Semiconductor Electronics

Semiconductor electronics is a branch of physics, that studies materials like silicon, which control electric current flow for making electronic devices like transistors and microchips used in computers, smartphones etc.

classification of solids on the basis of conductivity

On the basis electrical conductivity σ or resistivity ρ ($\rho = \frac{1}{\sigma}$), the solids are classified as

(i) Metals: Their resistivity is very low or conductivity is high.

$\rho \rightarrow 10^{-2} - 10^{-8}\ \Omega m$

$\sigma \rightarrow 10^{2} - 10^{8}\ S m^{-1}$

$S m^{-1} \rightarrow$ Siemens/meter (unit of σ)

e.g. all metals

(ii) Semiconductors: Their resistivity or conductivity intermediate to metals and insulators.

$\rho \rightarrow 10^{-5} - 10^{6}\ \Omega m$

$\sigma \rightarrow 10^{5} - 10^{-6}\ S m^{-1}$

e.g germanium (Ge), silicon (Si) etc.

(iii) Insulators: They have high resistivity or low conductivity.

$\rho \rightarrow 10^{11} - 10^{19}\ \Omega m$

$\sigma \rightarrow 10^{-11} - 10^{-19}\ S m^{-1}$

e.g wood, rubber, mica etc.

Types of semiconductors on the basis of their composition

1. Elemental Semiconductors These are pure elements mainly from group IV of periodic table.

Two primary elemental semiconductors are
(i) Silicon (Si) → Most widely used due to its abundance and stability.
(ii) Germanium (Ge) → Less common today due to Silicon's superior properties at high temperature

2. <u>Compound Semiconductors</u>: Made by two or more elements (usually group III-V or II-IV)
e.g. <u>Gallium Arsenide (GaAs)</u> → Used in radio frequency and microwave technologies.
<u>Indium Phosphide (InP)</u> → Used in fibre optics communications.
<u>Cadmium Sulfied (CdS)</u> → Used in optoelectronics

3. <u>Alloy Semiconductors</u>:
- Aluminium Gallium Arsenide (AlGaAs)
- Silicon Germanium (SiGe)

4. <u>Organic Semiconductors</u> → Based on organic compounds and polymers.
e.g Pentacene and Polyaniline

Energy Bands in solids

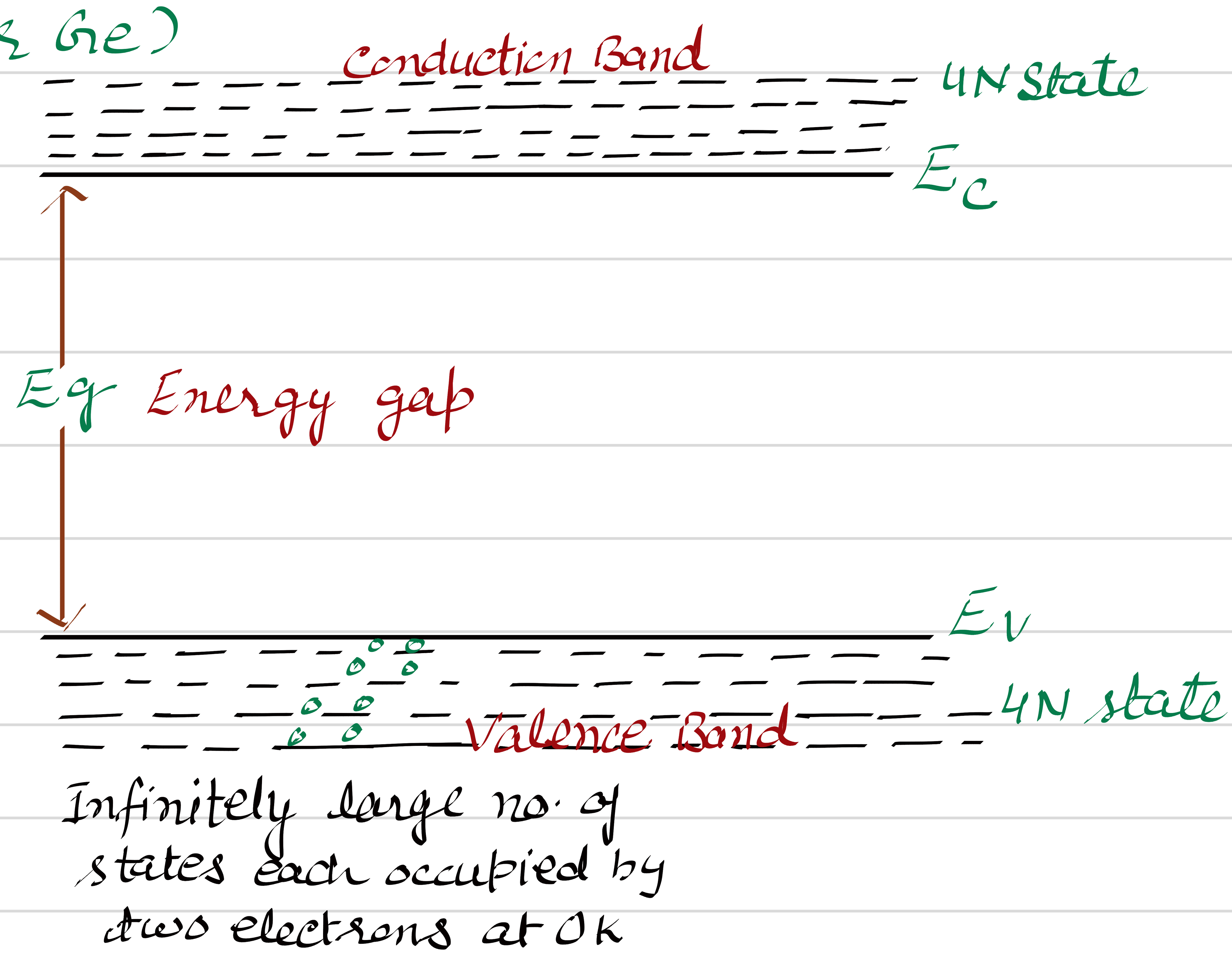
<u>Energy Band</u>: In a crystal due to interatomic interaction valence electrons of one atom are shared by more than one atom in the crystal. Now splitting of energy levels takes place. The collection of these closely spaced energy levels is called an energy band.

Valence Band: This energy band contains valence electrons. This band may be partially or completely filled with electron but never be empty.

Conduction Band: This band contains conduction electrons. This band is either empty or partially filled with electrons.
Electrons present in this band take part in the conduction of current.

Forbidden Band: This band is completely empty. The minimum energy required to shift an electron from valence band to conduction band is called band gap (E_g)

Energy Band positions in a Semiconductor at 0 K.
(For Si or Ge)

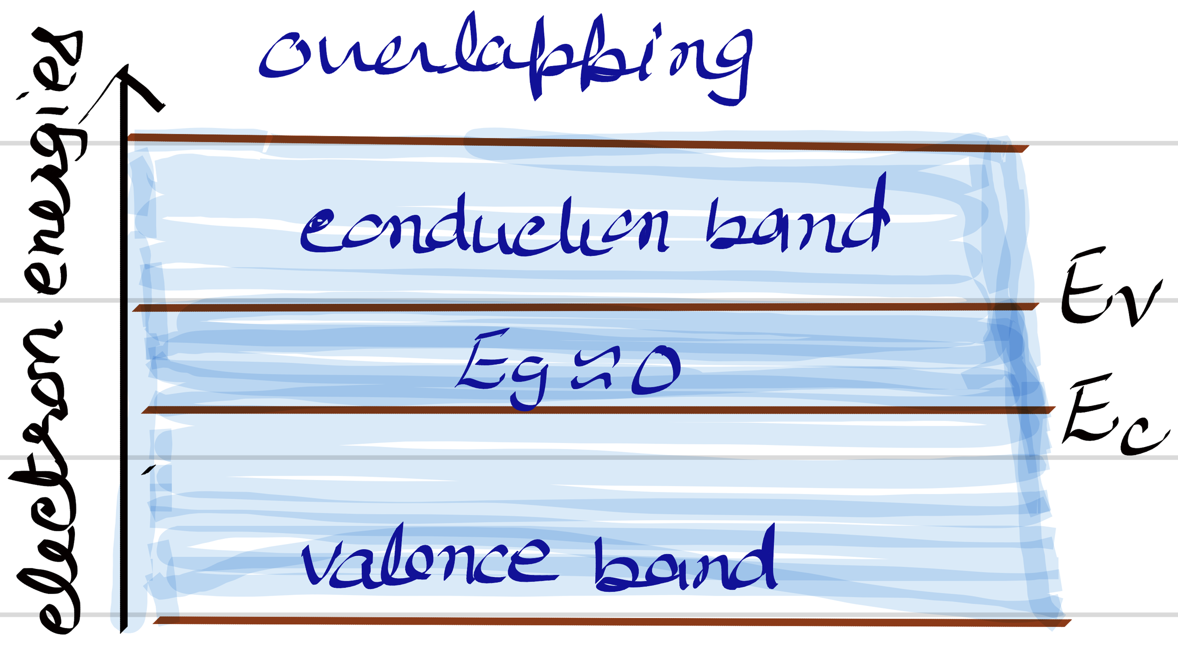


- Let Si or Ge crystal containing N atoms.
- Si, atomic no. 14
  $1s^2, 2s^2, 2p^6, 3s^2, 3p^2$
  4 valence electrons in the 3rd shell : $3s^2, 3p^2$
- Ge, atomic no. 32
  $1s^2, 2s^2, 2p^6, 3s^2, 3p^6, 3d^{10}, 4s^2, 4p^2$
  4 valence electrons in the 4th shell : $4s^2, 4p^2$
- For both no. of electrons in outermost orbit $= 2+2 = 4$
- Hence total no. of outer electrons $= 4N$
- Maximum possible electrons in the outer orbit $= 8$ (2s+6p)
- So for 4N valence electrons there are 8N available energy states
- Energy bands of these 8N states is split apart into two, separated by energy gap(E_g).
- Lower band is valence band and upper band is conduction band.
- $E_c \rightarrow$ lowest energy level in conduction band
  $E_v \rightarrow$ highest energy level in valence band.
- Gap b/w E_c and E_v is called Energy band gap (Energy gap E_g)

Classification of solids on the basis of Energy Bands

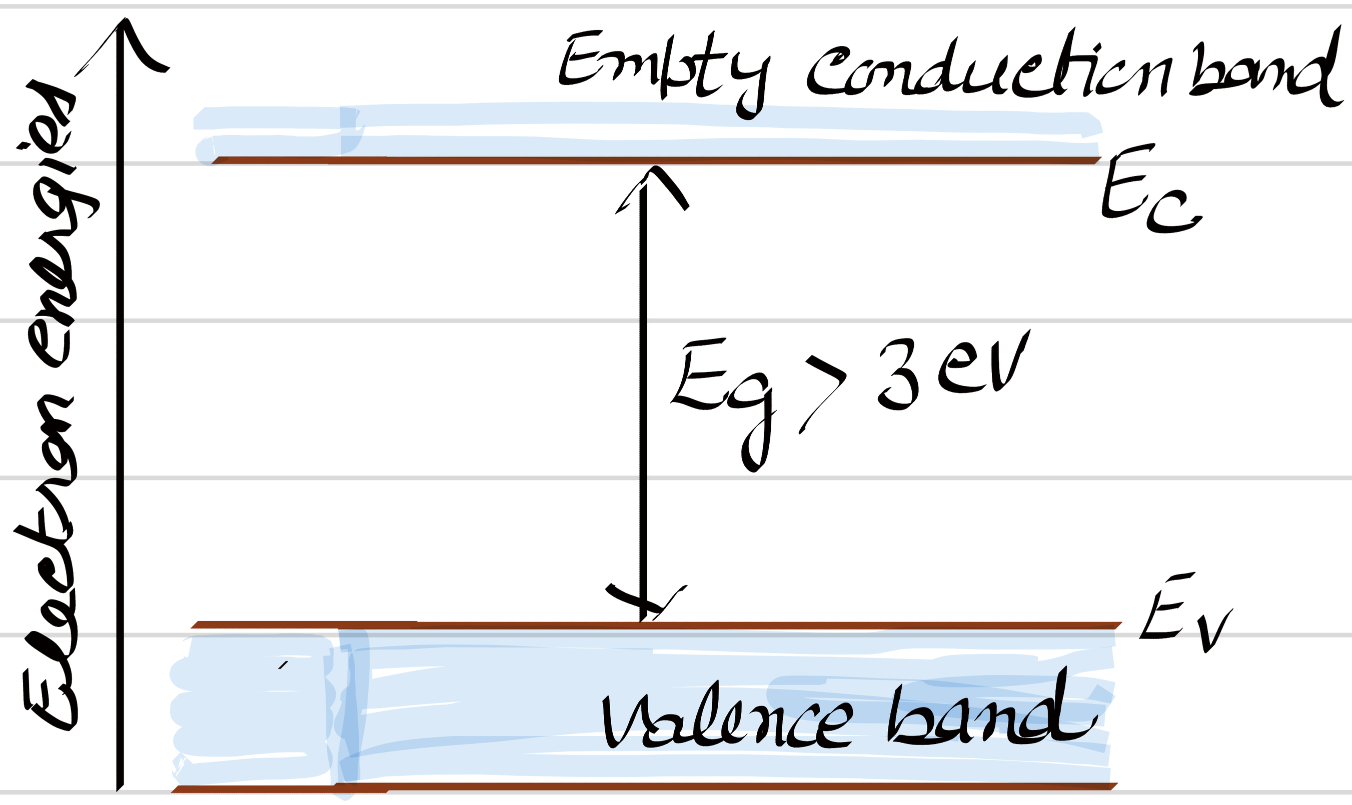
(1) For Metals

- Energy bands overlap
  $E_g = 0$
- Many free electrons present
- High electrical and thermal conductivity.



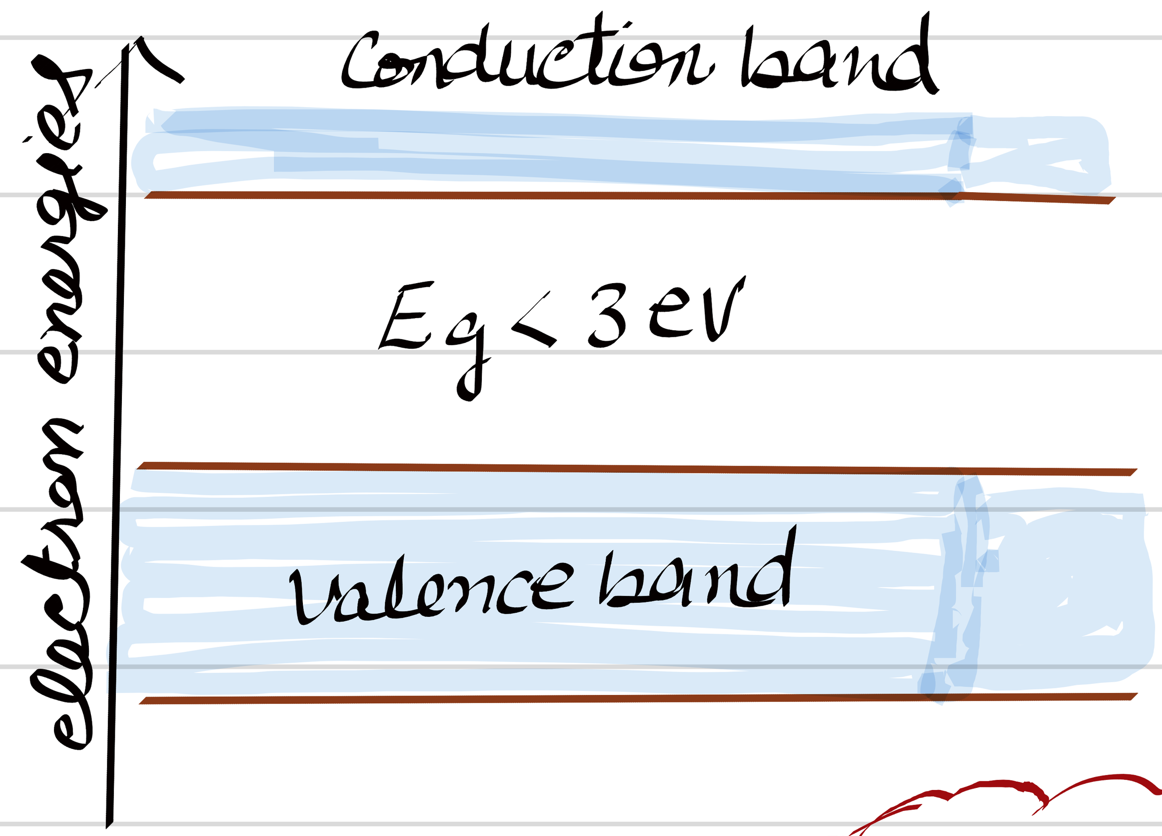
(II) **For Insulators:**

- Large band gap ($E_g > 3eV$)
- No free electrons
- Poor conductivity



(III) **For Semiconductors:**

- Moderate band gap ($E_g < 3eV$)
- conductivity depends on temperature. At room temp. electrons (less no.) jump to conduction band, improving conductivity



Doping
Process of adding impurity pentavalent or trivalent to an intrinsic semiconductor is called doping

Semiconductors

On the basis of purity:

- Intrinsic semiconductor (Pure semiconductor)
- Extrinsic semiconductor (Impure/doped semiconductor)

Intrinsic Semiconductors (Undoped semiconductor)

- It is a pure semiconductor.
- $n_e = n_h = n_i$

where $n_e \rightarrow$ no. of electrons, $n_h \rightarrow$ no of holes
$n_i \rightarrow$ intrinsic carrier concentration

- Charge carriers are generated by thermal energy at room temperature. i.e conductivity arises with temp.
- Low conductivity $\rightarrow$ no utility.
- Examples $\rightarrow$ Si and Ge (Tetravalent)

Extrinsic Semiconductors (Doped Semiconductors)

An extrinsic semiconductor is a doped or impure semiconductor with increased conductivity due to added impurities.

Extrinsic Semiconductors

Two types

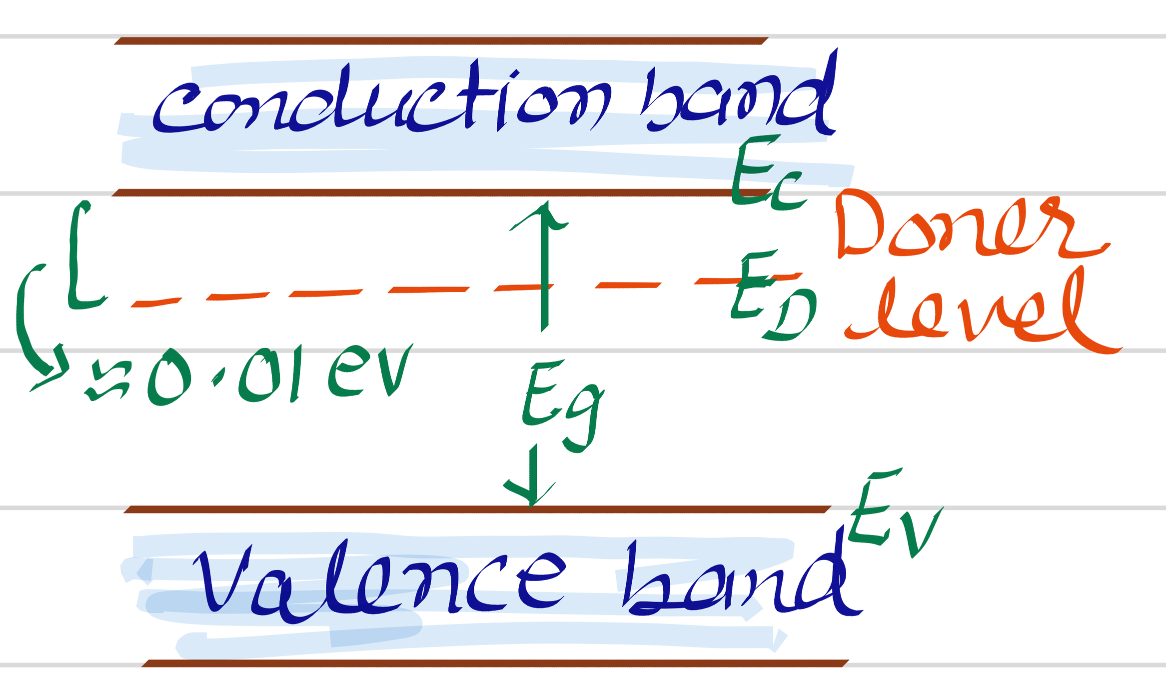
- n-type semiconductors
- p-type semiconductors

(one impurity atom added to 10^8 Ge, increases conductivity 16 times)

→ n-type Semiconductors

- Pentavalent impurity like phosphorus (P) arsenic (As), antimony (Sb) are added to intrinsic semiconductor which results extra electrons as charge carriers. (Doner atom electrons are charge carriers)
- Pentavalent impurity → Adding doner atom (V group elements (P, As, Sb)
- Electrons are majority carriers and holes are minority carriers. $n_e >> n_h$

  (Hole → vacant spot of electron act as +ve carrier)
- Doner level lies just below the conduction band making it easy for electrons to jump up to the conduction band.



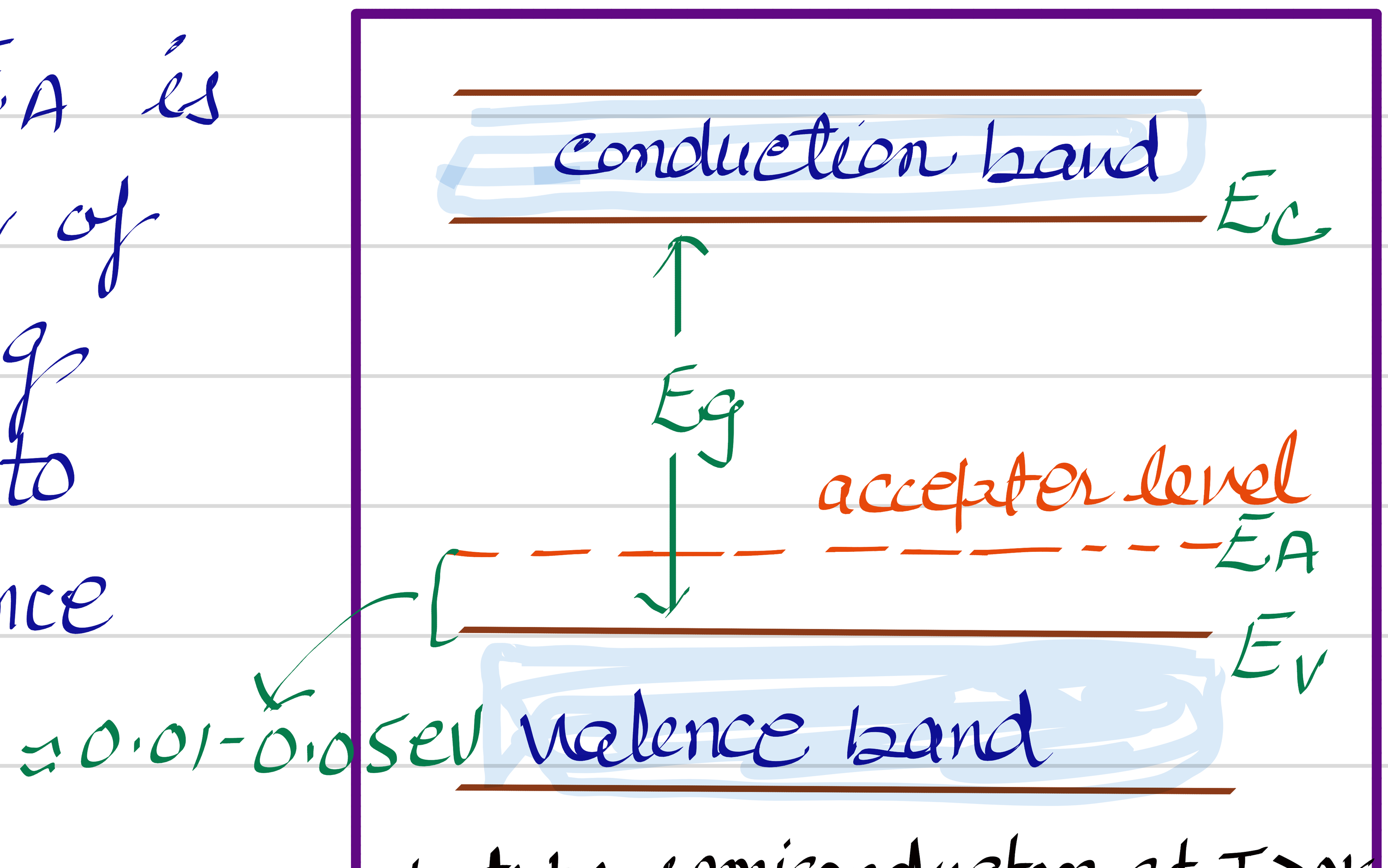
n-type semiconductor at T>0K

→ p-type Semiconductor

- Trivalent impurity like Boron (B), Gallium (Ga) Indium (In) are added to intrinsic semiconductor to get p-type semiconductor.
- Hole are majority charge carriers and electrons are minority charge carriers. $n_h >> n_e$

Accepter atoms create holes in p-type

- Accepter energy level E_A is slightly above the top E_V of the valence band, allowing electrons jump down into it to create mobile holes in valence band.



p-type semiconductor at T>0K

In thermal equilibrium

$$n_e n_h = n_i^2$$

n_e → electron concentration, n_h → hole concentration
n_i → intrinsic carrier concentration

p-n junction: The boundary between the p-type and n-type region is called p-n junction

* p-n junction is the basic building block of many semiconductor devices like transister etc.

Method of formation:

- An Al film is laid on an n type (Ge, Si) wafer and heated at 600°C. This is the diffusion method.
- Other methods are - growing method and alloying method.
- Two important processes occure during the formation of p-n junction: diffusion and drift.
- Electrons from n-side diffuse into p-side, filling available holes near the junction.
- This diffusion creates a depletion region at the junction, where there are no free electrons or holes.

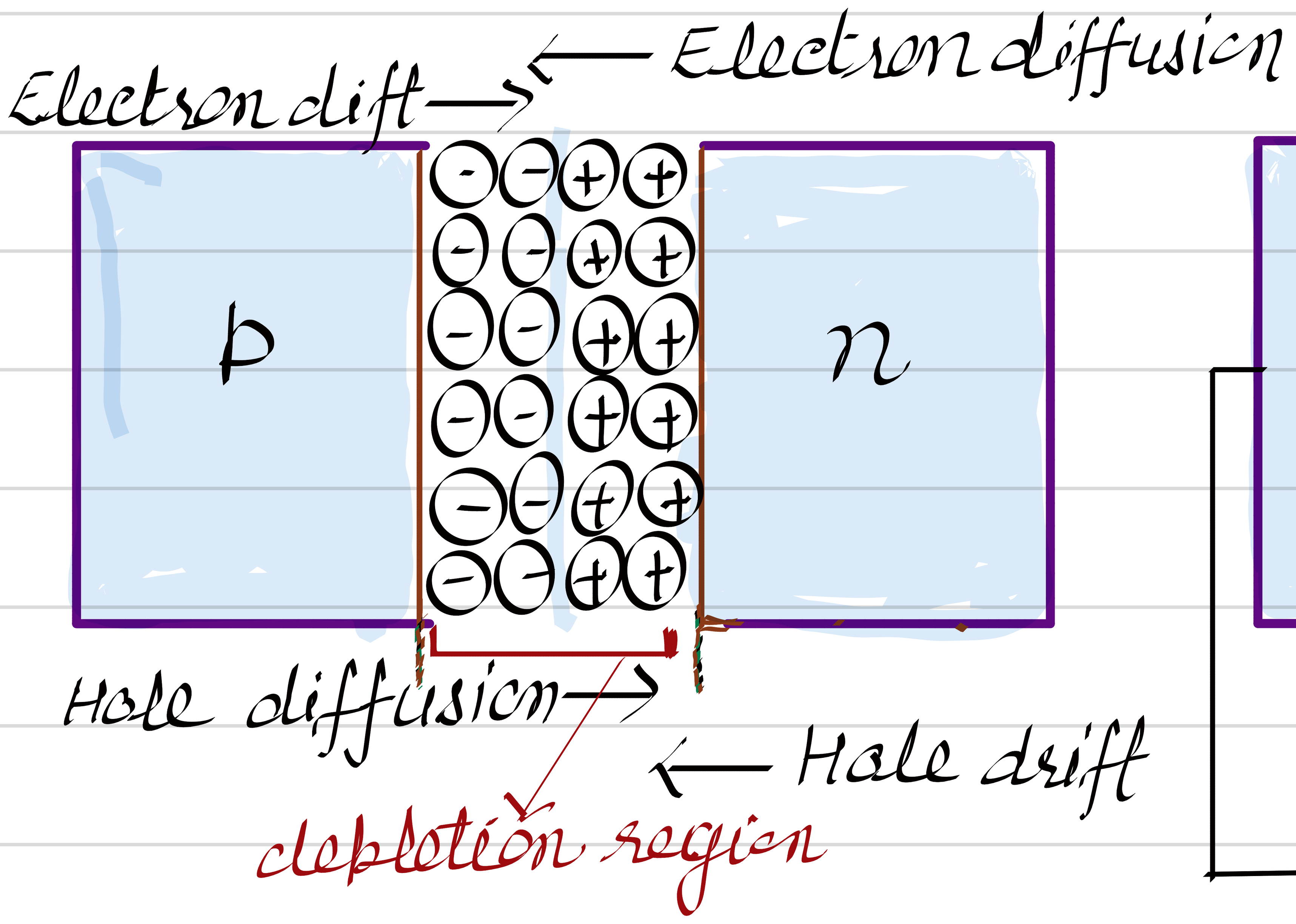
- In the depletion region +ve ions remain on the n-side and -ve ions remain on the p-side, forming an internal electric field.
- This electric field prevents further eletron-hole movement across the junction.

<u>Depletion Region</u>: Either side of the junction. (free from charge carries)

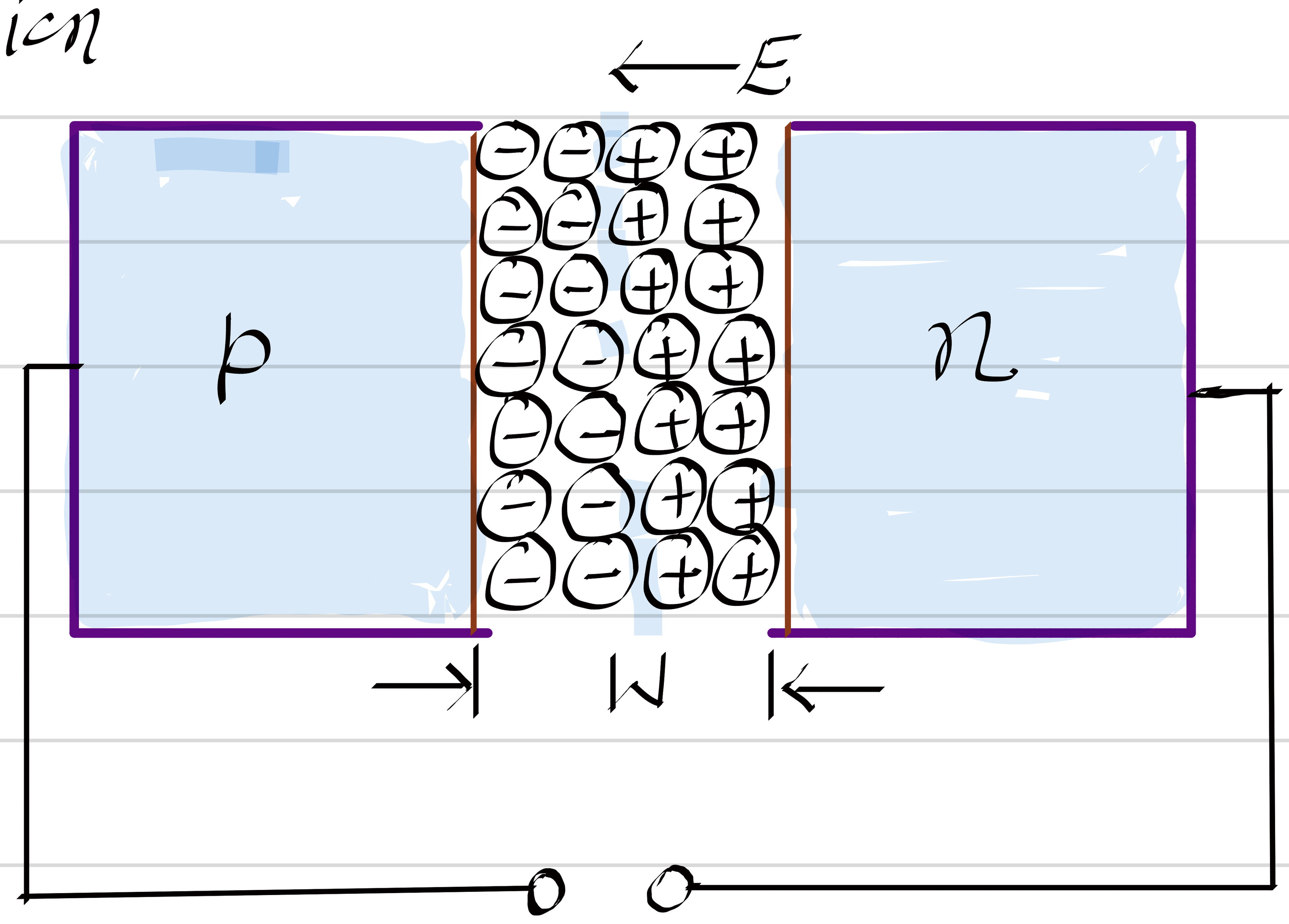
- Width of depletion layer ≈ 10^{-6} m (micrometer)

<u>Potential Barrier</u>: Potential difference across the depletion region. (Also known as built-in potential)

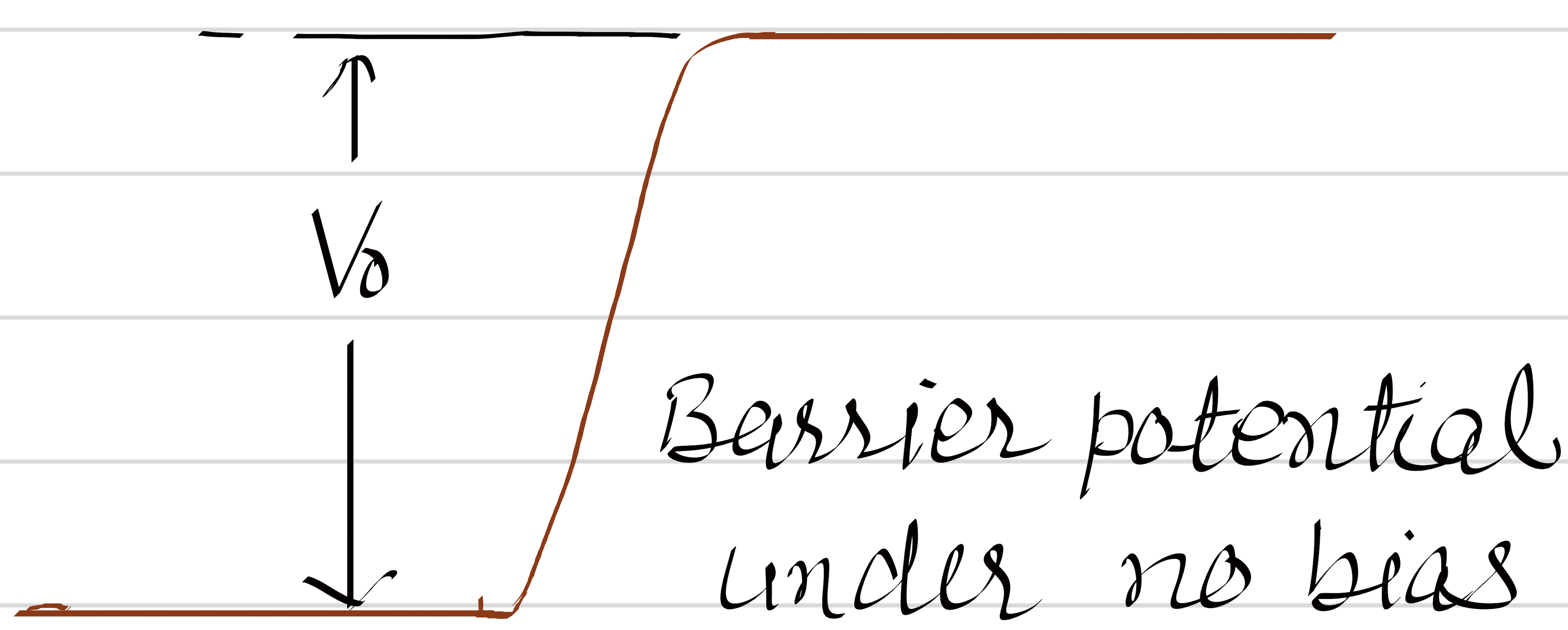
* For Ge, potential barrier is 0.3 volt
* For Si, potential barrier is 0.1 volt



(a) p-n junction formation



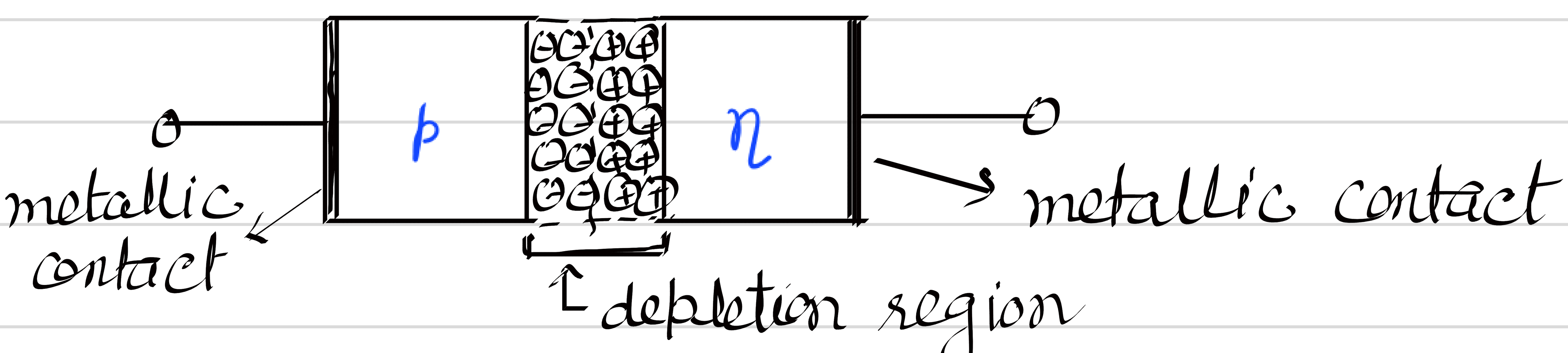
(b) Diode under equilibrium (V = 0)



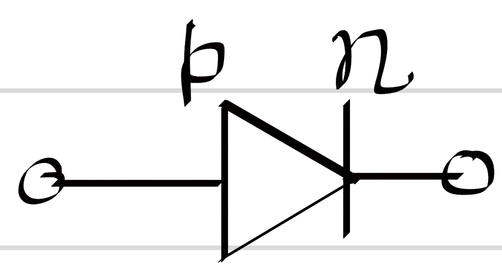
(c)

Semiconductor Diode

A semiconductor diode is basically a p-n junction with metallic contacts provided at the ends to apply external voltage.
It is a two terminal device.



Semiconductor diode

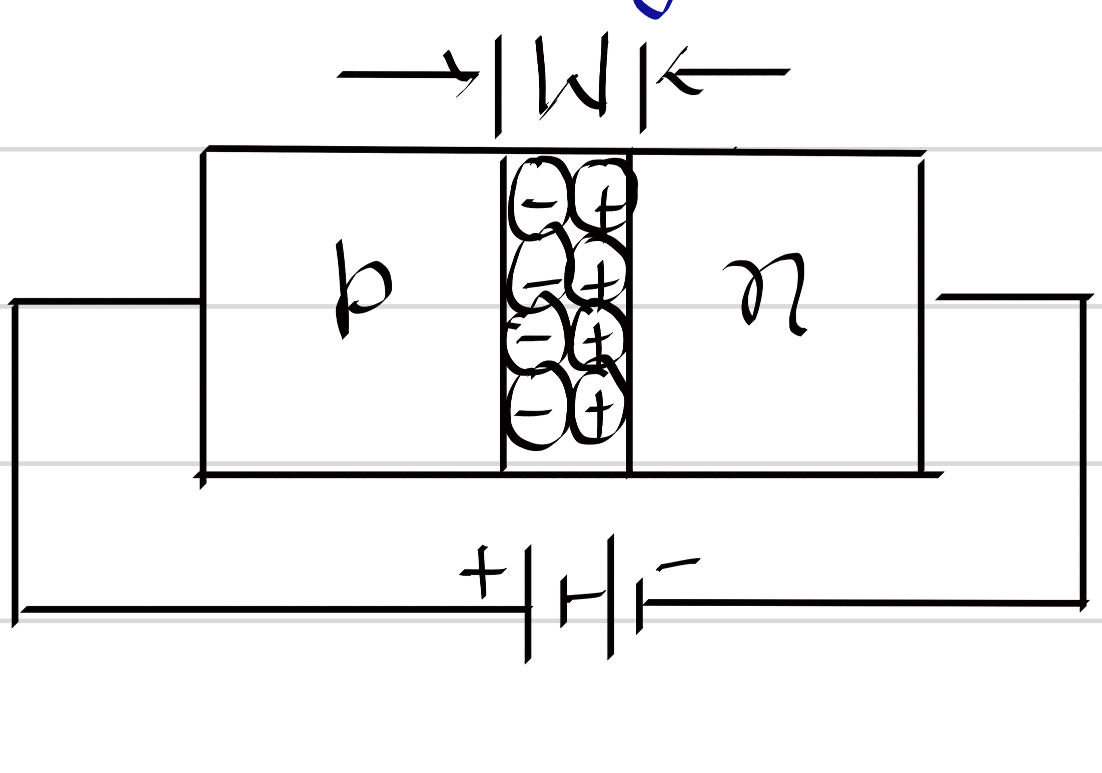


symbol

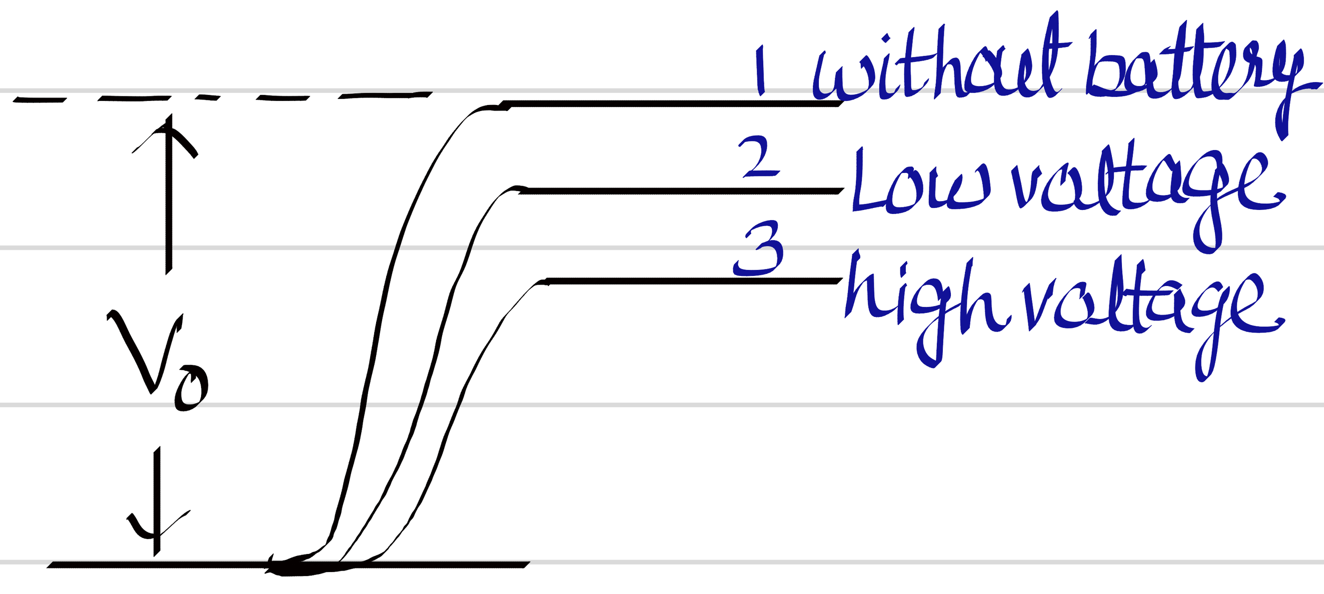
p-n junction diode under forward bias (Flow of current)

When an external voltage V applied across a semiconductor diode such that p-side is connected to the +ve terminal of the battery and n-side to the −ve terminal, it is said to be forward biasing.

- In F.B. potential barrier reduces across the junction, causing the electric field E to direct from p to n side.
- Holes from p side move towards junction and cross into n side and electrons from n side cross the depletion region towards p side.
- The F.B voltage reduces the width of depletion region making it easier for charge carriers (electrons and holes) to cross the junction.
- This process allows current to flow through the diode usually in mA.

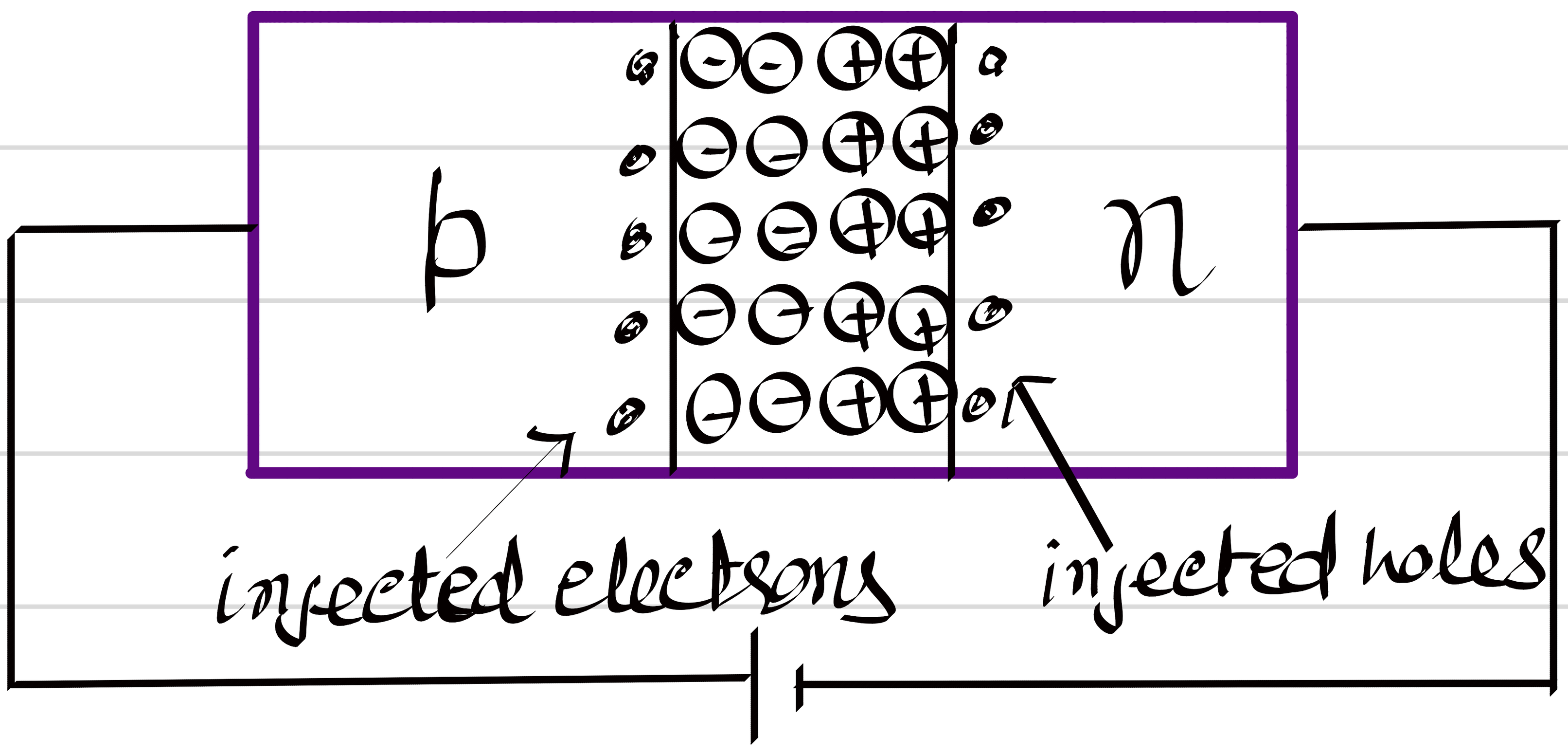


Forward Biasing.



Barrier potential

- In F.B minority carriers (electrons in p-region and holes in n-region) are pushed across the junction into opposite region.
- These injected minority carriers increases the concentration of electrons in the p-region and holes in n-region.
- The movement and recombination of minority carriers allow continuous flow of current through the diode.
- This process is known as minority carrier injection, which increases the current in F.B by increasing the movement and recombination of minority carriers across the junction.



Forward bias minority carrier injection

★ Majority charge carriers cross the junction due to external voltage (battery) and minority charge carriers cross the junction due to reduced barrier or electric field in the depletion region.

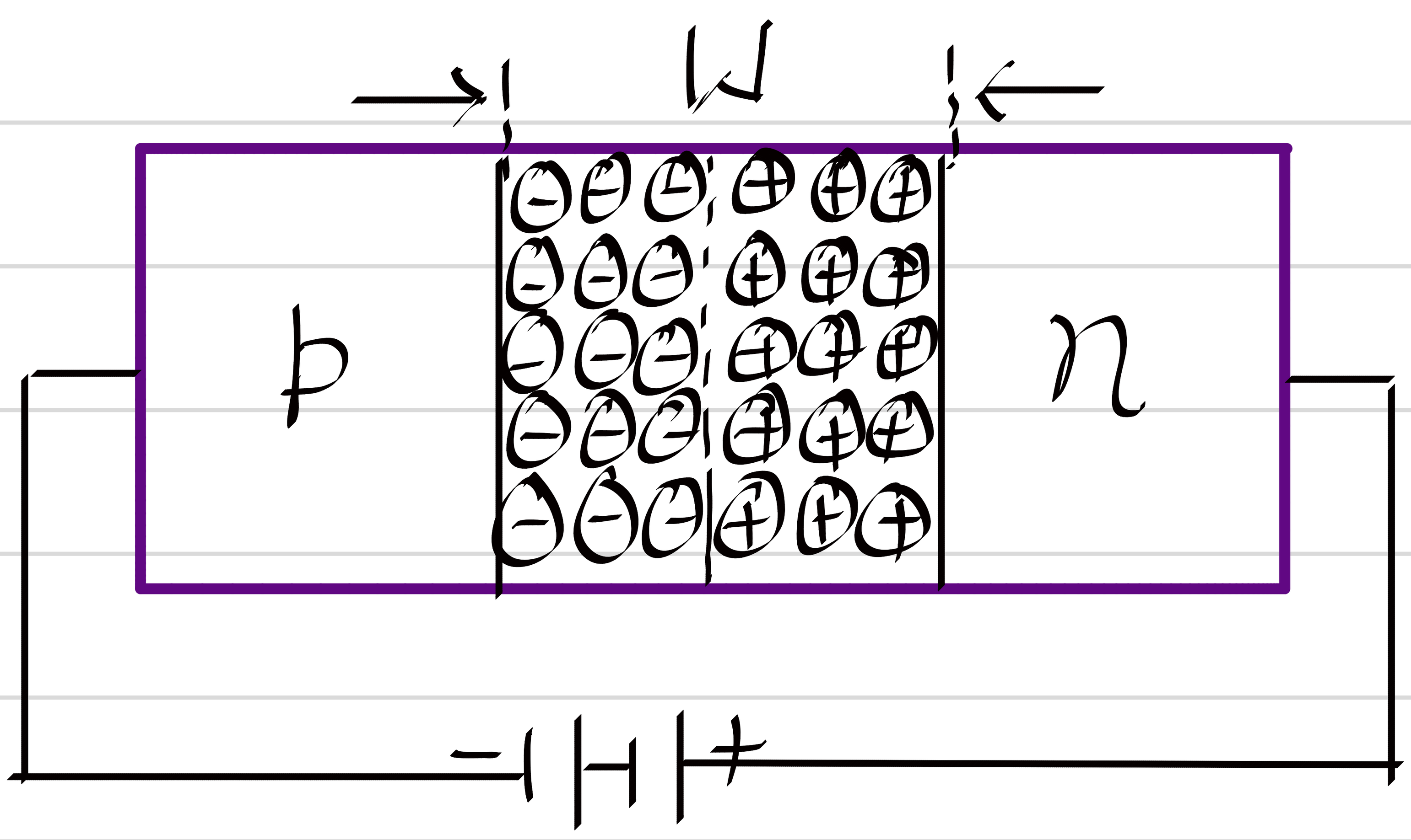
★ Key Characteristics of F.B

(I) p-side connected to +ve of battery and n-side to -ve
(II) Depletion region and potential barrier decreases.
(III) Majority carriers and minority carriers cross the junction and current flows through the diode in mA.

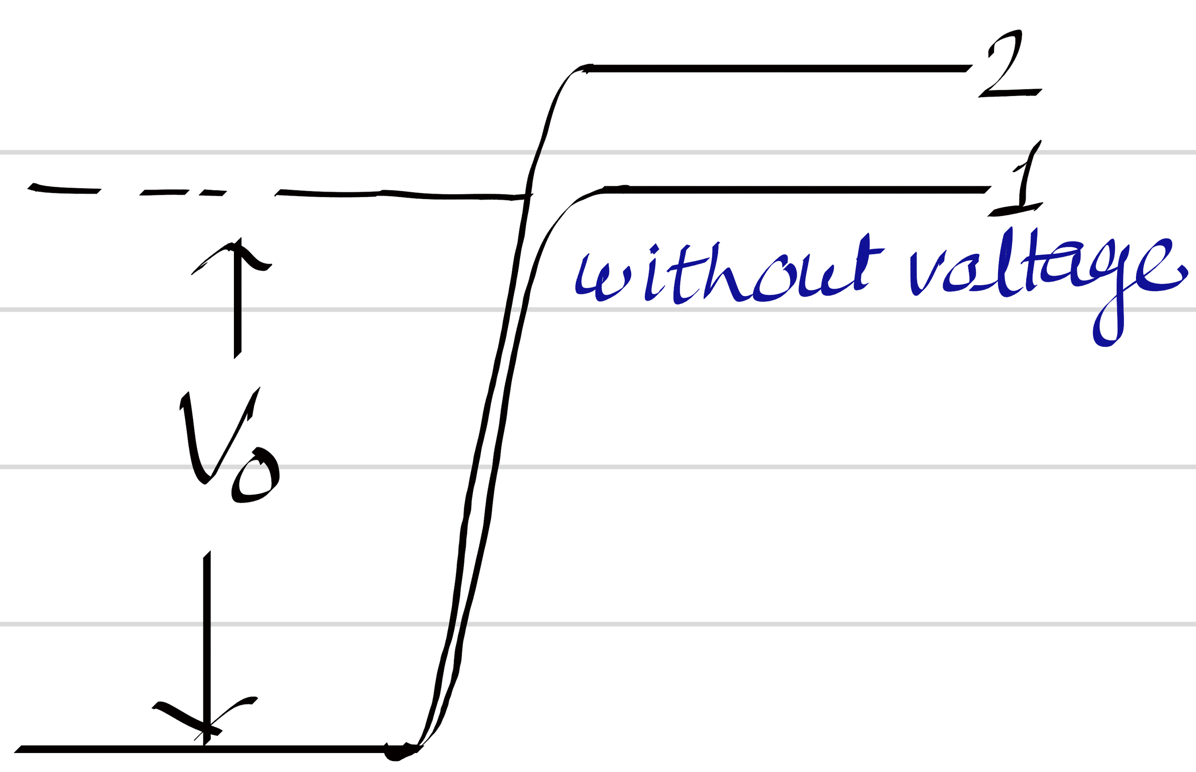
p-n junction diode under the Reverse Bias

When external voltage V is applied across the diode such that n-side is +ve and p-side is −ve it is said to be reverse bias.

- The direction of applied voltage is same as the direction of potential barrier hence barrier height increases and the width of depletion region increases.
- The effective barrier height in R.B is $V_0 + V$
- As barrier potential increases, the flow of electrons (n to p) and holes (p to n) suppressed.
- Diffusion current decreases enormously.
- A very small current called reverse saturation current flows due to minority carriers (drifted by electric field in R.B) which is negligible (in µA).
- Current does not increase with voltage until the breakdown voltage is reached.
- If the reverse voltage is exceeds a certain critical value (called breakdown voltage) the diode can break down, leading to a large current flow. (Avalanche or Zener breakdown)



Diode under reverse bias



Barrier potential under reverse bias

★ Key characteristic of R.B

(i) p-side is connected to -ve of battery and n-side to +ve.

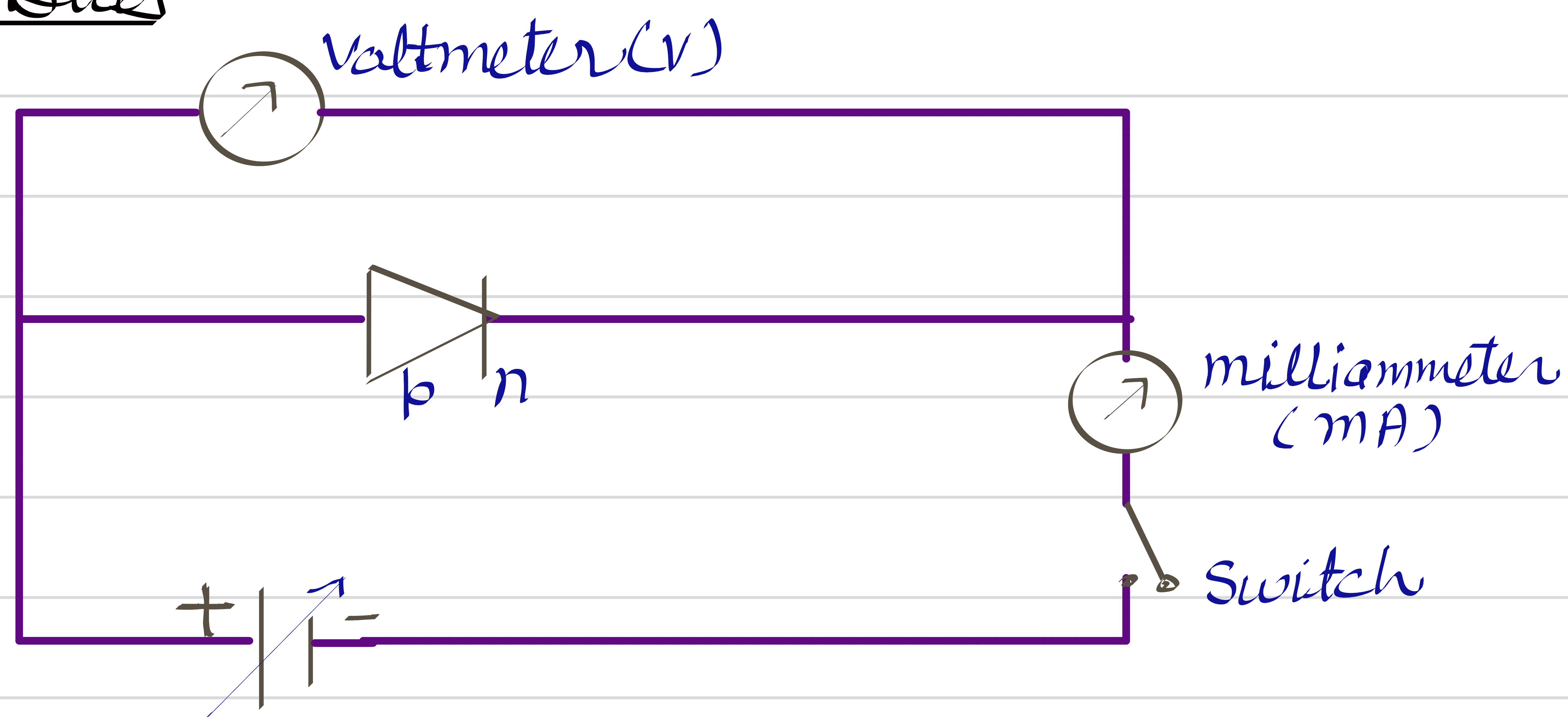
(ii) Height of barrier potential barrier increases and depletion region width increases.

(iii) Majority charge carriers are pulled away from the junction and minority charge carriers cross the junction and a very small (negligible) current flows (in uA).

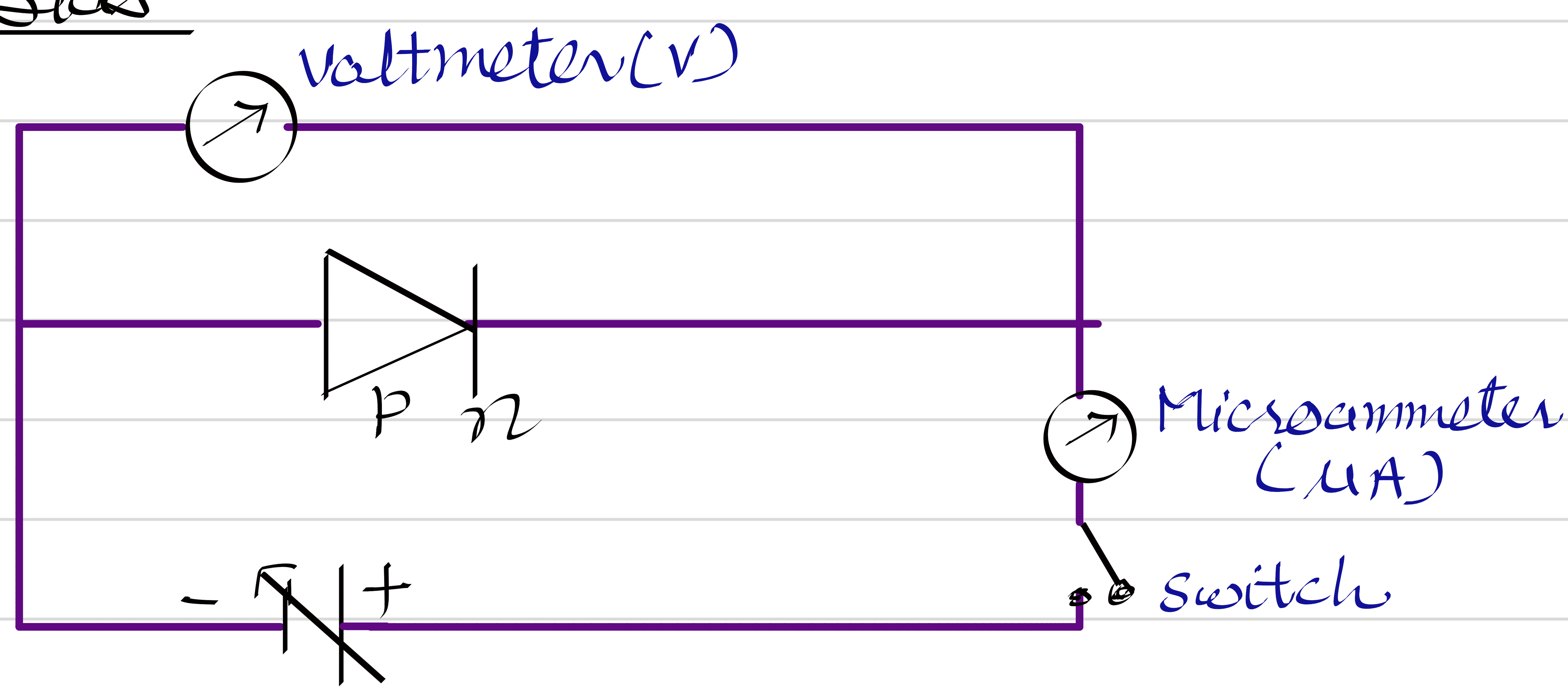
(iv) If reverse voltage is increased beyond breakdown voltage, large no. electrons and holes are generated and large current flows which can destroy the diode.

V-I Characteristics of a p-n junction diode

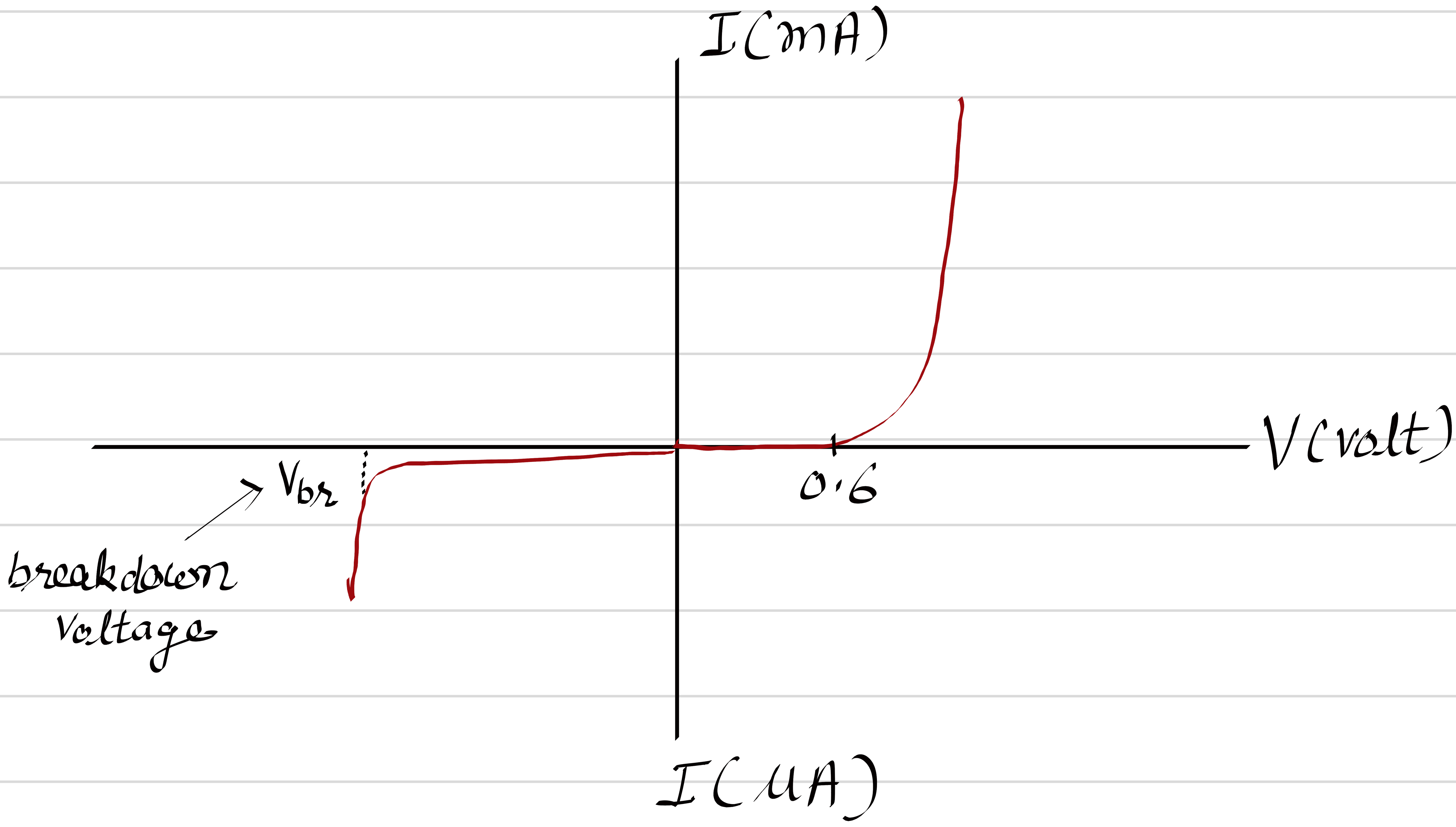
(i) Forward Bias



(ii) Reverse Bias



V-I characteristic of Si diode



Saturation current: In reverse bias, the current is very small and remain constant with change in bias. It is called reverse saturation current.

Threshold voltage: The minimum forward voltage at which a diode starts to conduct a significant current is called threshold voltage or cut in voltage. For Ge diode ~0·2V and for Si diode ~0·7V.

Dynamic Resistance (r_d):

In Forward Bias - It represents how much the current changes in the applied forward voltage.

$$r_d = \frac{dV}{dI} \simeq \frac{\text{Thermal Voltage}}{\text{Forward current}}$$

As forward current increases r_d decreases.

In reverse bias - In reverse bias the dynamic resistance is very high because current is minimal and nearly constant.

$$r_d = \frac{\text{Reverse bias voltage}}{\text{reverse saturation current}} \simeq \frac{V_R}{I_S}$$

In R.B. diode behave almost like open circuit until breakdown occurs.

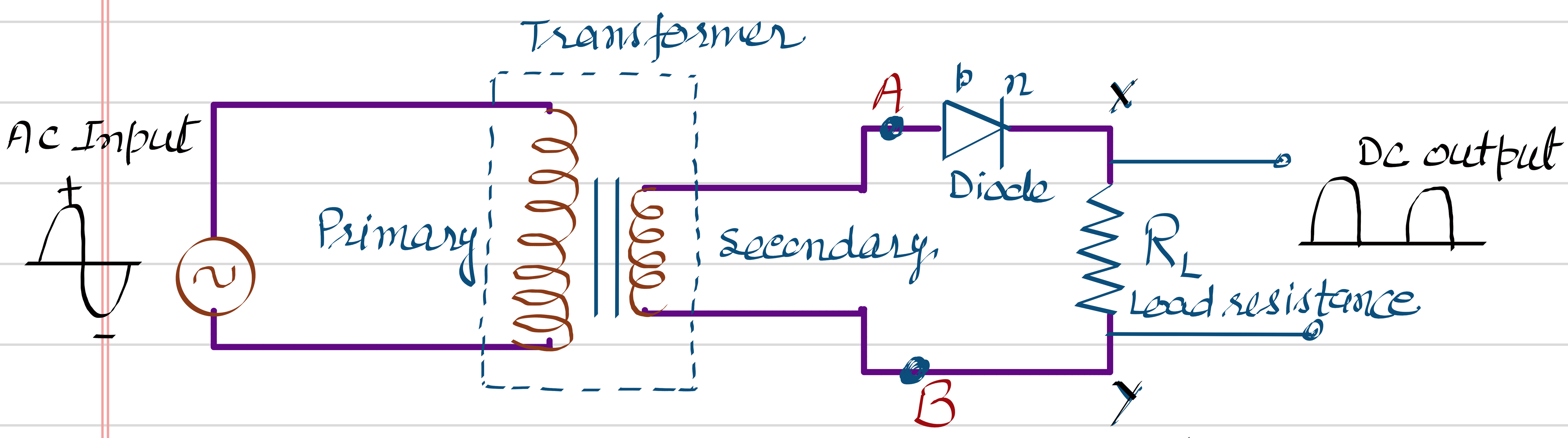
Application of Junction Diode as a Rectifier.

Rectifier: A rectifier is an electronic device that converts alternating current (AC) to direct current (DC). Rectifiers are essential in power supplies as most electronic devices require DC for operation.

* The property of diode to conduct current only in one direction (in F.B) and block it in R.B, is used to rectify the Alternating voltage.

Types of Rectifiers:

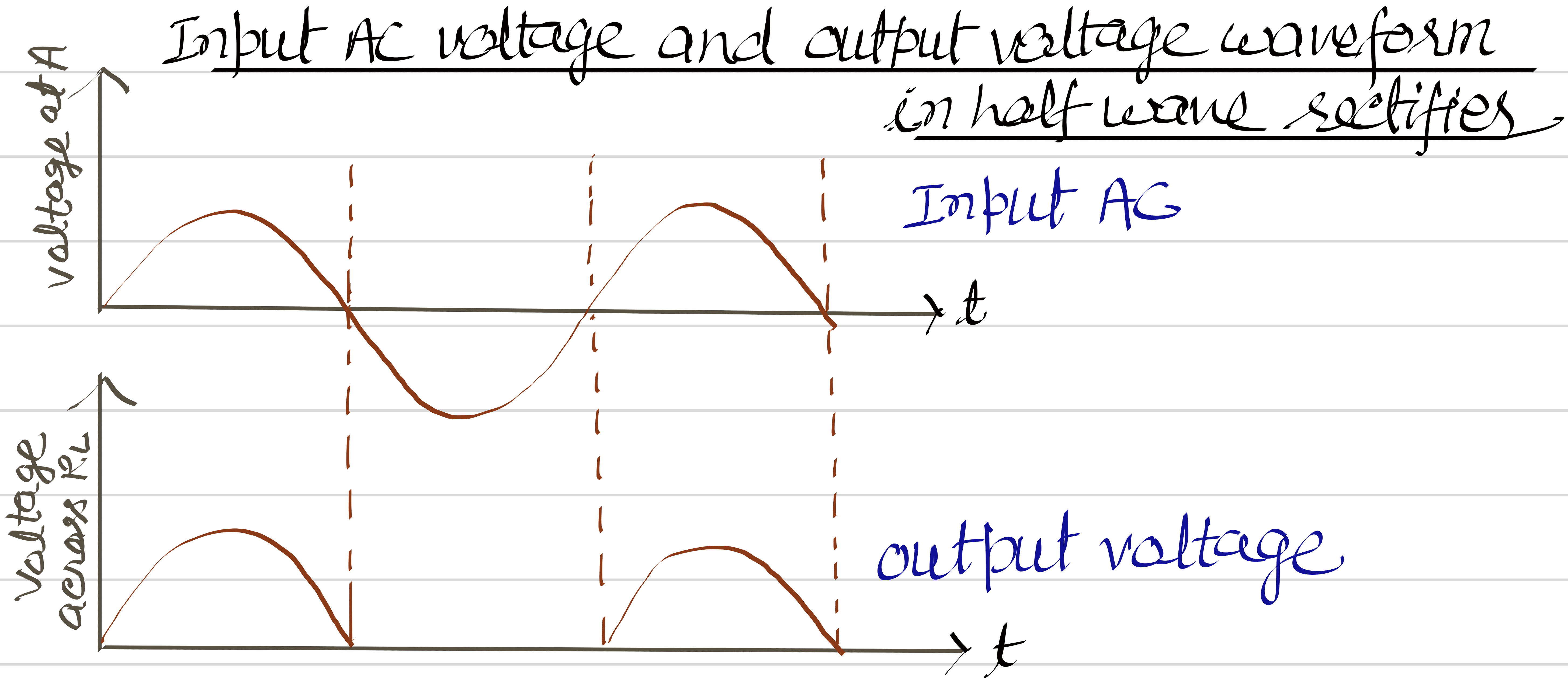
1. **Half-Wave Rectifier:** In half wave rectifier a single diode is used to convert only one half of AC cycle (either +ve or -ve) into DC.
A single junction diode act as a half wave rectifier.



Half Wave Rectifier circuit

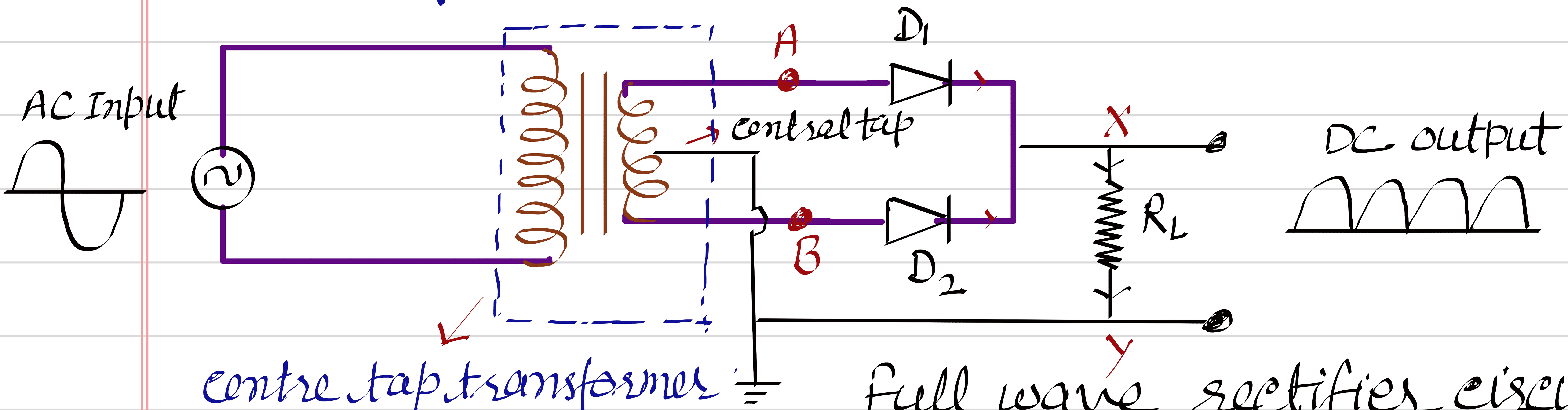
Working: (i) In first half of cycle of AC, when A is positive (+ve) and B is negative (-ve), the junction is in Forward bias (F.B). i.e current flows.

(ii) During the second half cycle of AC, when A is negative(-ve) and B is +ve, the junction is in reverse bias (R.B.). i.e current does not flow.



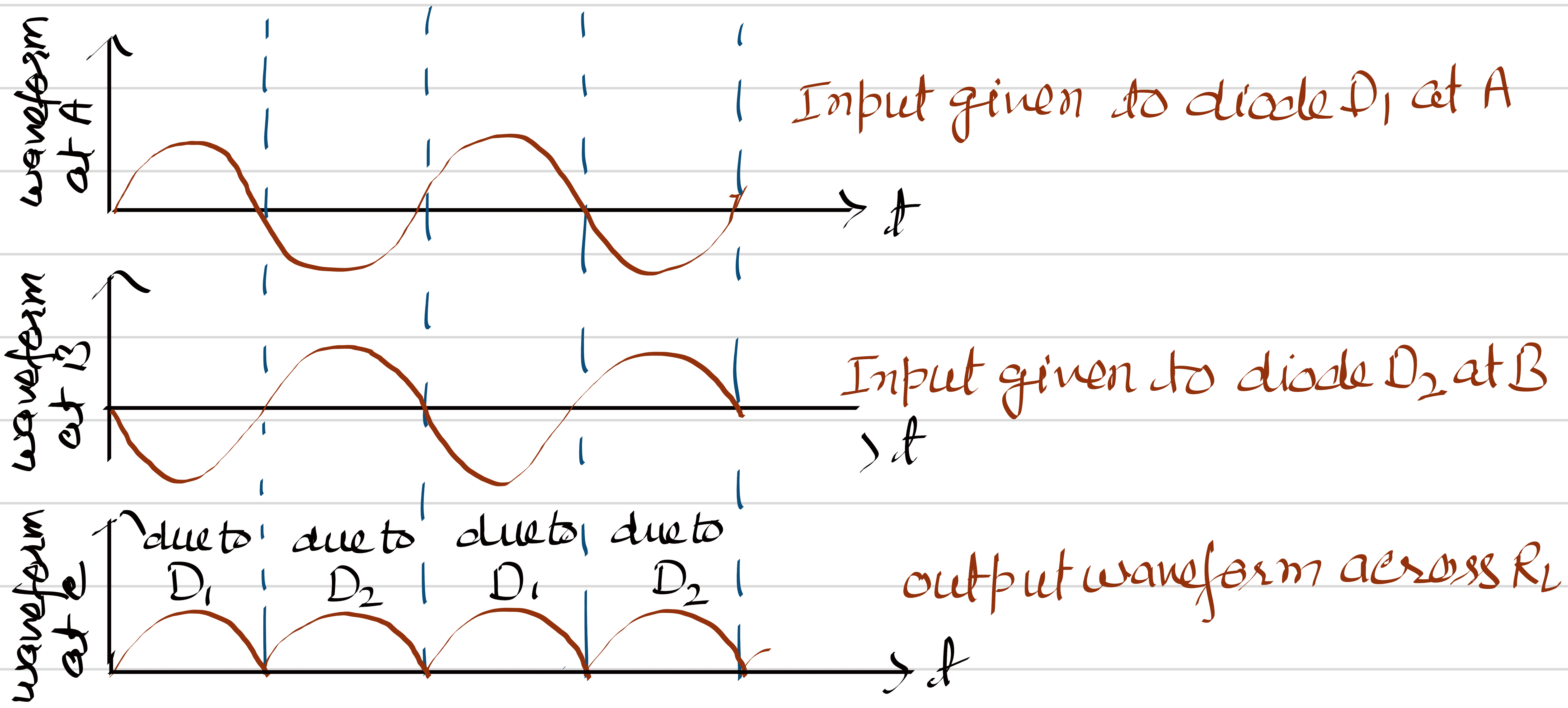
* Half wave rectifier uses only one diode, so it is simple and cost effective.
* Utilise only half of AC waveform so it is less efficient.
* Produces a DC output with large ripples. (ripples ↑ unwanted fluctuation in DC signal)
* Suitable for low-power applications.

2. **Full Wave Rectifier** In full wave rectifier two diodes are used. One diode rectifies one half cycle and the second diode rectifies second half cycle of AC input.



Full wave rectifier circuit

Input and output wave form in full wave rectifier



Working: (I) During first half cycle of AC input, 'A' is +ve and B is -ve. i.e diode D_1 is in F.B and current flows through D_1.

(II) During second half cycle of AC B is +ve. i.e diode D_2 is F.B and current flows through D_2.

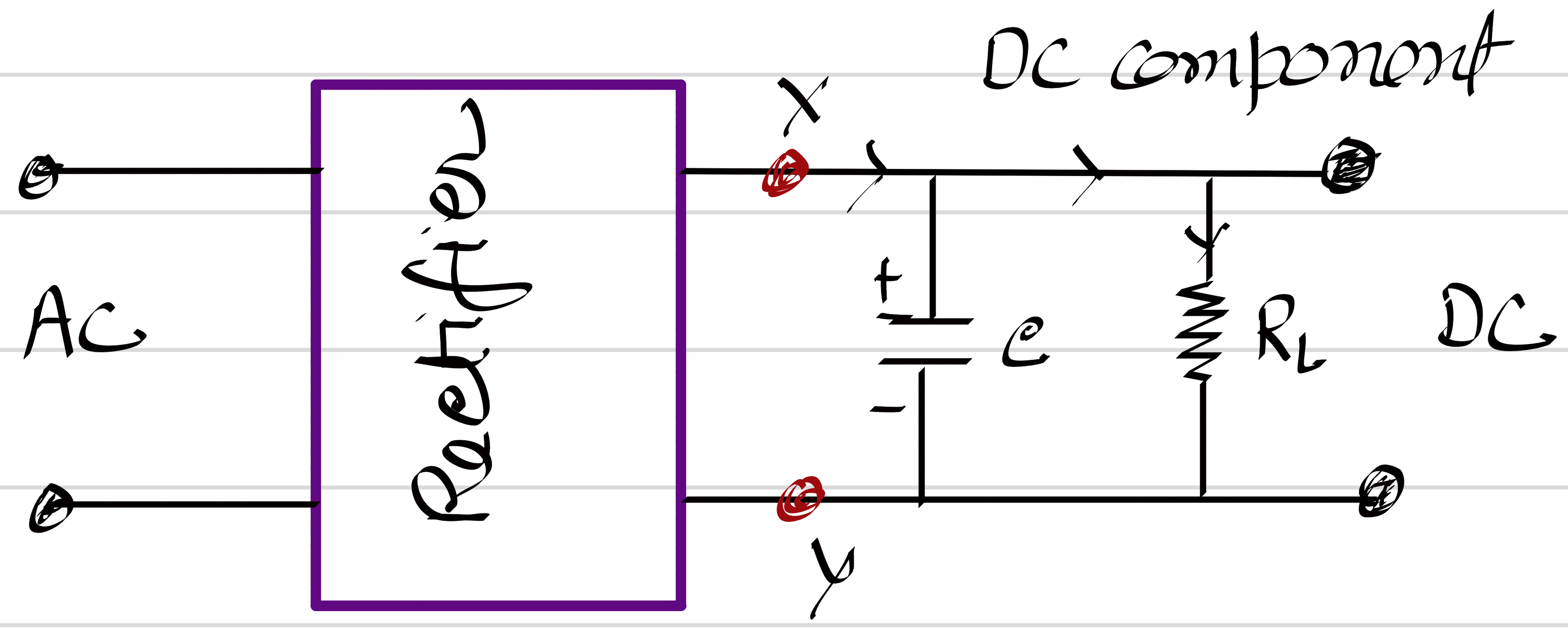
(III) Produces a smoother DC output with less ripple.

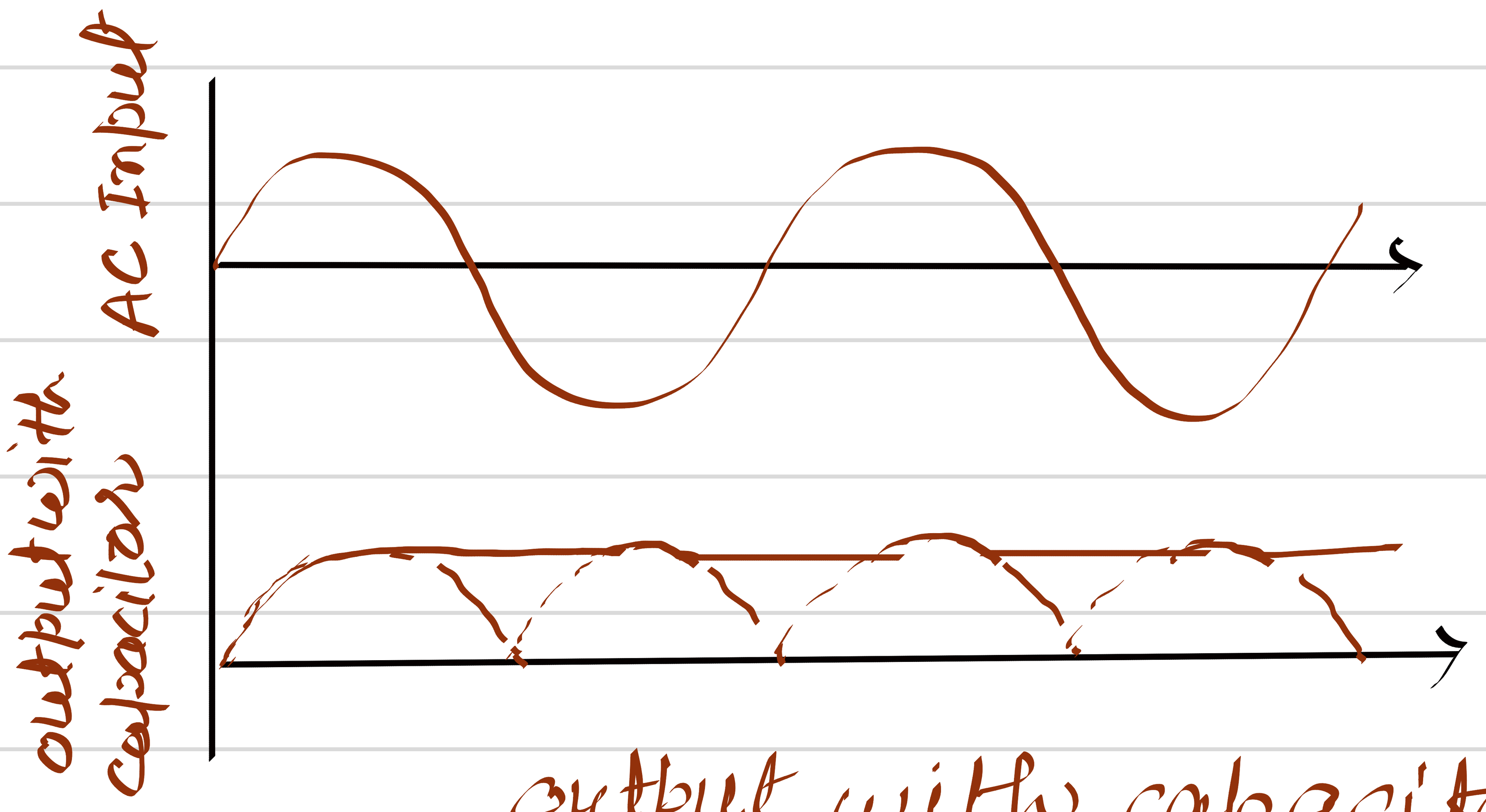
(IV) Output voltage is more consistent and stable than in half wave rectifier

Rectification of output DC voltage completely

(I) A capacitor filter is used to reduce the ripples in output DC voltage.

(II) Ripples are reduced by charging during peaks and discharging during valleys of rectified signal by using capaciter filter.





output with capacitor input filter

CHAPTER-14 Semiconductor Electronics: Materials, Devices and Simple Circuits

SECTION A

MCQ-1 MARK SECTION

1. The energy band gap is maximum in
(a) metals (b) superconductors (c) insulators (d) semiconductors

2. At absolute zero, silicon (Si) acts as
(a) non-metal (b) metal (c) insulator (d) none of these

3. The process of adding impurities to a pure semiconductor is called
(a) Mixing (b)Doping (c)Diffusing (d)None of the above

4. Silicon is doped with which of the following to obtain P type semiconductor
(a) Phosphorus (b) Gallium (c) Germanium (d) Bismuth

5. When an impurity is doped into an intrinsic semiconductor, the conductivity of the semiconductor
(a) Increases (b) decreases (c) remains the same (d) becomes zero

ASSERTION –REASONING TYPE QUESTIONS

Directions : In the following questions, A statement of Assertion (A) is followed by statement of Reason (R). Mark the correct choice as.

A ; If both Assertion and Reason are correct and the Reason is a correct explanation of the assertion.

B: If both Assertion and Reason are correct but Reason is not a correct explanation of the assertion.

C :If the Assertion is correct but Reason is incorrect.

D: If both the Assertion and Reason are incorrect.

6. **Assertion** :A pure semiconductor has negative temperature coefficient of resistance.
Reason :In a semiconductor on raising the temperature, more charge carriers are released,conductance increases and resistance decreases.

7. **Assertion** :A p-type semiconductors is a positive type crystal.
Reason :A p- type semiconductor is an uncharged crystal

8. **Assertion** :Silicon is preferred over germanium for making semiconductor devices.
Reason :The energy gap in germanium is more than the energy gap in silicon.

9. **Assertion** :The diffusion current in a p-n junction is from the p-side to the n-side.
Reason :The diffusion current in a p-n junction is greater than the drift current when the junction is in forward biased

10. **Assertion:** The energy gap between the valance band and conduction band is greater in silicon than in germanium.
Reason: Thermal energy produces fewer minority carriers in silicon than in germanium.

(a)semiconductor (b) conductor (c) insulator (d) none of these

2 MARKS QUESTIONS

13.What happens to the width of depletion layer of a p-n junction when it is (i)forward biased? (ii)reverse biased?

14. Explain, with the help of a circuit diagram, the working of a p-n junction diode as a half- wave rectifier.

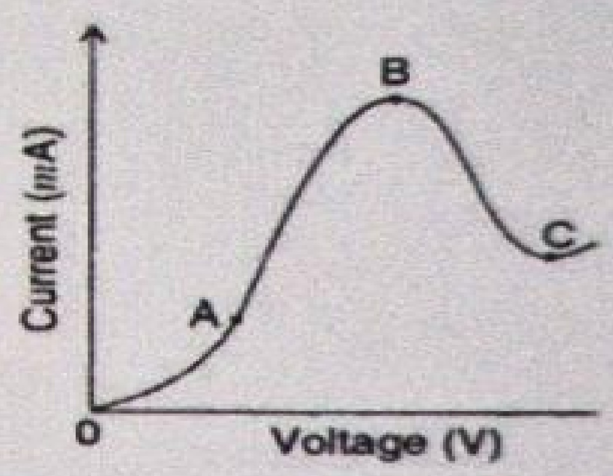
15.Distinguish between a metal and an insulator on the basis of energy band diagram.

16.Explain, how a depletion region is formed in a junction diode?

17. Carbon and silicon both have four valence electrons each, then how are they distinguished?

18. The graph shown in the figure represents a plot of current versus voltage for a given semi-conductor. Identify the region, if any, over which the semi-conductor has a negative resistance.

19. Plot a graph showing variation of current versus voltage for the material GaAs.

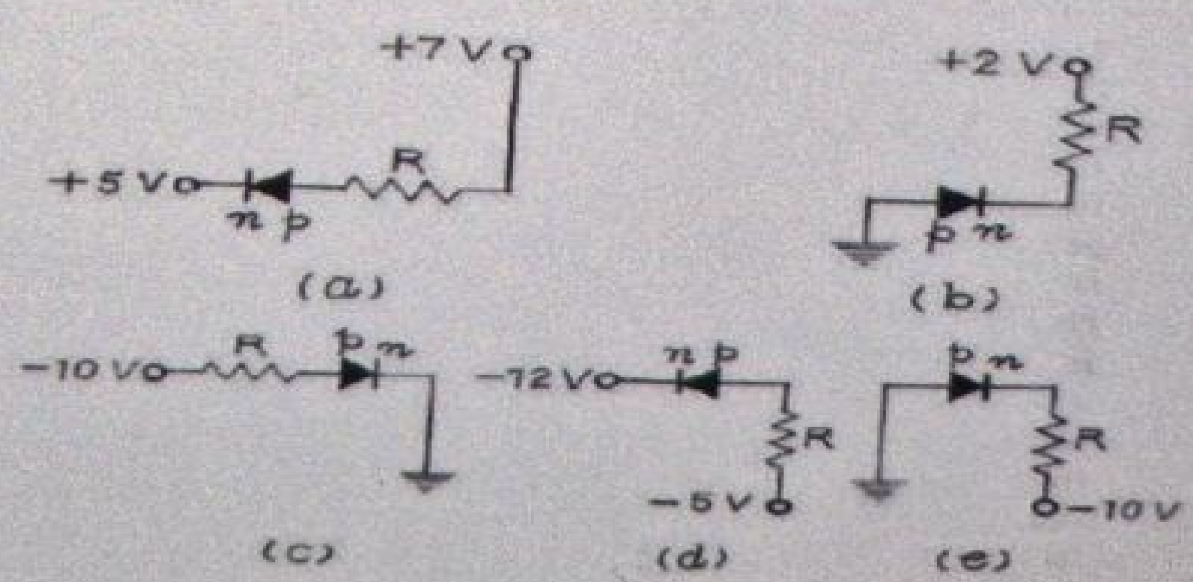


3 MARKS QUESTIONS

20.Draw the circuit diagram of a full wave rectifier using p-n junction diode. Explain its working and show the output and input waveforms. (CBSE-2011)

5 MARKS QUESTION

21. Indicate which of the following p- n diodes are forward biased and which are reverse biased:



22. (i) Sn, C and Si, Ge are all group 14 elements. Yet Sn is a conductor, C is an insulator while Si and Ge are semiconductor. Why?

(ii)Germanium and silicon junction diodes are connected in parallel. A resistance R, a 12 V battery, a milli ammeter (mA) and key (K) are connected as shown in figure. When Key (K) is closed, current begins to flow in milli ammeter. What will be the maximum reading of voltmeter connected across resistance R?

SECTION A- ANSWERS

(1 MARKS)

1.c 2.c 3.b 4.b 5. A 6. A 7. D 8. C 9. B 10. b