4/12/23

CHAPTER-14

SEMICONDUCTOR ELECTRONICS: MATERIALS, DEVICES AND SIMPLE CIRCUITS

Q What is band energy theory of a solid? • Differentiate between conductor, semi-conductor and insulator on the basis of energy band theory.

Ans. The conventional free electron theory based on Bohr's Model of Electrons distribution in an atom failed to explain the electrical behaviour of different material. Energy band theory has found successful in solving this problem.

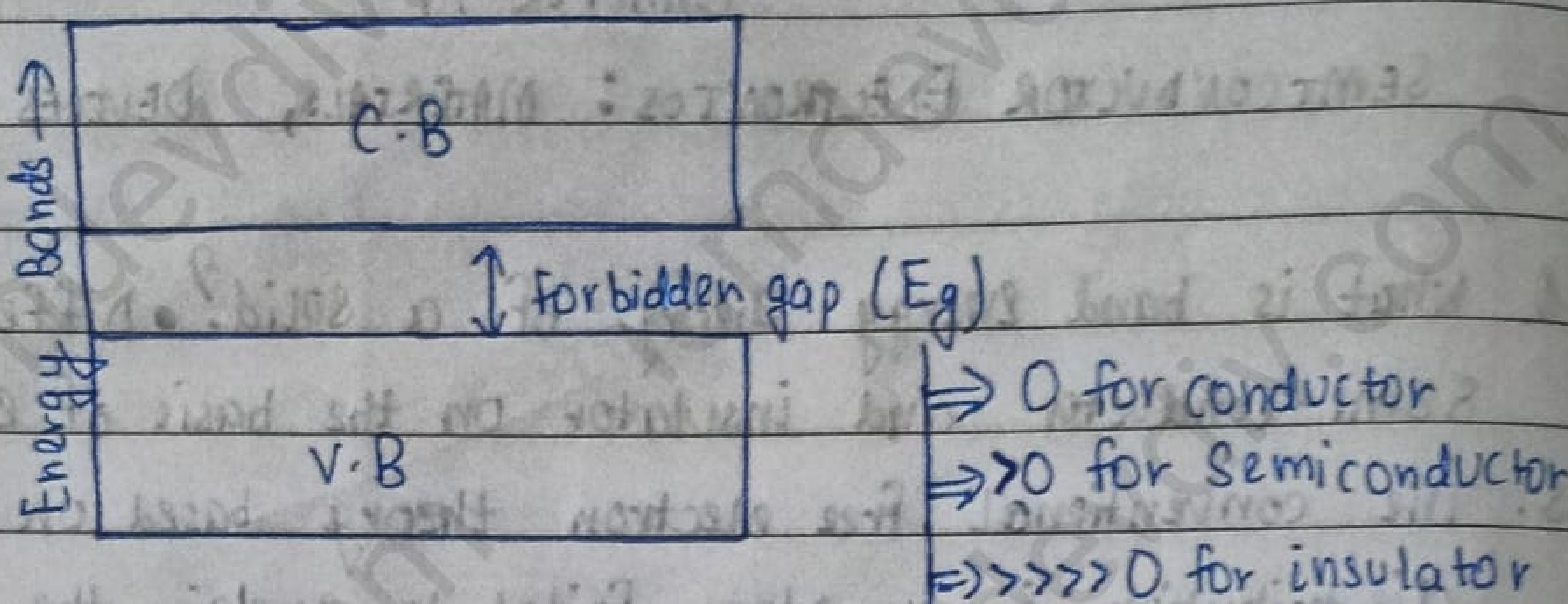
Electrons and isolated atoms are bound to the nucleus and can only have distinct energy levels. However, when a large number of atoms, say N, are brought ~~closest~~ closer to one another to form a solid, each energy level of isolated atom split into ~~an~~ N sublevels called states. These energy states are discrete but so closely spaced that they appear to form a continuous energy band.

A convenient way to representing ~~the~~ the energy of different orbit is known as energy level. The largest the orbit of an electron, the greater is its energy.

VALENCE BAND (VB)	CONDUCTION BAND (CB)
1. The highest occupied band is called VB.	1. The band above the VB is called CB.
2. The electrons occupied by this band are called valence electrons.	2. The electrons occupied by this band are called conductive or free electron.
3. VB can be either be completely or partially filled.	3. It may either be empty or partially filled with electrons.
4. VB can never be empty.	4. It can never be completely filled.

• FORBIDDEN GAP/BAND

The separation between valence band and conduction band on the energy band diagram is known as ~~energy band diagram~~ forbidden gap/band.

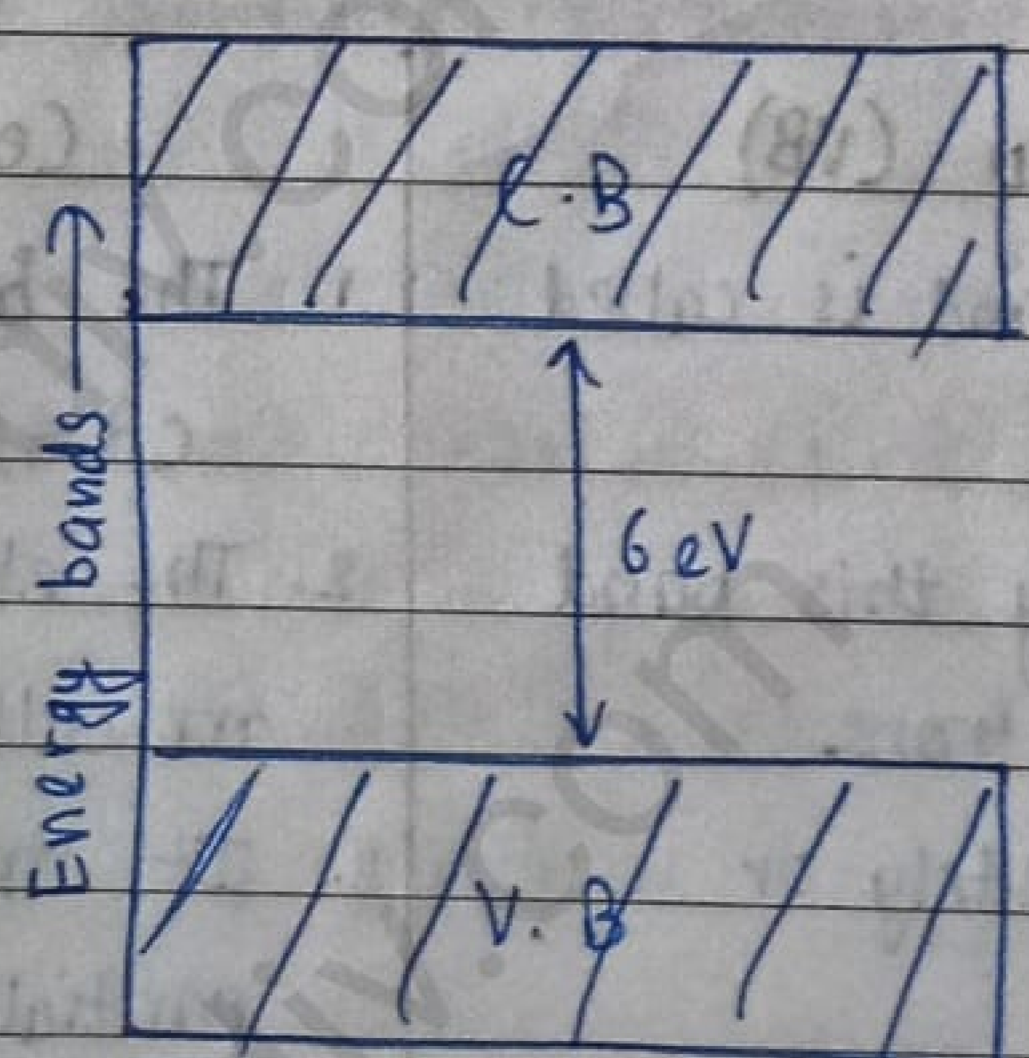


☆ CLASSIFICATION OF SOLID INTO INSULATOR, SEMICONDUCTOR AND CONDUCTOR

- INSULATOR

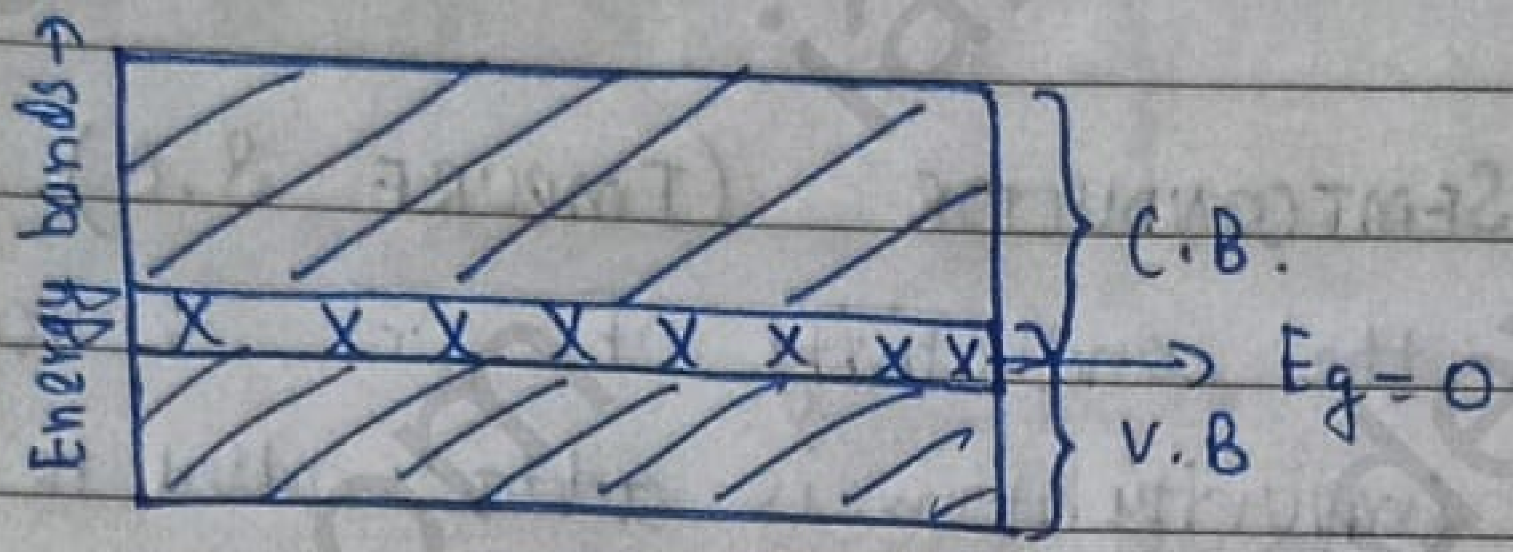
The solids in which valence band is completely occupied while the conduction band is empty are known as insulators. Further, the gap between V.B and CB is very large ≈ 6-7 eV. A very high electric field is required to push the valence electron to C.B. For this reason, the electrical conductivity of such materials is extremely small and may be regarded as nil. Resistance of an insulator decreases with increase in its temperature.

Examples: Diamond, Quartz, Plastic, etc.



- CONDUCTOR

~~Conductor~~ In terms of energy band, the VB and CB overlap to each other. Due to this overlapping, a slight potential difference across the conductor causes the free e^- to constitute electric current. Thus, the electric behaviour of conductors can be satisfactory. Explained by the band energy theory of materials. Such solids are known as conductors. In case of conductor, there is no energy gap between VB and CB.

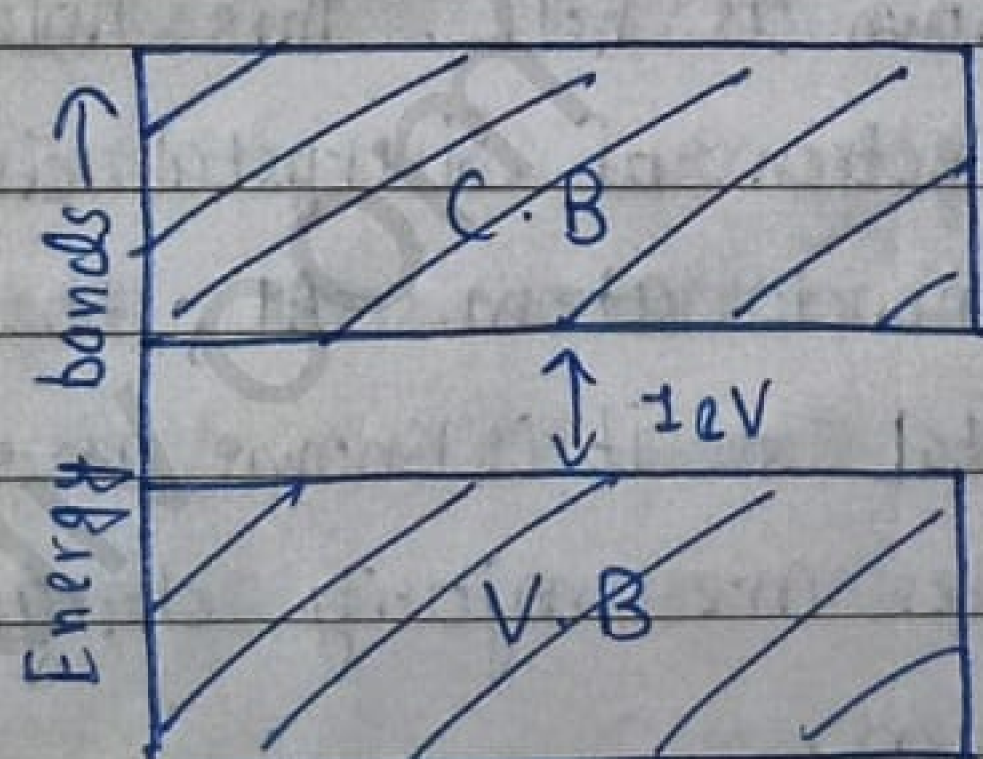


Examples: Cu, Mg, Na, etc.

- SEMICONDUCTOR

In terms of energy band, the valence band in semiconductor is almost filled and conduction band is almost empty. Further, the energy gap between VB and CB is very small ≈ 1eV. i.e. smaller electric field is required to push the electrons from VB to CB. Such solids are known as semiconductors. The electrical conductivity of semiconductor lies between insulator and conductor.

Examples: Silicon, Germanium.



☆ TYPES OF SEMICONDUCTOR

Semiconductors are of two types:

a) INTRINSIC
b) EXTRINSIC

- INTRINSIC SEMICONDUCTOR (PURE S.C)

Pure semiconductors are known as intrinsic semiconductors. Examples:

Silicon, Germanium.
Intrinsic semiconductor behaves as an insulator at 0K. Intrinsic semiconductor has no practical use due to low electrical conductivity.

- EXTRINSIC SEMICONDUCTOR (IMPURE S.C)

To increase the conductivity of pure semiconductor, a small amount of suitable impurity atom is ~~addao~~ added to crystal. This type of semiconductor is known as extrinsic semiconductor. The addition of impure atom is known as doping and added impurity is known as dopant. Extrinsic semiconductor are of two types:

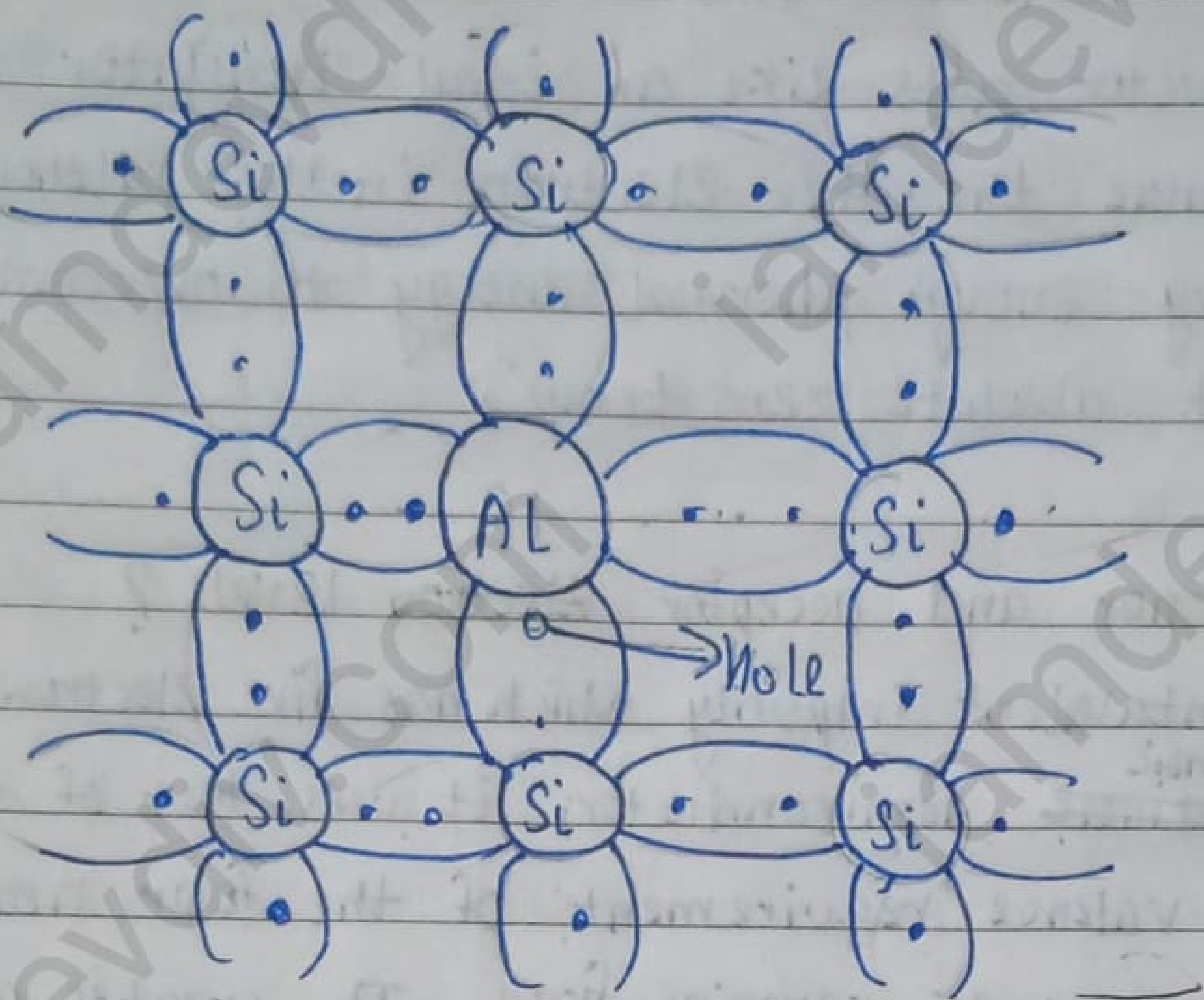
a) p-type
b) n-type

* p-type

When a trivalent impurity atom like Al, B is added to pure semiconductor then it is known as p-type semiconductor. When a trivalent impurity atom such as Al is added to Si crystal then its three electrons make covalent bond with Si and it has an empty space which is known as hole. This hole behaves as a positive charge carrier. Any electron of Si crystal drop into it and creating a fresh hole in the next atom. Al, the impurity atom ~~exce~~ accepts an electron from crystal so it is known as acceptor impurity. In p-type semiconductor, holes are majority charge carriers while e^- are minority charge carriers.

No. of holes > No. of e^-s

and net charge will be zero.



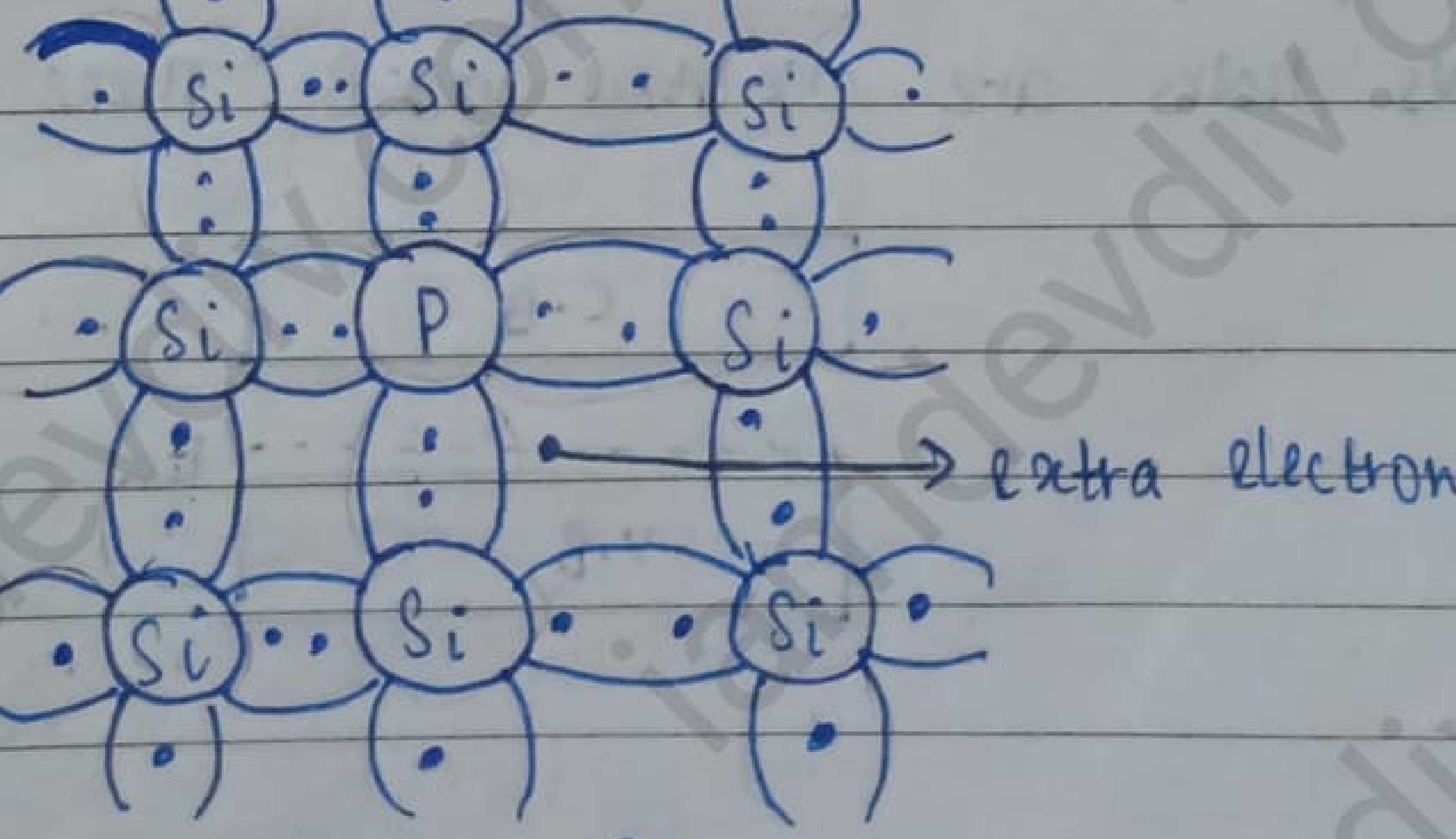
p-type S.C.

* n-type

When a pentavalent impurity atom like P is added to intrinsic semiconductor then it is known as n-type semiconductor. When pentavalent impurity atom P is added to Si crystal then its four valence electrons make covalent bond with neighbouring Si atom while fifth electron is free. This free electron acts as charge carrier. Pentavalent impurity atom donates an e^- to crystal so it is also known as donor impurity. In n-type semiconductor, electrons are majority charge carriers and holes are minority charge carriers.

No. of e^-s > No. of holes

and net charge will be zero.



n-type S.C.

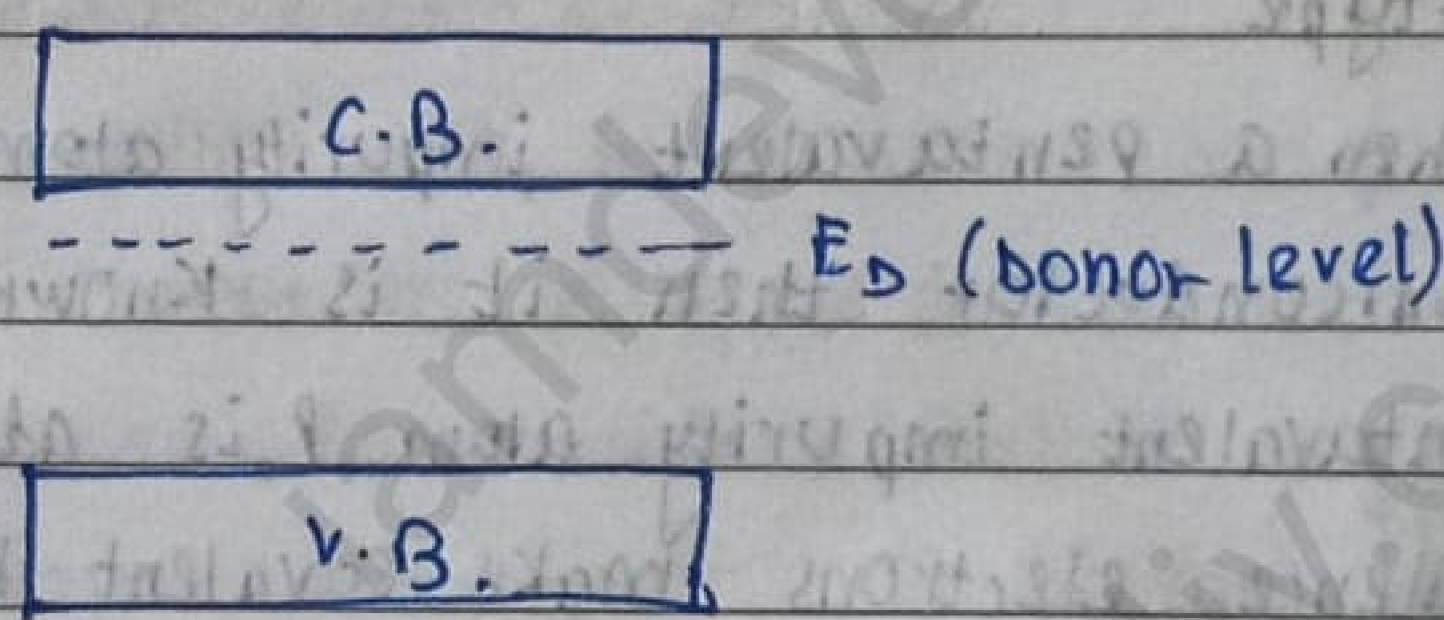
Q Why a pure semiconductor behaves like an insulator at 0K.

Ans. A semiconductor acts like an ideal insulator at absolute 0K. It is because the free electrons in the valence band of semiconductor will not carry enough thermal energy to overcome the forbidden energy gap at absolute zero temp^r.

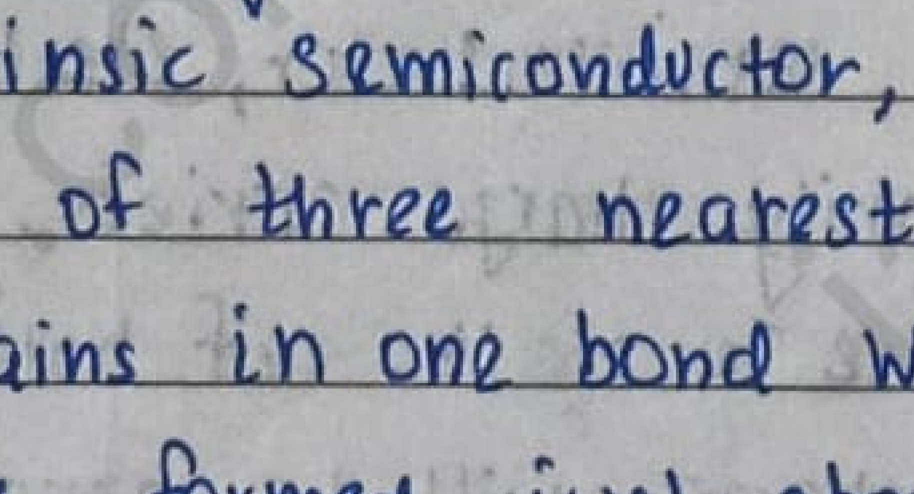
Q What are donor and acceptor ~~electron~~ levels?

Ans. When a pentavalent impurity which has five electrons in outershell is added in extrinsic ~~intrinsic~~ semiconductor, it uses four of these electrons to satisfy the valence requirement of the four nearest neighbour Si and the one e^- remains free. It creates a donor level which is just below the CB. The atom easily donates this e^- to the C.B so it is called donor and e^- is called donor e^-.

N-type



When a trivalent impurity atom which has $3e^-$ in outer shell is added in intrinsic semiconductor, it uses $3e^-$ to satisfy the valence requirement of three nearest neighbouring Si atom. An empty space remains in one bond which is known as hole. Due to this, an acceptor level is formed just above the valence bond. At room temp^r, e^-s are easily excited from VB to acceptor level and thus holes are created in V.B. These holes are majority charge carrier.



☆ MASS ACTION LAW

The law of mass action is a relation between concentration of free e^- and holes under thermal equilibrium. It states that under thermal equilibrium, the product of the free e^- concentration n and hole concentration P is equal to the constant square of intrinsic charge carrier n_i.

Mathematically, it is given by

$$np = n_i^2$$

where $n_i \simeq (P_i)$ is the no. of free e^- in intrinsic semiconductor and n and P are free e^- and hole concentrations for extrinsic semi conductor.

- CARRIER CONCENTRATION IN TERMS OF DONOR AND ACCEPTOR IMPURITIES

Let N_A be the concentration of acceptor atom and N_D be the concentration of donor atoms.

Since semiconductor is electrically neutral, magnitude of +ve charge density must be equal to -ve charge density.

$$N_D + P = N_A + n$$

P ↳ hole density; n ↳ free e^- concentration

In case of N-type S.C, $n >> p$ and $N_A = 0$

$$\therefore \boxed{n_n \simeq n_D} \quad \text{— ①}$$

Similarly, for P-type S.C, $P >> n$ and $N_D = 0$

$$\boxed{n_A \simeq P_p} \quad \text{— ②}$$

From mass action law,

$$n_n P_n \simeq n_i^2 \quad \text{(for n-type S.C)}$$

$$\Rightarrow P_n = \frac{n_i^2}{n_n}$$

$$\Rightarrow \boxed{P_n = \frac{n_i^2}{n_D}}$$ from (1)

Similarly,

$n_p P_p = n_i^2$ (for p-type S.C)

$$\Rightarrow n_p = \frac{n_i^2}{P_p}$$

$$\Rightarrow \boxed{n_p = \frac{n_i^2}{n_A}}$$

- **DRIFT CURRENT**

In the absence of electric field, the motion of charge carrier is random and net current is zero but if an electric field is applied to a semiconductor then each charge carrier gains a small velocity in same direction with other carriers. This velocity known as drift velocity and current flowing through S.C is known as drift current.

- **DIFFUSION CURRENT**

Whenever there is a difference in concentration of charge carrier in a S.C then the charge carriers have a tendency to move from region of higher concentration to ~~three~~ lower concentration of the same type of charge carriers, this movement of charge carriers results in a current called diffusion current.

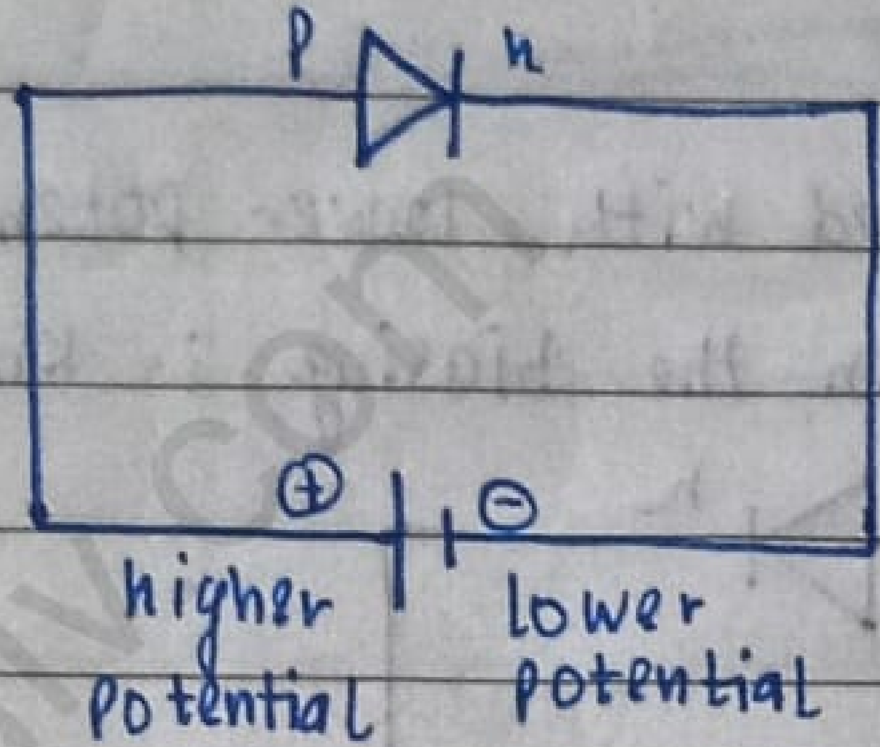
$$J_n = q D_n \frac{dn}{dx}$$

Diffusion

$$J_p = -q D_p \frac{dp}{dx}$$

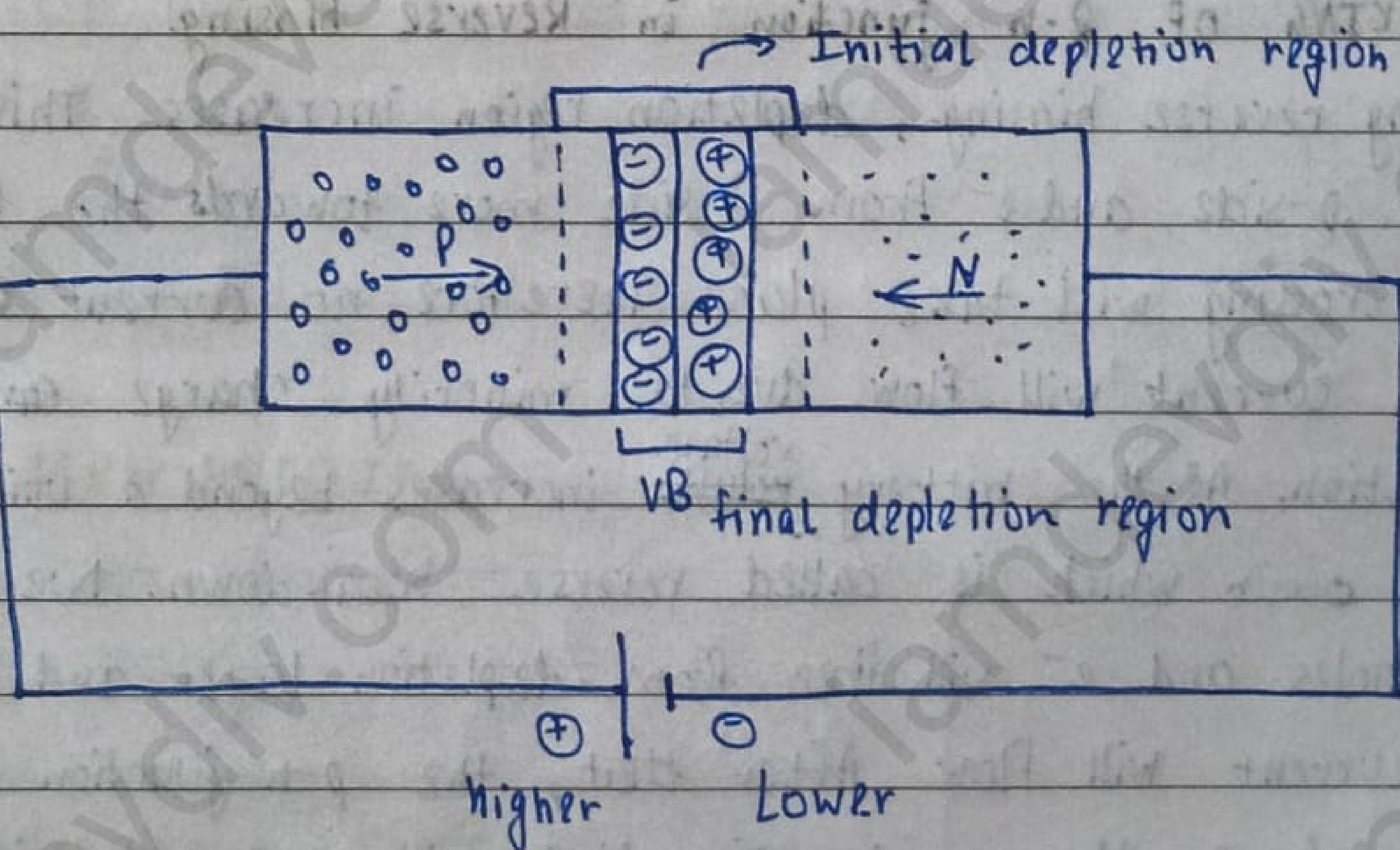
✩ FORWARD BIASING

When p-side of p-n junction diode is connected with higher potential and n-side of p-n junction diode is connected to lower potential then the biasing is called forward biasing.



- WORKING OF p-n junction diode in forward biasing

During forward biasing, depletion region decreases. This is because hole from p-side and e^- from n-side get repelled towards the junction.



* CASE - 1 (if $V < V_B$)

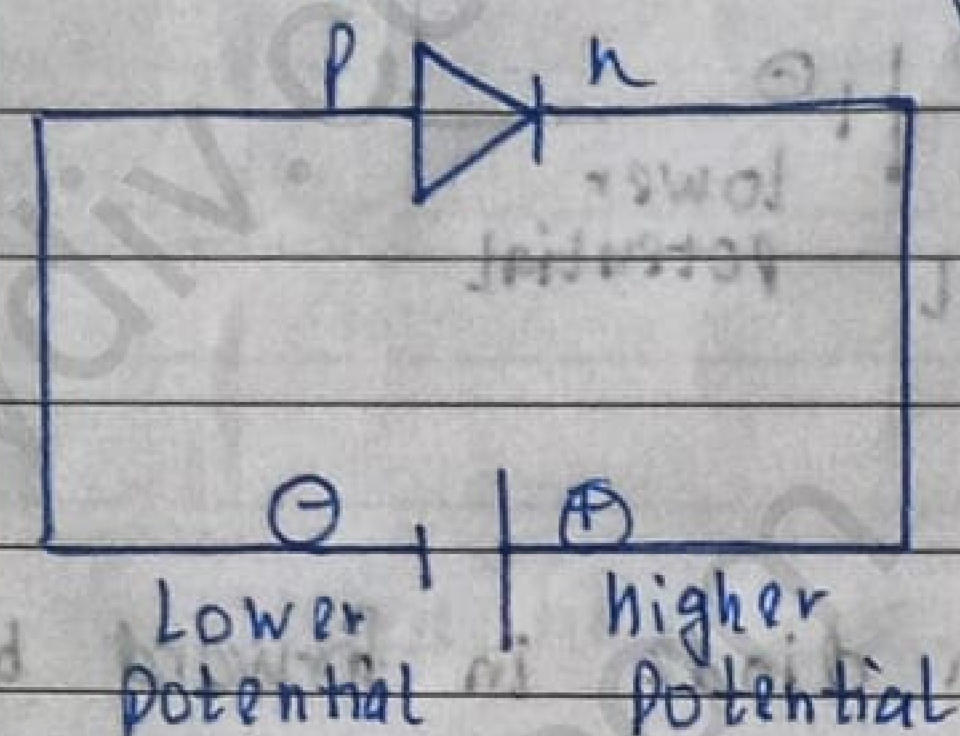
In this case, the hole from p-side and e^- from n-side are not able to cross the depletion layer. Therefore no current will flow and hence p-n junction diode will not conduct or we can say a very small amount of current flows due to minority charge carriers.

* CASE - 2 (if $V \geq V_B$)

In this case the holes from the p-side and e⁻ from the n-side are able to cross the depletion layer and hence a large amount of current will flow. Thus the p-n junction diode will conduct.

★ REVERSE BIASING

When p-side is connected with lower potential and n-side is connected with higher potential then the biasing is known as reverse biasing.

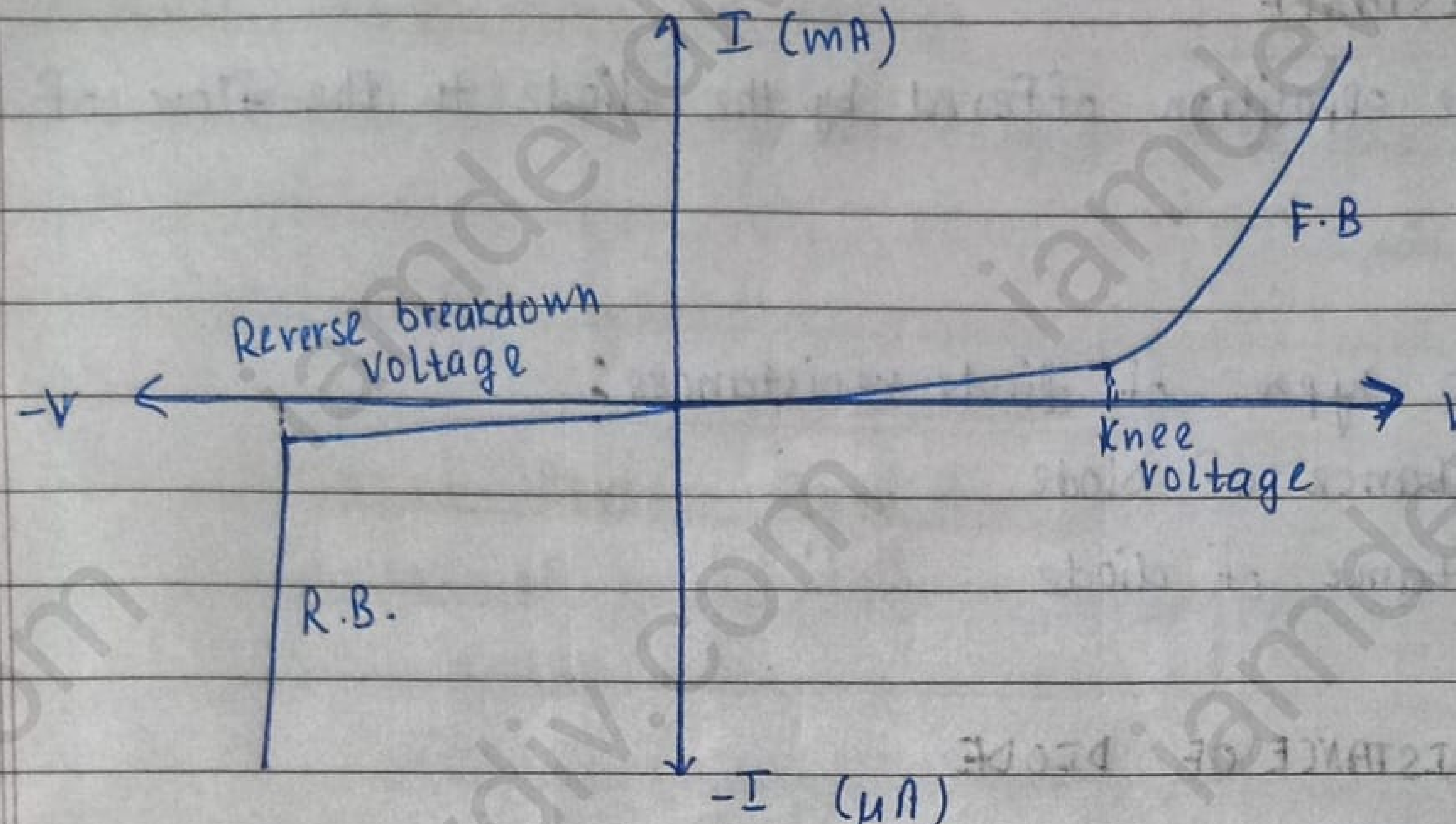


- **WORKING OF p-n junction in Reverse biasing**

During reverse biasing, depletion region increases. This is because holes from p-side and e⁻ from n-side move towards the battery. hence, no crossing will take place. There fore, no current will flow or a very small current will flow due to minority charge ~~car~~ carriers in reverse direction. As the battery ~~volume~~ voltage increases beyond a unit a breakdown will occur which is called reverse breakdown. Due to this, large no. of holes and e⁻ will free from depletion layer and hence large amount of current will flow. After that, the p-n junction diode will get damaged. so the p-n junction diode will work only in forward biasing and not in reverse biasing. ** (diagram on next page)

★ V-I CHARACTERISTICS OF p-n JUNCTION

Graph → Next page



- **FORWARD CHARACTERISTICS**
  It is the graph which shows the variation of forward current with forward bias voltage.

* **KNEE VOLTAGE**
  It is that forward bias voltage beyond which the current starts increasing rapidly.

- **REVERSE CHARACTERISTICS**
  It is the graph which shows the variation of Rererse current with reverse bias voltage.

* **REVERSE BREAKDOWN VOLTAGE**
  It is the reverse bias voltage at which current will increase abruptly /suddenly.

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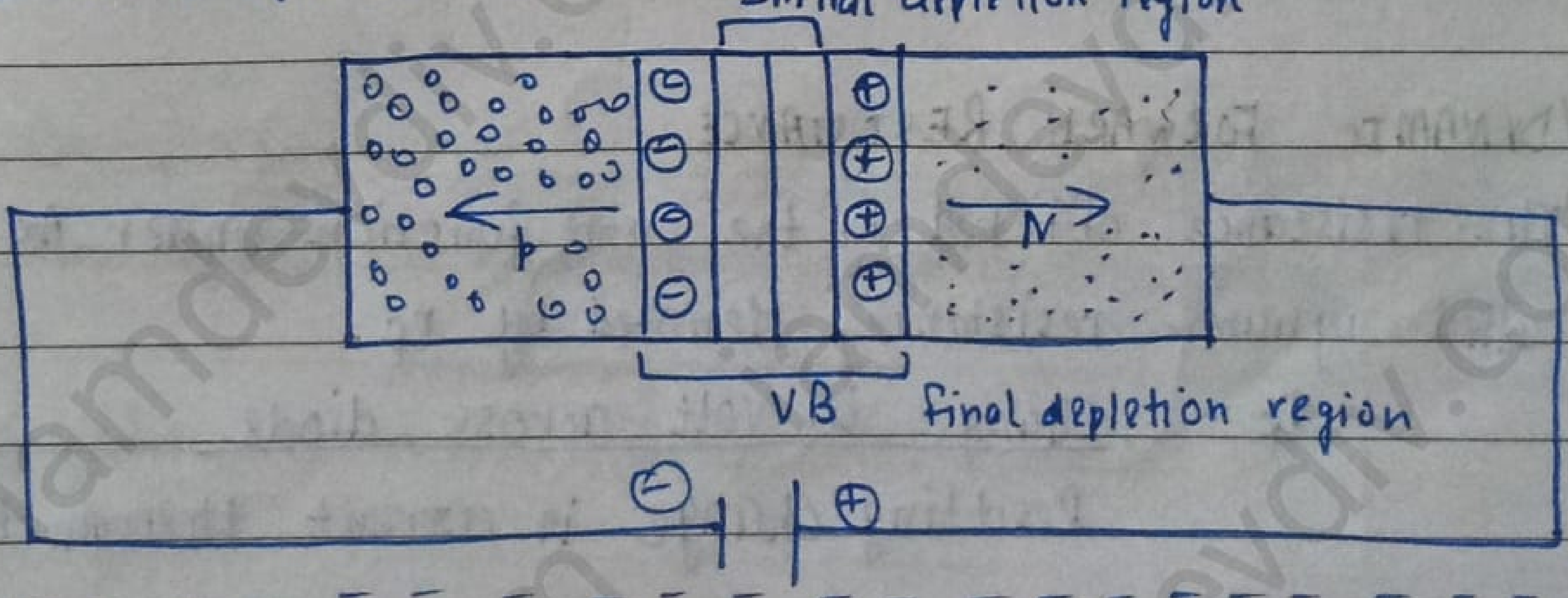


★ DIODE RESISTANCE

The effective opposition offered by the diode to the flow of current through it.

There are two types of diode resistances:

1) Forward resistance of Diode
2) Reverse resistance of diode

• FORWARD RESISTANCE OF DIODE

Its of two types:

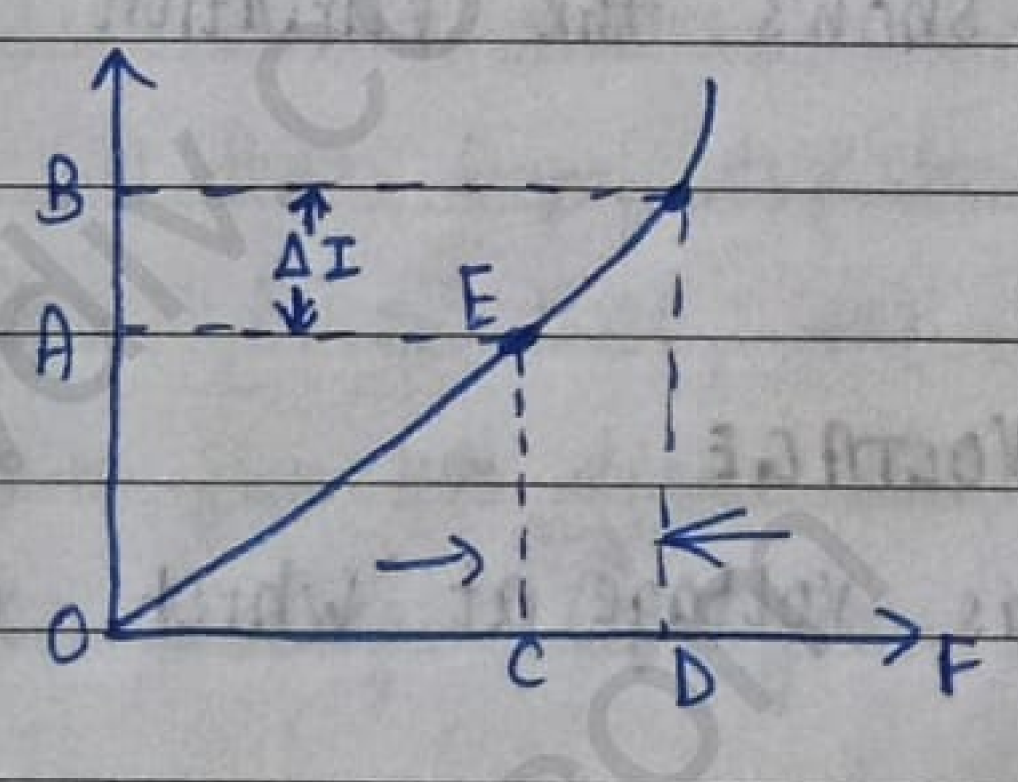
*DC/STATIC FORWARD RESISTANCE

This is the forward resistance of p-n junction diode when it is used in DC circuits and the applied forward voltage is DC.

This resistance is denoted by R_F and is calculated at a particular point on the forward characteristic.

$$R_F = \frac{\text{forward DC volt}}{\text{forward DC current}} = \frac{OC}{OA} \text{ at point } E$$

The static forward resistance is also called DC forward resistance.



*AC/DYNAMIC FORWARD RESISTANCE

The resistance offered by the p-n junction under AC conditions is called Dynamic resistance. denoted by r_f.

$$r_f = \frac{\text{change in volt across diode}}{\text{Resulting change in current through diode}} = \frac{\Delta V}{\Delta I}$$

- **REVERSE RESISTANCE OF DIODE**

The resistance offered by diode in reverse bias is known as reverse resistance.

They are of two types:

*** DC / STATIC REVERSE RESISTANCE**

It is the ratio of reverse DC volt to reverse current across the diode.

$$R_r = \frac{\text{Applied reverse D.C volt}}{\text{Reverse saturation current}}$$

$$R_r = \frac{V_R}{I_0}$$

*** AC / DYNAMIC REVERSE RESISTANCE**

It is the ratio of incremental change in the reverse volt applied to the corresponding change in the reverse current.

$$R_r = \frac{\text{Change in reverse volt}}{\text{Change in reverse current}}$$

$$R_r = \frac{\Delta V_R}{\Delta I_R}$$

*** RECTIFIER**

It is a device which convert AC into DC.

- **PRINCIPLE**

It is based on the fact that p-n junction diode will conduct heavily in forward bias and will not conduct in reverse bias.

- **TYPES OF RECTIFIER**

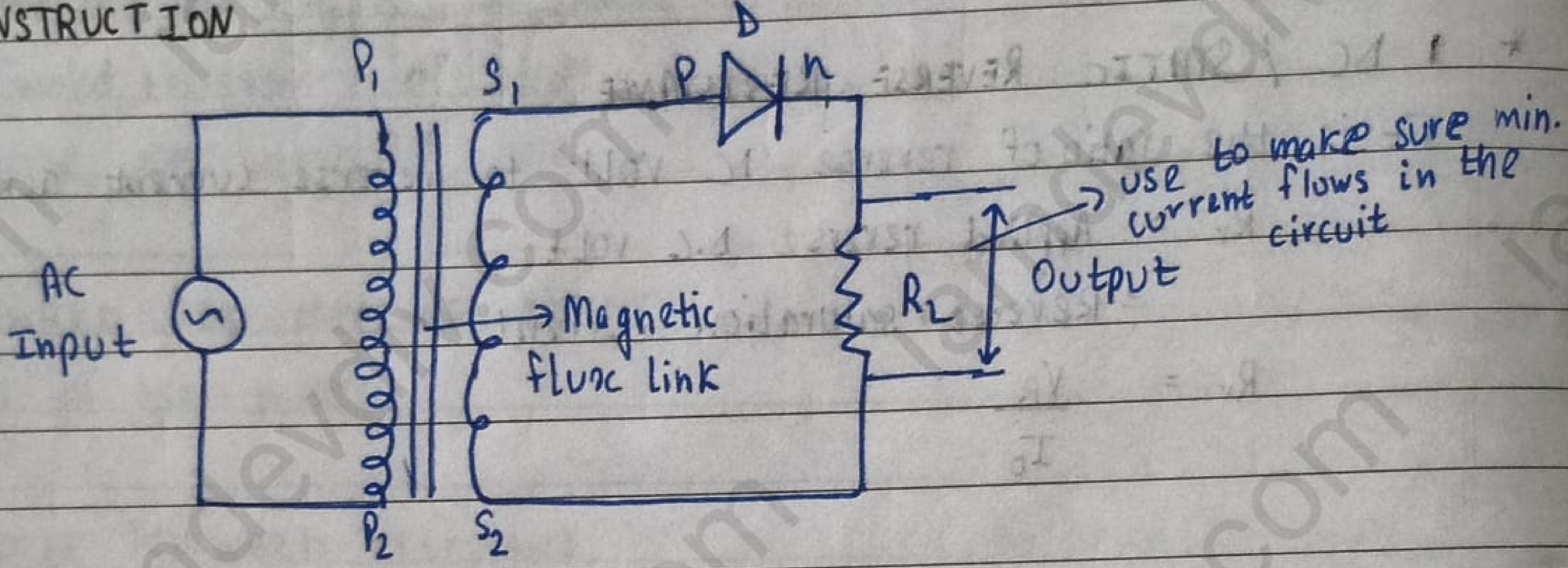
There are two types of rectifier:

1) Half wave rectifier
2) Full wave rectifier

1) HALF WAVE RECTIFIER

The rectifier which give output only for +ve half cycle but not for ~~the~~ -ve half cycle is called half wave rectifier.

* CONSTRUCTION

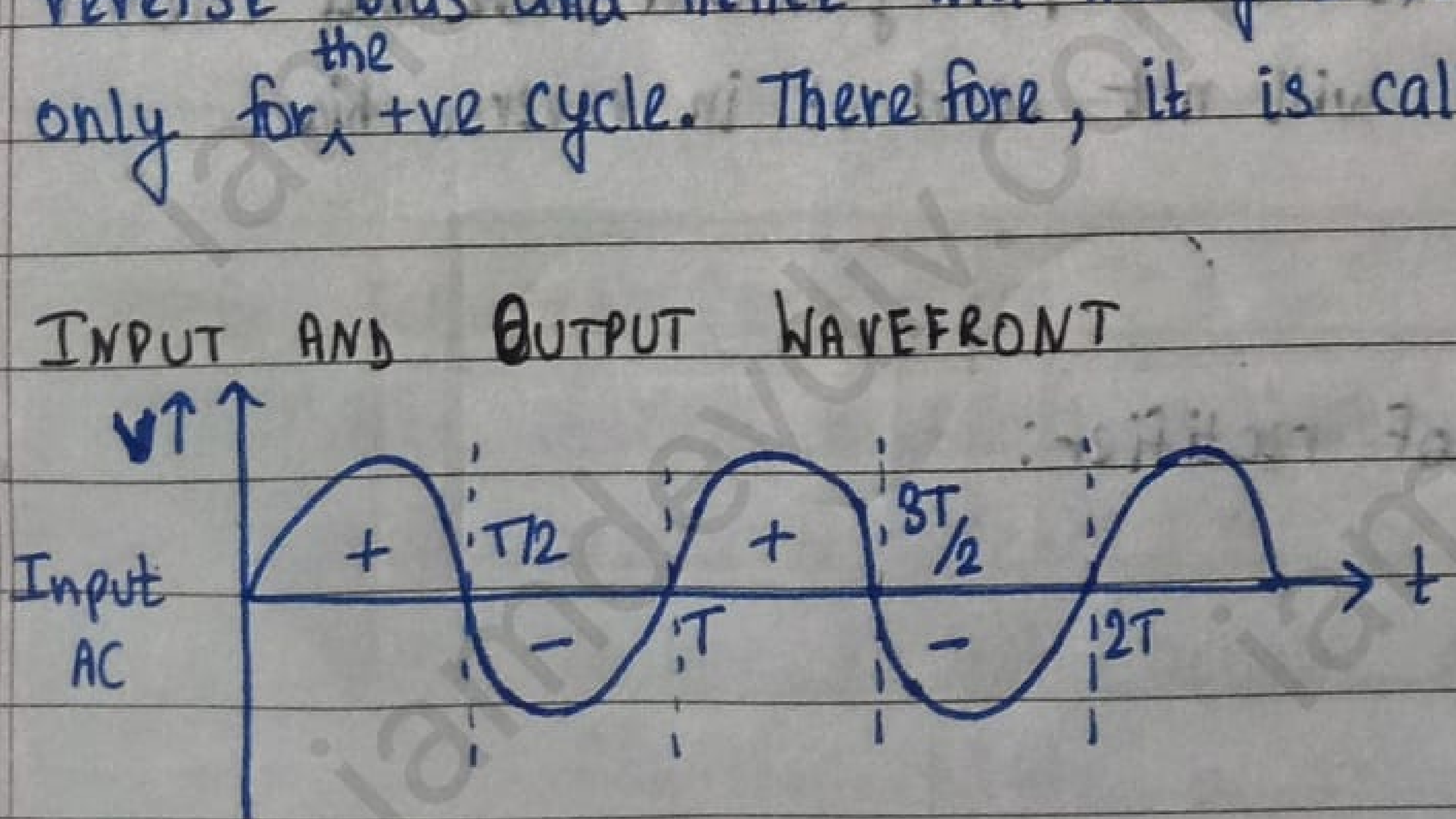


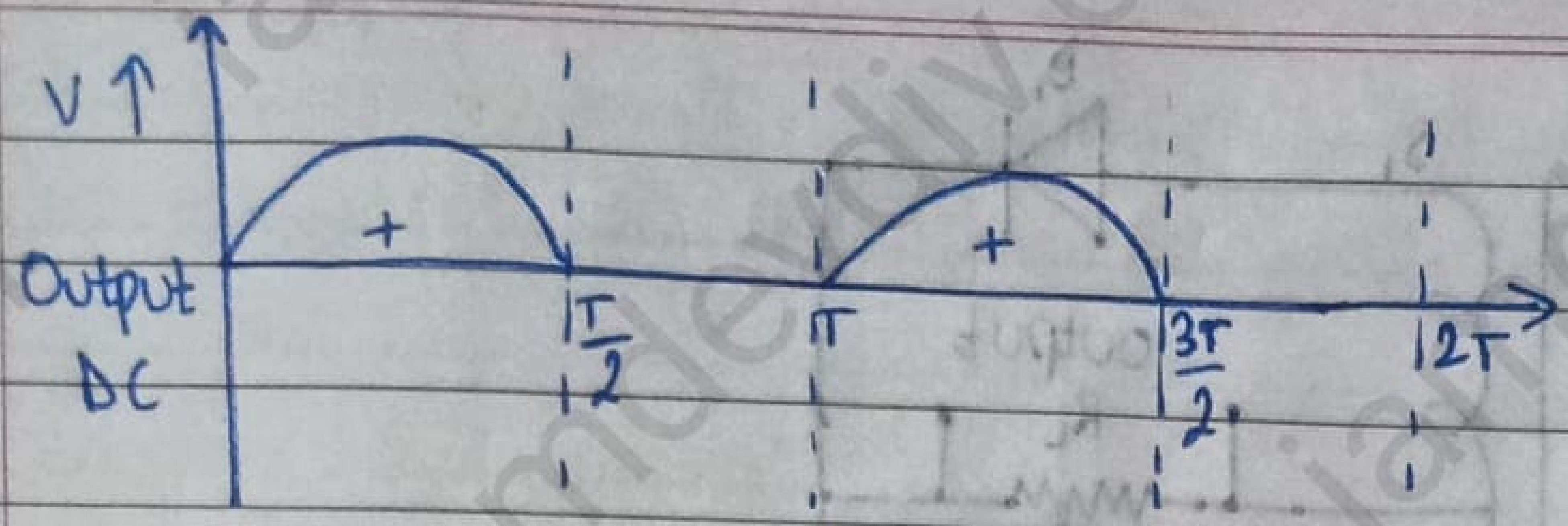
It consists of a step-down transformer with P_1, P_2 and S_1, S_2 as primary and secondary coils. AC input is connected across primary coil. A p-n junction diode with load resistance R_L are connected across secondary coil.

* WORKING

During the half cycle, let us consider P_1 to be -ve and P_2 to be +ve. Due to Lenz's law, S_1 become +ve and S_2 will become -ve. Hence, the diode will be in forward bias and will give output. During -ve half cycle P_1 will become +ve and P_2 will become -ve. Due to lenz's law, S_1 will become -ve and S_2 will become +ve. Therefore, the diode will be in reverse bias and hence will not give output. Thus, we get output only for the +ve cycle. Therefore, it is called half wave rectifier.

* INPUT AND OUTPUT WAVEFRONT





* AVERAGE VALUE OF OUTPUT CURRENT

$$i_{dc} = \frac{i_0}{\pi}$$

* MEAN SQUARE VALUE OF CURRENT

$$I_{rms} = \frac{i_0}{2}$$

* EFFICIENCY OF HALF WAVE RECTIFIER

$\eta = 40.5\%$

* RIPPLE EFFECT

The output of a rectifier is not pure D.C. but it has some components of A.C. also. These components are known as ripple factor.

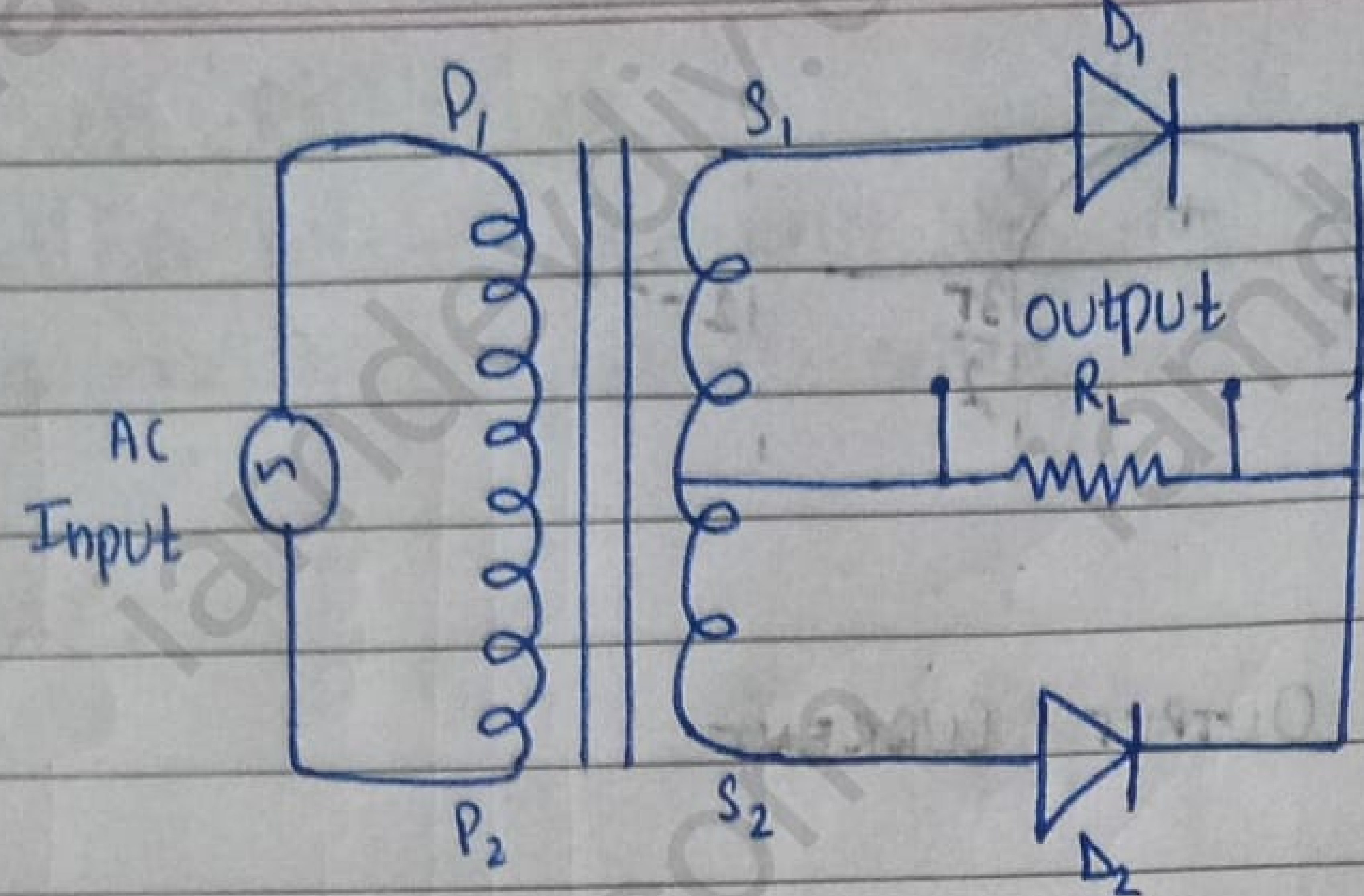
$r = 1.21$

2) FULL WAVE RECTIFIER

The rectifier which gives output for +ve half cycle as well as -ve half cycle is full wave rectifier.
Its of two types:

A) CENTRE TAP RECTIFIER

* CONSTRUCTION

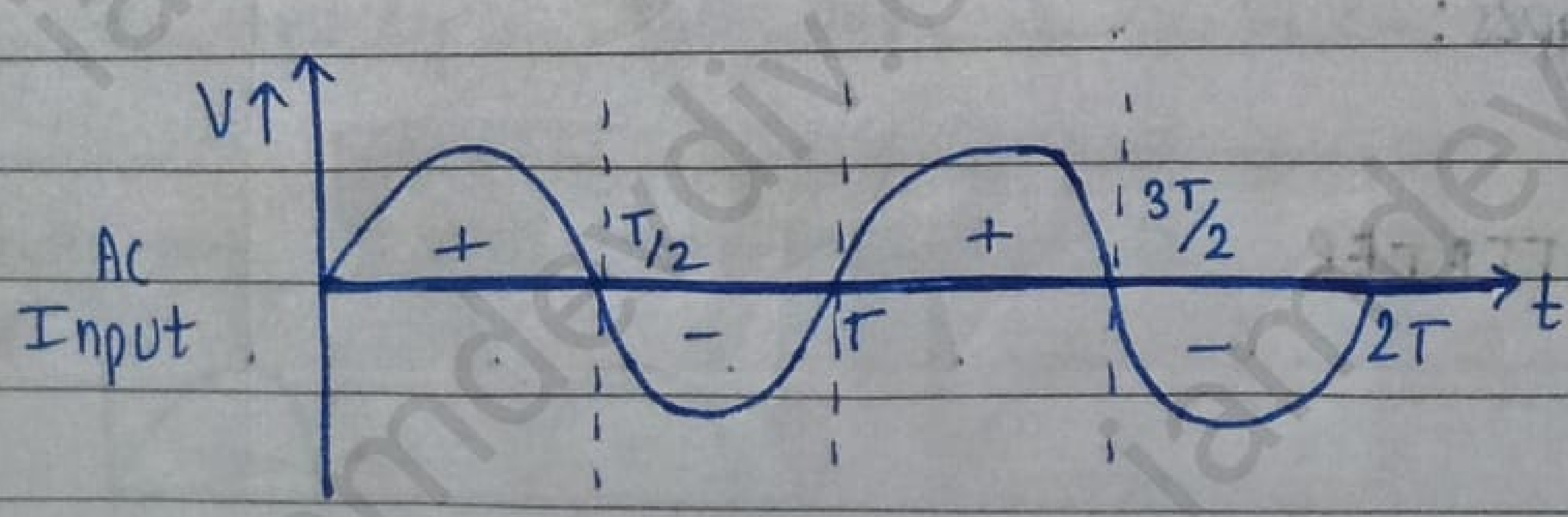


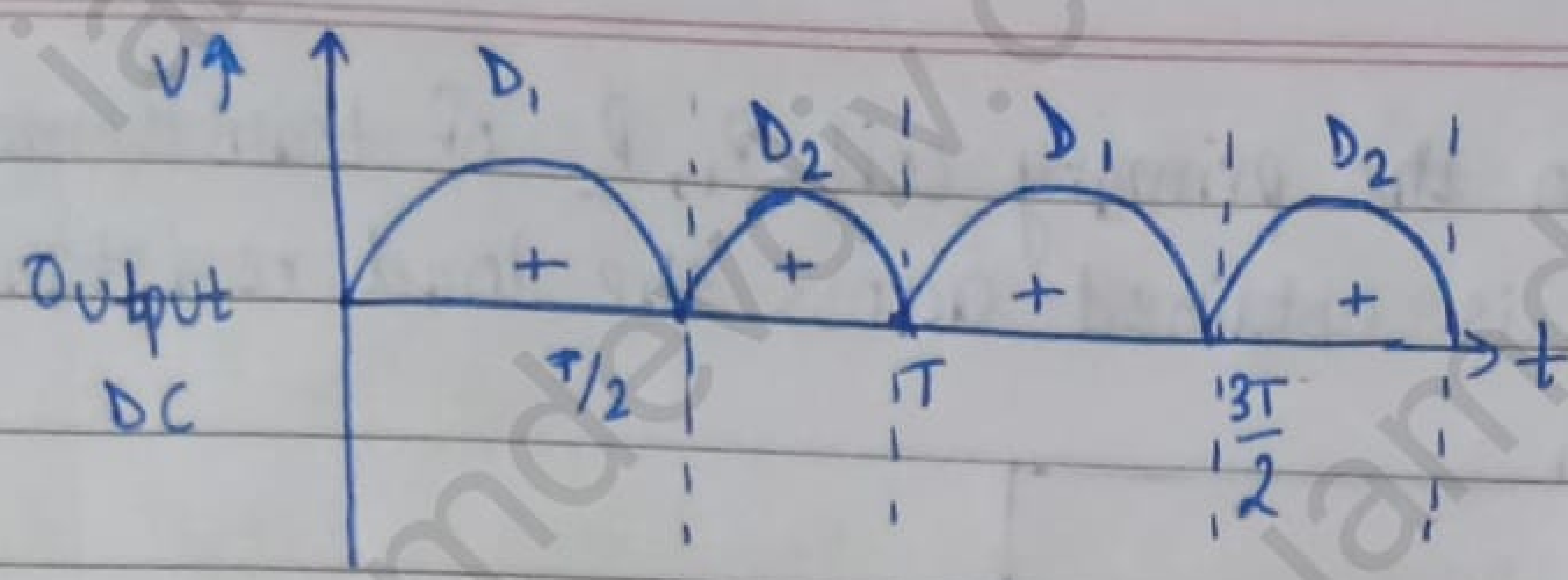
It consists of a step-down transformer with P_1, P_2 and S_1, S_2 as primary and secondary coil. Input AC is connected across primary and output is taken across secondary. Two diodes D_1 and D_2 with a load resistance are connected across secondary.

* WORKING

During +ve half cycle, let us consider P_1 to be -ve and P_2 to be +ve. Due to Lenz's law, S_1 will become +ve and S_2 will become -ve. Thus, the diode D_1 will be in forward bias and D_2 will be reverse bias. Therefore, we will get output through D_1. For the -ve half cycle, P_1 will become +ve and P_2 will become -ve. Due to Lenz's law, S_1 will become -ve and S_2 will be +ve. Therefore, the diode D_2 in forward bias and hence we will get output through D_2. Thus, it ~~gets~~ gives output for both the half cycle. Therefore, it is called full wave rectifier.

* INPUT AND OUTPUT WAVEFORMS





* AVERAGE VALUE OF CURRENT

$$i_{dc} = \frac{2i_0}{\pi}$$

* RMS VALUE OF CURRENT

$$I_{rms} = \frac{i_0}{\sqrt{2}}$$

* EFFICIENCY OF RECTIFIER

$\eta = 81\%$

* RIPPLE FACTOR

$r = 0.482$

B) FULL WAVE BRIDGE RECTIFIER

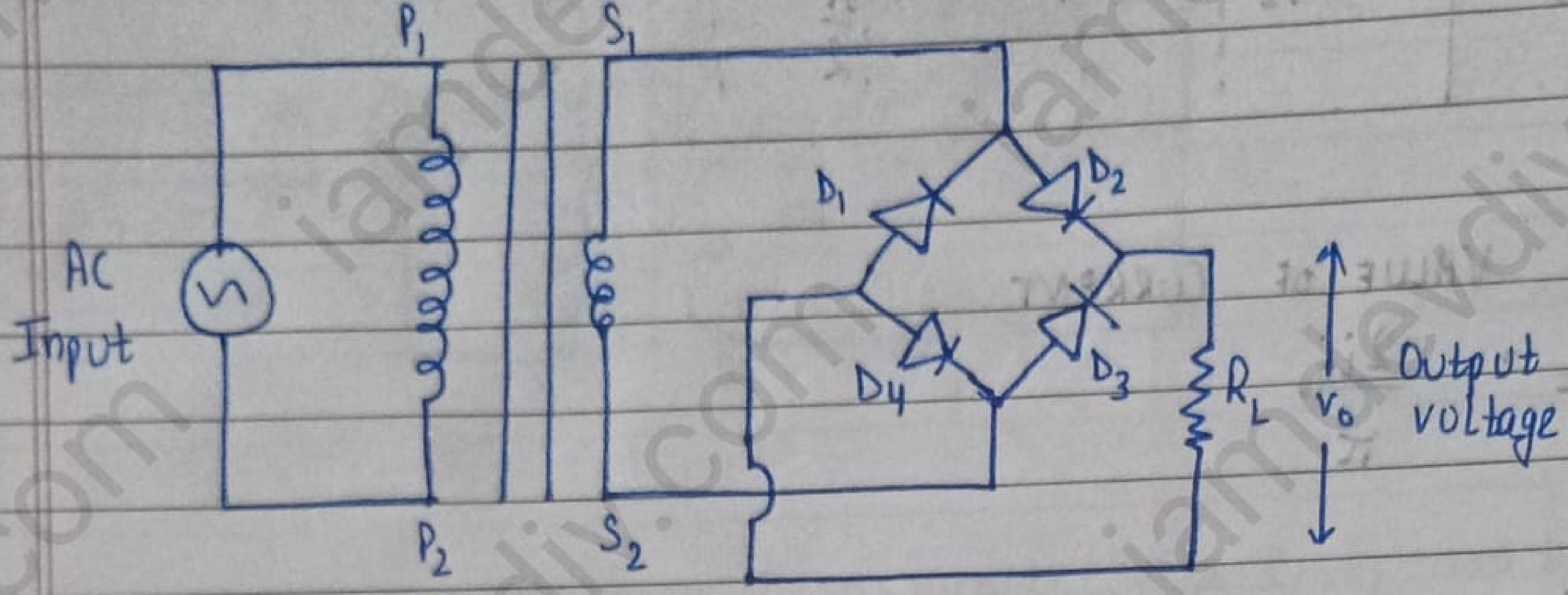
A full wave bridge rectifier is an electrical device which converts both half cycle of input AC into DC.

* PRINCIPLE

Its working is based on the principle that a p-n junction diode conduct when forward bias and do not conduct when reverse bias.

* CIRCUIT DIAGRAM

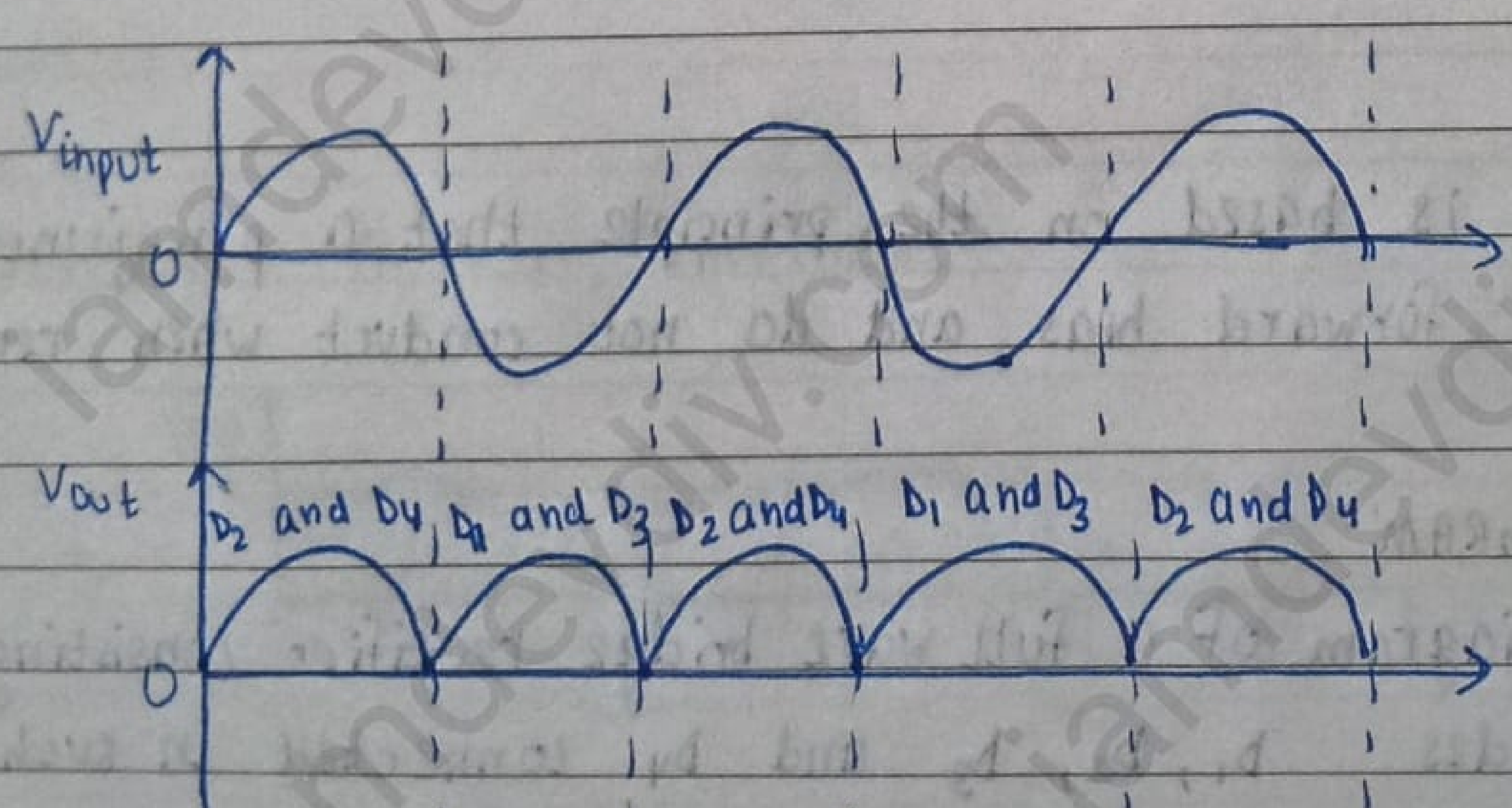
The circuit diagram of a full wave bridge rectifier consisting of 4-pn junction diodes D_1, D_2, D_3 and D_4 connected in such a way so as to form a bridge is shown in figure. P_1, P_2 and S_1, S_2 are primary and secondary coil of a step down transformer. The AC voltage is applied to the primary coil P_1, P_2 of transformer and the rectified output volt is obtained across the load resistance R_L.



* WORKING

i) During +ve half cycle of input AC signal S_1 becomes +ve and S_2 becomes -ve. So diodes D_2 and D_4 are forward bias while diodes D_1 and D_3 are reverse bias. Therefore, diodes D_2 and D_4 will conduct current across them but diodes D_1 and D_3 will not conduct. Due to current through R_L an output voltage V_0 is obtained across it.

ii) During -ve half cycle of input signal S_1 becomes -ve and S_2 becomes +ve so diodes D_1 and D_3 are forward bias while diodes D_2 and D_4 are reverse bias. Therefore, diodes D_1 and D_3 conduct current across them, but diodes D_2 and D_4 will not conduct. Due to current through R_L an output volt V_0 is obtained across it.



Efficiency and ripple factor same as centre tap rectifier

Q A Semiconductor has equal electron and hole concentration of $2\times10^{8}/m^3$. On doping with a certain impurity, the hole concentration increases to $4\times10^{10}/m^3$.

(i) What type of semiconductor is obtained on doping?
(ii) Calculate the new electron and hole concentration of semiconductor.
(iii) How does the energy gap vary with doping?

Sol. (i) p-type semiconductor

(ii) $n_e n_h = n_i^2$

$\because n_e = n_h$

$\Rightarrow n_e \times n_e = n_i^2$

$\Rightarrow n_e^2 = n_i^2$

$\Rightarrow n_e = n_i$

$n_e' n_h' = n_i^2$

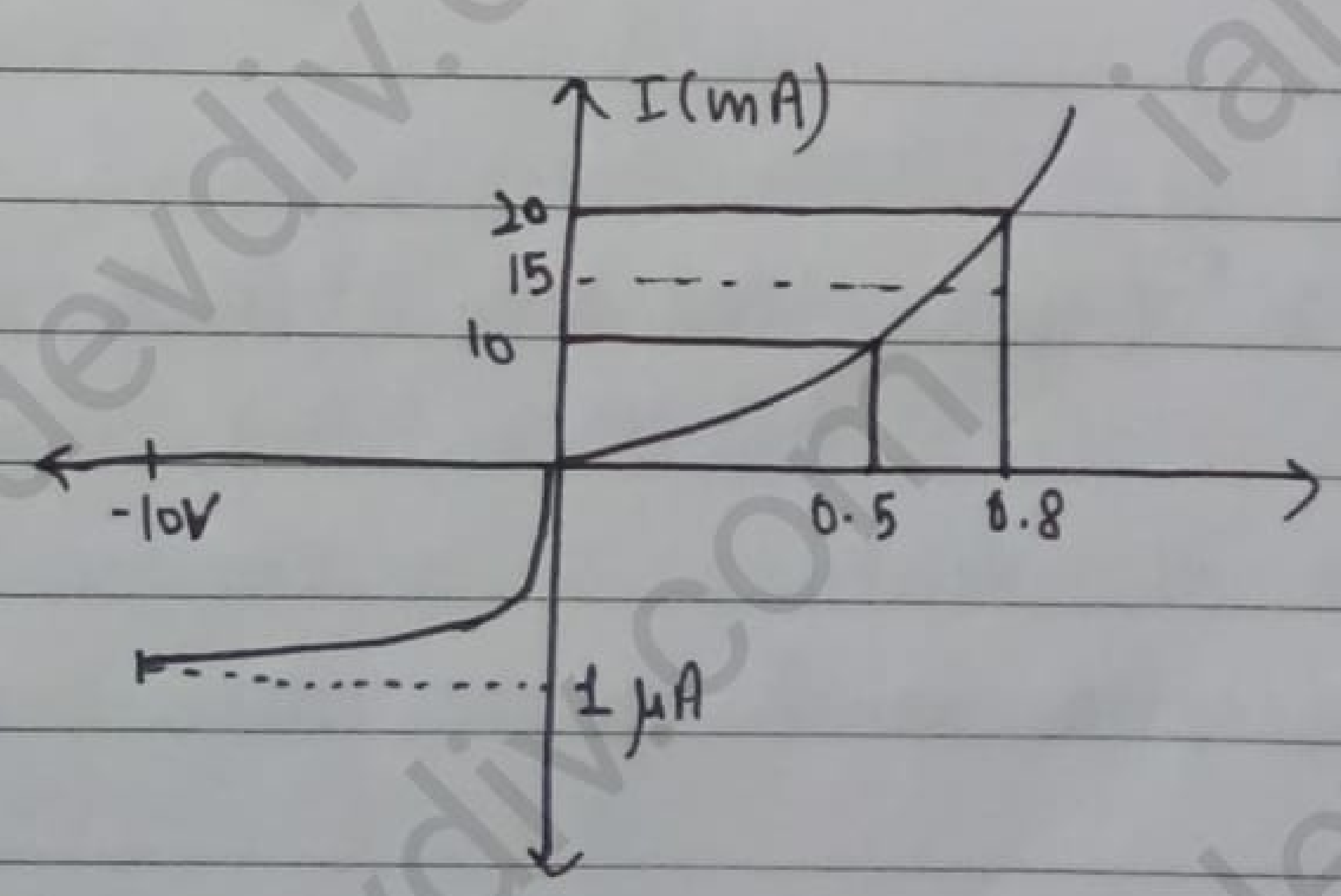
$\Rightarrow n_e' \times 4\times10^{10} = n_e^2$

$\Rightarrow n_e' = \dfrac{2\times10^{8}\times2\times10^{8}}{4\times10^{10}}$

$\Rightarrow n_e' = 10^{6}/m^3$

(iii) energy gap decreases with doping

Q Calculate the resistance of the diode



(a) 10mA ⟶ 20mA

(a) $r_d = \dfrac{\Delta V}{\Delta I} = \dfrac{0.8-0.5}{20-10} = \dfrac{0.3}{10} = 0.03\ \Omega$

(b) $R_s = \frac{V}{I} = \frac{10 \times 10^6}{1} = 10^7 \, \Omega$

Q. Suppose a pure Silicon crystal has 5×10^{28} atoms $/m^3$. It is doped by 1 ppm concentration of pentavalent As. Calculate the number of electrons and holes given,

$$n_i = 1.5 \times 10^{16} / m^3$$

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

$n_e n_h = n_i^2$

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