CHAPTER 1A

Industrial electronics is a branch of electronics that deals with power electronic devices such as thyristors, SCRs, AC/DC drives, meters, sensors, analyzers, load sells automatic test equipment, multimeters, data recorders, relays, resistors, semiconductors, transistors, waveguides, scopes, amplifiers, radio frequency (RF) circuit boards, timers, counters, etc. It covers all of the methods and facets of: control systems, instrumentation, mechanism and diagnosis, signal processing and automation of various industrial applications.

The scope of industrial electronics ranges from the design and maintenance of simple electrical fuses to complicated programmable logic controllers (PLCs), solid-state devices and motor drives. Industrial electronics can handle the automation of all types of modern day electrical and mechanical industrial processes. Some of the speciality equipment used in industrial electronics includes variable frequency converter and inverter drives, human-machine interfaces, hydraulic positioners and computer or microprocessor controlled robotics.

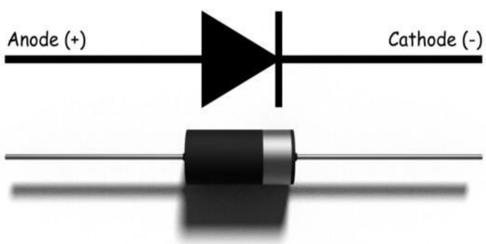
The electronics you may already know operates at very low power means in microwatts and microvolts where power electronics operates at very high power and voltage. So the industrial electronics is the study of electronic equipments which simply operates on high power and voltage. The gadgets such as Diac, Triac , Thyristor etc. are based on principle of electronics but operates at range of power electronics hence they are the part of power electronics or industrial electronics

Before we proceed to industrial electronics applications and let us learn first the common semiconductor devices, its construction and characteristics that is commonly used in industrial electronics.

POWER DIODES

A power diode is a two terminal device, where one terminal is an anode, and the second terminal is a cathode. If the anode voltage is higher than the cathode voltage, then the diode is forward biased and the forward current flows through the diode I_F.

It is semilar to rectrifier diode, however, it operates at high power and voltage. Because of this, Power diodes are usually mounted on the heat-sink to dissipate power during diode operation. And the power diode is usually characterised by average current, rms current and peak current.



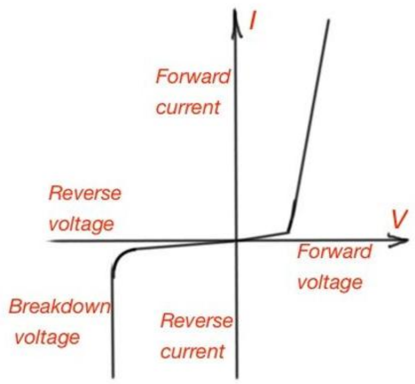


Figure 1. Voltage-current curve for diode

THYRISTOR

A thyristor is a solid-state semiconductor device with four layers of alternating P- and N-type materials. It acts exclusively as a bistable switch, conducting when the gate receives a current trigger, and continuing to conduct until the voltage across the device is reversed biased, or until the voltage is removed (by some other means). There are two designs, differing in what triggers the conducting state. In a three-lead thyristor, a small current on its Gate lead controls the larger current of the Anode to Cathode path. In a two-lead thyristor, conduction begins when the potential difference between the Anode and Cathode themselves is sufficiently large (breakdown voltage).

Some sources define silicon-controlled rectifier (SCR) and thyristor as synonymous. Other sources define thyristors as more ornately constructed devices that incorporate at least four layers of alternating N-type and P-type substrate.

In many ways the Silicon Controlled Rectifier, SCR or just Thyristor as it is more commonly known, is similar in construction to the transistor.

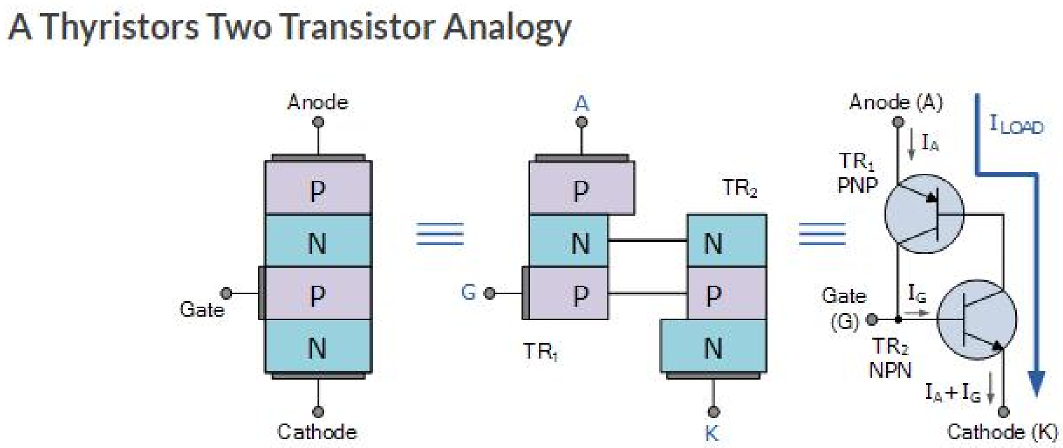
It is a multi-layer semiconductor device, hence the “silicon” part of its name. It requires a gate signal to turn it “ON”, the “controlled” part of the name and once “ON” it behaves like a rectifying diode, the “rectifier” part of the name. In fact the circuit symbol for the *thyristor* suggests that this device acts like a controlled rectifying diode.

However, unlike the junction diode which is a two layer (P-N) semiconductor device, or the commonly used bipolar transistor which is a three layer (P-N-P, or N-P-N) switching device, the Thyristor is a four layer (P-N-P-N) semiconductor device that contains three PN junctions in series, and is represented by the symbol as shown.

Like the diode, the Thyristor is a unidirectional device, that is it will only conduct current in one direction only, but unlike a diode, the thyristor can be made to operate as either an open-circuit switch or as a rectifying diode depending upon how the thyristors gate is triggered. In other words, thyristors can operate only in the switching mode and cannot be used for amplification.

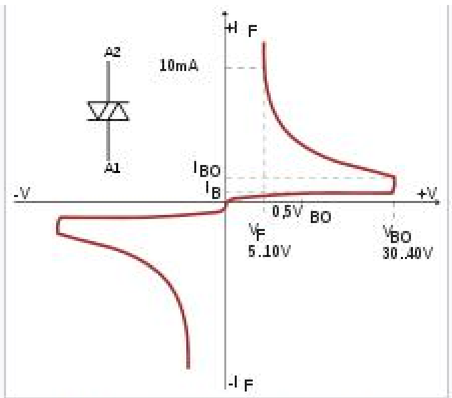
The silicon controlled rectifier SCR, is one of several power semiconductor devices along with Triacs (Triode AC’s), Diacs (Diode AC’s) and UJT’s (Unijunction Transistor) that are all capable of acting like very fast solid state AC switches for controlling large AC voltages and currents. So for the Electronics student this makes these very handy solid state devices for controlling AC motors, lamps and for phase control.

The thyristor is a three-terminal device labelled: “Anode”, “Cathode” and “Gate” and consisting of three PN junctions which can be switched “ON” and “OFF” at an extremely fast rate, or it can be switched “ON” for variable lengths of time during half cycles to deliver a selected amount of power to a load. The operation of the thyristor can be best explained by assuming it to be made up of two transistors connected back-to-back as a pair of complementary regenerative switches as shown.

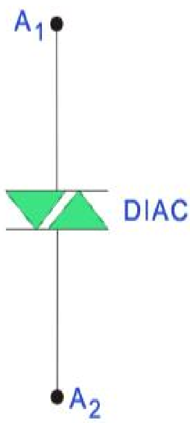


DIAC

A DIAC is a diode that conducts electrical current only after its breakover voltage (VBO) has been reached. DIAC stands for “Diode for Alternating Current”. A DIAC is a device which has two electrodes, and it is a member of the thyristor family. DIACs are used in the triggering of thyristors. The figure below shows a symbol of a DIAC, which resembles the connection of two diodes in series.



Typical DIAC voltage and current relationships. V_{BO} is the breakover voltage.



The advantage of a DIAC is that it can be turned on or off simply by reducing the voltage level below its avalanche breakdown voltage. DIACs are also known as a transistor without a base. It should also be noted that a DIAC can be either turned on or off for both polarities of voltage (i.e. positive or negative voltage). They also still works when avalanche breakdown occurs.

It is a device which consists of four layers and two terminals. The construction is almost the same as that of the transistor. But there are certain points which deviate from the construction from the transistor. The differentiating points are-

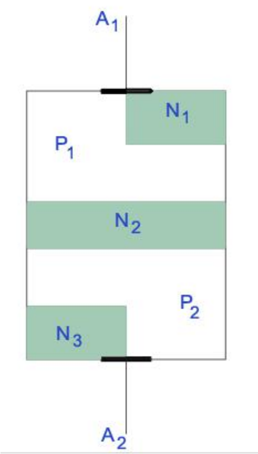
1. There is no base terminal in the DIAC
2. The three regions have almost the same level of doping
3. It gives symmetrical switching characteristics for either polarity of voltages

we can see that a DIAC has two p-type material and three n-type materials. Also, it does not have any gate terminal in it.

The DIAC can be turned on for both the polarity of voltages. When A2 is more positive with respect to A1 then the current does not flows through the corresponding N-layer but flows from P2-N2-P1-N1. When A1 is more positive A2 then the current flows through P1-N2-P2-N3.
The construction resembles the diode connected in series.

When the applied voltage is small in either polarity, a very small current flows which is known as leakage current because of the drift of electrons and holes in the depletion region. Although a small current flows, it is not sufficient to produce avalanche breakdown, hence the device remains in the non-conducting state.

When the applied voltage in either polarity exceeds the breakdown voltage, DIAC current rises and the device conducts in accordance with its V-I characteristics. The DIAC acts as an open circuit when the voltage is less than its avalanche breakdown voltage. When the device has to be turned off, the voltage must be reduced below its avalanche breakdown voltage.



TRIAC

Triacs are semiconductor devices that are widely used for switching medium power AC - their advantage is that they can switch both halves of alternating cycle.

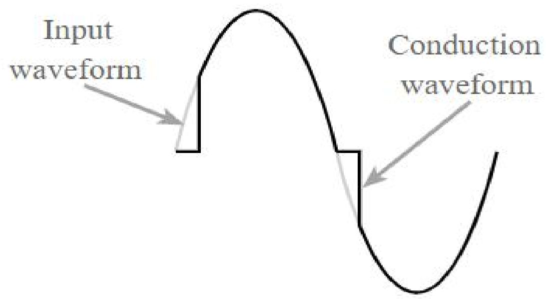
Triacs are electronic components that are widely used in AC power control applications. They are able to switch high voltages and high levels of current, and over both parts of an AC waveform. This makes triac circuits ideal for use in a variety of applications where power switching is needed.

One particular use of triac circuits is in light dimmers for domestic lighting, and they are also used in many other power control situations including motor control and electronic switches.

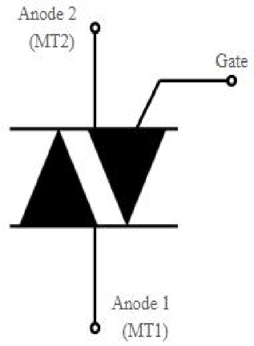
As a result of their performance, triacs tend to be used for low to medium power electronic switching applications, leaving thyristors to be used for the very heat duty AC power switching applications.

The triac is a development of the thyristor. While the thyristor can only control current over one half of the cycle, the triac controls it over two halves of an AC waveform.

As such the triac can be considered as a pair of parallel but opposite thyristors with the two gates connected together and the anode of one device connected to the cathode of the other, etc..



Triac switching waveform



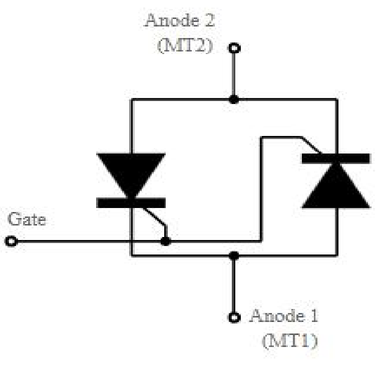
Triac circuit symbol

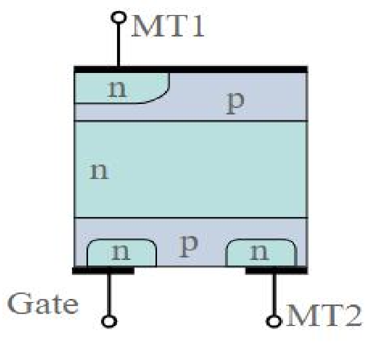
The fact that the triac switching action occurs on both halves of an AC waveform means that for AC electronic switching applications, the complete cycle can be used. For basic thyristor circuits, only half the waveform is used and this means that basic circuits using thyristors will not utilise both halves of the cycle. Two devices are required to utilise both halves. However the triac only requires one device to control both halves of the AC waveform and in many respects it is an ideal solution for an electronic switch for AC.

Like a thyristor, a triac has three terminals. However the names of these are a little more difficult to assign, because the main current carrying terminals are connected to what is effectively a cathode of one thyristor, and the anode of another within the overall device.

There is a gate which acts as a trigger to turn the device on. In addition to this the other terminals are both called Anodes, or Main Terminals These are usually designated Anode 1 and Anode 2 or Main Terminal 1 and Main Terminal 2 (MT1 and MT2). When using triacs it is both MT1 and MT2 have very similar properties.

or the operation of the triac, it can be imagined from the circuit symbol that the triac consists of two thyristors in parallel but around different ways. The operation of the triac can be looked on in this fashion, although the actual operation at the semiconductor level is rather more complicated.





Triac basic structure

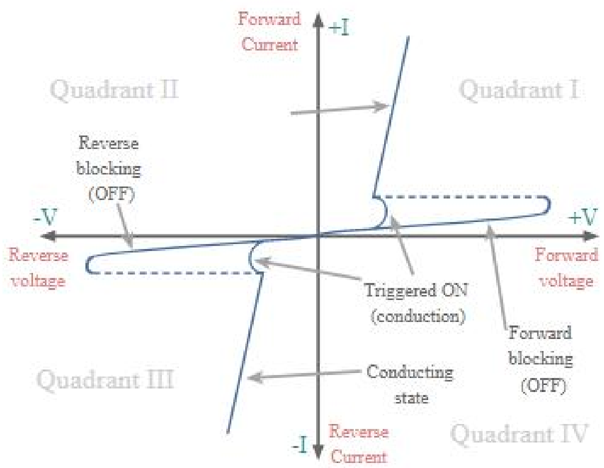
The triac structure is shown below and it can be seen that there are several areas of N-type and P-type material that form what is effectively a pair of back to back thyristors.

The triac is able to conduct in a number of ways - more than the thyristor. It can conduct current irrespective of the voltage polarity of terminals MT1 and MT2. It can also be triggered by either positive or negative gate currents, irrespective of the polarity of the MT2 current. This means that there are four triggering modes or quadrants:

- *I+ Mode* MT2 current is +ve, gate current is +ve
- *I- Mode* MT2 current is +ve, gate current is -ve
- *III+ Mode:* MT2 current is -ve, gate current is +ve
- *III- Mode:* MT2 current is -ve, gate current is -ve

It is found that the triac trigger current sensitivity is greatest when the MT2 and gate currents are both of the same polarity, i.e. both positive or both negative. If the gate and MT2 currents are of the opposite polarity then the sensitivity is typically about half the value of when they are the same.

The typical IV characteristic of a triac can be seen in the diagram below with the four different quadrants labelled.



Triac IV characteristic

PHOTO TRANSISTOR

The phototransistor is a semiconductor device that is able to sense light levels and alter the current flowing between emitter and collector according to the level of light it receives.

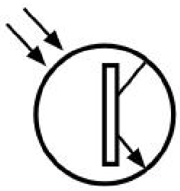
Phototransistors and photodiodes can both be used for sensing light, but the phototransistor is more sensitive in view of the gain provided by the fact that it is a bipolar transistor. This makes phototransistors more suitable in a number of applications.

The idea of the phototransistor has been known for many years. William Shockley first proposed the idea in 1951, not long after the ordinary bipolar transistor had been discovered. It was then only two years before the photo-transistor was demonstrated. Since then phototransistors have been used in a variety of applications, and their development has continued ever since.

Phototransistors are widely available and can easily be obtained quite cheaply from electronic component distributors - in view of their use in many electronic circuits and applications, they are available as part of the standard semiconductor device inventory.

Standard circuit symbols are essential for each type of electronic component, enabling circuit diagrams to be drawn easily and recognisable by all. The phototransistor symbol consists of the basic bipolar transistor symbol with two arrows pointing towards the junction of the bipolar transistor. This diagrammatically represents the operation of the phototransistor.

A typical phototransistor
Note the lens at the top and the fact that it only has two leads because the base is often left open circuit and no external connection is provided.



Phototransistor circuit symbol (for a device based around an NPN transistor)

Phototransistors can be based around both NPN transistors and PNP transistors and therefore it is perfectly possible to have a PNP phototransistor, and for this the direction of the arrow on the emitter is reversed in the normal way.

It can be seen that the phototransistor symbol shown does not give a base connection. Often the base is left disconnected as the light is used to enable the current flow through the phototransistor. In some instances the base may be biased to set the required operating point. In this case the base will be shown in the normal way on the phototransistor symbol.

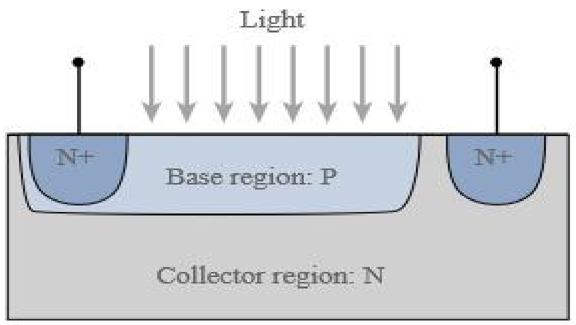
Although ordinary bipolar transistors exhibit the photosensitive effects if they are exposed to light, the structure of the phototransistor is specifically optimised for photo applications. The photo transistor has much larger base and collector areas than would be used for a normal transistor. These devices were generally made using diffusion or ion implantation.

Early photo transistors used germanium or silicon throughout the device giving a homo-junction structure. The more modern phototransistors use type III-V semiconductor materials such as gallium arsenide and the like. NPN transistor varieties are more popular in view of the fact that negative ground systems are used, and NPN transistors fit this mode of operation better.

Heterostructures that use different materials either side of the PN junction are also popular because they provide a high conversion efficiency. These are generally fabricated using epitaxial growth of materials that have matching lattice structures.

These photo transistors generally use a mesa structure. Sometimes a Schottky (metal semiconductor) junction can be used for the collector within a phototransistor, although this practice is less common these days because other structures offer better levels of performance.

In order to ensure the optimum conversion and hence sensitivity, the emitter contact is often offset within the phototransistor structure. This ensures that the maximum amount of light reaches the active region within the phototransistor.



Homojunction planar phototransistor structure

The phototransistor uses the basic bipolar transistor concept as the basis of its operation. In fact a phototransistor can be made by exposing the semiconductor of an ordinary transistor to light. Very early photo transistors were made by not covering the plastic encapsulation of the bipolar transistor with black paint.

The photo-transistor operates because light striking the semiconductor frees electrons / holes and causes current to flow in the base region.

Photo-transistors are operated in their active regime, although the base connection is generally left open circuit or disconnected because it is often not required. The base of the photo transistor would only be used to bias the transistor so that additional collector current was flowing and this would mask any current flowing as a result of the photo-action. For operation the bias conditions are quite simple. The collector of an NPN transistor is made positive with respect to the emitter or negative for a PNP transistor.

The light enters the base region where it causes hole electron pairs to be generated. This generation mainly occurs in the reverse biased base-collector junction. The hole-electron pairs move under the influence of the electric field and provide the base current, causing electrons to be injected into the emitter. As a result the photodiode current is multiplied by the current gain β of the transistor.

The performance of the phototransistor can be superior to that of the photodiode for some applications in view of its gain. As a rough guide, where a photodiode may enable a current flow of around 1μA under typical room conditions, a phototransistor may allow a current of 100μA to flow. These are very rough approximations, but show the order of magnitude of the various values and comparisons.

One of the drawbacks of the phototransistor is that is particularly slow and its high frequency response is very poor. Photo-diodes are much faster electronic components and are used where speed is essential despite their inferior sensitivity.

As already mentioned the photo-transistor has a high level of gain resulting from the transistor action. For homo-structures, i.e. ones using the same material throughout the semiconductor device, this may be of the order of about 50 up to a few hundred.

However for the hetero-structure devices, the levels of gain may rise to ten thousand. Despite their high level of gain the hetero-structure devices are not widely used because these semiconductor devices are considerably more costly to manufacture. A further advantage of all phototransistors when compared to the avalanche photodiode, another device that offers gain, is that the phototransistor has a much lower level of noise. Avalanche diodes of all forms are known for the large levels of noise they generate as a result of the avalanche process.

One of the main disadvantages of the phototransistor is the fact that it does not have a particularly good high frequency response. This arises from the large capacitance associated with the base-collector junction. This junction is designed to be relatively large to enable it to pick up sufficient quantities of light. For a typical homo-structure device the bandwidth may be limited to about 250 kHz. Hetero-junction devices have a much higher limit and some can be operated at frequencies as high as 1 GHz.

The characteristics of the photo-transistor under different light intensities. They are very similar to the characteristics of a conventional bipolar transistor, but with the different levels of base current replaced by the different levels of light intensity.

There is a small amount of current that flows in the photo-transistor even when no light is present. This is called the dark current, and represents the small number of carriers that are injected into the emitter. Like the photo-generated carriers this is also subject to the amplification by the transistor action.

Although these semiconductor devices are used in a huge number of electronic devices, circuits and applications, their advantages and disadvantages need to be weighed up to determine whether they are the right electronic component for the given application. Photoresistors or light dependent resistors LDRs; photodiodes; photodarlingtons, photo-FETs and even photo-thyristors and triacs are all available and may suit any given application.

Phototransistor advantages

- Have a relatively high gain and therefore they are relatively sensitive.
- These electronic components are relatively cheap as they are effectively a transistor that is open to light.
- They can be incorporated into an integrated circuit.
- Offer a reasonable speed.

Phototransistor disadvantages

- These devices cannot handle the high voltages of other semiconductor devices like photo-thyristors and triacs.
- In applications where they are exposed to transient voltage spikes and surges, they are open to damage
- Not as fast as other light sensitive electronic components like photo-diodes.

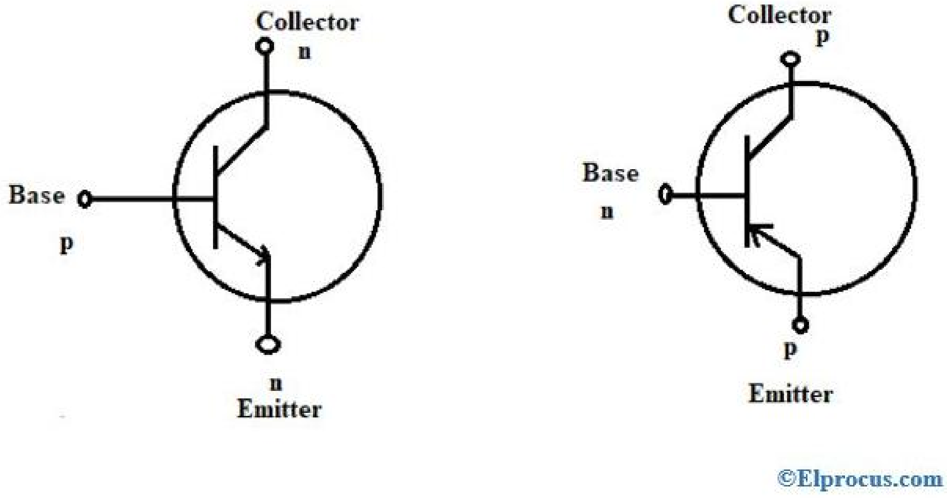
POWER TRANSISTOR

Transistors are three-terminal semiconductor electronic devices that can be used as switches or amplifiers. They can be of NPN or PNP polarity, and many different types are available with different power and switching speed ratings.

The three transistor terminals are known as base, emitter and collector respectively. If a battery and light are connected in series across an NPN transistor's collector and emitter, the transistor will not pass current and the lamp won't light. However, if a voltage, typically of about 0.7 V, is applied across the base and emitter, a small current will flow between these terminals. This turns the transistor on, so the lamp will light.

If the base-emitter voltage is varied, for example if it is driven by an audio signal, the large current flowing from collector to emitter will vary accordingly; this is how the transistor can be used as an amplifier as well as a switch.

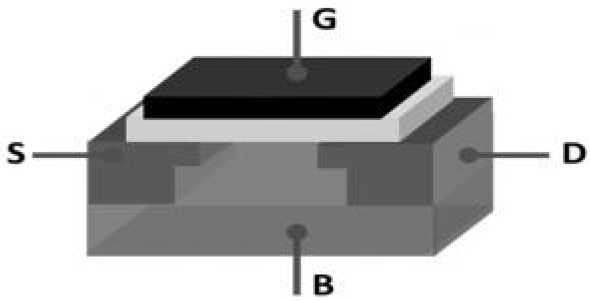
If a transistor designed to these concepts can handle more than 1 A of collector current, it is generally considered to be a power transistor. Such transistors must have low output resistance to deliver large load currents, and good junction insulation to resist high voltages. They must also dissipate heat very quickly to avoid overheating. The collector/base junction must be as large as possible, as most heat is generated in this area.



pnp-and-npn-transistor

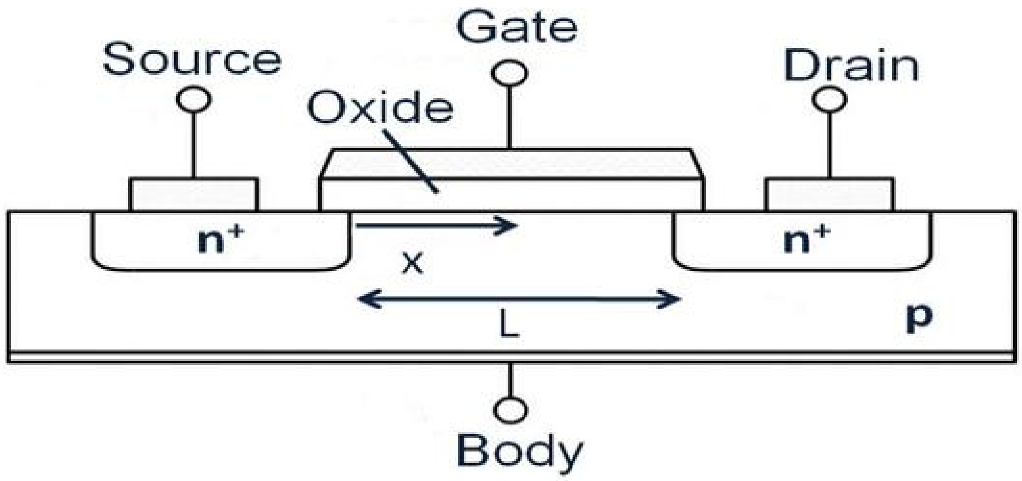
MOSFET

The MOSFET (Metal Oxide Semiconductor Field Effect Transistor) transistor is a semiconductor device that is widely used for switching purposes and for the amplification of electronic signals in electronic devices. A MOSFET is either a core or integrated circuit where it is designed and fabricated in a single chip because the device is available in very small sizes. The introduction of the MOSFET device has brought a change in the domain of switching in electronics. The MOSFET is a four-terminal device having source(S), gate (G), drain (D) and body (B) terminals. In general, The body of the MOSFET is in connection with the source terminal thus forming a three-terminal device such as a field-effect transistor. MOSFET is generally considered as a transistor and employed in both the analog and digital circuits. This is the basic introduction to MOSFET.



MOSFET

From the above **MOSFET structure**, the functionality of MOSFET depends on the electrical variations happening in the channel width along with the flow of carriers (either holes or electrons). The charge carriers enter into the channel through the source terminal and exit via the drain. The width of the channel is controlled by the voltage on an electrode which is called the gate and it is located in between the source and the drain. It is insulated from the channel near an extremely thin layer of metal oxide. The MOS capacity that exists in the device is the crucial section where the entire operation is across this.

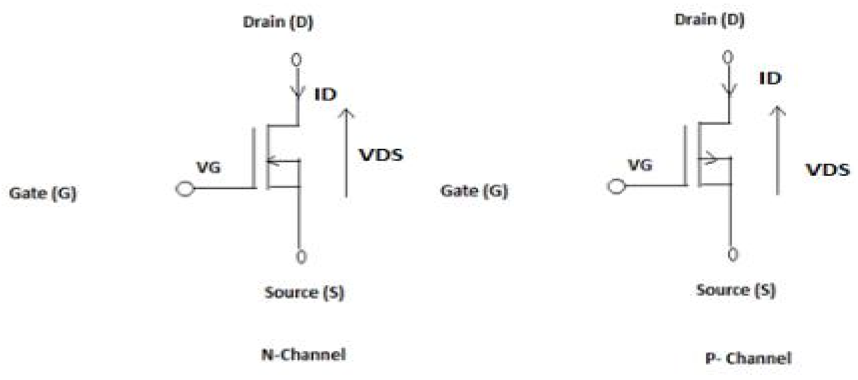


The MOSFET can function in two ways

- Depletion Mode
- Enhancement Mode

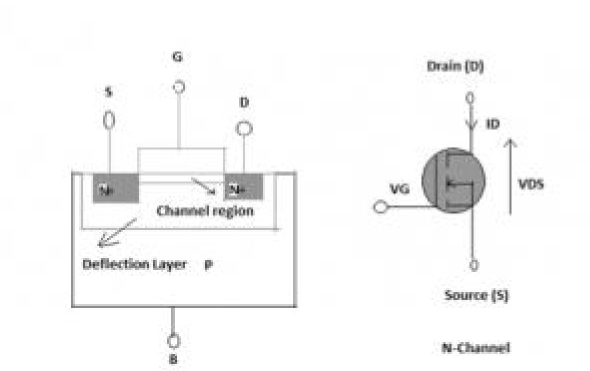
Depletion Mode:

When there is no voltage across the gate terminal, the channel shows its maximum conductance. Whereas when the voltage across the gate terminal is either positive or negative, then the channel conductivity decreases.



Enhancement mode:

When there is no voltage across the gate terminal, then the device does not conduct. When there is the maximum voltage across the gate terminal, then the device shows enhanced conductivity.



Enhancement Mode

The main principle of the MOSFET device is to be able to control the voltage and current flow between the source and drain terminals. It works almost like a switch and the functionality of the device is based on the MOS capacitor. The MOS capacitor is the main part of MOSFET. The semiconductor surface at the below oxide layer which is located between the source and drain terminal can be inverted from p-type to n-type by the application of either a positive or negative gate voltages respectively. When we apply a repulsive force for the positive gate voltage, then the holes present beneath the oxide layer are pushed downward with the substrate. The depletion region populated by the bound negative charges which are associated with the acceptor atoms. When electrons are reached, a channel is developed. The positive voltage also attracts electrons from the n+ source and drain regions into the channel. Now, if a voltage is applied between the drain and source, the current flows freely between the source and drain and the gate voltage controls the electrons in the channel. Instead of the positive voltage, if we apply a negative voltage, a hole channel will be formed under the oxide laye

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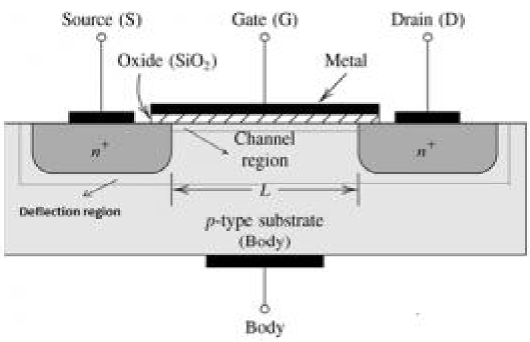
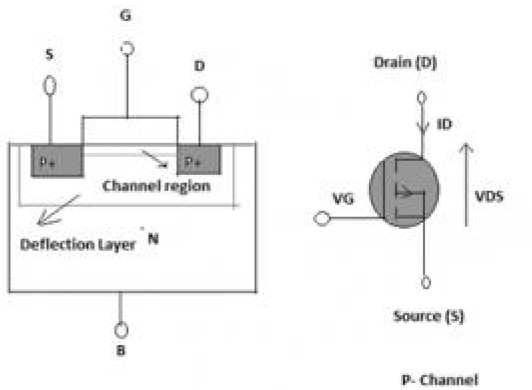


MOSFET Block Diagram

P-Channel MOSFET:

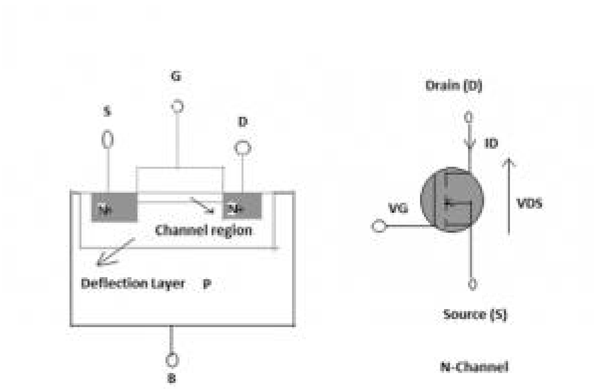
The P- channel MOSFET has a P- Channel region located in between the source and drain terminals. It is a four terminal device having the terminals as gate, drain, source, and body. The drain and source are heavily doped p+ region and the body or substrate is of n-type. The flow of current is in the direction of positively charged holes. When we apply the negative voltage with repulsive force at the gate terminal, then the electrons present under the oxide layer with are pushed downwards into the substrate. The depletion region populated by the bound positive charges which are associated with the donor atoms. The negative gate voltage also attracts holes from the p+ source and drain region into the channel region.



P Channel Enhanced Mode

N- Channel MOSFET:

The N-Channel MOSFET has an N- channel region located in between the source and drain terminals. It is a four-terminal device having the terminals as gate, drain, source, body. In this type of MOSFET, the drain and source are heavily doped n+ region and the substrate or body are of P- type. The current flow in this type of MOSFET happens because of negatively charged electrons. When we apply the positive voltage with repulsive force at the gate terminal then the holes present under the oxide layer are pushed downward into the substrate. The depletion region is populated by the bound negative charges which are associated with the acceptor atoms. Upon the reach of electrons, the channel is formed. The positive voltage also attracts electrons from the n+ source and drain regions into the channel. Now, if a voltage is applied between the drain and source the current flows freely between the source and drain and the gate voltage controls the electrons in the channel. Instead of positive voltage if we apply negative voltage then a hole channel will be formed under the oxide layer.



Enhancement Mode N Channel

MOSFET Regions of Operation

To the most general scenario, the operation of this device happens mainly in three regions and those are as follows:

- Cut-off Region – It is the region where the device will be in the OFF condition and there zero amount of current flow through it. Here, MOSFET functions as a basic switch and is so employed as when they are necessary to operate as electrical switches.
- Saturation Region – In this region, the devices will have their drain to source current value as constant without considering the enhancement in the voltage across the drain to source. This happens only once when the voltage across the drain to source terminal increases more than the pinch-off voltage value. In this scenario, the device functions as a closed switch where a saturated level of current across the drain to source terminals flows. Due to this, the saturation region is selected when the devices are supposed to perform switching.
- Linear/Ohmic Region – It is the region where the current across the drain to source terminal enhances with the increment in the voltage across the drain to source path. When the MOSFET devices function in this linear region, they perform amplifier functionality.

Let us now consider the switching characteristics of MOSFET

A semiconductor too such as MOSFET or Bipolar Junction Transistor are basically functioned as switches in two scenarios one is ON state and the other is OFF state. To consider this functionality, let us have a look at the ideal and practical characteristics of the MOSFET device.

Ideal Switch Characteristics

When a MOSFET is supposed to function as ideal switch, it should hold the below properties and those are

- In the ON condition, there has to be the current limitation that it carries
- In the OFF condition, blocking voltage levels should not hold any kind of limitations
- When the device functions in ON state, the voltage drop value should be null
- The resistance in OFF state should be infinite
- There should be no restrictions on the speed of operation

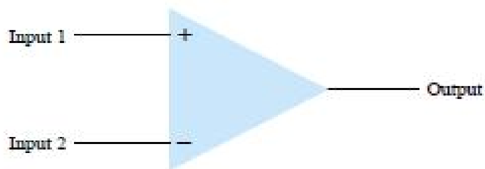
Practical Switch Characteristics

As the world is not just stuck to ideal applications, the functioning of MOSFET is even applicable for practical purposes. In the practical scenario, the device should hold the below properties

- In the ON condition, the power managing abilities should be limited which means that the flow of conduction current has to be restricted.
- In the OFF state, blocking voltage levels should not be limited
- Turning ON and OFF for finite times restricts the limiting speed of the device and even limits the functional frequency
- In the ON condition of the MOSFET device, there will be minimal resistance values where this results in the voltage drop in forwarding bias. Also, there exists finite OFF state resistance that delivers reverse leakage current
- When the device is performing in practical characteristics, it loses power on ON and OFF conditions. This happens even in the transition states too.

OP-AMPS

An operational amplifier, or op-amp, is a very high gain differential amplifier with high input impedance and low output impedance. Typical uses of the operational amplifier are to provide voltage amplitude changes (amplitude and polarity), oscillators, filter circuits, and many types of instrumentation circuits. An op-amp contains a number of differential amplifier stages to achieve a very high voltage gain.

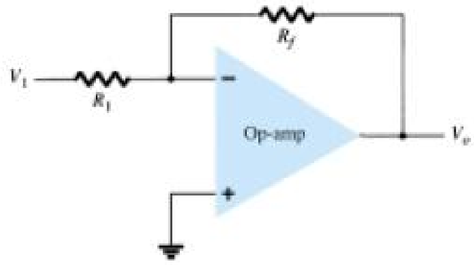


The figure shows a basic op-amp with two inputs and one output as would result using a differential amplifier input stage. The plus i/p is non-inverting i/p while the minus i/p is the inverting i/p. The signal appeared to the plus i/p will appeared in the same phase at the o/p but the signal to the minus i/p will be shifted in phase by 180° at the o/p. IC 741 is popular op. amp. used in many circuits.

Characteristics of an Op. Amp.

An ideal operational amplifier has the following important characteristics which do not drift with temperature:

1. Input resistance = ∞
2. Output resistance = 0
3. Bandwidth = ∞
4. Voltage gain = -∞
5. Vout = 0 when V1 = V2 ; independent of the magnitude of V1



Operations of Op. Amp.

The basic circuit connection using an op-amp is shown in the figure. The circuit shown provides operation as a constant-gain multiplier. An input signal, *V*1, is applied through resistor *R*1 to the minus input. The output is then connected back to the same minus input through resistor *Rf*. The plus input is connected to ground. Since the signal *V*1 is essentially applied to the minus input, the resulting output is opposite in phase to the input signal.

$$\text{voltage gain} = -\frac{R_f}{R_1} = -1$$

Unity Gain

If *Rf*=*R*1, the gain is so that the circuit provides a unity voltage gain with 180° phase inversion. If *Rf*is exactly*R*1, the voltage gain is exactly 1.

$$\text{voltage gain} = -\frac{R_f}{R_1} = -10$$

Constant Magnitude Gain

If *Rf*is some multiple of *R*1, the overall amplifier gain is a constant. For example, if *Rf*= 10*R*1, then and the circuit provides a voltage gain of exactly 10 along with an 180° phase inversion from the input signal. If we select precise resistor values for *Rf*and *R*1, we can obtain a wide range of gains, the gain being as accurate as the resistors used and is only slightly affected by temperature and other circuit factors.

Virtual Ground

Using the virtual ground concept, we can write equations for the current *I* as follows:

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

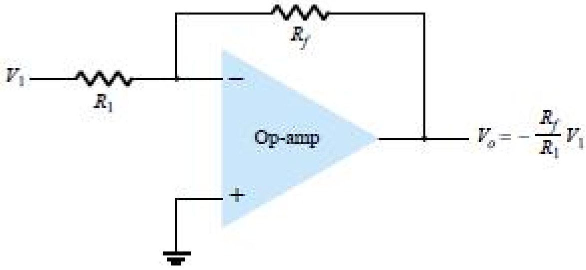
which can be solved for *Vo* /*V*1:

$$\frac{V_o}{V_1} = -\frac{R_f}{R_1}$$ **----------------------- eqn. 1**

Where Rf/R1 is the constant gain factor

PRACTICAL APPLICATIONS OF OP-AMP CIRCUITS

Inverting Amplifier



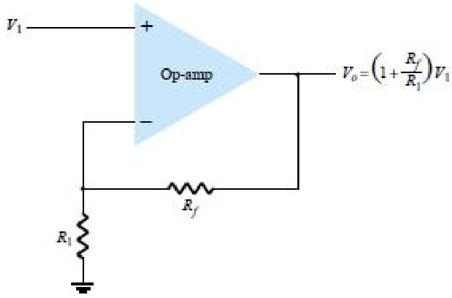
The most widely used constant-gain amplifier circuit is the inverting amplifier, as shown in the fig. It is more widely used because it has better frequency stability. The output is obtained by multiplying the input by a fixed or constant gain, set by the input resistor (*R*1) and feedback resistor (*Rf*)—this output also being inverted from the input Using Eqn. 1, we can write output voltage as

$$V_o = -\frac{R_f}{R_1} V_1$$ **----------------------- eqn. 2**

The negative sign indicates that the sign of the o/p is inverted in comparison to the input.

The gain is calculated as: **G = Rf/R1 --------eqn. 3**

Noninverting Amplifier

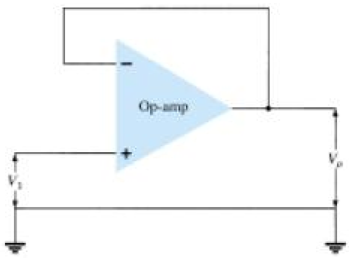


The noninverting amp.is given by the fig. The input V1 is connected to the plus input. So we can solve for the gain

$$\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$ **------------eqn. 4**

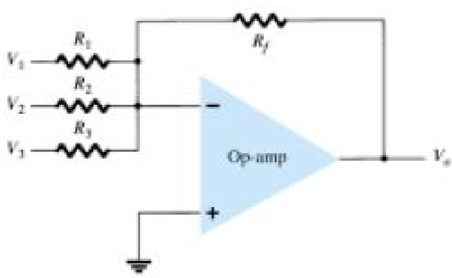
And the output voltage is $V_o = \left(1 + \frac{R_f}{R_1}\right) V_1$ **------------eqn. 5**

Unity Follower



The unity-follower circuit, as shown in Fig. 14.17a, provides a gain of unity (1) with no polarity or phase reversal. From the circuit it is clear that *Vo* = *V*1 and that the output is the same polarity and magnitude as the input

Summing Amplifier

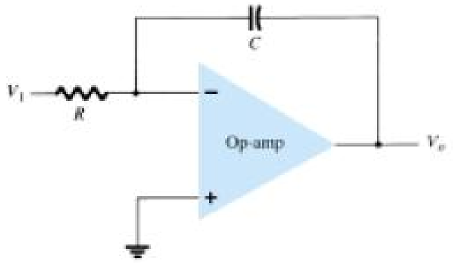


Probably the most used of the op-amp circuits is the summing amplifier circuit shown in the figure. The circuit shows a three-input summing amplifier circuit, which provides a means of algebraically summing (adding) three voltages, each multiplied by a constant-gain factor. The output voltage can be expressed in terms of the inputs as

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

In other words, each input adds a voltage to the output multiplied by its separate constant-gain multiplier. If more inputs are used, they each add an additional component to the output.

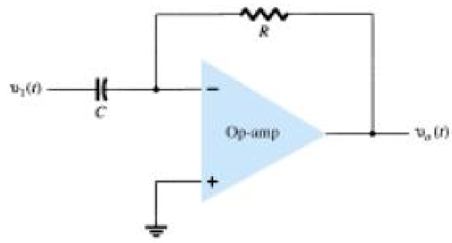
Integrator



So far, the input and feedback components have been resistors. If the feedback component used is a capacitor, as shown in the fig., the resulting connection is called an *integrator.* The output voltage becomes proportional to the integral of the input signal.

$$v_o(t) = -\frac{1}{RC}\int v_1(t)\,dt$$

Differentiator



If the resistor R and capacitor C are interchange from the integrator ckt, as shown in the fig. it becomes a differentiator which gives tie derivatives of the i/p signal.

$$v_o(t) = -RC\frac{dv_1(t)}{dt}$$

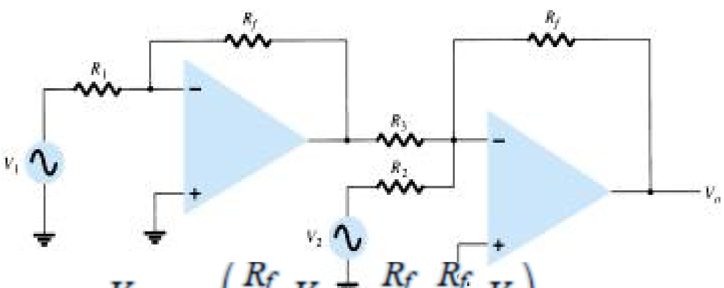
If the i/p signal V1=sinωt, we get

$$Vo = -RC\frac{d(\sin\omega t)}{dt} = -RC\omega\cos\omega t$$

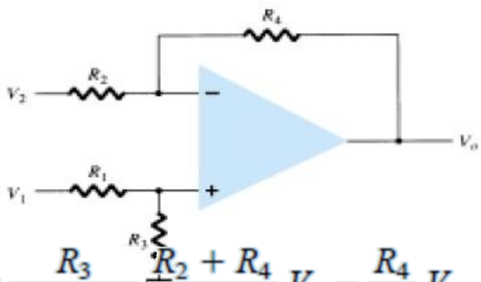
The equation suggests that the magnitude of the o/p voltage increases linearly with increasing freq. and hence the differentiator has high gain at higher frequency.

Subtracting Amplifier

Two signals can be subtracted, one from the other, in a number of ways. The figure shows two op-amp stages used to provide subtraction of input signals. The resulting output is given by:



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

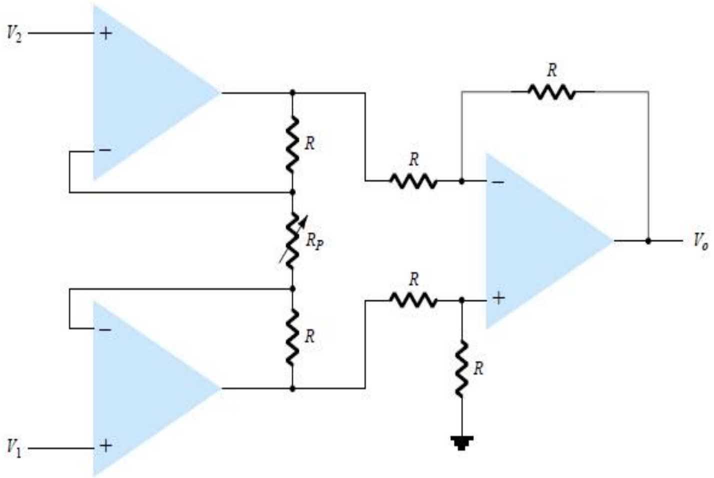


$$V_o = \frac{R_3}{R_1 + R_3}\frac{R_2 + R_4}{R_2}V_1 - \frac{R_4}{R_2}V_2$$

Instrumentation Amplifier

A general purpose instrumentation amplifier is one which work from a variety of sources and drive a variety of o/p equipment. To be able to do this, it must have the following properties:

a. A differential input
b. A single-ended output
c. A high input impedance
d. A simple means for adjusting the gain
e. High CMRR



A circuit providing an output based on the difference between two inputs (times ascale factor) is shown in Fig. A potentiometer is provided to permit adjustingthe scale factor of the circuit. While three op-amps are used, a single-quad op-amp ICis all that is necessary (other than the resistor components). The output voltage can beshown to be

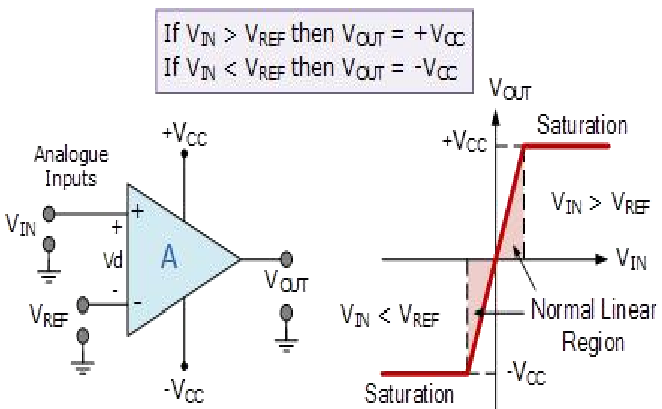
$$V_o = \left(1 + \frac{2R}{R_P}\right)(V_1 - V_2) = k(V_1 - V_2)$$

Now lets us check how this ckt. meets the five requirements

1. Since it has differential inputs
2. o/p is single ended
3. since there is no resistor on either i/p terminal to shunt, so high i/p impedance of op.amp.
4. from eqn 6, by using a single resistor r, we can adjust the gain
5. CMRR is the ratio of the gain for in-phase signal to the out-of phase signals. It should be high for a good instrumentation amp.

COMPARATOR

The comparator is an electronic decision making circuit that makes use of an operational amplifiers very high gain in its open-loop state, that is, there is no feedback resistor.



With reference to the op-amp comparator circuit above, lets first assume that V_{IN} is less than the DC voltage level at V_{REF}, ($V_{IN} < V_{REF}$). As the non-inverting (positive) input of the comparator is less than the inverting (negative) input, the output will be LOW and at the negative supply voltage, -Vcc resulting in a negative saturation of the output.

If we now increase the input voltage, V_{IN} so that its value is greater than the reference voltage V_{REF} on the inverting input, the output voltage rapidly switches HIGH towards the positive supply voltage, +Vcc resulting in a positive saturation of the output. If we reduce again the input voltage V_{IN}, so that it is slightly less than the reference voltage, the op-amp's output switches back to its negative saturation voltage acting as a threshold detector.

Then we can see that the op-amp voltage comparator is a device whose output is dependant on the value of the input voltage, V_{IN} with respect to some DC voltage level as the output is HIGH when the voltage on the non-inverting input is greater than the voltage on the inverting input, and LOW when the non-inverting input is less than the inverting input voltage. This condition is true regardless of whether the input signal is connected to the inverting or the non-inverting input of the comparator.

We can also see that the value of the output voltage is completely dependent on the op-amps power supply voltage. In theory due to the op-amps high open-loop gain the magnitude of its output voltage could be infinite in both directions, ($\pm\infty$). However practically, and for obvious reasons it is limited by the op-amps supply rails giving V_{OUT} = +Vcc or V_{OUT} = -Vcc.

IGBT- INSULATED GATEBIPOLAR TRANSISTOR

The **Insulated Gate Bipolar Transistor** also called an **IGBT** for short, is something of a cross between a conventional Bipolar Junction Transistor, (BJT) and a Field Effect Transistor, (MOSFET) making it ideal as a semiconductor switching device.

The IGBT Transistor takes the best parts of these two types of common transistors, the high input impedance and high switching speeds of a MOSFET with the low saturation voltage of a bipolar transistor, and combines them together to produce another type of transistor switching device that is capable of handling large collector-emitter currents with virtually zero gate current drive.

Typical IGBT

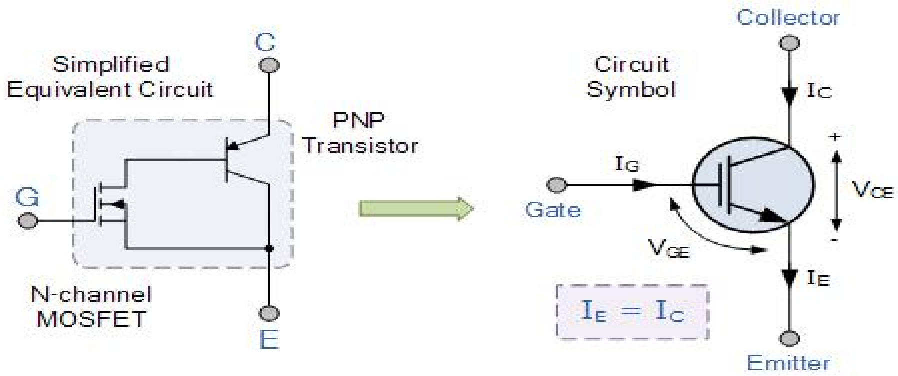
The Insulated Gate Bipolar Transistor, (IGBT) combines the insulated gate (hence the first part of its name) technology of the MOSFET with the output performance characteristics of a conventional bipolar transistor, (hence the second part of its name).

The result of this hybrid combination is that the "IGBT Transistor" has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET.

GBTs are mainly used in power electronics applications, such as inverters, converters and power supplies, were the demands of the solid state switching device are not fully met by power bipolars and power MOSFETs. High-current and high-voltage bipolars are available, but their switching speeds are slow, while power MOSFETs may have higher switching speeds, but high-voltage and high-current devices are expensive and hard to achieve.

The advantage gained by the insulated gate bipolar transistor device over a BJT or MOSFET is that it offers greater power gain than the standard bipolar type transistor combined with the higher voltage operation and lower input losses of the MOSFET. In effect it is an FET integrated with a bipolar transistor in a form of Darlington type configuration as shown.

Insulated Gate Bipolar Transistor



We can see that the insulated gate bipolar transistor is a three terminal, transconductance device that combines an insulated gate N-channel MOSFET input with a PNP bipolar transistor output connected in a type of Darlington configuration.

As a result the terminals are labelled as: **Collector**, **Emitter** and **Gate**. Two of its terminals (C-E) are associated with the conductance path which passes current, while its third terminal (G) controls the device.

The amount of amplification achieved by the insulated gate bipolar transistor is a ratio between its output signal and its input signal. For a conventional bipolar junction transistor, (BJT) the amount of gain is approximately equal to the ratio of the output current to the input current, called Beta.

For a metal oxide semiconductor field effect transistor or MOSFET, there is no input current as the gate is isolated from the main current carrying channel. Therefore, an FET's gain is equal to the ratio of output current change to input voltage change, making it a transconductance device and this is also true of the IGBT. Then we can treat the IGBT as a power BJT whose base current is provided by a MOSFET.

The **Insulated Gate Bipolar Transistor** can be used in small signal amplifier circuits in much the same way as the BJT or MOSFET type transistors. But
∠Ⓢ ⇗↗○ IGBT ▱□Ⓜ⊥≟∅○Ⓢ ⇗↗○ Ⓛ□✓
conduction loss of a BJT with the high switching speed of a power MOSFET an

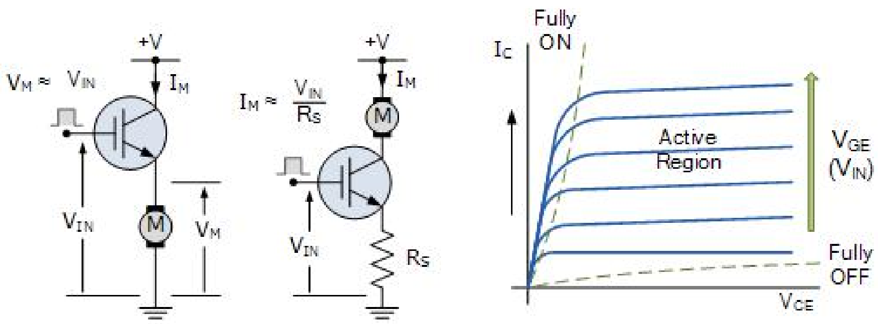
optimal solid state switch exists which is ideal for use in power electronics applications.

Also, the IGBT has a much lower “on-state” resistance, RON than an equivalent MOSFET. This means that the I2R drop across the bipolar output structure for a given switching current is much lower. The forward blocking operation of the IGBT transistor is identical to a power MOSFET.

When used as static controlled switch, the insulated gate bipolar transistor has voltage and current ratings similar to that of the bipolar transistor. However, the presence of an isolated gate in an IGBT makes it a lot simpler to drive than the BJT as much less drive power is needed.

An insulated gate bipolar transistor is simply turned “ON” or “OFF” by activating and deactivating its Gate terminal. Applying a positive input voltage signal across the Gate and the Emitter will keep the device in its “ON” state, while making the input gate signal zero or slightly negative will cause it to turn “OFF” in much the same way as a bipolar transistor or eMOSFET. Another advantage of the IGBT is that it has a much lower on-state channel resistance than a standard MOSFET.

IGBT Characteristics



Because the IGBT is a voltage-controlled device, it only requires a small voltage on the Gate to maintain conduction through the device unlike BJT’s which require that the Base current is continuously supplied in a sufficient enough quantity to maintain saturation.

Also the IGBT is a unidirectional device, meaning it can only switch current in the “forward direction”, that is from Collector to Emitter unlike MOSFET’s which have bi-directional current switching capabilities (controlled in the forward direction and uncontrolled in the reverse direction).

The principal of operation and Gate drive circuits for the insulated gate bipolar transistor are very similar to that of the N-channel power MOSFET. The basic difference is that the resistance offered by the main conducting channel when current flows through the device in its “ON” state is very much smaller in the IGBT. Because of this, the current ratings are much higher when compared with an equivalent power MOSFET.

The main advantages of using the **Insulated Gate Bipolar Transistor** over other types of transistor devices are its high voltage capability, low ON-resistance, ease of drive, relatively fast switching speeds and combined with zero gate drive current makes it a good choice for moderate speed, high voltage applications such as in pulse-width modulated (PWM), variable speed control, switch-mode power supplies or solar powered DC-AC inverter and frequency converter applications operating in the hundreds of kilohertz range.

A general comparison between BJT's, MOSFET's and IGBT's is given in the following table.

IGBT Comparison Table

Device Characteristic	Power Bipolar	Power MOSFET	IGBT
Voltage Rating	High <1kV	High <1kV	Very High >1kV
Current Rating	High <500A	Low <200A	High >500A
Input Drive	Current, h_{FE} 20-200	Voltage, V_{GS} 3-10V	Voltage, V_{GE} 4-8V
Input Impedance	Low	High	High
Output Impedance	Low	Medium	Low
Switching Speed	Slow (uS)	Fast (nS)	Medium
Cost	Low	Medium	High

We have seen that the **Insulated Gate Bipolar Transistor** is semiconductor switching device that has the output characteristics of a bipolar junction transistor, BJT, but is controlled like a metal oxide field effect transistor, MOSFET.

One of the main advantages of the IGBT transistor is the simplicity by which it can be driven “ON” by applying a positive gate voltage, or switched “OFF” by making the gate signal zero or slightly negative allowing it to be used in a variety of switching applications. It can also be driven in its linear active region for use in power amplifiers.

With its lower on-state resistance and conduction losses as well as its ability to switch high voltages at high frequencies without damage makes the **Insulated Gate Bipolar Transistor** ideal for driving inductive loads such as coil windings, electromagnets and DC motors.