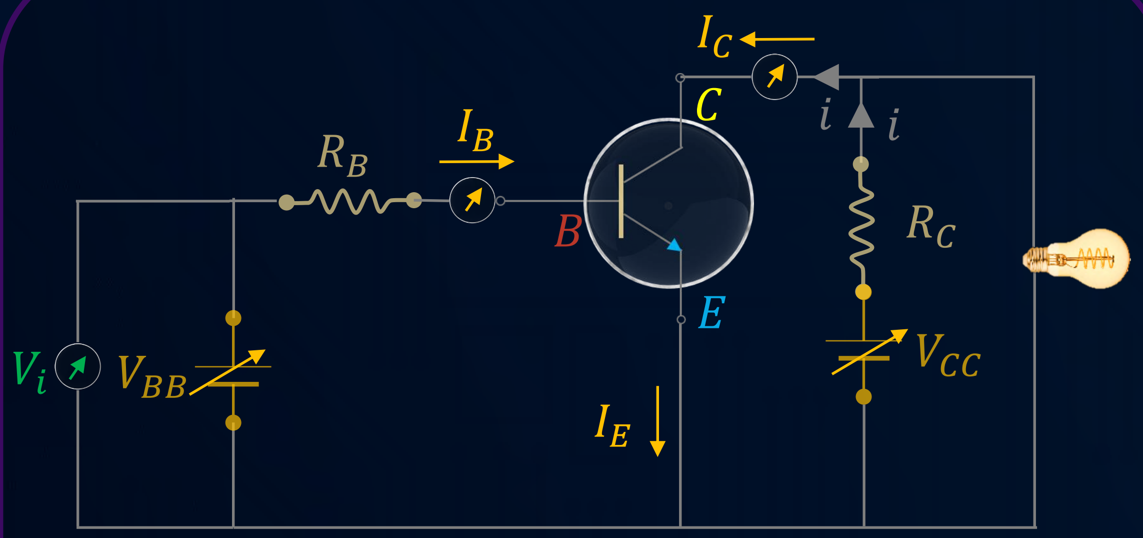


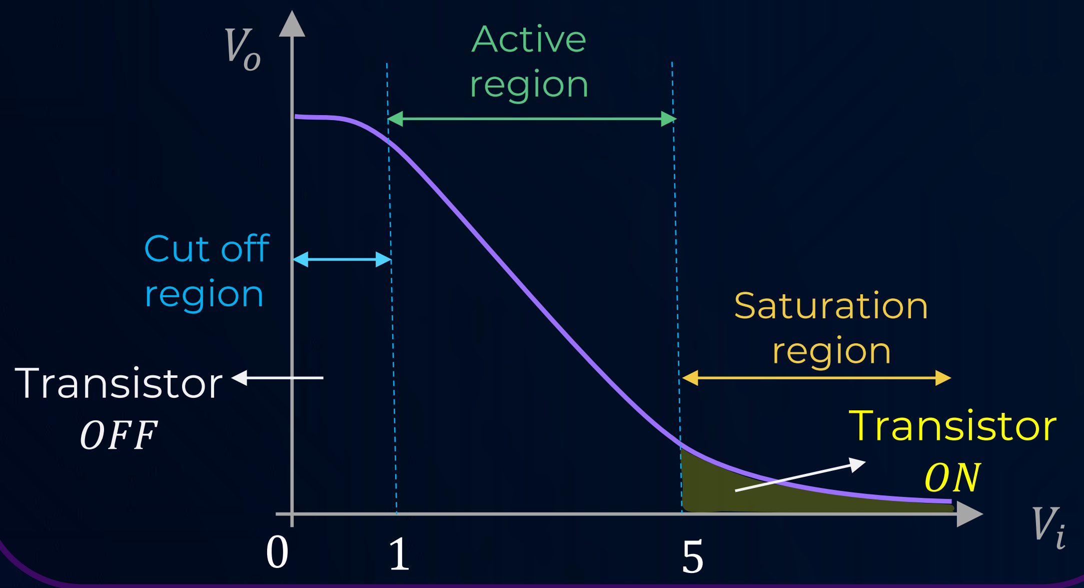
Transistors as Switch

- Cut off region → Transistor OFF
- Saturation region → Transistor ON

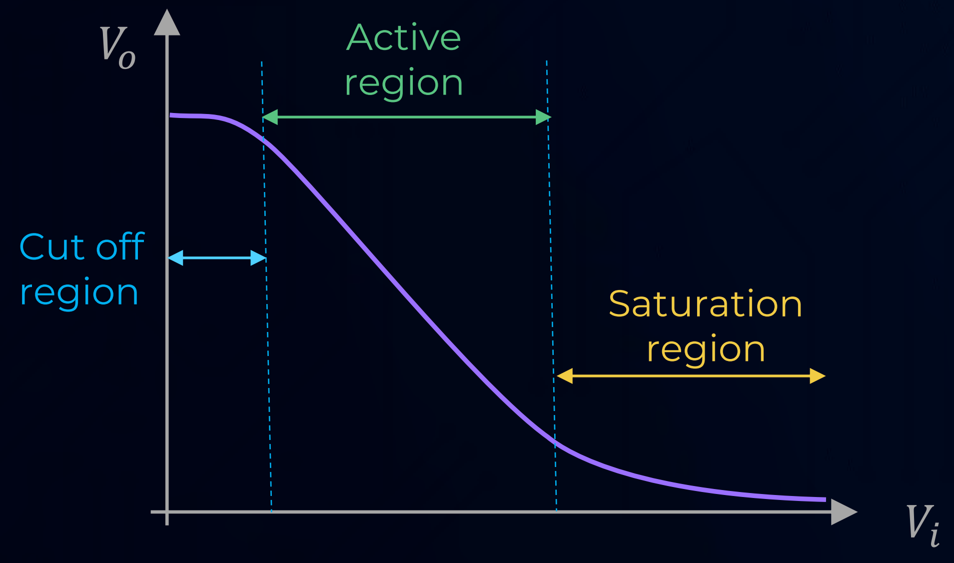
When $V_i > 5\ V$, the transistor goes to the saturation region. → Current flows through the transistor ($I_C \neq 0$) → Output (V_O) $\cong 0$ → Bulb doesn't glow

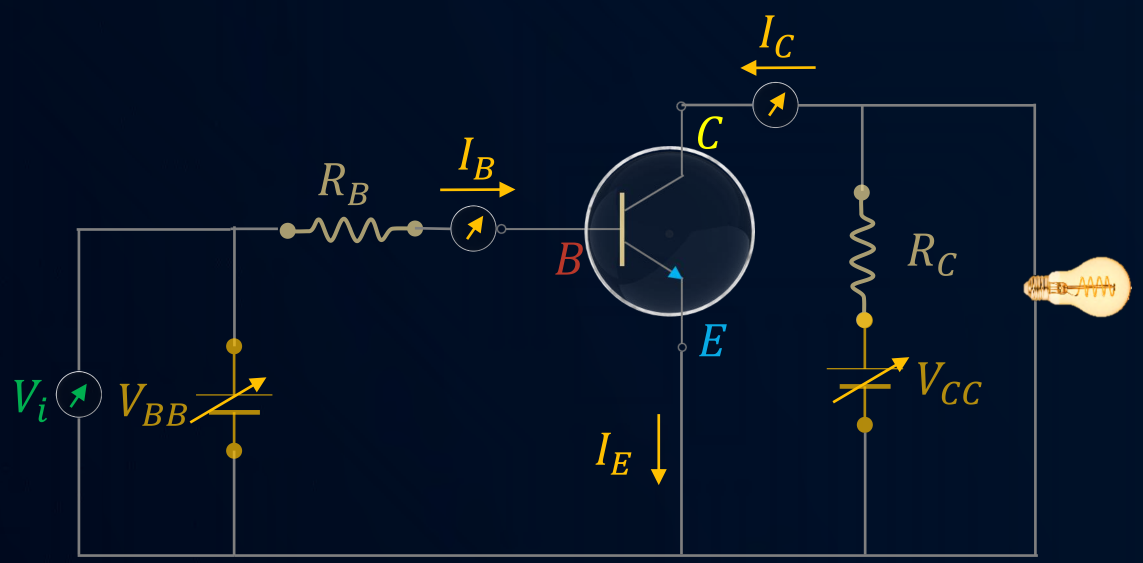
- Voltages are designed in such a way that the transistor does not remain in an active state.





Transistors as Switch



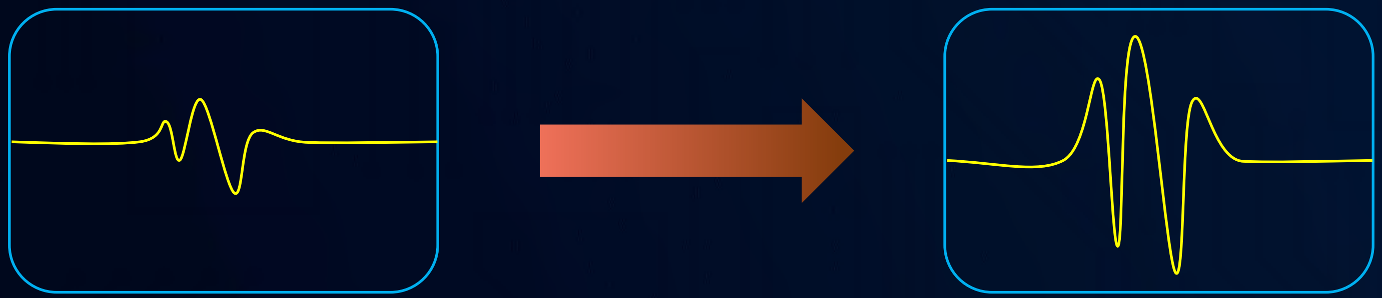


- Transistor
  - Cut-Off → Switch-Off
  - Saturation → Switch-On

- Bulb
  - Cut-Off → Glow
  - Saturation → Not Glow

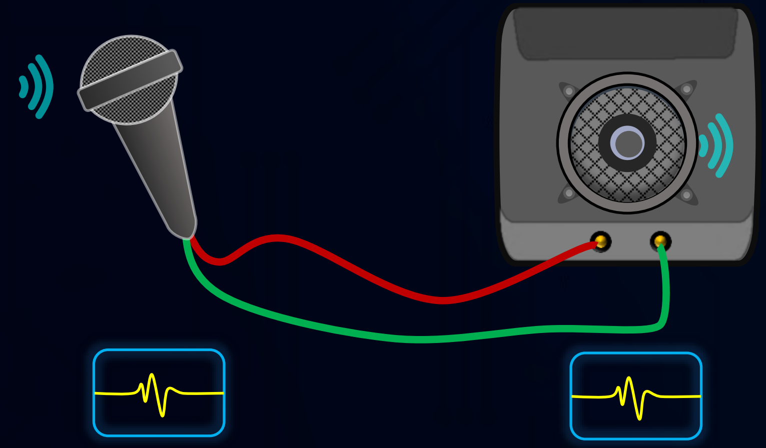
Amplification

Amplification is a process of electronically increasing power of a signal.

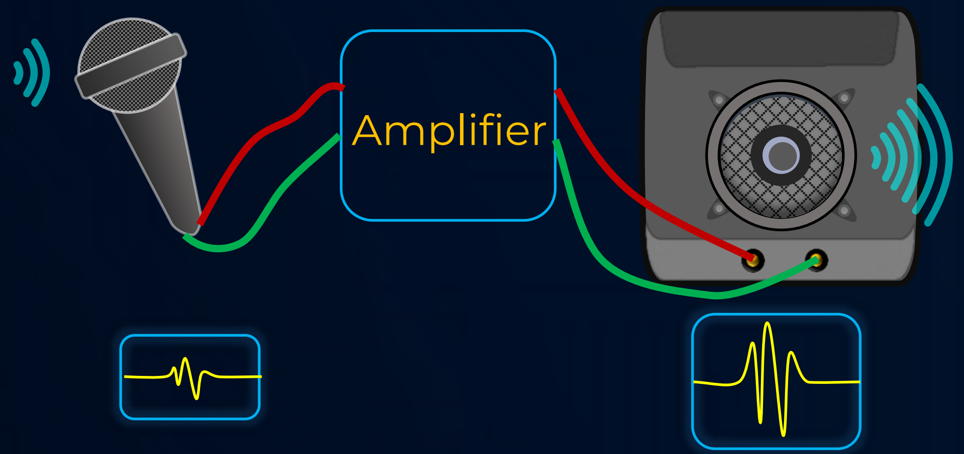


- Transistors are used to amplify signals.

Need For Amplification



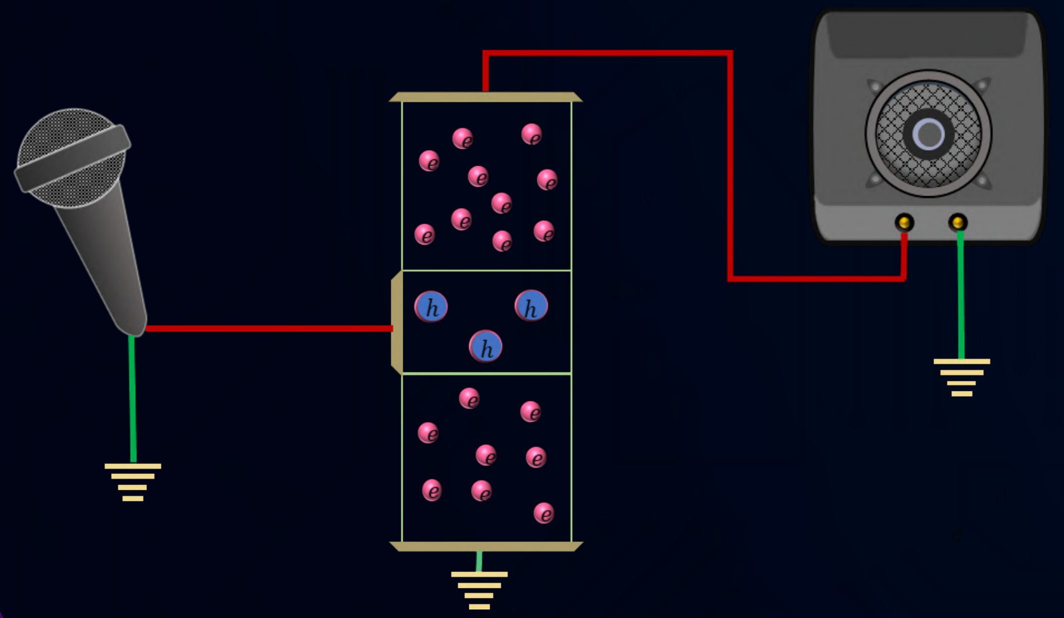
Output without Amplification

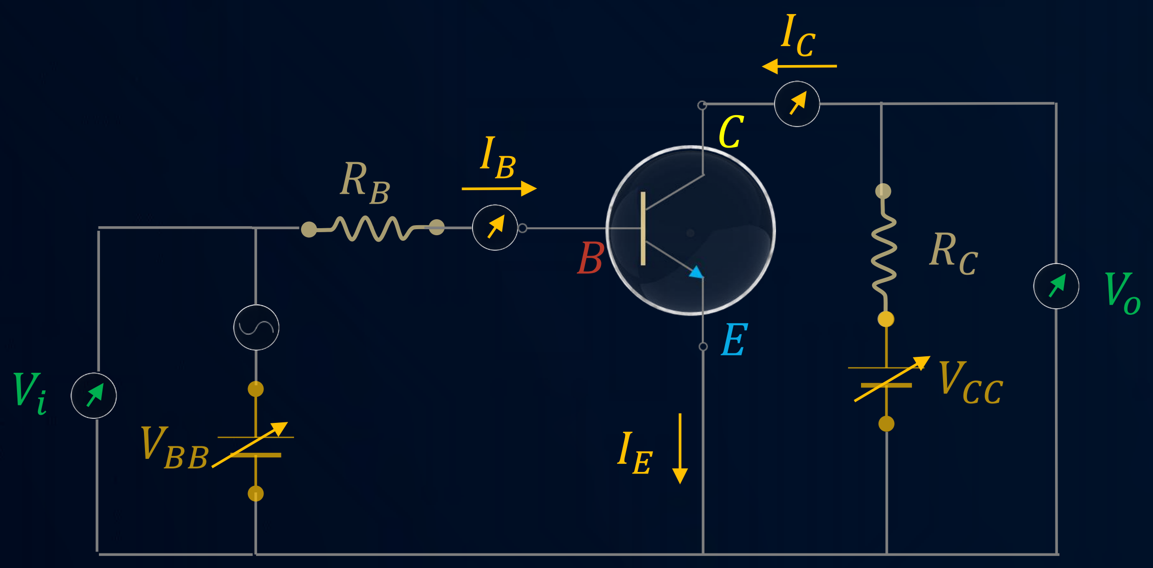


Output with Amplification

- A microphone converts a sound signal into an electrical signal which goes to the speaker. The speaker replicates that electrical signal and by vibrating, it produces the sound back.
- Without an amplifier, the strength of the electrical signal that the speaker receives is the same as that of the mic. Hence, the loudness of the sound will not increase.
- An amplifier increases the amplitude of the electrical signal produced by the mic keeping the nature of the signal (waveform) the same.
- This means the audio that the mic receives will remain the same after amplification, but its loudness will increase.
- Hence, the sound produced by the speaker will be much louder than the original sound.

Transistor as Amplifier



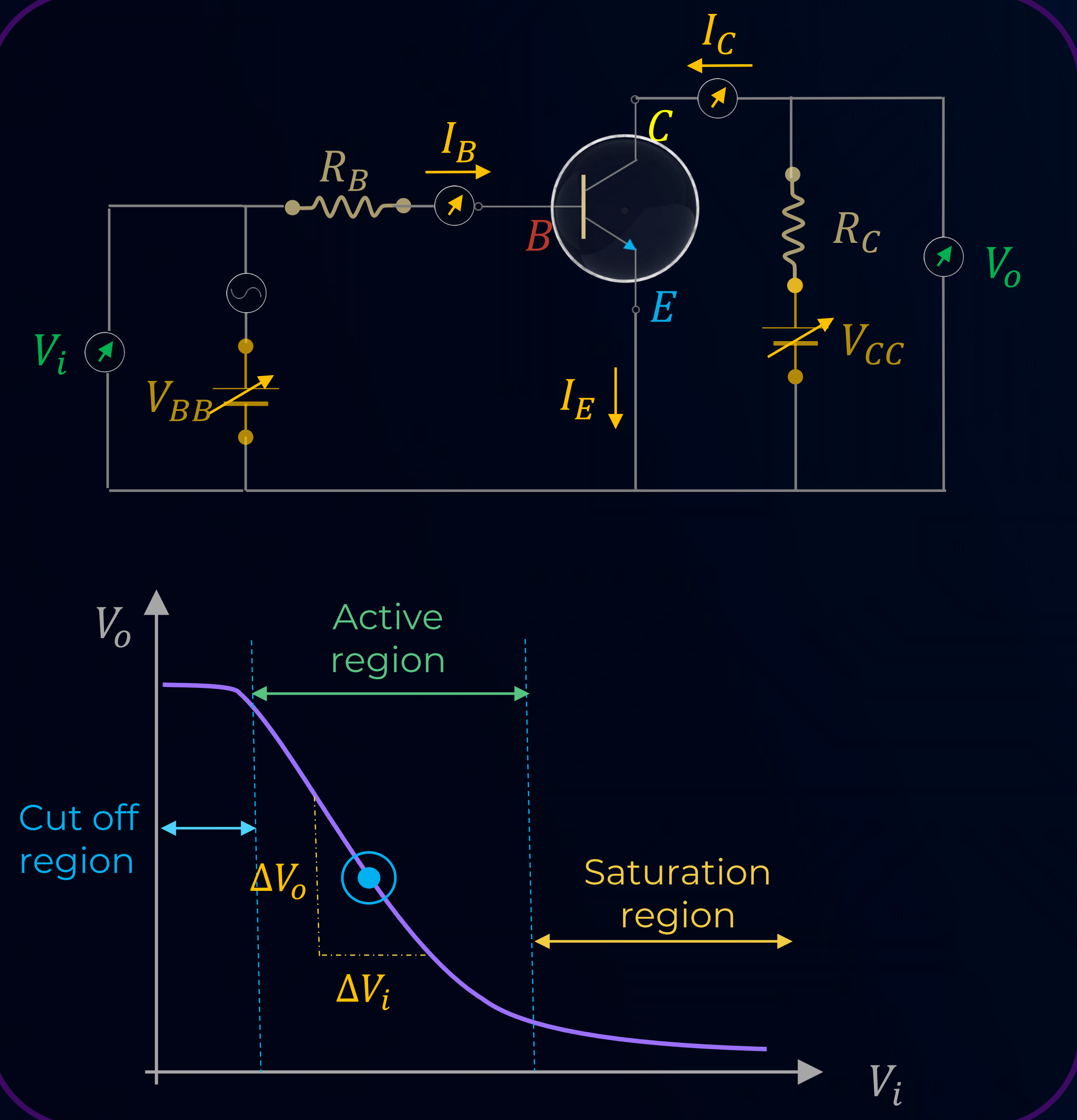


- We know that,

  Current gain in CE mode: $\beta_{ac} = \frac{\Delta I_C}{\Delta I_B} \Rightarrow \Delta I_C = \beta \Delta I_B$

- This property is used to amplify weak signals by supplying them at base junction and getting an amplified output at collector junction.

Transistor as Amplifier



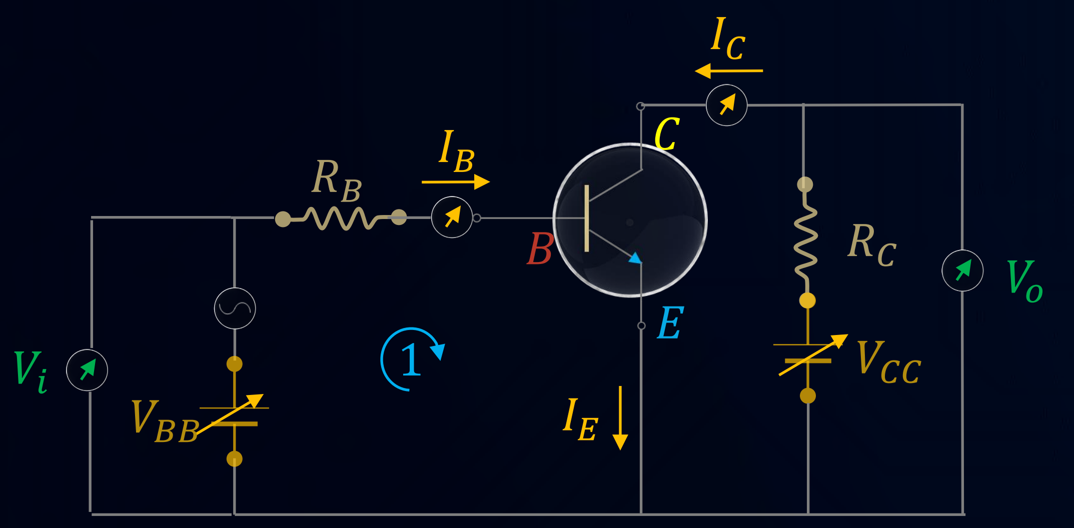
- Transistor to be used as an amplifier, should be operated in the mid of the active region.
- The voltage can be greater or lower than the mean voltage. If a transistor is operated at a point close to the saturated region, there may be a chance that the voltage can go to the saturated region; in that case, the output voltage will be zero.

Voltage gain of an amplifier,

$$A_V = \frac{\Delta V_o}{\Delta V_i}$$

- ΔV_o and ΔV_i are out of phase.

Transistor as Amplifier



Applying Kirchhoff's law for loop 1

$$V_{BB} = I_B R_B + V_{BE}$$

$$V_i = I_B R_B + V_{BE} \qquad [V_{BB} = V_i]$$

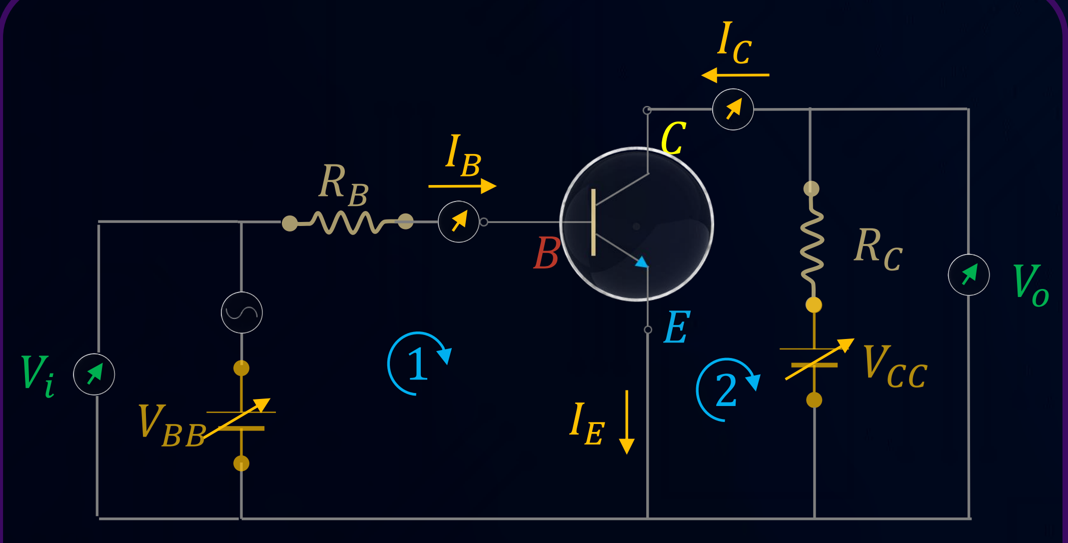
$$\Delta V_i = \Delta I_B R_B + \Delta V_{BE}$$

$$\Delta V_i = \Delta I_B R_B + \Delta I_B r_i \qquad \therefore \left[r_i = \frac{\Delta V_{BE}}{\Delta I_B}\right]$$

$$\Delta V_i = \Delta I_B (R_B + r_i) \quad \ldots (1)$$

- Since r_i keeps on changing as we change the voltage across BE junction, it is known as dynamic resistance of BE junction.

Transistor as Amplifier



Applying Kirchhoff's law for loop 2

$$V_{CC} = I_C R_C + V_{CE} \quad \Rightarrow \quad V_O = V_{CE} = V_{CC} - I_C R_C$$

$$\Delta V_0 = -\Delta I_C R_C \quad \dots (2)$$

Voltage gain of an amplifier,

$$A_V = \frac{\Delta V_o}{\Delta V_i} = \frac{-\Delta I_C R_C}{\Delta I_B (R_B + r_i)} = -\beta_{ac} \frac{R_C}{R_B + r_i}$$

- r_i can be neglected as compared to R_B.

Voltage gain of an amplifier(A_v):

$$A_v = -\beta \frac{R_C}{R_B}$$

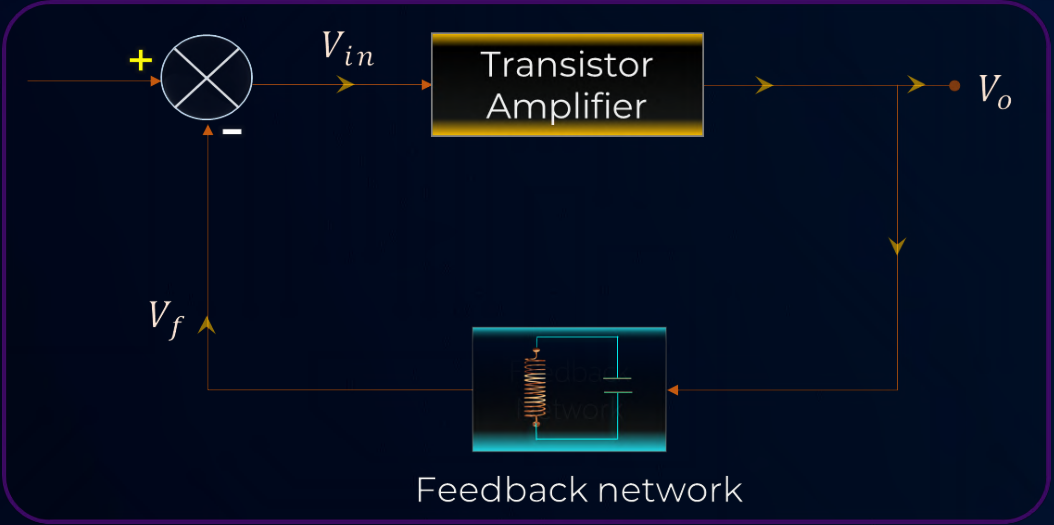
Power gain / Power Amplification (A_p):

$$A_p = \beta \times A_v = -\beta^2 \frac{R_C}{R_B}$$

- The negative sign represents that output voltage is opposite in phase with respect to input voltage.

Feedback Network

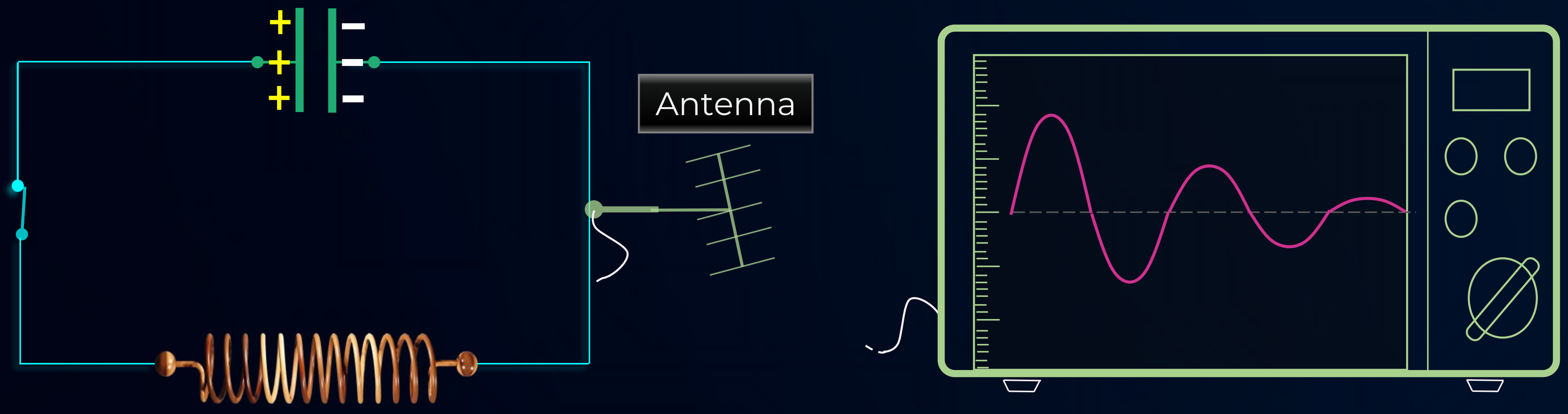
Feedback is a network which takes sample of output signal (which may be voltage or current) and feeds back to the input.



- Due to external disturbances, the input signal keeps on fluctuating and thereby, affecting the output.
- To maintain the accurate output, some of the output is taken and fed back to the input signal as an error signal so that the damping can be compensated.

Oscillatory Circuit

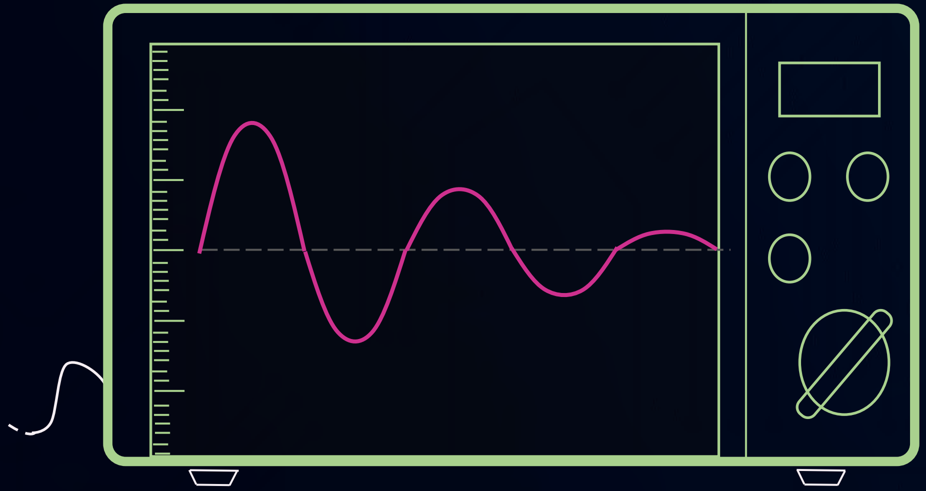
Oscillators are electronic circuits that generate a continuous periodic waveform at a precise frequency.



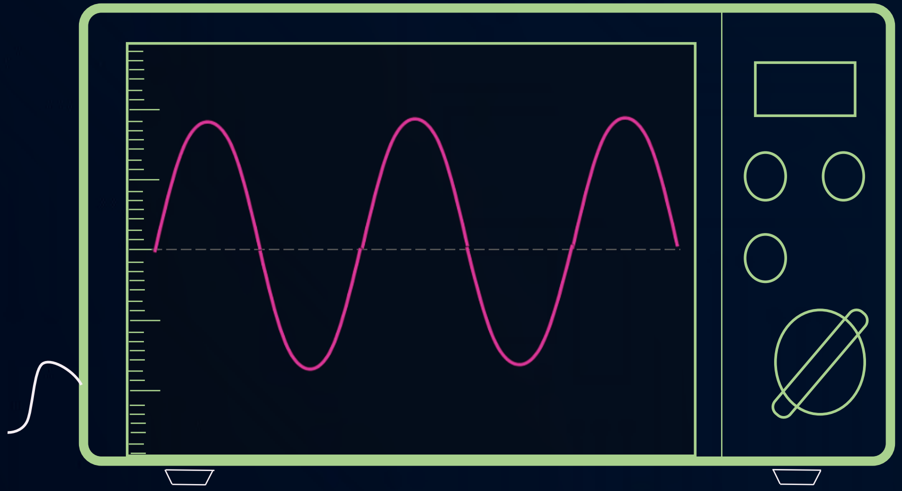
$L - C$ Oscillator circuit

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Oscillatory Circuit



Damped Signal

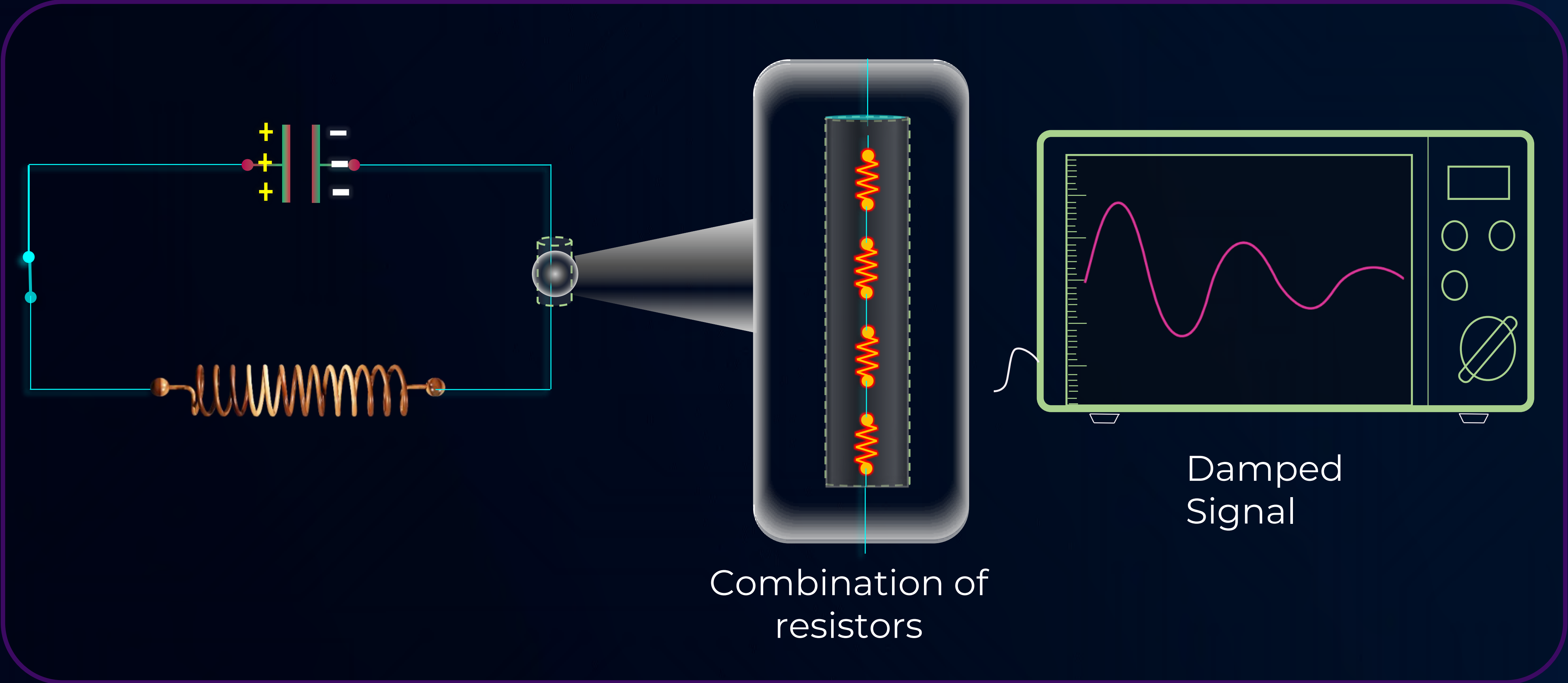


Undamped Signal

- The oscillation whose amplitude decreases gradually with time.
- Oscillation does not continue for a longer time.

- The oscillation whose amplitude remain constant.
- There are no power losses. Hence oscillation can move for a long time.

Oscillatory Circuit



- The current flowing in the circuit encounters resistance, due to which the energy is dissipated in the form of heat. Hence, the magnitude of the signal keep on decreasing and we get a damped oscillation.

Transistor as Oscillator

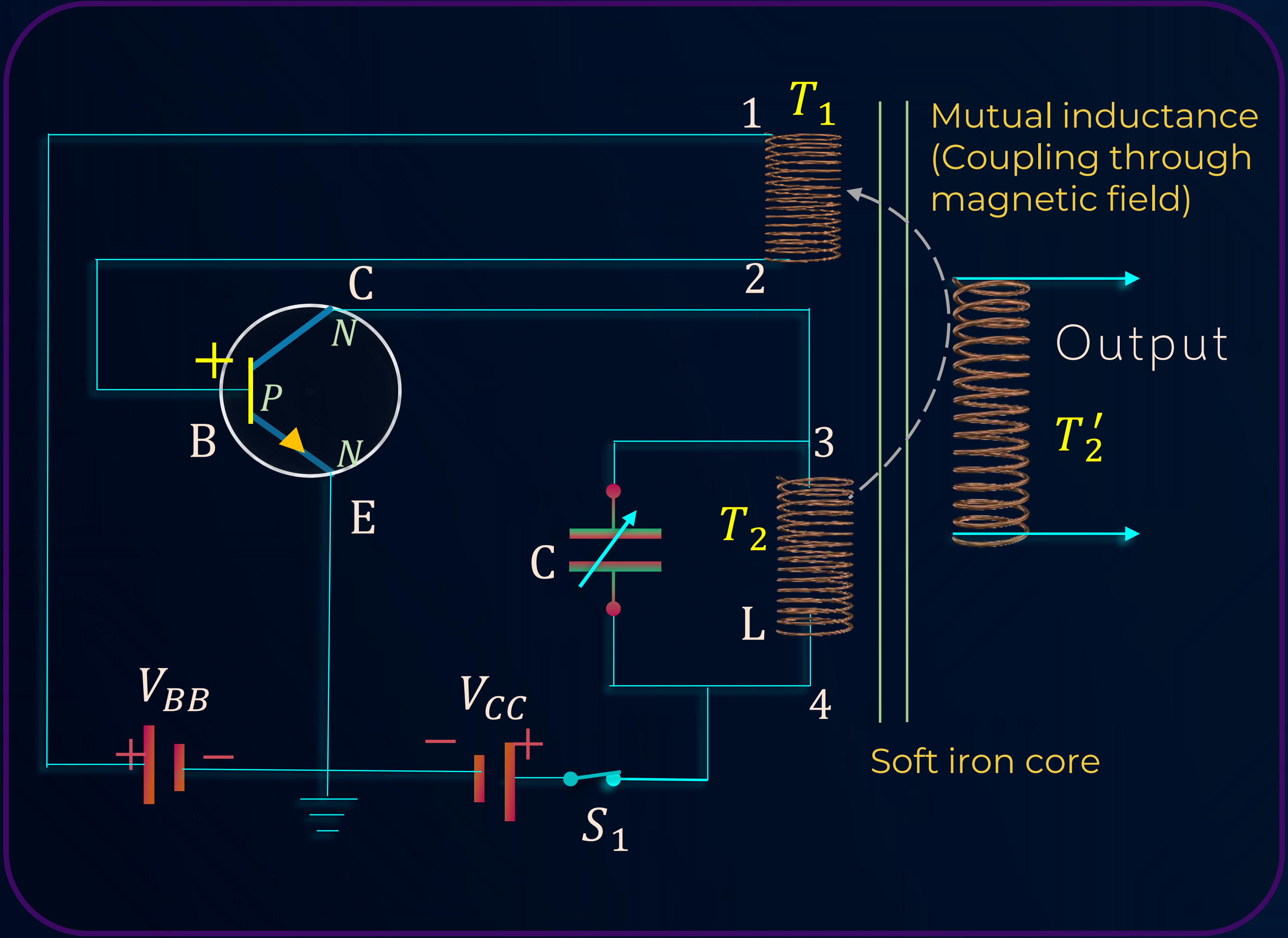
Construction:

- n-p-n transistor in CE mode, such that,

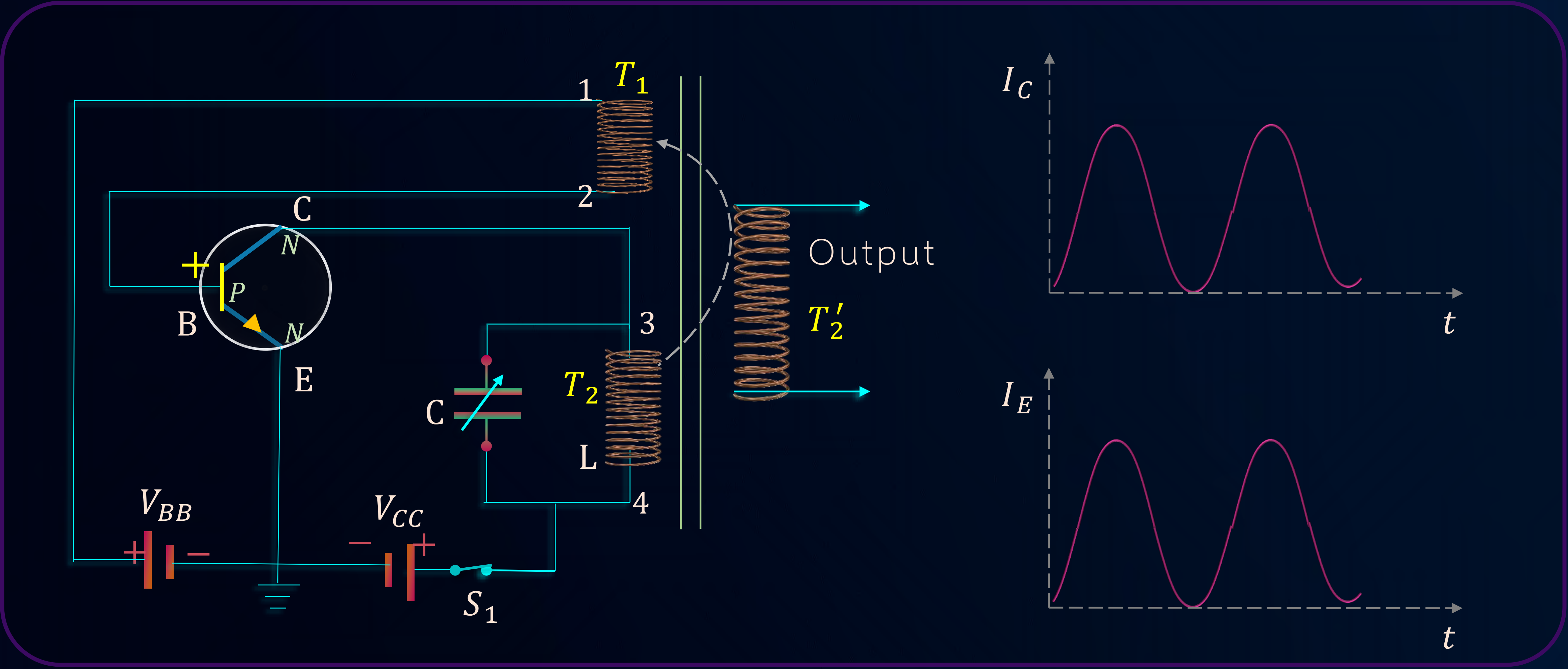
  Base-Emitter junction: Forward biased.
  Base-Collector junction: Reverse biased.

- L-C circuit is connected on the output side.
- T_1 inductor is connected on the input side.

- Inductors T_1 and T_2 are mutually coupled by winding them on a soft iron core. The output is extracted from the inductor T_2'.



Transistor as Oscillator

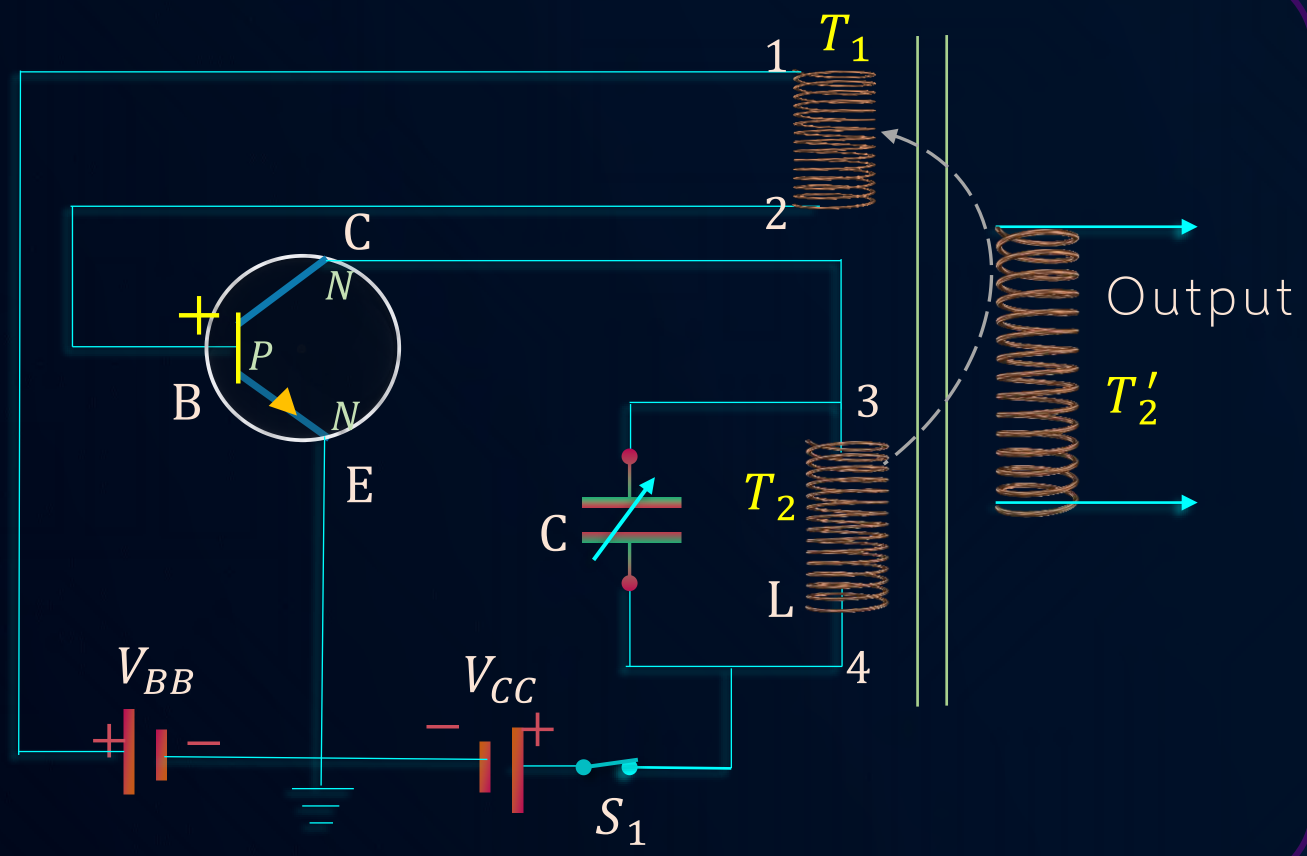


- By this way, the collector current oscillates b/w a maximum (i.e., the saturation value) and zero value. Therefore, we get an output that has a constant amplitude.

Transistor as Oscillator

- Feedback is accomplished by inductive coupling from one coil winding (T_1) to another coil winding (T_2).

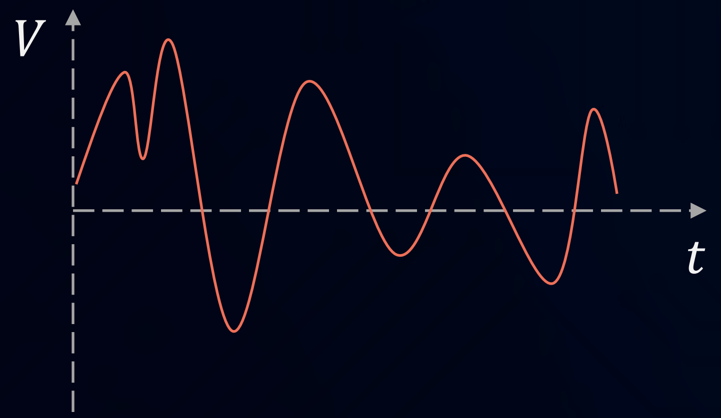
- Transistor state keeps changing between cut-off and saturation region.



Digital Electronics

Analog signal

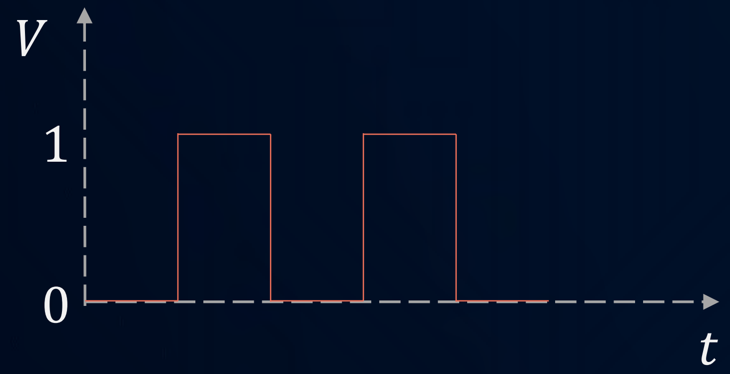
- Continuous value of voltage or current



- In amplifiers, oscillators etc.

Digital signal

- Only discrete value of voltages $(0 \rightarrow 0\,V, 1 \rightarrow 5\,V)$



- Digital watches, computers, robots etc.

- In Digital Electronics, we deal with two (binary) levels of voltages, i.e. Digital signals.

Binary System

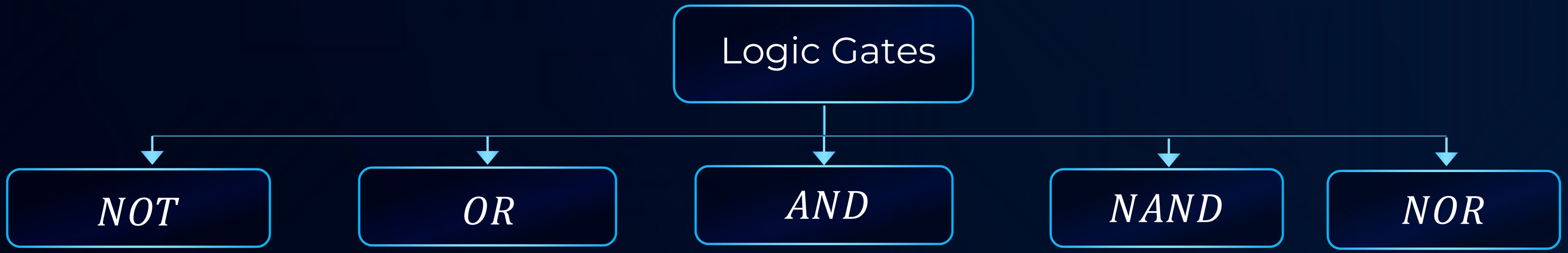
Binary System: A system with 2 states only $0\ or\ 1$.

ON	OFF
TRUE	FALSE
1	0

- A binary number system uses only two digits 0 and 1. Each binary digit is called a bit.
- The base of binary number system is 2, instead of 10 which is the base in decimal number system.

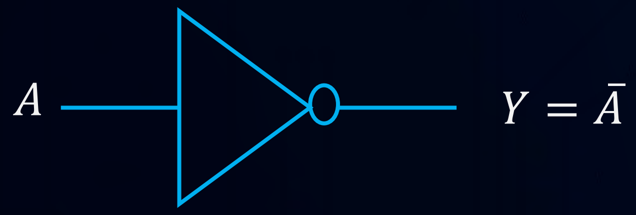
Logic Gates

- A logic gate is a digital circuit that follows certain logical relationship between input and output voltages.
- Logic gates are made of different combinations of diodes or transistors.



Logic Gates

NOT Gate



$$Y = \textit{NOT}\ A$$
$$Y = \bar{A}$$

Truth Table:

A	Y
0	1
1	0

OR Gate

$$Y = A\ \textit{OR}\ B$$
$$Y = A + B$$

Truth Table:

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

AND Gate

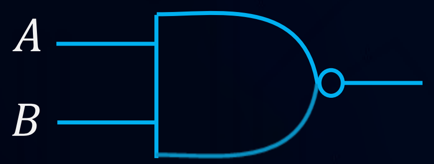
$$Y = A\ \textit{AND}\ B$$
$$Y = A \cdot B$$

Truth Table:

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

Logic Gates

NAND Gate



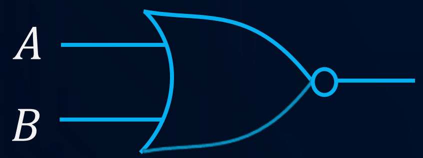
$Y = \overline{A.B}$

$$Y = \overline{A.B}$$

Truth Table:

A	B	$A.B$	Y
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

NOR Gate



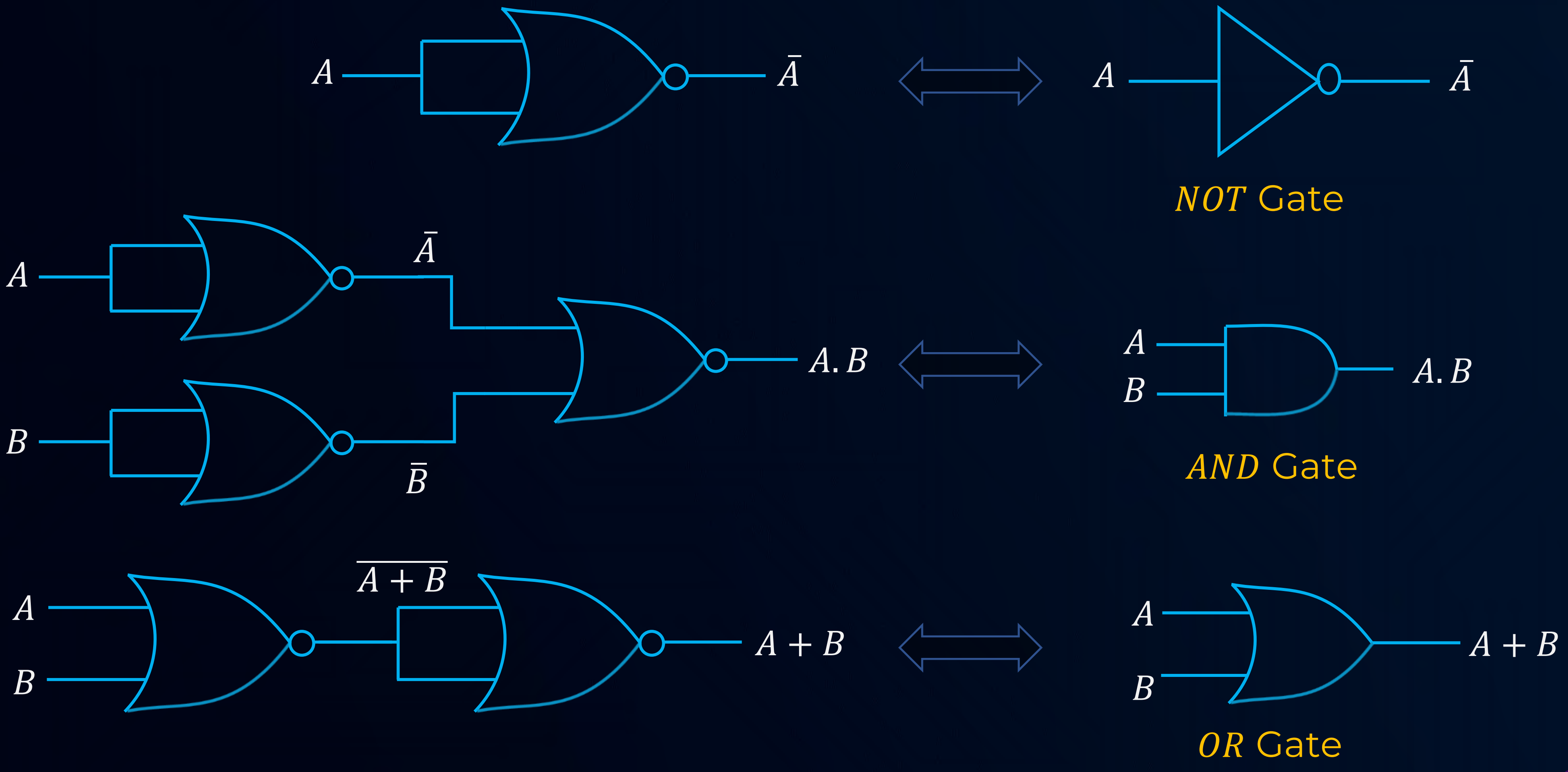
$Y = \overline{A + B}$

$$Y = \overline{A + B}$$

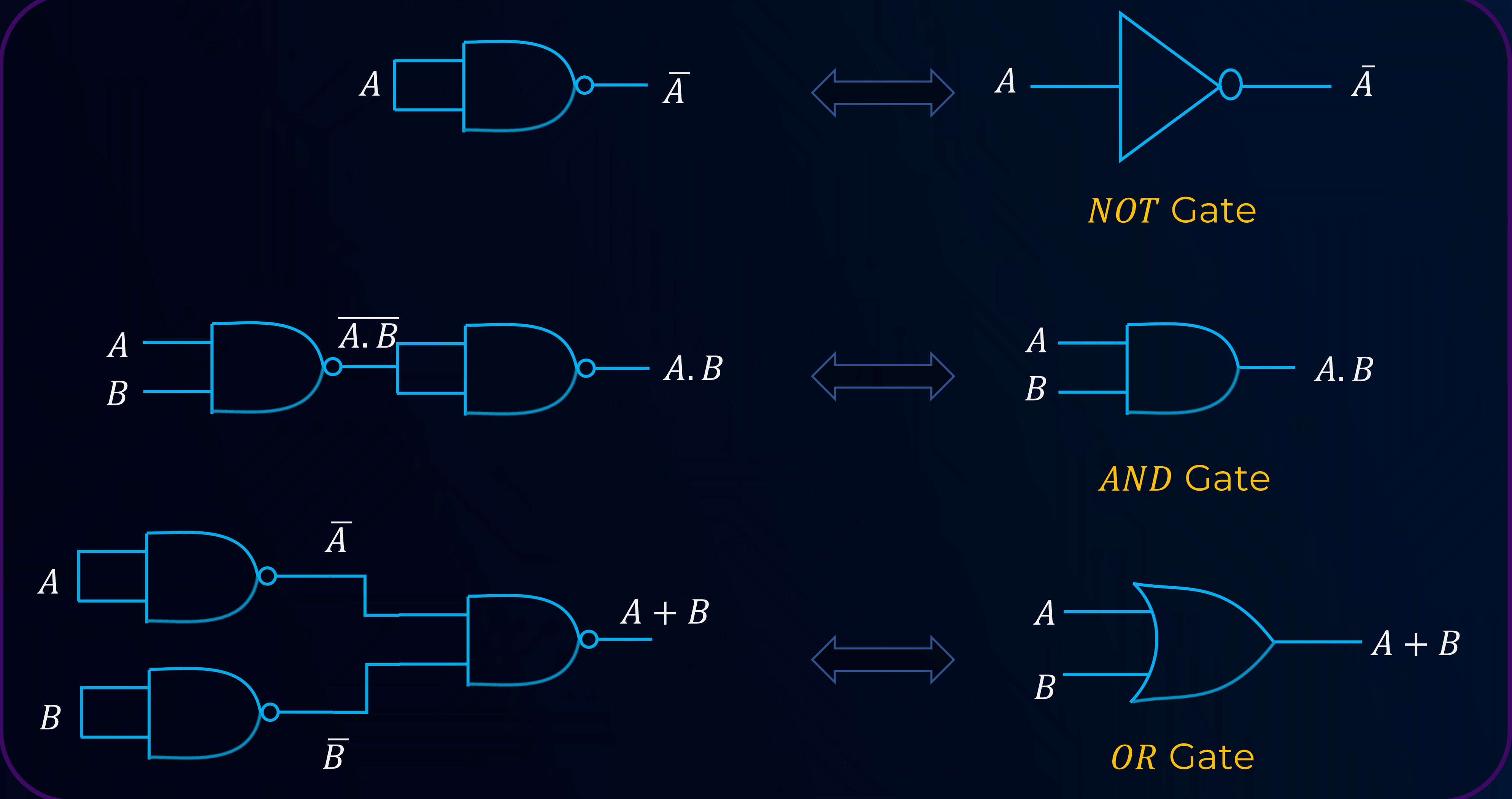
Truth Table:

A	B	$A + B$	Y
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

NOR as Universal Gate



$NAND$ as Universal Gate



Laws of Boolean Algebra

OR Laws: $A + 0 = A$ | $A + 1 = 1$ | $A + A = A$ | $A + \bar{A} = 1$

AND Laws: $A \cdot 0 = 0$ | $A \cdot 1 = A$ | $A \cdot A = A$ | $A \cdot \bar{A} = 0$

Compliment Laws: $\bar{\bar{A}} = A$

Commutative property:

$$A + B = B + A$$

$$A \cdot B = B \cdot A$$

Associative property:

$$A \cdot (B \cdot C) = (A \cdot B) \cdot C$$

$$A + (B + C) = (A + B) + C$$

Distributive property:

$$A \cdot (B + C) = A \cdot B + A \cdot C$$

$$(A + B) \cdot (C + D) = A \cdot C + A \cdot D + B \cdot C + B \cdot D$$

De-Morgan Theorem

First theorem:

The compliment of the sum of two variables is equal to the product of the compliment of each variable.

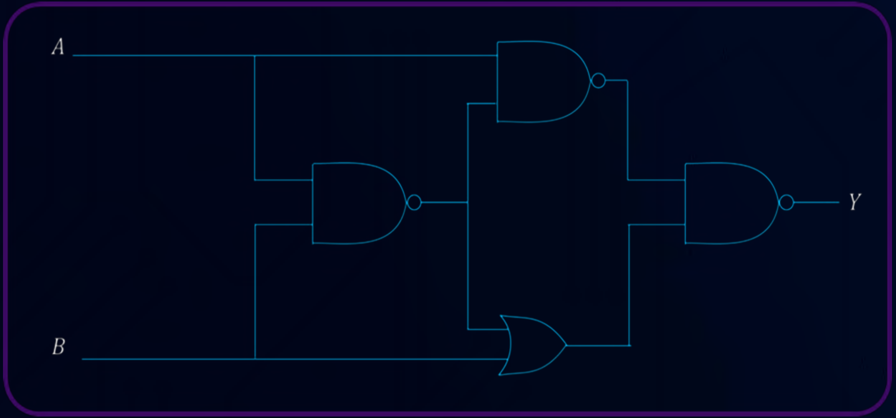
$$\overline{A + B} = \bar{A}.\bar{B}$$

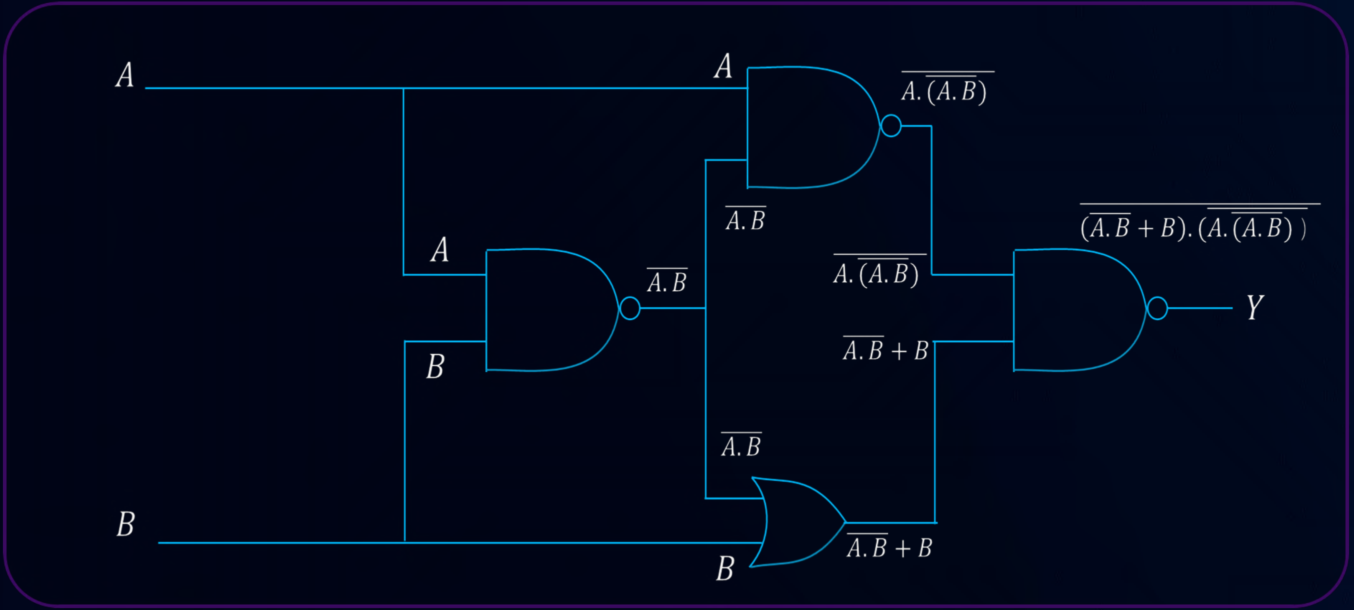
Second theorem:

The complement of the product of two variables is corresponding to the sum of the complement of each variable.

$$\overline{A \cdot B} = \bar{A} + \bar{B}$$

Find the output of the circuit.





$$Y = \overline{(\overline{A.B} + B).(\overline{A.\overline{(A.B)}})}$$

Applying De-Morgan's Theorem,

$$Y = (\overline{\overline{A.B} + B}) + (\overline{\overline{A.\overline{(A.B)}}})$$

$$Y = ((\overline{\overline{A.B}}).\bar{B}) + (A.(\overline{A.B}))$$

$$Y = (A.B.\bar{B}) + (A.(\bar{A} + \bar{B})) \quad (\because B.\bar{B} = 0)$$

$$Y = A.\bar{A} + A.\bar{B}$$

$$Y = A.\bar{B}$$

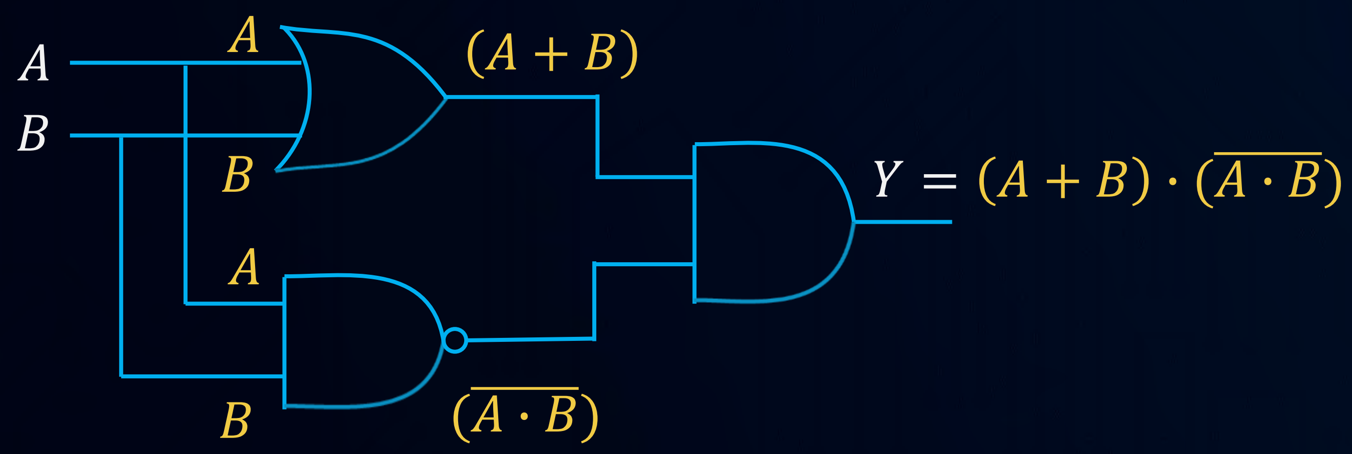
A. $\bar{A}B$

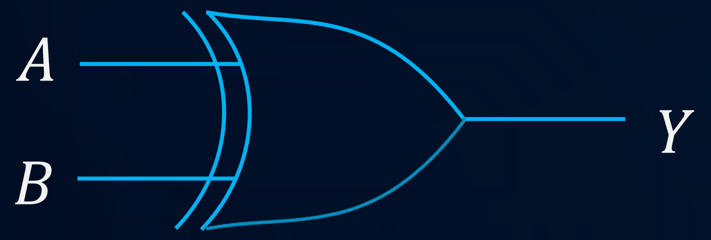
B. $AB + \overline{AB}$

C. $A.\bar{B}$

D. $\bar{A}B + A\bar{B}$

XOR Gate





$$Y = (A + B).(\overline{A.B}) = A \cdot \bar{B} + B \cdot \bar{A}$$

$$Y = (A + B) \cdot (\overline{A \cdot B})$$

$$Y = (A + B) \cdot (\bar{A} + \bar{B})$$

$$Y = A \cdot \bar{A} + A \cdot \bar{B} + B \cdot \bar{A} + B \cdot \bar{B}$$

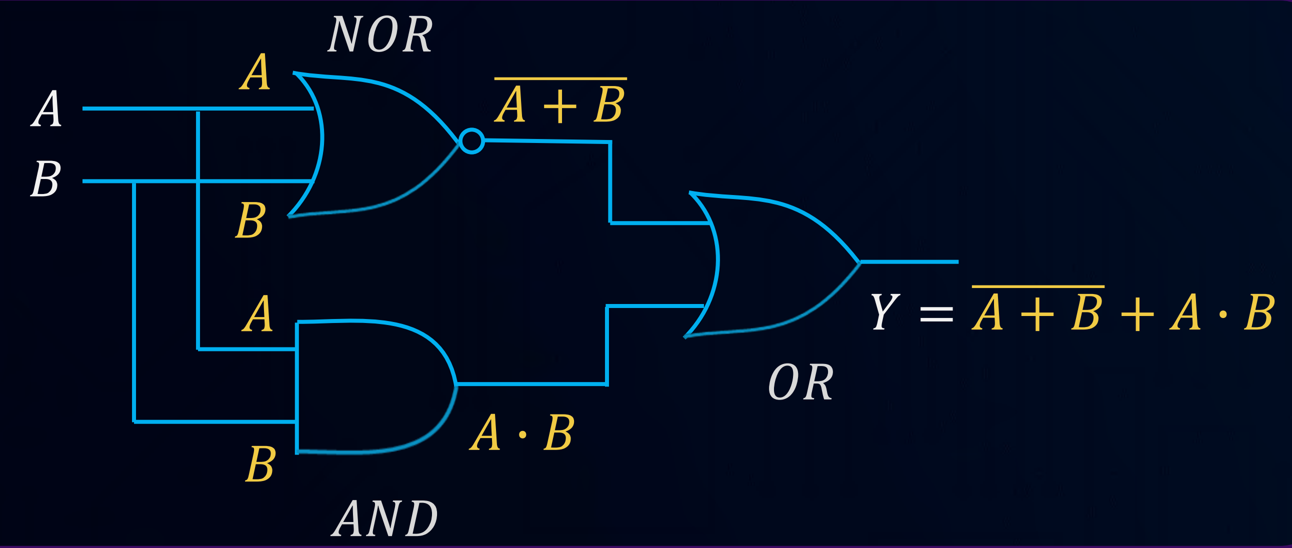
$$Y = A \cdot \bar{B} + B \cdot \bar{A}$$

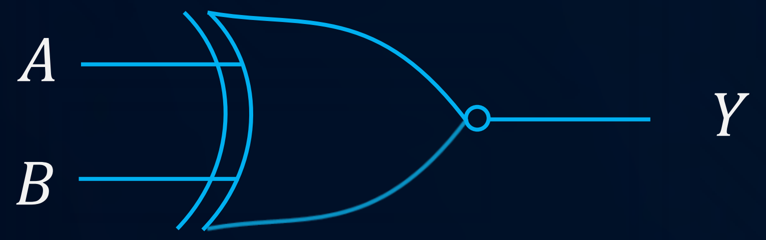
Truth Table:

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Conclusion: If both inputs are same, output is low.

$XNOR$ Gate





$$Y = (A \cdot B) + (\overline{A+B})$$

$$Y = (A \cdot B) + (\overline{A+B})$$

Using De-Morgan's Theorem,

$$Y = (A \cdot B) + (\bar{A}.\bar{B})$$

Conclusion: If both inputs are same, output is high

Truth Table:

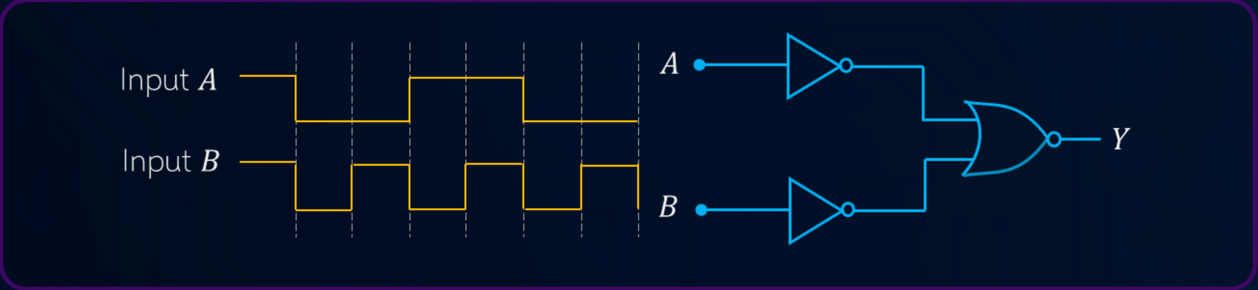
A	B	Y
0	0	1
0	1	0
1	0	0
1	1	1

The logic circuit shown below has the input waveforms 'A' and 'B' as shown. Pick out the correct output waveform.

$$Y = \overline{(\bar{A} + \bar{B})}$$

$$Y = \overline{\overline{A \cdot B}} \qquad \because \overline{A \cdot B} = \bar{A} + \bar{B}$$

$$Y = A \cdot B$$



Truth Table:

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1