ICS 2200 ELECTRONICS

Electronics is the study of conduction current in solids, gases, vacuum and liquids.

It is a branch of engineering that comes from the 2 words: Electrons – negatively charged particle in an atom, Mechanics – Study of motion of an electron.

Electronics is also study of electrons and how they can be used to perform different functions.

-The ability to control movement of electrons or electron flow is the basic of electronics; it specializes in digital computers, audio systems, communication systems, and automatic control.
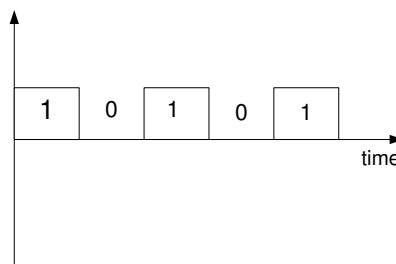
Analogue Signal

An analogue signal is one whose amplitude is changing with time continuously. This is shown in the diagram below.
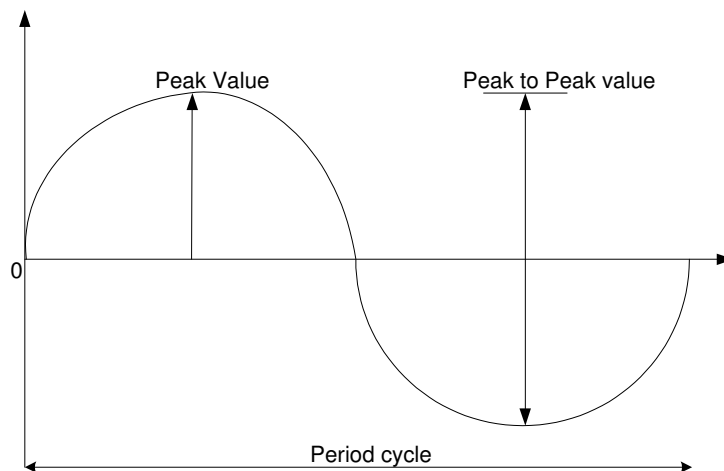
Characteristic of analogue signals:

- An analogue signal varies continuously with time. It is typical of nature e.g light, end waves and voice. They have been used for the last 100 years.

Digital signal

Characteristics of Digital Signals

- They do not vary with time. Occur in discrete form.
- Typical of technology. They can be produced from analogue signals through analogue to digital conversion.
- They have been used for about 50 years with invention of vacuum tubes and transistors.

Applications of electronics
-        Communication – satellites
-        Medicine
-        Entertainment - 3 stereos, HIFI systems, Ipod
-        Industrial applications – Assembly lines
-        Transport – Autopilot, tracking systems, missile guiding
-        Military / defense/ security – Biometrics
-        Astronomy
-        Instrumentation – Electronic pianos
Radar – Radio detection and ranging can be used for all the above e.g in medicine to detect cancer

PHYSICAL AND CHEMICAL STATES OF MATTERS
- *Matter* is anything that occupies spaces and has weight.
- The basic building block of matter is an atom.

   Matter exists in three physical states –
   - Solid
   - Liquid
   - Gas
   When is exists in liquid or gas its dimension are determined by the container.
   Chemical states of matter include:
   - Elements
   - Compounds
   - Mixtures

- ❖ *Element:* - is a substance that cannot be broken into simpler substances. It has only one kind of atom e.g. Mg, K, Na, Oxygen.

Hydrogen	H	1
Helium	He	2
Lithium	Li	3
Beryllium	Be	4
Boron	B	5
Carbon	C	6
Nitrogen	N	7
Oxygen	O	8
Fluorine	F	9
Neon	Ne	10
Sodium	Na	11
Magnesium	Mg	12
Aluminium	Al	13
Silicon	Si	14
Phosphorous	P	15
Sulphur	S	16
Chlorine	Cl	17
Argon	Ar	18
Potassium	K	19
Calcium	Ca	20

- *Compound* - is formed by chemical combination of two or more elements e.g. Nacl, MgO, H_2O etc.
- *Mixtures* – Combination of substances where the individual elements poses the same properties as when they were alone e.g. Air.

All matter is composed of atoms and molecules.
The smallest particle into which a compound can be divided and retain its physical properties is called a **molecule**.

The smallest particle into which an element can be divided and retain its chemical properties is called an **atom**.
Electric charge: - The quantity of electricity in a body

THE ELECTRON THEORY
- Every atom has one or more electron and one nucleus. The nucleus contains the protons and Neutrons.
- The simplest atom is that of hydrogen and consists on one electron orbiting around the nucleus.
- The nucleus has only one proton apart. In a simple hydrogen atom the nucleus is made of protons and neutrons of approximately equal numbers.
- The electrical charge of an electron is negative and that of a proton is +ve and neutron is neutral.
- A normal atom is electrically neutral containing an equal number of +vely charged atoms and –vely charged electrons. Meaning that the charge per electron and proton is equal but opposite in polarity.
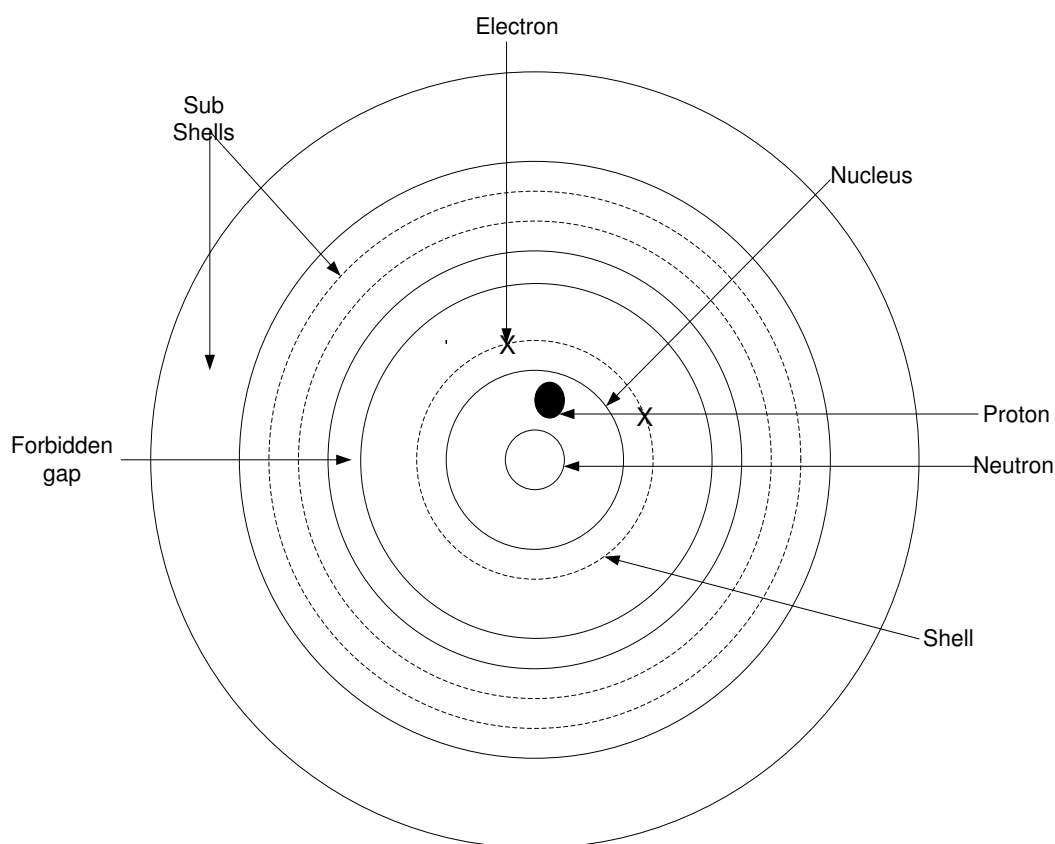
THE ATOM MODEL

- One of the men who contributed greatly to the development and understanding of atomic structure Neil Bohrls.
- He developed a model for atoms which restricted the orbits of atom electrons to well defined shells of levels. i.e. Electron do not crowd together in mass rather more round in different orbits.
- An atomic level of such orbits is termed as a shell which can be defined as the spherical orbit of an electron or electrons.
- The figure above shows the structure of a carbon atom.

- **Nucleus** -is the innermost part of an atom. It contains protons and neutrons.
- **Electron**-negatively charged particle revolving in specified orbits called quantum energy levels.
- **Proton**-positively charged particle in the nucleus.
- **Neutron**-particle with no charge in the nucleus.
- **Shell**-section where electrons orbit, it has subshells and quantum energy levels. The number of electrons (N) in a shell is given by the general formulae $N = 2n^2$ where n is the shell number.
- **Subshell**-section with electrons inside a shell, several of them make a shell. The number of electrons in a subshell is given by the general formula: $2+4(m-1)$, where m is the subshell number.
- **Forbidden gap**-section where electrons can not orbit, is between two subshells.
- The first theory of Bohrl was that an electron in an atom can revolve in certain specified orbits without the emission of radiant energy. The theory explains the stability of an atom.
- Second theory was that an electron may make a transition from one of its specified non radiating orbits to another of lower energy. When it does so a single proton is emitted whose energy difference between the initial and final states and whose frequency f is given by the relation below.

$$hf = E_i - E_f$$

Where h is plank's constant, E_i and E_f are the energies of initial and final state.

THE EXCLUSION PRINCIPLE

- Paul's exclusion principle states that no two electrons can occupy the same quantum mechanical state since different states correspond to different distances from the nucleus.
- In a complex atom there's no room for all the electrons in state near the nucleus. Some are forced into states further away having higher energies.
- The maximum number of electrons per shell is given by $2n^2$ where n is the shell number counting outwards from the nucleus.
- Sub-shell electrons = $2 + 4(m-1)$, where m is the subshell number

1st	2é
2nd	2é, 6é
3rd	2é, 6é, 10é
4th	2é, 6é, 10é, 14é
5th	2é, 6é, 10é, 14é, 18é
6th	2é, 6é, 10é, 14é, 18é, 22é

<u>**Example**</u>

Determine the maximum n<u>o</u> of electrons in the 3rd shell

$$\text{Max No} = 2^n$$
$$N = 3$$
$$= 2 \times 3^2$$
$$= 18es$$

ATOMIC NUMBER & ATOMIC WEIGHT

Atomic number of an element is determined by the number of protons in each of it's atoms of that element

$$B = 5 \quad 2{:}3$$
$$S = 16 \quad 2.3.6$$

Atomic weight of an element is determined by comparing the weight of it's atoms of carbon = 12

VALENCE ELECTORNS (State electron)

- o Are those electrons in the outermost shell of an atom. The number of valence electrons in an atom determines it'd stability or instability both electrically and chemically.
- o For all the atoms with two shall the outermost shell is full when it has 8 *es* if the atom if the atom has fewer than 8*es* in the outermost shell then the atom is electrically and chemically unstable and active.
- o Electrically the valence electrons can be moved from their own atoms and are some times referred to as free electrons.
- o It's possible to detach an orbit electron from an atom leaving the atom with an access the charge. The atom in this state is called a +ve ion or cation.
- o Alternatively the neutral atom may be given an addition orbit/electron in which case the atom assumes a negative charge. Which is called an -ve or anion.
- o An ion is any atoms that is not electrically balanced and that has gained or lost electrons.

Energies that change electrical balance include:-

a- Chemical energy – dry cells, batteries
b- Mechanical energy e.g generators
c- Light energy
d- Heat energy (Friction)
e- Magnetic energy

Conduction in a gas

Cathode   Space Charge   Gas Molecules   Anode
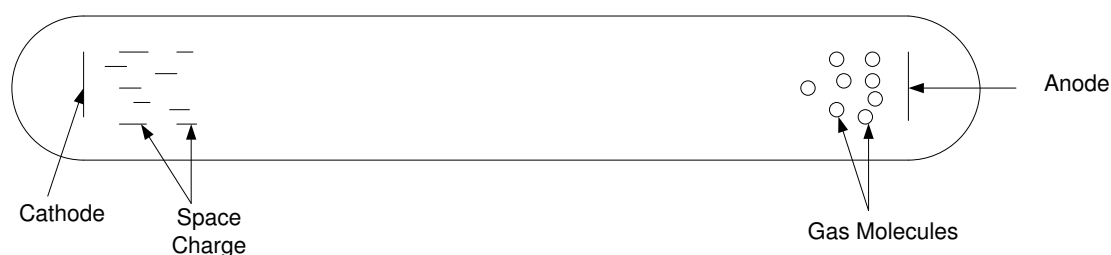
Conduction in gases takes place through ionization. Accelerating electrons strike the molecular and ionize it.The gas should have low pressure. It cannot conduct under normal pressure.

Conduction in a vacuum
A vacuum can only conduct electromagnetic waves e.g. light

Material used in electrical & electronic circuits
Solids
Types of solids
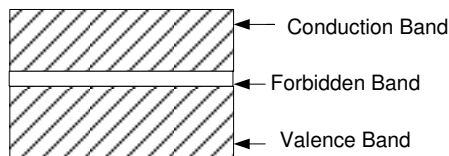- Conductors   - Insulators   -Semiconductors

Conductors
- o These are materials that allow current to pass through.
- o They have 1-3 electrons in outermost shell.
- o Have metallic bond
- o Have free electrons.
- o Have low resistance.
- o The conduction band and valence band overlap and are very small.

- o Resistance increases with increase in temperature.
- o Eg = 0ev

    Examples of conductors are all metals.

Insulators
- o These are materials that do not allow current to pass through.
- o They have 5 to 8 electrons in outermost shell.
- o They have a structure that has covalent bonding that results in no free electrons that allow conduction of an electric current.
- o Insulators have a very large energy gap between the conduction band and the valence band.
- o Eg = 5ev
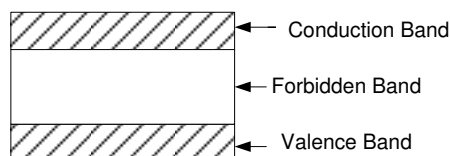
Semiconductors
These are materials that have poor conductivity at low temperatures and good conductivity at high temperatures.

Characteristics of Semiconductors
- o They have 4 electrons in outermost shell / band
- o Their atomic structure has covalent bonds
- o They have a moderate number of free electrons
- o Eg = 1.1ev
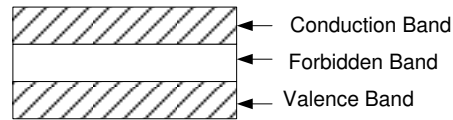
- o They have a moderately sized of forbidden band
- o There are two types : Intrinsic and Extrinsic

Intrinsic semi conductors

These are semi conductors in their pure form e. g silicon, germanium. Conduction takes place through holes and electrons.

Silicon Structure 2:8:4
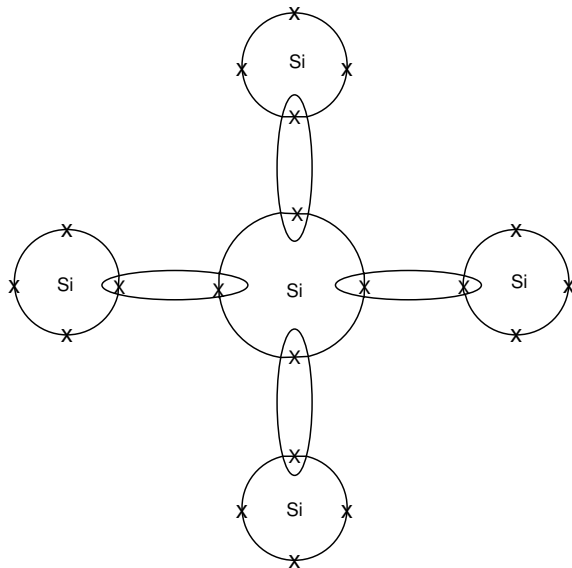
Extrinsic Semiconductors
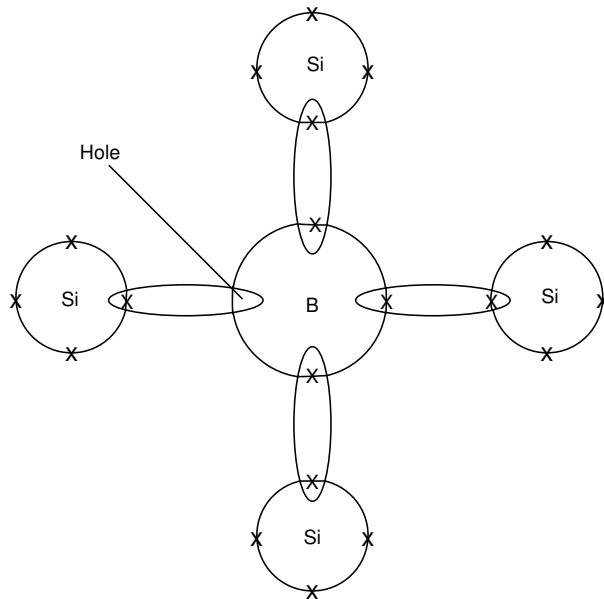These are semiconductors to which impurities have been added through the process of doping.

There are two types: P-type
                    N-type

P – Type
This is formed by process of adding trivalent impurities into the crystal structure of silicon. Trivalent impurities include boron

Boron 2:3
Silicon 2:8:4

Holes are the majority carriers in P-type semiconductors thus it is an acceptor semiconductor. Conduction is by movement of holes. Holes move in the direction of conventional current.

N – type
This is formed by adding pentavalent impurities e.g. phosphorous, arsenic, antimony.
Silicon 2:8:4
Phosphorous 2:8:5
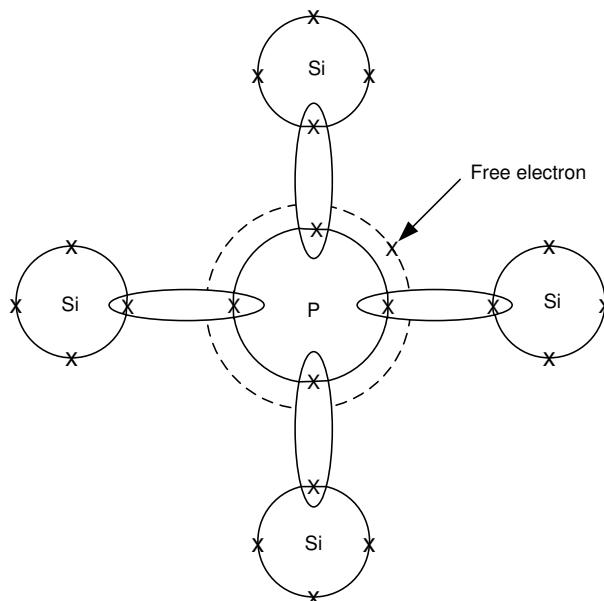
Majority charge carriers are electrons and thus conduction is by electron flow. Electron flow is opposite to the direction of flow of conventional current.

Terms and concepts

Charge   Amount of current passing through a given point for a given time.
                It is the ability to attract or repel electrons.
                $Q = It$

Current	Is the rate of flow of charge. SI unit is Amperes (A)
	$I = Q/t$

Voltage   Is the energy which drives charge across a circuit. It is also called electromotive force (emf). SI unit is volts (V)

Potential difference   Is the energy which drives charge across a component in a circuit. SI unit is also V

Power   Rate of energy dissipation in a component. Is the amount of energy dissipated in a conductor carrying a current of 1A. If the p.d across the conductor 1V

$P = Voltage*Current = IV$

SI unit is Watts (W)

RESISTORS.

Resistor   A resistor is a passive component which apposes the flow of current in Q circuit

Passive component   (i) Does not add strength to a signal

(ii) Does not require power to operate

Active components e.g. diodes, transistor require power to operate and strength to a signal

Resistance (R) represented by the unit [Ω]. This is the opposition to the flow of current.

Factors affecting resistance of a conductor
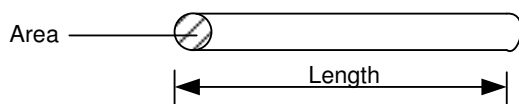
(a) Length (m) R α L
(b) Cross sectional Area R α L/A
(c) Resistivity (symbol ρ) and units (Ωm) R α ρ
(d) Temperature

The formula for resistance is $R = \rho\dfrac{L}{A}$

COLOUR CODING

4 colour Band resistor
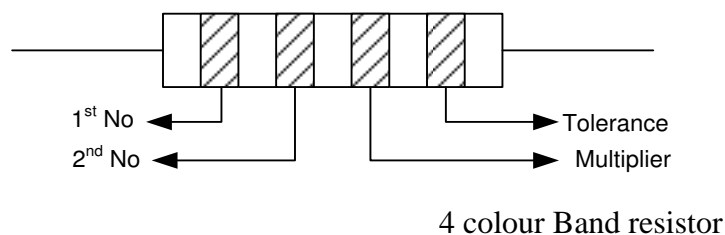
Number	Colour	Multiplier	Tolerance
0	Black	10^0	
1	Brown	10^1	$\pm 1\%$
2	Red	10^2	$\pm 2\%$
3	Orange	10^3	
4	Yellow	10^4	
5	Green	10^5	
6	Blue	10^6	
7	Violet	10^7	
8	Grey	10^8	
9	White	10^9	
-	Gold	10^{-1}	$\pm 5\%$
-	Silver	10^{-2}	$\pm 10\%$
-	No. band	-	$\pm 20\%$

Resistor color coding is the process of representing resistance of resistor using colour bands. The colour bands are indicated on the surface of the resistor.

Colour coding comes in 2 types: 4 colour resistors

                                  5 colour resistors

For 4 colour band resistors the 1st colour band represent the 1st Number, 2nd colour representing the 2nd no, 3rd colour band representing multiplier / no of zeros, last colour band representative tolerance.

Tolerance is the deviation from the exact value and can be represented by %. For a five colour band resistor the 1st 3 bands representing the numbers, the fourth represents the multiplier, the last represents the tolerance.

Converting from colour bands to resistance

Orange, Brown, Blue, Silver

    3   1   x 10^6 $\pm 10\%$

Range due to tolerance gives $31 \times 10^6 \pm 31 \times 10^5$

$$= 27.9 \times 10^6 \text{ to } 34.1 \times 10^6 \ \Omega$$

Convert from resistance to colour bands

(i) $36 \times 10^6 \ \Omega \pm 1\%$

    Orange, Blue, Yellow, Brown

(ii) $845678 \pm 10\%$

    This can be approximated to $850000 \pm 10\% = 85 \times 10^4 \pm 10\%$
    This gives the following   Grey, Green, Yellow, Silver

(iii) $4K54 \pm 2\%$
    This is equivalent to $4.5 \times 10^3 \pm 2\% = 45 \times 10^2 \pm 2\%$
    This gives the following colour code Yellow, Green, Red, Red

(iv) Give the values and the tolerances of the resistors below if the color-codes from right to left are.

i. Brown, Orange, Black, Red
   Solution:

   Red, Black, Orange, Brown
     2   0 10^3 1%
   $20 \times 10^3 \pm 1\%$

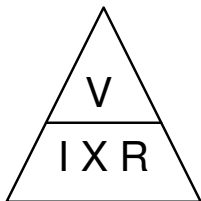ii. Yellow, brown, Green
   Solution:

   Green, Brown, Yellow

     5   1 10^4 20%
   $51 \times 10^4 \pm 20\%$

Ohms Law

The current passing through a conductor is proportional to the voltage applied across it provided all external factors are constant.

$I \propto V$

$$I = \frac{V}{R} \qquad V = IR \qquad R = \frac{V}{I}$$

$$P = IV = I^2 R = \frac{V^2}{R}$$

Resistor circuits

The circuit shown below has the resistors connected in series.
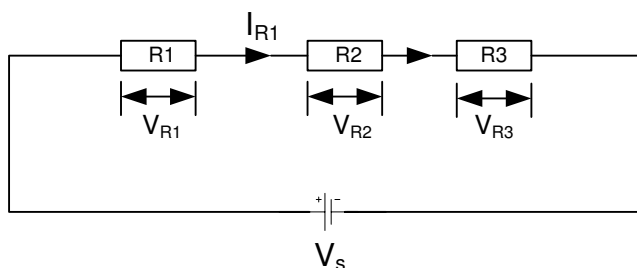
$$I = I_{R1} = I_{R2} = I_{R3}$$
$$V_s = V_{R1} + V_{R2} + V_{R3} = I_{R1} R_1 + I_{R2} R_2 + I_{R3} R_3 = I(R_1 + R_2 + R_3)$$

Thus $R_t = R_1 + R_2 + R_3$
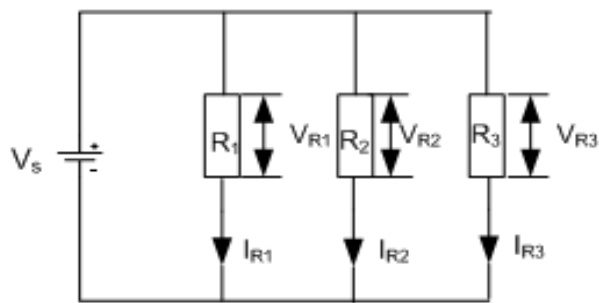
$$I = I_{R1} = I_{R2} = I_{R3}$$
$$V_s = V_{R1} = V_{R2} = V_{R3}$$
$$I_t = I_{R1} + I_{R2} + I_{R3} = \frac{V_{R1}}{R_1} + \frac{V_{R2}}{R_2} + \frac{V_{R3}}{R_3} = V_s\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

Thus $\frac{1}{R_t} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$

Example

Three resistors R1 = 900R, R2 = 5K8, R3 = 7M4 are connected in series across voltage supply of 200V

(a)　Calculate the total resistance (b) calculate the total current (c) Determine the current passing through each of the resistors (e) Voltage across each resistor

Solution

(a)　$R_t = 900 + 5800 + 7.4 \times 10^6 = 7406700\ \Omega = 7.407 \times 10^6$

(b)　$I = \frac{V_s}{R_t} = \frac{200}{7406700} = 2.700 \times 10^{-5}\ A$

(c)　$V = IR$

$V_1 = \frac{200}{7406700} \times 900 = 0.0243\ V$

$V_2 = \frac{200}{7406700} \times 5.8 \times 10^3 = 0.1566\ V$

$V_3 = \frac{200}{7406700} \times 7.4 \times 10^6 = 199.8\ V$

Parallel Circuit

(a)　$\frac{1}{R_t} = \left(\frac{1}{900} + \frac{1}{5800} + \frac{1}{7.4 \times 10^6}\right)$

Therefore $R_t = 779.022\ \Omega$

(b)　$I_t = \frac{V_s}{R_t} = \frac{200}{779}.022 = 0.257\ A$

(c)　$V_{Rt} = V_{R1} = V_{R2} = V_{R3} = 200V$

$$\text{(d)} \quad I_{R1} = \frac{V_{R1}}{R_1} = \frac{200}{900} = 0.222 \ A$$

$$I_{R2} = \frac{V_{R2}}{R_2} = \frac{200}{5800} = 0.034 \ A$$

$$I_{R3} = \frac{V_{R3}}{R_3} = \frac{200}{7.4 \ x \ 10^6} = 2.703 \ x \ 10^{-5} \ A$$

Combined circuit
Example
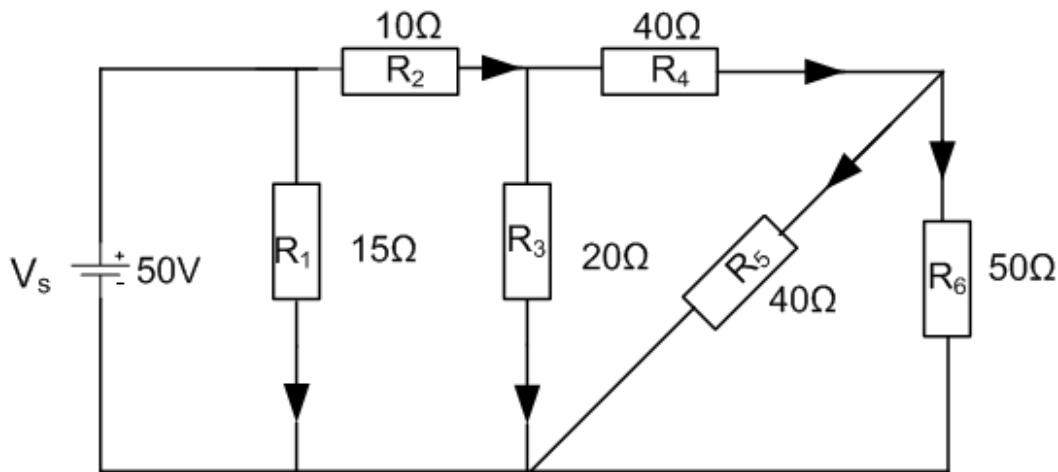
(a) Total Resistance \qquad (c) Current through each resistor
(b) Total Current \qquad (d) Voltage through each resistor

Solution

$$\text{(a)} \quad \frac{1}{R_a} = \left(\frac{1}{R_5} + \frac{1}{R_6}\right) = \left(\frac{1}{40} + \frac{1}{50}\right) = \frac{9}{200}$$

$$R_a = \frac{200}{9} = 22.22\Omega$$

$$R_b = R_a + R_4 = 22.22\Omega + 40\Omega = 62.22\Omega$$

$$\frac{1}{R_c} = \left(\frac{1}{R_b} + \frac{1}{R_3}\right) = \left(\frac{1}{62}.22 + \frac{1}{20}\right) \quad \text{Thus } R_c = 15.135\Omega$$

$$R_d = R_2 + R_c = 10\Omega + 15.135\Omega = 25.135\Omega$$

$$\frac{1}{R_t} = \left(\frac{1}{R_1} + \frac{1}{R_d}\right) = \left(\frac{1}{15} + \frac{1}{25}.135\right) \quad \text{Thus } R_t = 9.39\Omega$$

$$\text{(b)} \quad I_t = \frac{V_s}{R_t} = \frac{50}{9}.39 = 5.32 \ A$$

(c) $V_{R1} = V_{Rd} = V_{Rt} = 50V$

$$I_{R1} = \frac{V_{R1}}{R_1} = \frac{50}{15} = 3.33 \ A$$

$$I_{Rd} = \frac{V_{Rd}}{R_d} = \frac{50}{25}.135 = 1.989 \ A$$

$$I_{R2} = I_{Rc} = I_{Rd} = 1.989\ A$$

$$V_{R2} = I_{R2}\,x\,R_2 = 1.989\ x\ 10 = 19.89V$$

$$V_{Rc} = I_{Rc}\,x\,R_c = 1.989\ x\ 15.135 = 30.104V$$

$$V_{R3} = V_{R6} = V_{Rc} = 30.104\ V$$

$$I_{R3} = \frac{V_{R3}}{R_3} = 30.\frac{104}{20} = 1.505\ A$$

$$I_{Rb} = \frac{V_{Rb}}{R_b} = 30.\frac{104}{62}.22 = 0.484\ A$$

$$I_{R4} = I_{Ra} = I_{Rb} = 0.484\ A$$

$$V_{R4} = I_{R4}\,x\,R_4 = 0.484\ x\ 40 = 19.35V$$

$$V_{Ra} = I_{Ra}\,x\,R_a = 0.484\ x\ 22.22 = 10.754V$$

$$V_{R6} = V_{Ra} = V_{Rs} = 10.754V$$

$$I_{R5} = \frac{V_{R5}}{R_5} = 10.\frac{754}{40} = 0.269\ A$$

$$I_{R6} = \frac{V_{R6}}{R_6} = 10.\frac{754}{50} = 0.215\ A$$

Example

Obtain the number of 2-watt resistors and their resistance value needed to yield an equivalent 1000Ω 10-watt resistor.

Solution:

Series:

$$No\,of\,resistors = \frac{Total\,wattage}{Wattage\,for\,one\,reisistor} = \frac{10}{2} = 5\,resistors$$

$$R_t = R_1 + R_2 + R_3 + R_4 + R_5 = 5R$$

$$1000 = 5R$$

$$R = \frac{1000}{5} = 200\Omega$$

Parallel:

$$No\,of\,resistors = \frac{Total\,wattage}{Wattage\,for\,one\,reisistor} = \frac{10}{2} = 5\,resistors$$

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} = \frac{5}{R} = \frac{1}{1000}$$

$$R = 1000 \times 5 = 5000\Omega$$

Constant voltage source
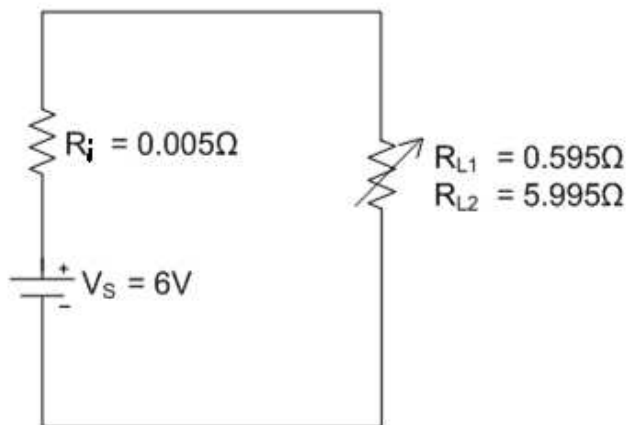
R_i – Internal resistance
R_L – Load resistance

$R_i \ll R_L$

It is a voltage source which has very low internal resistance / impedance as compared to the external impedance/ load resistance i.e. $R_i \ll R_L$

$$Z = R + jX$$

$$Z = \frac{R + jX}{\sqrt{R^2 + X^2}} \bigg/ \tan^{-1}\frac{X}{R}$$

$R_t = R_i + R_{L1} = 0.005 + 0.595 = 0.6\ \Omega$
$I_t = \dfrac{V_s}{R_t} = \dfrac{6}{0}.6 = 10\ A$
$V_{RL} = I_t R_L = 10\times 0.595 = 5.95\ V$

2nd Case
$R_t = R_i + R_{L2} = 0.005 + 5.995 = 6\ \Omega$
$I_t = \dfrac{V_s}{R_t} = \dfrac{6}{6} = 1\ A$
$V_{RL} = I_t R_L = 10\times 5.995 = 5.995\ V$
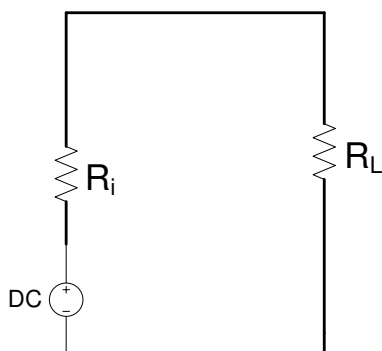
Constant Current Source
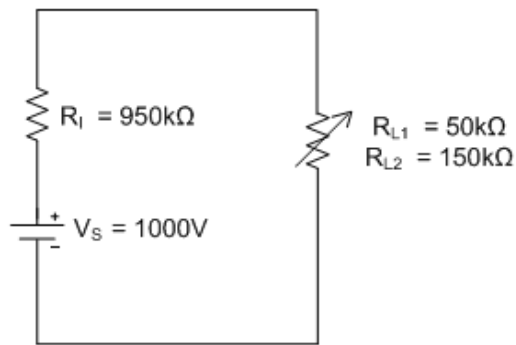
It has a very high internal resistance / impedance as compared to external / load resistance / impedance

1st Case

$$R_t = R_i + R_{L1} = 950 + 50 = 1000 \text{ k}\Omega$$
$$I_t = I_{RL} = \frac{V_s}{R_t} = \frac{1000}{1000 \times 10^3} = 1 \times 10^{-3} \text{ A}$$

2nd case

$$R_t = R_i + R_{L2} = 950 + 150 = 1100 \text{ k}\Omega$$
$$I_t = I_{RL} = \frac{V_s}{R_t} = \frac{1000}{1100 \times 10^3} = 0.909 \times 10^{-3} \text{ A}$$
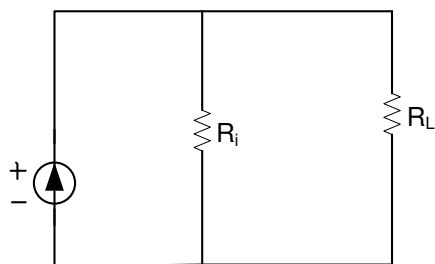
If you short circuit constant voltage source get a constant current source

THEVENIN'S THEOREM
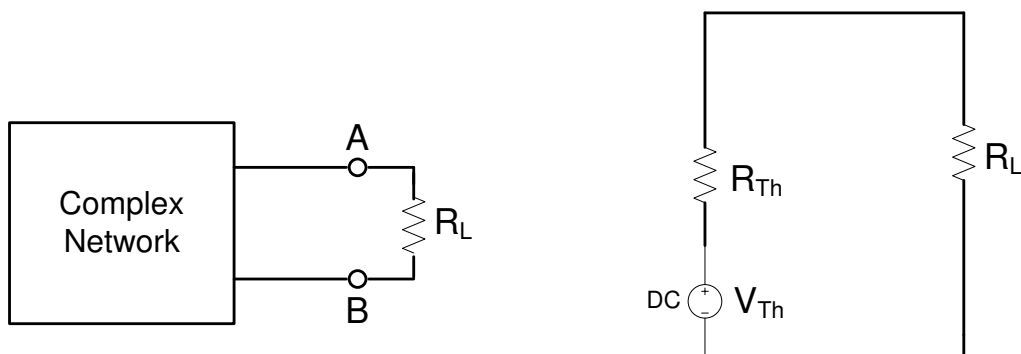
A complex network with resistance and voltage sources can be converted to a single resistor R_{th} in series with a single voltage source V_{Th} where R_{Th} is the total resistance obtained when

looking into the complex network after the voltage sources have been replaced by their internal resistances or short circuits, when point A and B is open. V_{Th} is the voltage across the two terminals A and B when the load resistance is removed

General case
Convert the circuit below to Thevenin's equivalent circuit.
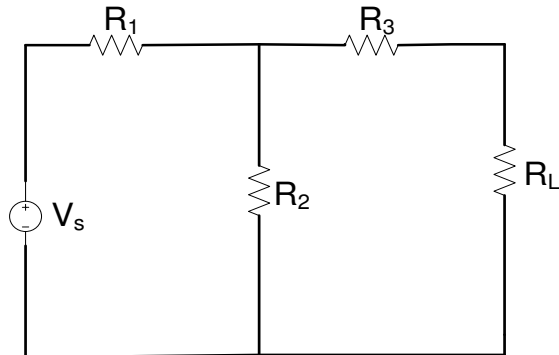
Step 1 Get R_{Th}
Open R_L, short circuit the source and look into the network then get R_{Th}.
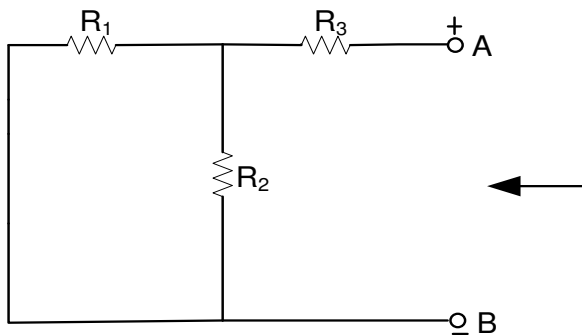
$$R_t = R_{Th=} R_3 + \frac{R_1 R_2}{R_1 + R_2}$$

Step 2 Get V_{Th}
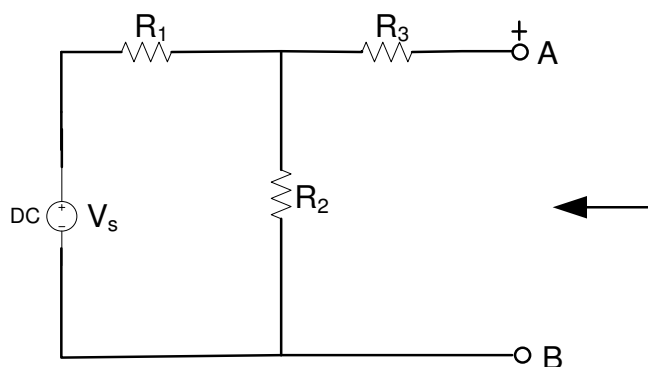
No current flow through terminals AB thus no current flow through R_3.

$$V_{R3} = V_s \frac{R_2}{R_1 + R_2} = V_{Th}$$

$$I_{RL} = \frac{V_{Th}}{R_{Th} + R_L}$$
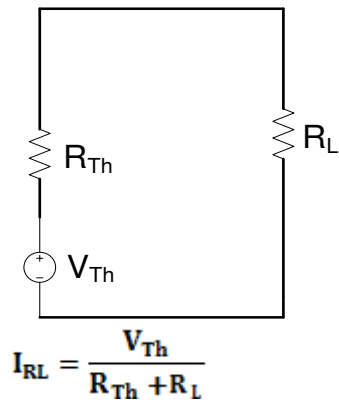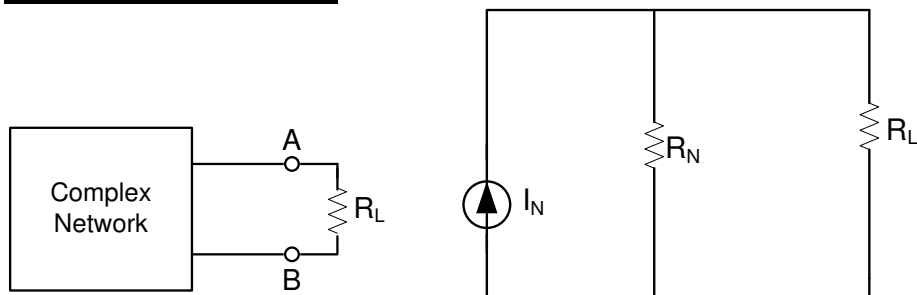
NORTONS THEOREM

Norton's theorem states that a complex network with several resistance and several voltage sources can be converted to a single current source I_N in parallel with a single resistor R_N.

General case
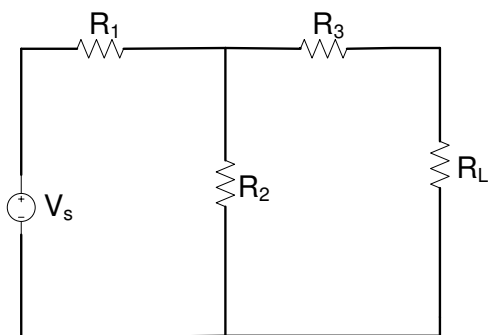
Short R_L and calculate the current passing through the short circuit I_N. Note that $R_N = R_{Th}$
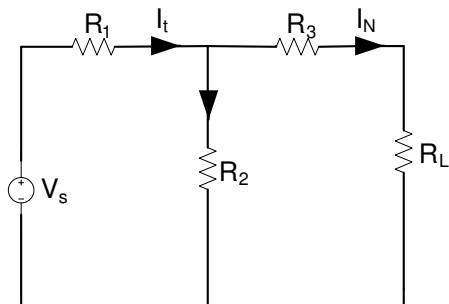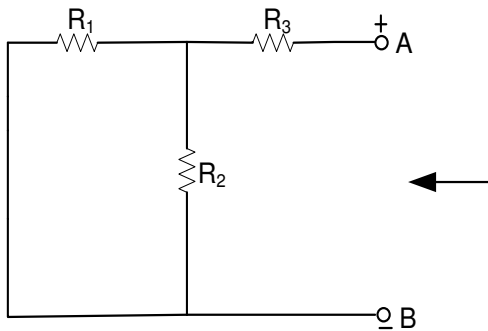

$$R_t = R_1 + \frac{R_2 R_3}{R_2 + R_3}$$

$$I_t = \frac{V_s}{R_t}$$

Using current divider theorem the value for I_N can be calculated as shown below

$$I_N = \frac{I_t R_2}{R_2 + R_3} = \frac{V_s R_2}{R_t(R_2 + R_3)} = \frac{V_s}{R_1 + \dfrac{R_2 R_3}{R_2 + R_3}} \; x \; \frac{R_2}{R_2 + R_3}$$

$$I_N = \frac{V_s R_2}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

$$R_N = R_{Th}$$
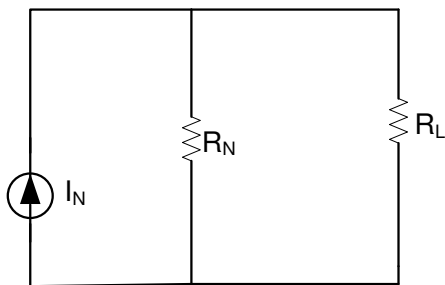
$$I_{RL} = \frac{I_N R_N}{R_N + R_L}$$

Example
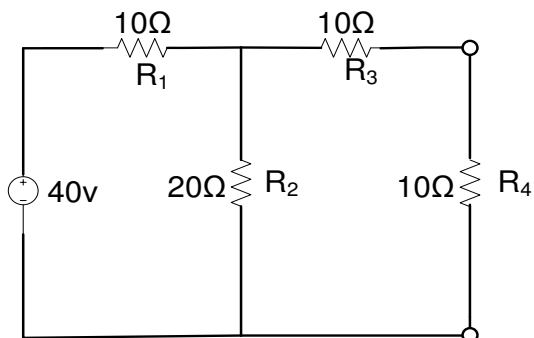
Calculate the current passing through R_4 using Norton's Theorem.

Solution

Step 1: Short-circuit R_4
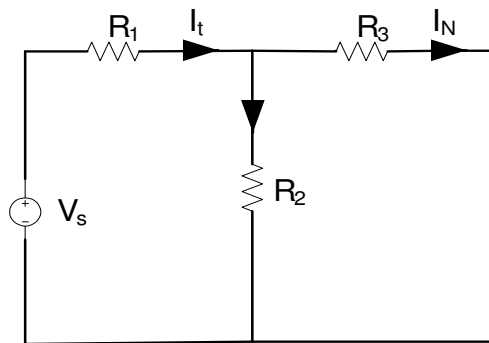
$$R_t = 10 + 20//10$$
$$= 10 + \frac{20x10}{20 + 10} = 16.67 \; \Omega$$

$$I_t = \frac{V_s}{R_t} = \frac{40}{16}.67 = 2.4 \; A$$

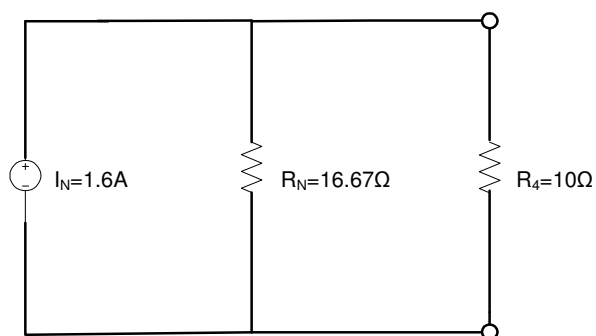$$I_{R3} = I_N = \frac{I_t R_2}{R_2 + R_3} = \frac{2.4 \, x20}{(20 + 10)} = \frac{48}{30} = 1.6 \; A$$
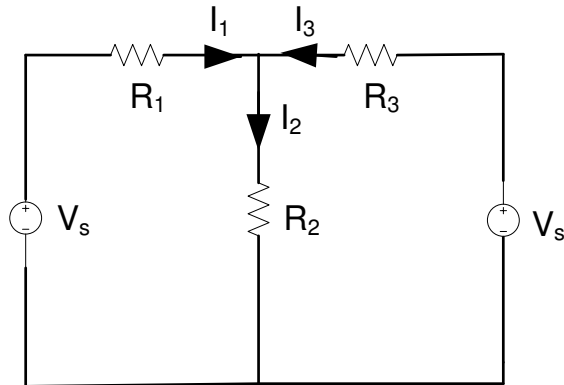
Step 2: Find R_N

Short-circuit the source
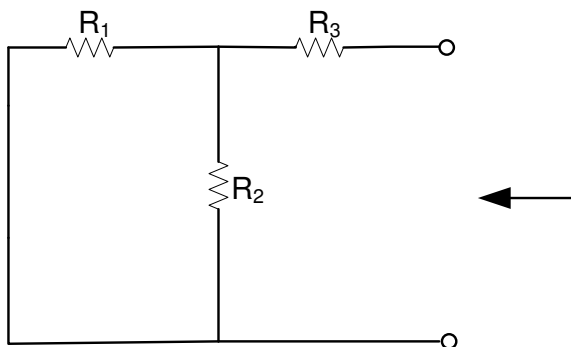
$$R_N = 10 + \frac{10 \, x \, 20}{10 + 20} = 16.67 \; \Omega$$
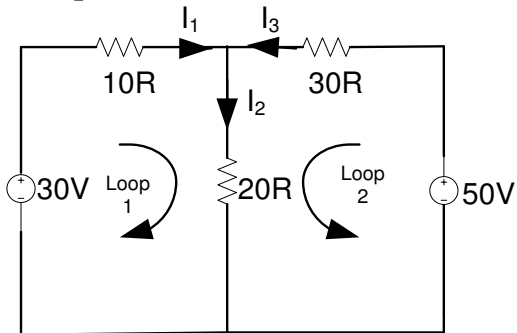
The final circuit is shown below

$$I_{R4} = \frac{1.6 \, x \, 16.67}{10 + 16.67} = 1 \; A$$

Analysis of a circuit having more than one voltage source

Mesh analysis
Example

Calculate the values for I_1, I_2 and I_3 in the circuit shown above.
Solution
Using Kirchoff's current law the two loops have the following expressions
$$10I_1 + 20I_2 = 30$$
$$30I_3 + 20I_2 = 50$$
but $I_1 + I_3 = I_2$

Therefore
$$10I_1 + 20I_1 + 20I_3 = 30I_1 + 20I_3 = 30$$
$$30I_3 + 20I_1 + 20I_3 = 50I_3 + 20I_1 = 50$$

Simplifying and eliminating I_3 results in
$$4I_1 + 10I_3 = 10$$
$$15I_1 + 10I_3 = 15$$
$I_1 = 0.4545$ A, $I_2 = 1.273$ A and $I_3 = 0.8185$ A

Factors considered when selecting a resistor
- o   Resistance value
- o   Power rating
- o   Tolerance
- o   Accuracy
- o   Durability
- o   Stability

- o Flexibility
- o Quality

Resistor Types

Resistors can be broadly categorized as fixed, variable, and special-purpose. Each of these resistor types is discussed in detail with typical ranges of their characteristics.

Fixed Resistors

The fixed resistors are those whose value cannot be varied after manufacture. Fixed resistors are classified into composition resistors, wire-wound resistors, and metal-film resistors.

Wire-Wound Resistors. Wire-wound resistors are made by winding wire of nickel-chromium alloy on a ceramic tube covering with a vitreous coating. The spiral winding has inductive and capacitive characteristics that make it unsuitable for operation above 50 kHz. The frequency limit can be raised by noninductive winding so that the magnetic fields produced by the two parts of the winding cancel.

Composition Resistors. Composition resistors are composed of carbon particles mixed with a binder. This mixture is molded into a cylindrical shape and hardened by baking. Leads are attached axially to each end, and the assembly is encapsulated in a protective encapsulation coating. Color bands on the outer surface indicate the resistance value and tolerance. Composition resistors are economical and exhibit low noise levels for resistances above 1 MW. Composition resistors are usually rated for temperatures in the neighborhood of 70°C for power ranging from 1/8 to 2W. Composition resistors have end-to-end shunted capacitance that may be noticed at frequencies in the neighborhood of 100 kHz, especially for resistance values above 0.3 MW.

Metal-Film Resistors. Metal-film resistors are commonly made of nichrome, tin-oxide, or tantalum nitride, either hermetically sealed or using molded-phenolic cases. Metal-film resistors are not as stable as the wire-wound resistors. Depending on the application, fixed resistors are manufactured as precision resistors, semiprecision resistors, standard general-purpose resistors, or power resistors. Precision resistors have low voltage and power coefficients, excellent temperature and **time stabilities**, low noise, and very low reactance. These resistors are available in metal-film or wire constructions and are typically designed for circuits having very close resistance tolerances on values. Semiprecision resistors are smaller than precision resistors and are primarily used for current-limiting or voltage-dropping functions in circuit applications. Semiprecision resistors have long-term temperature stability. General-purpose resistors are used in circuits that do not require tight resistance tolerances or long-term stability. For general-purpose resistors, initial resistance variation may be in the neighborhood of 5% and the variation in resistance under full-rated power may approach 20%. Typically, general-purpose resistors have a high coefficient of resistance and high noise levels. Power resistors are used for power supplies, control circuits, and voltage dividers where operational stability of 5% is acceptable. Power resistors are available in wire-wound and film constructions. Film-type power resistors have the advantage of stability at high frequencies and have higher resistance values than wire-wound resistors for a given size.

Variable Resistors

Potentiometers. The potentiometer is a special form of variable resistor with three terminals. Two terminals are connected to the opposite sides of the resistive element, and the third

connects to a sliding contact that can be adjusted as a voltage divider. Potentiometers are usually circular in form with the movable contact attached to a shaft that rotates. Potentiometers are manufactured as carbon composition, metallic film, and wire-wound resistors available in single-turn or multiturn units. The movable contact does not go all the way toward the end of the resistive element, and a small resistance called the *hop-off* resistance is present to prevent accidental burning of the resistive element.

Rheostat. The rheostat is a current-setting device in which one terminal is connected to the resistive element and the second terminal is connected to a movable contact to place a selected section of the resistive element into the circuit. Typically, rheostats are wire-wound resistors used as speed controls for motors, ovens, and heater controls and in applications where adjustments on the voltage and current levels are required, such as voltage dividers and bleeder circuits.

Special-Purpose Resistors
Integrated Circuit Resistors. Integrated circuit resistors are classified into two general categories: semiconductor resistors and deposited film resistors. Semiconductor resistors use the bulk resistivity of **doped** semiconductor regions to obtain the desired resistance value. Deposited film resistors are formed by depositing resistance films on an insulating substrate which are etched and patterned to form the desired resistive network. Depending on the thickness and dimensions of the deposited films, the resistors are classified into thick-film and thin-film resistors.
Semiconductor resistors can be divided into four types: diffused, bulk, pinched, and ion-implanted.
Diffused semiconductor resistors use resistivity of the diffused region in the semiconductor substrate to introduce a resistance in the circuit. Both *n*-type and *p*-type diffusions are used to form the diffused resistor.

CAPACITORS
A component constructed from conductive plate and dielectric in between them and can be used to store charge. Capacitance is the ability of a capacitor to store charge.
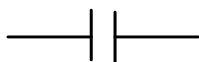Capacitance is measured in farads (F).
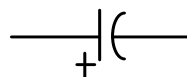Factors affecting capacitance include

(a)   Dielectric material (ε)- Permittivity is the ability of material to allow an electronic field to pass through, the extent to which a material affects magnetic field

ε_r = Relative permittivity , ε_0 = permittivity of free space 8.854 x 10^{-12} F/m or

$$\frac{1}{36\Pi} \times \frac{10^{-9}F}{m}$$

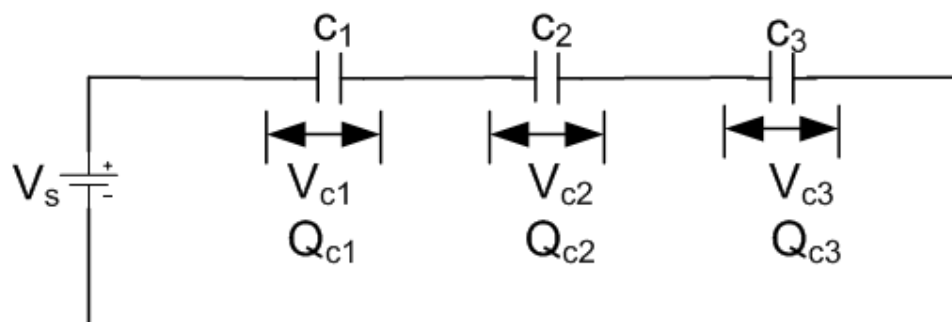   Ceramic capacitor   electrolytic capacitor
(b)   Capacitance is directly proportional to the effective area of the plates. C α **A**
(c)   Capacitance is inversely proportional to the distance of separation between the plates.

$$C \alpha \frac{1}{d}$$
$$C = \varepsilon_r \varepsilon_o \frac{A}{d}$$

Charging and discharging of capacitors
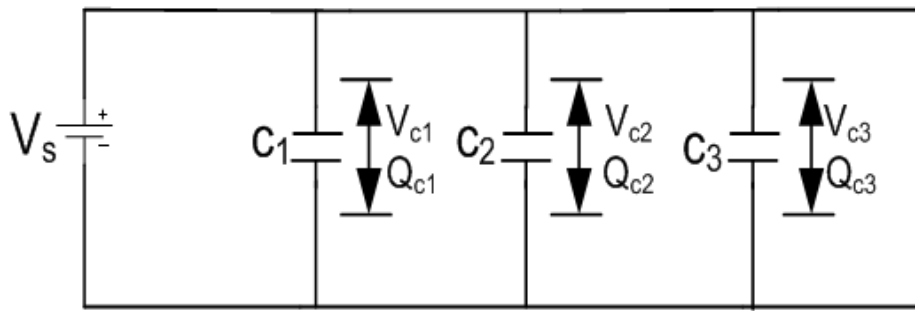**Charging**

Series Connection of Capacitors

$$Q_t = Q_{c1} = Q_{c2} = Q_{c3}$$

$$V_s = V_{c1} + V_{c2} + V_{c3} = Q_t\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)$$

Therefore

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Parallel Connection of Capacitors

$V_s = V_{c1} = V_{c2} = V_{c3}$
$Q_t = = Q_{c1} + Q_{c2} + Q_{c3} = V_s(C_1 + C_2 + C_3)$
Therefore
$C_t = C_1 + C_2 + C_3$
Energy stored in a capacitor is given by

$$E = \frac{CV^2}{2} = \frac{QV}{2} = \frac{Q^2}{2C}$$

Effect of capacitor on alternating current

Capacitive reactance (X_c) is the opposition of flow of a.c by a capacitor. It is expressed using (Ω). The formula for capacitive reactance is

$$X_c = \frac{1}{2\Pi fC} \ (\Omega)$$

Notice that the formula is dependent of frequency thus no current will pass through when using direct current since frequency is equal to zero.

Types of Capacitors
Capacitors are used to filter, couple, tune, block dc, pass ac, bypass, shift phase, compensate, feed through, isolate, store energy, suppress noise, and start motors. They must also be small, lightweight, reliable, and withstand adverse conditions. Capacitors are grouped according to their dielectric material and mechanical configuration.

Non-electrolytic capacitors
Ceramic Capacitors
Ceramic capacitors are used most often for bypass and coupling applications. Ceramic capacitors can be produced with a variety of *K* values (dielectric constant). A high *K* value translates to small size and less stability. High-*K* capacitors with a dielectric constant >3000 are physically small and have values between 0.001 to several microfarads.
Good temperature stability requires capacitors to have a *K* value between 10 and 200. If high *Q* is also required, the capacitor will be physically larger. Ceramic capacitors with a zero temperature change are called **negative-positive-zero (NPO)** and come in a capacitance range of 1.0 pF to 0.033 mF. An N750 temperature-compensated capacitor is used when accurate capacitance is required over a large temperature range. The 750 indicates a 750-ppm decrease in capacitance with a 1°C increase in temperature (750 ppm/°C). This equates to a 1.5% decrease in capacitance for a 20°C temperature increase. N750 capacitors come in values between 4.0 and 680 pF.

Film Capacitors

Film capacitors consist of alternate layers of metal foil and one or more layers of a flexible plastic insulating material (dielectric) in ribbon form rolled and encapsulated.

Mica Capacitors

Mica capacitors have small capacitance values and are usually used in high-frequency circuits. They are constructed as alternate layers of metal foil and mica insulation, which are stacked and encapsulated, or are silvered mica, where a silver electrode is screened on the mica insulators.

Paper-Foil-Filled Capacitors

Paper-foil-filled capacitors are often used as motor capacitors and are rated at 60 Hz. They are made of alternate layers of aluminum and paper saturated with oil that are rolled together. The assembly is mounted in an oil filled, hermetically sealed metal case.

Electrolytic Capacitors

Electrolytic capacitors provide high capacitance in a tolerable size; however, they do have drawbacks. Low temperatures reduce performance, while high temperatures dry them out. The **electrolytes** themselves can leak and corrode the equipment. Repeated surges above the rated working voltage, excessive ripple currents, and high operating temperature reduce performance and shorten capacitor life. Electrolytic capacitors are manufactured by an electrochemical formation of an oxide film on a metal surface. The metal on which the oxide film is formed serves as the **anode** or positive terminal of the capacitor; the oxide film is the dielectric, and the **cathode** or negative terminal is either a conducting liquid or a gel.

Aluminum Electrolytic Capacitors. Aluminum electrolytic capacitors use aluminum as the base material. The surface is often etched to increase the surface area as much as 100 times that of unetched foil, resulting in higher capacitance in the same volume. Aluminum electrolytic capacitors can withstand up to 1.5 V of reverse voltage without detriment. Higher reverse voltages, when applied over extended periods, lead to loss of capacitance. Excess reverse voltages applied for short periods cause some change in capacitance but not to capacitor failure. Large-value capacitors are often used to filter dc power supplies. After a capacitor is charged, the rectifier stops conducting and the capacitor discharges into the load, until the next cycle. Then the capacitor recharges again to the peak voltage. The D*e* is equal to the total peak-to-peak ripple voltage and is a complex wave containing many harmonics of the fundamental ripple frequency, causing the noticeable heating of the capacitor.

Tantalum Capacitors. Tantalum electrolytics are the preferred type where high reliability and long service life are paramount considerations. Tantalum capacitors have as much as three times better capacitance per volume efficiency than aluminum electrolytic capacitors, because tantalum pentoxide has a dielectric constant three times greater than that of aluminum oxide. The capacitance of any capacitor is determined by the surface area of the two conducting plates, the distance between the plates, and the dielectric constant of the insulating material between the plates. In tantalum electrolytics, the distance between the plates is the thickness of the tantalum pentoxide film, and since the dielectric constant of the tantalum pentoxide is high, the capacitance of a tantalum capacitor is high. Tantalum capacitors contain either liquid or solid electrolytes. The liquid electrolyte in wet-slug and foil capacitors, generally sulfuric acid, forms the cathode (negative) plate. In solid-electrolyte capacitors, a dry material, manganese dioxide, forms the cathode plate.

Foil Tantalum Capacitors. *Foil tantalum capacitors* can be designed to voltage values up to 300 V dc. Of the three types of tantalum electrolytic capacitors, the foil design has the lowest capacitance per unit volume and is best suited for the higher voltages primarily found in older designs of equipment. It is expensive and used only where neither a solid-electrolyte nor a wet-slug tantalum capacitor can be employed. Foil tantalum capacitors are generally designed for operation over the temperature range of –55 to +125°C (–67 to +257°F) and are found primarily in industrial and military electronics equipment.

Solid-electrolyte sintered-anode tantalum capacitors differ from the wet versions in their electrolyte, which is manganese dioxide. Another variation of the solid-electrolyte tantalum capacitor encases the element in plastic resins, such as epoxy materials offering excellent reliability and high stability for consumer and commercial electronics with the added feature of low cost. Still other designs of "solid tantalum" capacitors use plastic film or sleeving as the encasing material, and others use metal shells that are backfilled with an epoxy resin. Finally, there are small tubular and rectangular molded plastic encasements. *Wet-electrolyte sintered-anode tantalum capacitors,* often called "wet-slug" tantalum capacitors, use a pellet of sintered tantalum powder to which a lead has been attached. This anode has an enormous surface area for its size. Wet-slug tantalum capacitors are manufactured in a voltage range to 125 V dc.

INDUCTORS
An inductor is a device which can store magnetic energy. It's made from a coiled wire.

Circuit symbol

Inductance is the ability to store magnetic energy. It is measured in Henrys (H).

Inductance depends on several factors

(a) No. of turns
(b) Medium surrounding the inductor/core and its permeability(μ). Permeability is the ability of a material to affect the magnetic field H
(c) Geometry of the conductor
(d) Cross sectional area

Self –Inductance
This is the ability of material / coil to induce emf at the surroundings

Mutual inductance
This is the process by which changing voltage in a conductor induces emf in a second conductor which is in the opposite direction (Lenz's Law)

Types of inductors

Transformers
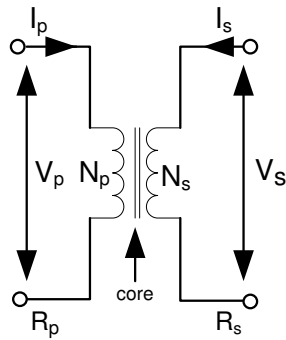
A transformer is a device which can change the level of voltage from high to low or vice versa. It is made from 2 coils wound on a core close to each other sometimes on top of the other. It uses mutual induction to operate.

The phase difference between the primary coil and secondary coil voltage is 180^0 as shown in the diagram below.
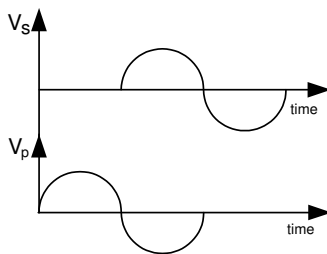
For an ideal transformer input power = output power ($P_p = P_s$) since there is no power loss.

For practical transformer $P_p > P_s$. This necessitates the definition of efficiency of a transformer which is the ratio of output power to input power.

$$\eta = \frac{P_s}{P_p} \times 100$$

where η is efficiency

Losses in a transformer
(a) Heat losses
(b) Eddy currents leakage current
(c) Hysteresis due to magnetization of the core
(d) Mechanical losses e.g. sound

Step-up transformer   Step-down transformer
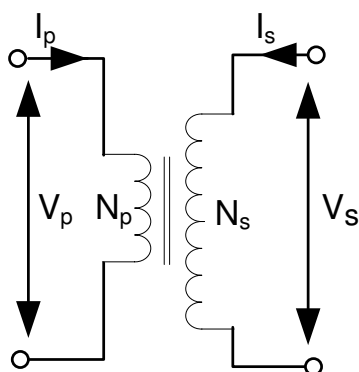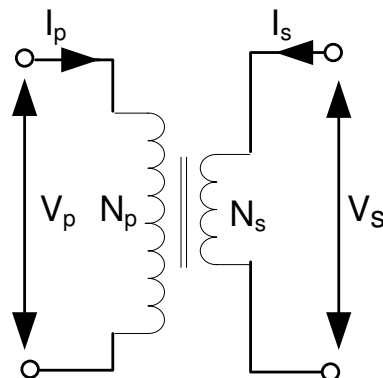
$N_p < N_s$, $V_p < V_s$ and $I_p > I_s$ $N_p > N_s$, $V_p > V_s$ and $I_p < I_s$

Transformation Ratio

$$n = \frac{V_p}{V_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p}$$

This is the ratio by which the voltage is transformed.

Example

A transformer has the following parameters: $N_P = 400$, $N_S = 2000$, $V_S = 20V$, $I_p = 0.5A$, $\eta = 90\%$. Find I_s

$$\frac{I_S}{I_P} = \frac{N_p}{N_s}$$

$$I_s = \frac{N_p}{N_s} \times I_P = \frac{400 \times 0.5}{2000} = 0.1A$$

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \xRightarrow{thus} V_p = \frac{N_p \times V_s}{N_s} = \frac{400 \times 20}{200} = 4V$$

$$\eta = \frac{P_s}{P_p} \times 100 = 90 \xRightarrow{thus} \frac{I_s \times V_s}{I_p \times V_p} = \frac{I_s \times 20}{40 \times 0.5} = 0.9$$

$$I_s = 0.09A$$

SEMICONDUCTOR DIODES

Circuit symbol

A diode is a device which allows current to flow only in one direction. It is made from P – type and N – type semiconductors joined together. It has a depletion layer/ P – N junction / potential barrier.

Formation of the depletion layer
Depletion layer is formed when a p – type and n- type semiconductor are joined. The electrons in the n – type semiconductor adjacent to the p – type semi conductor more to fit in the holes which are also at the junction. This results to the creation of positive and negative ions which don't have any charge carriers. This section is referred to as a depletion layer. It can also be called a potential barrier since the positive ions on the n– side are at a higher potential than the negative ions in the p - side. The movement of ions process is called diffusion.

The diffusion process stops after some time because the positive ions will repel the holes and the negative ions will repel the electrons.
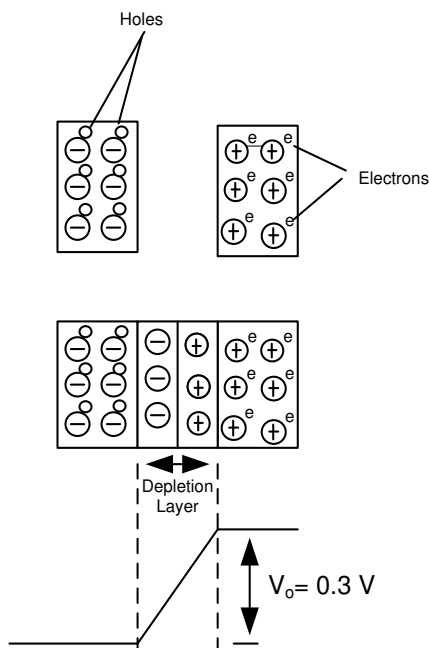
Biasing of a Diode
Forward bias
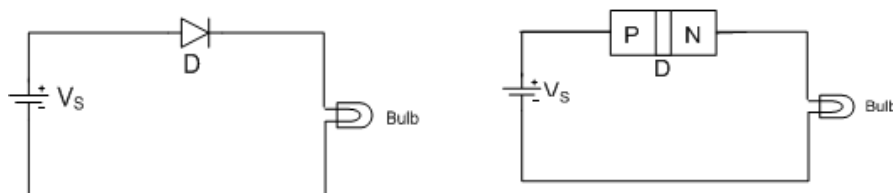
This is where the anode is connected to the power supply while the cathode is connected to the negative terminal. This leads to a continuous supply of electrons and continuous supply of holes at the junction which makes current to flow therefore the bulb lights up.

Germanium starts conducting at 0.2 – 0.3v, silicon 0.6 – 0.7v. The depletion layer disappears.

Reverse Bias
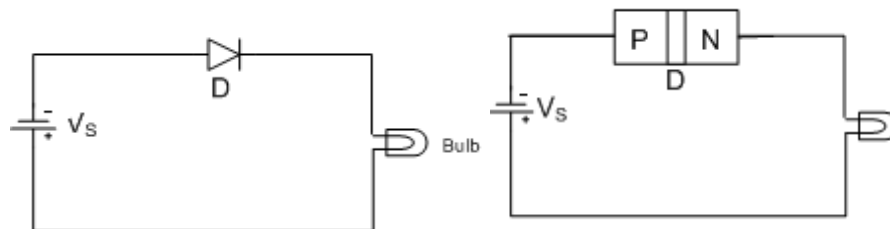
The anode is connected to negative terminal while the cathode is connected to positive terminal of power supply. The width of the depletion layer is enlarged due to majority charge carriers (electrons) moving away from the junction.

There's only minimal current which flows in the diode due to minority charge carriers. This current is referred to as leakage current and is expressed in terms of μA which cannot make the bulb light up.

VI characteristics of a diode
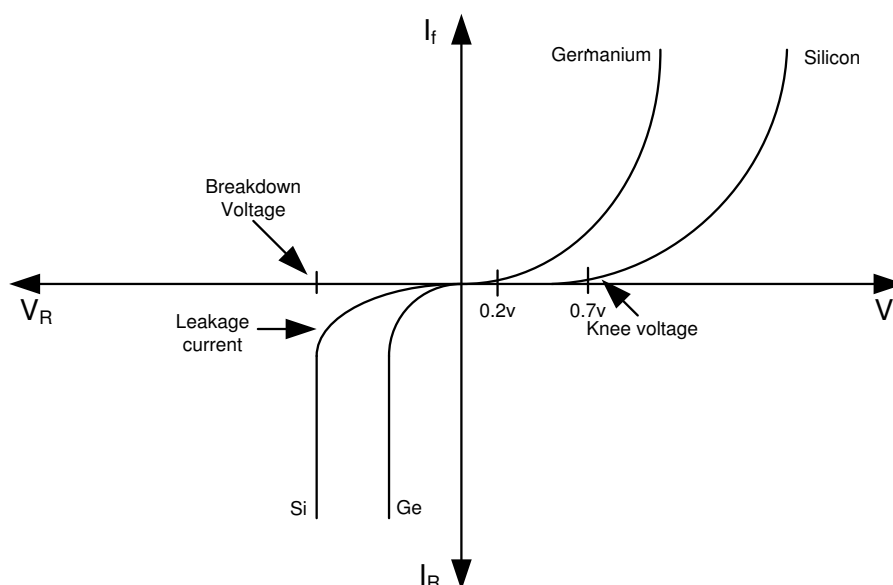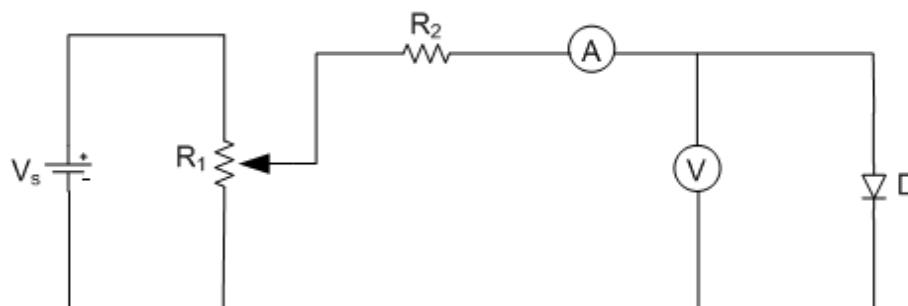
In the forward bias connection germanium starts conducting at 0.2V while silicon starts conducting at 0.7V. Further to increment of voltage leads to corresponding increment of current and the diode behaves like a normal conductor. The voltage at which the diodes start conducting current is called knee voltage. In reverse bias, when the voltage is at zero there is a very small amount of current which flows called leakage current. Increment of voltage does not affect that current if it is within the limit the diode can withstand. The current in a diode is affected by temperature.

If the voltage is increased beyond a point where the diode cannot withstand it breaks down. The minority electrons moving at high speed detach the electrons which are bonded thus breaking down the junction. This point can be called breakdown voltage or peak inverse voltage (PIV). The electrons at this point are called avalanche electrons. This current can damage the diode.

Diode static equation

$$i_o = I_o\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$$

i_0 - Diode current
I_0 - Temp dependant saturation current
V_D - Diode terminal voltage
η - Empirical constant Ge = 1, Si = 2
V_T -Thermal voltage

$$V_T = \frac{kT}{q}$$

k = Boltzmann's constant = 1.38 x 10^{-28} J/K
T= Absolute temp
q = 1.6 x 10^{-19} C

Diode parameters
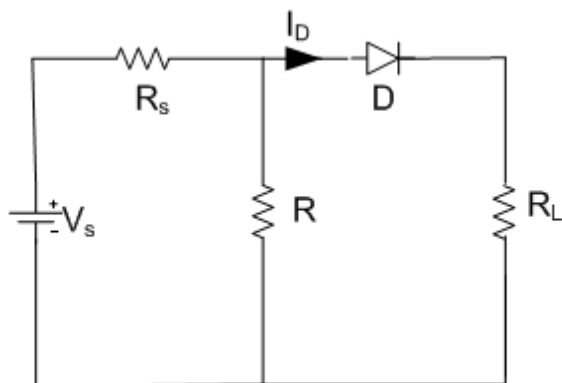
Using Thevenin's theorem
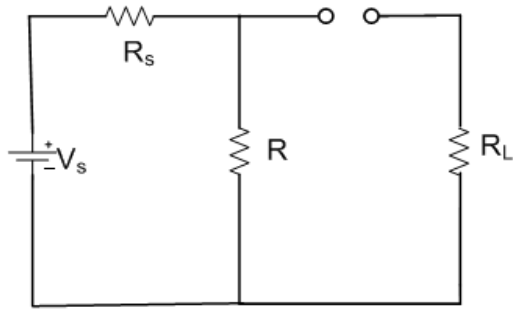
No current flows through R_L

$$V_{Th} = V_s \frac{R}{R_L + R}$$

R_{Th} can be calculated using the diagram below.
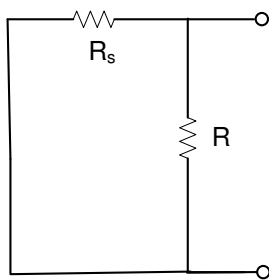
$$R_{Th} = \frac{R_s R}{R + R_s}$$
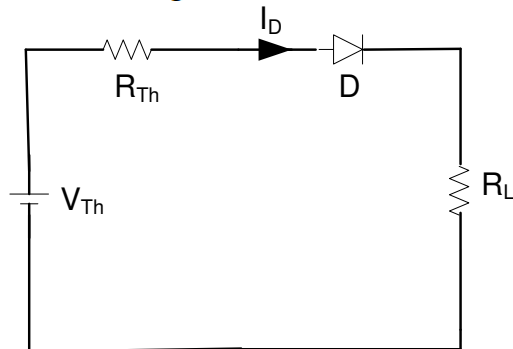
$$I_D = \frac{V_{Th}}{R_L + R_{Th}}$$

r_{dc} – d.c. resistance

Plot a load line superimposed in characteristics of a diode. The d.c load line crosses the x axis at V_{Th} and y-axis at V_{Th} / R_{Th}. The x axis has V_D and the y axis has I_D.
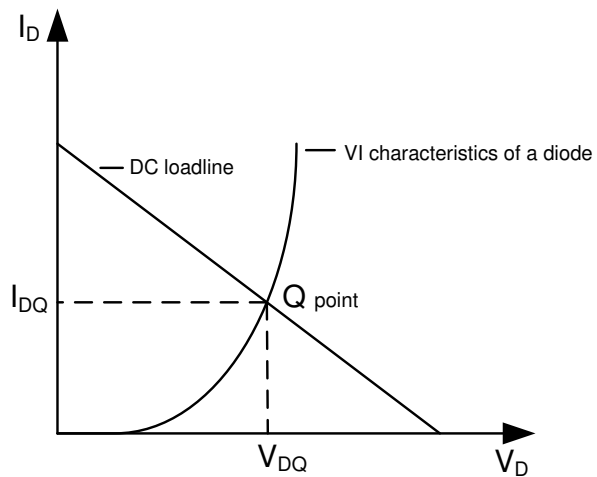
A Q point (quiescent point) gives the operating parameters of a diode or transistors

$$r_{dc} = \frac{V_{DQ}}{I_{DQ}}$$

Note that I_D represents d.c while i_d represents small signal a.c. quantities.
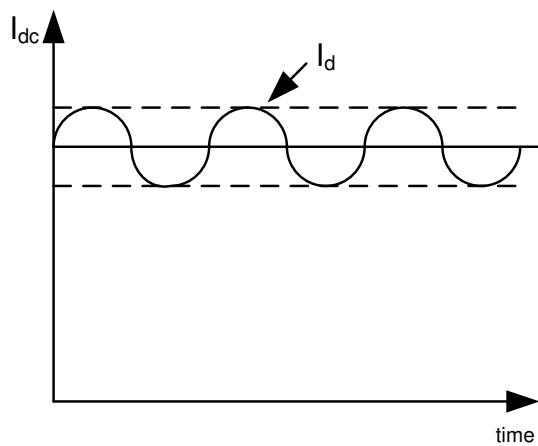
r_{ac} - a.c resistance
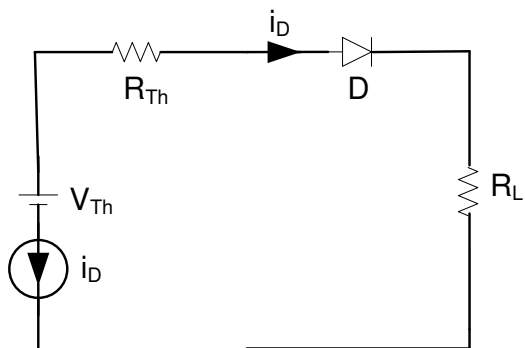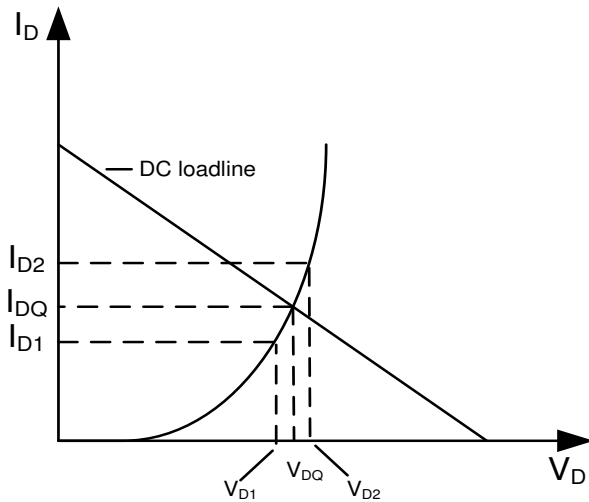
$$r_{ac} = \frac{Change\ in\ V_D}{Change\ in\ i_D} = \frac{V_{D2} - V_{D1}}{i_{D2} - i_{D1}} = \frac{\Delta V_D}{\Delta i_D}$$

Diode Models

Approximate Model
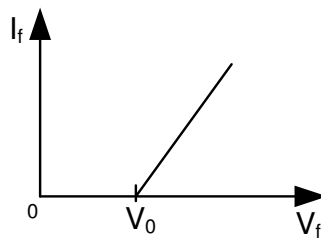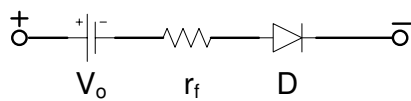
Simplified Model
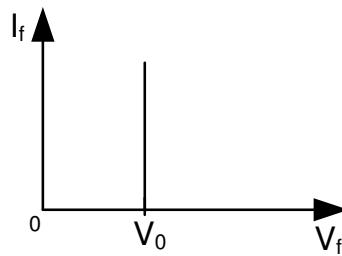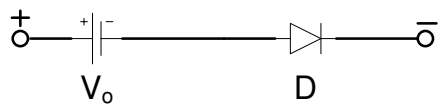
Ideal Model
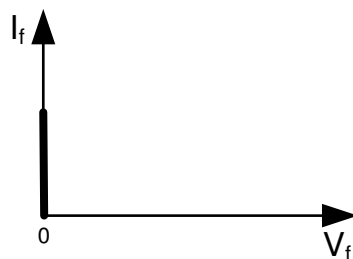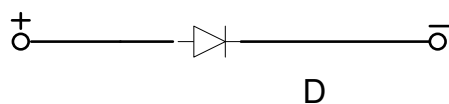
V_o – Turn on voltage   0.3V – Germanium

                                   0.6V- 0.7V - Silicon

Example
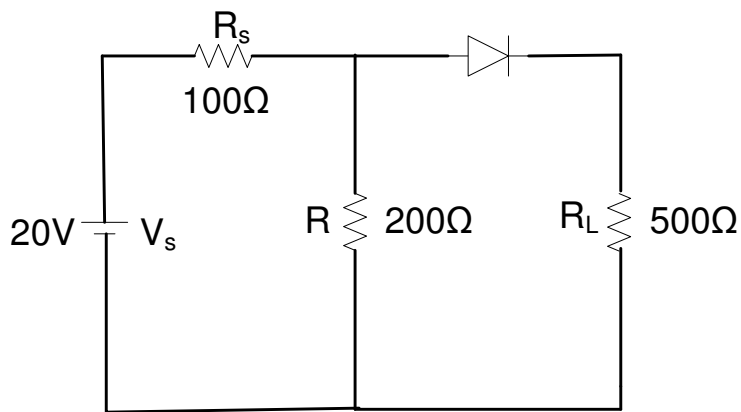
Draw the load line of the circuit.
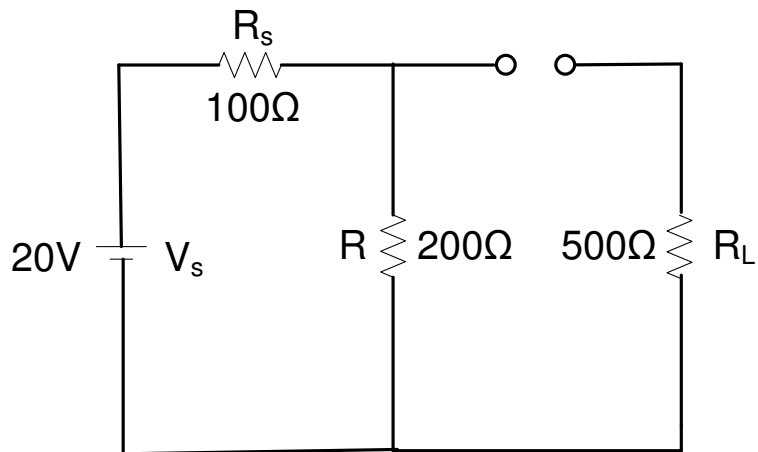
$$V_{Th} = \frac{20 \times 200}{100 + 200} = 13.33 \ \Omega$$

Calculate the value for R_{Th}
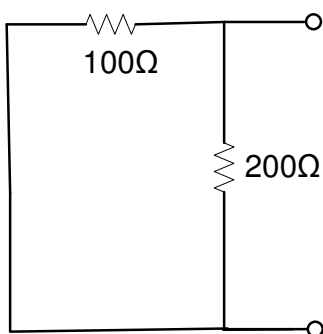
$$R_{Th} = \frac{R_s R}{R_s + R} = \frac{200 \times 100}{200 + 100} = 66.67 \ \Omega$$

$$\frac{V_{Th}}{R_{Th}} = \frac{13.33}{66.67} = 0.2 \ A$$

$$i_D = \frac{V_{Th}}{R_{Th}} - \frac{V_D}{R_{Th}}$$

Thus when $i_D = 0$, $V_D = V_{Th}$

$V_D=0$, $\quad i_D = \dfrac{V_{Th}}{R_{Th}}$
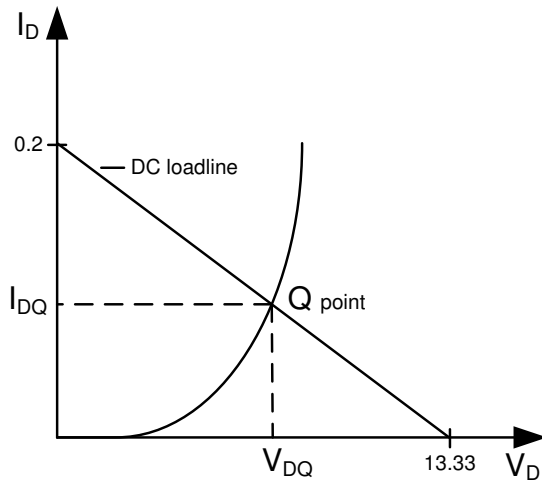
$$r_{dc} = \frac{V_{DQ}}{I_{DQ}}$$

Example
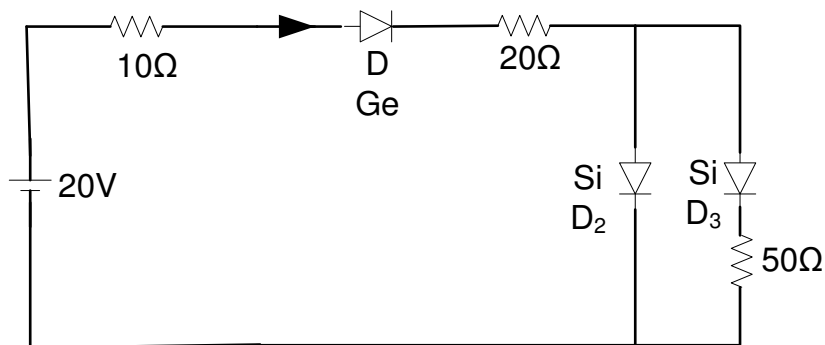
Calculate the dissipation of power in the 20Ω resistor.

Take Ge= $r_f = 1\Omega$

$\quad$ S$_i$ = r_f = 2Ω

Solution
Equivalent circuit
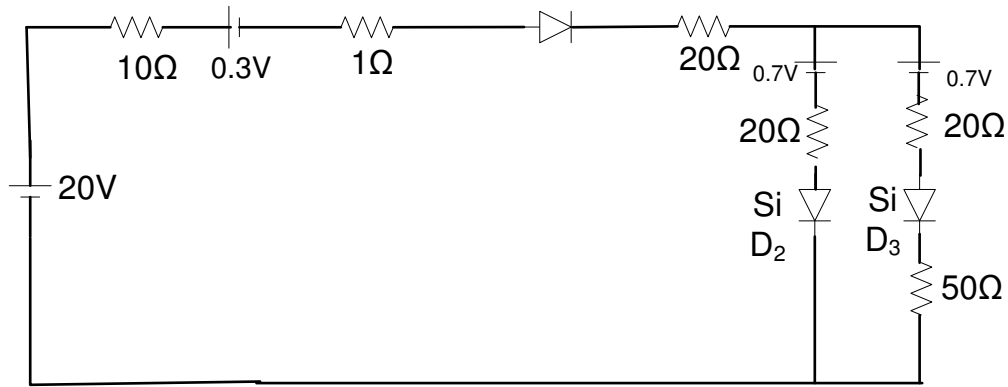
$$\text{The } D_2 \text{ and } D_3 \text{ equivalent resistance } \frac{52 \times 2}{52 + 2} = 1.926 \ \Omega$$

Equivalent potential drops across the silicon diodes is 0.7V
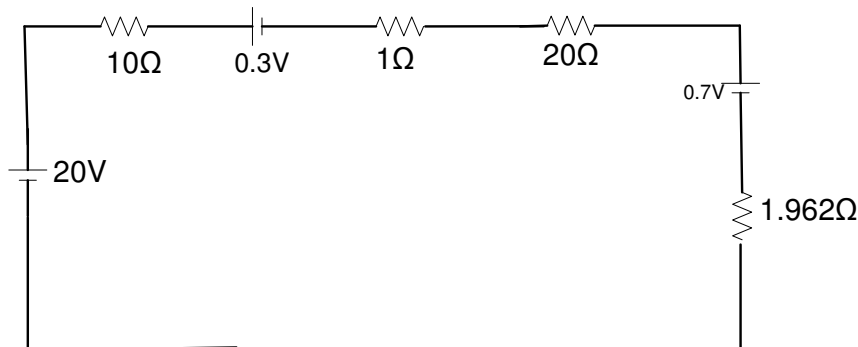
$$R_t = 32.926 \ \Omega$$
$$V_{Rt} = 20 - 0.3 - 0.7 = 19$$
$$I_t = \frac{V_{Rt}}{R_t} = \frac{19}{32}.926 = 0.577A$$
$$P_{20R} = I_t{}^2 R = (0.577)^2 20 = 6.66W$$

Types of Diodes
(a) LED
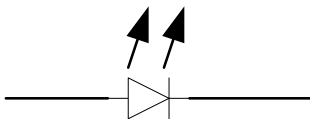
Circuit symbol

A light emitting diode (LED) is a diode which emits light when forward voltage is applied across it. It is a transducer which changes bacterial energy to light energy

Construction
It is constructed using materials such as Gallium arsenide and Gallium phosphide. They can produce different colours depending on the materials used.

Gallium arsenide – Red
Gallium phosphide – Green

Operation
It is operated in the forward – bias mode .When forward voltage is applied, electrons in the conduction band move to the valence band to fill the holes. In the process they emit light energy
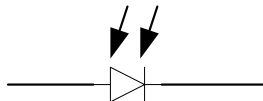
Characteristic Curve
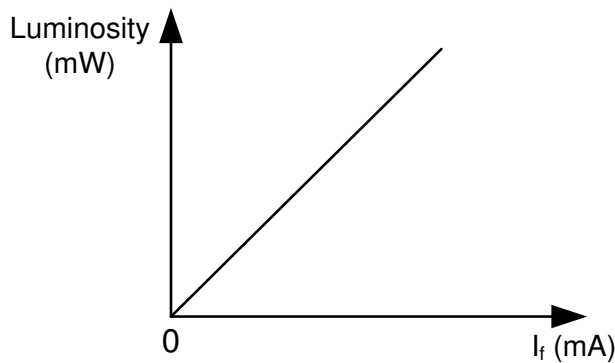
Voltage rating – 1 – 3 V
Current rating – 20 – 10mA

Applications
1. Digital displays e.g. seven segment
2. Indicators (power)
3. Networks (fiber optics) since it converts electrical energy to light energy.

PHOTODIODE

Circuit symbol

A photodiode is a diode made from photoconducting material such as germanium that changes light energy to electric energy. It is therefore a transducer.

Construction
It is made from p-type and n-type semiconductors which are sensitive to light energy. They have a large surface area compared to normal diodes.

Operation
Doping is higher than other diodes to increase reverse bias current. It is always operated in reverse bias. When a reverse voltage is applied electrons move from the valence band to the conduction band increasing the conductivity of the material. These are minority charge carriers.

Characteristic Curve

I_R
(μA)

0

E (light Intensity)
(mW/cm^2)

I_R
(μA)

light Intensity

0

V_R
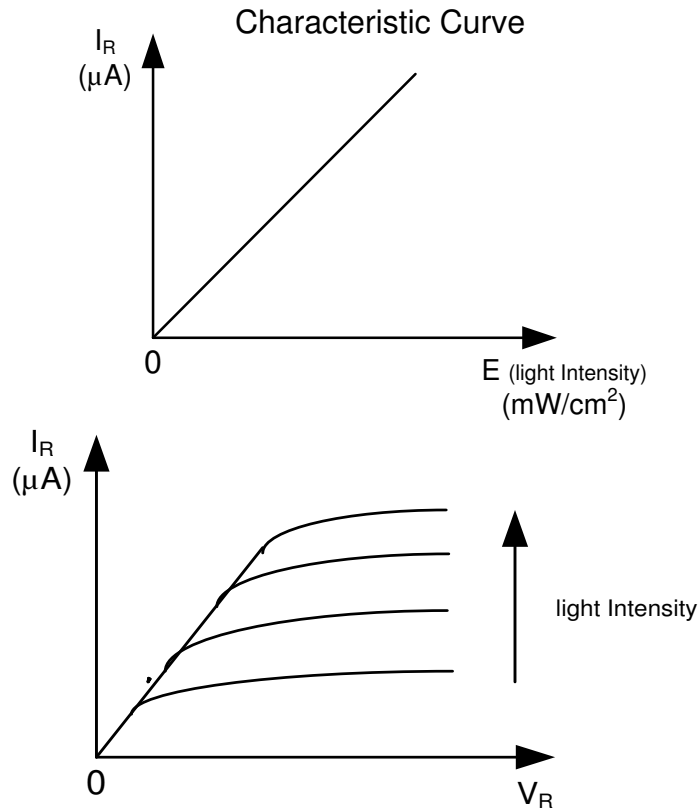
Dark current $I_R = \dfrac{V_R}{R_R}$ where R_R is the dark resistance

Applications
1. Automatic switching systems
2. Alarm circuits
3. Fiber optic networks to change light energy to electric energy
4. Counting

Factors affecting light intensity
1. Light intensity
2. Applied voltage
3. Material of the photodiode
4. Surface area

TUNNEL DIODE

Circuit symbol
A tunnel diode is a diode exhibits negative resistance between 2 points of forward voltage

Construction
It is very highly doped which makes the depletion layer small in size as a result electrons can move across the junction with application of minimal voltage or no voltage at all. This is called tunneling effect.

Operation
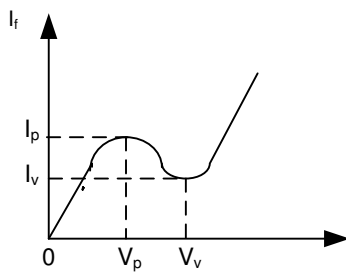
When forward voltage is applied due to tunneling effect there will an increment of current up to a peak point. After that the tunneling effect reduced which leads to a decrement of current up to a valley point. Further increment of voltage from this point leads to a corresponding increment of current where the diode stars behaving like a normal diode.

Applications
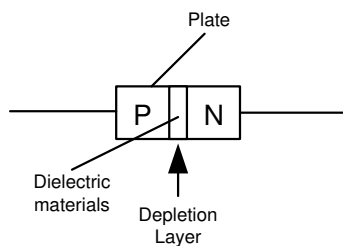1. Oscillators e.g. in tuning circuits
2. Fast switches

VARACTOR DIODE
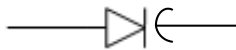
circuit symbol
A varactor diode is a diode which behaves like a variable capacitor.

Construction

The p - type and n – type semiconductors act as the plates, P – N junction as the electric material and length of junction as distance between the plates.

Operation
It is operated on reverse bias mode. When you increase the reverse bias voltage the thickness of the depletion layer is increased resulting in a reduction of the effective capacitance and vice – versa.
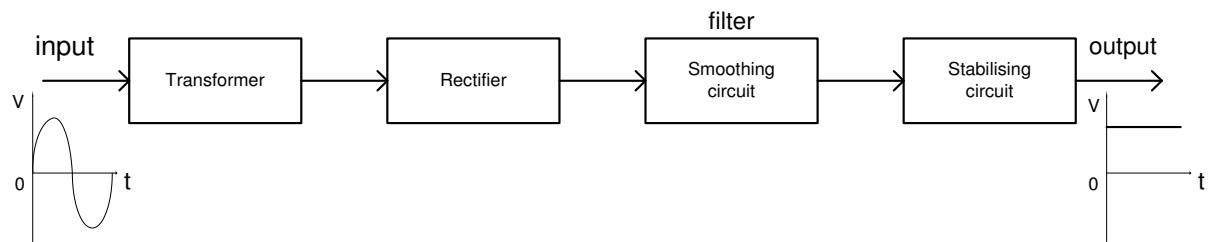
$$C = \frac{\varepsilon A}{d}$$

C
(capacitance)

V_R
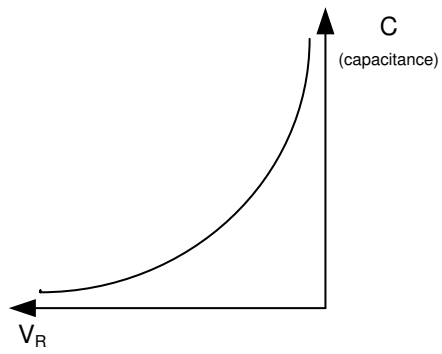
Applications

(a) Tuning circuit log with inductors

$$f_r = \frac{1}{2\Pi\sqrt{LC}}$$

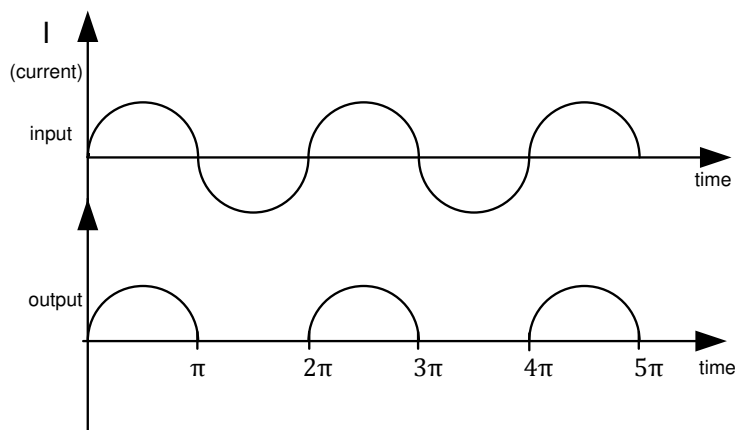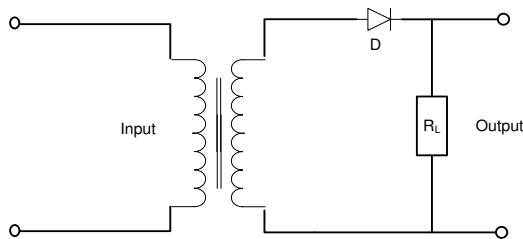where f_r is resonance frequency

LINEAR POWER SUPPLY

RECTIFIERS

A rectifier is made from rectifier diodes which have a high power rating and peak inverse voltage/ breakdown voltage. The most common material used to make these diodes is silicon

There are two types
(a)   Half Wave Rectifier
(b)   Full Wave Rectifier

Half wave – rectifiers (HWR)

Operation

During the first half cycle the diode is forward biased allowing current to pass through and therefore an output can be from the resistor R_L. During the second half cycle the diode is reverse biased as a result no current passes through and there is no output appearing at R_L.

Only the positive half cycles are appearing at the output and are referred to as ripples whose frequency is the same as that of the input waveform.

Average value (output)

$$I_{dc} = \frac{1}{2\pi} \int_0^\pi i \, d\theta \qquad\qquad \text{where } i = I_m \sin\theta$$

$$I_{dc} = \frac{1}{2\pi} \int_0^\pi I_m \sin\theta \, d\theta$$

$$\frac{I_m}{2\pi}[-\cos\theta]_0^\pi d\theta = \frac{I_m}{2\pi}[-\cos\pi + \cos 0] = \frac{I_m}{\pi} = 0.3183 I_m$$

$$P_{dc} = I_{dc}V_{dc} = I_{dc}^2 R_L$$

Rms value of a.c output current

$$I_{rms}^2 = \frac{1}{2\pi} \int_0^\pi i^2 \, d\theta = \frac{1}{2\pi} \int_0^\pi (I_m \sin\theta)^2 \, d\theta = \frac{I_m^2}{2\pi} \int_0^\pi \frac{(1 - \cos 2\theta)}{2} = \frac{I_m^2}{4}$$

Therefore

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

$$P_{ac} = I_{rms}^2(R_L + r_f) = \left(\frac{I_m}{2}\right)^2 (R_L + r_f)$$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{I_{dc}^2 R_L}{I_{rms}^2(R_L + r_f)} = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{2}\right)(R_L + r_f)^2}$$
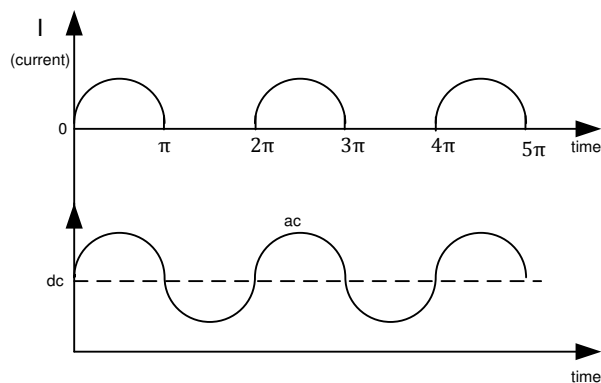
$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{4}{\pi^2\left(1 + \frac{r_f}{R_L}\right)} = 0.\frac{405}{\left(1 + \frac{r_f}{R_L}\right)}$$

$r_f \ll R_L$, $\eta = 0.405$
$= 40.5\%$ is the efficiency of a half-wave rectifier
Ripple Factor
Ripple factor is the ratio of ac to dc current (I_1ac/I_1dc)

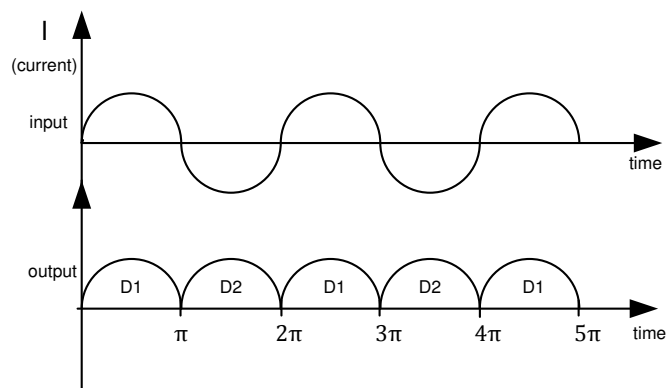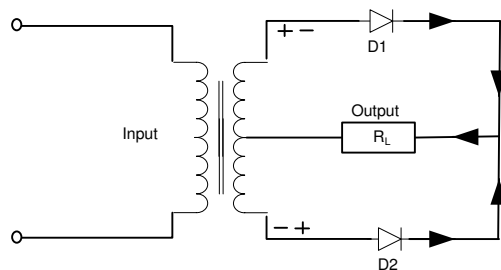Effective rms value

$$I_{rms}^2 = I_{dc}^2 + I_{ac}^2$$

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2}$$

$$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

$$\frac{I_{ac}}{I_{dc}} = \sqrt{\frac{I_{rms}^2}{I_{dc}^2} - 1} = \sqrt{\frac{\left(I_m/2\right)^2}{\left(I_m/\pi\right)^2} - 1} = \sqrt{\frac{\pi^2}{4} - 1} = 1.21$$

Full-wave Rectifier
(a) Centre-Tapped Rectifier

Operation
When the input waveform is positive going i.e. first half cycle D_1 is forward biased and D_2 is reverse biased. There will be an output at R_L as a result of D_1. During the second half cycle D_2 is forward biased and D_1 is reverse biased. There will be an output as a result of D_2.

The two currents are in the same direction and therefore they appear on the positive side of the time – line as ripples whose frequency is twice that of the input waveform.

Average value

$$I_{dc} = \frac{1}{\pi}\int_0^\pi i\, d\theta \qquad\qquad \text{where } i = I_m \sin\theta$$

$$I_{dc} = \frac{1}{\pi}\int_0^\pi I_m \sin\theta\, d\theta$$

$$\frac{I_m}{\pi}[-\cos\theta]_0^\pi d\theta = \frac{I_m}{\pi}[-\cos\pi + \cos 0] = \frac{2I_m}{\pi} = 0.6366I_m$$

$$P_{dc} = I_{dc}V_{dc} = I_{dc}^2 R_L$$
$$P_{ac} = I_{rms}^2 R_L$$

Rms value of a.c output current

$$I_{rms}^2 = \frac{1}{\pi}\int_0^\pi i^2\, d\theta = \frac{1}{\pi}\int_0^\pi (I_m\sin\theta)^2\, d\theta = \frac{I_m^2}{\pi}\int_0^\pi \frac{(1-\cos 2\theta)}{2} = \frac{I_m^2}{2}$$

Therefore

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

$$P_{ac} = I_{rms}^2(R_L + r_f) = \left(\frac{I_m}{2}\right)^2 (R_L + r_f)$$

Efficiency of a full wave rectifier

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{I_{dc}^2 R_L}{I_{rms}^2(R_L + r_f)} = \frac{\left(\frac{2I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{\sqrt 2}\right)(R_L + r_f)^2}$$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{8}{\pi^2\left(1 + \frac{r_f}{R_L}\right)} = 0.\frac{811}{\left(1 + \frac{r_f}{R_L}\right)}$$

$r_f \ll R_L$, $\eta = 0.811$

         = 81.1% is the efficiency of a full-wave rectifier

The full wave rectifier thus has very high efficiency

Ripple Factor
Ripple factor is the ratio of ac to dc current ($I_{1}ac/I_{1}dc$)
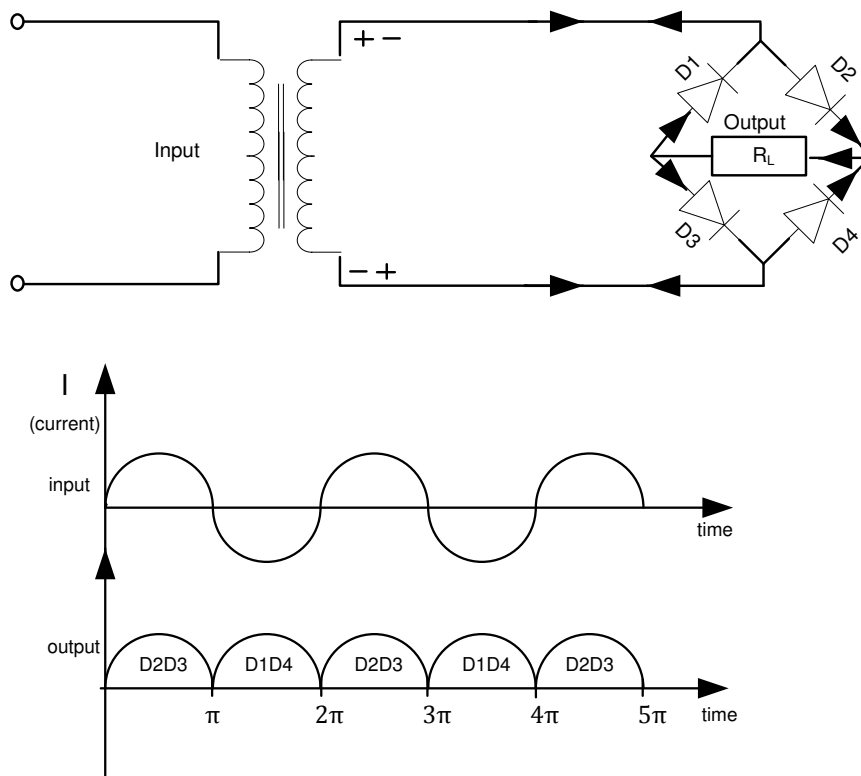$$I_{rms}^2 = I_{dc}^2 + I_{ac}^2$$
$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2}$$
$$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

$$\frac{I_{ac}}{I_{dc}} = \sqrt{\frac{I_{rms}^2}{I_{dc}^2} - 1} = \sqrt{\frac{\left(I_m/\sqrt 2\right)^2}{\left(2I_m/\pi\right)^2} - 1} = \sqrt{\frac{\pi^2}{8} - 1} = 0.48$$

Bridge Rectifier

During the first half cycle D_2 and D_3 are forward biased while D_1 and D_4 are reverse biased therefore an output will appear at R_L as a result of D_2 and D_3. During the second half cycle diode D_1 and D_4 are forward biased while diodes D_2 and D_3 are reverse biased therefore there will be an output at R_L is as a result of D_1 and D_4.

The currents are in the same direction in the resistor R_L therefore they will appear on the positive side of the time – line. They are also called ripples and have a frequency twice that of the input waveform.

Example
A half- wave rectifier with transformer of transformation ratio of 10:1 has the following parameters.
$V_{in} = 250\sin wt$ V
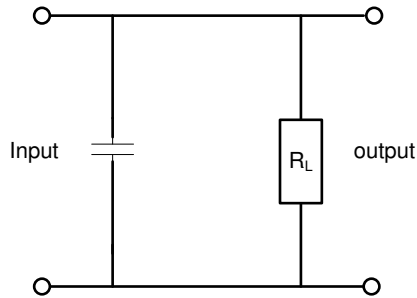$r_f = 20\ \Omega$
$R_L = 800\ \Omega$
Calculate
Vm, I_{dc}, I_{ac}, P_{dc}, η, V_{dc}, ripple factor
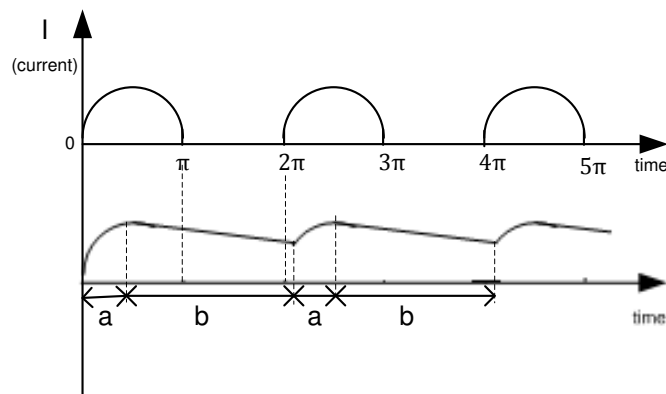
Smoothing circuits (filter)
This is a section in the power supply which removes the a.c component present in the output of a rectifier. It is made using of capacitors and inductors or a combination of both.

(a) Capacitor filter
(b) Choke input (inductor)
(c) Capacitor input filter

Capacitor Filter

Half-wave rectifier

Capacitor filter

a – Charging

b – Discharging

$$V_C = V_S\left(1 - e^{\left(-t/RC\right)}\right)$$

$$V_C = V_S e^{\left(-t/RC\right)}$$

It consists of a capacitor and a resistor connected in parallel. During the appearance of the first ripple the capacitor will charge to a maximum V_m. The ripple will collapse very fast leaving the capacitor to discharge. Because the capacitor takes a longer time to discharge when the second ripple appears it finds the capacitor still discharging and picks up from there charging the capacitor again to a maximum V_m. The process continues so long as there is an input to the filter

This will result to an output with more of DC component than the input waveform

Full wave rectifier
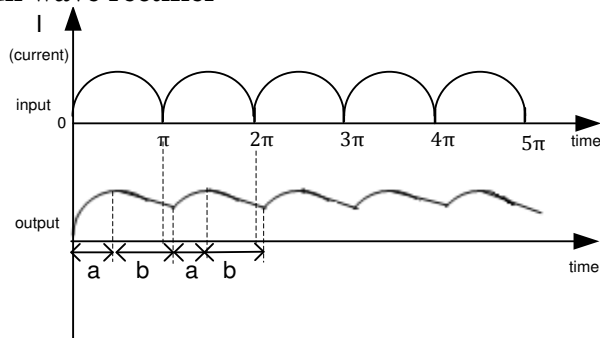
The operation is the same as that of a half-wave rectifier, the only difference being that the output of full-wave rectifier filter has more d.c component than the half waveform rectifier

filter. To get a more refined d.c, several circuits of the same kind can be connected after the first circuit.

Ripple factor is less than of half – wave rectifier i.e. ripple factor HWR $>$ FWR

Choke Input Filter
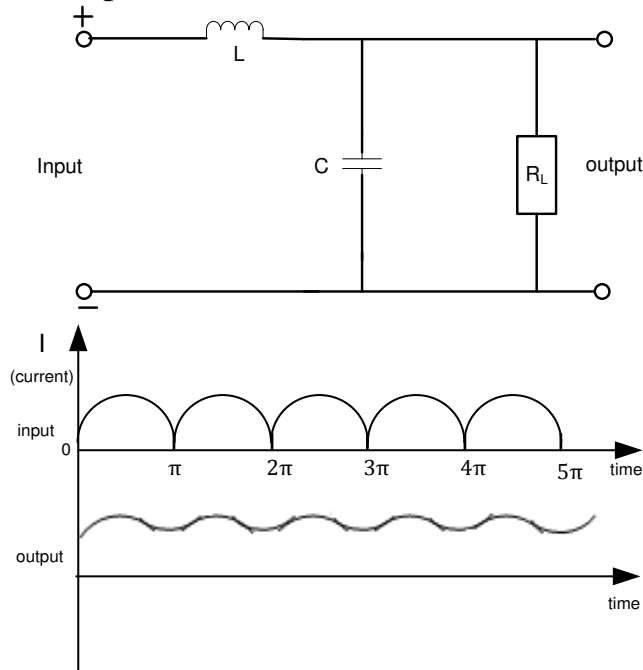
It consists of an inductor in series with a parallel combination of a capacitor and resistor. The inductor will oppose some of the a.c component present in the input. Whatever passes through the inductor is bypassed by the capacitor C. Therefore there will be a minimized a.c at the output. The d.c passes through the inductor without opposition and goes straight to the output since it cannot pass through the capacitor.

**Capacitor input filter (Π filter)**
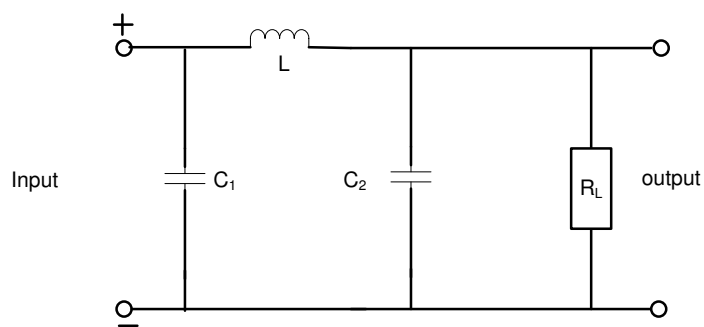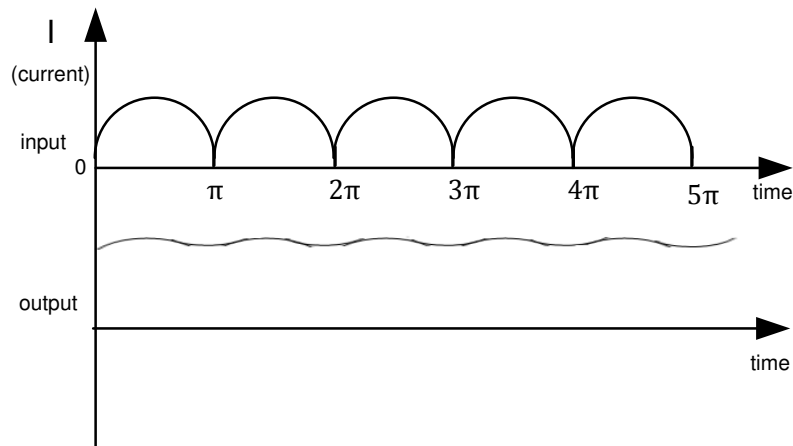
The first capacitor C_1 bypasses of the a.c component present at the input. Whatever is left is blocked by the inductor L and whatever passes through the inductor is bypassed by C_2. The dc component passes through the inductor to the output. This results to a more refined d.c component. Several combinations of the circuit can produce even more refined d.c component.

Stabilizing circuit / voltage regulator
It is constructed by use of zener diode or a transistor or both.
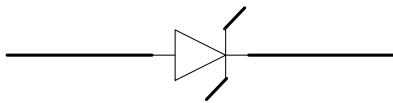

Zener diode circuit symbol

A zener diode uses the principle of reverse breakdown to provide a constant output voltage.

Construction
The doping is higher than that of normal diodes. This will make it to breakdown without getting damaged. It breaks down earlier than the other diodes depending on the reverse voltage rating. It has a higher power rating

Operation
It is operated in reverse bias mode. If the voltage is increased beyond breakdown voltage the diode breaks down. Any further increment of voltage will still give a constant output voltage as shown in the diagram below.
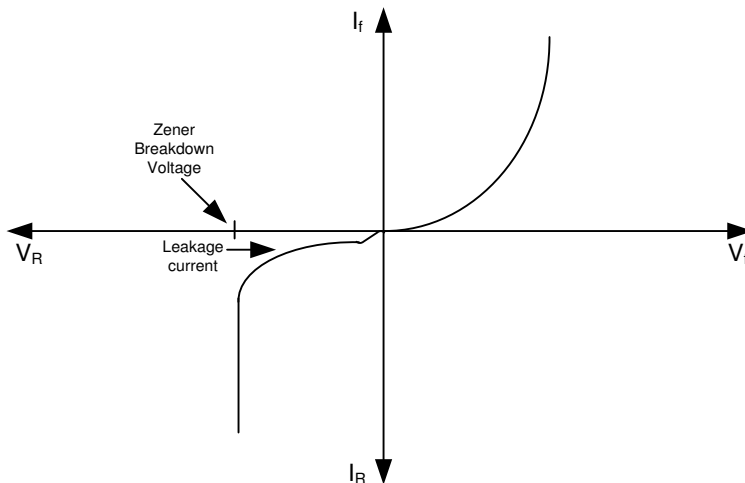
In forward bias it behaves like any other diode conducts at (Si – 0.7V, Ge- 0.3V). In reverse bias the diode breaks down when there is an increase of voltage beyond breakdown voltage. Only a small amount of current flows through before breakdown voltage called leakage current.
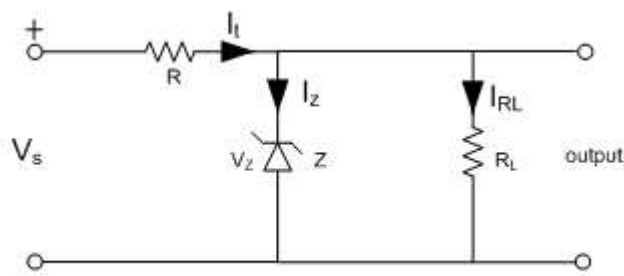
It is connected together with an external resistor to limit amount of current related to diode the rating.
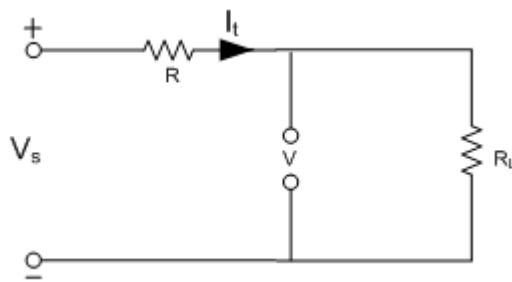
Equivalent circuit of the zener diode
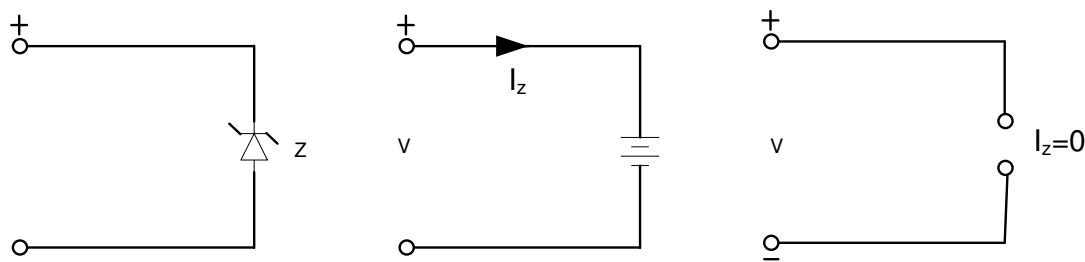
In the on state the zener diode is replaced by zener voltage or breakdown voltage
In off state it is replaced by an open circuit and assuming the leakage current $I_z = 0$
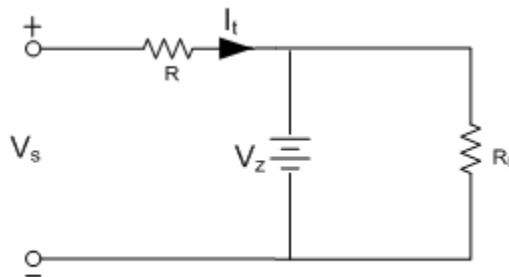
Zener Diode circuits Analysis

Off state

$$V_{RL} = \frac{V_S R_L}{R + R_L}$$

$$V > V_Z$$

On state

$$I_{RL} = \frac{V_Z}{R_L} \qquad\qquad I_t = \frac{V_S - V_Z}{R} = I_{RL} + I_Z$$

Example

R = 500Ω
R$_L$= 800Ω
V$_s$ = 40V
V$_z$ = 15V

Calculate I$_{RL}$, I$_t$, I$_{z,}$ P$_z$ in the on state and I$_t$ in the off state.
Solution

On state

$$I_{RL} = \frac{V_Z}{R_L} = \frac{15}{800} = 0.01875 \text{ A} \qquad\qquad I_t = \frac{V_S - V_Z}{R} = \frac{40 - 15}{500} = \frac{25}{500} = 0.05A$$
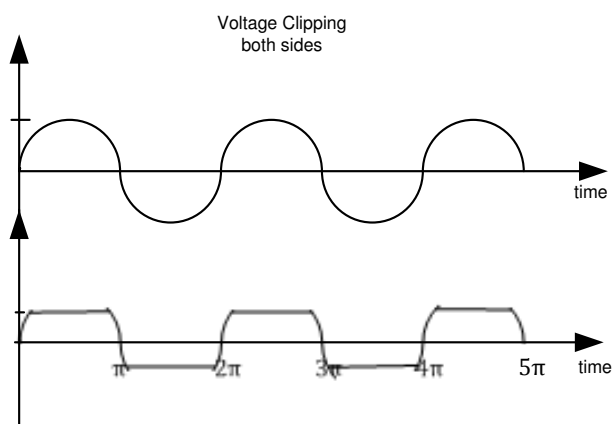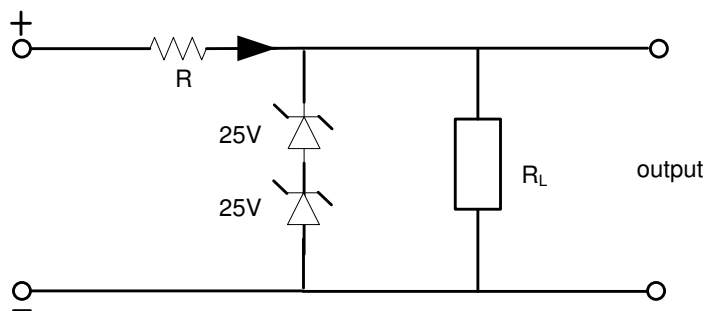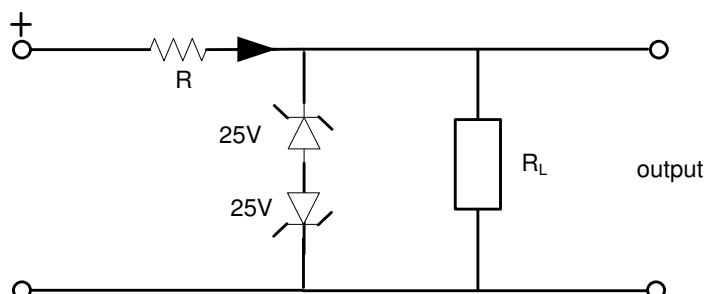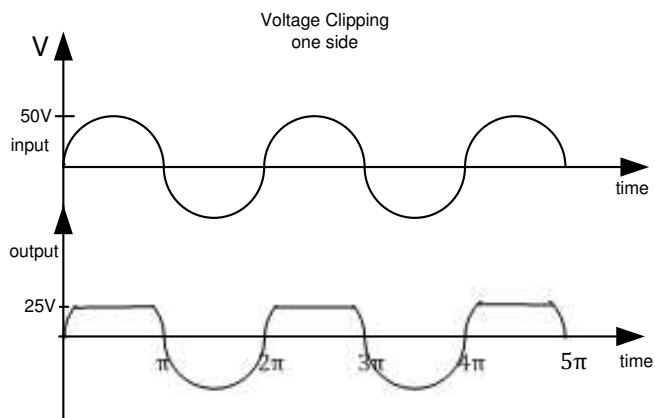
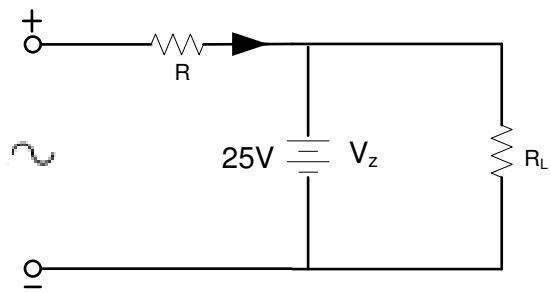$$I_Z = I_t - I_{RL} = 0.05 - 0.01875 = 0.03125A \qquad P_Z = I_Z V_Z = 0.03125 \text{ x } 15 = 0.46875 \text{ } A$$

Off state

$$I_t = \frac{V_S}{R + R_L} = \frac{40}{500 + 800} = \frac{400}{1300} = 0.031A$$

I$_t$ in off and on state is different. In the on state diode bypasses most of the current shorting the resistor R$_L$.

Voltage Clipping
one side

output

output

Voltage Clipping
both sides

TRANSISTORS

A transistor is an active device which can increase the strength of a signal. It is manufactured by use of p – type and n – type semiconductor materials.

Transistor = Transfer resistor

a) Types BJT – Bipolar junction transistor – Linear amplifier to boost an electrical signal
                                             - Electronic switch

b) FET - Field effect transistor

Bipolar Junction Transistor

It is constructed by sandwiching n– type materials between 2 p – type materials or a p-type material between 2 n – type materials. It used electrons and holes as charge carriers.

It has 2 junctions J_1 and J_2

It has 3 terminals: Emitter
                          Base
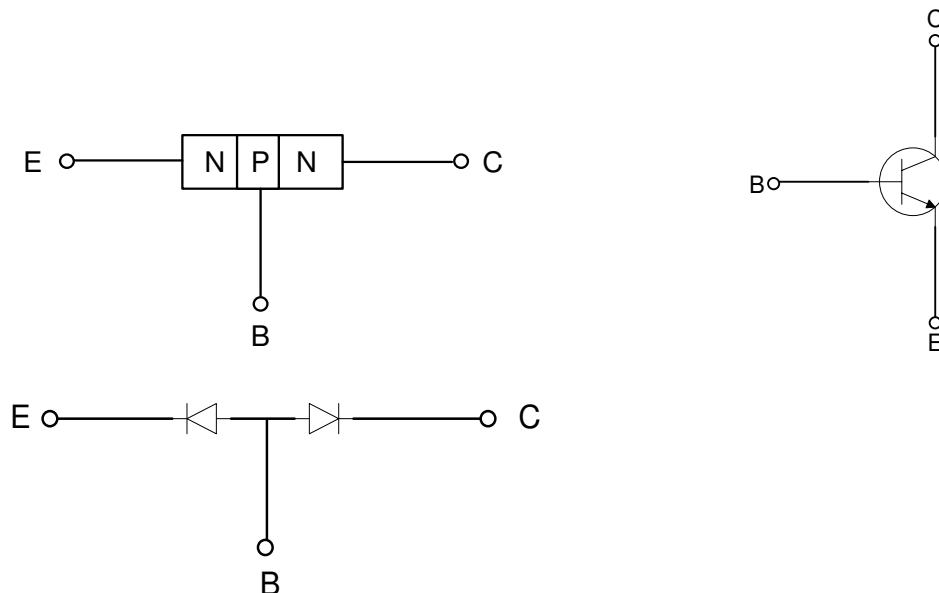   Collector

The emitter emits the majority charge carriers, collector collects the charge carriers, the base controls those charge carriers moving from the emitter to the collector.

There are two types of BJT transitors
 (i) PNP
(ii) NPN

NPN Transistor
Construction

It is constructed by sandwiching a p – type material between 2 n – type materials. It is like 2 diodes connected back to back. The arrows in the circuit symbol indicate the direction of current when the transistor is in operation. The emitter is heavily doped so that it can emit a large amount majority charge carriers (electrons).

The base is very thin and very lightly doped so as to allow majority charge carriers to move from the emitter to the collector with minimal time possible and reduce the base current by

reducing the amount of charge comes recombining when the features above increase the collector current and reduce the base current. (Transistor amplifier)

The collector is larger in size than the other two and moderately doped. Large size makes it able to dissipate large amount of power without getting damaged. Moderate doping also reduced the amount of power dissipated.

$$P = I_C^2 R$$

$$R = \rho \frac{L}{A}$$

Operation
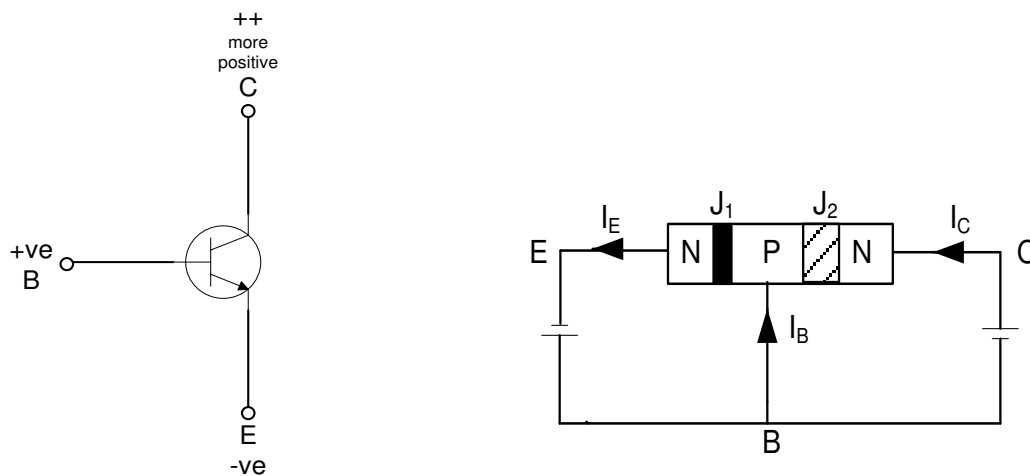
For a transistor to effectively operate the base emitter junction is supposed to be forward – biased while the collector-base junction is reverse biased. This is done by connecting the emitter to negative potential, the base to positive potential and the collector to more positive potential.

The negative potential at the emitter repels the electrons which are the majority charge carries. As they reach the base very few of them will combine with holes to form the base current I_B (5%). The rest will be attracted by the more positive potential at the collector and then they pass through the base to form the collector current (95% /98%)

Base and collector cannot be interchanged due to doping levels
Using KCL $I_C + I_B = I_E$

PNP transistor
Construction
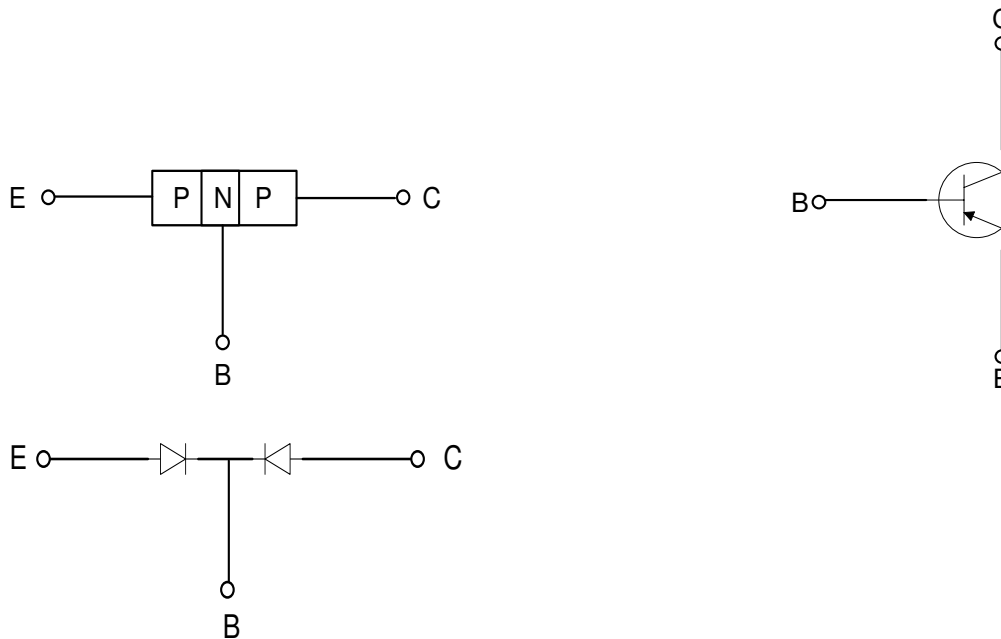
The n − type semiconductor is sandwitched between 2 p- type semiconductors. It is like 2 diodes connected front to front. The direction of the arrow in the circuit symbol indicates the direction of current when the transistor is in operation.

The size and doping levels for the emitter, base and collector are the same as those of the NPN transistor.

Operation
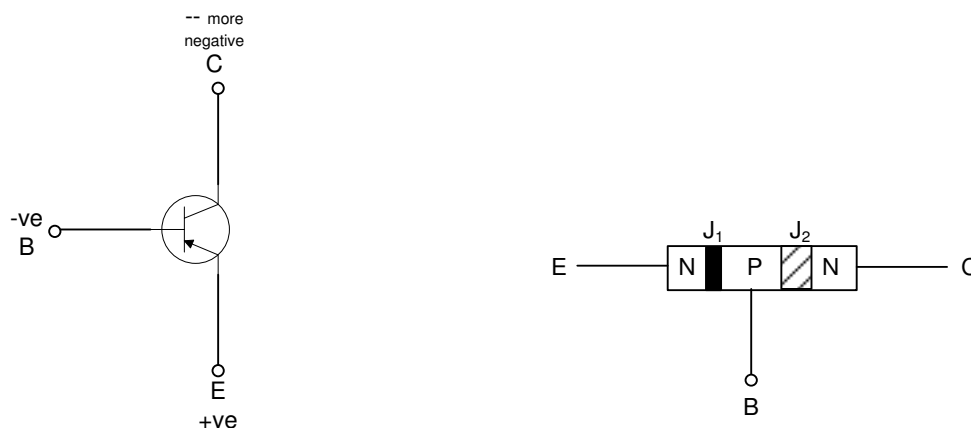
The B − E junction is forward biased while the collector − base junction is reverse biased. This is done by connecting the emitter at the positive potential, the base to a negative potential and collector to a more negative potential.

The positive potential at E repels the holes which are majority charge carriers which move through the base by being attracted by the more negative potential at the collector. A few of those charged carriers will recombine at the base to form I_B (base current 2% - 5%) while the rest move through to the collector to form the collector current (95%)

Using KCL
$I_E = I_C + I_B$
100%   95%   5%

Transistor modes of connection (configurations)

A transistor has 3 terminals and since the input has 2 terminals and the output 2 terminals, one of the transistor terminals is made to be common so that the input and output can be measured. The common terminal is usually connected to the ground.

All the common connections should maintain a forward bias for the B − E junction and a reverse bias for the C − B junction. The configurations are given by common base (CB), Common emitter (CE) and common collector (CC). They can be used for different applications.

1. Common Base (CB) connection
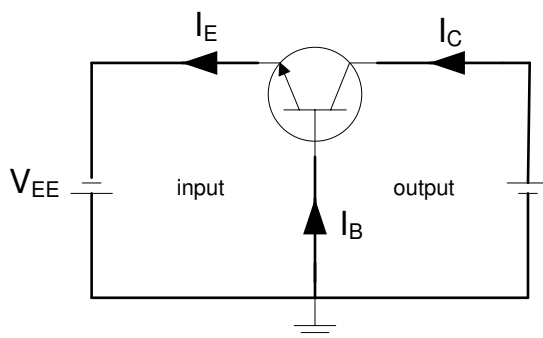
Negative potential obtained by rectification on lower side of the time line. The base is common to the input and the output.

Parameters

Input   Output

Input current = I_E Output current = I_C
Input voltage = V_{BE} Output voltage = V_{CB}

Input resistance = $\dfrac{V_{BE}}{I_E} = h_{IB}$ Output resistance = $\dfrac{V_{CB}}{I_C} = h_{OB}$

Input power = $I_E V_{BE}$ Output power = $I_C V_{CB}$

$$\text{Current gain} = \frac{I_C}{I_E} = \alpha = h_{FB}$$

α is the measure of the quality of a transistor, the higher the value of α, the better the transistor in the sense that the collector current more closely equals the emitter current.

$$I_C = \alpha I_E \qquad I_B = I_E - I_C = I_E - \alpha I_E = (1 - \alpha) I_E$$

Parameter	Instantaneous	d.c	Total
Emitter I	i_e	I_E	i_E
Collector I	i_c	I_C	i_C
Base I	i_b	I_B	i_B
BE voltage	v_{be}	V_{BE}	v_{BE}
Hybrid	h_{ib}	h_{IB}	h_{IB}

Reverse voltage gain $= \dfrac{V_{BE}}{V_{CB}} = h_{RB}$ voltage gain $= \dfrac{V_{CB}}{V_{BE}}$

Input impedance $= h_I$ Output impedance $= \dfrac{V_{CB}}{I_C} = h_{OB}$
Output admittance $= h_o$
Forward current gain $= h_f$
Reverse voltage gain $= h_{RB}$

Power gain $= \dfrac{\text{Output power}}{\text{Input power}} = \dfrac{V_{CB}I_C}{V_{BE}I_E} = A_p$
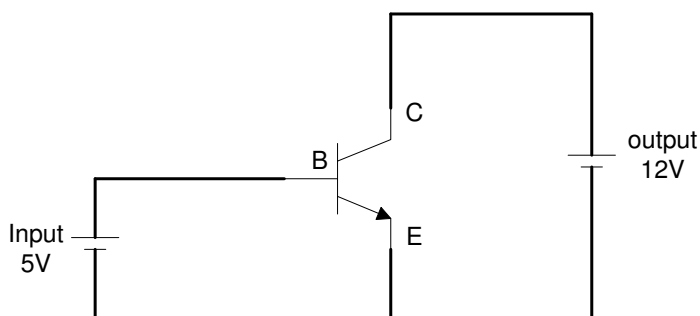
A_v = Voltage gain
A_i = Current gain
Power gain in decibels (dB) $= 10 \log_{10} A_p$
Voltage gain in dB $= 20 \log_{10} A_v$
Current gain in dB $= 20 \log_{10} A_i$

Application of CB - connection : Impedance matching

2. Common Emitter (CE) configuration

In this case the emitter is common to the input and output therefore it is grounded.
Parameters

Input Output
Input current $= I_B$ Output current $= I_C$
Input voltage $= V_{BE}$ Output voltage $= V_{CE}$

Input resistance $= \dfrac{V_{BE}}{I_B} = h_{IE}$ Output resistance $= \dfrac{V_{CE}}{I_C}$

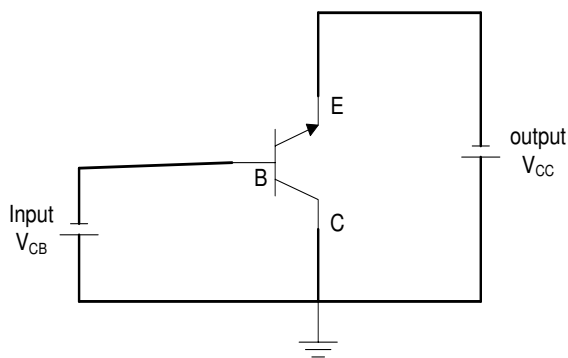Input power $= I_E V_{BE}$ Output power $= I_C V_{CE}$

Current gain $= \dfrac{I_C}{I_B} = \beta = h_{FE}$ - Forward current gain of common emitter configuration

$$h_{OE} = \dfrac{I_C}{V_{CE}} = \dfrac{1}{r_o}$$

Reverse voltage gain $= \dfrac{V_{BE}}{V_{CE}}$

This connection is used for impedance matching where the output has a lower impedance. It is mostly applied where a gain is required.

Common Collector Connection

Input

Input current $= I_B \cong \mu A$

Input voltage $= V_{CB} \cong 20V$

Input resistance $= \dfrac{V_{CB}}{I_B} \cong k\Omega$

Input power $= I_B V_{CB}$

Output

Output current $= I_E$

Output voltage $= V_{CE}$

Output resistance $= \dfrac{V_{CE}}{I_C}$

Output power $= I_E V_{CE}$

$I_E = I_B + I_C$
$= I_B + \beta I_B = (1+\beta)I_B$

Output current $= (1+\beta)$ x input current

Gain

Current gain $= \dfrac{I_E}{I_B} = \theta$ or $\gamma = h_{FC}$

$$\theta = \dfrac{I_E}{I_C} = \dfrac{I_E}{I_C} x \dfrac{I_C}{I_B} = \dfrac{\beta}{\alpha} = \dfrac{\beta}{\beta/(1+\beta)} = 1+\beta$$

Voltage gain $= \dfrac{V_{CE}}{V_{CB}}$

Reverse Voltage gain $= h_{RC} = \dfrac{V_{CB}}{V_{CE}}$

$\cong 1$

Applications
(i)   It can be used in current gain or power gain circuit
(ii) It can be used for impedance matching to isolate two circuits.

Relationship between current gains

$$\alpha = \frac{I_C}{I_E} \qquad \beta = \frac{I_C}{I_B} \qquad \theta = \frac{I_E}{I_B} \qquad I_E = I_C + I_B$$

(i) α in terms of β

$$\alpha = \frac{I_C}{I_E} = \frac{I_C}{I_C + I_B} = \frac{\beta}{\beta + 1}$$
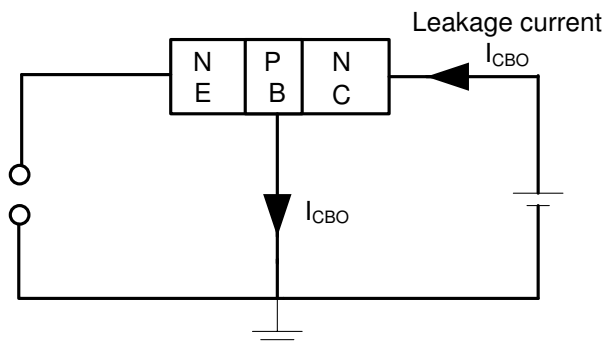
(ii) β in terms of α

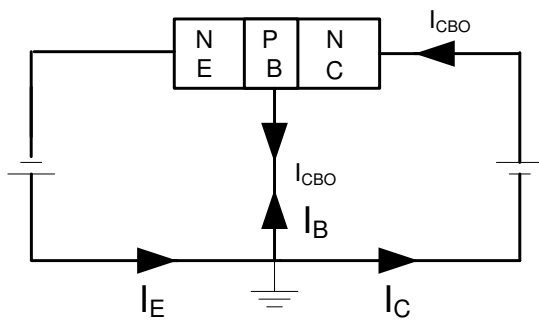$$\beta = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha}{1 - \alpha}$$

Leakage Current
Transistors (BJT)

Leakage current is caused by the flow of minority charge carriers in a transistor and flows in the PN junction in the common base connection.

I_{CBO} leakage current is the current which flows from C to B when the emitter is open.

$$I_C = \alpha I_E + I_{CBO}$$
$$\qquad \text{Majority} \qquad \text{minority}$$
$$\qquad \text{Carriers} \qquad \text{carriers}$$

$$I_C = \alpha(I_C + I_B) + I_{CBO}$$

$$I_C - \alpha I_C = I_B + I_{CBO}$$

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO} = \beta I_B + (1 + \beta) I_{CBO}$$

Similarly

$$I_C = \alpha I_E + I_{CBO}$$
$$I_E - I_B = \alpha I_E + I_{CBO}$$
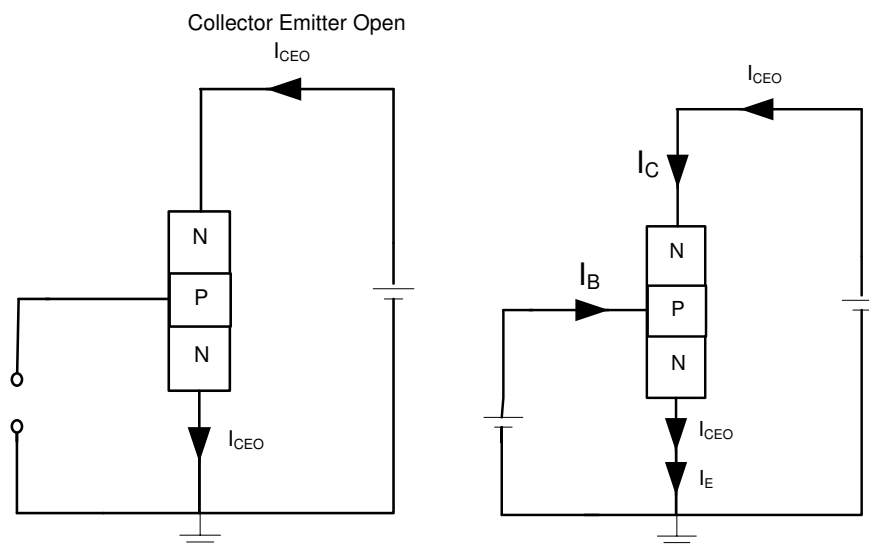$$I_B = \underbrace{I_E - \alpha I_E} - I_{CBO}$$

$$I_B = I_{Bmajority} - I_{CBO}$$
$$I_B = (1 - \alpha)I_E - I_{CBO}$$

I_{CBO} – Collector- to- base leakage current

I_{CBO} is exactly like the reverse saturation current I_s of a reverse biased diode.

I_{CBO} is extremely temperature dependent i.e. it doubles for every 10^0C rise for germanium and 6^0C for silicon.

$$I_C = \frac{\alpha}{1 - \alpha}I_B + \frac{1}{1 - \alpha}I_{CBO}$$
$$I_C = \frac{1}{1 - \alpha}I_{CBO} = I_{CEO}$$

I_C is magnified by a factor of $1+\beta$

$$I_C = \beta I_B + I_{CEO}$$
$$I_E = I_C + I_B = \beta I_B + I_{CEO} + I_B$$

$$I_E = (1+\beta)I_B + I_{CEO} = (1+\beta)I_B + \frac{1}{1 - \alpha} I_{CEO}$$

Thermal Runaway

This is a situation where an increment of current leads to an increment of temperature in a semiconductor. The increment of temperature in turn leads to an increment of current, the process continues and if not kept in control can damage the transistor.

Si = 10^0C rise in temperatures doubles the current
Ge = 6^0C rise in temperature doubles the current

TRANSISTOR STATIC CHARACTERISTICS

There are VI characteristics of transistors connected in different configurations. They help in determining the optimal operation of a transistor.

They are

 (i) Input characteristics   - Graph of input current against input voltage
(ii) Output characteristics   - Graph of output current against output voltage
(iii) Transfer characteristics   - Graph of output current against input current

Common base
(i) Input characteristics
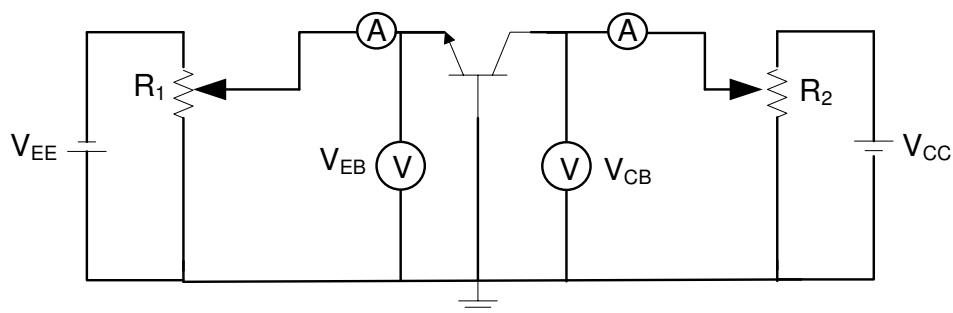
The input characteristics are given by the input current (I_E) against input voltage (V_{BE}) for a constant value of output voltage V_{CB}.

First, V_{CB} is kept at a constant value while V_{BE} is varied by the use of R_1. The corresponding I_E is noted and a curve is drawn
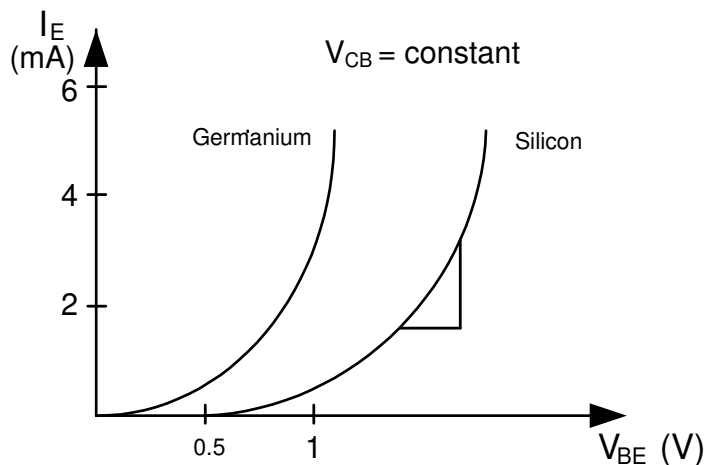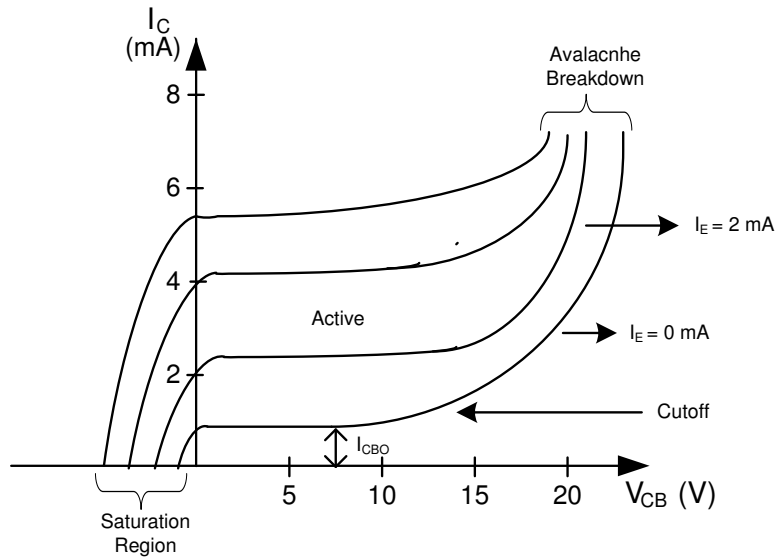

It behaves like a forward biased diode since the input base-emitter junction is forward biased. When V_{BE} is increased the transistor will start conducting at 0.7V (Si). Further increment of V_{BE} will lead to a corresponding increment of I_E.
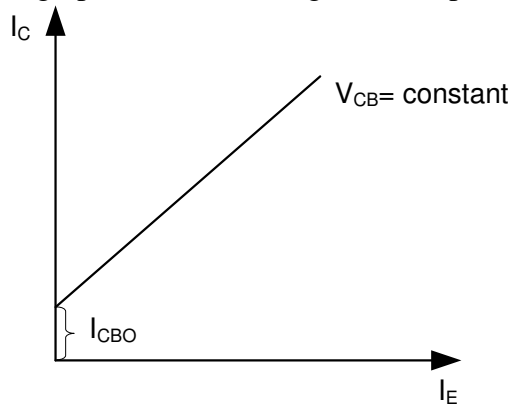
Admittance $= \dfrac{I_E}{V_{BE}}$

(ii) Output Characteristics

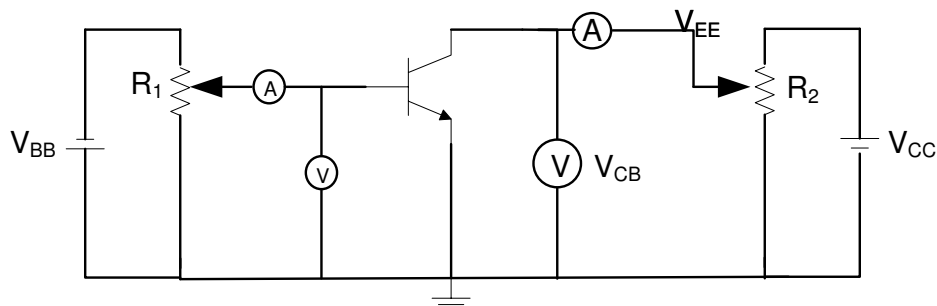I_E is kept constant while V_{CB} is varied in discrete steps and I_C is measured.

The graph can be used to get α. I_C is practically independent of V_{CB} over the working range.
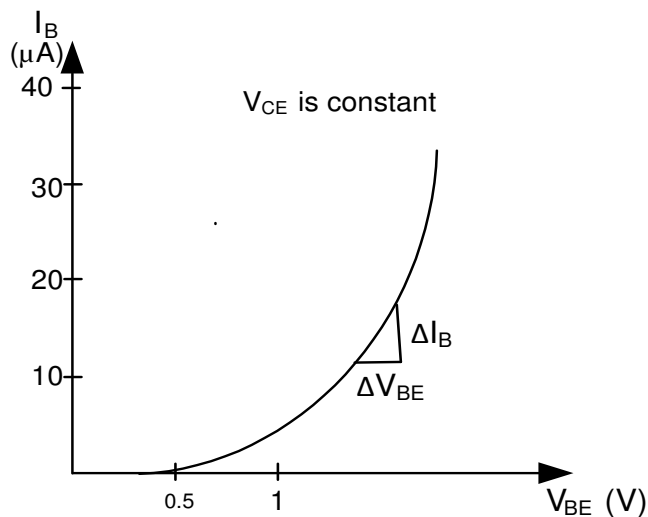

Gain can be calculated from the curve.

Common Emitter Connection

Input characteristics

This is a plot of I_B against V_{BE} for constant V_{CE}. V_{CC} is kept at a constant value while V_{BE} is varied at appropriate steps as I_B is measured for the corresponding steps.

When $V_{CE} = 0$, the base – emitter junction is forward biased. The junction behaves as forward biased diode. At a constant value of V_{BE} when V_{CE} is increased, the width of the depletion region at the collector-base junction will increase and hence the width of the base will decrease. This effect causes a decrease in base current I_B, therefore the curve shifts to the right as V_{CE} increases. The curve is exactly the same as that of a forward biased diode where with increment of V_{BE} the transistor starts conducting at 0.7V (silicon) or 0.2V (Ge). Further increment of V_{BE} results in a corresponding increment of I_B. The graph can be used to determine the input admittance or impedance where from initial stages of the curve the resistance is high (4kΩ) which reduces as V_{BE} increases.

Output characteristics
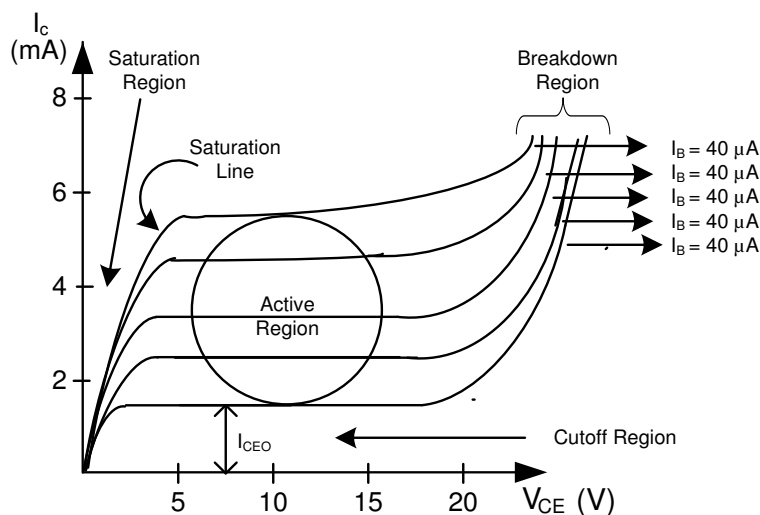
For $I_B = 0$ and $V_{CE} \cong 0$ the only current passing the transistor is leakage current I_{CEO}. When V_{CE} is increased there is in further increment of I_C and the transistor cannot hold any more and as a result it breaks down. If I_B is increased from zero to a few volts of V_{CE} the transistor will be in saturation mode. The curves will be similar to the one of $I_B = 0$

Regions of Transistor Operation
Saturation region
This is where $V_{CE} = 0$ up to a few volts ($\cong 0.5V$).Both the collector-base junction and base-emitter junction are forward biased and therefore the collector is collecting all the electrons emitted by the emitter. The transistor behaves like a switch which is on

Cut off region
This is where $I_B = 0$. Both junctions are reverse biased therefore only a small leakage current flows through which is called I_{CEO}. The transistor behaves like a switch which is off.

Active Region
This is where V_{CE} range from a few volts to around 30V depending on the type of transistor. I_B is also slightly above 0. The transistor is normally biased where the collector base junction is reverse biased while the base-emitter junction is forward biased. Most of the applications of the transistor use this region to operate e.g. amplification.

Breakdown region
V_{CE} is beyond 30V depending on the type of transistor. The base-emitter junction is forward based while collector-base junction reverse biased. At this part the transistor breakdown resulting to uncontrollable flow of current. This is called avalanche breakdown
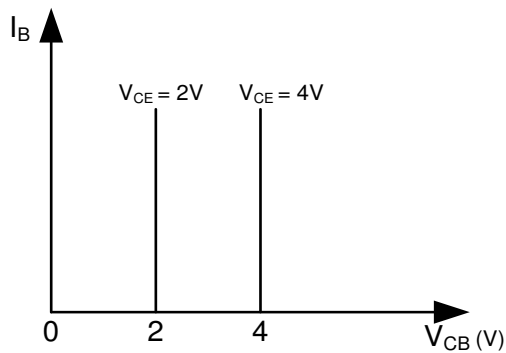
Transfer Characteristics
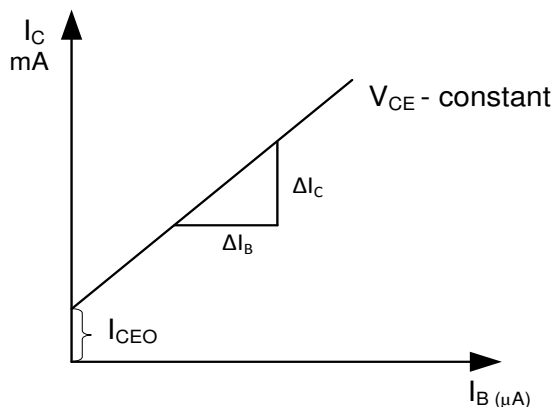
It is a plot of I_C against I_B. When $I_B = 0$, I_C has got some value which is referred to as leakage current I_{CEO}. This graph can be used to determine the forward current gain for collector-emitter connection.
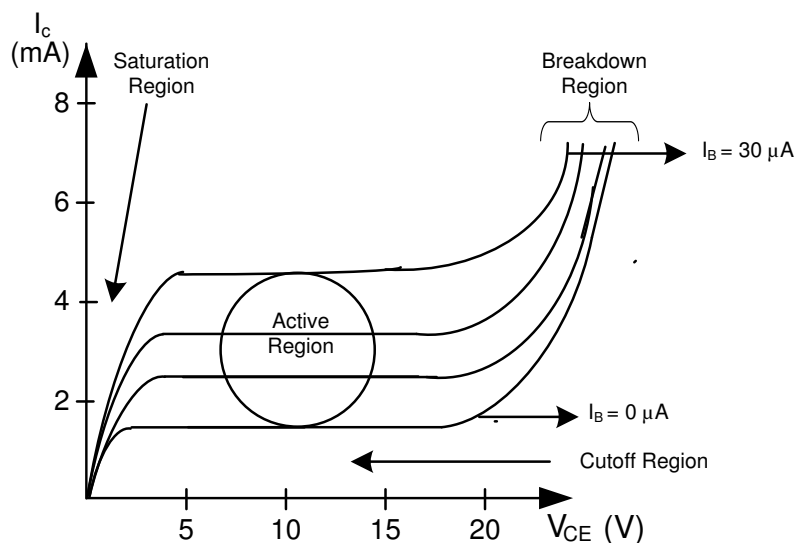
Common Collector Connection
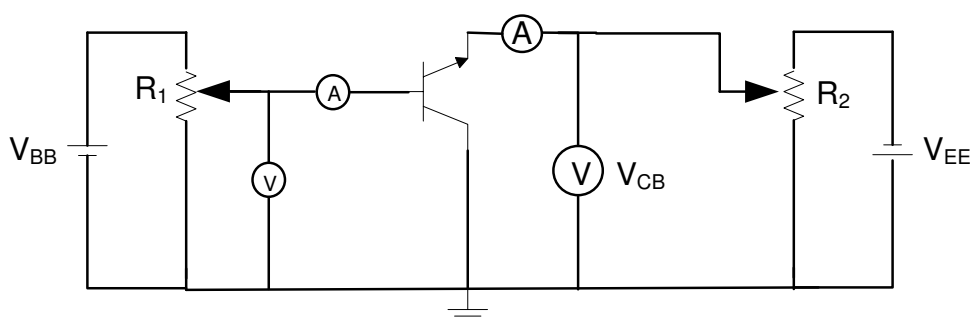
Input Characteristics

$$V_{CE} = V_{CB} + V_{BE}$$

It is a plot of I_B against V_{CB} while V_{CE} is kept constant. V_{CE} is dependent on both V_{CB} and V_{BE} by the use of the following relation

$$V_{CE} = V_{CB} + V_{BE}$$

If V_{CE} is kept constant and V_{CB} is increased V_{BE} will reduce up to a point where V_{CB} is equal to VCE. I_B will be given by zero. The graph can be used to determine the input impedance and reverse voltage gain.

Output Characteristics

This is a plot of I_E against V_{CE} while I_B is kept constant. The plot is exactly same as that of the output characteristics for the collector-emitter junction connection because I_E is almost equal to I_C. This graph can be used to determine impedance or admittance and forward current gain for the common collector connection.

**Transfer Characteristics**
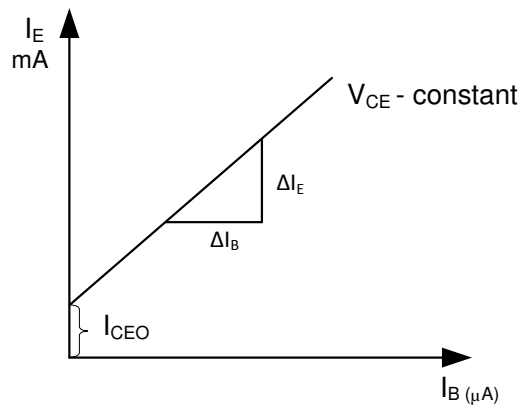
Methods of transistor biasing

This is the process of connecting a transistor voltage supplies together with resistors so that it can operate normally. The collector-base junction is reverse biased and base-emitter junction is forward biased. The methods of biasing a transistor are listed below.

(i)   Base bias
(ii) Base Bias with emitter feedback
(iii) Base Bias with collector feedback
(iv) Base Bias with collector and emitter feedback
(v)   Emitter Bias with two supplies
(vi) Voltage divider bias

Base Bias
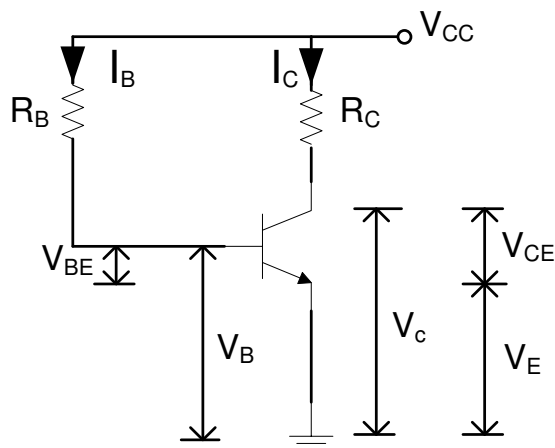
$V_C = V_{CE}$ Stability factor $s = 1 + \beta$

$I_C + I_B = I_E$

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

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

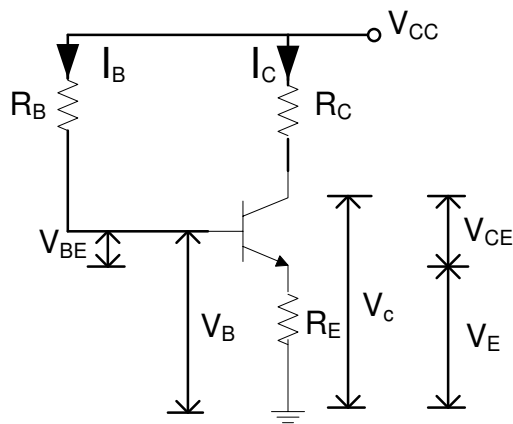$I_C = \dfrac{V_{CC} - V_{CE}}{R_C}$ $I_B = \dfrac{V_{CC} - V_{BE}}{R_B}$ $I_{C(sat)} = \dfrac{V_{CC}}{R_C}$ since $V_{CE} \simeq 0V$

$\text{Max } V_{CE} = V_{CC}$

$I_C \cong 0A$

Base Bias with Emitter Feedback

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E$$
$$V_{CC} = I_B R_B + V_{BE} + I_E R_E$$
$$I_C = \frac{V_{CC} - V_{CE}}{R_C + R_E/\alpha} \qquad\qquad \text{since } I_E = {}^{I_C}/\alpha$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C + \dfrac{1+\beta}{\beta} R_E}$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (1+\beta)R_E} \qquad\qquad \text{since } I_E = \theta I_B = (1+\beta)I_B$$
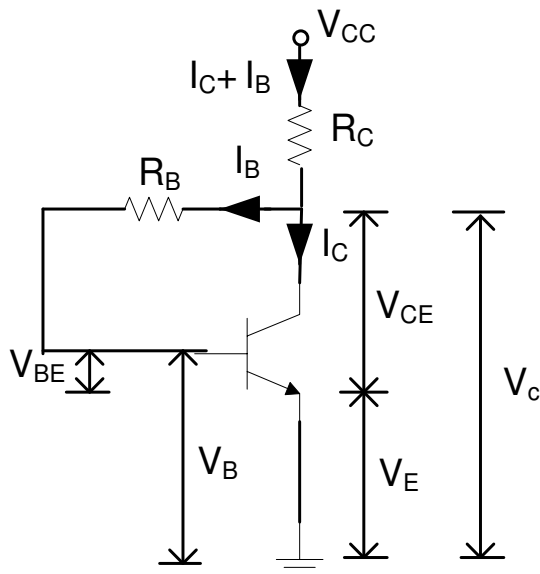
$$V_C = V_{CE} + V_E \qquad\qquad V_B = V_{BE} + V_E \qquad\qquad V_E = I_E R_E$$

Negative feedback-output is fed back to input

Base Bias with Collector Feedback
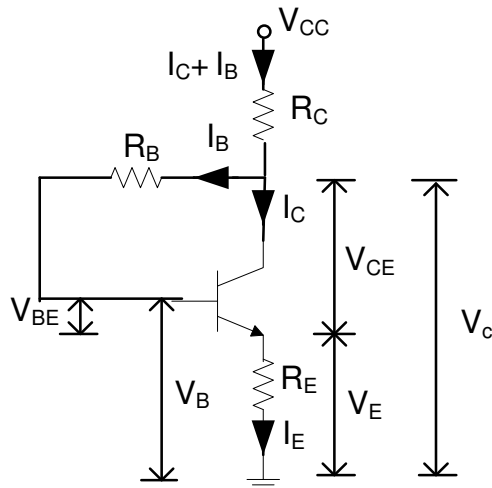
Equations

$$V_{CC} = (I_C + I_B)R_C + V_{CE}$$
$$V_{CC} = (I_C + I_B)R_C + I_B R_B + V_{BE}$$
$$V_C = V_{CE}$$
$$V_C = V_{CC} - (I_C + I_B)R_C$$
$$V_C = I_B R_B + V_{BE}$$

Base Bias with Collector and Emitter Feedbacks

$$I_E = I_C + I_B$$
$$V_{CC} = (I_C + I_B)R_C + V_{CE} + I_E R_E$$
$$V_{CC} = (I_C + I_B)R_C + I_B R_B + V_{BE} + I_E R_E$$
$$V_E = I_E R_E$$
$$V_C = V_{CE} + V_E \qquad V_C = V_{CC} - (I_C + I_B)R_C \qquad V_C = I_B R_B + V_{BE} + I_E R_E$$
$$I_C(sat) \rightarrow V_{CE} = 0$$
$$V_{CC} = (I_C + I_B)R_C + I_E R_E$$
$$V_{CC} = I_E R_C + I_E R_E \qquad\qquad I_E = \frac{I_C}{\propto}$$
$$V_{CC} = \frac{I_C}{\propto}(R_C + R_E)$$
$$\frac{I_C}{\propto} = \frac{V_{CC}}{R_C + R_E}$$
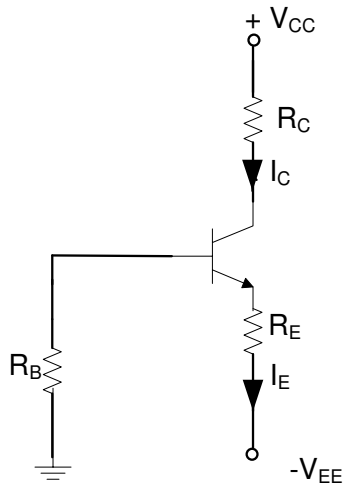$$I_C = \frac{V_{CC}}{R_C + R_E}(\propto)$$
$$I_{sat} = \frac{V_{CC}}{R_C + R_E}\left(\frac{\beta}{1 + \beta}\right) = \frac{V_{CC}}{R_C + R_E}$$

$$V_{CE}(cutoff) \rightarrow I_C = 0$$

$$V_{CC} = (I_C + I_B)R_C + I_E R_E + V_{CE}$$

$$V_{CC} = V_{CE}$$

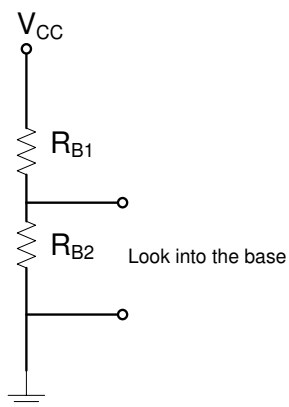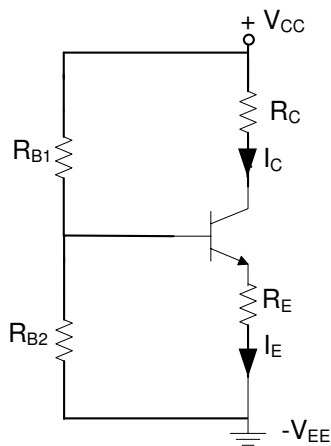## Emitter bias with 2 power supplies
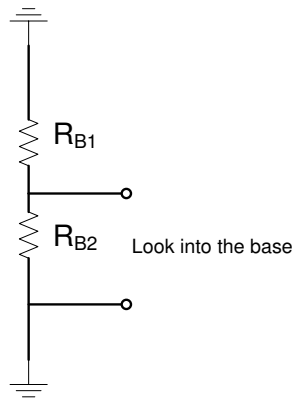
$$V_{CC} = I_C R_C + I_B R_B + V_{CB}$$
$$V_{CC} = I_C R_C + V_{CE} + I_E R_E + V_{EE}$$
$$V_{EE} = I_E R_E + I_B R_B + V_{BE}$$

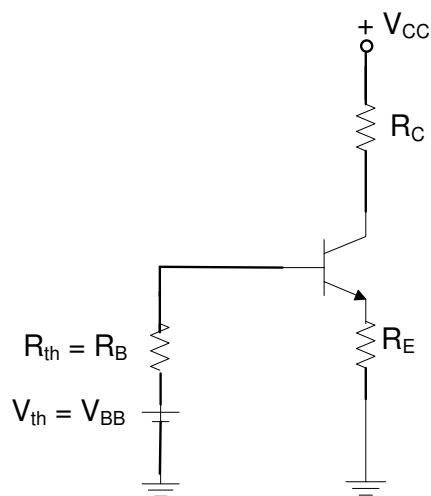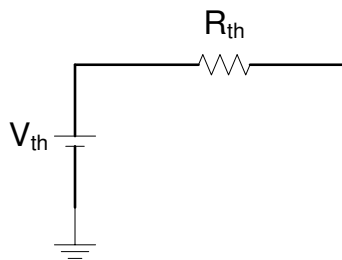## Voltage divider bias

$$V_{Th} = \frac{V_{CC} R_{B2}}{R_{B1} + R_{B2}}$$

$$R_{Th} = \frac{R_{B1} R_{B2}}{R_{B1} + R_{B2}}$$
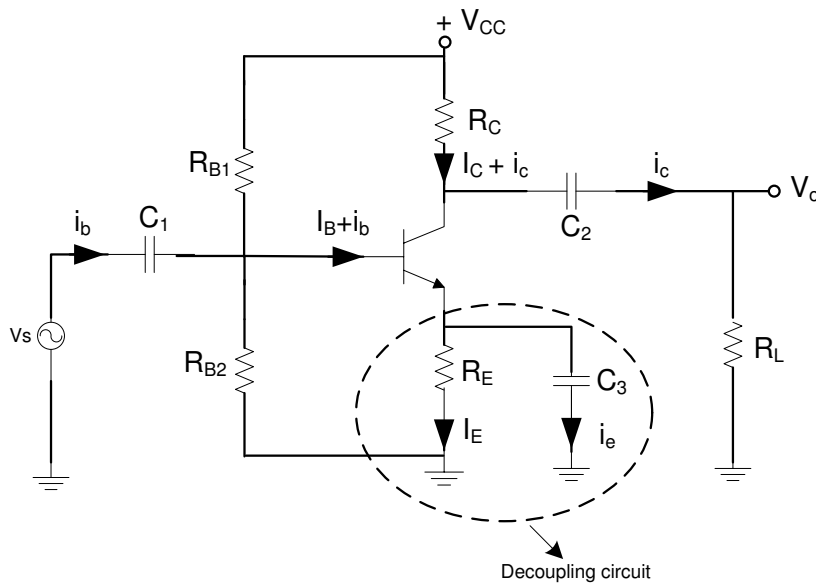

$R_{th} = R_B$

$V_{th} = V_{BB}$

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

$V_{CC} = I_C R_C + V_{CB} + I_B R_B - V_{BB}$

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

$V_C = V_{CC} - I_C R_C$ $\qquad\qquad\qquad\qquad V_C = V_{CE} + I_E R_E$

Single Stage Amplifier

Decoupling circuit

R_{B1}, R_{B2} − Potential dividers where R_{B1} is used to reverse bias the collector-base junction and R_{B2} is use to forward bias the base-emitter junction.

R_C and R_L are used to facilities the collection of the output signal

R_E is used to feedback any changer in I_C so as to stabilize the bias condition

$$V_2 = V_{BE} + I_E R_E$$

C1 - Blocks any direct current from the source

C2 - Blocks any direct current from appearing at the output

C3 (decoupling capacitor) - Bypasses high frequency alternating current signal to the ground which interferes with the bias condition if fed back.

$$i_C = \alpha i_E$$
$$i_B = (1 - \alpha)i_E$$
$$\frac{i_C}{i_B} = \beta = \frac{\alpha}{1 - \alpha}$$

Since $\alpha \cong 1$ then β has a very large value thus there is a large current gain from the base to the collector in the common emitter configuration.

D.C load line

This is a line drawn on the output characteristics of a transistor connection and for common emitter connection it gives all the possible values of I_C and V_{CE} depending on the load seen by I_C. It is developed by opening all the capacitors and shorting all the a.c sources.
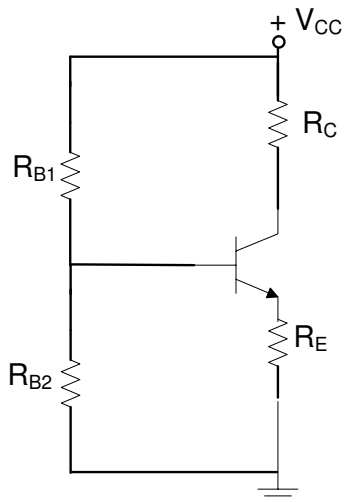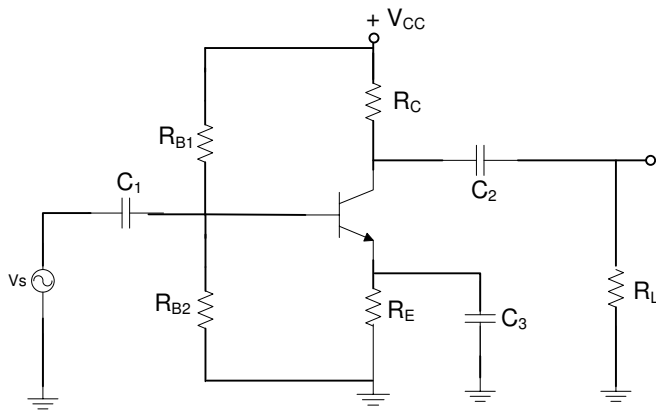
Using the common emitter equation

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

$$V_{CC} = I_C R_C + V_{CE} + \frac{I_C}{\alpha} R_E \quad \alpha \cong 1$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C + \frac{R_E}{\alpha}} \cong \frac{V_{CC} - V_{CE}}{R_C + R_E}$$

$$I_C = \frac{-V_{CE}}{R_C + R_E} + \frac{V_{CC}}{R_C + R_E}$$

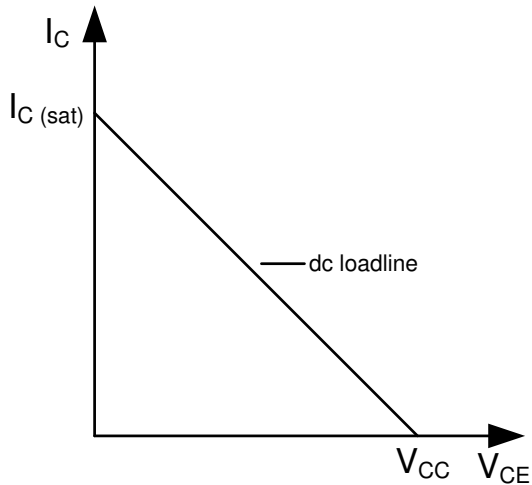$$y = mx + c \xRightarrow{Thus} m = \frac{-1}{R_C + R_E}, c = \frac{V_{CC}}{R_C + R_E}$$

x-intercept $I_C \cong 0$ $V_{CE} = V_{CC}$ $V_{CE(cutoff)} = V_{CC}$

y-intercept $V_{CE} \cong 0V$

$$I_C = \frac{V_{CC}}{R_C + R_E} \qquad\qquad I_{C(sat)} = \frac{V_{CC}}{R_C + R_E}$$

Operating point/ Q – point / Quiescent point / silent / Quiet point
This is the point at which the transistor operates without the a.c signal. The point at which the
line of the current I_B intersects with the load line gives the operating point. It is located at the
middle of the load line for the optimum transistor operation.

$$I_{CQ} = \frac{1}{2}I_{C(sat)} \qquad\qquad V_{CEQ} = \frac{1}{2}V_{CC}$$

This way the maximum possible swing of an a.c signal can be obtained

D.C load and a.c signal
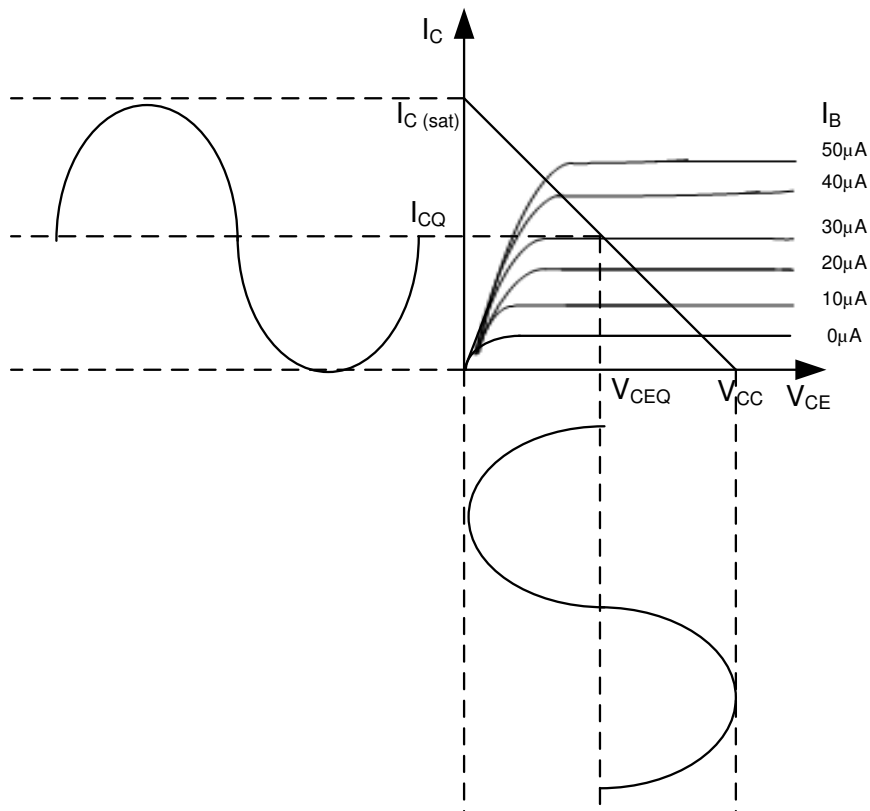
$$I_{pp} = 2I_{CQ}$$
$$V_{pp} = 2V_{CEQ}$$

where I_{pp} is the peak to peak current
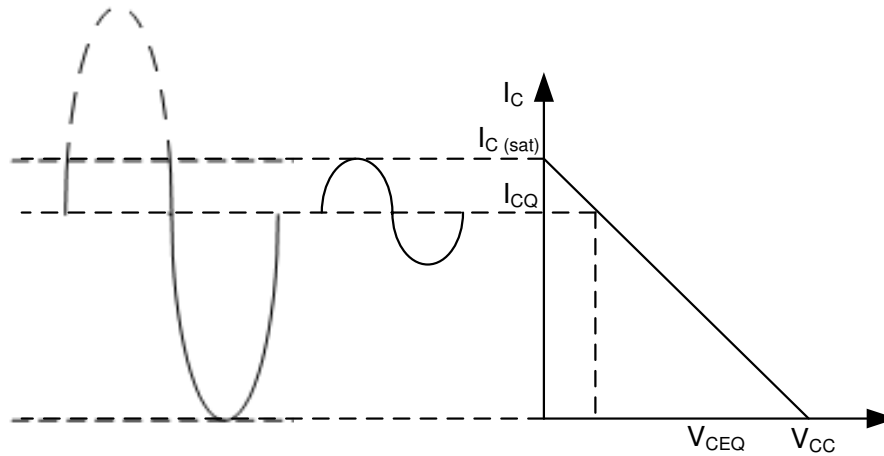
$$I_{C(sat)} - I_{CQ} < I_{CQ}$$

When the operating is close to $I_{C(sat)}$ then clipping of the output waveform will occur due to saturation
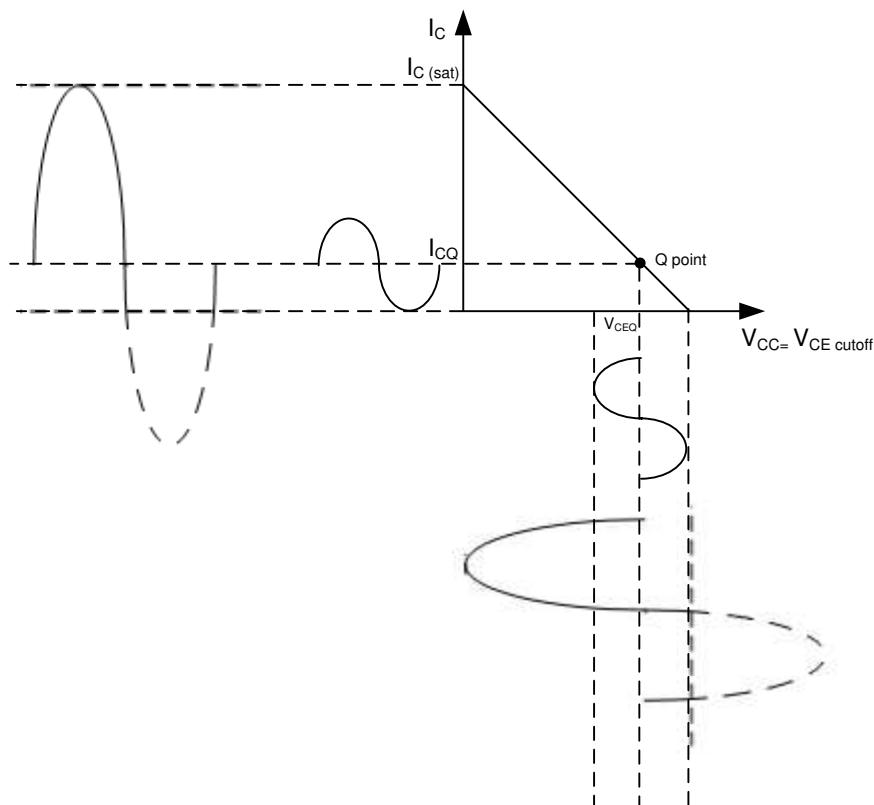
$$I_{C(sat)} - I_{CQ} > I_{CQ}$$
$$Max = 2I_{CQ}$$

When I_C is increasing from the Q – point, V_{CC} is decreasing since the load line has a negative gradient. When the operating point is close to $V_{CE (cutoff)}$ clipping starts occurring due to cutoff value of V_{CE}.

A.C load line

This is the line which give the different value of i_c and v_{ce} depending on the load as seen by i_C. ($i_C = I_C$ (d.c) + i_c (a.c)). It is the line which obtained by adding a small signal to the already biased circuit.

A.C equivalent circuit

Obtained by: shorting all capacitors

Grounding all d.c sources
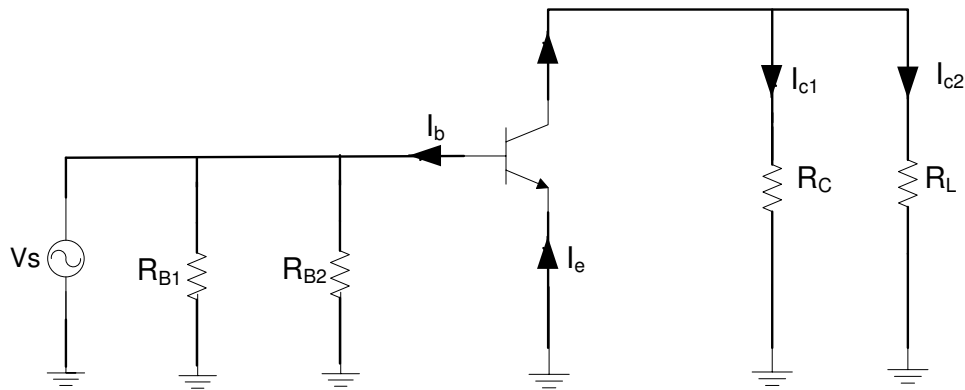
a.c load (R_{ac})

$$R_{ac} = \frac{R_C R_L}{R_C + R_L} \qquad R_{ac} < R_{dc} \text{ (always)}$$

$$I_{C(sat)} = I_{CQ} + \frac{V_{CEQ}}{R_{ac}}$$
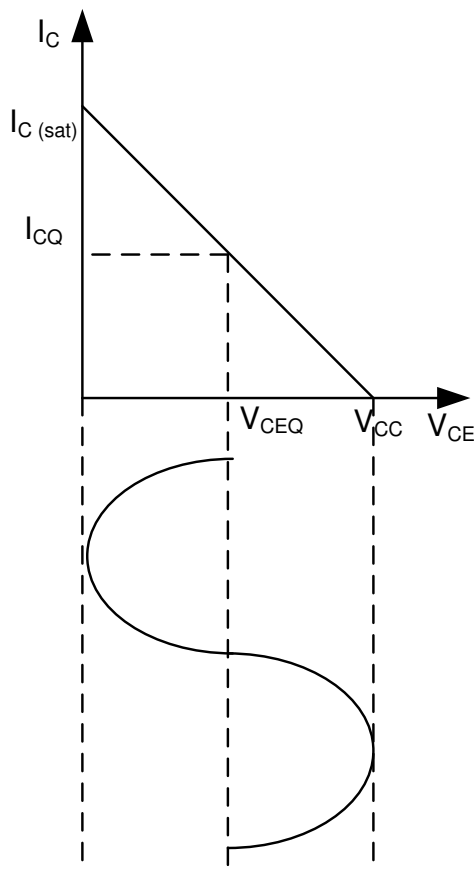
$$V_{CE(cutoff)} = V_{CEQ} + I_{CQ}R_{ac}$$
$$V_{pp} = 2I_{CQ}R_{ac}$$
$$V_{pp} = 2V_{CEQ}$$

For clipping not to occur, then the lesser value is considered.
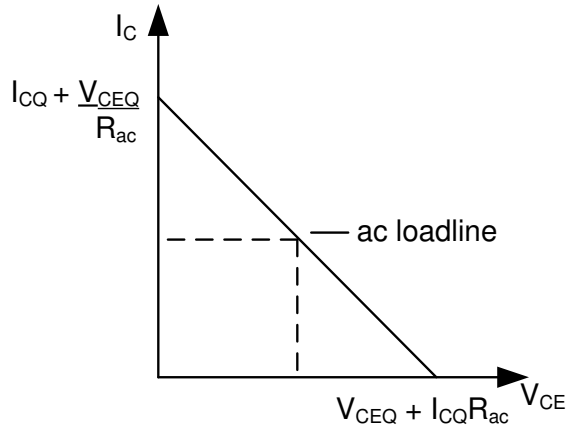
Since $R_{ac} < R_{dc}$ the gradient of the a.c load line is steeper.

Causes of transistor Q – point variation
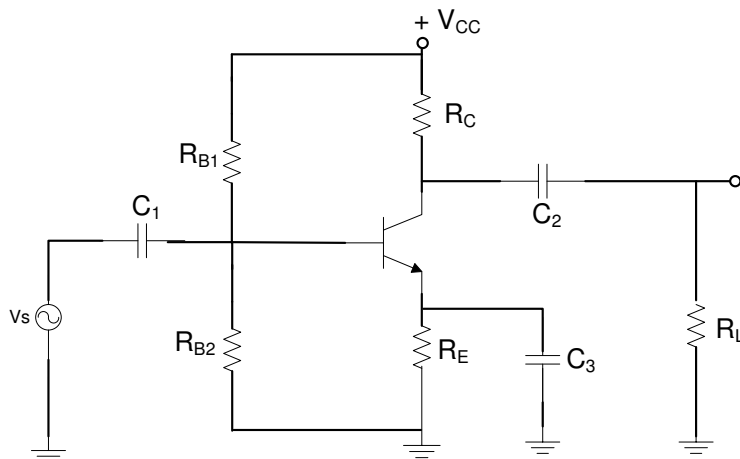
(i) If any of the resistors of the amplifiers is faulty. Then resistors go faulty they became open

If R_C or $R_E = \infty$

$$I_C = \frac{V_{CC}}{R_C + R_E} = \frac{V_{CC}}{\infty}$$ the transistor is in cutoff.

If $R_{B2} = \infty$ then the transistor is off

(ii) If any of the capacitors goes faulty the capacitor becomes a short
(iii) High temperature can cause thermal runway.
(iv) Change of transistor

Stability Factor

This is the rate of change of I_C with respect to I_{CBO}

$$S = \frac{dI_C}{dI_{CBO}}$$ where I_B and β are kept constant.

Common Emitter configuration

$$I_C = \beta I_B + (1 + \beta)I_{CBO}$$

$$\frac{dI_C}{dI_C} = \frac{d\beta I_B}{dI_C} + \frac{d(1 + \beta)I_{CBO}}{dI_C}$$

$$1 = \frac{d\beta I_B}{dI_C} + (1 + \beta)\frac{dI_{CBO}}{dI_C}$$

$$1 = \beta\frac{dI_B}{dI_C} + (1 + \beta)\frac{1}{S} \quad \overset{thus}{\implies} \quad (1 + \beta)\frac{1}{S} = 1 - \beta\frac{dI_B}{dI_C}$$

$$S = \frac{(1 + \beta)}{1 - \beta\frac{dI_B}{dI_C}}$$

$$S = \frac{\left(1 + {R_B}/{R_E}\right)}{1 + {R_B}/{(1 + \beta)R_E}}$$

R_B – Resistance on the base side
R_E – Resistance on the emitter side

Design of a single stage Low Power Amplifier

Specifications

Current through R_{B1} and R_{B2}, $I_1 \geq 10$ I_B

$I_C = 2mA$ (if $> 2mA$ then clipping occurs hence to faithful amplification)
(if $> 15mA$ then the transistor burns out)

I_C should be more than a.c signal by 20% to avoid clipping e.g. if the Q point is changed

Example

If a common emitter circuit connection has the following parameters: $V_{CC} = 9V$, $V_{CE} = 3V$, $V_{BE} = 0.3V$, $I_1 = 10I_B$, $I_C = 2mA$, $R_C = 2.2$ kΩ and $\beta = 50$. Determine R_{B1}, R_{B2} and R_E.

Solution

Using the common emitter equation

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E = I_C R_C + V_{CE} + \frac{(1 + \beta)}{\beta}I_C R_E$$

$$9 = 2\,x\,2.2 + 3 + \frac{51}{50}x\,2\,xR_E$$

$$R_E = 784\ \Omega$$

$$I_B = \frac{I_C}{\beta} = \frac{2}{50} = 0.04\ mA$$

$$I_1 = 10\,x\,I_B = 10\,x\,0.04 = 0.4\ mA$$

$$R_{B1} + R_{B2} = \frac{V_{CC}}{I_1} = \frac{9}{0.4 \times 10^{-3}} = 22.5 \text{ k}\Omega$$

$$V_B = V_{BE} + I_E R_E = 0.3 + \frac{51}{50} \times 2 \times 784 = 0.3 + 1.6 = 1.9 \text{ V}$$

$$R_{B2} = \frac{V_B}{I_1} = 1. \frac{9}{0.4 \times 10^{-3}} = 4.75 \text{ k}\Omega$$

$$R_{B1} = 22.5 - 4.75 = 17.75 \text{ k}\Omega$$

Example

Hence determine the coordinates of the operating point and the stability factor S in a common emitter germanium transistor amplifier circuit, shown below, the bias is provided by self bias, i.e. emitter resistor and potential divider arrangement. The various parameters are: V_{CC}=16 V, R_C=3kΩ, R_E= 2kΩ, R_{B1}=56 kΩ, R_{B2}=20 kΩ and α=0.985.
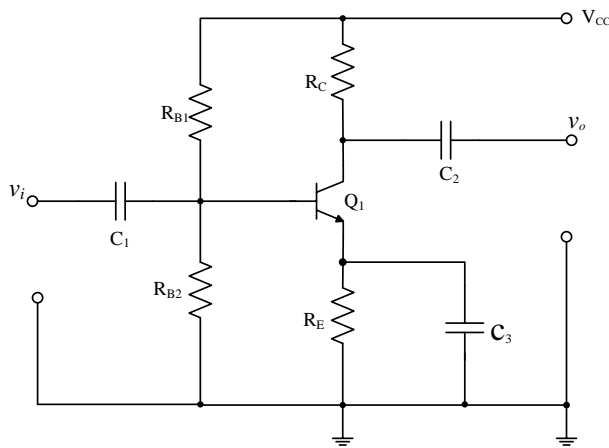
Solution:

For a germanium transistor, V_{BE}=0.3V. As α=0.985,

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.985}{1-0.985} = 66$$

To find the coordinates of the operating point

Thevenin's voltage, $V_T = \dfrac{R_2}{R_1 + R_2} V_{CC} = \dfrac{20 \times 10^3}{76 \times 10^3} \times 16 = 4.21V$

Thevenin's resistance, $R_B = \dfrac{R_1 R_2}{R_1 + R_2} = \dfrac{20 \times 10^3 \times 56 \times 10^3}{76 \times 10^3} = 14.737 \, k\Omega$

The loop equation around the base circuit is

$$V_T = I_B R_B + V_{BE} + (I_B + I_C)R_E, = \frac{I_C}{\beta} R_B + V_{BE} + \left(\frac{I_C}{\beta} + I_C\right)R_E$$

$$4.21 = \frac{I_C}{66} \times 14.737 \times 10^3 + 0.3 + I_C\left(\frac{1}{66} + 1\right) \times 2 \times 10^3$$

$3.91 = I_C(0.223 + 2.03) \times 10^3$. Therefore, $I_C = \dfrac{3.91}{2.253 \times 10^3} = 1.73 \, mA$

Since I_B is very small $I_C \approx I_E = 1.73 \, mA$, Therefore, $V_{CE} = V_{CC} - I_C R_C - I_E R_E$

$$= V_{CC} - I_C (R_C - R_E) = 16 - 1.73 \times 10^{-3} \times 5 \times 10^3 = 7.35V$$

Therefore, the coordinates of the operating point are $I_C = 1.73mA$ and $V_{CE} = 7.35V$.

To find the stability factor S.

$$S = (1+\beta) \frac{1 + \dfrac{R_B}{R_E}}{1 + \beta + \dfrac{R_B}{R_E}} = (1+66) \frac{1 + \dfrac{14.737}{2}}{1 + 66 + \dfrac{14.737}{2}} = 7.537$$

Problem

Given the following values for a common emitter circuit: R_{B1}=47 kΩ , R_L= 10 kΩ, R_{B2} = 10 kΩ , R_C = 3.3 kΩ, R_E = 2 kΩ, $\beta = 200$, V_{CC} = 20V

(i)   Draw d.c and a.c load lines and determine operating point.
(ii) Determine whether the transistor is operating close to the saturation or cut off.

Problem

Explain the operation of various biasing methods and their advantages and disadvantages. Use suitable expressions where necessary.

UNIPOLAR TRANSISTOR / FIELD EFFECT TRANSISTOR

- ➤ Generally FET is a 3-terminal unipolar solid state device in which current is controlled by an electric field.
- ➤ There are 2 types of FETS
  - o Junction FET (JFET).
  - o Metal oxide semi-conductor FET (MOSFET).
- ➤ Both can either be: P-channel or
                          N-channel

JUNCTION FIELD EFFECT TRANSISTOR

Fig (a): N-channel   N-channel cct symbol   Fig (b): P-channel   P-channel cct symbol
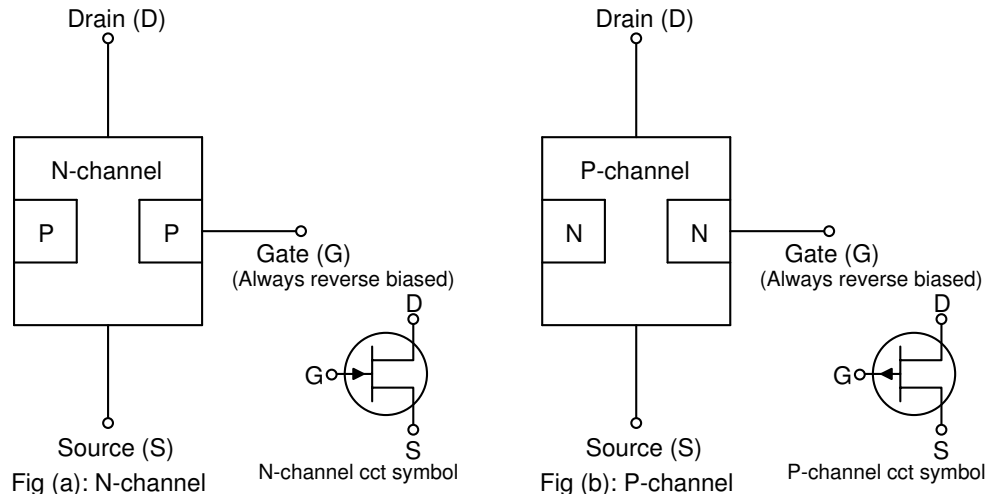
- ➤ As an illustration an N-channel is fabricated by diffusing 2-P type junctions on opposite sides of N-type semi-conductor material as shown in fig (a).
- ➤ These junctions form 2 PN diodes called gates and the area between them is called a channel.
- ➤ The 2 P-type regions are internally connected and a single lead is brought out called the gate terminal.
- ➤ Direct connections are made at the two ends of the bar.
- ➤ One is called the source terminal (S) and the other drain terminal (D).
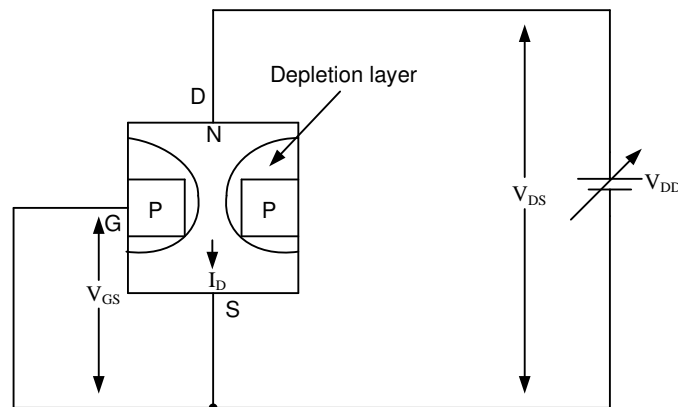
Operation

- ➤ The gates are always reverse biased and therefore the gate current I_g is practically zero.
- ➤ The source terminal is always connected to that end of the drain supply which provides the necessary charge carriers.
- ➤ As an example an N-channel JEET is discussed when either V_{GS} or V_{DS} or both are changed.

a) **When $V_{GS}=V_{DS}=0V$.**

Drain (D)

Uniform depletion layer

N

P   P   Gate (G)

Source (S)
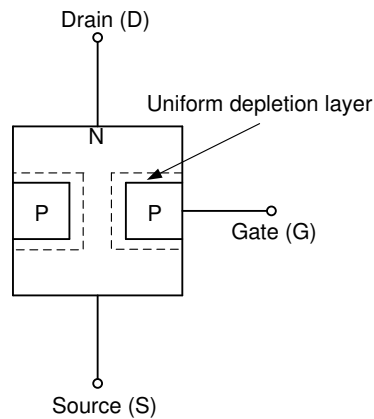
➢ Since $V_{DS}=0$ the drain current $I_D=0$ thus depletion regions around the PN junction are equal in thickness and symmetrical.

**b) When $V_{GS}=0$ and V_{DS} is increased from zero.**

➢ Electrons which are the majority charge carriers flow through the channel from the source to the drain.
➢ Due to this flow there is a uniform voltage drop across the channel resistance.
➢ This voltage drop acts as reverse bias at the gate.
➢ The gate is more negative with respect to those points which are nearer to the drain than those to source, therefore the depletion regions penetrates more deeply into the channel at points which lie closer to the drain than source.

$$I_D = \frac{V_{DS}}{R_{DS}}$$

As V_{DS} is increased, the current I_D increases up to a maximum value I_{DSS} (saturation current).

➢ At this stage $I_D=I_{DSS}$ which is constant.
➢ Under this condition the channel cross-sectional area becomes minimum and the channel is said to be pinched off and the corresponding value of V_{DS} is called pinch off voltage (V_P).
➢ In case V_{DS} is increased beyond this point, V_P, I_D does not increase. It remains constant until the JFET breaks down and I_D increases to an excessive value.

c) When $V_{DS}=0$ and V_{GS} is decreased from zero.
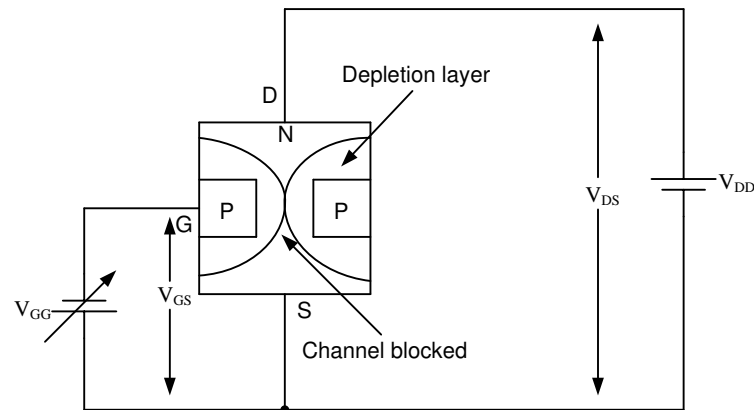
➤ V_{GS} is made more negative, increasing the gate reverse bias and therefore increasing the thickness of depletion.

➤ As V_{GS} is increased to the -ve, a point is reached when the 2 depletion regions touch one another and the channel is cut off.

➤ This value of V_{GS} that cuts the channel off is called $V_{GS(off)}$

d) When V_{GS} is -ve and V_{DS} is increased.

➤ As V_{GS} is made more -ve, values of V_P as well as breakdown voltage are decreased.

➤ N/B: Since the gate voltage controls the main current, JFET is called a voltage controlled device.

➤ A P-channel JFET operates exactly in the same manner as N-channel except that channel carriers are holes, and the polarities of both V_{DD} and VGS are reversed.

JFET CHARACTERISTICS
1. Drain characteristics
2. Transfer characteristics

Drain Characteristics
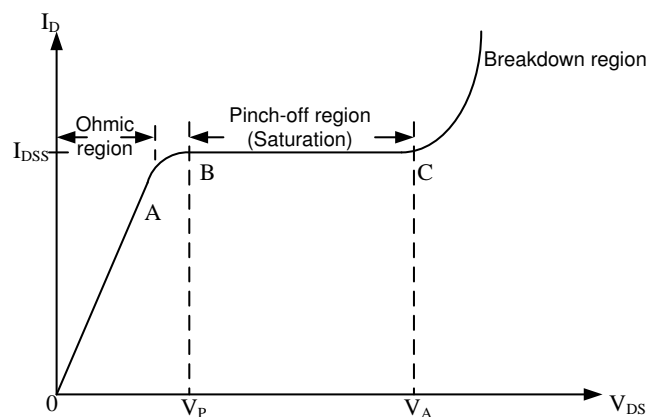
a) Ohmic Region

➤ I_D varies directly with V_{DS} following ohms law where the transistor behaves like resistor.

b) Pinch-off / Saturation region

➤ This is also called the amplifier region where I_D is relatively independent of V_{DS}.

- In this region, the drain current is given by the following equation;

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

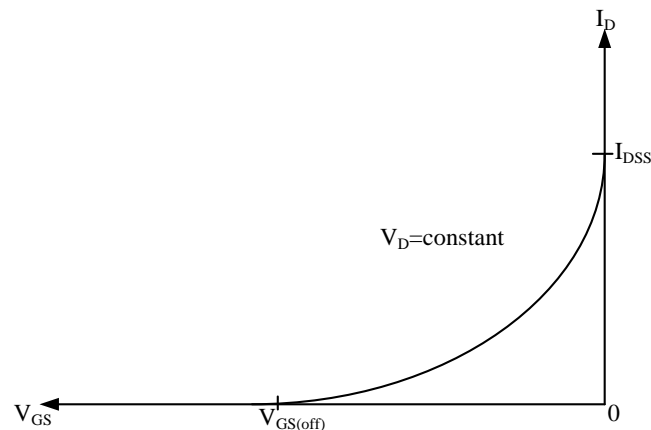- A transistor operated in this region is a like a switch which is on.

c) Breakdown Region
- It is also called the avalanche region.
- I_D increases to an excessive value.

d) Cut off region
- This is the region where the transistor is not conducting where $V_{GS} = V_{GS(off)}$.
- A transistor operated in this region is a like a switch which is off.

Transfer characteristics

- This shows that when $V_{GS}=0$, $I_D=I_{DSS}$ and when $I_D=0$, $V_{GS}=V_{GS(off)}$.
- The characteristics approximately follows the equation;

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$
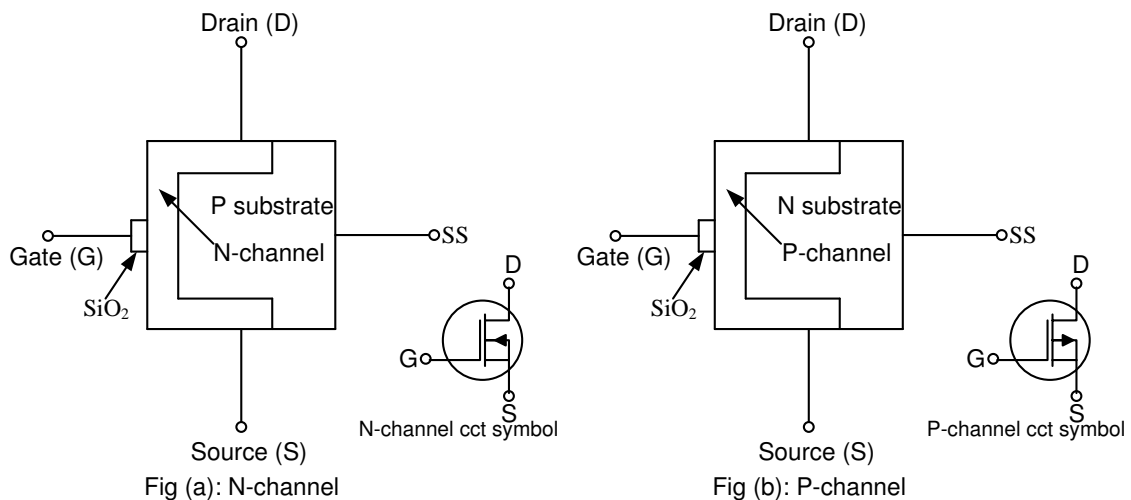
MOSFET OR IGFET (insulated Gate FET)
- There are 2 types and are given by depletion enhancement MOSFET (DE) and enhancement only MOSFET.

DE MOSFET
- It is called so because it can be operated both in depletion mode and enhancement mode by changing the polarity of V_{GS}.

Construction

Fig (a): N-channel

Fig (b): P-channel

- ➢ As shown the gate is insulated from its conducting channel by an ultra thin metal oxide insulating film of silicon dioxide.
- ➢ The MOSFET is different from JFET in that the gate voltage that controls I_D can both be +ve and -ve unlike the JFET which is always reverse biased.
- ➢ Silicon dioxide and the channel form a parallel plate capacitor.

Operation
a) Depletion mode of N-channel (DE MOSFET)
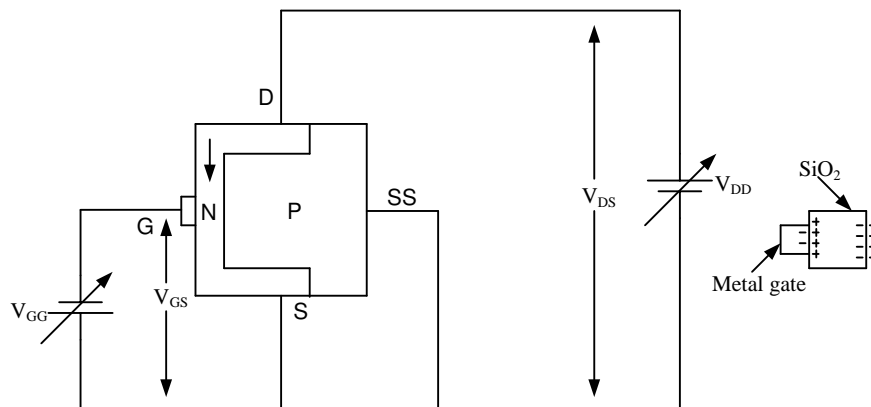
- ➢ When $V_{GS}=0$ electrons flow from the source to the drain through the conducting channel.
- ➢ When the gate has -ve voltage, it depletes the N-channel off it electrons by inducing +ve charge in it; therefore the greater the -ve voltage on the gate, the greater is the reduction of electrons in the channel and therefore less conductivity.
- ➢ Too much of -ve voltage i.e. V_{GS} can cut off the channel and this voltage is called V_{GS} (off).

b) Enhancement mode of the N-channel
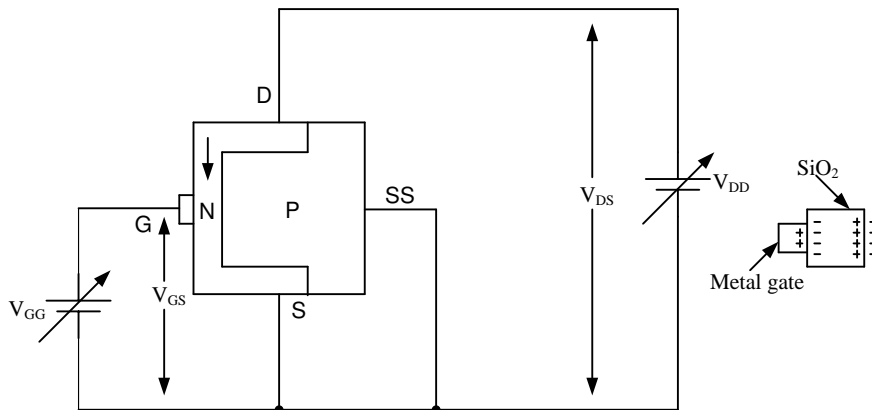
> ➢ When +ve voltage is applied to the gate the input gate capacitor creates free electrons in the channel which increases I_D.
> ➢ This increased number of electrons increases or enhances the conductivity of the channel.
> ➢ As the +ve gate voltage is increased, conductivity of source to drain is increased and therefore the current flowing increases.
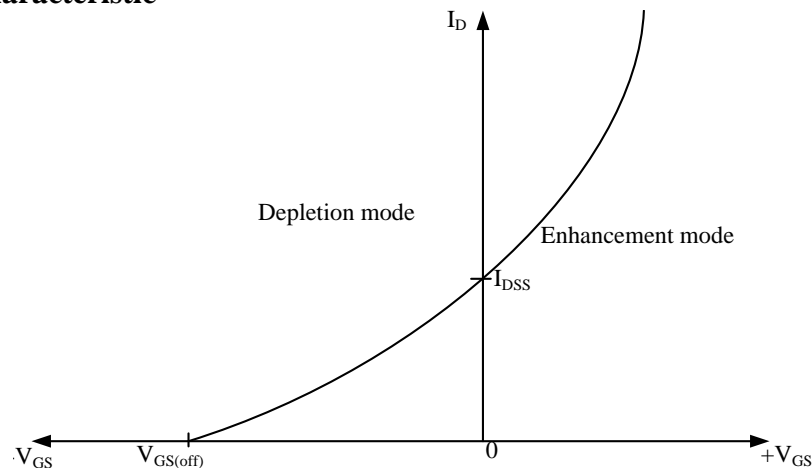
Characteristics of a DEMOSFET

a) Static characteristics
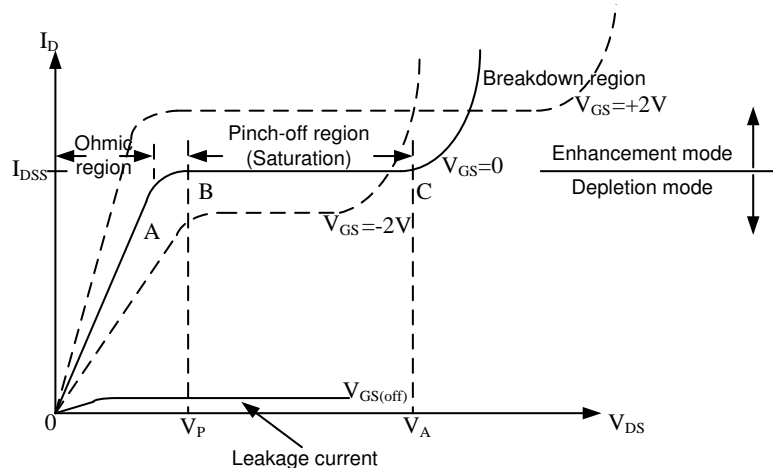
> ➢ It acts in the enhancement made when the gate is +ve with respect to the source and in the depletion mode when the gate is -ve.
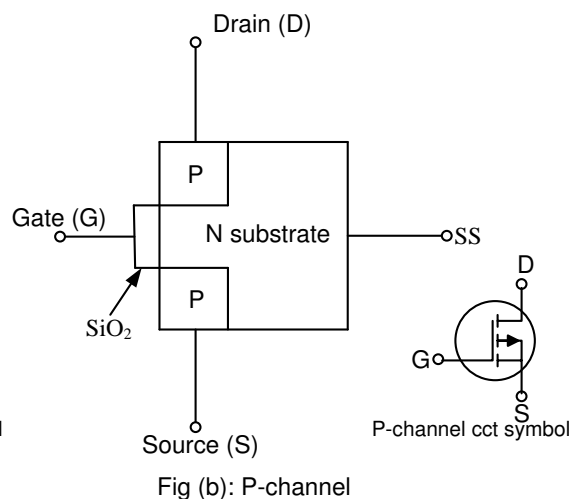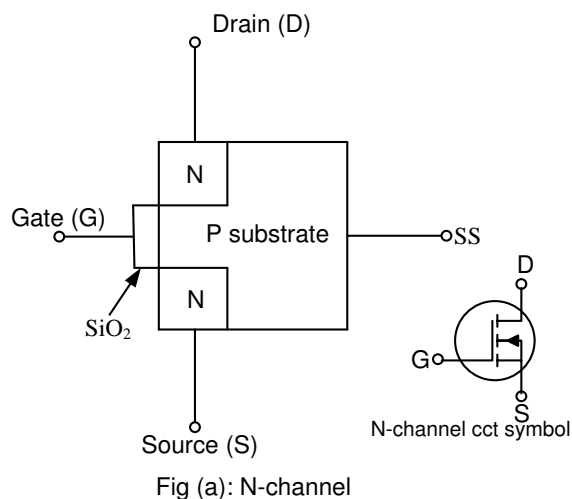
b) Transfer characteristic

> For a given V_{DS}, I_D flows even when $V_{GS}=0$ but keeping V_{DS} constant as V_{GS} is made more -ve, I_D decreases till it becomes zero at $V_{GS}=V_{GS(off)}$.
> When used in the enhancement mode, I_D increases as V_{GS} is increased +vely.

ENHANCEMENT ONLY N-CHANNEL MOSEFET (NMOS)
Construction

Fig (a): N-channel   Fig (b): P-channel

> There is a channel between the source and the drain which has a P substrate cutting into it.
> It operates with the +ve gates only.

Operation
> When $V_{GS} = 0$, I_D is non-existent.
> For I_D to flow a significant +ve gate voltage must be applied.
> This voltage produces a thin layer of electrons close to the metal oxide film which stretches from the source to the drain.
> This thin layer provides the channel with electrons hence N-types material referred to as N-type inversion layer or a virtual N-channel.
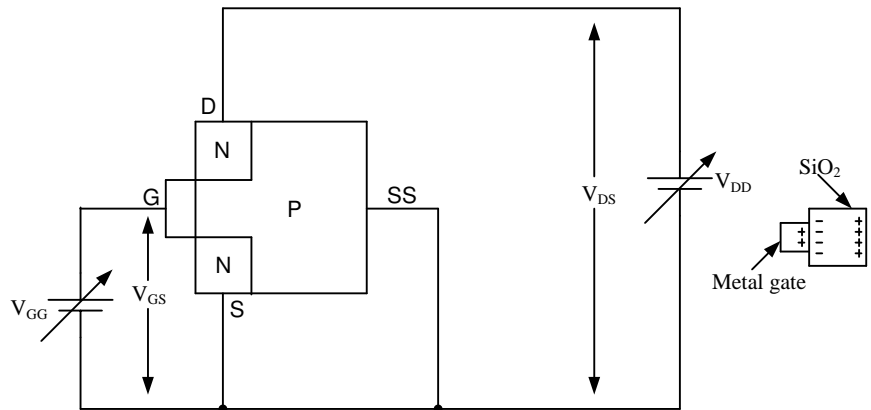
> The minimum gate source voltage which produces the N-type inversion layer is called threshold voltage $V_{GS(th)}$.
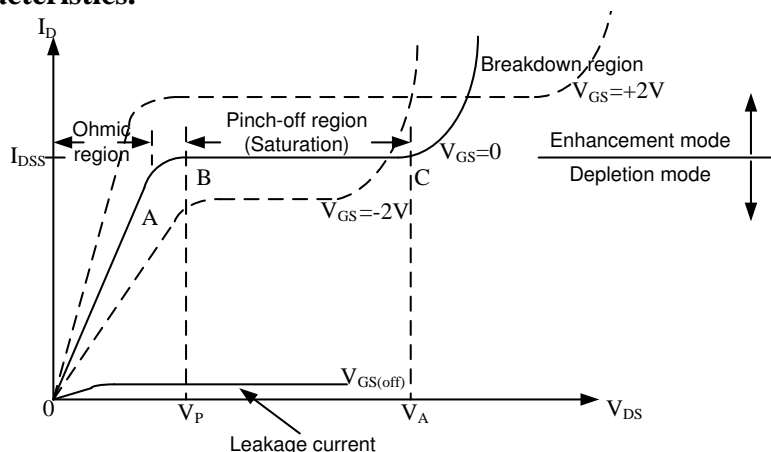> For a given V_{DS} as V_{GS} is increased, the virtual channel deepens and I_D increases therefore;

$$I_D = K\left(V_{GS} - V_{GS(th)}\right)^2$$

Where k is constant which depends on a particular MOSFET.

Characteristics of an N-channel enhancement only MOSFET

a) **Static characteristics.**

> Electrons which are the majority charge carriers flow through the channel from the source to the drain.
> Due to this flow there is a uniform voltage drop across the channel resistance.
> This voltage drop acts as reverse bias at the gate.
> The gate is more negative with respect to those points which are nearer to the drain than those to source, therefore the depletion regions penetrates more deeply into the channel at points which lie closer to the drain than source.

- $$I_D = \frac{V_{DS}}{R_{DS}}$$

  - As V_{DS} is increased, the current I_D increases up to a maximum value I_{DSS} (saturation current).
> At this stage $I_D = I_{DSS}$ which is constant.
> Under this condition the channel cross-sectional area becomes minimum and the channel is said to be pinched off and the corresponding value of V_{DS} is called pinch off voltage (V_P).

➤ In case V_{DS} is increased beyond this point, V_P, I_D does not increase. It remains constant until the JFET breaks down and I_D increases to an excessive value.

b) Transfer characteristic.
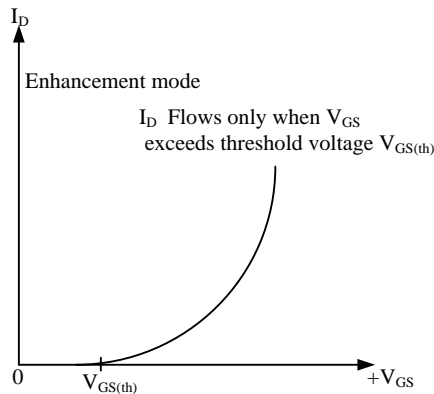
➤ For I_D to flow a significant +ve gate voltage must be applied.
➤ It starts conducting at $V_{GS}=V_{GS(th)}$.
➤ As V_{GS} is increased further there is a corresponding increment of I_D. This increment follows the following formula.

$$I_D = K(V_{GS} - V_{GS(th)})^2$$

Where k is constant which depends on a particular MOSFET.

Parameters considered when purchasing JFET(s)
➤ The gate source breakdown voltage.
➤ The gate reverse leakage current.
➤ The gate source cut-off voltage.
➤ The drain current at zero gate voltage.
➤ The forward trans-conductance.
➤ The input capacitance.
➤ The switching consideration.
➤ The drain source on resistance.
➤ Power rating.

## Parameters considered when purchasing MOSEFET(s)
➤ Breakdown voltage.
➤ Forward trans-conductance.
➤ Drain source on resistance.
➤ Switching characteristics.
➤ Zero gate voltage drain current.
➤ Input capacitance.

BIASING OF FETS
JFET (DC Biasing)
➤ It can be biased using either;
  ○ Separate power source V_{GG}.
  ○ Some form of self biasing.
  ○ Source biasing.
  ○ Voltage divider bias.
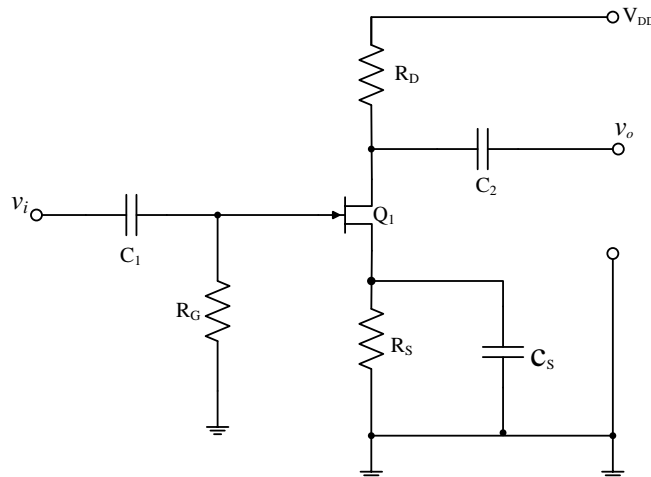
a) A separate power source V_{GG}.
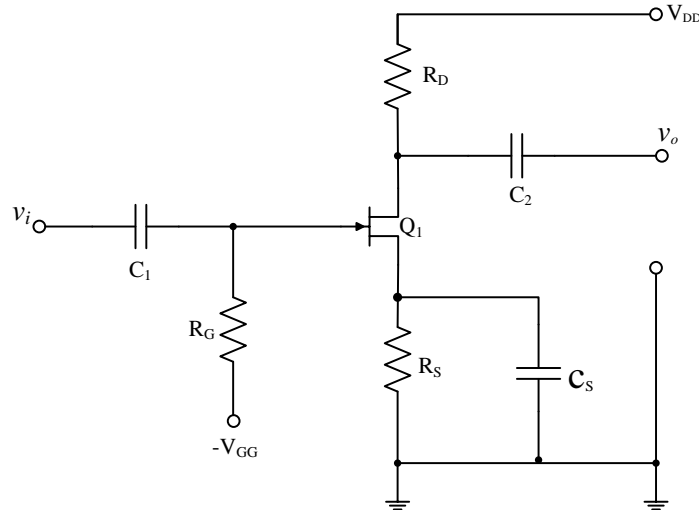
$$V_{DD} = I_D R_D + V_{DS} + I_S R_S$$
$$V_{GG} = I_G R_G + V_{GS} + I_S R_S$$
$$V_{GG} = V_{GS} + I_S R_S \text{ since } I_G \approx 0$$

b) Self biasing

$$V_{DD} = I_D R_D + V_{DS} + I_S R_S$$
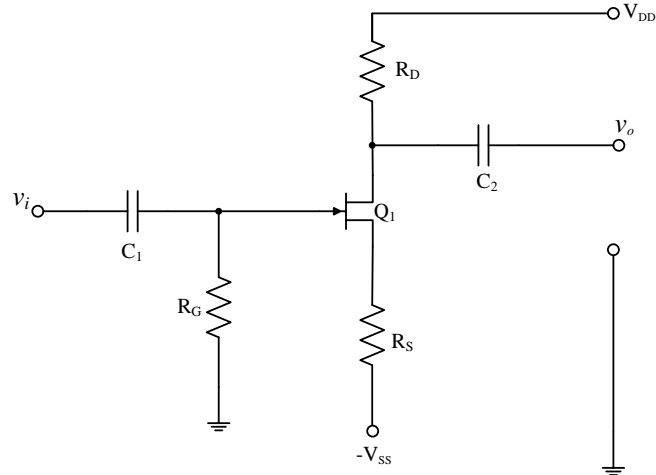$$V_S = I_S R_S$$
$$V_D = V_{DD} - I_D R_D \text{ or } V_{DS} + I_S R_S$$
$$I_G R_G + V_{GS} + I_S R_S = 0$$
$$V_{GS} = -I_S R_S \text{ since } I_G \approx 0$$

➤ V_{GS} bias is obtained from the flow of drain current I_D through R_S and $V_S = I_S R_S$ and $V_{GS} = -I_S R_S$.
➤ The gate is kept at this much -ve potential (voltage) with respect to the ground.
➤ Addition of R_G does not upset this d.c bias because no gate current flows through it apart from the gate leakage current.
➤ Without R_G the gate would be floating which would collect some charge and cut off the JFET.
➤ Also R_G serves the purpose of avoiding short circuiting of the a.c input voltage V_{in}.
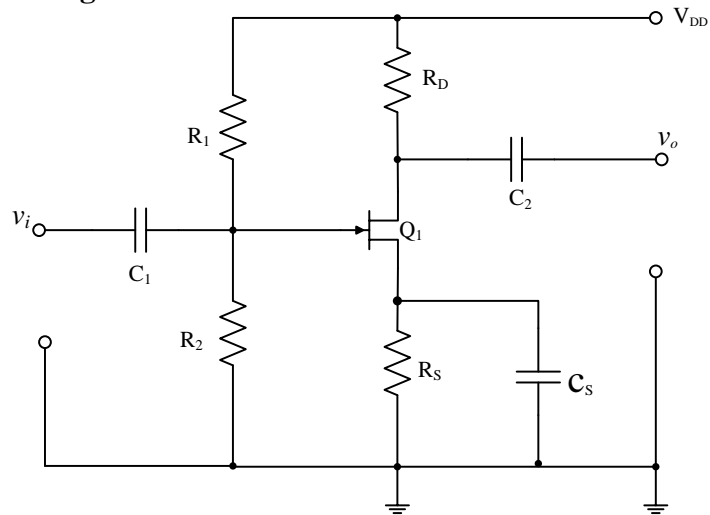
c) Source Biasing

$$V_D = V_{DD} - I_D R_D$$
$$V_{SS} = I_G R_G + V_{GS} + I_S R_S$$
$$V_{SS} = V_{GS} + I_S R_S \text{ since } I_G \approx 0$$

d) Voltage divider biasing
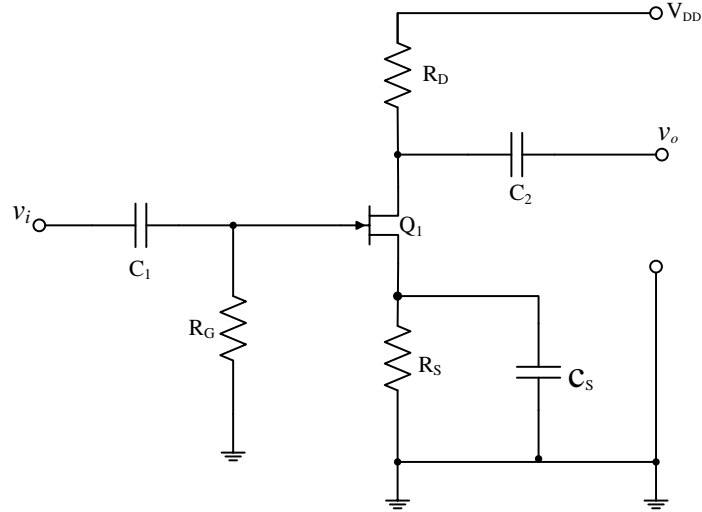

$$V_{DD} = V_{R_2} + V_{R_1}$$
$$V_{DD} = I_D R_D + V_{DS} + I_S R_S$$
$$V_{R_2} = \frac{V_{DD}}{R_1 + R_2} \times R_2$$
$$V_{R_2} = V_{GS} + I_D R_S$$

Example

Find the values of V_{DS} in the circuit below if $I_D=4mA$, $V_{DD}=12V$, $R_D=1k5$ and $R_S=500R$.

$$V_S = I_S R_S = 4\times 10^{-3} \times 500 = 2V$$
$$V_D = V_{DD} - I_D R_D$$
$$V_D = 12 - 1.5\times 10^{-3} \times 4\times 10^{-3} = 6V$$
$$V_{DS} = V_D - V_S = 6 - 2 = 4V$$

Example

In the amplifier given in the figure below $V_{DD}=20V$, $R_1=15.7M\Omega$, $R_2=1M\Omega$, $R_D=3k\Omega$, $R_S=2k\Omega$ and $I_{DQ}=1.5mA$. Calculate V_{GSQ} and V_{DSQ}.
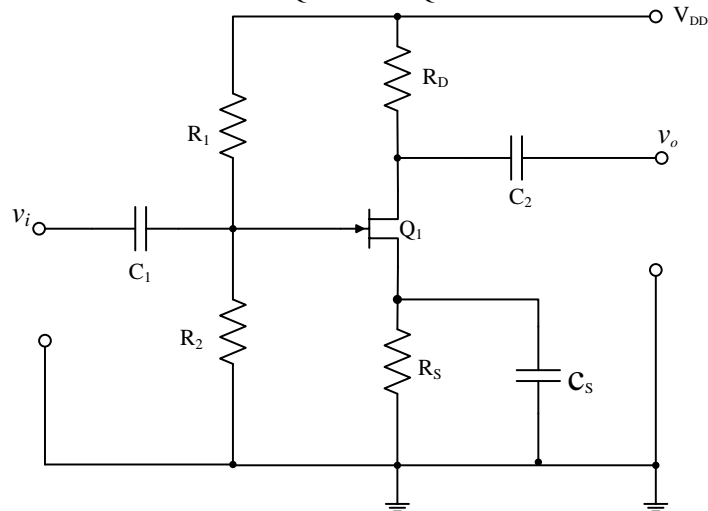
$$V_{R_2} = \frac{V_{DD}}{R_1 + R_2} \times R_2 = \frac{20}{15.7+1}\times 1 = 1.2V$$
$$V_{R_2} = V_{GSQ} + I_D R_S$$
$$V_{GSQ} = V_{R_2} - I_D R_S = 1.2 - 1.5\times 10^{-3} \times 2\times 10^3 = -1.8V$$
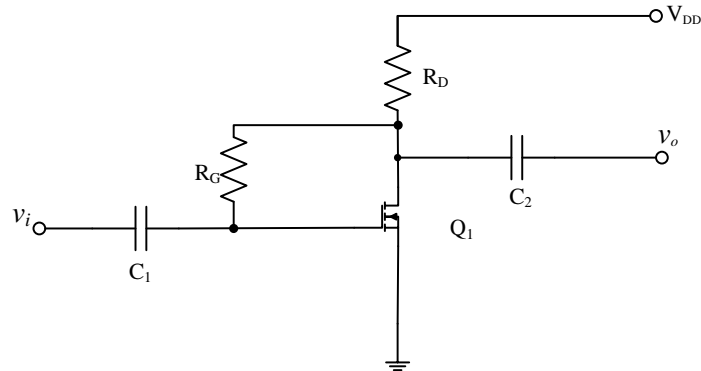$$V_D = V_{DD} - I_D R_D = 20 - 1.5\times 10^{-3} \times 3\times 10^3 = 15.5V$$
$$V_S = I_S R_S = 1.5\times 10^{-3} \times 2\times 10^3 = 3V$$
$$V_{DS} = V_D - V_S = 15.5 - 3 = 12.5V$$

BIASING OF E-ONLY MOSFETS
a) Drain Feedback Bias.

$$V_{GS} = -V_{DS}$$
$$V_D = V_{DD} - I_D R_D = V_{DS}$$

b) Voltage Divider Bias.
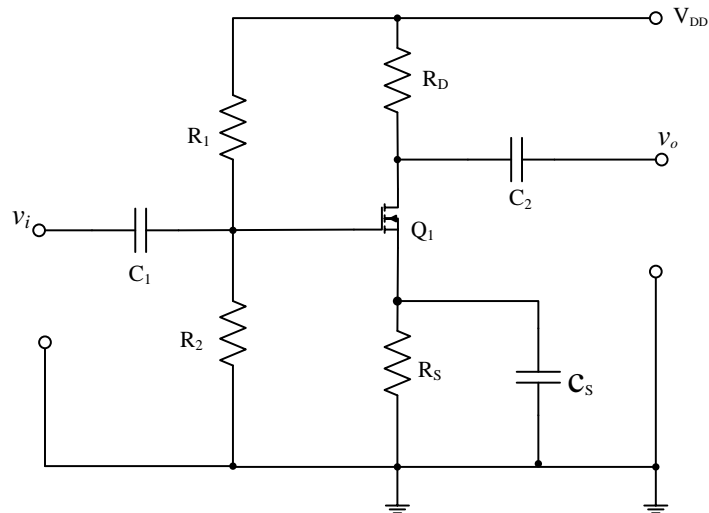
$$V_{DD} = V_{R_2} + V_{R_1}$$
$$V_{DD} = I_D R_D + V_{DS} + I_S R_S$$
$$V_{R_2} = \frac{V_{DD}}{R_1 + R_2} \times R_2$$
$$V_{R_2} = V_{GS} + I_D R_S$$

➢ Since for this MOSFET V_{GS} must be greater than $V_{GS(th)}$, it can be biased only in 2 ways i.e. drain feedback bias and voltage divider bias.
➢ For both cases, the gate voltage is made more +ve than the source by an amount greater than $V_{GS(th)}$.

Example

For the E-MOSFET amplifier given above (voltage divider bias) I_D=4mA, V_{GS}=10V, R_1=6kΩ, R_2=9kΩ, R_D=1kΩ, R_S=0Ω, V_{DD}=25V and $V_{GS(th)}$=5V. Calculate V_{GS} and V_{DS} for the circuit.

$$V_{R_2} = \frac{V_{DD}}{R_1 + R_2} \times R_2 = \frac{25}{9+6} \times 9 = 15V$$

$$V_{R_2} = V_{GS} = 15V$$

$$K = \frac{I_D}{\left(V_{GS} - V_{GS(th)}\right)^2} = \frac{4 \times 10^{-3}}{(10-5)^2} = 0.16mA/V^2$$

$$I_D = 0.16(15-5)^2 = 16mA$$

$$V_{DS} = V_{DD} - I_S R_S = 25 - 16 \times 10^{-3} \times 1 \times 10^3 = 9V$$

Exercise

An N-channel E-MOSFET has the following parameters: I_D on=4mA at V_{GS}=10V and $V_{GS(off)}$=5V. Calculate the I_D for V_{GS}=8V. Ans. 1.44mA.

FET AMPLIFIERS
DE MOSFET Amplifier
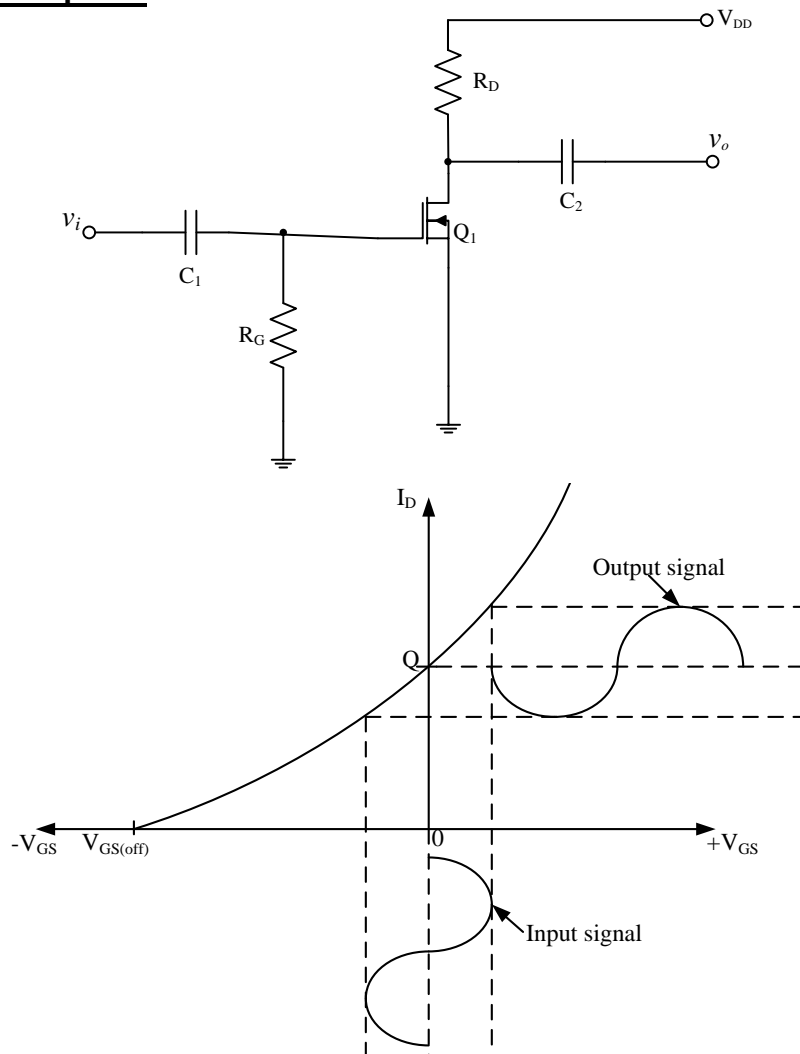
- ➢ A zero biased N-channel DEMOSFET with an a.c source capacitor coupled to the gate is given above.
- ➢ The input a.c V_{in} causes V_{GS} to swing above and below its zero value therefore producing a swing in I_D.

- ➤ The -ve swing in V_{GS} produces depletion and I_D is decreased.
- ➤ A +ve swing in V_{GS} produces enhancement mode making I_D to increase.

E-MOSFET Amplifier
- ➤ The gate is biased with a +ve voltage such that V_{GS} is more than $V_{GS(th)}$.
- ➤ The signal voltage produces a swing in V_{GS} below and above its Q point value.
- ➤ This in turn causes a swing in I_D and hence in $I_D R_D$.
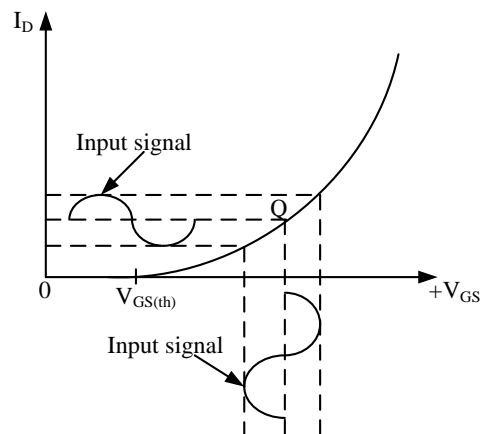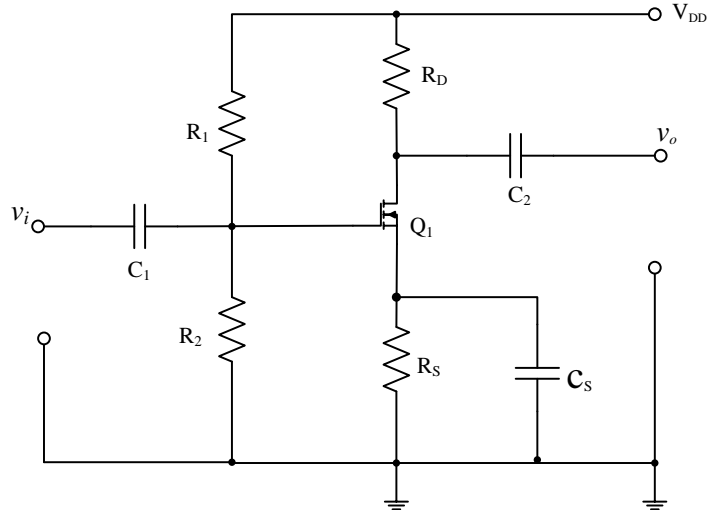
FET CONFIGURATIONS
Common Source (CS)
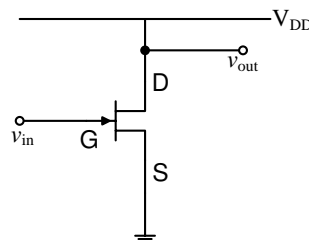
Input parameters
- ➤ Input voltage=V_{GS}
- ➤ Input current=I_G
- ➤ Input impedance V_{GS}/I_G
- ➤ Input power=$I_G V_{GS}$

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Output Parameters
- ➢ Output voltage=V_{DS}
- ➢ Output current=I_D
- ➢ Output impedance=V_{DS}/I_D
- ➢ Output power=$I_D V_{DS}$

- ➢ Current gain =I_D/I_G
- ➢ Voltage gain =V_{DS}/V_{GS}

<u>Common Drain (CD)</u>

Input parameters
- ➢ Input voltage=V_{DG}
- ➢ Input current=I_G
- ➢ Input impedance V_{DG}/I_G
- ➢ Input power=$I_G V_{DG}$

Output Parameters
- ➢ Output voltage=V_{DS}
- ➢ Output current=I_S
- ➢ Output impedance=V_{DS}/I_S
- ➢ Output power=$I_S V_{DS}$

- ➢ Current gain =I_S/I_G
- ➢ Voltage gain =V_{DS}/V_{DG}

<u>Common Gate (CG)</u>
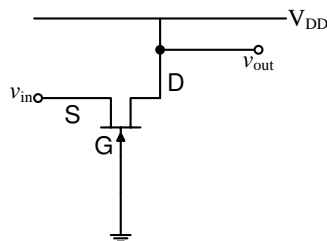
Input parameters
- ➢ Input voltage=V_{GS}
- ➢ Input current=I_S
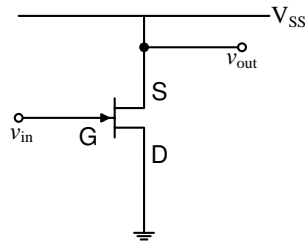- ➢ Input impedance V_{GS}/I_S
- ➢ Input power=$I_S V_{GS}$

Output Parameters
- ➢ Output voltage=V_{DG}
- ➢ Output current=I_D

- Output impedance=V_{DG}/I_D
- Output power=$I_D V_{DG}$

- Current gain =I_D/I_S
- Voltage gain =V_{DG}/V_{GS}

Applications of FETS(s)
- Input amplifiers in oscilloscopes, electronic voltmeters and other measuring and testing equipment because of the very high R_{in} (input resistance), which reduces the loading effect to the minimum.
- Logic circuits where it is kept off when there is a zero input while it is turned on with very little power input e.g. OR, NAND, AND & NOR gates.
- Mixer operations of FM and T.V receivers.
- Voltage variables resistors in operational amplifiers (OP-AMPS).
- Large scale integration IC's and computer memories because they come in small sizes.

SILICON CONTROLLED RECTIFIER (SCR) (THYRISTOR)
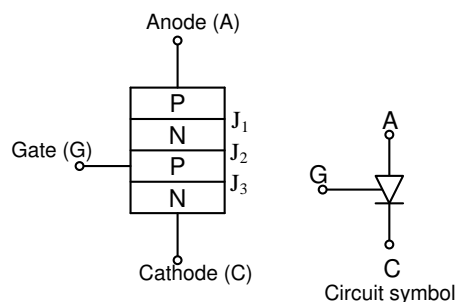
- It is a 4 layer P-N-P-N device which is basically a rectifier with a controller element.
- It consists of 3 diodes connected back to back with a gate connection.

Construction
- It is a 3 terminal 4 layer transistor with the layers being alternately of P-type and N-type silicon.
- It has 3 junctions J_1, J_2 and J_3 and the 3 terminals are given by the anode, cathode and the gate.
- The function of the gate is to control the firing of the SCR.

Biasing
- With the polarity of the source as shown in (a) J_1 and J_3 are forward biased while J_2 is reverse biased hence no current except leakage current flows through the SCR.
- With polarity as shown in (b) J_1 and J_3 are reverse biased while J_2 forward biased. Again no current flows through the SCR.
- However if the anode voltage in (a) is increased to a critical value called the forward break-over voltage V_{BO} is reached when J_2 breaks down and SCR suddenly switches to a highly conducting state.
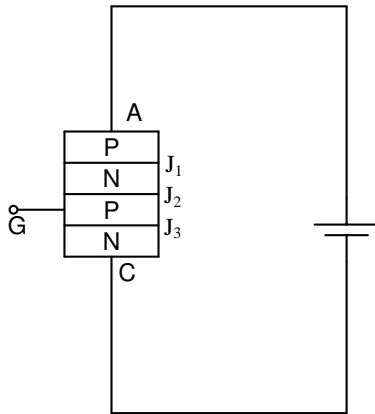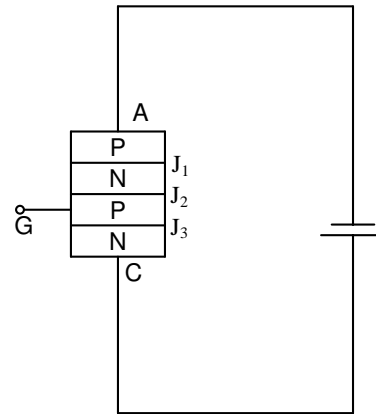
Fig. (a)   Fig. (b)

➤ Conduction can also be achieved by connecting the gate to a given voltage which forward biases J_2.

➤ In this condition the SCR has little forward resistance of the range 0.1 to 1.2Ω and the voltage drop across it is very low, about 1V.

➤ For the case of (b) where the current flow is blocked by the 2 reverse biased junctions, when V is increased, a point is reached when zener breakdown occurs which may destroy the SCR.

➤ Therefore the SCR is a unidirectional device.

➤ This can be shown in the characteristics curve given below:-

I_H is min I for SCR to conduct
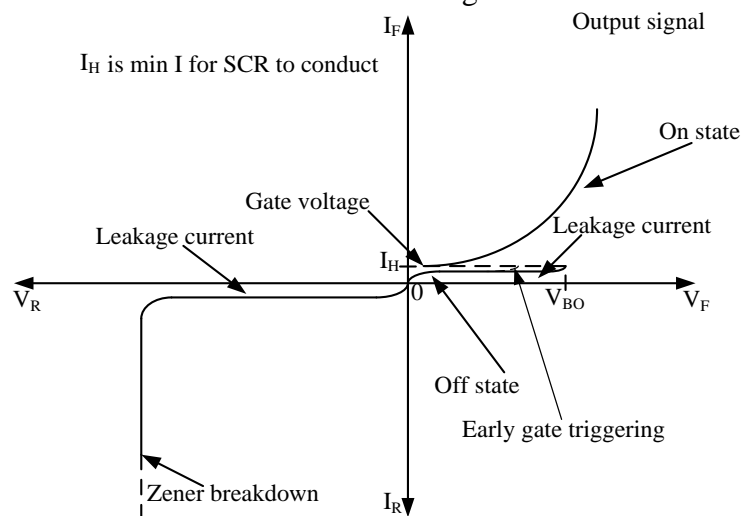
Two transistor analogy

➤ Its operation can be described using 2 transistor analogy therefore the SCR can be split into 2 three-layers as shown in (a) and represented using transistors as shown in (b).

➤ From (b) it can be noted that:

The collector current of Q_1 is also the base current of Q_2 and the base current of Q_1 is the collector current of Q_2.

Fig (a)   Fig (b)
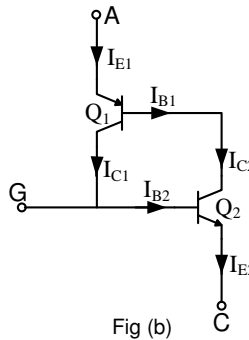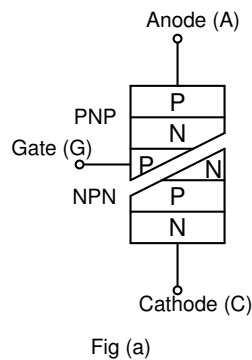
> If the voltage applied across A and C is increased such that J_2 breaks down then the current through the device rises and therefore I_{E1} begins to increase and then;
>   o I_{C1} increases.
>   o Since $I_{C1}=I_{B2}$, I_{B2} also increases.
>   o Therefore I_{C2} increases.
>   o $I_{C2}=I_{B1}$ hence I_{B1} increases.
>   o Consequently both I_{C1} and I_{E1} increase, therefore a regenerative action occurs whereby an initial increment in current produces further increase in the same current. Soon a maximum current is reached limited by external resistance.
>   o The 2 transistors are fully turned on and the voltage across them falls to very low values.
> The typical turn on time is 0.1 to 1.0 µs.

Firing and triggering of SCR
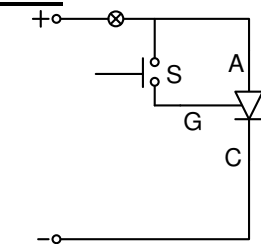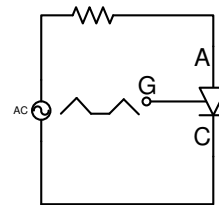
(a) dc firing circuit   (b) pulse signal circuit

> It is operated normally with anode voltage slightly less than V_{BO} forward break- over voltage and is triggered into conduction by a low power gate pulse.
> Once it's on the gate has no control on the device current.
> This gate signal can be a d.c firing signal or a pulse signal.
> For (a) when the switch is open the SCR does not conduct and the lamp is off. When the switch is closed, a +ve voltage is applied to the gate which forward biases the centre the centre PN junction and the SCR is made to conduct and the lamp is on.
> The SCR remains in the conduction state until the supply voltage is removed
> Once fired the SCR remains on even when the triggering pulse is removed, therefore a number of techniques are used to turn it off and they are given by:-
>   o Anode current interruption.
>   o Reversing the polarity of anode-cathode voltage.
>   o Reducing current through the SCR below the holding current I_H and this is referred to as low current drop out.

Applications
> Power control.

- ➤ Relay controls.
- ➤ Regulated power suppliers.
- ➤ Static switches.
- ➤ Motor control.
- ➤ Invertors.
- ➤ Battery charges.
- ➤ Heater controls.
- ➤ Phase controls.

Phase control
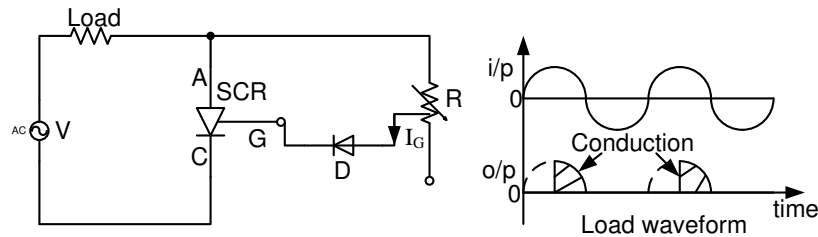
- ➤ The gate triggering is driven from the supply. The variable resistor R limits the gate current during the +ve half cycle of the supply.
- ➤ If R is set to a low value, the SCR will trigger almost immediately at the beginning of the +ve half cycle of the input.
- ➤ But if R is set to high resistance, the SCR may not switch on until the peak of the +ve half cycle.
- ➤ By adjusting R between the two extremes, the SCR is made to switch on somewhere between the beginning and peak of the positive half cycle between 0 and 90º.
- ➤ N/B: If I_G is not enough to trigger the SCR at 90º, then the device will not trigger at all.
- ➤ The diode D is used to protect the gate from -ve voltage which would otherwise be applied to it during the -ve half cycle.
- ➤ Therefore at the instant SCR switch on:

$$R = \frac{V - V_D - V_G - I_G R_L}{I_G}$$

Exercise

- ➤ The circuit for phase control is connected to an a.c. supply V=50 sin θº, R_L=50Ω the gate current I_G=100μA and V_G=0.5V. Determine the range of adjustment of R for the SCR to be triggered between 30º between 90º; take V_D=0.7V.

$$R = \frac{V - V_D - V_G - I_G R_L}{I_G}$$

$$R = \frac{50\sin 30 - 0.7 - 0.5 - \left(100 \times 10^{-6} \times 50\right)}{100 \times 10^{-6}}$$

$$R = 237950 = 238k\Omega$$

$$R = \frac{50\sin 90 - 0.7 - 0.5 - \left(100 \times 10^{-6} \times 50\right)}{100 \times 10^{-6}}$$
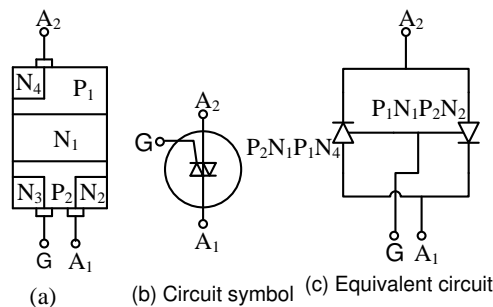
$$R = 487950 = 488k\Omega$$

Major considerations when ordering for SCR

➢ The peak forward and reverse breakdown voltages.
➢ Maximum forward current.
➢ Gate trigger voltage and current.
➢ Minimum holding current I_H.
➢ Power dissipation.
➢ Maximum change of voltage time dv/dt (switching).

TRIAC (TRIODE A. C.)
Construction

(a)   (b) Circuit symbol   (c) Equivalent circuit

➢ It's a 5 layer bi-directional device which can be triggered into conduction by both +ve and -ve voltages at its anode and with both the +ve and -ve triggering pulses at the gates.
➢ It behaves like 2 SCR's connected in parallel upside down with respect to each other.

Operation
a) When A_2 is +ve:
➢ The current flows from $P_1N_1P_2N_2$.
➢ The 2 junctions P_1N_I and P_2N_2 are forward biased whereas N_1P_2 junction is reverse biased.
➢ The gate can be either +vely or -vely biased to turn on the triac as follows:
  o +ve gate with respect to A_1 forward biases the P_2N_2 junction and breakdown occurs as in normal SCR.
  o -ve gate forward biases P_2N_3 junction and current carriers injected into P_2 turn on the triac.

b) When A_1 is +ve:
➢ Current flows from $P_2N_1P_1N_4$
➢ 2 junctions P_2N_1 and P_1N_4 are forward biased whereas N_1P_I is reverse biased
➢ As earlier, conduction can be achieved by applying a +ve or -ve voltage to the gate as follows:
  o A +ve gate with respect to A_1 injects current carriers by forward biasing P_2N_2 junction and therefore initiates conduction.
  o A -ve gate injects current carriers by forward biasing P_2N_3 junction thereby triggering conduction.
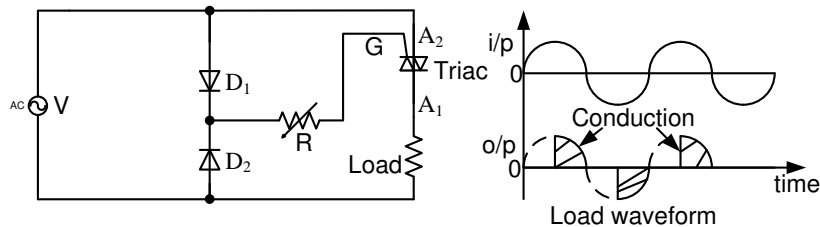
VI Characteristics
➢ It shows that a triac has same forward blocking and forward conducting characteristics as an SCR but for either polarity of voltage applied to the main terminal.
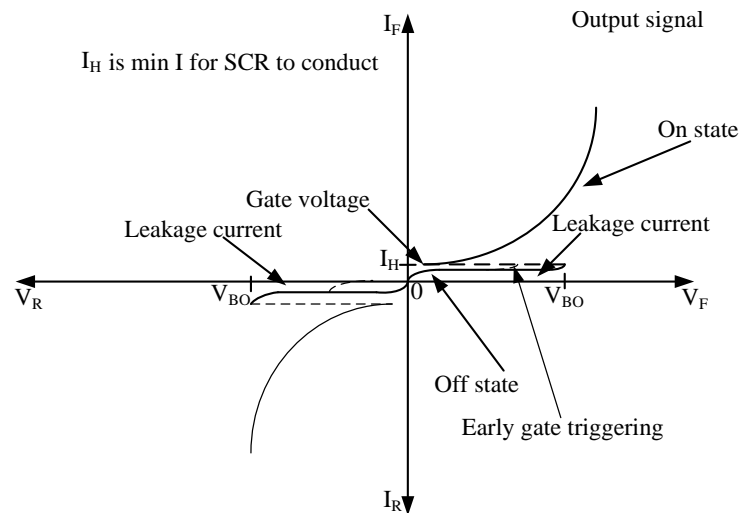
Applications

➢ It can be used to control a.c. power to a load by switching on and off during the +ve and -ve half cycles.

o During the +ve ½ cycle the input, diode D_1 is forward biased, D_2 is reverse biased and the gate is +ve with respect to A_1.
o By adjusting R, the point at which conduction starts can be varied i.e from 0 to 90º.

➢ It can be used as a static switch to turn a.c power on and off.
➢ Minimizing radio interferences.
➢ Light control.
➢ Motor speed control.

N/B: The only disadvantage of a triac is that it takes longer time to recover from off state hence its use is limited to a.c supply frequencies of up to 400Hz.

Major considerations when ordering triacs.

➢ Break over voltage.
➢ Switching speed.
➢ Voltage symmetry.
➢ Maximum change of voltage with time.
➢ Break back voltage.
➢ Maximum current.
➢ Break over current / holding current (min).
➢ Power dissipation.

DIAC (DIODE AC)
## Construction

(a) (b) Circuit symbol
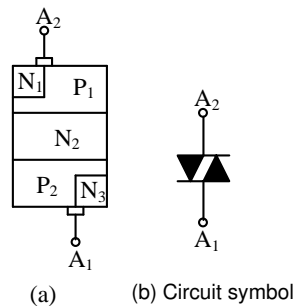
- ➤ It can breakdown in either direction.
- ➤ It has only 2 terminals and is like a triac without its gate.
- ➤ When anode A_1 is +ve the current path is $P_2N_2P_1N_1$.
- ➤ Similarly when A_2 is +ve the current path is $P_1N_2P_2N_3$.
- ➤ A diac is designed to trigger triacs or provide protection against over voltage.
- ➤ Its operation can be visualized as 2 diodes connected on series.
- ➤ Voltage applied across it in either direction turns on one diode and reverse biases the other, hence it can be switched from off to on state for either polarity of the applied voltage.
- ➤ The symmetrical by directional switching characteristics are given below:-
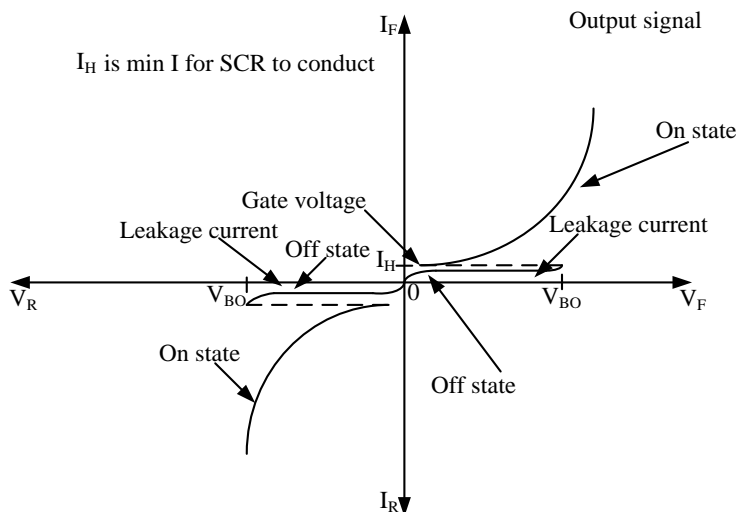
Considerations
- ➤ Break over voltage (typically from 20-40V).
- ➤ Voltage symmetry.
- ➤ Break back voltages.
- ➤ Break over current (typically from 50-200µA).
- ➤ Power dissipation.

SILICON CONTROLLED SWITCH
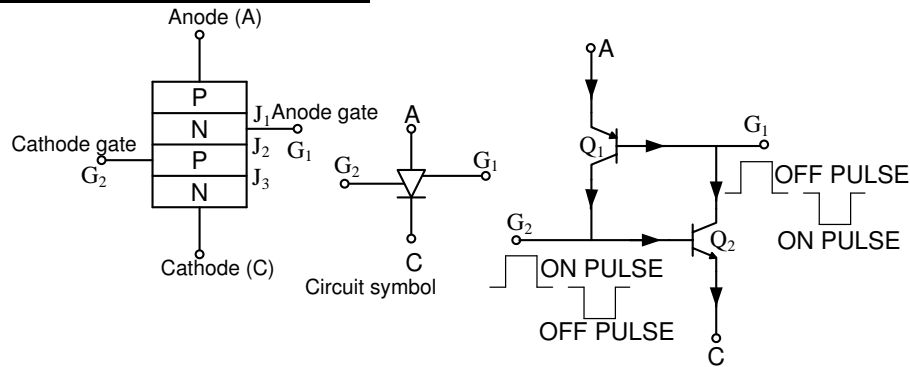
- It is a 4 layer 4 terminal PNPN device having anode A cathode C, anode gate G_1 and Cathode gate G_2 as shown in figure above.
- It is a low current SCR with 2 gate terminals.
- The 2 transistor equivalent circuit is shown above.
- The device may be switched on or off by a suitable pulse applied at the gate.
- As shown a -ve pulse is required at the anode gate G_1 to turn the device on whereas a +ve pulse is required to turn it off.
- Similarly at cathode gate G_2 a -ve pulse is required to switch it off and a +ve pulse to turn it on.
- When a +ve pulse is applied to G_1 it forward biases Q_1 which is turned on.
- The resulting heavy collector current I_C being the base current of Q_2 turns it on hence the SCS is switched on.
- A +ve pulse at G_1 will reverse bias EB junction Q_1 thereby switching the SCS off.

V/I Characteristics
- They are essentially the same as those of SCR.
- As compared to SCR, an SCS has much reduced turn off time.
- Moreover it has higher controlled and triggering sensitivity and a more predictable firing situation.

Applications
- It can be used in counter registers and timing circuits of computers.
- Pulse generators to generate pulses.
- Voltage sensors.
- Oscillators.

OPERATIONAL AMPLIFIERS (OP-AMP)
- ➤ An OP-AMP is a very high-gain, high input resistance directly-coupled negative-feedback amplifier which can amplify signals having frequency ranging from 0Hz to 1MHz.
- ➤ It's named so because it was originally designed to perform mathematical operations such as summation, subtraction, multiplication, differentiation and integration.

Op-Amp symbol
- ➤ The standard symbol is as shown in the figure below;
- ➤ The Op-amp's input can be single-ended or double-ended (or differential input) depending on whether input voltage is applied to one input terminal only or to both.
- ➤ Similarly, output can also be either single-ended or double-ended. But the most common configuration is two input terminals and a single output.
- ➤ All Op-amps have minimum of 5 terminals;
    - o Inverting input terminal
    - o Non-inverting input terminal
    - o Output terminal
    - o Positive bias supply terminal
   - o Negative bias supply terminal
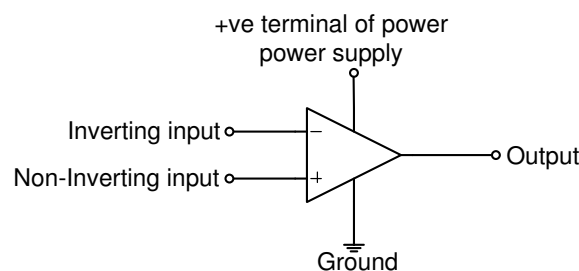
Polarity convention
- ➤ In the figure above, input terminals are marked (-) and (+) which indicates the inverting and non-inverting terminals only i.e. a single applied to the -ve input terminal will be amplified but phase-inverted at the output terminal.

Ideal OP-AMP
- ➤ When Op-amp is operated without feedback it is said to be in the open-loop condition (i.e. the word open-loop means that feedback path or loop is open)
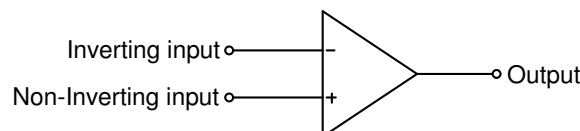

Properties (characteristics)
- ➤ Infinite voltage gain ($A_v = \infty$)
- ➤ Infinite input resistance ($R_{in} = \infty$), means input current is zero.
- ➤ Zero output resistance ($R_o = 0$), means V_o is not dependent on the load resistance.
- ➤ Infinite bandwidth (can amplify signals of frequency ranging from zero to infinite).

Properties of a practical Op-amp
- ➤ High voltage gain ($A_v = 10^6$)
- ➤ High input resistance ($R_{in} = 10^6$), means input current is zero.

> Low output resistance ($R_o = 10^{-6}$), means V_o is not dependent on the load resistance.
> High bandwidth (can amplify signals of frequency ranging from zero to infinite).

Virtual ground and summing point


Virtual ground
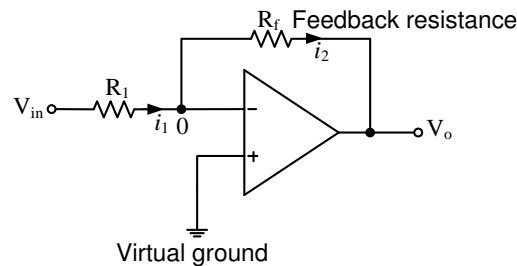
> The above circuit is an Op-amp which employs -ve feedback using resistor R_f to feed back a portion of the output to the input.
> Since input and feedback currents are algebraically added at point A, it's called the summing point.
> Since the input voltage V_1 at the inverting terminal of an Op-amp is forced to very small value that, for all practical purposes is assumed to be zero, point A is essentially at ground voltage and thus called a virtual ground.
> NB: this is not the actual ground as shown above.
> V_1 is reduced to almost zero since when V_{in} is applied point A attains some +ve potential and at the same time Vo is brought into existence. Due to the -ve feedback, some fraction of the output voltage is fed back to point A out of phase with the voltage already existing there due to V_{in}. The algebraic sum of the two is almost zero such that $V_1 = 0$.
> Also a virtual short exists between the two terminals of an Op-amp because $V_1 = 0$. (It's virtual because no current flows (i.e. $i = 0$) despite the existence of a short).

Applications of an Op-amp
> As a scalar or linear constant-gain amplifier, i.e. both inverting and non-inverting.
> As a unity follower (buffer).
> Adder or summer.
> Subtractor.
> Integrator.
> Differentiator.
> Comparator.

Inverting amplifier (negative scalar)

Virtual ground
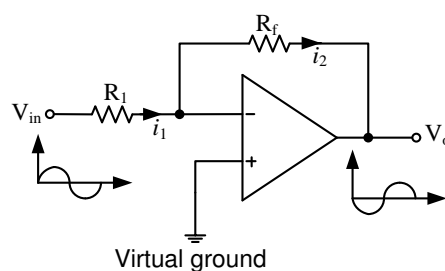
Applying KCL $i_1 = i_2$
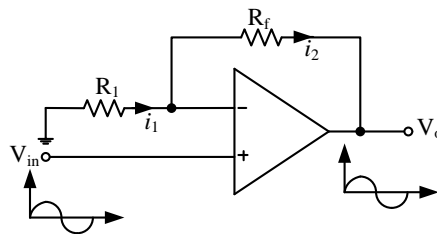
$$i_1 = \frac{V_{in} - 0}{R_1} = \frac{V_{in}}{R_1}$$

$$i_2 = \frac{0 - V_o}{R_f} = -\frac{V_o}{R_f}$$

$$\frac{V_{in}}{R_1} = -\frac{V_o}{R_f}$$

$$Voltage\ gain = A_v = \frac{V_o}{V_{in}} = -\frac{R_f}{R_1}$$

➢ Thus the closed-loop gain depends on the ratio of the two external resistors R_1 and R_f and is independent of the amplifier parameters.

Non-Inverting amplifier (positive scalar)

➢ The input voltage V_{in} is applied to the non-inverting terminal. The polarity of V_o is the same as that of V_{in}.
➢ Because of virtual short between the two Op-amp terminals, the voltage across R_1 is the input voltage V_{in}. Also V_o is applied across the series combination of R_1 and R_f.

$$i_1 = i_2$$

$$i_1 = \frac{0 - V_{in}}{R_1} = -\frac{V_{in}}{R_1}$$
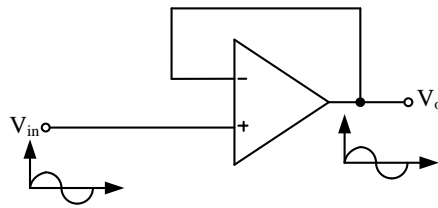
$$i_2 = \frac{V_{in} - V_o}{R_f}$$

$$-\frac{V_{in}}{R_1} = \frac{V_{in} - V_o}{R_f}$$

$$-\frac{V_{in}}{R_1} = \frac{V_{in}}{R_f} - \frac{V_o}{R_f}$$

$$\frac{V_o}{R_f} = \frac{V_{in}}{R_1} + \frac{V_{in}}{R_f}$$

$$Voltage\ gain = \frac{V_o}{V_{in}} = \frac{R_f}{R_1} + \frac{R_f}{R_f} = 1 + \frac{R_f}{R_1}$$

Unity follower

> ➢ Provides a gain of unity without any phase reversal.
> ➢ It's useful as a buffer or isolation amplifier because it allows input voltage V_{in} to be transferred as output voltage while at the same time preventing load resistance from loading down the input source. It's due to the fact that its $R_o=0$ and $R_{in}=\infty$.
> ➢ From the gain of non-inverting Op-amp, we have;

$$Voltage\ gain = \frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}$$

But since in this case $R_1=R_f=0$,
$$Voltage\ gain = 1 + 0 = 1$$

Adder or summer
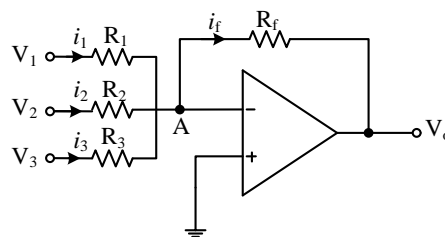
> ➢ Provides an output proportional to or equal to the algebraic sum of two or more input voltages each multiplied by a constant gain factor.
> ➢ Since point A is a virtual ground, then

$$i_1 = \frac{V_1 - 0}{R_1} = \frac{V_1}{R_1}$$

$$i_2 = \frac{V_2 - 0}{R_2} = \frac{V_2}{R_2}$$

$$i_3 = \frac{V_3 - 0}{R_3} = \frac{V_3}{R_3}$$

$$i_f = \frac{0 - V_o}{R_f} = -\frac{V_o}{R_f}$$

Applying KCL to the virtual point, we get
$$i_f = i_1 + i_2 + i_3$$

Equating them results to $\dfrac{V_1}{R_1} + \dfrac{V_2}{R_2} + \dfrac{V_3}{R_3} = -\dfrac{V_o}{R_f}$

$$\frac{V_o}{R_f} = -\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

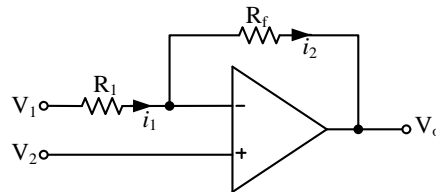$$V_o = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$$

Taking $R_1=R_2=R_3=R$ gives

$$V_o = -\frac{R_f}{R}\left(V_1 + V_2 + V_3\right)$$

If $R_f=R$ then

$$V_o = -\left(V_1 + V_2 + V_3\right)$$

Subtractor

- ➤ Its function is to provide an output proportional to or equal to the difference of two input signals.
- ➤ Applying KCL to the virtual point, we get

$$i_1 = i_2$$

$$i_1 = \frac{V_1 - V_2}{R_1}$$

$$i_2 = \frac{V_2 - V_o}{R_f}$$

Equating the two results to $\dfrac{V_1 - V_2}{R_1} = \dfrac{V_2 - V_o}{R_f}$

$$\frac{V_1}{R_1} - \frac{V_2}{R_1} = \frac{V_2}{R_f} - \frac{V_o}{R_f}$$

$$\frac{V_o}{R_f} = \frac{V_2}{R_1} + \frac{V_2}{R_f} - \frac{V_1}{R_1}$$

$$\frac{V_o}{R_f} = V_2\left(\frac{1}{R_1} + \frac{1}{R_f}\right) - \frac{V_1}{R_1}$$

$$V_o = V_2\left(\frac{R_f}{R_1} + \frac{R_f}{R_f}\right) - R_f\frac{V_1}{R_1}$$

$$V_o = V_2\left(\frac{R_f}{R_1} + 1\right) - R_f\frac{V_1}{R_1}$$

Omitting 1 results to

$$V_o = \frac{R_f}{R_1}\left(V_2 - V_1\right)$$

Taking $R_f=R_1$ gives

$$V_o = V_2 - V_1$$