Semiconductor Electronics: Materials, Devices And Simple Circuits

Classification of Metals, Conductors, and Semi-conductors

- Metals – Possess very low resistivity (or high conductivity)
  Their resistivities lie in the range: (10^{-2} Ω m to 10^{-8} Ω m)
  Their conductivities lie in the range: (10^{2} S m^{-1} to 10^{8} S m^{-1})

- Semi-conductors – Possess resistivity or conductivity intermediate to metals and insulators
  Their resistivities lie in the range: (10^{-5} Ω m to 10^{6} Ω m)
  Their conductivities lie in the range: (10^{5} S m^{-1} to 10^{-6} S m^{-1})

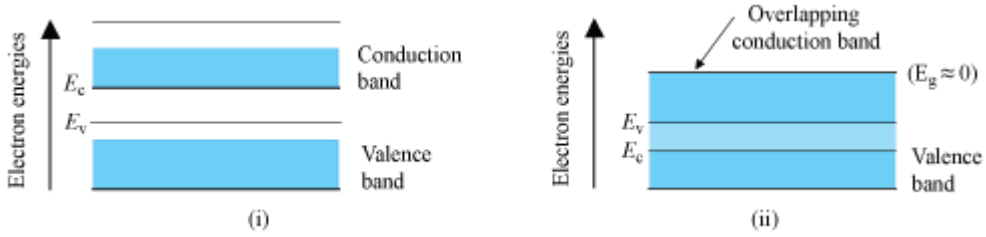
- Insulators – Possess high resistivity (or low conductivity)
  Their resistivities lie in the range: (10^{11} Ω m to 10^{19} Ω m)
  Their conductivities lie in the range: (10^{-11} S m^{-1} to 10^{-19} S m^{-1})

- Semi-conductors are of two types:

- Elemental semi-conductor – Example: Si and Ge

- Compound semi-conductor – Examples:
  • Organic: doped pthalocyanines, anthracene, etc.
  • Organic polymers: polypyrrole, polythiophene, etc.
  • Inorganic: CdS, GaAs, CdSe, etc.

- **Energy band diagram of metals or conductors**

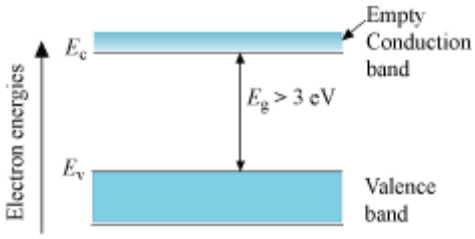


- Conduction band is partially filled and the valence band is partially empty or the conduction and valence band overlap.

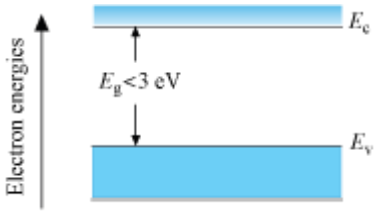
- Due to overlap, electrons can easily move into the conduction band. This situation makes a large number of electrons available for electrical conduction.

- When the valence band is partially empty, electrons from their lower levels can move to higher levels making conduction possible.

- **Energy band diagram for insulators**



- Large band gap E_g exists. ($E_g > 3$ eV)
- Since there are no electrons in the conduction band, no electrical conduction is possible.
- The electron cannot be excited from the valence band to the conduction band by thermal excitation.
- **Energy band diagram for semi-conductors**

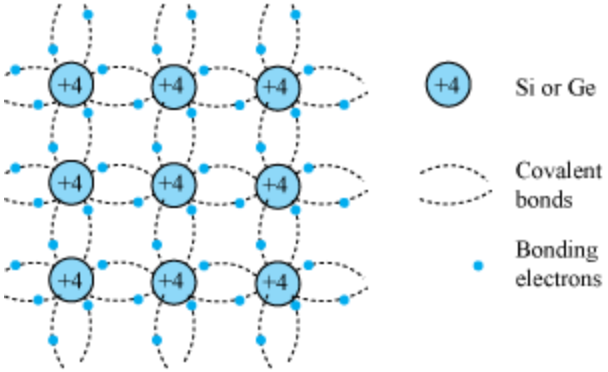


- Energy band gap E_g is small. ($E_g < 3$ eV)
- At room temperature, some electrons from valence band cross the energy gap and enter the conduction band.

Intrinsic Semiconductor

- A pure semi-conductor which is free of every impurity is called intrinsic semi-conductor.

  Example – Ge and Si



The crystal structure of Ge/ Si in 2-D is shown above.

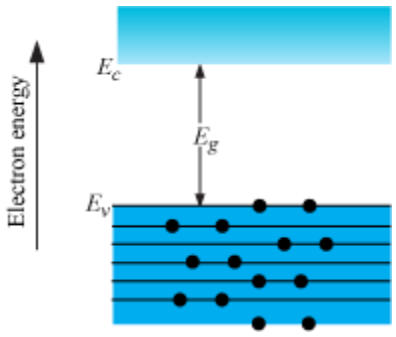
- In intrinsic semi-conductors, the number of free electrons n_e is equal to the number of holes n_h.

  That is, $n_e = n_h = n_i$

  Where,

  $n_i \rightarrow$ Intrinsic carrier concentration

- An intrinsic semi-conductor will behave similar to an insulator at $T = 0$ K



- Eg is the energy band gap between valence band and conduction band.
- The value of E_g for Si and Ge are 1.1 eV and 0.7 eV, respectively.

Extrinsic Semiconductor

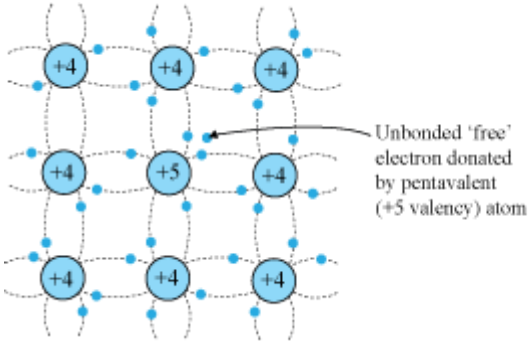
A semi-conductor with impurity atom added to it is called extrinsic semi-conductor.

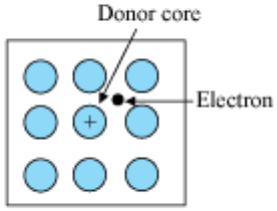
Two types of extrinsic semi-conductors are:

n-type semi-conductor

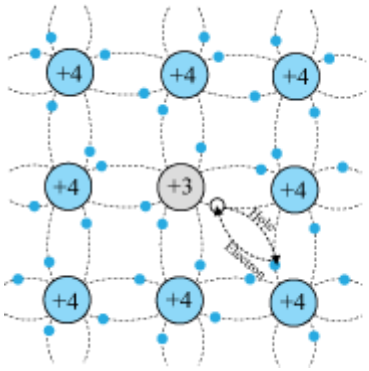
p-type semi-conductor

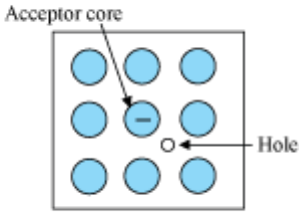
- *n*-type semi-conductor
- Doped with pentavalent atoms such as arsenic or phosphorous or antimony or bismuth
- Impurity atom has five valence electrons, which will replace Si or Ge atoms.
- Pentavalent dopant donates one extra electron for conduction and hence, is known as donor impurity.
- Total number of conduction electrons n_e is due to the electrons contributed by donors and those generated intrinsically while the total number of holes n_h is only due to the holes from the intrinsic source.
- The rate of recombination of holes would increase due to increase in the number of electrons. Therefore, the number of holes would get reduced further.
- Electrons are the majority carriers and holes are the minority carriers. Therefore, they are called *n*-type semi-conductors.
- For *n*-type semi-conductors, $n_e >> n_h$





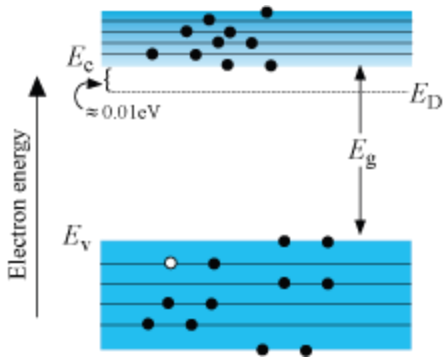
- *p*-type semi-conductor
- Doped with trivalent atoms such as aluminium, boron, or indium, etc.
- Dopant has one valence electron less than Si or Ge. Therefore, the atom can form covalent bonds with three neighbouring Si atoms, but does not have any electron to offer to the fourth Si atom.
- Therefore, the bond between the fourth neighbour and the trivalent atom has a vacancy or hole.



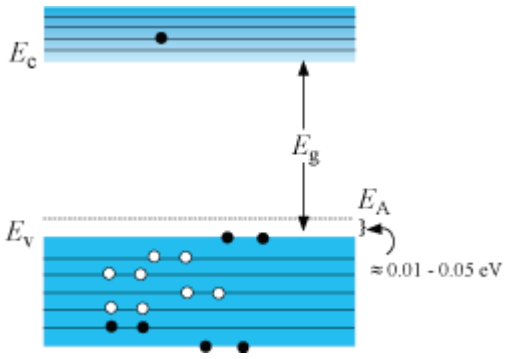


- Hole is available for conduction. One acceptor atom gives one hole.
- Holes are the majority carriers and electrons are the minority carriers.
- For *p*-type semi-conductor, $n_h >> n_e$

  Energy band diagram of the semi-conductors at $T > 0$ K,



n-type semi-conductor

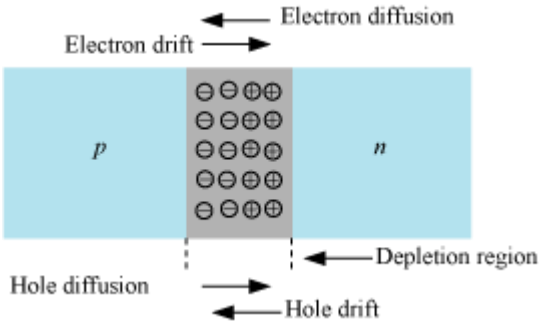


p-type semi-conductor

Diodes & Rectifiers

p-n Junction Formation

- A thin *p*-type semi-conductor wafer is considered. A part of it is converted into *n*-Si by adding a small quantity of pentavalent impurity.
- Wafer now contains a *p*-region and *n*-region and a metallurgical junction between *p*-, and *n*-region.
- *n*-type semi-conductor has more concentration of electrons than hole and *p*-type semi-conductor has more concentration of holes than electron. Therefore, the holes diffuse from *p*-side to *n*-side and electrons diffuse from *n*-side to *p*-side.
- When an electron diffuses from *n* to *p*, it leaves behind it an ionised donor on *n*-side. The ionised donor (+ ve charge) is immobile as it is bounded by the surrounding atoms.
- Therefore, a layer of positive charge is developed on *n*-side of the junction.
- Similarly, a layer of negative charge is developed on the *p*-side.

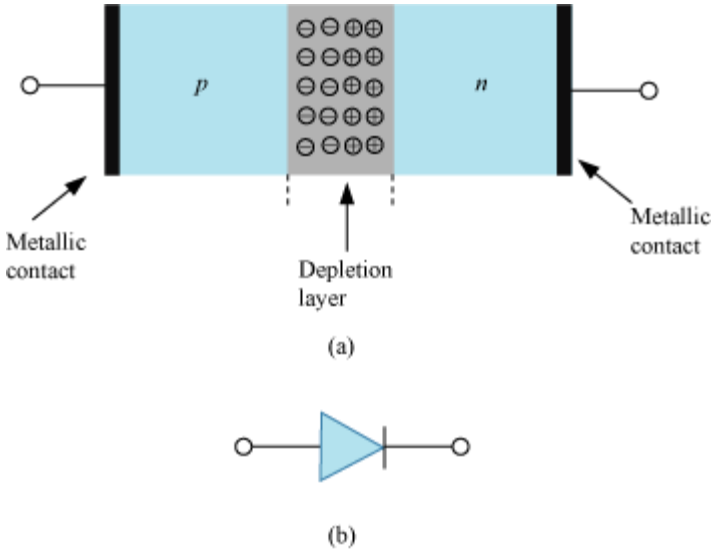


- This space-charge region on either side of the junction together is called depletion region.
- The positive space-charge region on *n*-side of the junction and negative space-charge region on *p*-side of the junction, appearing as electric field, is developed and directed from + ve charge to − ve charge.
- Due to the field, an electron from *p*-side moves to *n*-side and a hole from *n*-side of the junction moves to *p*-side.
- The motion of charge carriers due to electric field is called drift current and is opposite in direction to the diffusion current.
- Initially, diffusion current is large and drift current is small. As diffusion continues, the space charge regions on either side of the junction extends, thereby increasing the electric field strength and hence drift current. The process continues until the diffusion current is equal to drift current.

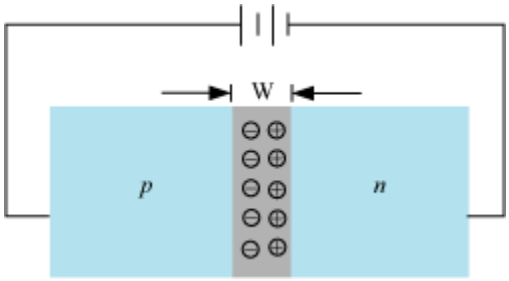
- Thus, a *p*-*n* junction is formed. Under equilibrium, there is no net current.
- Loss of electrons from the *n*-region and gain of electron by the *p*-region causes a difference of potential across the junction of two regions. This potential tends to prevent the movement of electron from *n* to *p* region. Therefore, it is called a barrier potential.

Semi-conductor Diode

- A semi-conductor diode is basically a *p*-*n* junction with metallic contacts provided at the ends for the application of an external voltage.
- A *p*-*n* junction diode is symbolically represented as shown in the figure below.

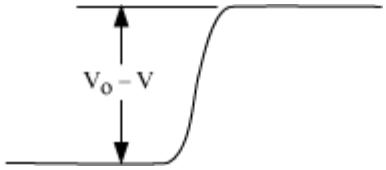


***p*-*n* junction diode under forward bias**



- *p*-side is connected to positive terminal and *n*-side to the negative terminal.
- Applied voltage drops across the depletion region.
- Direction of applied voltage (V) is opposite to the build in potential (V_0).
- As the depletion layer width decreases, the barrier height is reduced.

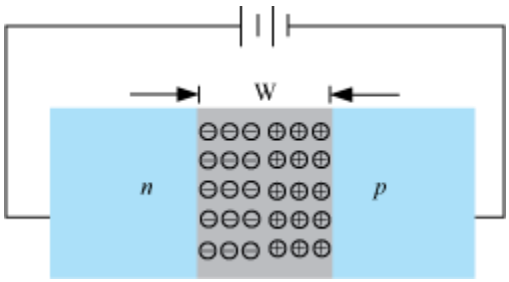
- Effective barrier height under forward bias is ($V_0 - V$).



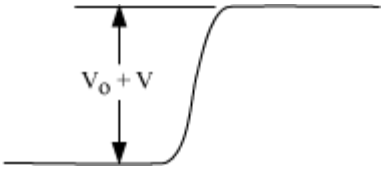
- Electron in *n*-region moves towards the *p*-*n* junction and holes in *p*-region move towards the junction. The width of the depletion layer decreases and hence, it offers less resistance.
- Diffusion of majority carriers takes place across the junction.

  This leads to forward current.

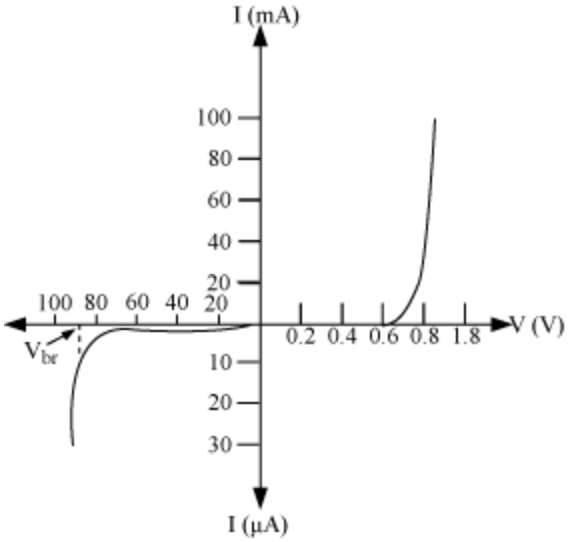
  ***p*-*n* junction diode under reverse bias**



- Positive terminal of battery is connected to *n*-side and negative terminal to *p*-side.
- Reverse bias supports the potential barrier. Therefore, the barrier height increases and the width of depletion region also increases.
- Effective barrier height under reverse bias is ($V_0 + V$).



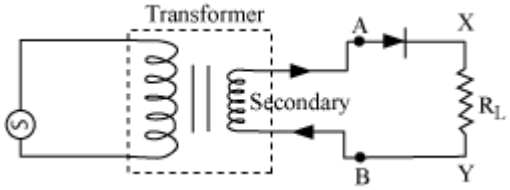
- No conduction across the junction due to majority carriers; few minority carriers cross the junction after being accelerated by high reverse bias voltage
- This constitutes a current that flows in opposite direction – celled reverse current.



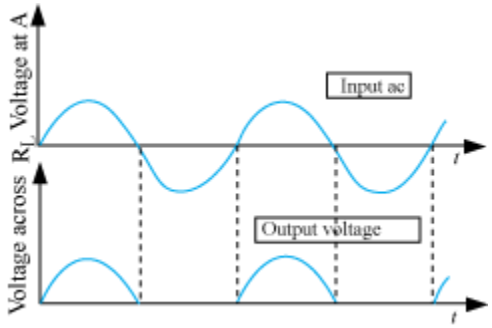
Rectifier

It is a device used for converting alternating current/voltage into direct current/voltage.

- **Half wave rectifier** is based on the principle that the resistance of *p-n* junction becomes low when it is forward biased and becomes high when reverse biased.



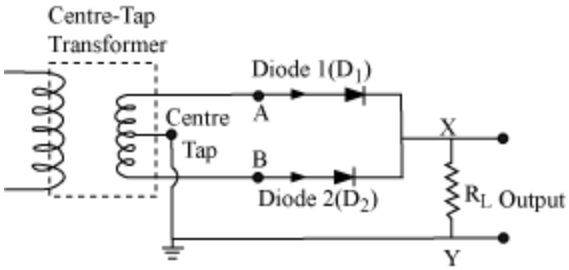
- When voltage at A is positive, it conducts; and when negative, it does not conduct.
- Therefore, in the positive half cycle of ac, there is a current through R_L and we obtain O/P voltage.
- In the negative half cycle, there is no current.



- Since the rectified output of this circuit is only for half of *i/p* ac wave, it is called half wave rectifier.

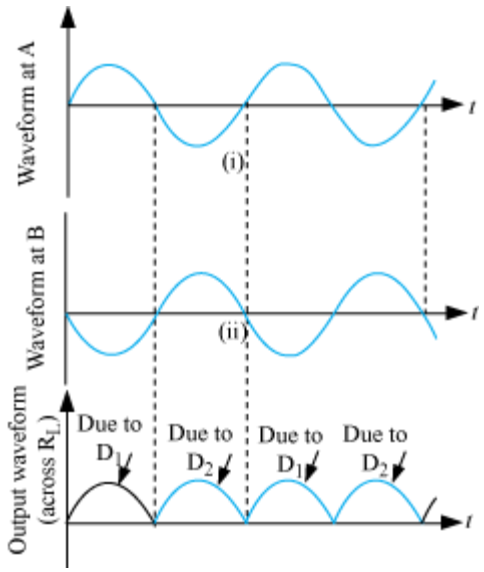
Full –wave rectifier

- Two diodes are used to give rectified O/P corresponding to both positive as well as negative half cycles.



- When voltage at A with respect to the centre tap is positive, and the voltage at B is negative. Then, D_1 is forward biased and D_2 is reversed biased. Hence, D_1 conducts and D_2 does not.

- When voltage of A becomes negative, then B becomes + ve. Therefore, D_1 does not conduct and D_2 conducts. Hence, we obtain output voltage during both the positive as well as negative half of cycle.



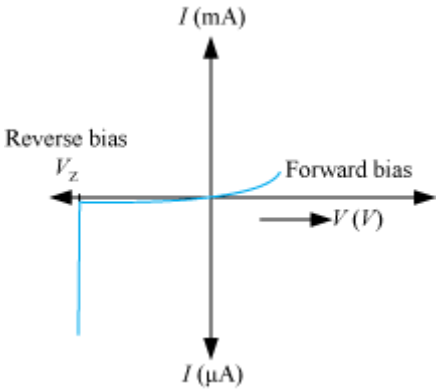
Special Purpose p-n Junction Diodes

Zener Diode

- It can operate in the reverse breakdown voltage region continuously without being damaged.

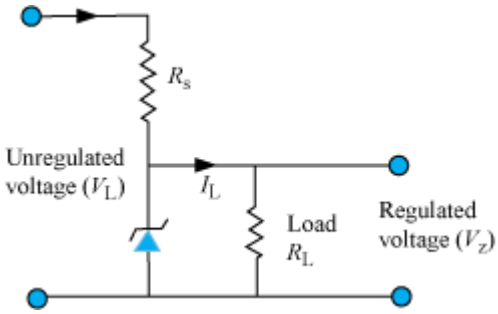
- It is represented by the symbol given below:

- It is a heavily doped *p*-*n* junction. As a result, the depletion region formed is very thin and the electric field of the junction is extremely high even for a small reverse bias voltage.
- The *I*-*V* characteristics of a Zener diode are shown in the figure below:



- It is widely used to regulate the voltage across the circuit.

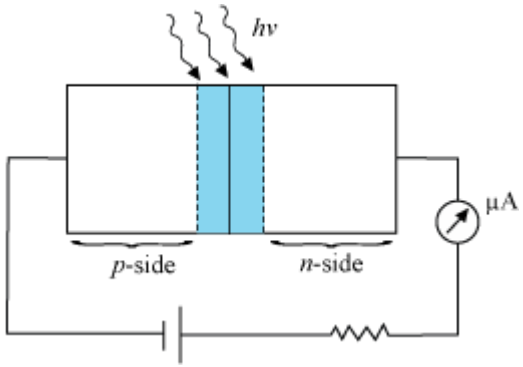
Zener Diode as Voltage Regulator



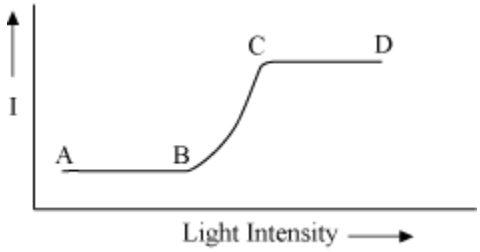
- After the break down voltage, a small change in the voltage across the Zener diode produces a large change in the current through the circuit.
- If the voltage is increased beyond the Zener voltage, then the resistance of the diode drops considerably.
- A Zener diode and a resistor are connected to a fluctuating DC supply such that the diode is reverse biased.

- When the voltage across the diode tends to increase, the current through the diode rises out of proportion and causes a sufficient increase in the voltage drop across the resistor. Therefore, the O/P voltage lowers back to normal.

Photodiode

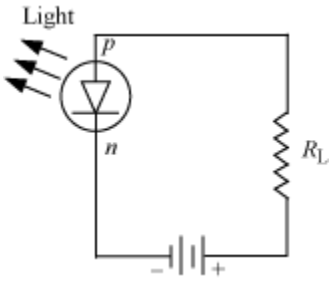


- A junction diode made from light sensitive semiconductor is called a photodiode.



- Current AB that flows when no light is incident is called dark current.
- When photons of light of energy *hv* fall on the photodiode, more electrons from the valence band move to the conduction band, provided *hv* is greater than the forbidden energy gap.
- The current in the circuit increases as the intensity of light is increased. Part BC represents the increase in the current.
- When the current is not increased with the increase in the intensity of light, the photodiode is said to be saturated. Part CD of the graph represents the saturated current.

Light Emitting Diodes (LEDs):



- All junction diodes emit some light when forward biased.

- A junction diode is made of gallium arsenide (GaAs). The energy is released in the infrared region, while those made of gallium arsenide phosphide (GaAsP) emit radiation in the visible region. They are called LEDs.

- The most important part of an LED is the *p*-*n* junction. The junction acts as a barrier to the flow of electrons between the *p* and *n* regions. Only when sufficient voltage is applied to the LED, the electrons cross the junction into the *p*-region and current flows through it.

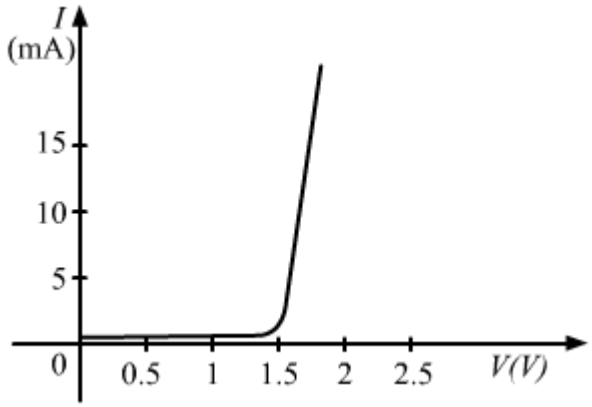
- The diode is encapsulated with a transparent cover so that emitted light can come out.

- LEDs are biased such that the light emitting efficiency is maximum.

- Semiconductors used to fabricate visible LEDs must have a band gap of at least 1.8 eV.
- LEDs have low operational voltage and less power. They requires less warm-up time.

_V-I_ characteristics of LED:

- On forward biasing an LED, the anode voltage is increased in small steps. The current does not flow until the barrier potential is reached.
- The barrier potential depends on the type of semiconductors used. For example, the barrier potential for Ga-As-P LED is about 1.5 V.
- When the voltage applied in the forward direction is equal to or greater than the barrier potential, current flows through the LED and it begins to emit light.
- The LED current increases with the voltage. The intensity of light emitted also increases.



Advantages of LEDs:

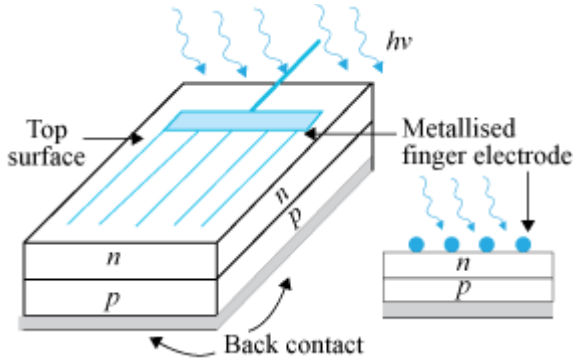
- LEDs cost less.
- They require low operating voltages and low power.
- They are light weight and durable.
- They have a high operating speed.
- LEDs with different spectral colours are available.

Applications of LEDs:

- They are used as indicators of various measurement systems and measuring instruments.
- They are used in advertising boards, rolling displays in offices, banks, airports, stations, etc.
- Infrared LEDs are used in burglar alarms.
- LEDs are also use to illuminate traffic signals.
- They are used as brake and fuel indicators in bikes and cars.
- They are used in 7-segment display units, which are used to display outputs of various instruments in decimal digit formats.

Solar Cell

- It is a semiconductor device used to convert photons of solar light into electricity.



- It generates emf when solar radiation fall on the *p*-*n* junction.

- A *p*-type silicon wafer of about 300 μm is taken over which a thin layer of *n*-type silicon is grown on one side by diffusion process.

- The generation of emf by a solar cell when light falls on it is due to following three processes:

    1. The light close to the junction generates e-h pairs.

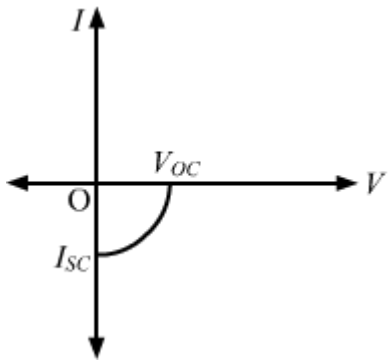
    2. The electric field of the depletion region separates the electrons and holes.

    3. The electrons reaching the *n*-side are collected by the front contact, while the holes reaching the *p*-side are collected by the back contact. Thus, the *p*-side becomes positively charged and the *n*-side becomes negatively charged, giving rise to photovoltage.

- Semiconductors with band gaps close to 1.5 eV are ideal materials for the fabrication of solar cells.

_V-I_ characteristic of a solar cell:
The *V-I* characteristic of a solar cell as follows:

- I_{sc} is the short-circuit current when the load resistance R_L is zero.
- V_{oc} is the open-circuit voltage when R_L is infinity.



Advantages of a solar cell:

- It harnesses solar energy that is free from all kinds of pollutions. Thus, they are eco-friendly.
- It is highly durable and, hence, requires no maintenance.

Applications of solar cells:

- They are used for operating satellites, sensors or equipments set up in deep forests or at mountain tops.
- They are used in communication stations, mobile military operations, etc.
- They are used in hand-held calculators, watches, portable TV sets, etc.
- They are also used to supply power to emergency phones on express highways.

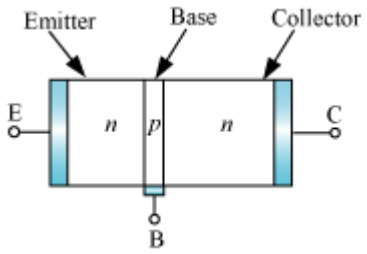
Junction Transistor

There are two types of transistors:

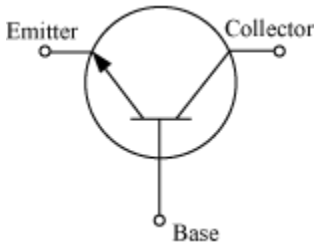
- *n*-*p*-*n* transistor
- *p*-*n*-*p* transistor

***n*-*p*-*n* transistor**

- Two segments of *n*-type semi-conductor are separated by a segment of *p*-type semi-conductor.
- Schematic representation:

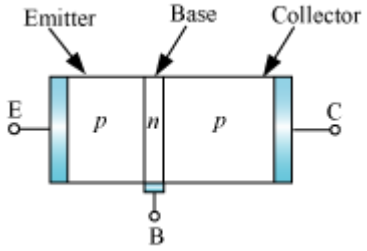


- Symbol

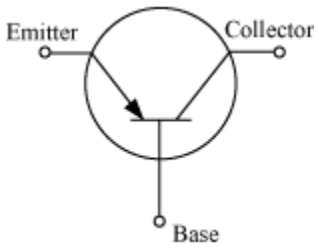


***p*-*n*-*p* transistor**

- Two segments of *p*-type semi-conductor separated by a segment of *n*-type semi-conductor
- Schematic representation



- Symbol



Three segments of transistor:

- Emitter – Segment is on one side of the transistor. It is of a moderate size and heavily doped. It supplies a huge number of majority carriers for the current flow through the transistor.
- Base – It is the central segment. It is very thin and lightly doped.
- Collector – It collects major portion of the majority carrier supplied by the emitter. It is moderately doped and large in size compared to emitter.

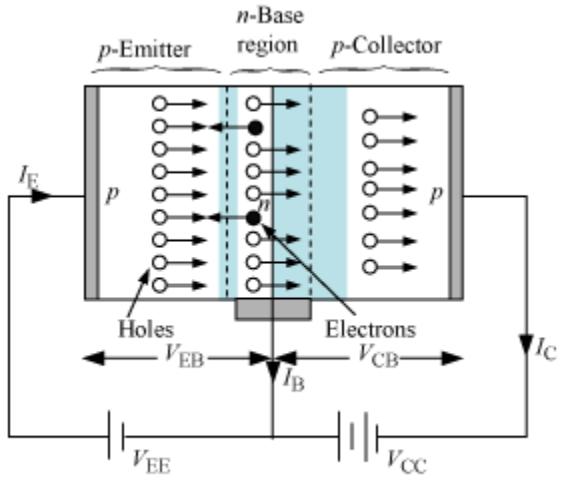
Applications of transistor:

Transistor is used as

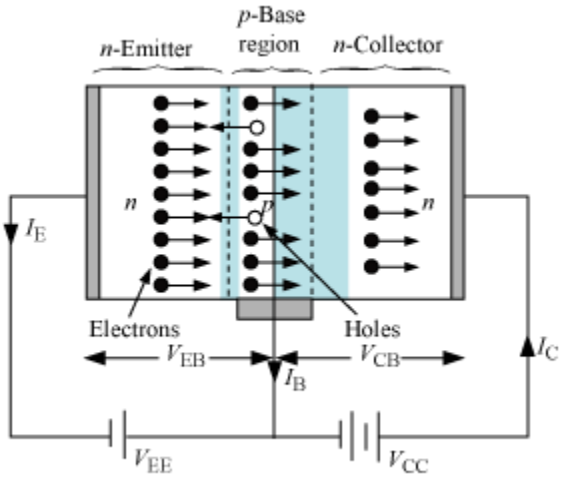
(i) amplifier,

(ii) oscillator and,

(iii) switching circuits.



(a)



(b)

- V_{CC} and V_{EE} create the biasing. The biased transistor is said to be in active state.
- V_{CB} – Collector base voltage

  V_{EB} – Base emitter voltage
- Base is the common terminal for the two power supplies whose other terminals are connected to emitter and collector respectively.
- Heavily doped emitter has a high concentration of majority carriers, which will be holes in *p*-*n*-*p* transistor and electron in an *n*-*p*-*n* transistor.
- These majority carriers enter the base region in large numbers. The base is lightly doped. Therefore, it has few majority carriers.

- In *p*-*n*-*p*, the base has the majority carriers as electrons. The large number of holes entering the base from the emitter swamps the small number of electrons there.
- Since the base collector junction is reverse biased, the holes which appear as minority carriers at the junction can easily cross the junction and enter the collector.
- Base is made thin so that the holes cross the junction instead of moving to the base terminal.
- I_h– Hole current

  I_e – Electron current

  Total current in a forward biased diode is $I_h + I_e$.

  ∴ Emitter current

  $I_E = I_h + I_e$

  Base current, $I_B << I_h + I_e$ (as major part of I_E goes to collector)

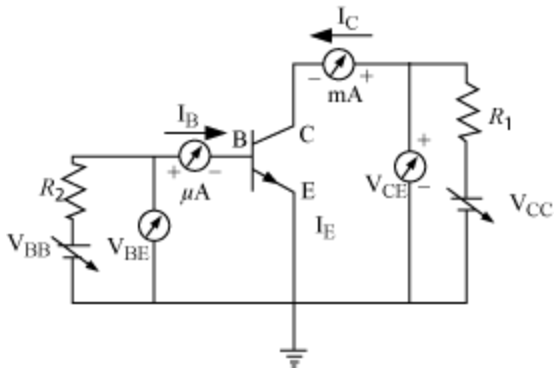
  $\therefore I_E = I_C + I_B$
- Direction of motion of electron is opposite to current. However, the direction of motion of holes is identical with the direction of conventional current.
- In active state of the transistor, the emitter-base junction acts as a low resistance while the base collector acts as a high resistance.
- Transistor works as an amplifier with its emitter-base junction forward biased and base collector junction reverse biased.

Basic Transistor Circuit Configuration

Three configurations of a transistor:

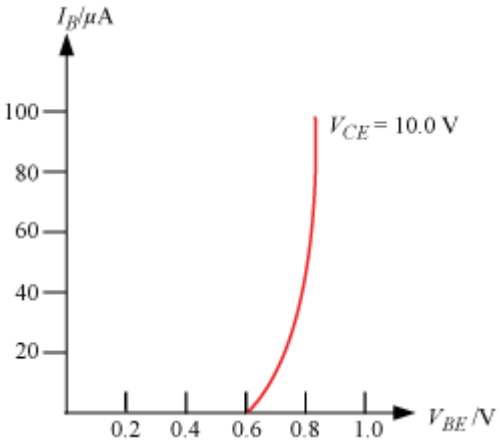
- Common emitter (CE)
- Common base (CB)
- Common collector (CC)

CE configuration is the most widely used transistor.

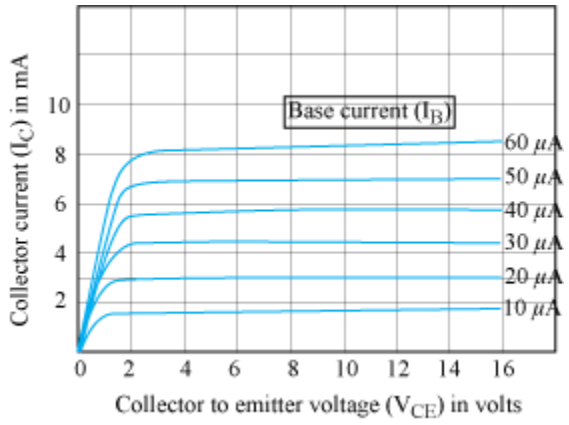


- Variation of base current (I_B) with the base emitter voltage V_{BE} is called input characteristics.
- Variation of collector current I_C with the collector – Emitter voltage V_{CE} is called output characteristics.

Input characteristics



Output characteristics



Parameters of Transistors

- Input resistance (r_i)

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

ΔV_{BE} – Base-emitter voltage

ΔI_B – Base current

V_{CE} – Constant collector-emitter voltage

- Output resistance (r_0)

$$r_0 = \left(\frac{\Delta V_{CE}}{\Delta I_C} \right)_{I_B}$$

ΔV_{CE} – Collector-emitter voltage

ΔI_C – Collector current

I_B – Base current

- Current amplification factor (β)

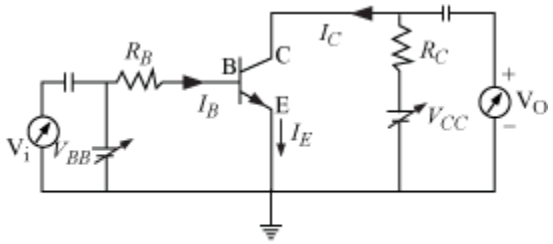
$$\beta_{ac} = \left(\frac{\Delta I_c}{\Delta I_B} \right)_{V_{CE}}$$

I_C – Collector current

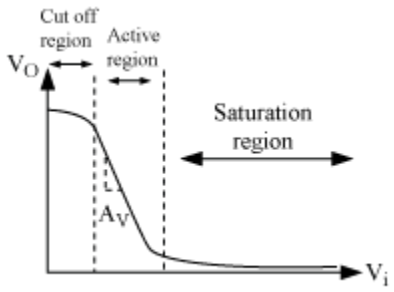
I_B – Base current

V_{CE} – Constant collector-emitter voltage

Transistor as a device



(a)



(b)

Transistor as a Switch

- When the transistor is used in the cut-off or saturation region, it acts as a switch.

  Applying Kirchhoff's voltage rule to above figure,

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

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

  Where,

  V_{BB} – dc input voltage (V_i)

  V_{CE} – dc output voltage (V_o)

  $\therefore V_i = I_B R_B + V_{BE}$ and

  $V_o = V_{CC} - I_C R_C$

- When Vi < 0.6, the transistor is in cut-off.

  Therefore, $I_C = 0$

  $\therefore V_o = V_{CC}$

  When $V_o > 0.6$ V, then I_C increases. Therefore, V_o decreases as the term $I_C R_C$ increases.

- With increase in V_i, I_C increases almost linearly and as a result, V_o decreases linearly till its value becomes less than about 1.0 V.
- Change becomes non-linear and the transistor goes to saturation. If V_i is increased further, then V_o becomes almost zero.
- When V_i is low, V_o is high and if V_i is high, then V_o is low. When the transistor is not conducting, it is said to be switched off and when it is driven into saturation, it is said to be switched on.

Transistor as an Amplifier

- When the transistor operates in the active region, it acts as an amplifier.
- If ΔV_o and ΔV_i are small changes in o/p and i/p voltage, then $\Delta V_o/\Delta V_i$ is called small signal voltage gain, A_V.

$V_o = V_{CC} - I_C R_C$

$\Delta V_o = 0 - R_C \Delta I_C$

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

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

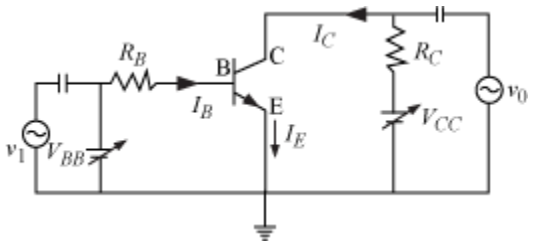
$\therefore A_V = - R_C \Delta I_C / R_B \Delta I_B$

$= - \beta_{ac} (R_C/R_B)$

Where, β_{ac} is equal to $\Delta I_C / \Delta I_B$

Transistor as an Amplifier (CE Configuration)

- Operating point is fixed in the middle of its active region.



- An ac i/p signal v_i is superimposed on bias V_{BB} (dc). The o/p is taken between collector and ground.
- Applying Kirchhoff' law to the output loop,

$V_{CC} = V_{CE} + I_C R_C$

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

$v_i \neq 0$

Then, $V_{BB} + v_i = V_{BE} + I_B R_B + \Delta I_B (R_B + r_i)$

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

$$\therefore v_i = \Delta I_B \left(R_B + r_i \right)$$

$$= r \Delta I_B$$

$$\beta_{ac} = \frac{\Delta I_C}{\Delta I_B} = \frac{i_c}{i_b}$$

It is current gain denoted by A_i.

- Change I_C due to change in I_B causes a change in V_{CE} and the voltage drop across resistor R_C, because V_{CC} is fixed.

  $\therefore \Delta V_{CC} = \Delta V_{CE} + R_C \Delta I_C = 0$

  $\Rightarrow \Delta V_{CE} = - R_C \Delta I_C$

- Change in V_{CE} is the o/p voltage V_o.

  $\therefore V_o = \Delta V_{CE} = - \beta_{ac} R_C \Delta I_B$

- Voltage gain of amplifier

$$A_v = \frac{V_o}{V_i} = \frac{\Delta V_{CE}}{r \Delta I_B}$$

$$= -\beta_{ac} \frac{R_C}{r}$$

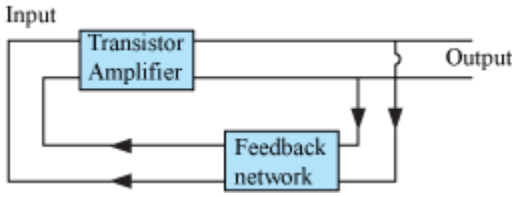
Negative sign represents that the o/p voltage is in opposite phase to i/p voltage.

- Power gain (A_P) is the product of current gain and voltage gain.

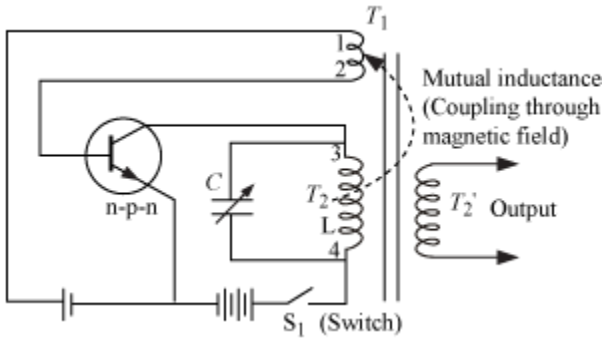
  $A_P = \beta ac \times A_v$

  Feed back amplifier and transistor oscillator

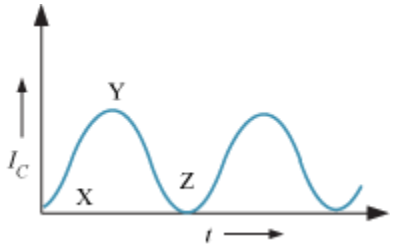
- In oscillator, the ac o/p is produced without any external i/p signal.
- An oscillator is a device in which the o/p power is returned back to the i/p, in phase with the starting power (i.e., as a positive feedback).



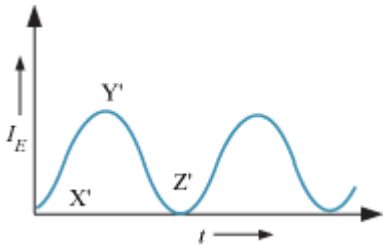
- Feedback can be achieved by inductive coupling or LC or RC network.



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



- The current increases from *X* to *Y*.
- Coupling between T_2 and T_1 causes a current to flow in the emitter current. It is a feedback from i/p to o/p.

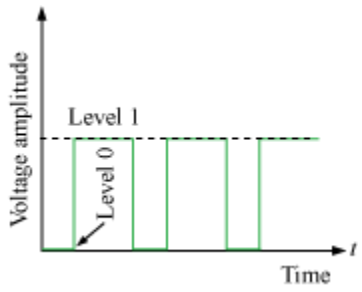


- As a result, this feedback current also increases from X' to Y'.
- Current in T_2 connected in the collector circuit acquires value Y as the transistor becomes saturated.
- There is no further increase in collector current to the magnetic field amount. T_2 stops growing. Due to static field, there is no feedback from T_2 to T_1. Collector current decreases from Y to Z.
- Decrease in I_C causes the magnetic field to decay around the coil T_2.
- T_1 also decays. Emitter current reaches Z' when transistor is cut-off. Both I_E and I_C stop flowing.
- Therefore, the transistor comes back to its original state.
- Resonant frequency of this tuned circuit determines the frequency at which the oscillator will oscillate.

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

Digital Electronics and Logic Gates

- In digital electronics, we use only two levels of voltage – '0' and '1'.

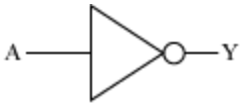


Logic Gates

- A gate is a digital circuit that follows a certain logical relationship between the input and output voltage.

- NOT, AND, OR, NAND, NOR are the five common logic gates.
- NOT gate

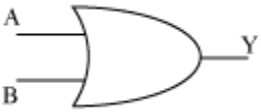
  The output is the inverted version of the input.



Truth table	
Input	Output
A	Y
0	1
1	0

- OR gate

  The output is 1 when either of the input or both the inputs are 1.

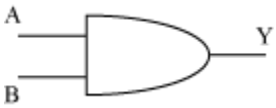


Truth table		
I	O	O/P

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

- AND gate

  The output is 1 only when both the inputs are 1.

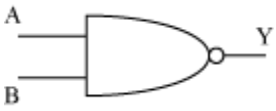


Truth table		
I	O	O/P
A	B	Y
0	0	0
0	1	0

1	0	0
1	1	1

- NAND

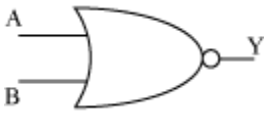
  Output is the inverted version of the output of AND gate.



Truth table		
I	O	O/P
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

- NOR gate

  Output is the inverted version of the output of OR gate.



Truth table		
I	O	O/P
A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

Integrated Circuits (IC)

- It is the concept of fabricating an entire circuit on a small single chip of a semi-conductor.
- Monolithic integrated circuit is a widely used technique in which a single chip is used. Its dimension is 1 mm × 1 mm or even smaller.
- Depending on the nature of input signals, ICs can be of two types.
- Linear or analogue ICs: The linear ICs process analogue signals, which change smoothly and continuously over a range of values between a maximum and a minimum. The output is directly proportional to the input. Example: operational amplifier
- Digital ICs − These process signals that have only two values. These contain logic gates.

(Logic gate ≤ 10) → Small scale integration

(Logic gate ≤ 100) → Medium scale integration

(Logic gate ≤ 1000) → Large scale integration

(Logic gate > 1000) → Very large scale integration