SEMICONDUCTOR PHYSICS: DIODE AND APPLICATIONS

(e-content for UG)

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OBJECTIVE OF THE PRESENTATION

- **This is an e-content developed for UG students of Physics Core Semester-IV (Paper Code: PHYCC410)**
- **The main objective is to provide the students a detailed acquaintance on the topic**

  " Semiconductor Physics:

  Diode and its applications"

  which forms the basics of Analog Electronics .
- **This initiative has been taken by Patna University under the guidelines given by UGC.**

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SEMICONDUCTOR : AN INTRODUCTION

- As the name suggests, Semiconductor is a material with properties midway between a conductor and an insulator.
- Silicon and Germanium are the commonly used semiconductors which forms the basis of semiconductor devices which play a major role in the development of Electronics.

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Band Theory of Solids

- In order to understand the structure and properties of semiconductors, one must go through the band theory of solids.
- Every solid consist of large no. of atoms. In an isolated atom, the energy of an electron in one atom is definite.
- In solids, atoms are closely packed so that electron in one atom is influenced by nuclei of several atoms so that electronic shells overlap.
- The electrons then possess a range of energy values rather than the fixed energy value, bringing the formation of bands.

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ENERGY BAND DIAGRAM

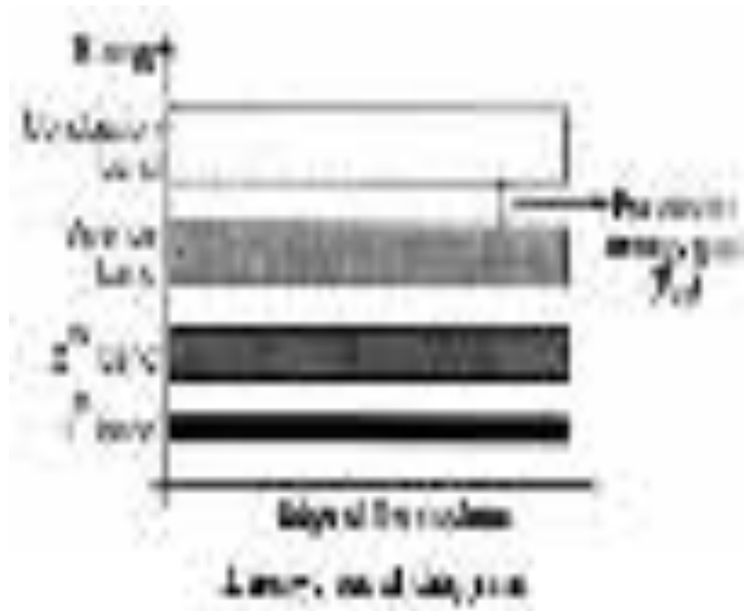

Fig 1. Energy band diagram in a solid showing V.B, C.B and F.B

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INSULATORS

- Those materials which have poor electrical conductivity. For eg. Glass, diamond etc.
- These have the forbidden energy gap of a high value
- Eg > 5 eV.
- The resistivity of insulators are of the order of $10^{12}\ \Omega cm$
- These have a positive temperature coefficient of resistance.
- These have an empty conduction band and fully filled valence band.

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CONDUCTORS

- These materials have high electrical conductivity. For eg. Metals.
- This means that conductors allow a generous flow of current through them when a potential difference of specified magnitude is applied across it.
- These have no forbidden energy gap ie. The Valence band and Conduction band overlap.
- The resistivity of conductors is of the order of $10^{-6}\ \Omega cm$
- These have a positive temperature coefficient of resistance.

SEMICONDUCTORS

- The substances whose electrical conductivity lies between conductors and insulators are called semicinductors. For eg. Si ,Ge etc.
- These have resistivity lying in the range $10^2 - 10^9 \Omega cm$
- It possess a negative temperature coefficient of resistance.
- Conductivity depends on the rise in temperature or the addition of certain impurity elements (doping).
- These have partially filled V.B and C.B with a gap Eg of about 1.1eV .

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ENERGY BAND DIAGRAM IN INSULATOR, SEMICONDUCTOR AND CONDUCTOR

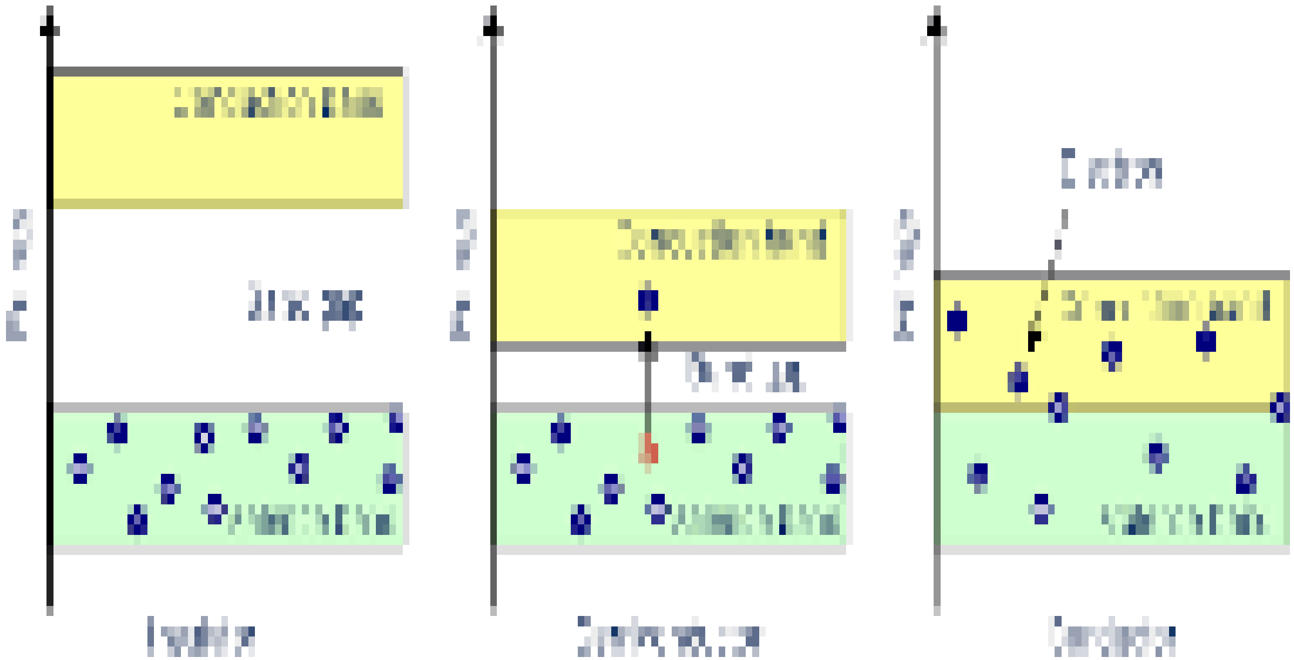

Fig 2. Band diagram showing differences between conductor, insulator and semiconductor

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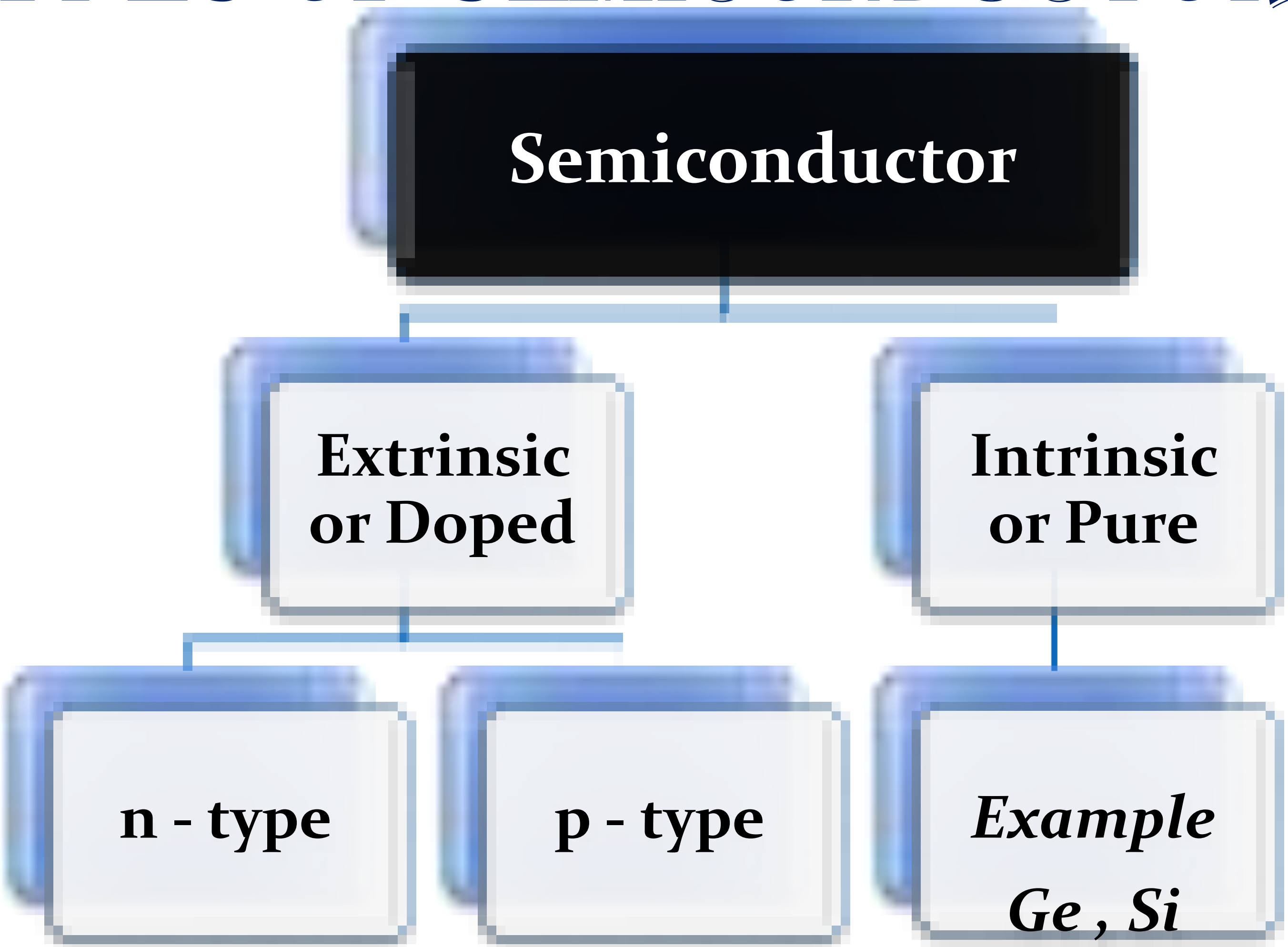
Types of Semiconductors



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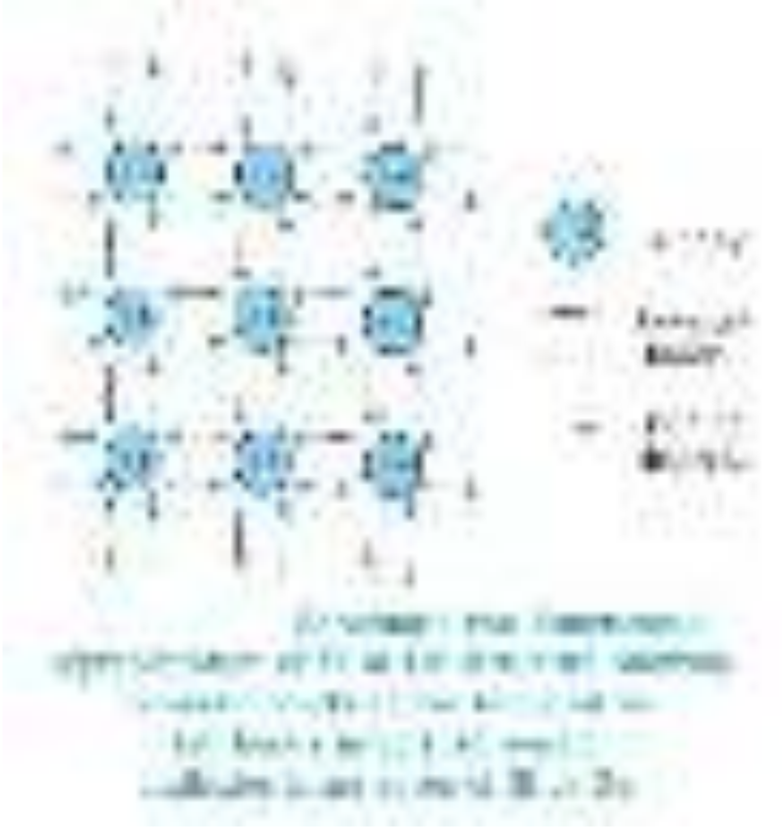
INTRINSIC SEMICONDUCTOR



- Pure form of semiconductor
- Number of conduction electron equals the number of holes i.e,
- $N_e = N_h$
- Example :- Silicon , Germanium
- Conductivity is dependent on temperature and hence it is low

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EXTRINSIC SEMICONDUCTOR

- **Impure form of semiconductor obtained by doping ie. Addition of certain impurity atoms in small quantities.**
- **Doping agents are usually pentavalent or trivalent atoms known as donor or acceptor atoms.**
- **Number of conduction electrons is not equal to the number of holes created.**
- **These are categorised into two types:**

n-type and p-type

N Type Semiconductor

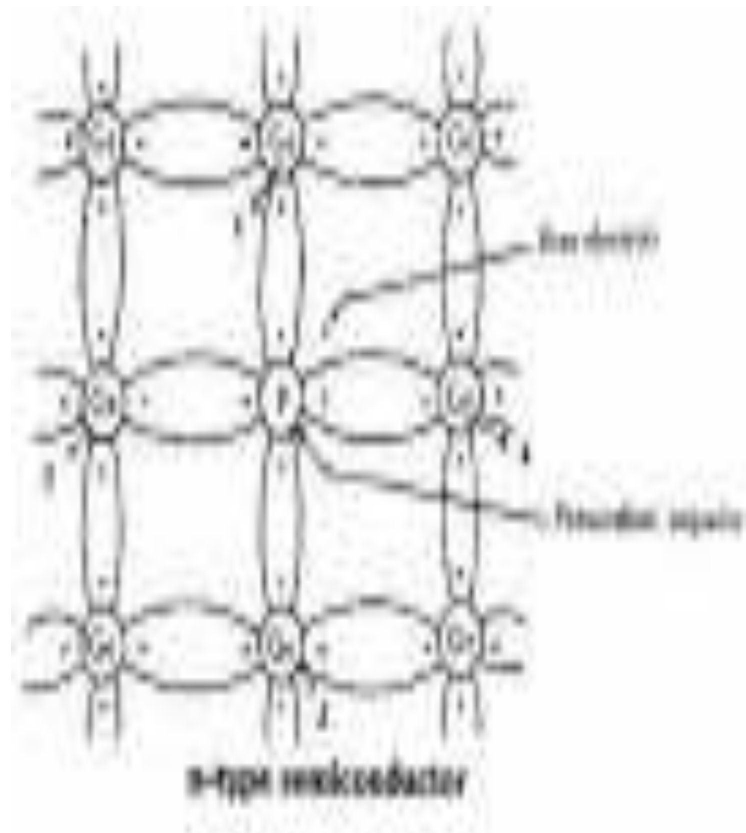
Formed by doping a pure semiconductor with pentavalent impurity like Bismuth, Phosphorus etc .

Each donor atoms provides one excess free electron to the crystal structure.

The number of free electrons is more than the number of holes.

$n_e >> n_h$

The net current will be due to free electrons which are the majority carriers.



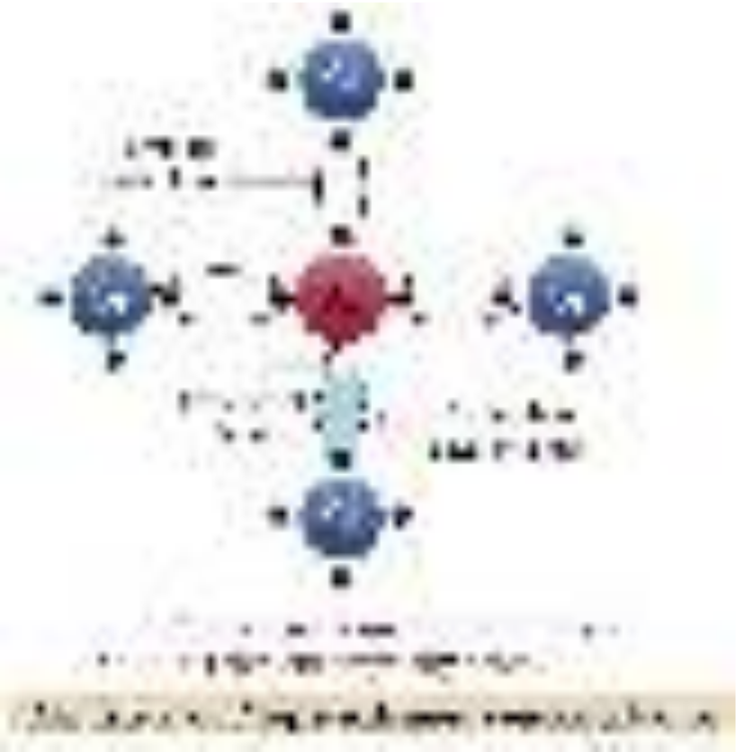
P TYPE SEMICONDUCTOR

Formed by doping a pure semiconductor with trivalent impurity like Aluminium, Boron etc .

Each acceptor atoms provides one excess hole to the crystal structure.

The number of free electrons is less than the number of holes. $n_h >> n_e$

The net current will be due to free electrons which are the majority carriers.



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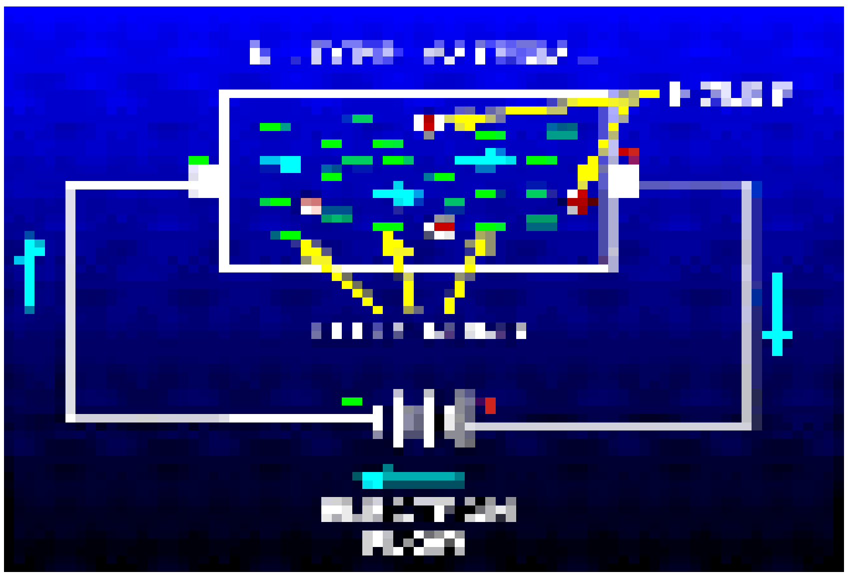
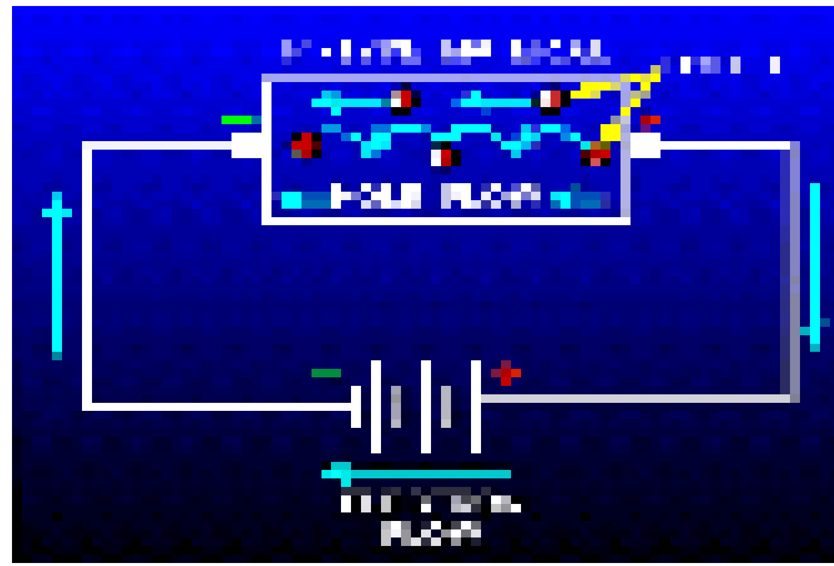
CURRENT FLOW IN SEMICONDUCTOR





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Conductivity and Mobility

- The current in semiconductor is the combined effect of drift as well as diffusion of charge carriers when a potential is applied.
- The mobility of charge carriers is defined as the drift velocity per unit elctric field.

$$\mu = \frac{v_d}{E} = \frac{i}{n_0 e A E} = \frac{J}{n_0 e A} \quad m^2 V^{-1} s^{-1}$$

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- Conductivity is defined as the current density per unit electric field.

$$\sigma = \frac{J}{E} = \frac{n_0 e v_d}{E} = n_0 e \mu \quad \Omega^{-1}$$

- Conductivity is directly proportional to mobility ie. More the mobility, greater is the conductivity.
- The conventional current is due to both electrons and holes so

$$\sigma = ne\mu_n + pe\mu_p = e(n\mu_n + p\mu_p)$$

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P-N JUNCTION

- Boundary or interface between two types of semiconductor materials; the p-type and the n-type, inside a single crystal of semiconductor.

The p-type contains an excess of holes while the n-type contains an excess of electrons.

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P-N junction are elementary “building blocks” of semiconductor electronic devices such as diodes , transistors, LEDs etc.

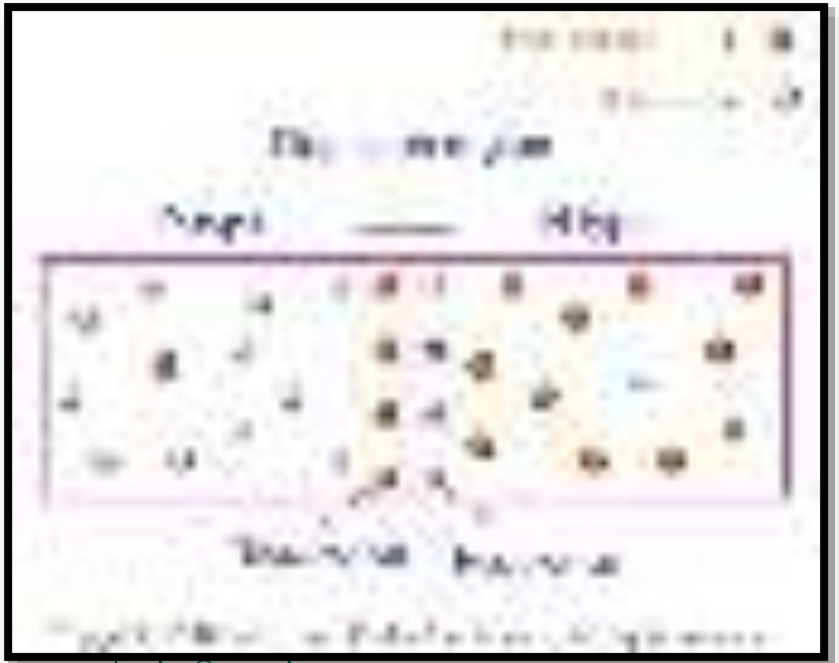
During the formation of a p-n junction, following two phenomenon takes place :-

Formation of :-

1) Depletion layer
2) Barrier potential

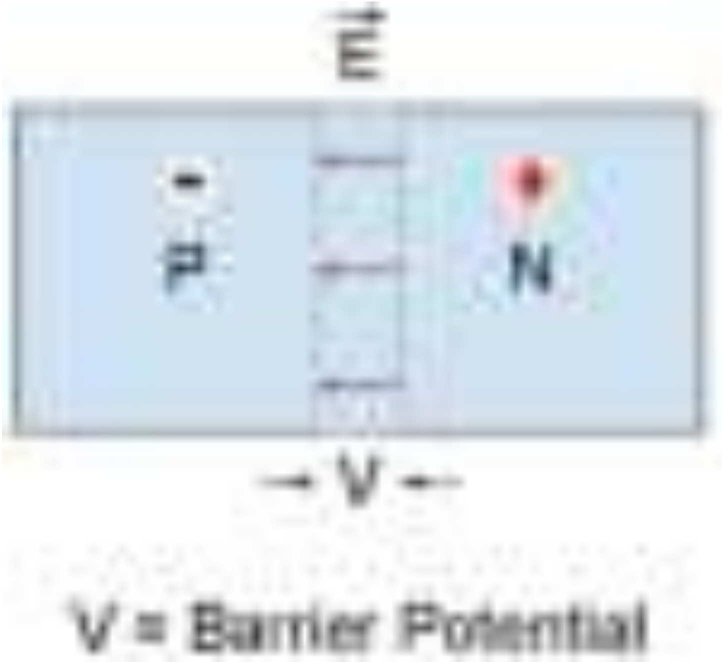
Depletion layer :- During the formation of p-n junction, a thin layer is set up both sides of the junction and is so-called because it is depleted or devoid of free charge carriers. It's width is about 1micrometer.

When a p-n junction is formed, at that instant, holes are still in p-region and electrons in the n-region



Junction or Barrier voltage (V_b)

- Since depletion layer of P-N Junction diode has no free charge carrier, but only fixed rows of oppositely charged ion on it's two sides because of this charge separation, an electric potential V_b is established across the junction even when junction is not connected to any external source of emf.
- It is known as junction or barrier potential.



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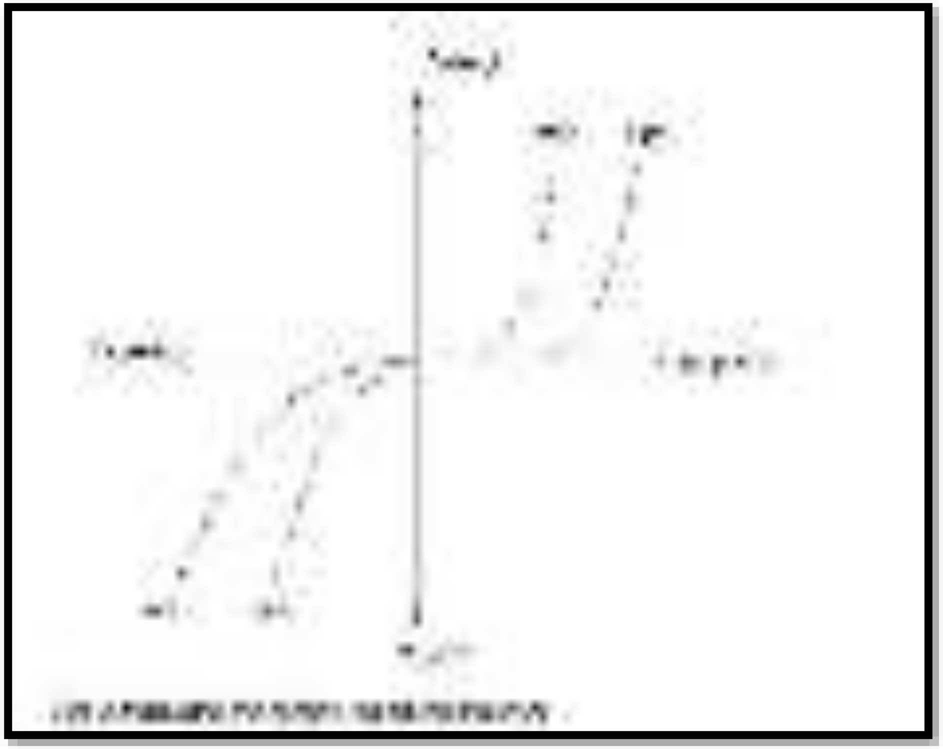
Processes involved in the P-N Junction :-

1 Holes from the P-side diffuse into the N-side where they combine with free electrons
2. Free electrons from the N-side diffuse into the P-side where they combine with holes
3. The diffusion current decays exponentially both with time and distance from the junction
4. Due to departure of free and mobile carriers from both sides of the junction, a depletion layer is formed. This layer contains only immobile or fixed ions of opposite polarity.
5. These uncovered by fixed ions set up a potential barrier across the junction. This potential difference opposes the diffusion of free majority charge carriers from one side of the junction to the other, till the process is completely stopped.
7. The width of depletion layer depends on the doping level.

Effects of Temperature on barrier potential



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P-N JUNCTION DIODE

Two terminal device which allows the flow of current in one direction only.

Has negligible resistance in one direction whereas very high resistance in other direction.

Blocks current in the reverse direction when the reverse voltage is within a specified range. Above this range, the reverse barrier breaks.

The voltage at which this breakdown occurs is called "reverse breakdown voltage". When the voltage of the circuit is higher than the reverse breakdown voltage, the diode is able to conduct electricity in the reverse direction.

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Types of Diodes

Zener diode,
P-N junction diode,
Tunnel diode
Varactor diode,
Schottky diode,
Photo diode,
Avalanche diode,
Light Emitting Diode.

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ADVANTAGES OF DIODES

No filament is necessary

Occupies lesser space

Long life

Operates at low voltage and consumes less power

Smaller in size and light in weight

Fast in operation

Forward bias

- P → positive
  N → negative
- Potential barrier reduces.
- Width of depletion layer decreases.
- Junction provides very small resistance.
- Forward current flow in circuit.
- Order of forward current is milli ampere.

Reverse bias

- P → negative
  N → positive
- Potential barrier increases.
- Width of depletion layer increases.
- Junction provides high resistance.
- Reverse current flow in circuit.
- Order of current is micro or nano ampere.

P-N Junction can basically work in two modes :-

1. Forward bias mode
2. Reverse bias mode

FORWARD BIASING …

A battery of emf (v) greater than the barrier potential (Vb) is connected across a p-n junction in a such a way that the +ve terminal of the battery is connected to the p-region and –ve terminal of battery is connected to n-region of the semiconductor.

It allows the current to flow across the junction easily. It can be explained in two ways :-

the +ve terminal of battery repel the holes whereas the -ve terminal of battery repel the electrons. Due to this, both electrons and holes are driven toward the junction.

the external potential reduces the barrier potential and the thickness of depletion layer.

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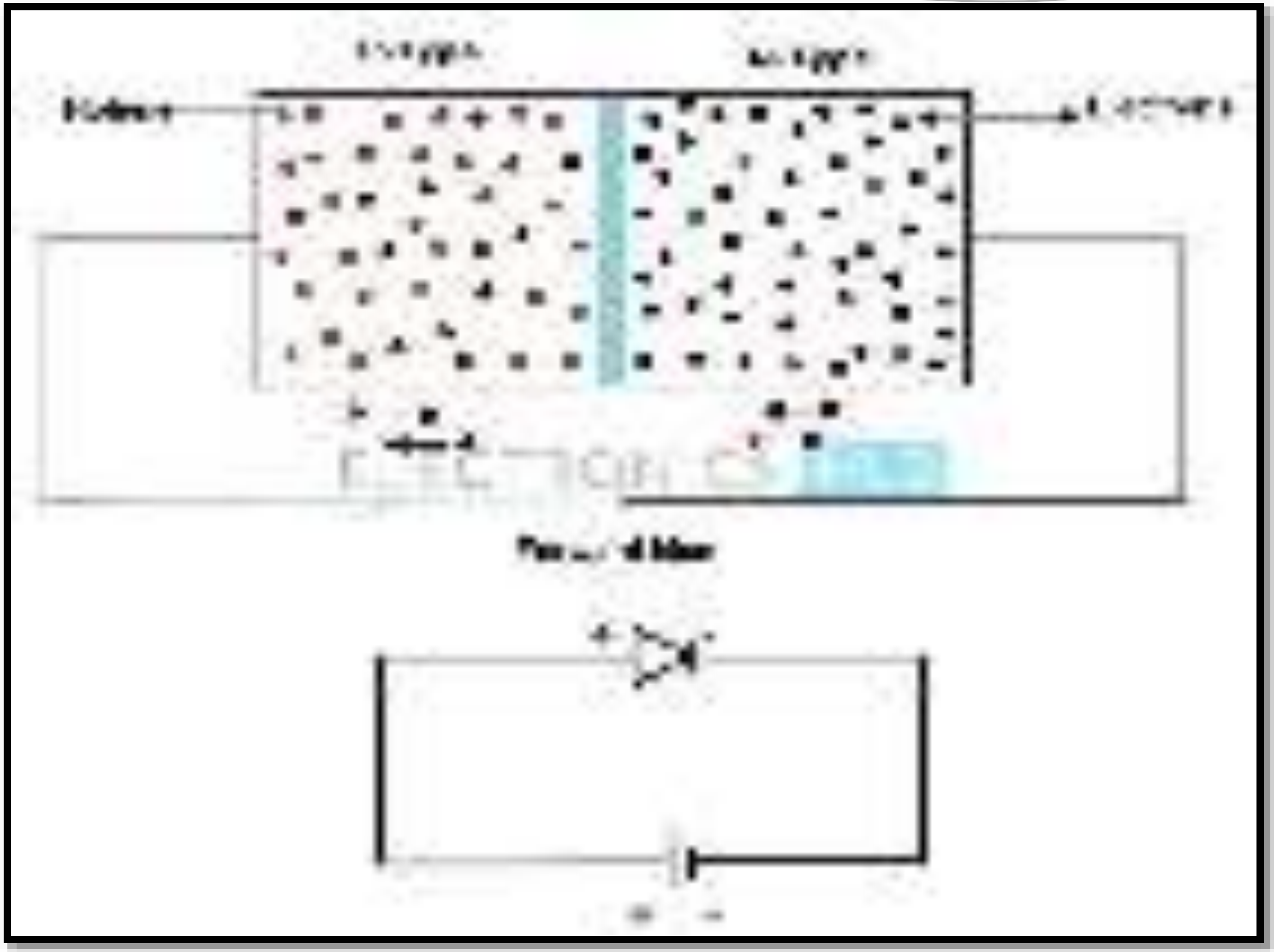

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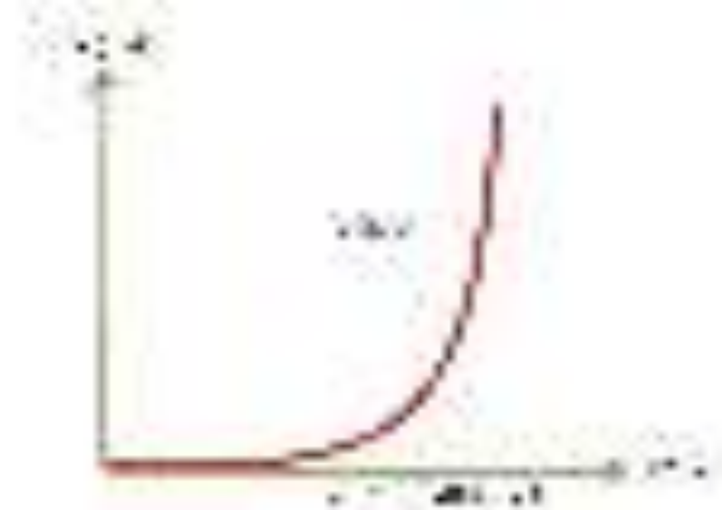
FORWARD V/I CHARACTERISTIC

- There is an exponential rise in the forward current with the applied voltage.
- The forward voltage at which the flow of current through p-n junction starts increasing rapidly is called 'KNEE VOLTAGE'
- It is practically same as the barrier potential.
- For $V < V_{th}$, current flow is negligible.
- At room temperature, V_{th} for Si is 0.7v and that for Ge is 0.3v.



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REVERSE BIASING

The +ve terminal of the applied battery is connected with the n-region and the –ve terminal is connected with the p-region of the semiconductor,

In this condition, very small current flows across the junction. This is because :-

- The holes are attracted by the –ve terminal and the electrons are attracted by the +ve terminal of applied battery, due to which they move away from the junction.
- The applied voltage, in this case, increases the barrier potential and the width of the depletion layer due to which majority charge carriers are not able to cross the junction.

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REVERSE V/I CHARACTERISTIC

- In reverse bias, there is no current due to majority charge carriers.
- However small amount of current is there due to minority charge carriers.
- For these minority charge carriers (electrons in p-region and holes in n-region), the applied voltage acts as forward biased.
- This small value of current in reverse biasing is called 'reverse saturation current'.
- This current depends on temperature.

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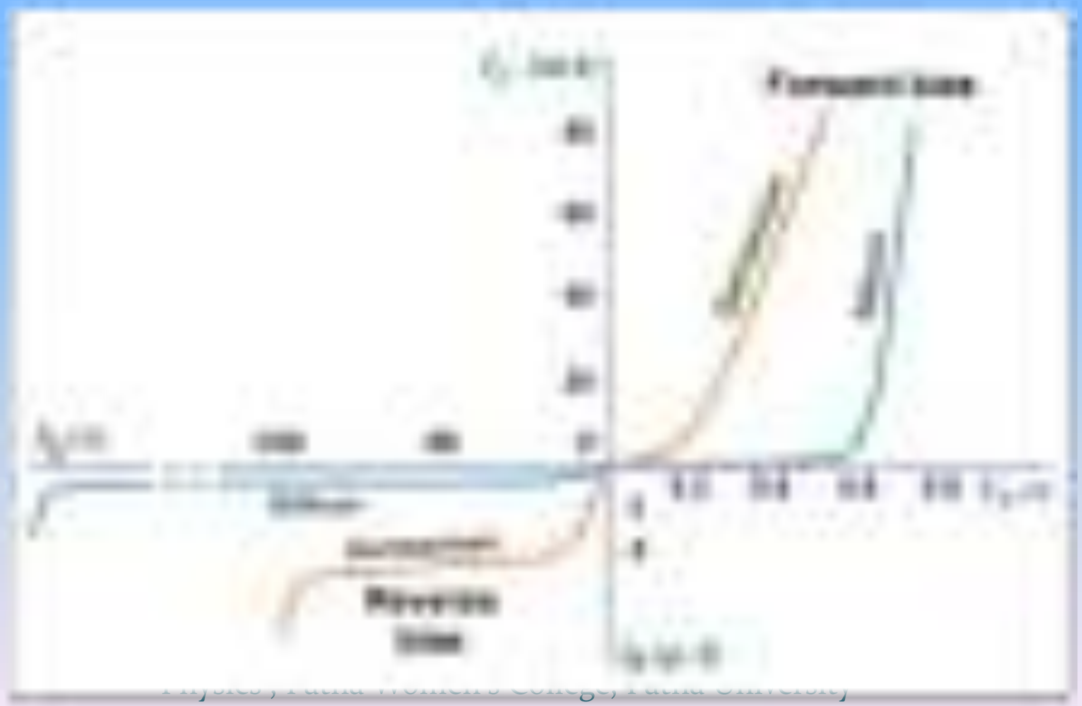
V/I Characteristic of PN Junction Diode

It is seen that the leakage current of Ge junction is much more than that of Si junction.



Diode Applications

As power or rectifier diodes :-

They convert 'AC current ' into ' DC current ' for dc power supplies of electronic circuits.

A diode is like a one way value that allows an electrical current to flow in only one direction. This process is called rectification.

Principle :- It's working is based on the fact that the resistance of the P-N junction diode become low when forward bias and high when reverse bias.

Types :- i) half wave rectifier

ii) full wave rectifier

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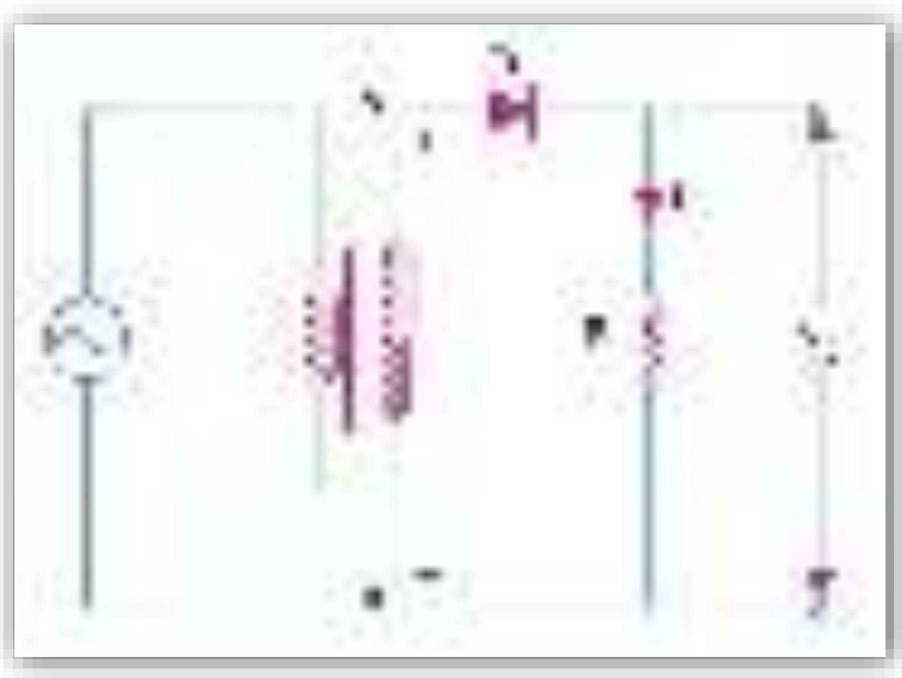
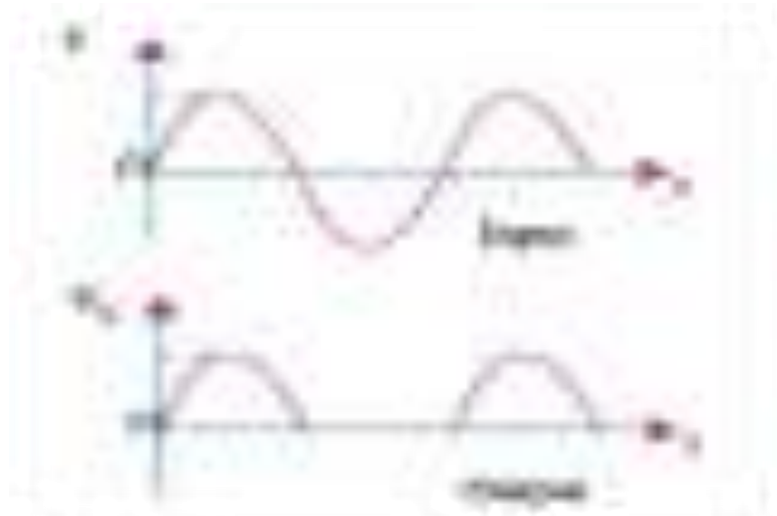
Half Wave Rectifier





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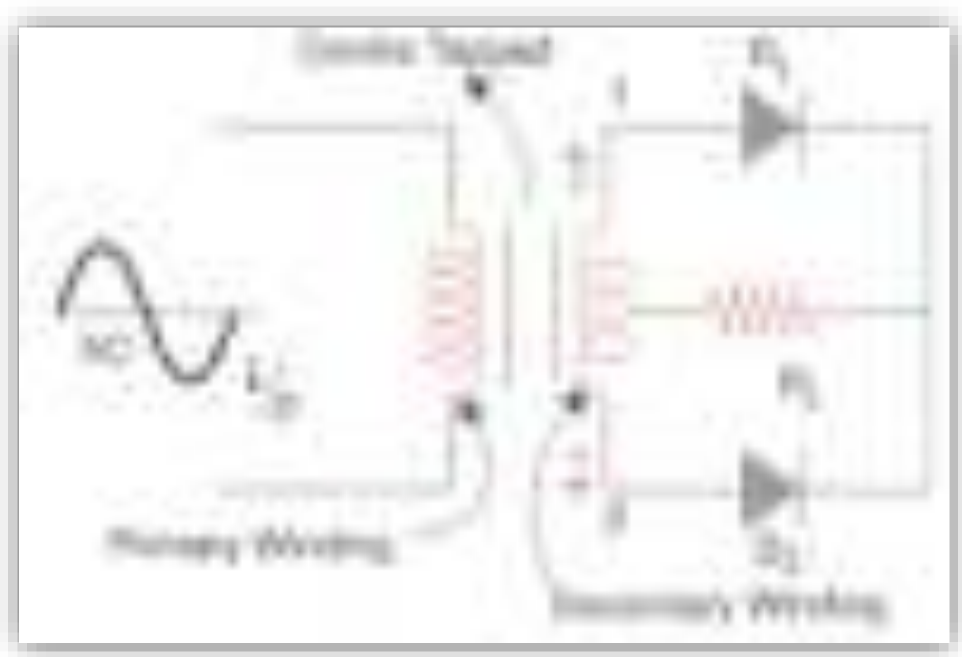
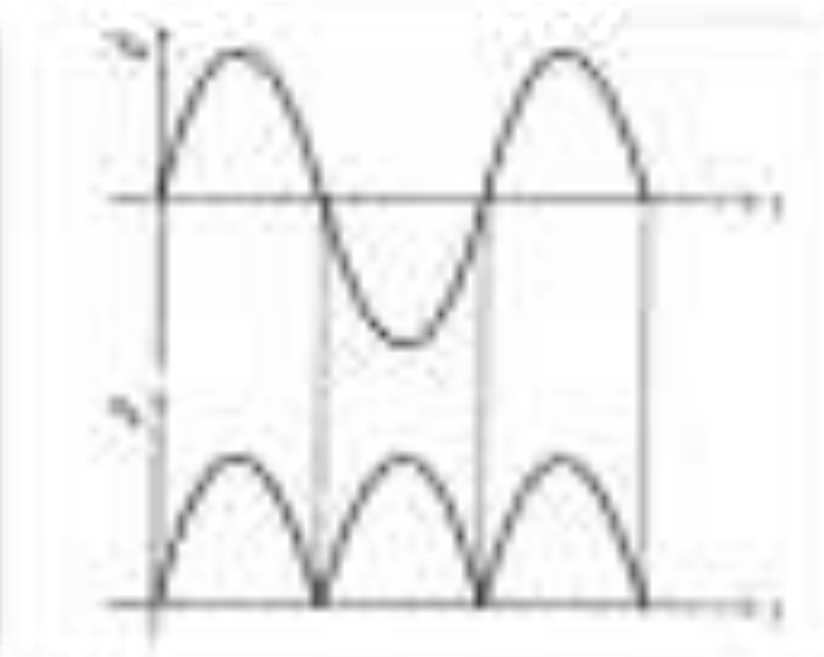
FULL WAVE RECTIFIER





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Zener Diode as Voltage Regulator

Symbol :-

- It is a special purpose diode.
- Designed to operate in reverse bias and breakdown region.
- Used as voltage regulator.

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- Heavily doped both p and n types of the junction.
- Thin depletion layer.
- High electric field.

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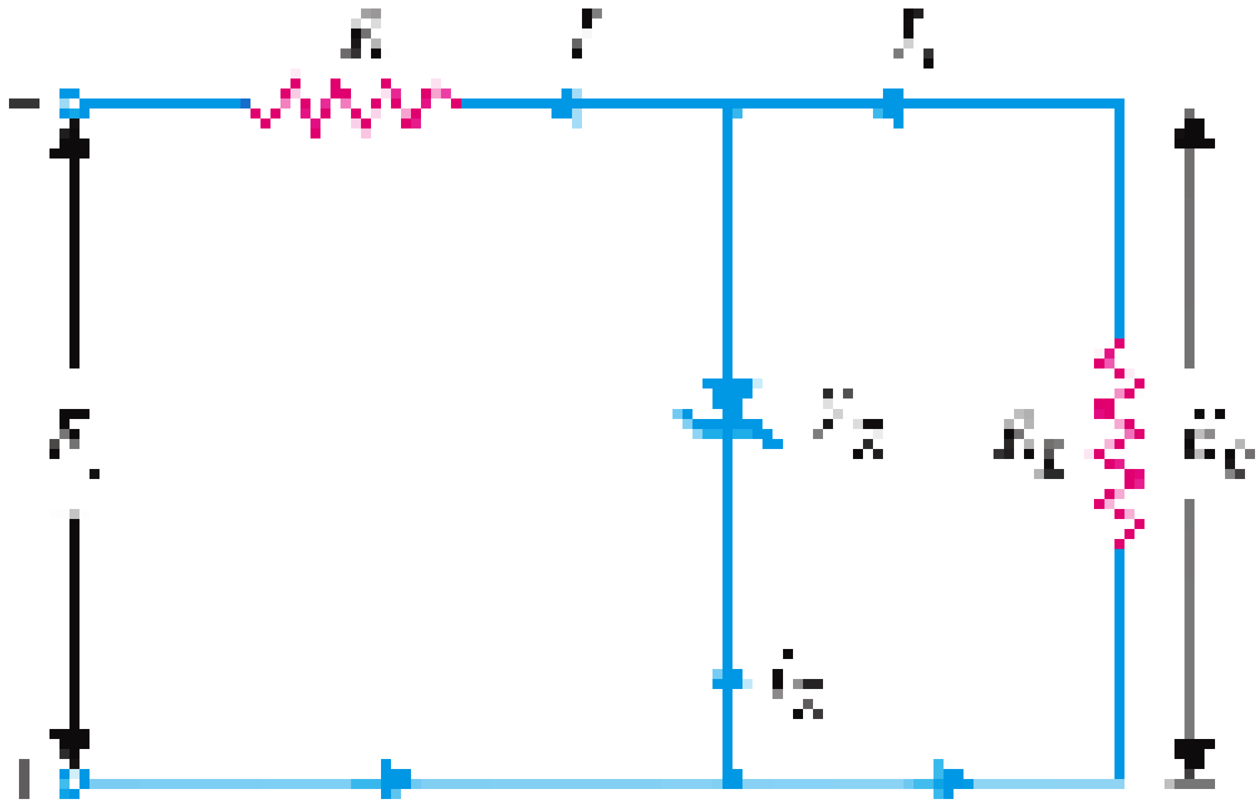
❖ The zener diode regulates the input signal either a.c or variable d.c to its Zener voltage.



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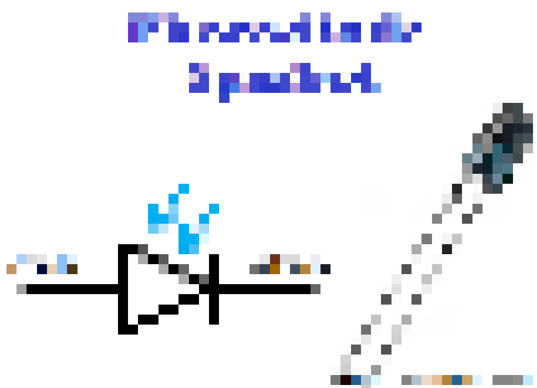
PHOTODIODE

- It is an optoelectronic device which works on the principle of conversion of light into electricity.
- It starts operating when light of a particular frequency is incident upon it and the current increases with the increase of intensity.



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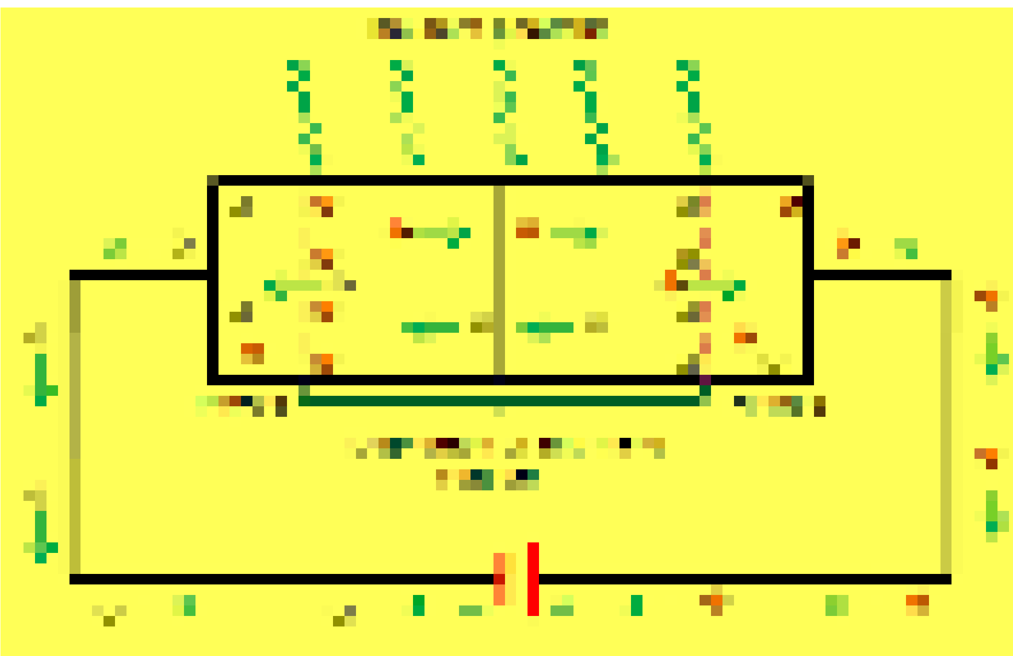
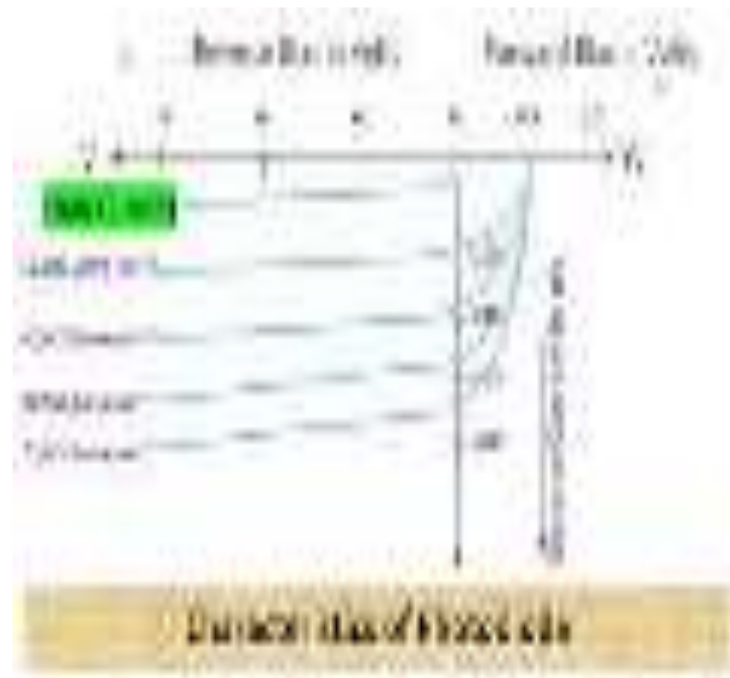
PHOTODIODE CHARACTERISTICS





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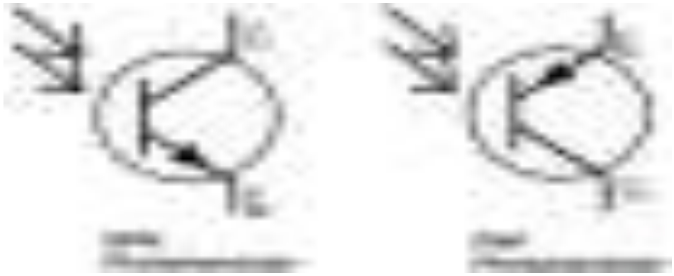
PHOTOTRANSISTOR

- It is a transistor whose base is illuminated with light.
- It operates when the light intensity increases so as to satisfy the biasing condition for BE junction, when base becomes positively biased wrt emitter



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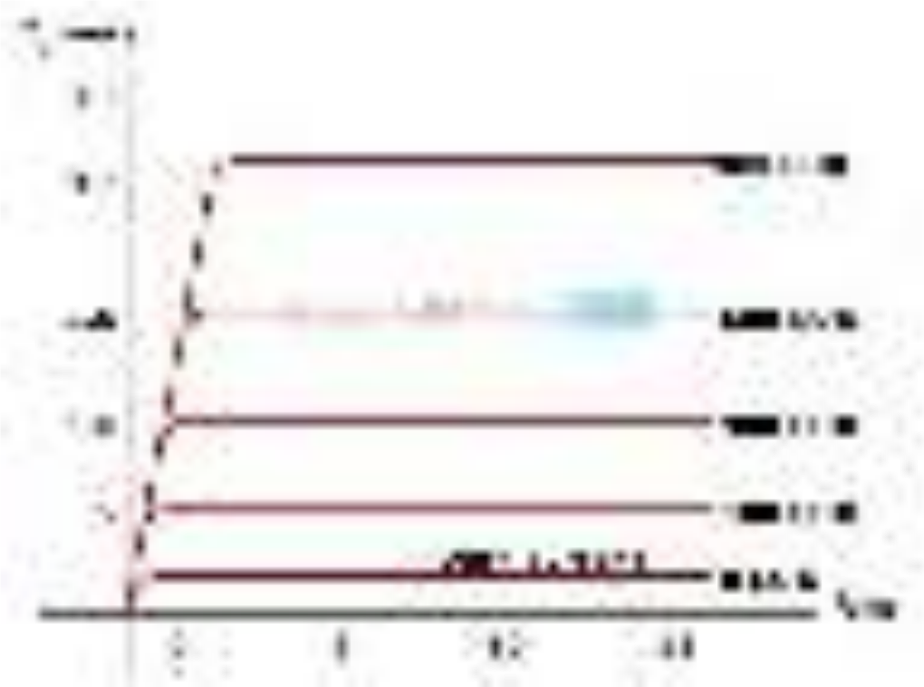
Characteristics of Phototransistor



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DIODE APPLICATIONS(CONTD.)

- Varactor diodes :- They are used for voltage controlled tuning circuits as may be found in radio and TV receivers. For this purpose, the diode is deliberately made to have a certain range of junction capacitance.

- In logic circuits used in computers.

- As signals diodes in communication circuit for modulation and demodulation of small signals.

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THANK YOU

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