Semiconductor Devices :

Conductors, Insulators & Semi-conductors

Classification of solids

① **Metals** - low resistivity, high conductivity

② Insulators - high resistivity, low conductivity

③ Semi-conductors - conductivity & resistivity in betⁿ metals & insulators

Types of semi-conductors

(a) Elemental semiconductors - available in natural forr
eg Si, Ge

(b) Compound semiconductors - made by compounding metals

eg (i) Inorganic semi-conductor - CdS, GaAs
(ii) Organic " - anthracene
(iii) Organic polymer " - polyaniline

Energy Band of solids (Band Theory)

- Electrons of each isolated atom have discrete energy levels.
- When 2 similar atoms are brought closer, then there is an interaction between valence electrons
- This interaction causes splitting of each individual energy level into 2 slightly different energy levels.

- The splitting occurs because Pauli's exclusion principle forbids 2 electrons to have same Quantum state.
- The atoms in a solid are so close that the energy levels produced after splitting will be so close to each other that they appear as continuous.
- These closely spaced energy levels form an energy band.
- If the energy band contains no. of electrons equal to no. of electrons permitted by Pauli's principle, then it is said to be completely filled.

Formation of bands

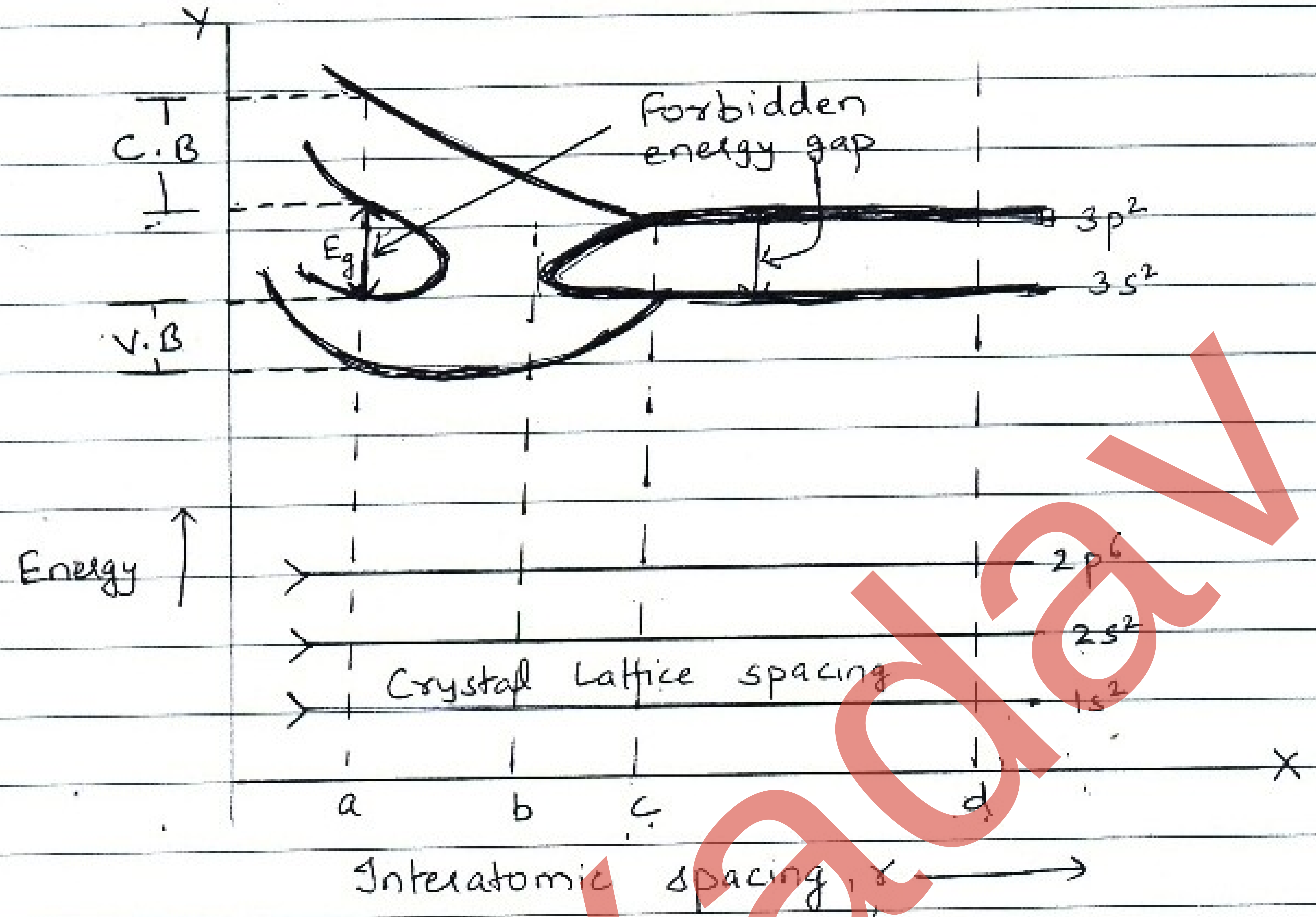
Consider a single crystal of Si having N atoms. Each atom can be associated with a lattice site.

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

So, for 8N available energy sites there are 4N electrons.

① If interatomic spacing of Si atoms is very large i.e. $r = d >> a$, there is no interatomic interaction.

Each atom behaves as free atom so each of N atoms has its own identical energy levels which are sharp, discrete & distinct.



② $c < r < d$ – no visible splitting of energy levels

③ $r = c > a$

Interaction betⁿ outermost electrons ($3s^2$ & $3p^2$) of silicon atoms becomes appreciable & so energy of electrons corresponding to 3s & 3p levels start changing.

④ $b < r < c$

The energy of 3s & 3p levels of each atom gets slightly modified. Instead of a single 3s or 3p level there occurs a large no. of closely spaced energy levels.

Now, 2N energy states of s-level will not have same energy but will be spread in small energy band.

Similarly 6N energy states of p-level will be spread in small energy bands.

Due to this, the energy gap betⁿ s & p levels of an isolated atom reduces.

⑤ $r = b$
At this stage, the energy gap between 3s & 3p levels completely disappears & all the 8N levels are distributed in a continuous manner forming an energy band & it is not possible to distinguish betⁿ 3s & 3p electrons.

⑥ $r = a$ (actual interatomic spacing)
At this stage, the energy of the band of 8N levels splits into 2 bands - band of 4N energy levels of completely filled electrons & 4N unfilled energy levels.
These 2 energy bands are separated by a small energy gap.
The lower energy level band of 4N filled levels is called Valence Band (V.B)
The upper energy level band of 4N unfilled levels is called Conduction Band (C.B.)
The energy gap betⁿ V.B & C.B is called forbidden energy gap.

Conductors, Insulators & Semi-conductors on basis of band theory

- A solid is made up of large no. of atoms. The energy levels of atom get modified due to the presence of other surrounding atom.
- The energy levels in outermost shells of all atoms form VB & CB separated by forbidden energy gap.

- **Valence Band** - The energy levels containing valence electrons is called V.B.

Fermi level - The highest energy level which an electron can occupy in VB at 0K.

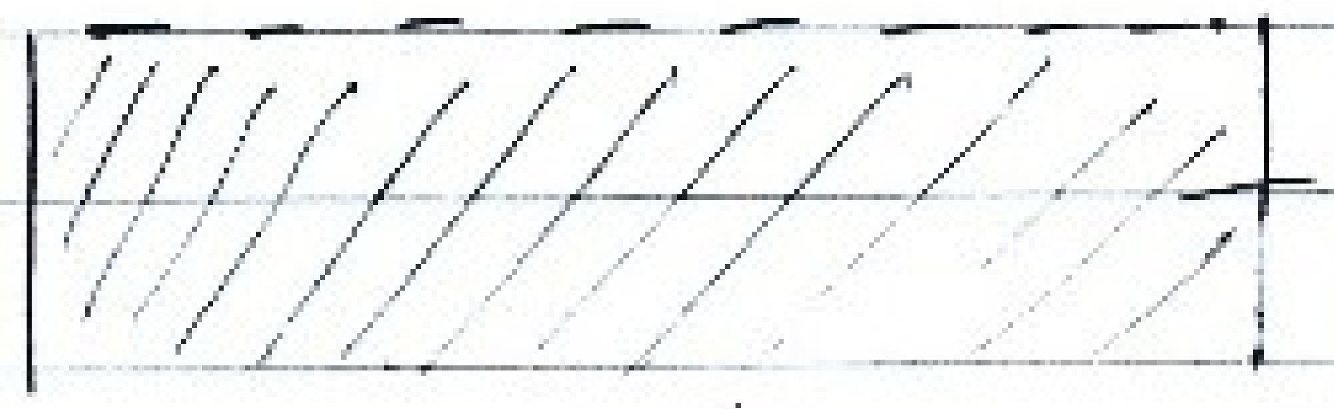
Conduction Band - Lowest unfilled energy band formed just above VB

- At 0K, fermi-level as well as all the lower energy levels are completely occupied by electrons.
As tem. rises, electrons absorb energy & get excited.
The excited electrons jump to higher energy levels.
These electrons in higher energy levels are larger distance from the nucleus & are more free as compared to electrons in lower energy levels.

Depending on energy gap bet^n VB & CB solids behave as conductors insulators & semiconductors.

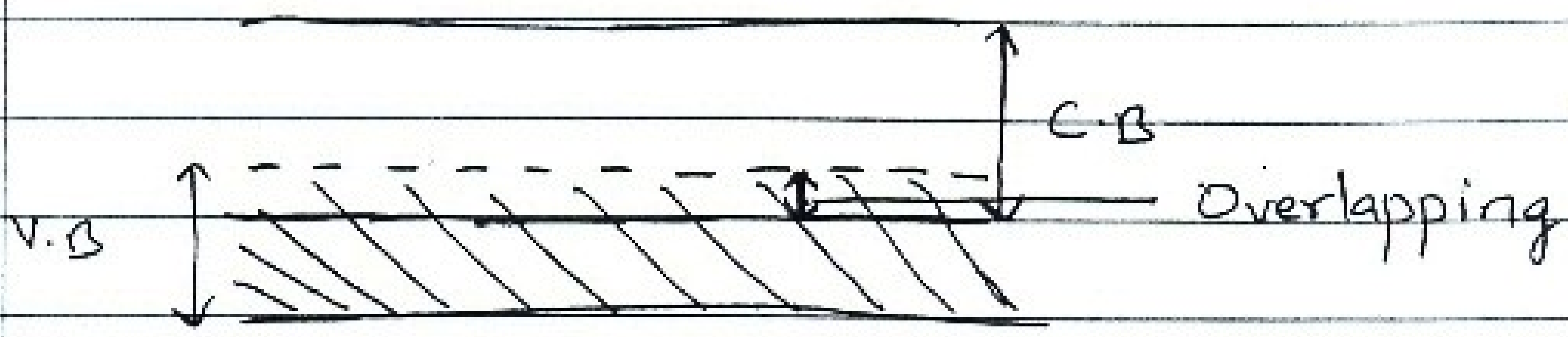
① **Conductors**
There are 2 possible energy band structure in conductors

(a) VB partially empty CB partially filled



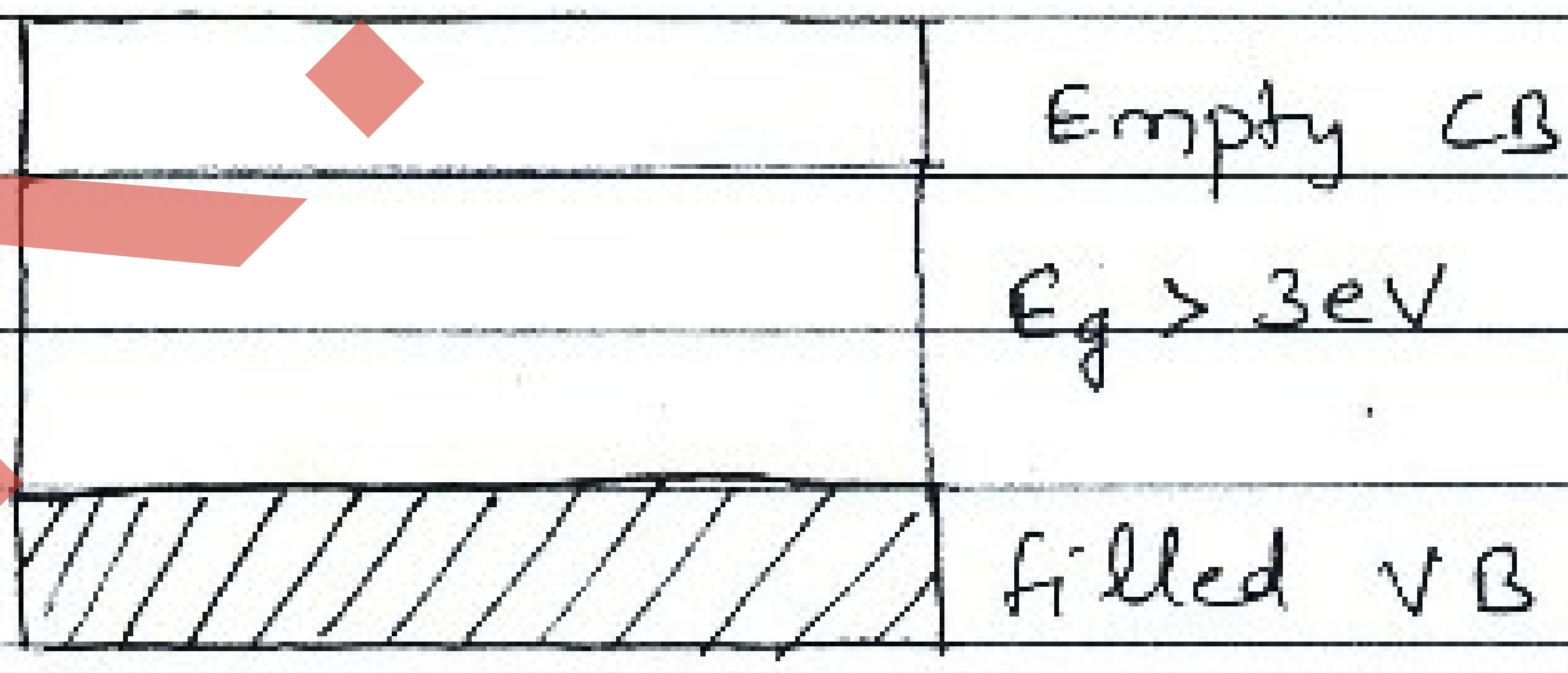
Partially filled CB

(b) VB & CB overlap with no energy gap



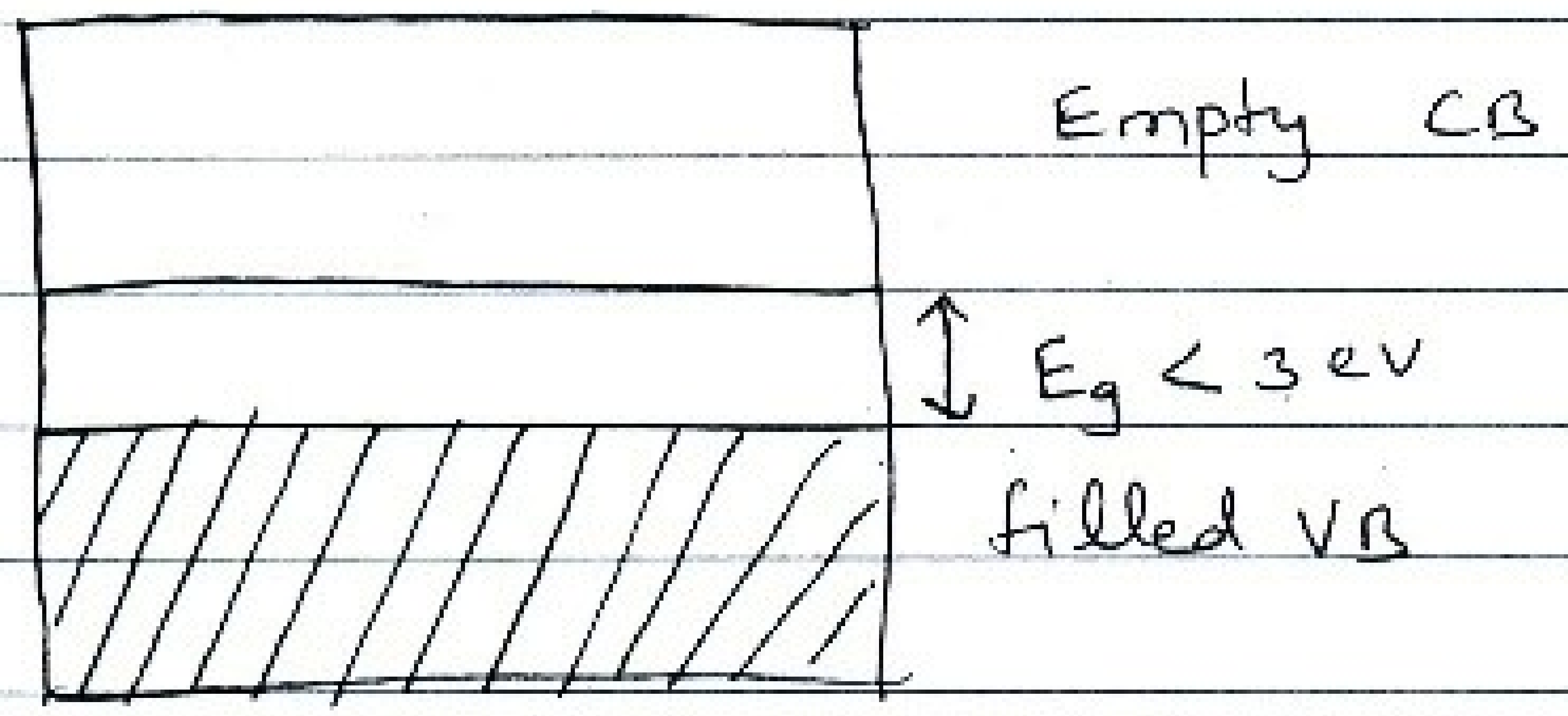
Many electrons (below fermi level) by acquiring little more energy from any sourc can shift to higher energy level in CB. & behave as free-electron.
Even when a small electric field is applied across the metal, these free electron start moving in a direction opp. to electric field.
Due to this current begins to flow through it & so metal behaves as conductor.

② Insulators



Energy gap E_g is very large (6eV for diamond)
It means the minimum energy required to take electrons from VB to CB is very large.
When electric field is applied across such a solid, the electrons find it difficult to acquire such a large energy & so CB. remains empty. & no electron flows occurs.
So they behave as insulators.

③ Semi-conductors



The size of E_g is neither too large nor too small

At 0K, electrons are not able to cross E_g & so semiconductor behaves as insulator.

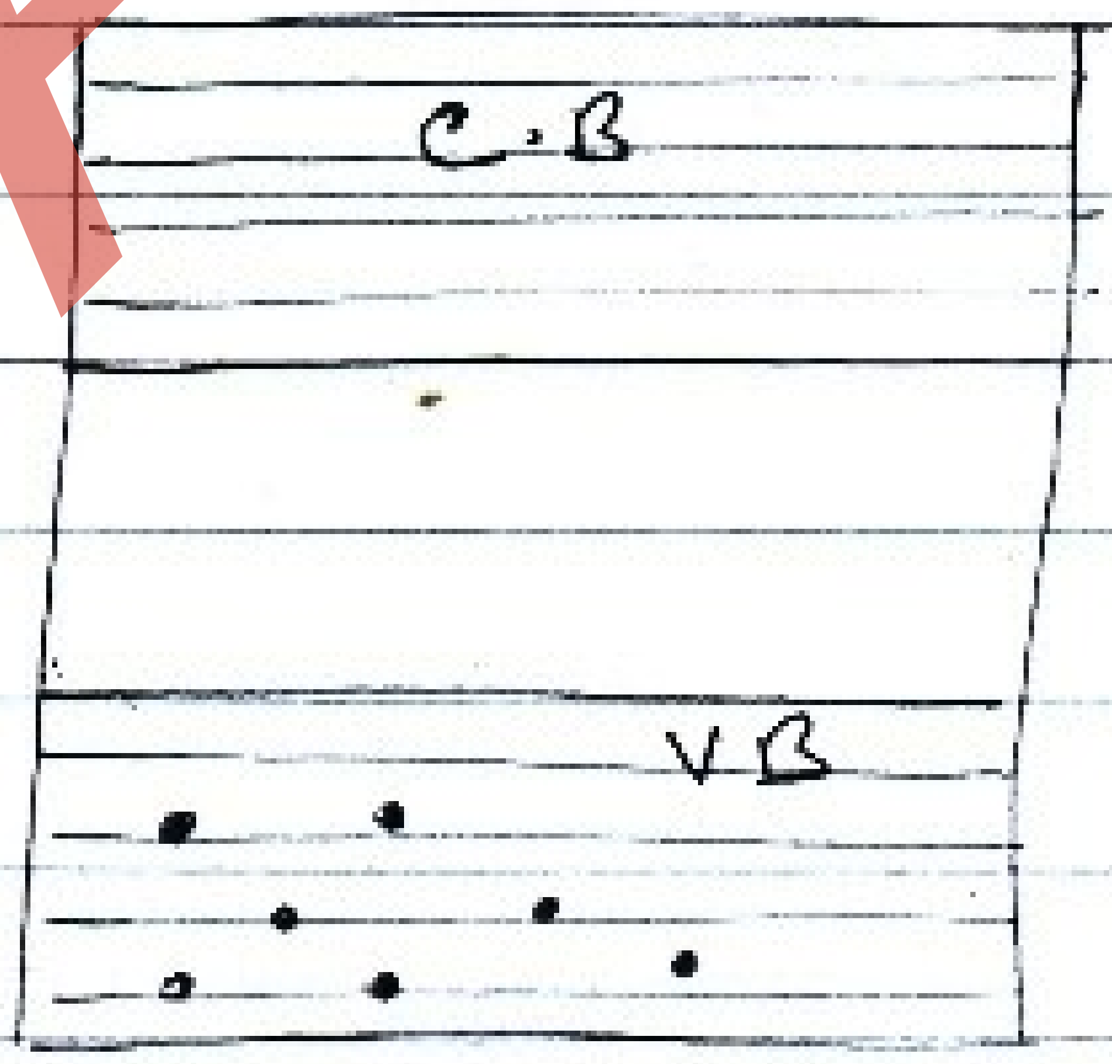
At room tem. some electrons in VB acquire thermal energy greater than E_g & go to CB where they move under the influence of even a small electric field.

Thus, it acquires small conductivity at room tem.

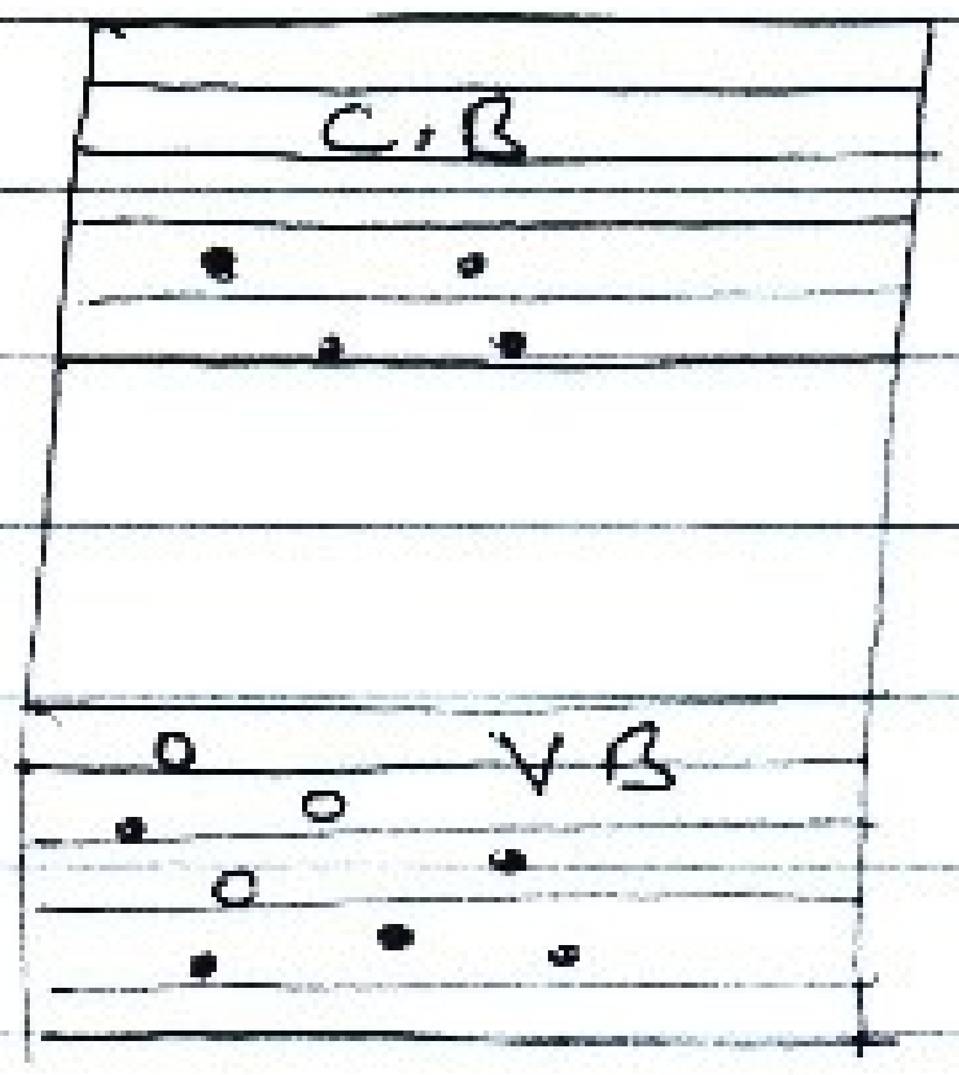
Current Carriers in semi-conductors

This can be understood in 2 ways

(1) From energy band diagram of semiconductor



At 0K

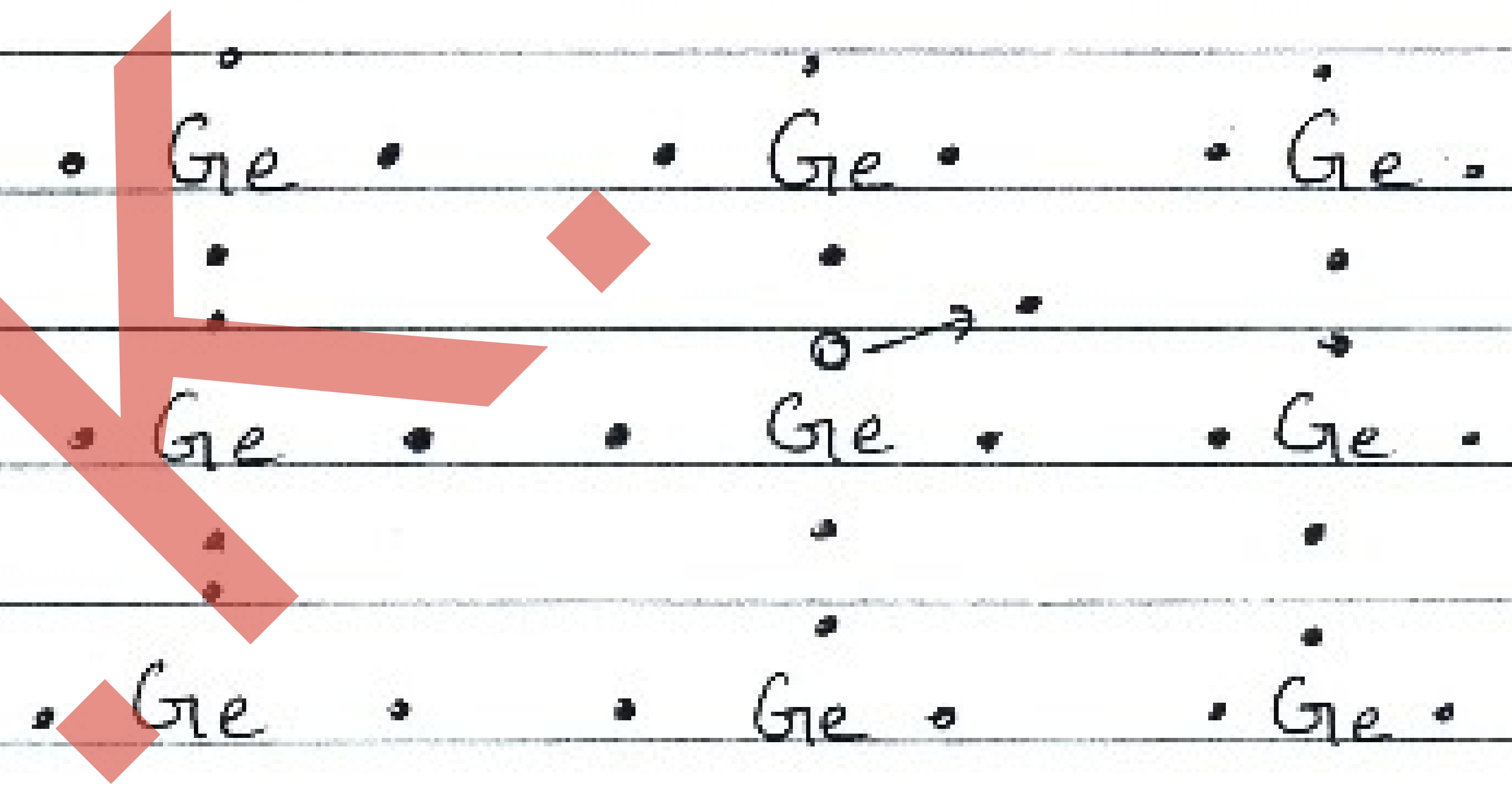


At room tem

- At 0K, the semi-conductor behaves as insulator as no electron from VB cross E_g & go to C.B.
- But at higher tem. some of the electrons gain energy due to thermal agitation & move fo VB to CB
- Due to this a vacancy called hole is created in VB at a place where the electron was present.
- Hole is considered as +ve charge having charge equal to that of electron.
- So, electrons & holes are current carriers in semi-conductors.

(2) In terms of valence bond model

Consider the example of Ge



- Each Ge atom has 4 valence electrons which it uses in forming 4 covalent bonds with 4 neighbouring atoms.
- Even at room tem., a valence electron gains enough thermal energy & breaks away from covalent bond & is free to move through the crystal lattice
- This electron leaves behind a vacancy/void

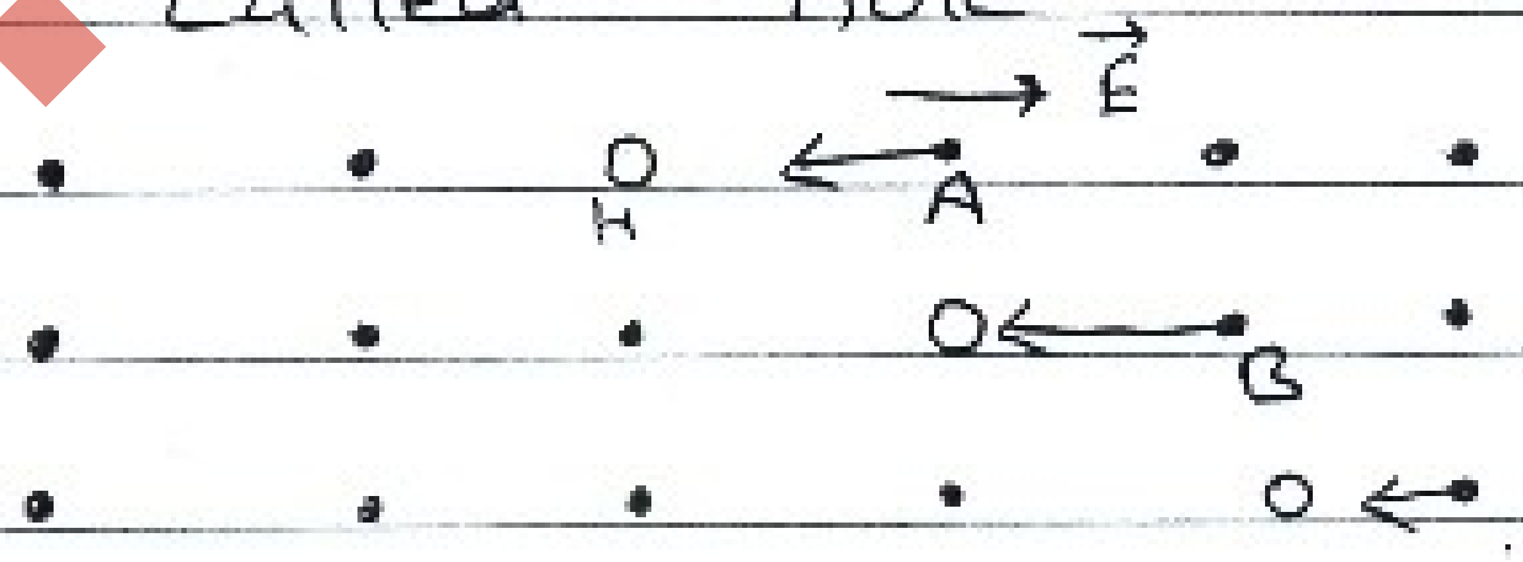
in the covalent bond

- This absence of an electron from a bond is called hole (shown by open circle).
- An electron from a neighbouring bond can break away & can be attracted by this +ve hole, thus completing the covalent bond & creating a hole at some other place
- Hence hole moves randomly through crystal lattice.

Intrinsic Semi-conductors

" The pure semi-conductor in which the electrical conductivity is totally governed by electrons excited from VB to CB & in which no impurity atoms are added to increase their conductivity is called intrinsic semiconductor & its conductivity is called intrinsic conductivity."

- At 0K, semiconductor is insulator but E_g is small.
- At room tem., the electrons in the VB get sufficient thermal energy & cross over to CB where they are free to conduct electricity.
- Each free electron leaves behind a vacant state called hole



- When an electric field $\vec{E}$ is applied across the semiconductor, an electron A from neighbouring bond moves into this hole H
- This leaves behind a vacancy at A & another electron at B moves to fill the new hole & so on

- Hence, under the influence of electric field $\vec{E}$ electrons drift in opp. direction of $\vec{E}$ & holes move in direction of $\vec{E}$
- So, there are 2 types of currents in the semiconductor – one due to electrons in CB & other due to holes in VB.
- Both the currents add up to give total current in the direction of $\vec{E}$.

In an intrinsic semi-conductor
no. of free electrons = no. of holes.

So, $n_e = n_h = n_i$

here, n_e – electron density in C.B.
n_h – hole " " VB
n_i – number density of current carriers (electrons & holes) in pure semi-conductor.

The fermi-level of an intrinsic semi-conduct lies mid-way bet^n its V.B & C.B.

Doping

- The electrical conductivity of intrinsic semi-conductors is very small.
- It can be enormously increased by adding calculated quantity of impurity atoms.

"The process of adding a desirable impurity atoms to a pure semi-conductor to modify its properties is called doping."

The impurity atoms added are called dopants & the semiconductor doped with impuri

Requirements for doping

The dopant has to be such that

1) it does not distort the original pure s-c lattic
2) it occupies only a very few of the origin semi-conductor atom sites in the crystal.
3) its size & the size of the semi-conducto atoms should be nearly same.

Methods of doping

1) By adding the impurity atoms to an extrem pure sample of molten semi-conductor
2) By heating the crystalline semi-conductor in a atmosphere of dopants atoms or molecules so th dopant atoms diffuse into semi-conductor.

Extrinsic Semi-conductor

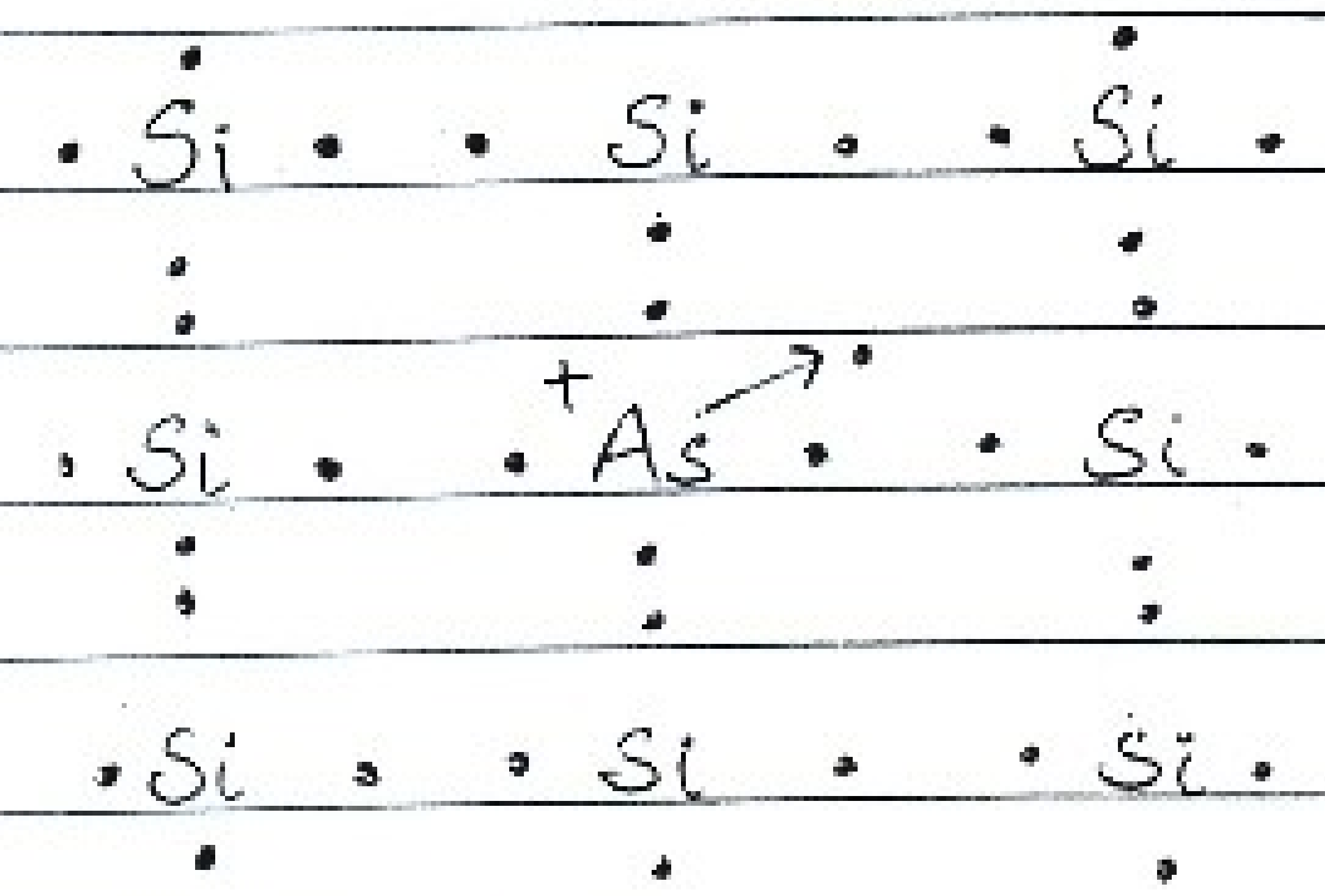
A semi-conductor doped with suitable impurit atoms so as to increase its conductivity is called an extrinsic semi-conductor.

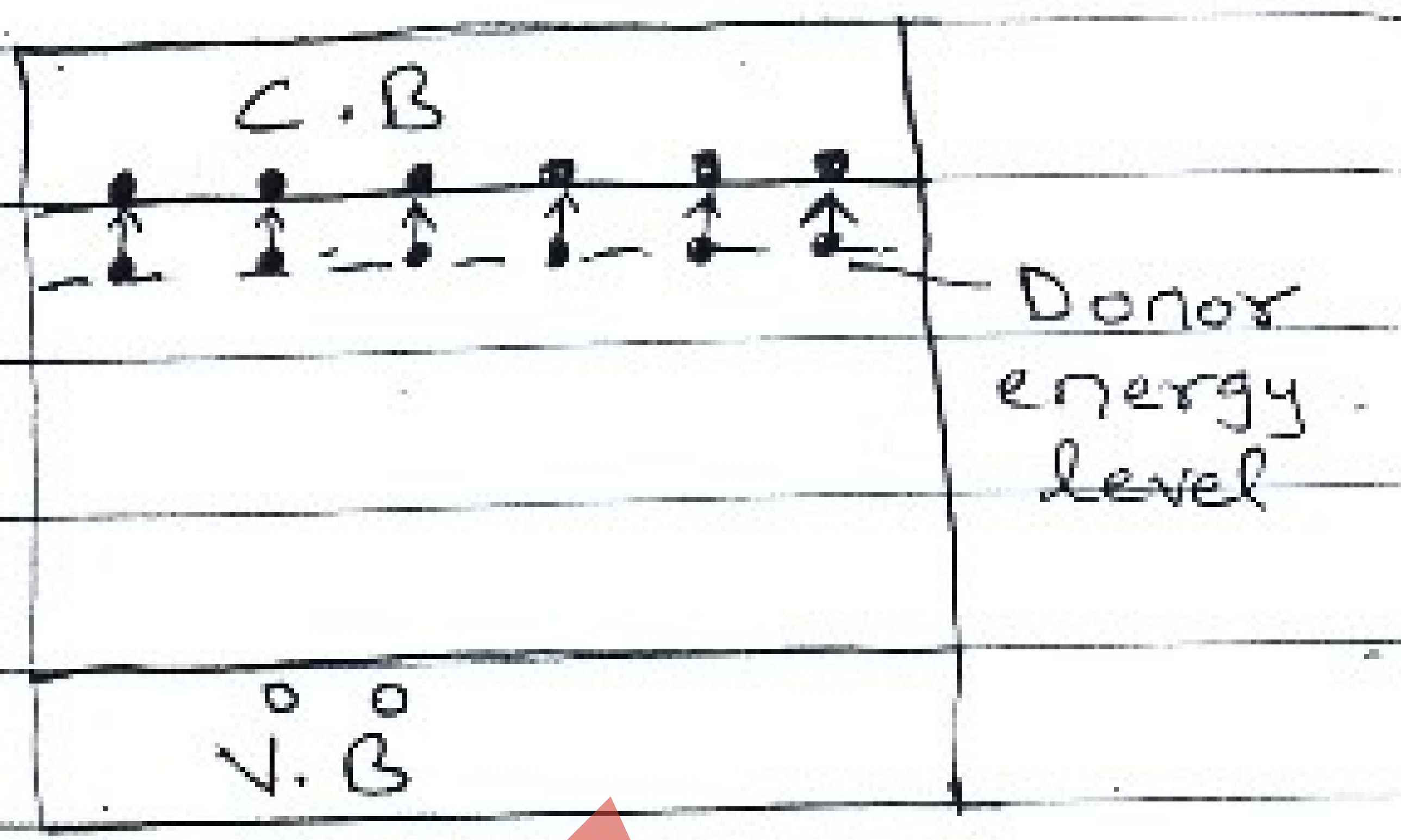
Types of extrinsic semi-conductors

1) n-type semiconductor
2) p-type semiconductor

① n-type semiconductor

If the impurity atoms of an element belong to group V of periodic table such as Arsenic (As), Phosphorus (P) or Antimony (Sb) be added to a semi-conductor like Si or Ge.





then only 4 of the 5 valence electrons from each impurity atom participate in forming covalent bonds & the 5th electron from each impurity atom is almost free to conduct electricity.

- There is a very weak attraction of this electron towards the +vely charged impurity atom
- A very small energy (~ 0.01 eV for Ge and 0.05 eV for Si) is required to detach this electron from the atom. So this electron can be readily freed by the thermal energy of room tem.

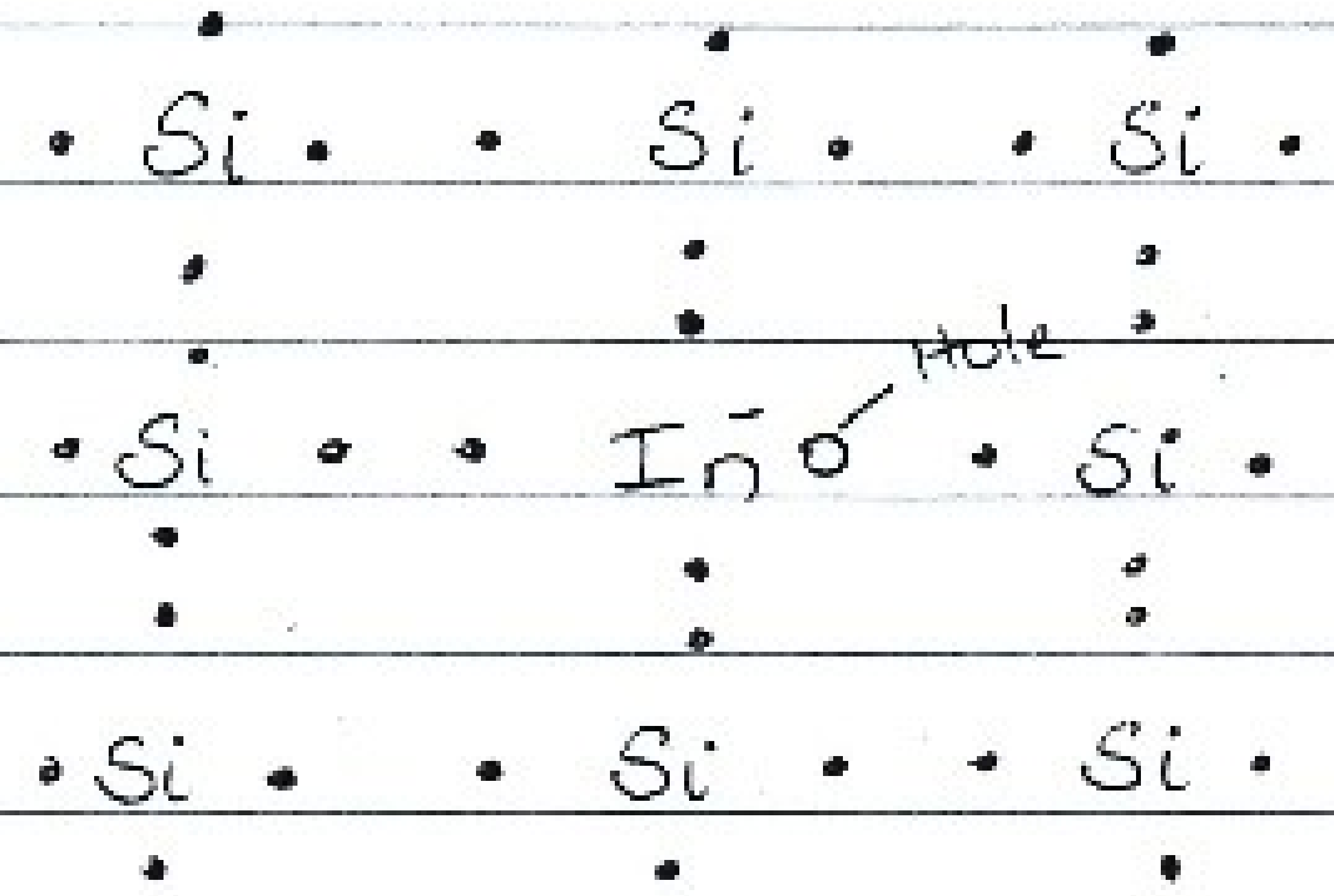
"The pentavalent impurity atoms are called donors because they donate electrons to the host crystal & the semi-conductor doped with donors is called n-type semi-conductor."

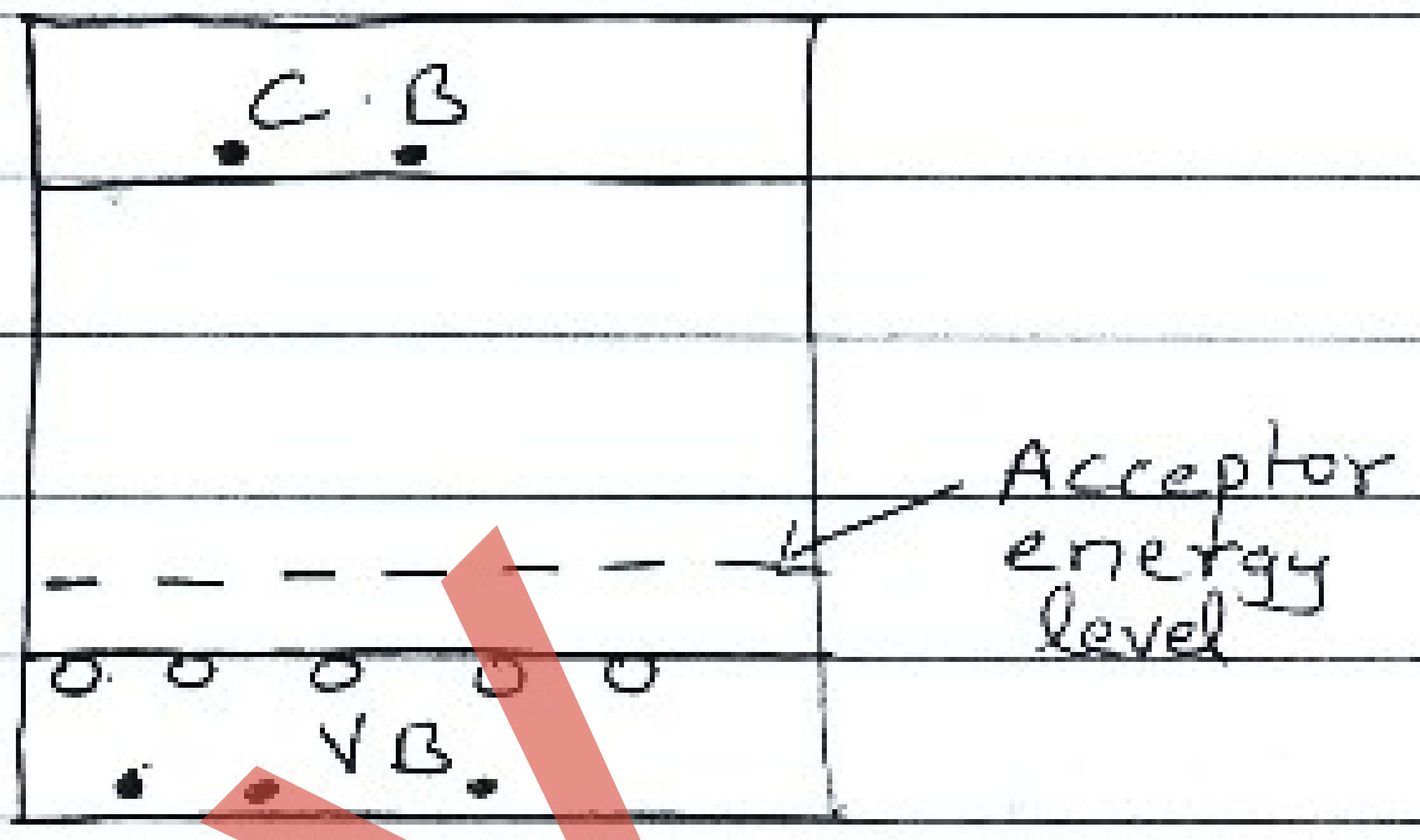
Here the donor electrons are the majority charge carrier & holes are the minority carriers.

$$n_e >> n_h$$

* In enery band diagram, the electron lie in the donor level as their enery is less but on applying/increasing tem. they move to C.B.

② p-type semi-conductor





- In impurity atoms of an element belonging to group III like B, Al, Ga or In are doped in a pure semiconductor of Si or Ge, each of these trivalent impurity atoms forms only 3 covalent bonds with neighbouring Si atoms and one covalent bond is left incomplete due to deficiency of an electron.
- The Si-In bond is completed by taking an electron from a neighbouring Si-Si bond.
- So, In atom is -vely charged & creates a vacancy or a hole in that bond.
- An electron from the next neighbouring bond can move into this hole producing another hole & so on.
- The hole contributes towards the increase in conductivity of the semi-conductor.

"The trivalent impurity atoms are called acceptors because they create holes which can accept electrons from nearby bonds. The semi-conductor doped with acceptor type impurity is called p-type s.c"

- In a p-type semi-conductor, there is a weak attraction betⁿ hole & -vely charged acceptor ion.

- Here the energy level E_B lies just above the V.B. This energy level is called acceptor energy level.
- As $E_B < E_g$ (energy gap), so electrons from VB can be easily excited thermally to acceptor energy level, which leave behind holes in VB.
- These holes act as +ve charge carriers.

Here, holes are majority charge carriers & electrons are minority charge carriers.

$$n_h >> n_e$$

* The electron & hole conc. in a semiconductor in thermal equilibrium is

$$n_e n_h = n_i^2$$

Q Suppose a pure Si-crystal has 5×10^{28} atoms m^{-3}. It is doped by 1 ppm conc. of pentavalent As. Calculate the no. of electrons & holes. Given $n_i = 1.5 \times 10^{16}$ m^{-3}.

Ans 1 ppm $= 10^{-6}$

So no. of 'As' atoms doped $= \frac{5 \times 10^{28}}{10^6} = 5 \times 10^{22}$ m^{-3}

As one 'As' atom donates one electron, so no. of free electrons

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

Now, $n_h = \frac{n_i^2}{n_e} = \frac{1.5 \times 1.5 \times 10^{32}}{5 \times 10^{22}} = 4.5 \times 10^{9}$ m^{-3}

Difference bet^n Intrinsic and Extrinsic semiconductor

Intrinsic Semi-conductor	Extrinsic semi-conductor
1) Pure semi-conducting material with no impurity added	1) Prepared by doping small amount of impurity atoms to pure semiconducting material.
2) Electrical conductivity low	2) Electrical conductivity high
3) No. of free electrons in C.B = No. of holes in V.B	3) n-type → $n_e >> n_h$ p-type → $n_h >> n_e$
4) Conductivity is a function of tem.	4) Function of tem. & conc. of dopant
5) Eg → pure Si, Ge	5) n-type → Si, Ge doped with As, P p-type → " " " In, B

Difference bet^n n-type and p-type

n-type semiconductor	p-type semiconductor
1) Obtained by doping Si or Ge with pentavalent impurity atoms of As, P or Sb	1) Trivalent impurity atoms of In, B or Al
2) Each impurity atom provides a free electron & is called donor	2) Each impurity atom create a hole in the crystal & is called acceptor
3) Donor level just below C.B.	3) Acceptor level just above V.B.
4) majority charge carrier - electrons minority " " - holes	4) majority charge carrier - holes minority " " - electro
5) $n_e >> n_h$	5) $n_h >> n_e$

Semi-Conductor Devices.

p-n Junction

It is a combination of n-type and p-type semi-conductors in close contact.

A p-n junction can't be made just by placing a p-type semi-conductor in close contact with n-type semi-conductor. Both types of impurities must be grown in a single crystal

* Junction implies boundary of transition betn n-type & p-type S.C material

Fused junction technique

i) Here n-type or p-type 'Si' crystals are cut into thin slices called wafers

ii) If on the wafer of n-type 'Si' an 'Al' film is placed & heated to 580°C, Al diffuses into 'Si'. Thus a p-type semi-conductor is formed on a n-type semi-conductor.

iii) Similarly, a p-n junction can also be formed by diffusion of 'P' into a p-type 'Si' wafer.

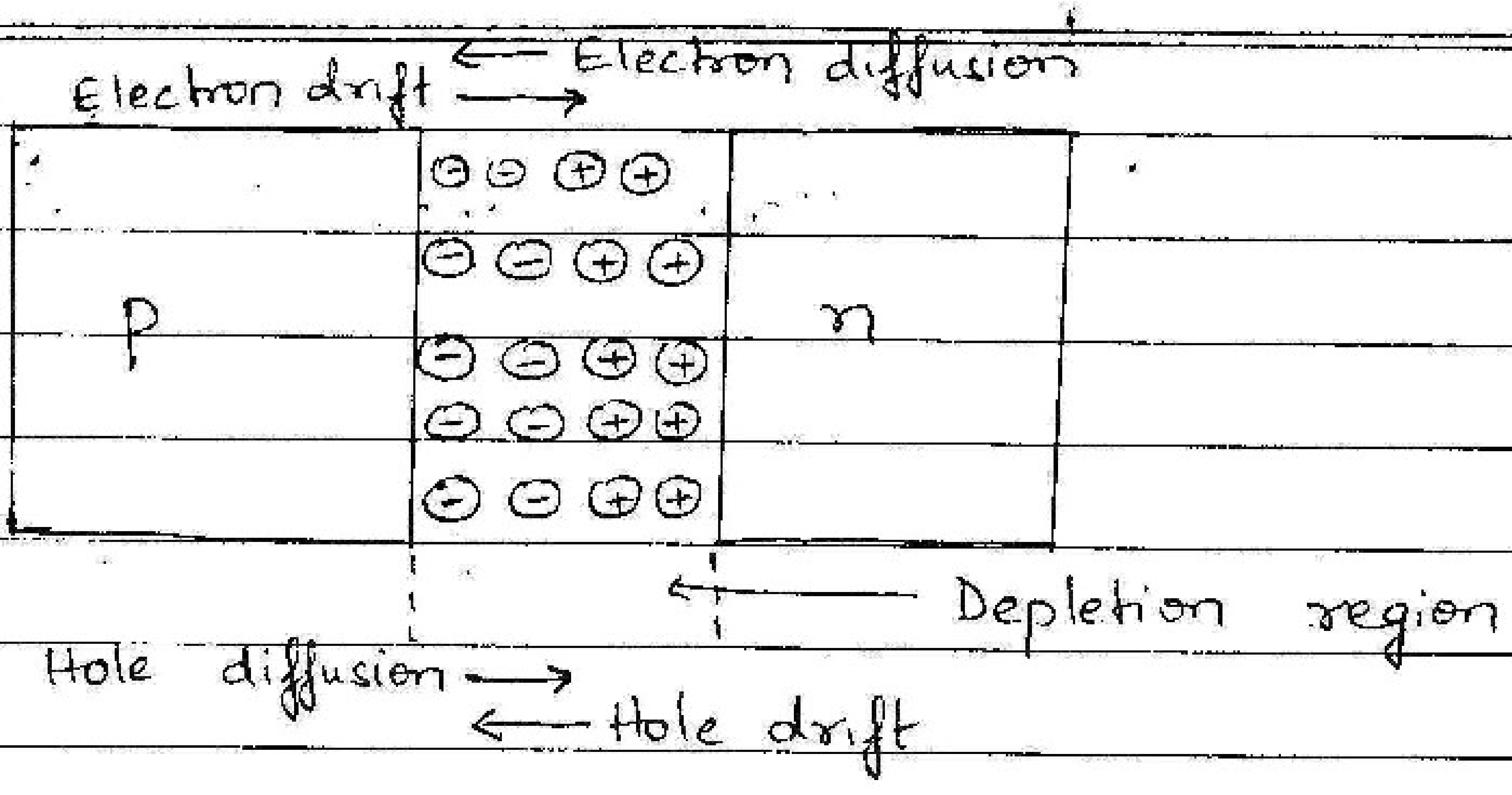
iv) The wafer on which a p-n junction is formed is cut into small pieces.

v) Each piece is enclosed in a capsule case with electrical connections coming out from p-region & n-region.

Formation of p-n junction (process)

1) As soon as a p-n junction is formed the majority charge carriers begin to diffuse from regions of high conc. to low conc. regions

2) So electrons from n-region diffuse into p-region & holes from p-region diffuse into n-region



3) When an electron diffuses from n→p, it lea behind an ionised donor (+ve charge) on n-side. This ionised donor is immobile as it is bond ~~by~~ to surrounding atoms.

4) As the electrons continue to diffuse from n a layer of +ve charge on n-side of the junction is developed.

5) Similarly, when a hole diffuses from p→n, it lea behind an ionised acceptor (-ve charge) on p-side which is immobile. As holes continue to diffuse a layer of -ve charge on p-side is developed

6) This space-charge region on either side of the junction together is known as depletion region, as the electrons & holes taking part in the initia movement across the junction depleted the regio of its free charge.

7) Due to +ve charge region on n-side & -ve charge region on p-side of the junction an electric field directed from +ve charge t -ve charge develops.

8) Due to this field, an electron on p-side of junction moves to n-side and a hole on n-side of junction moves to p-side

9) The motion of charge carriers due to

electric field is called drift.
So drift current (opp. in direction to diffusion current) starts.

10) Initially, diffusion current is large and drift current is small.

11) As the diffusion process continues, the space charge regions on either side of the junction extend, & hence the electric field & the drift current.

12) This process continues until diffusion current equals drift current

13) Thus a p-n junction is formed

Potential barrier (V_B)

The electric field developed sets a potential barrier at the junction which opposes the diffusion of majority charge carriers into opposite regions.
The polarity of the potential oppose the diffusion so that a condition of equilibrium exist.
So, n-material is +ve relative to p & vice-versa.

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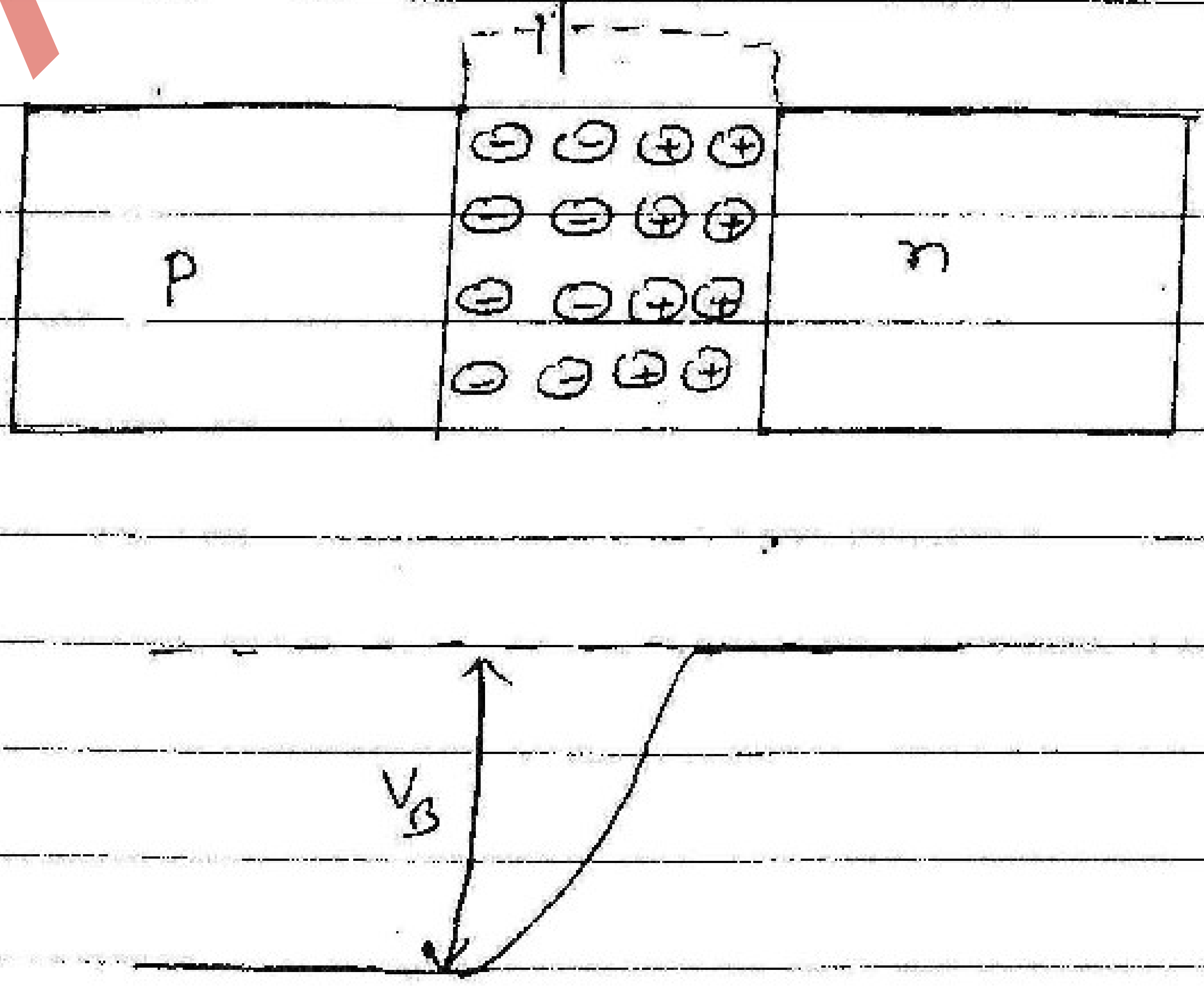
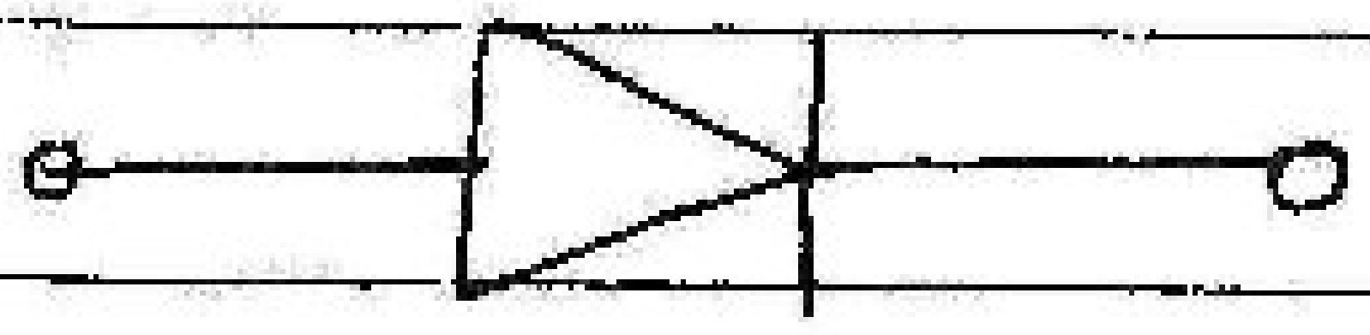
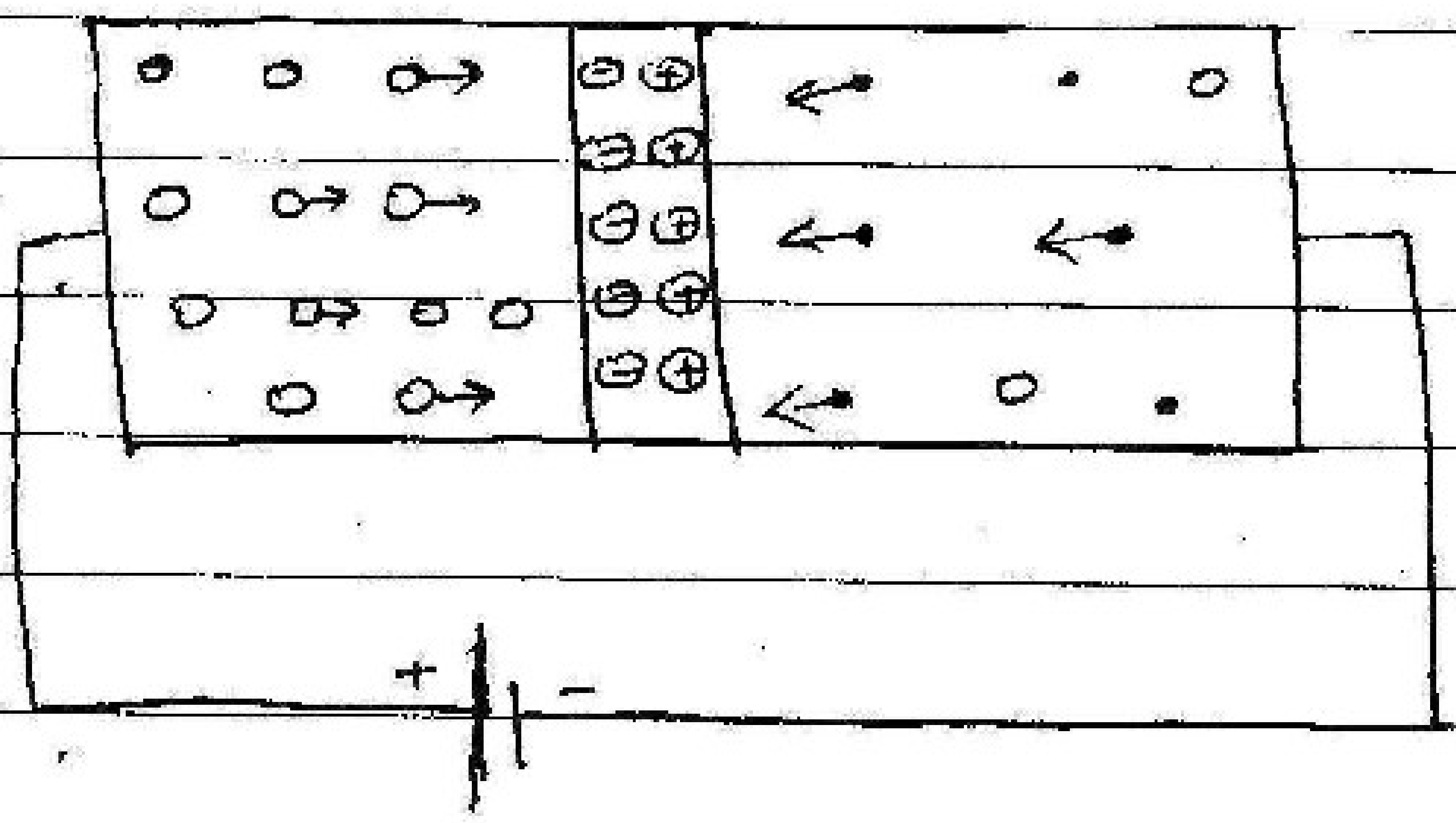


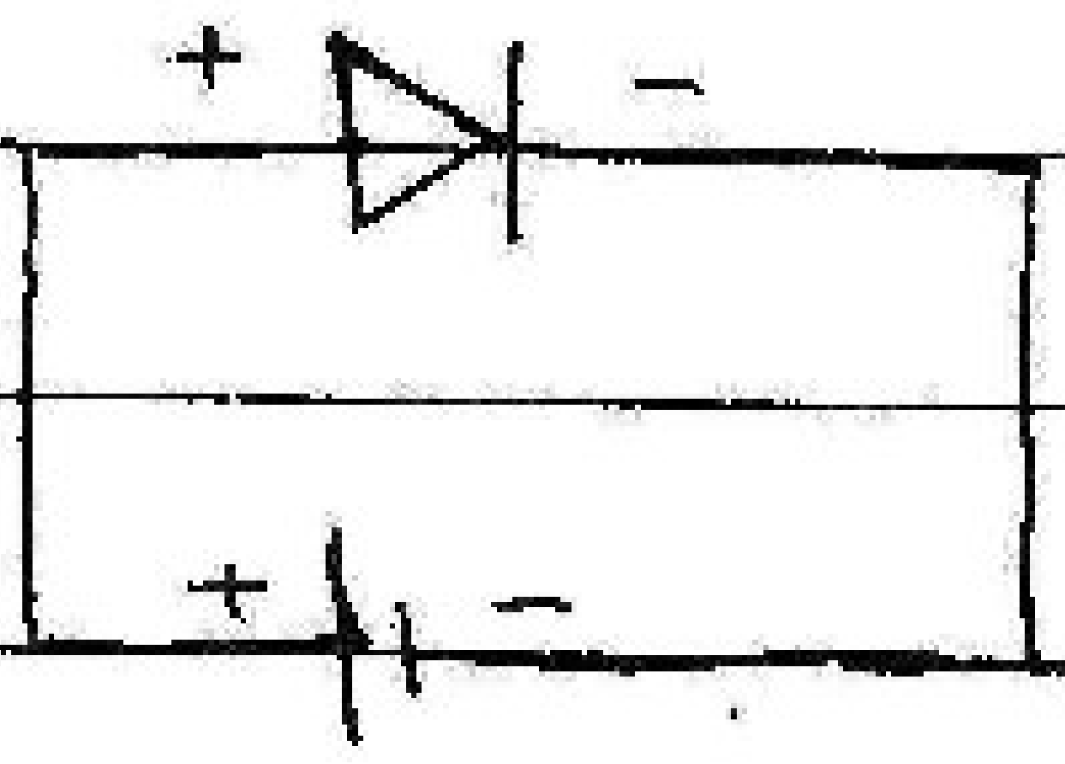
Diagram showing p-n junction at equilibrium & potential across the junction.

Symbol of p-n junction diode

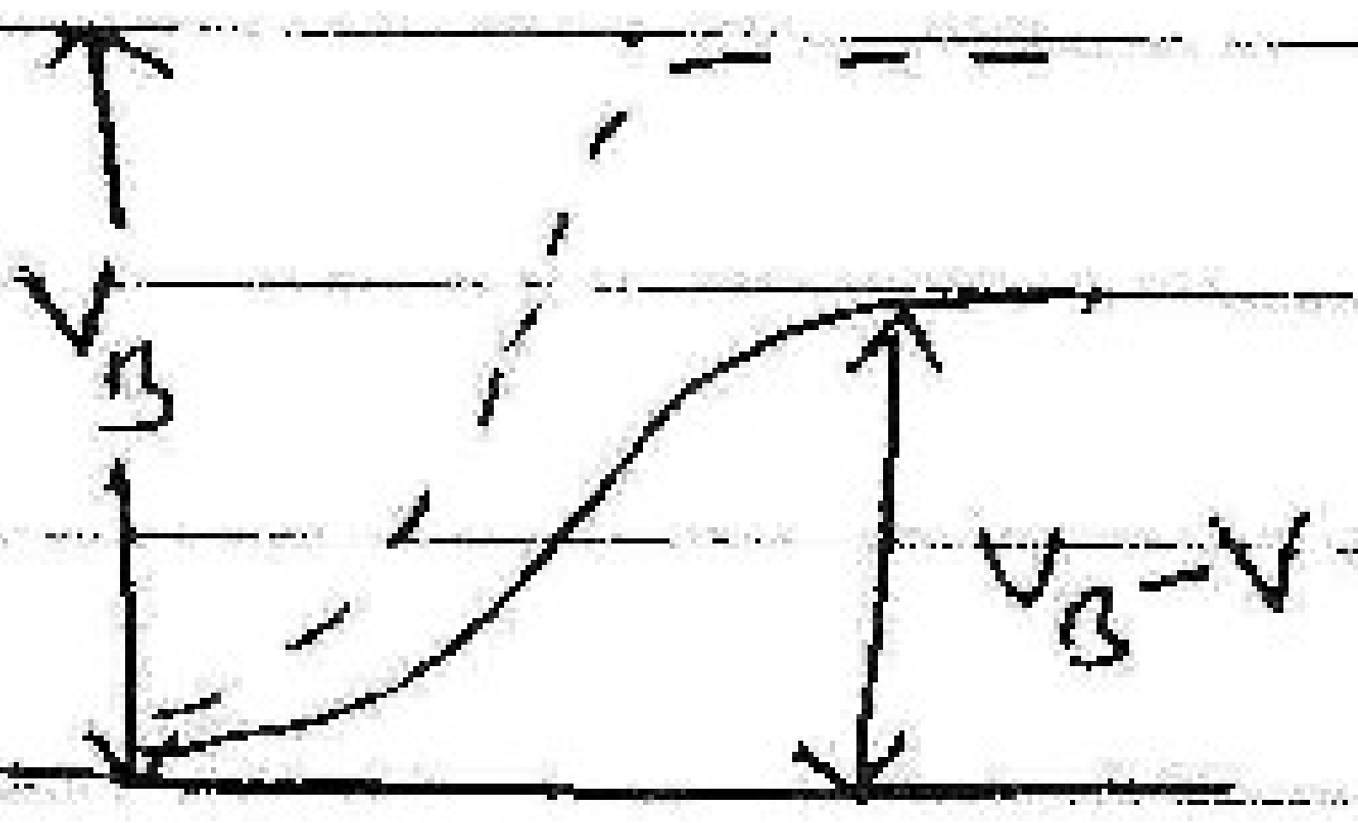


Forward biased p-n junction





- A p-n junction is said to be forward biased if +ve terminal of external battery i connected to p & -ve terminal to n-side of p-n junction.
- The applied voltage drops significantly across the depletion region & negligibly across the p-si & n-side of the junction because the resistance of the depletion region is very high as compare to resistance of p & n-region.
- The direction of applied voltage (V) is opp. to V_B & so the depletion layer width decreases & barrier height is reduced.
- The effective height of barrier is $V_0 - V$



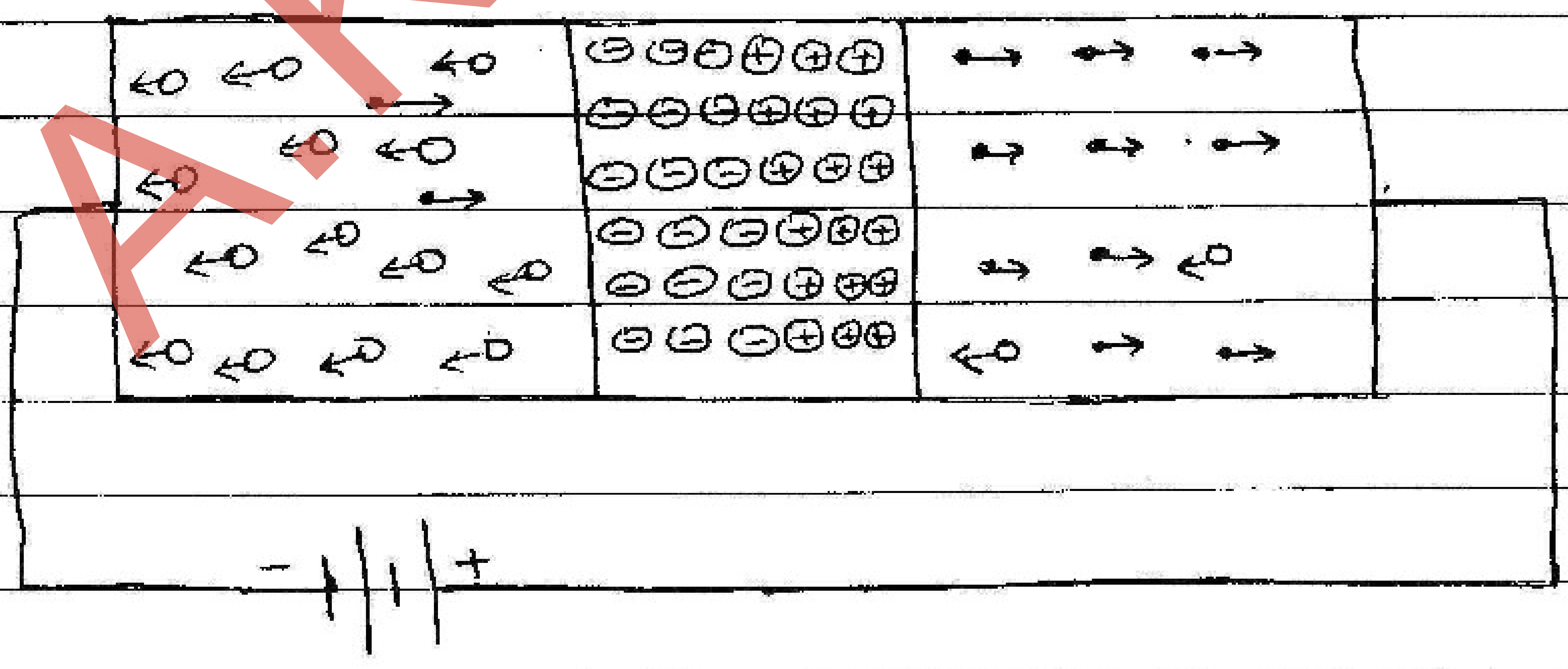
- As soon as battery connection is made, holes are repelled by +ve terminal & electrons are repelled by -ve terminal of battery towards the junction.

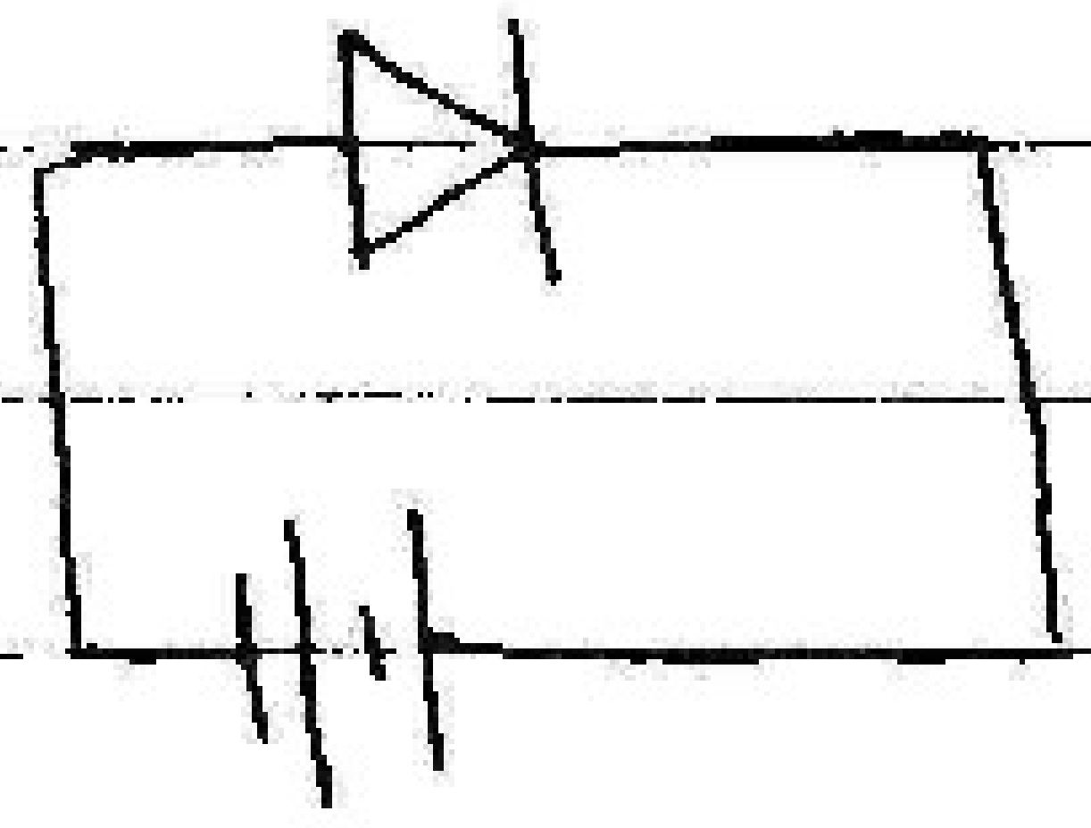
The +ve potential of p-region attracts the electrons from n-region & the -ve potential of n-region attracts holes from p-region. Due to this, the diffusion of majority carriers takes place across the junction.

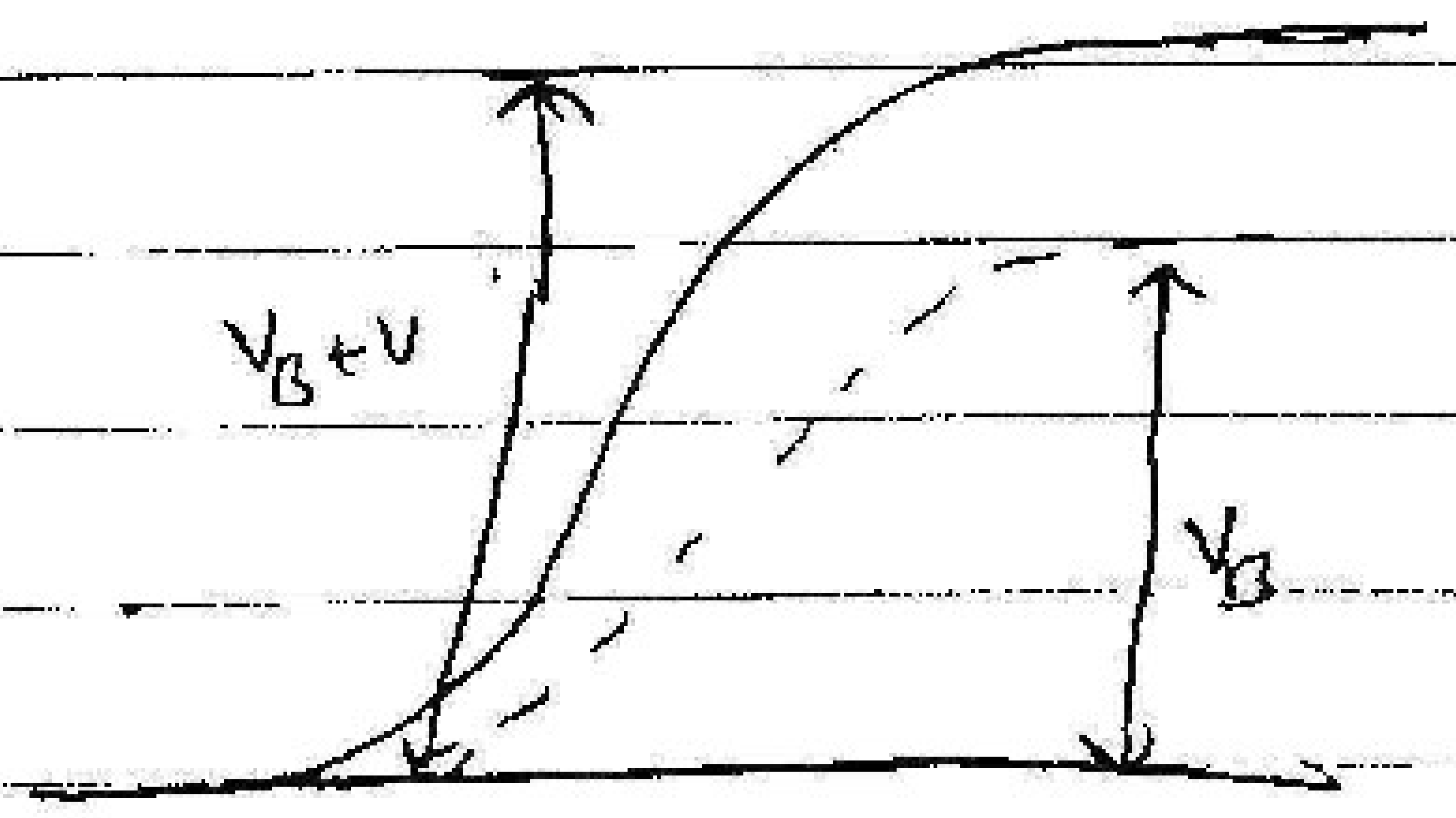
So, an electric current will flow due to migration of majority carriers across the p-n junction which is called forward current.

Since a small increase in forward voltage shows the large increase in forward current, so the resistance of p-n junction is low.

Reverse biased p-n junction



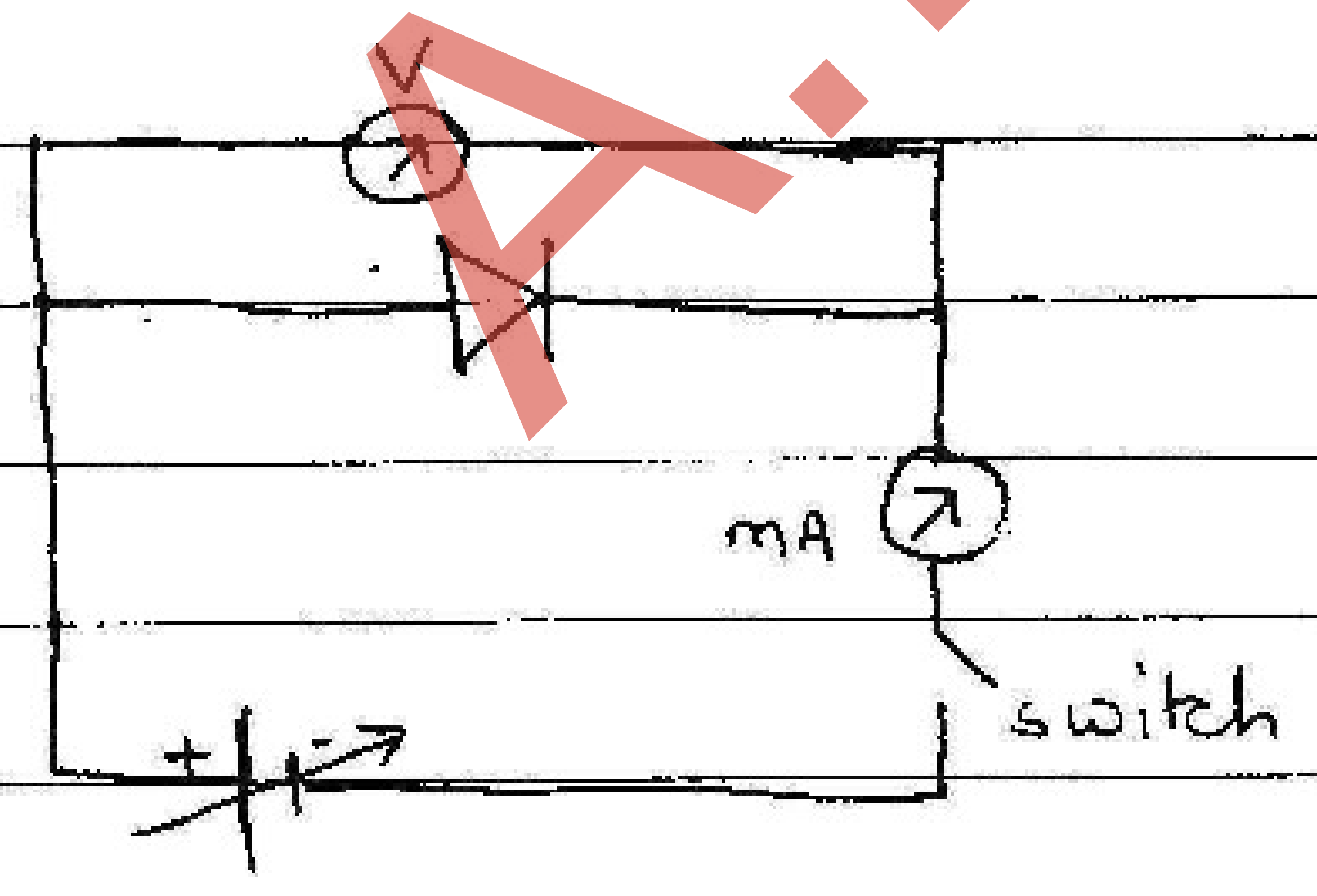




- When p-side of diode is connected to -ve terminal of battery & n-side to +ve terminal, the diode is said to be reverse biased
- During reverse biasing, the width of depletion region increases & barrier potential increases to $V_B + V$
- So, the majority charge carriers can not move across the junction.
- However, a very-very small current may flow (in opp. direction to that of forward current) due to motion of minority carriers.
- Thus in reverse biasing, a negligible current flows due to minority charge carriers known as reverse saturation current.

Characteristics of p-n junction diode

① Forward biased characteristics



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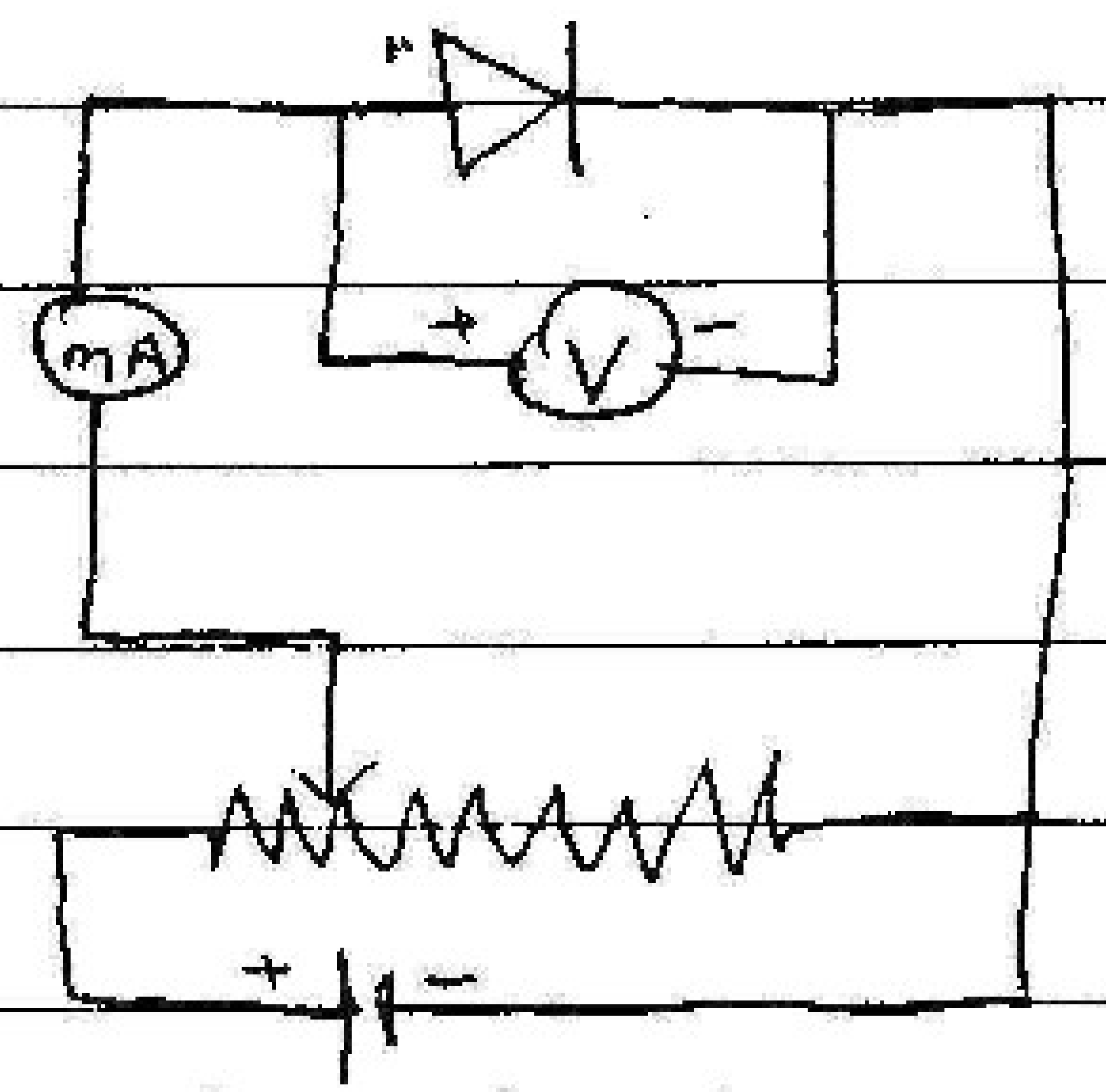
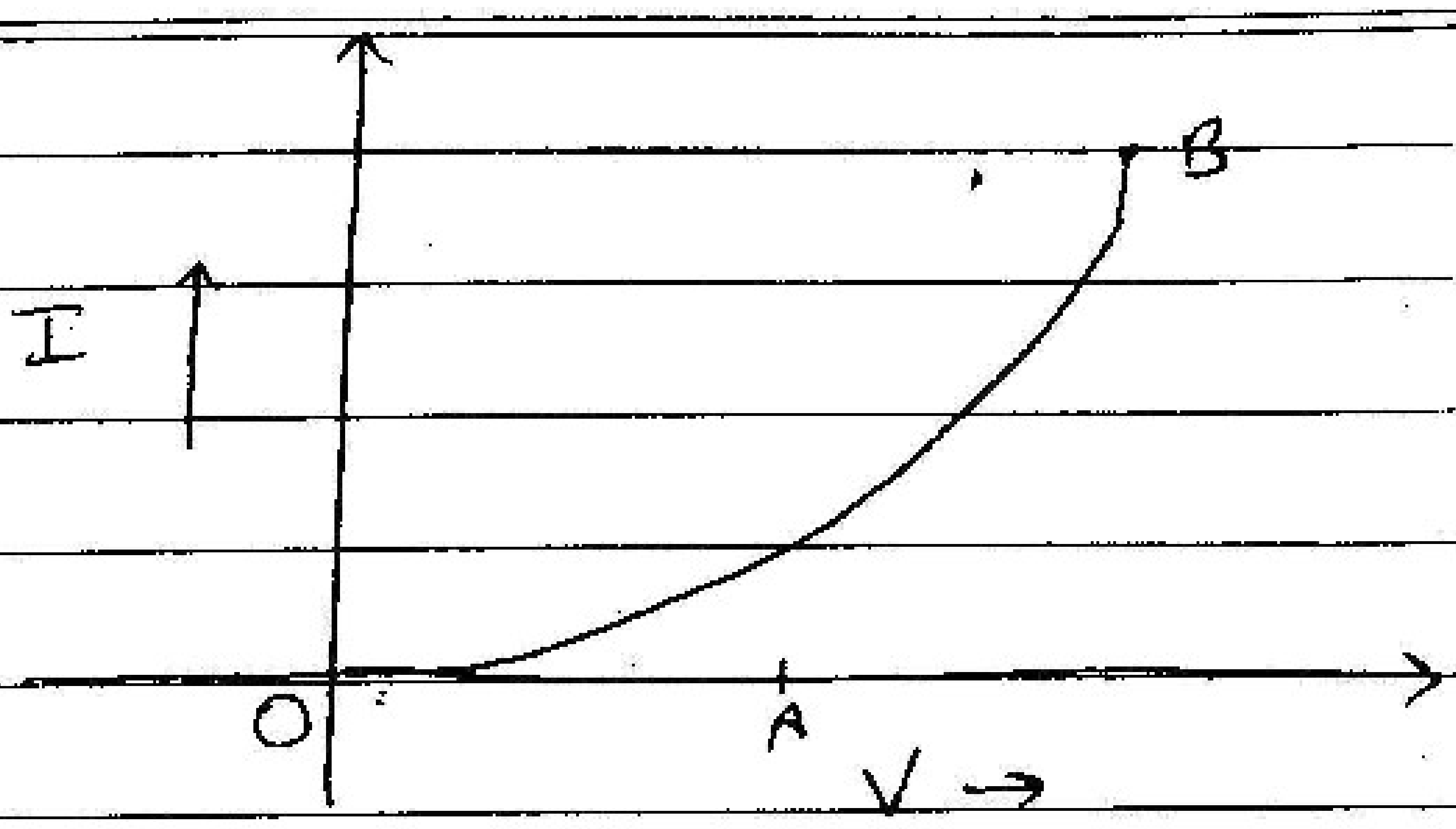


(Pradeep's)

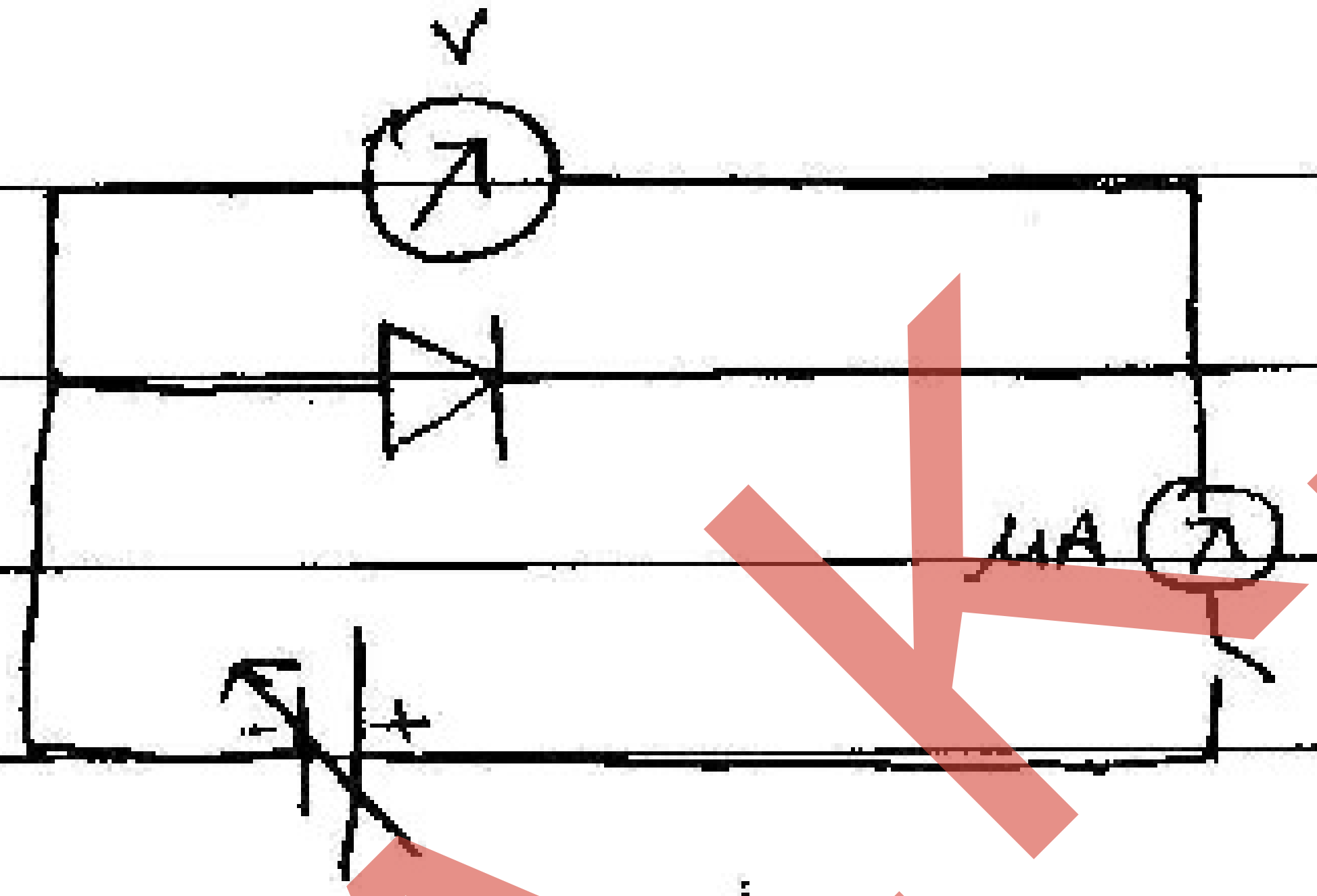
- The battery is connected to the diode through a potentiometer or rheostat so that the applied voltage can be changed.
- For different values of V, value of I is noted & a graph is plotted.



At 1st current increases very slowly. But after a certain voltage called threshold voltage or Knee voltage, the current increases exponentially even for a very small increase in voltage.

At this voltage, diode offers low resistance

② Reverse biased characteristics



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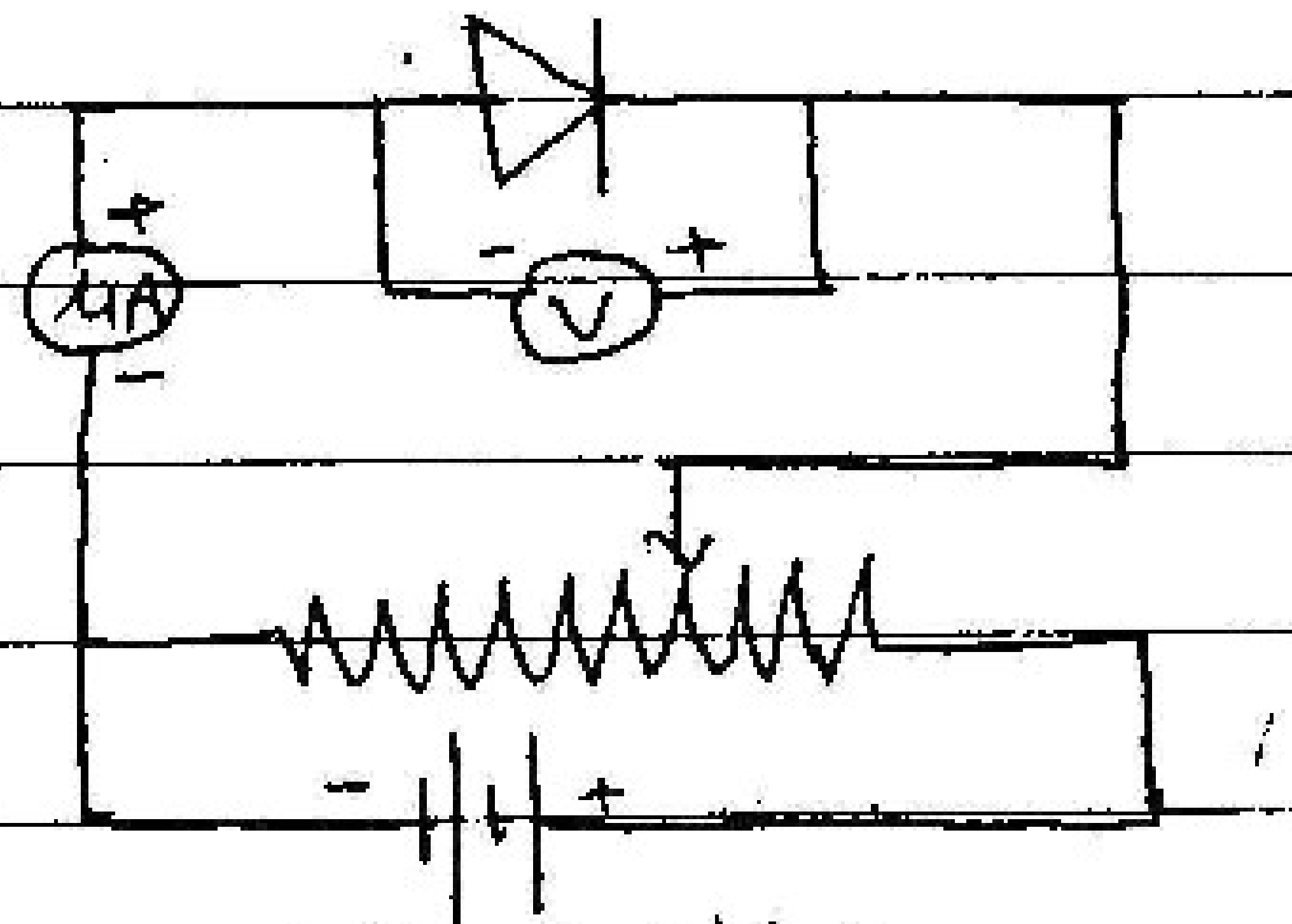
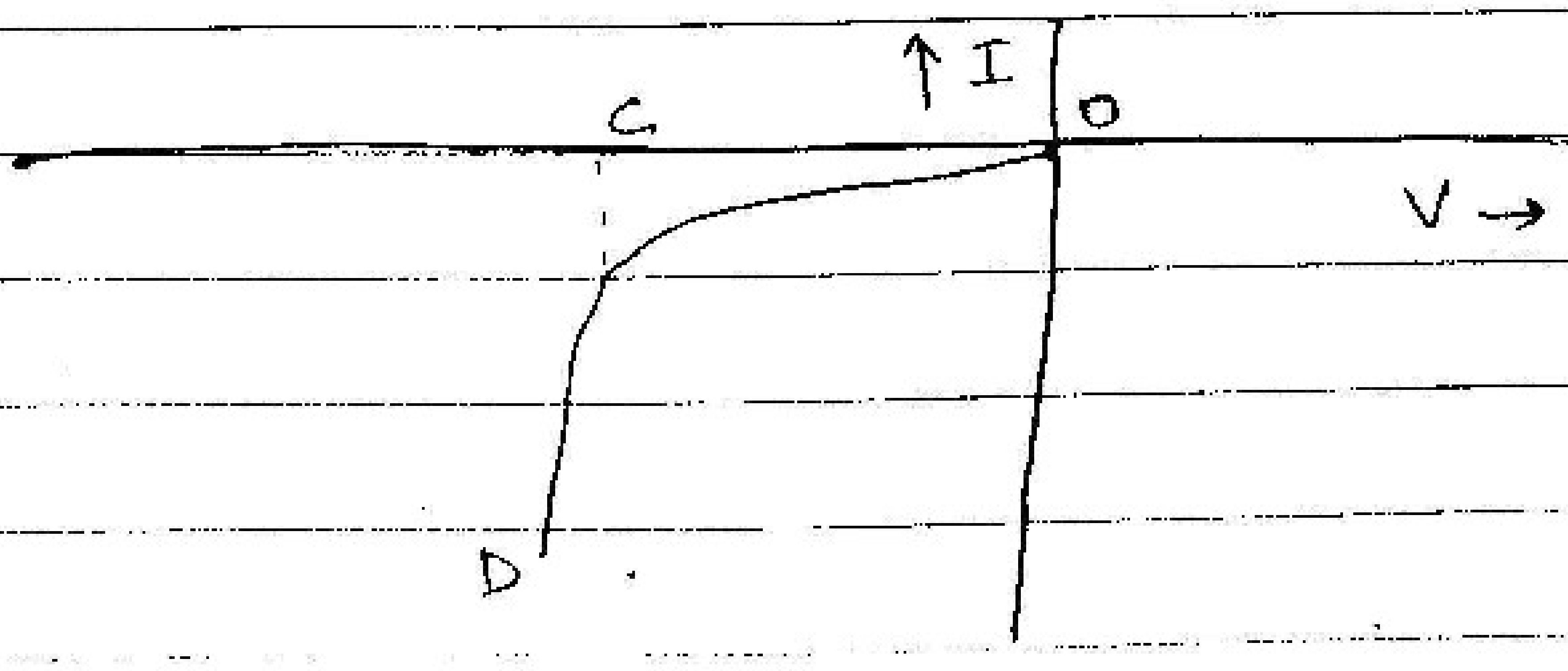


(Pradeep's)

Here micro-ammeter is used as current is very-very small. When V is increased & corresponding values of I measured, the graph is plotted.



It is clear that reverse current is almos constant & hence called reverse saturation current. It implies that diode resistance is very high. As reverse voltage reaches C (called break down voltage) current increases sharply.
[If this current exceeds the rated value of p-n junction, the p-n junction will get damaged]

Dynamic resistance or A.C. resistance of Junction Diode

It is defined as the ratio of small cha in voltage ∆V to a small change in current

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

The value of r_d is low in forward bias & high in reverse bias.

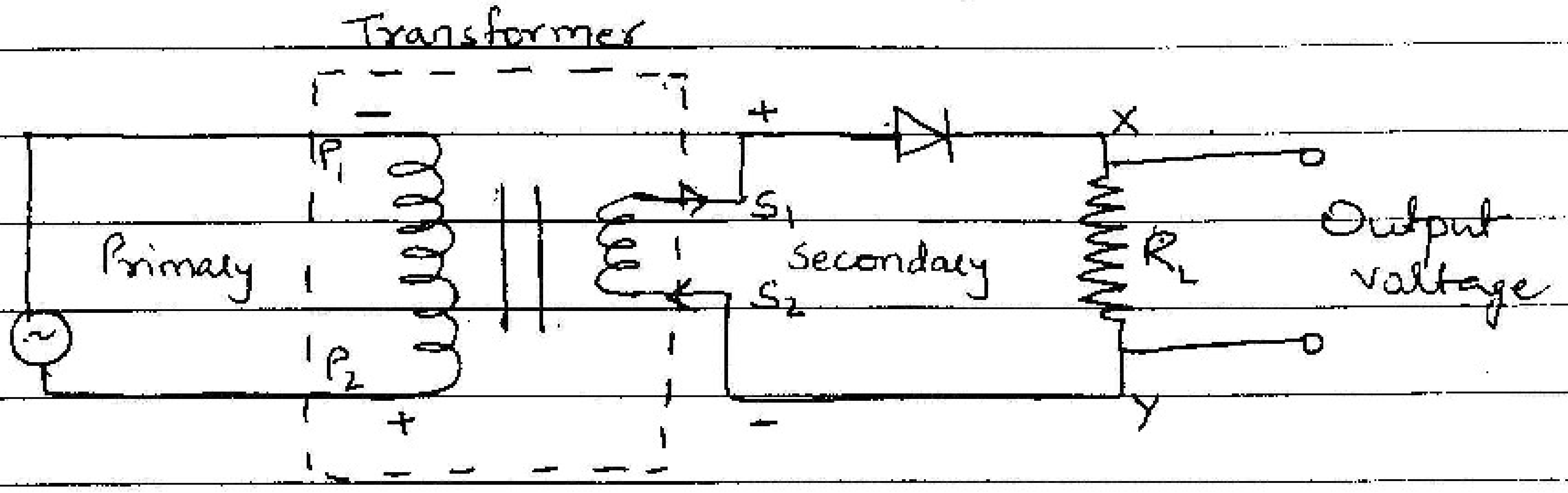
* In forward biase, beyond Knee voltage V varies almost linearly with ∆I. In this region r_d is independent of V.

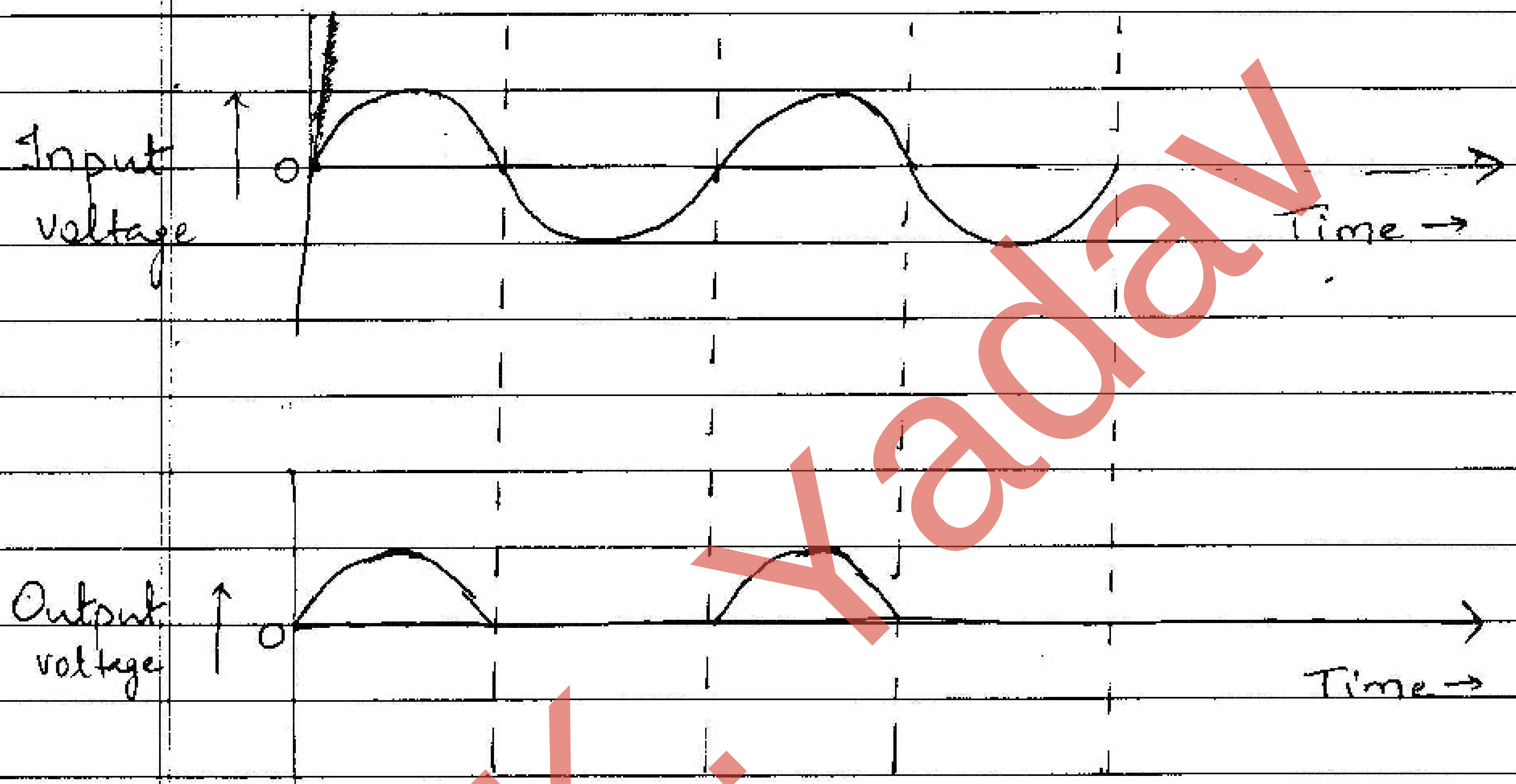
p-n junction diode as rectifier

→ An electronic device which converts a.c or a.v into d.c or d.v is called rectifier.

→ A junction offers low resistance for current to flow when forward biased, but a very high resistance when reverse biased.
It thus allows current in one direction & acts

① p-n junction diode as half wave rectifier





Principle

The resistance of p-n junction becomes low when forward biased & high when reverse biased.

Circuit diagram

1) A.C. to be rectified is connected to primary P_1P_2 of a stepdown transformer
2) S_1S_2 - secondary coil of the step-down transformer S_1 connected to p & S_2 connected to n
3) Output is taken across load resistance R_L.

Working

① During +ve half cycle of input A.C let P_1 is -ve

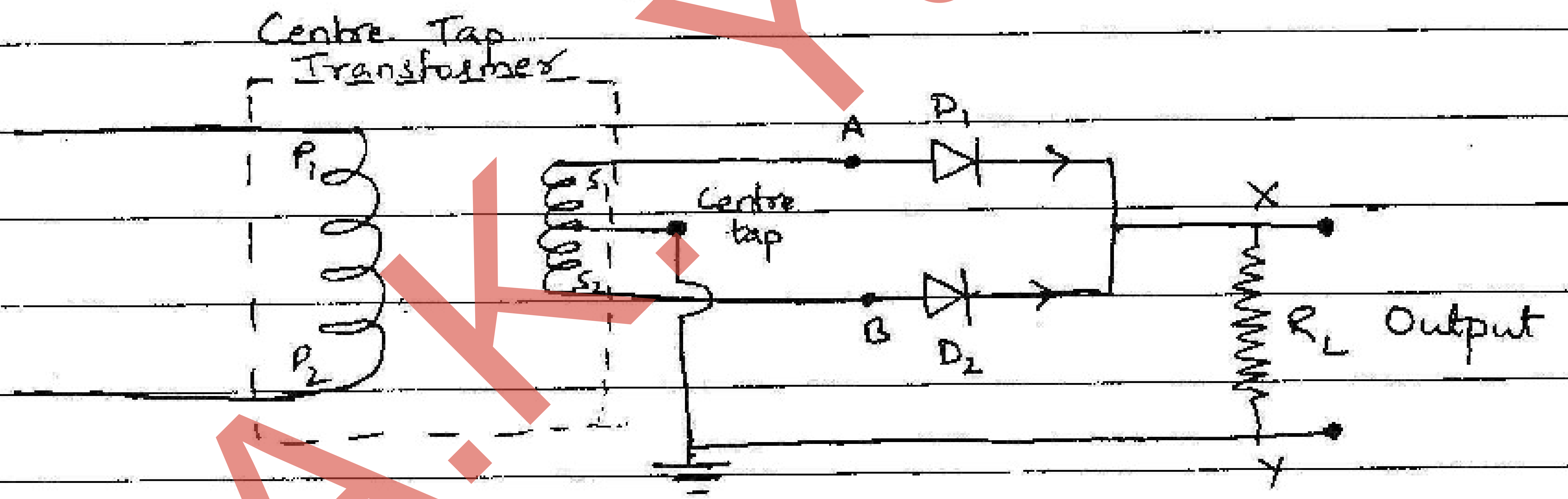
& P_2 is +ve. Due to induction $S_1 \rightarrow$ +ve, $S_2 \rightarrow$ -ve. So, p-n junction is forward biased & we get output across R_L.

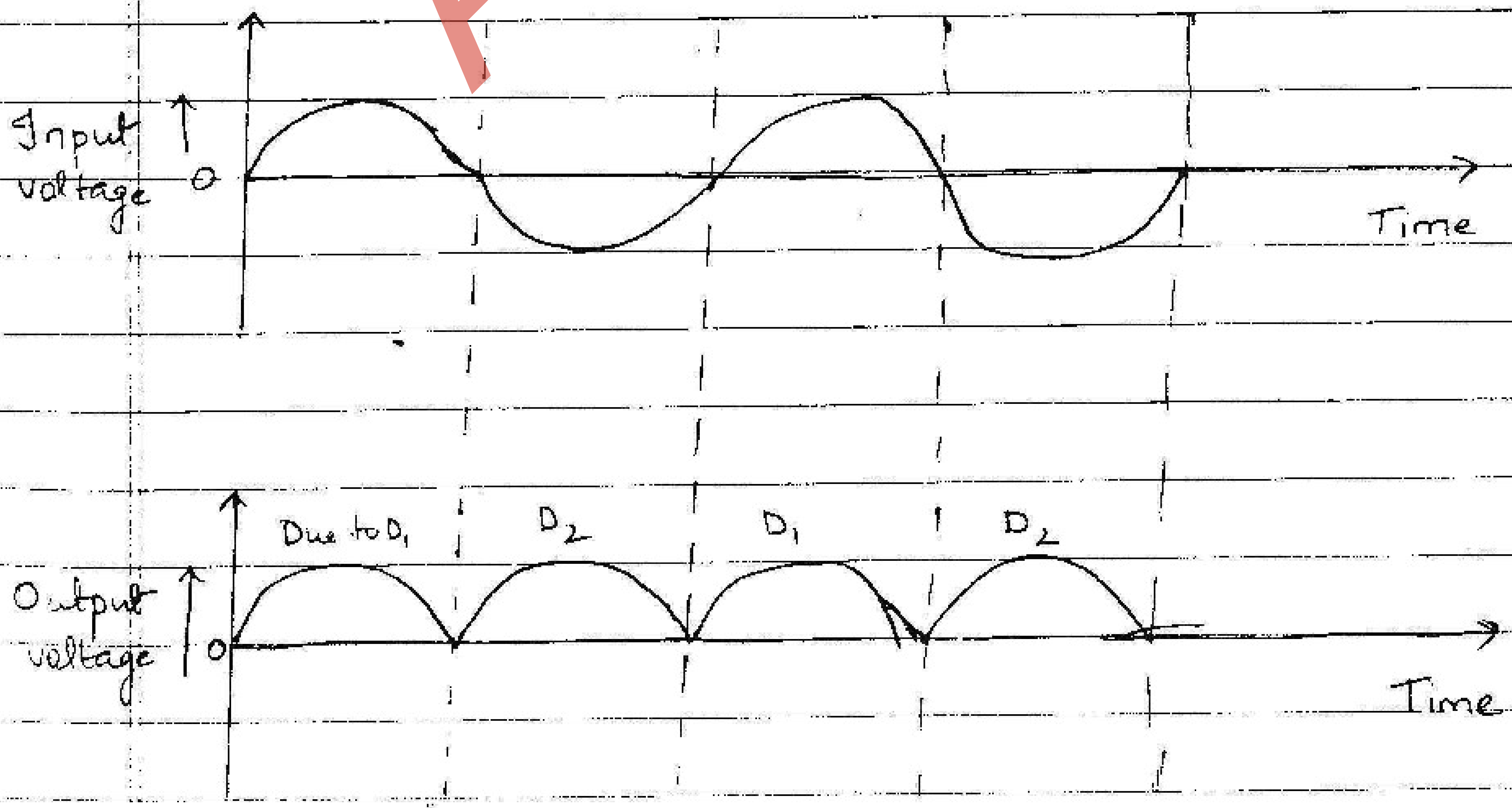
② During -ve half cycle of input A.C.

$P_1 \rightarrow$ +ve, $P_2 \rightarrow$ -ve ; Due to mutual induction $S_1 \rightarrow$ -ve, $S_2 \rightarrow$ +ve, so p-n junction reverse biased It offers high resistance & so no flow of current & so output across R_L.

The complete process is repeated. So we get output corresponding to one half of the wave only. So this process is called half wave rectification.

② full wave rectifier

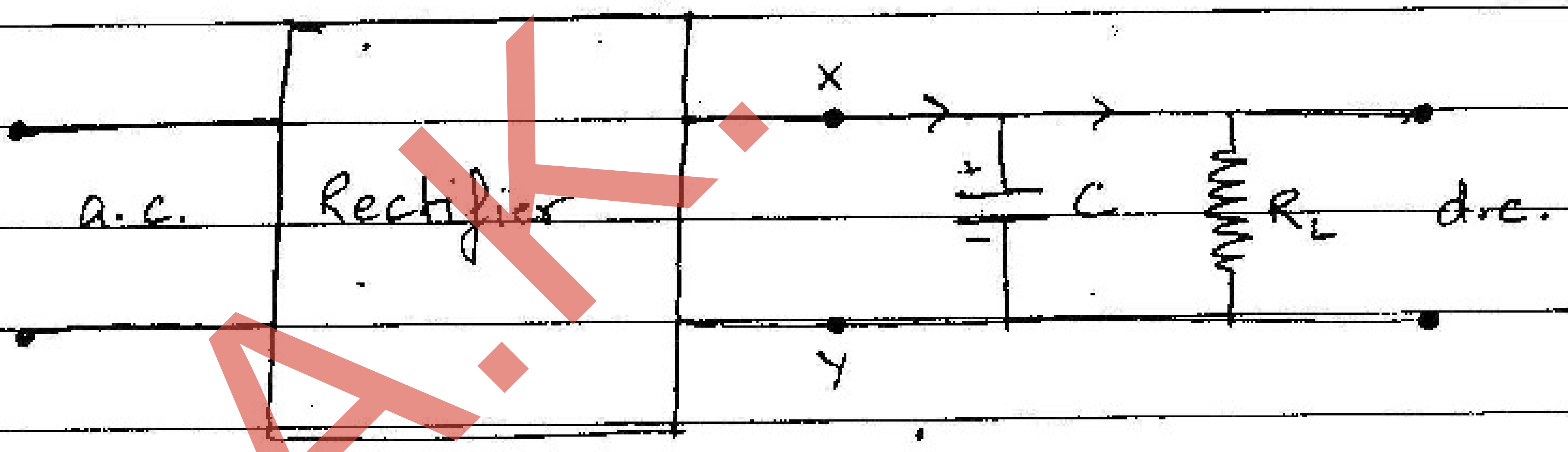




Working

- During +ve half cycle of input A.C., D_1 is forward biased & D_2 is reverse biased. So, forward current flows due to D_1
- During -ve half cycle, D_2 is forward biased & D_1 is reverse biased, so forward current flows due to D_2.
- The output signal is unidirectional (i.e. the current through R_L flows in same direction) but it does not have a steady value
- To get steady value of dc output, a capacitor is connected across the output terminals parallel to R_L.

Since these additional circuits appear to filter out a.c. ripples & give pure d.c. voltage so they are called filters



→ When the voltage across the capacitor is rising, it gets charged.

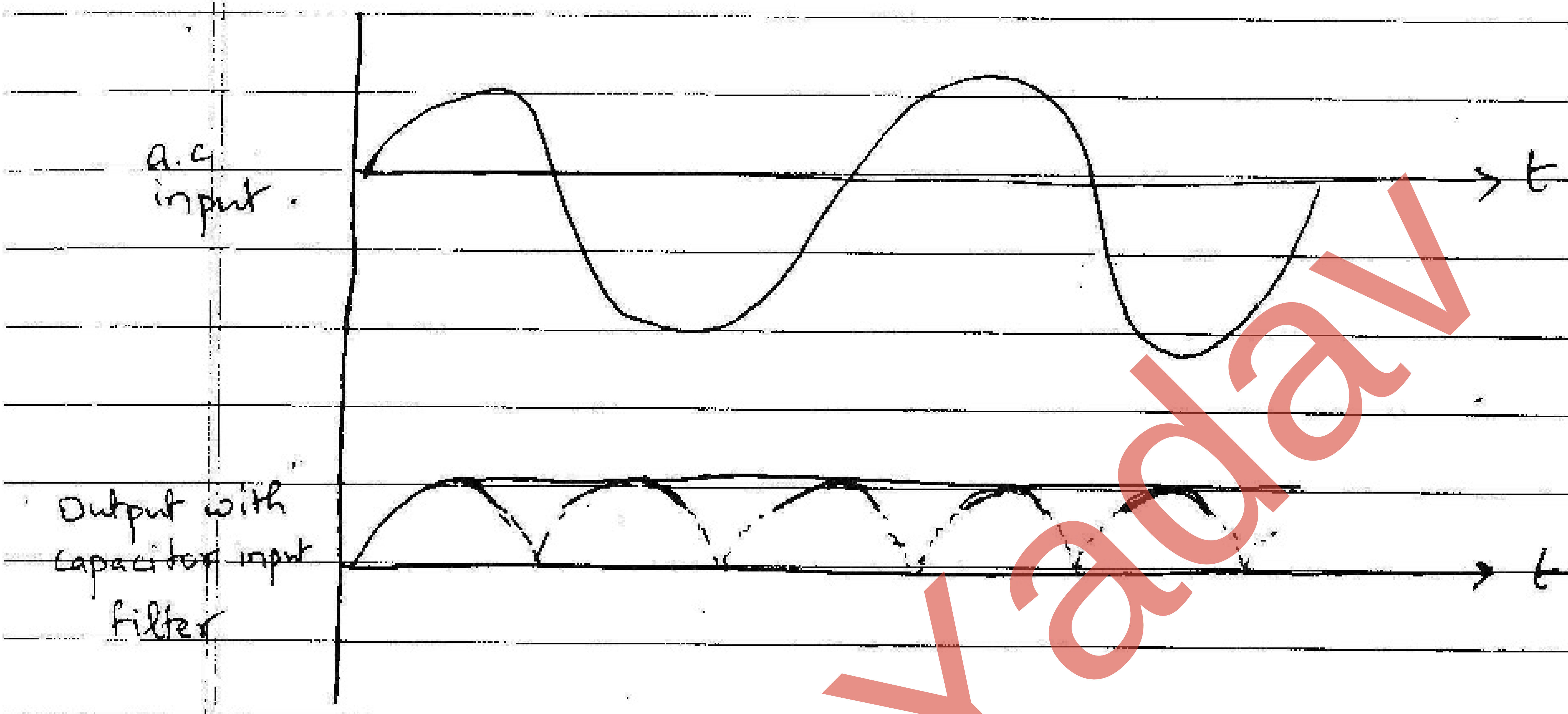
→ If there is no external load, it remains charged to peak voltage of rectified output.

→ When there is load (resistance) it gets discharged through the load & voltage across it begins to fall

→ In next half-cycle, it agains get charged to peak value.

→ The rate of fall of voltage across C is inversely proportional to the product of C & R_L (called time constant)

→ To make time constant large, value of C should be large so capacitor input filters use large capacitors.



The output voltage obtained by using capacitor input filter is nearer to peak voltage of rectified voltage

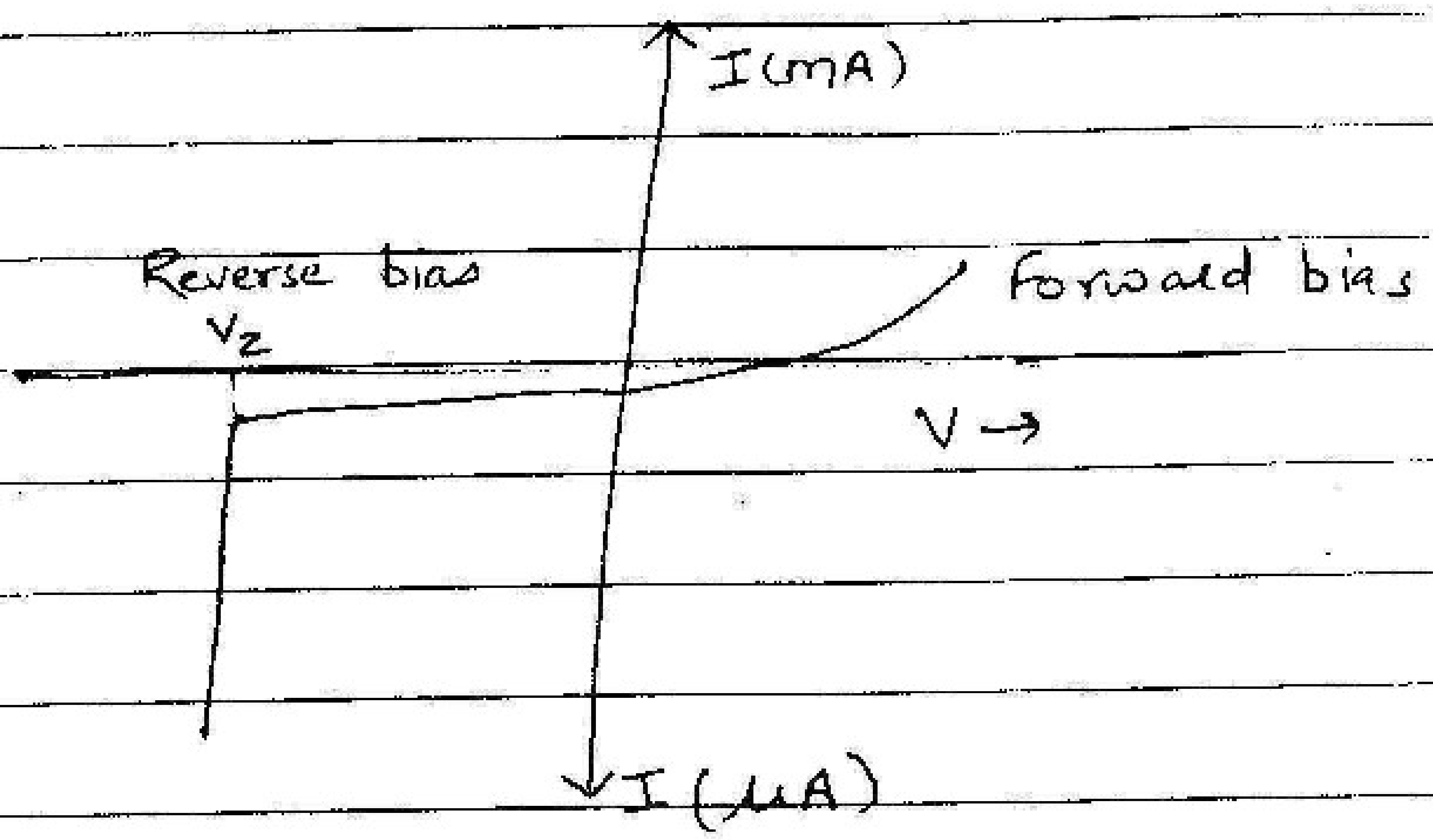
Special purpose p-n junction diodes

① Zener diode (⏚)

(i) It is designed specially to operate under reverse bias in break down region & is used as a voltage regulator

(ii) It is made by heavily doping p-side & n-side of p-n junction.
Due to it the depletion region becomes very thin & the electric field is very high

(iii) The V-I characteristic of Zener diode is shown



from the fig. -

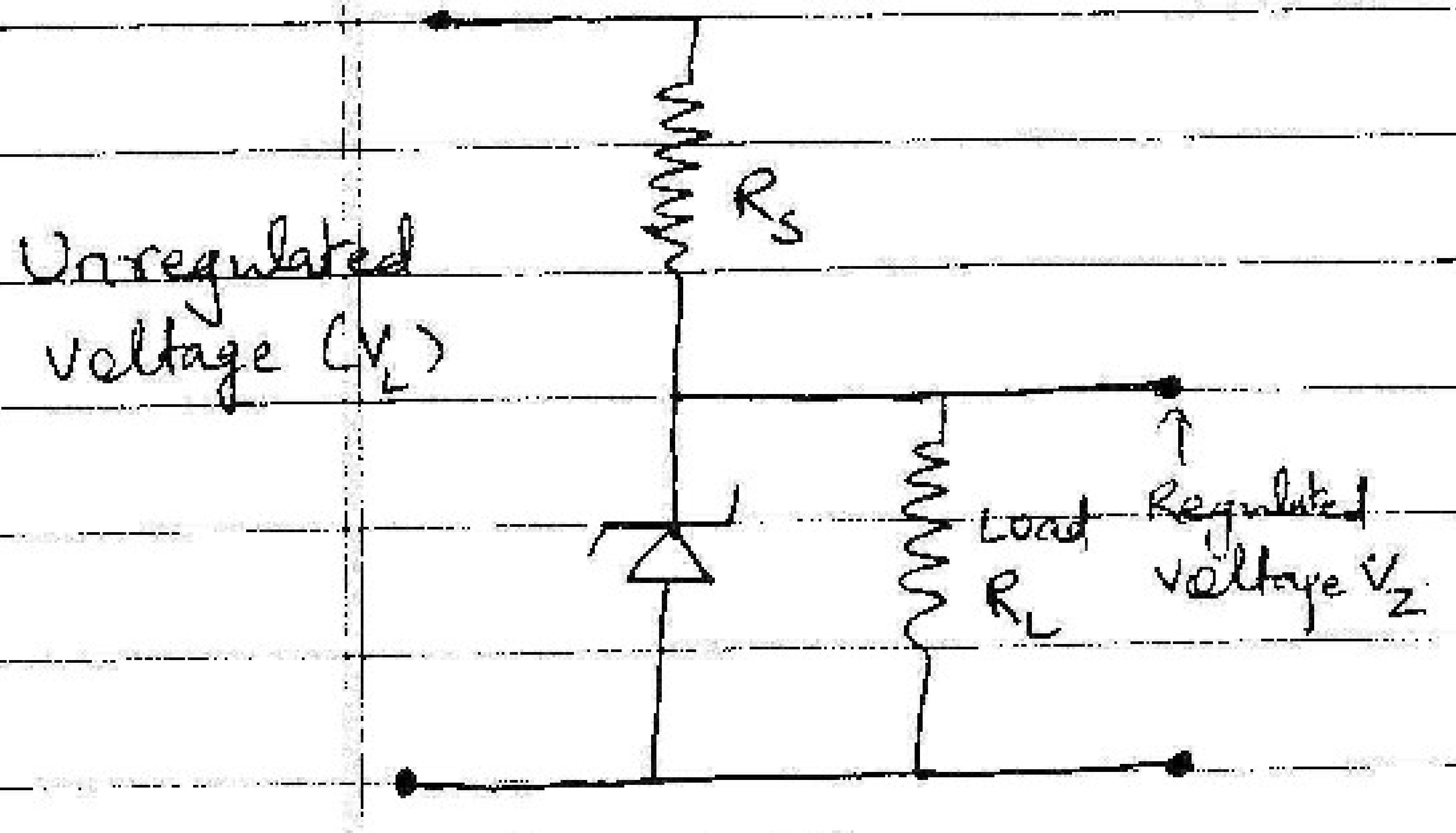
(a) When the applied reverse voltage reaches the breakdown voltage V_Z, there is large change in reverse current

(b) After V_Z, a large change in current can be produced by almost insignificant change in reverse voltage.

i.e. Zener voltage remains constant even though current through Zener diode varies over a wide range

(This property is used for regulating supply voltages)

Zener diode as voltage regulator



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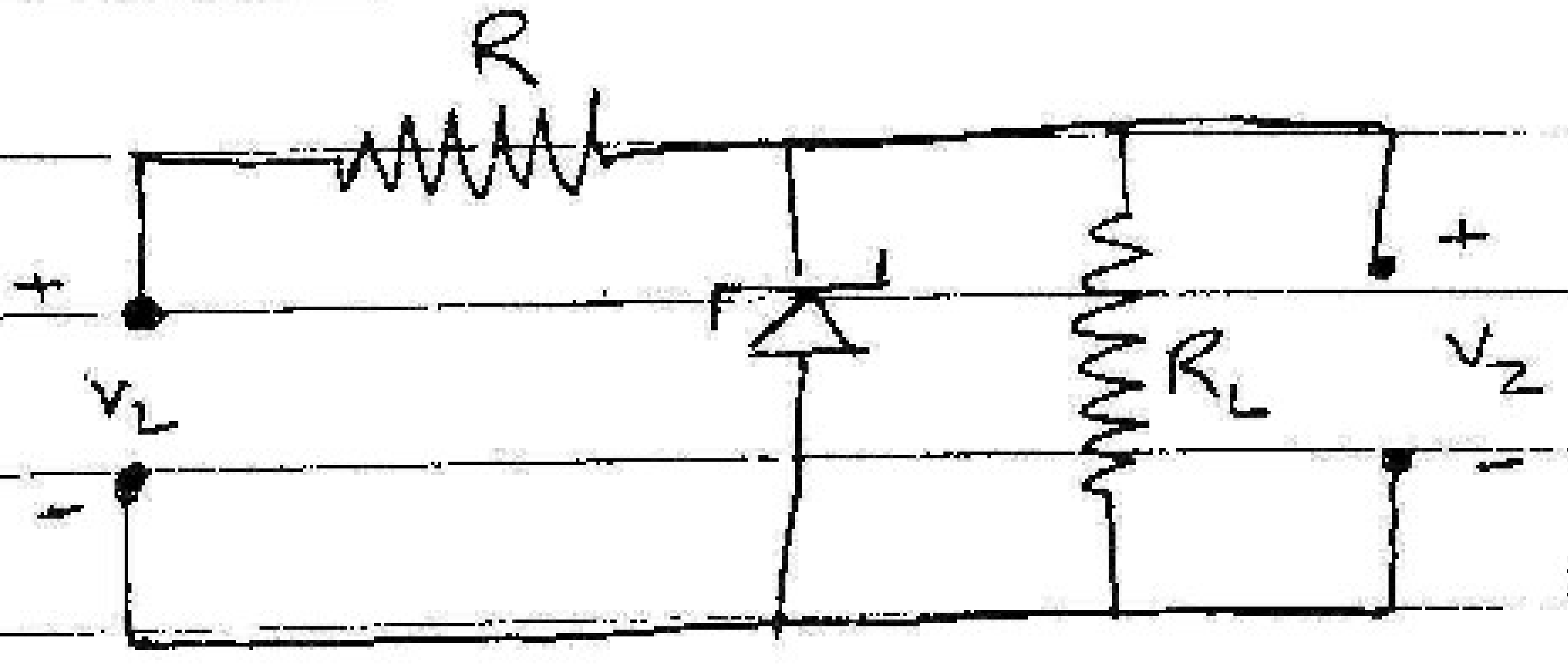


('Pradeep's)

★ When the a.c. input voltage of rectifier fluctuates, its rectified output also fluctuates. To get const dc voltage from

Working

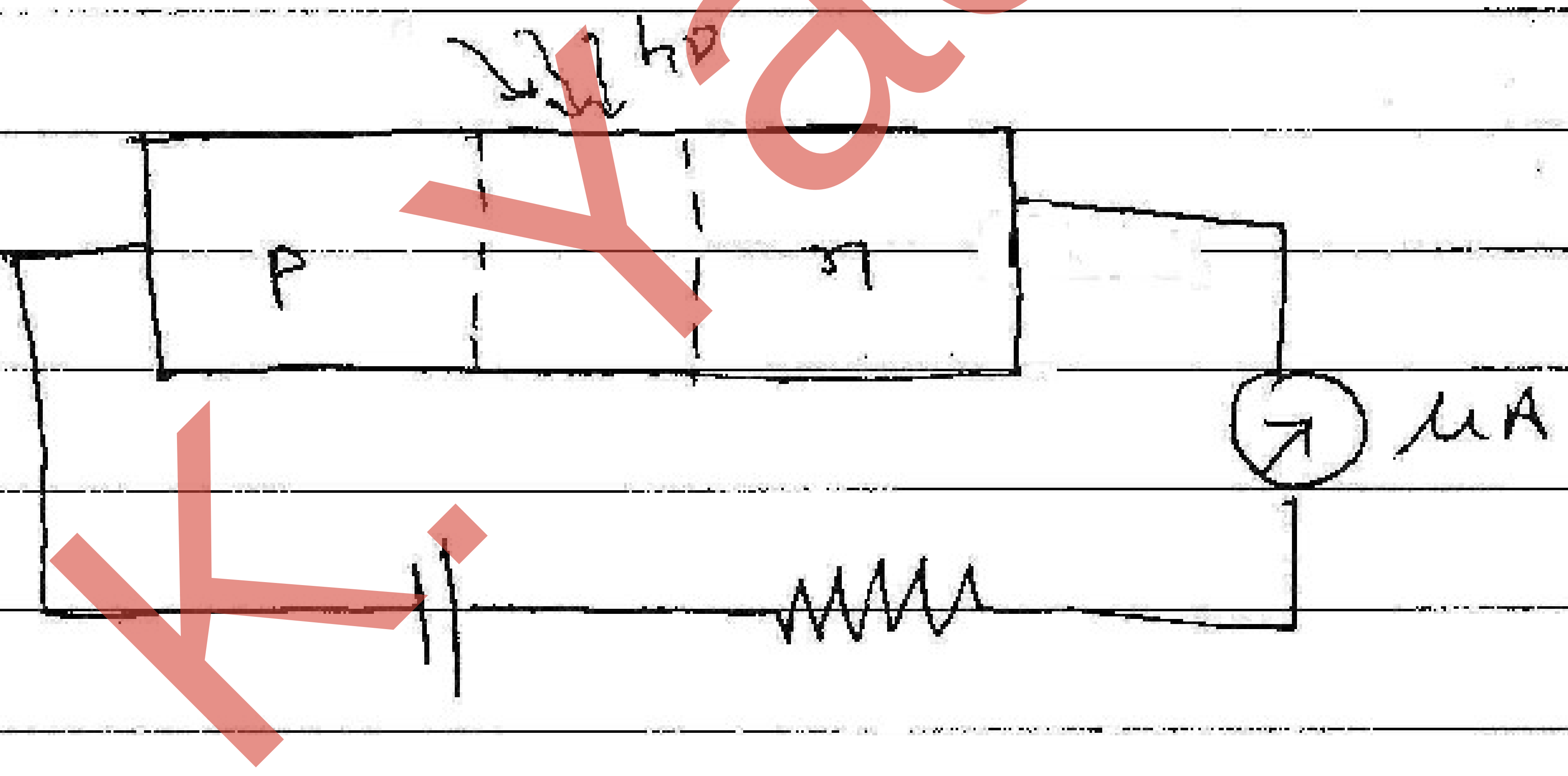
→ When the input d.c. voltage increases beyond a certain limit, the voltage across Zener diode becom constant (= V_Z), but the current through Zener diod circuit rises sharply.

→ Due to this there is increase in voltage across R_s but voltage across Zener diode remains constant.

→ As R_L is connected in parallel so voltage across R_L remains same as V_Z.

→ So, the output voltage remains constant.

② Photodiode



i) It is a reverse biased p-n junction made from a photosensitive semiconductor

ii) When light of appropriate frequency (the energy associated with incident photon should be greater than the energy gap in the semi-conductor so that electrons can pass from VB to CB) is ____ incident on the junction, additional holes & electrons are created near the junction due to breaking of covalent bonds.

iii). These light generated minority carriers cross the junction & contribute to reverse current.

iv) So, current in the circuit increases.

v) This current called photoconductive varies linearly with incident light intensity.

Use of photodiode

1) In photodetector to detect optical signals (As it is easier to observe change in current with change in intensity)
2) Reading of computers, punch cards
3) light operated switches

③ Light emitting diode (LED)

→ It is a photoelectronic device which converts electrical energy into light energy.
→ It is a heavily doped p-n junction diode which emits spontaneous radiation in forward biasing.

Working

a) When the diode is forward biased electrons are sent from n→p & holes from p→n.
b) At the junction boundary the conc. of minority carriers increases as compared to equilibrium conc. (no bias case).
c) So, at junction boundary, excess minority carriers are there which combine with majority carriers near the junction.
d) Due to this combination energy is released in form of photons [Photons of energy equal to energy gap are emitted]
e) When forward current is small, intensity of emitted light is small.
f) As forward current increases, the intensity of light increases & reaches a max.

* On further increasing of current, intensity decreases.

g) LEDs are biased such that light emitting efficiency is max.

☆ In case of 'Si' & 'Ge' diodes, the energy release is infra-red radiation.
In case of GaAs or InP, the energy released is visible light & so is called LED.

Use – in remote control, burglar alarm system, calculators, optical comminucation.

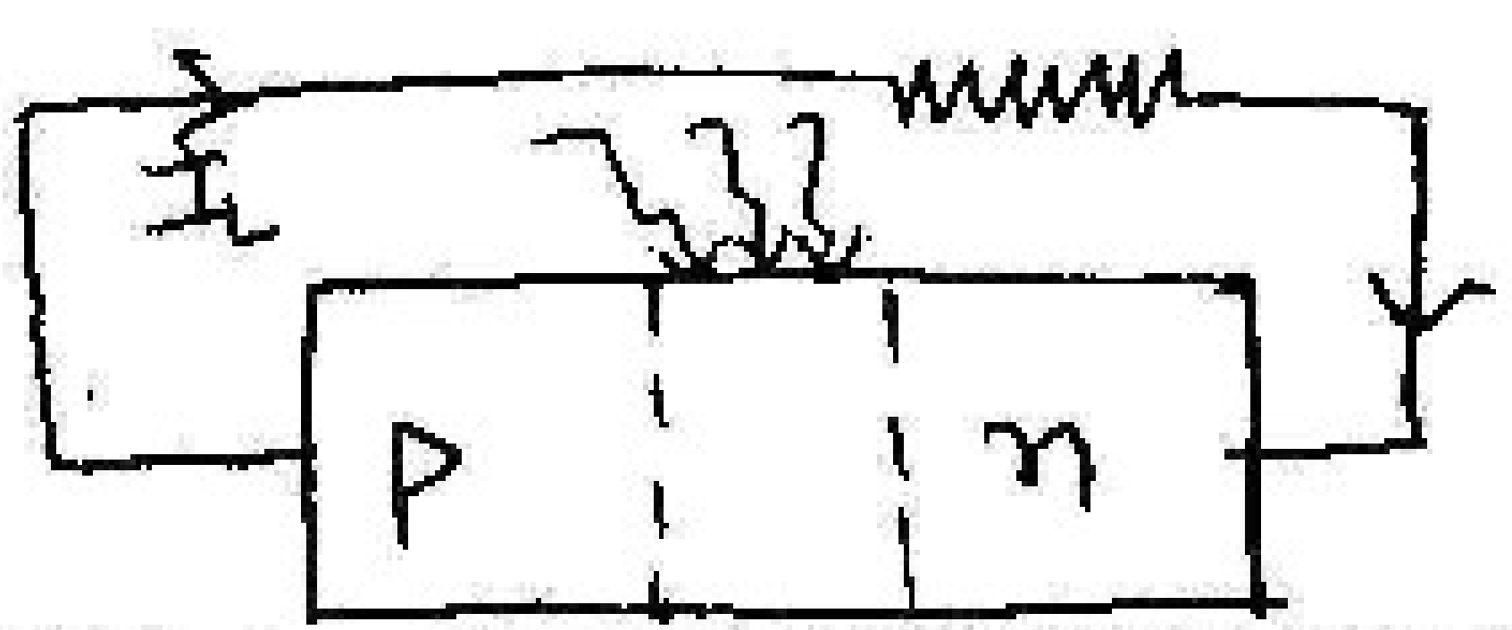
Advantages of LED over incandescent lamps

i) Low operational voltage, less power
ii) Fast action, no warm up time
iii) Bandwidth of emitted light is nearly monochromat
iv) Fast on-off switching capability
v) Long life.

④ Solar cell

- It is a p-n junction which generates emf when solar radiation fall on it.
- It works on the same principle as the photodiode except no external bias is applied & the junction area is large (for more solar radiation & more power.

Construction



Working

(a) generation → electron - hole pairs are generated due to light (with $h\nu > E_g$) in the depletion region

(b) Separation → separation of electrons & holes due to electric field of depletion region.
Electrons are swept to n-side & holes to p-side.

(c) collection → the electrons reaching n-side are collected by front contact & holes reaching p-side are collected by back contact.

Thus p-side becomes +ve & n-side becomes -ve giving rise to photovoltage.

When an external load is connected a photocurrent I_L flows through load.

* Semi-conductors with band gap 1.5 eV are ideal material for solar cell

* Imp. criteria for selection of material for solar cell are -

(a) band gap (1-1.8 eV)
(b) high optical absorption
(c) electrical conductivity
(d) cost.

* Any light with photon energy greater than E_g can be used for solar cells.

* Solar cells are made of → Si, GaAs, CdTe

✡ Width of depletion layer & magnitude of potential barrier depend on doping conc. on the 2 sides of p-n junction.

→ If doping conc. in n-type & p-type semiconduct forming p-n junction is small, the diffusing electrons & holes move large distances across the junction before suffering collision with another hol or electron.

Due to this, the width of p-n junction is large & junction field is small.

→ Opposite if doping conc. is high/large.

✡ If width of depletion region, $d = 10^{-6}$ m

barrier electric field $E = \frac{V}{d} = \frac{0.7 \text{ (for Si)}}{10^{-6}} \approx 7\times10^{5}\ \text{V m}^{-1}$
$\searrow$ very high