POWER ELECTRONICS

Introduction:

Power electronics is important branch of electrical (power) and electronics engineering. Electrical engineering deals with generation, transmission, distribution and utilization of electric energy at high efficiency. Electronics engineering deals with conversion and control of electrical energy.

Definition: Power electronics is the applications of solid-state electronics for the control and conversion of electrical power.

The electrical energy in one form is given at the input. The power electronics system converts the electrical energy in the other form.

Example:

Rectifier converts AC electrical energy into DC electrical energy. In this conversion Rectifier is a power electronic system, so the power electronic system performs conversion of electrical energy and also controls the amount of output electrical energy.

Applications:

- Aerospace.
- Commercial.
- Industrial.
- Residential.
- Telecommunication.

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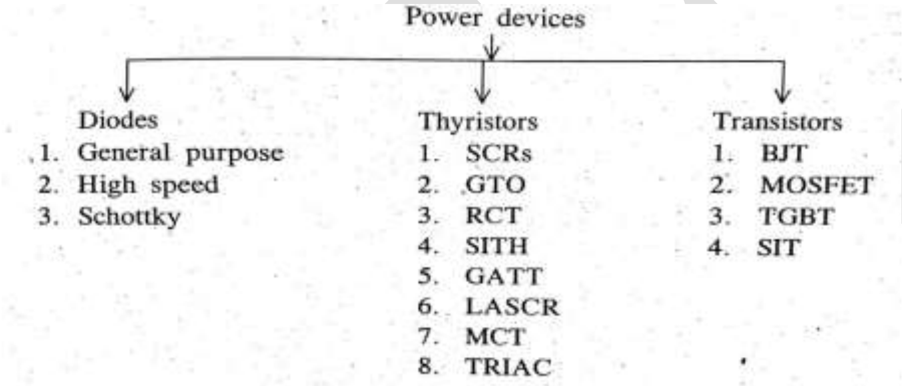
UNIT 1
POWER SEMICONDUCTOR DEVICES

Semiconductor is a material, that is neither a good conductor nor a good insulator, but that conducts more electricity when heat, light or voltage is added.

- Solid crystalline substances such as germanium or silicon having electrical conductivity greater than insulators but less than good conductors.
- Power semiconductor devices are used as ON/OFF switches in power control circuit.
- Power semiconductor devices are classified into three types, they are
    1. Power diodes.
    2. Power thyristors.
    3. Power transistors.

Power semiconductor devices are further classified as follows:



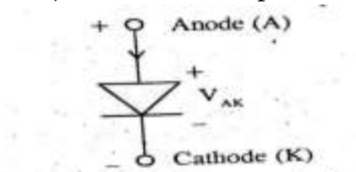
SCR: Silicon controlled rectifier.
GTO: Gate turn off thyristor.
RCT: Reverse conducting thyristor.
SITH: Static induction thyristor.
GATT: Gate assisted turn off thyristor.
LASCR: Light activated silicon-controlled rectifier.
MCT: MOS controlled thyristor.
TRIAC: Triode for alternating current.
BJT: Bipolar junction transistor.
MOSFET: Metal oxide semiconductor field effect transistor.
IGBT: Insulated gate bipolar transistor.
SIT: Static induction transistor.

POWER DIODE:

Diode: Diode is a two terminal electronic component that only conducts current in one direction.
Diodes are mainly classified into two types depending upon power, they are

1. **Signal diode:** Signal diode is a low power p-n junction uncontrolled device.
2. **Power diode:** Power diode is a high power p-n junction uncontrolled device.

Power diodes are required (Needful) in most of the power converters.

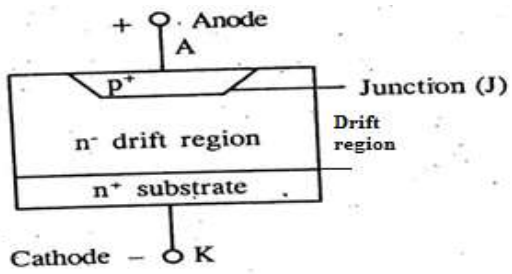


Symbol of power diode

When anode (A) is positive with respect to the cathode (K), diode starts conducting. Normally a forward bias of 1Volt is sufficient to make the diode to conduct and current starts flows from anode to cathode.

The Diode does not conduct when cathode voltage is greater than the anode voltage, then the diode is said to be reverse bias or blocking mode.

Structure:



In the above figure, n^+ substrate is heavily doped and the doping level should be about $10^{19}/cm^3$, this acts as a cathode of the diode.

A lightly doped n^- layer is called as drift region, the doping level of n^- layer is about $10^{14}/cm^3$.

The Pn junction is forward by diffusing a heavily doped P^+ region. This P^+ region forms anode of the diode.

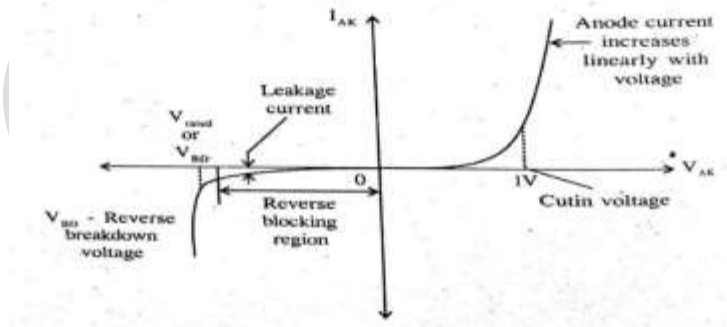
The thickness of n^- drift layer depends upon the breakdown voltage of the diode. For higher breakdown voltage the drift region is wide. The n^- drift region is absent in low power signal diode.

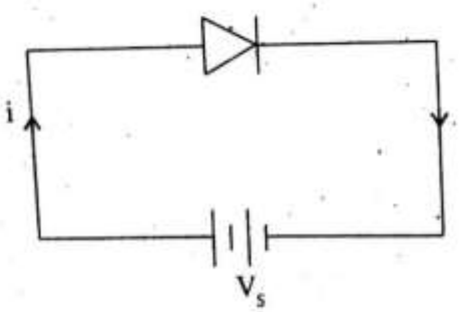
Conductivity modulation:

When the diode is forward biased, the holes will be injected from the P^+ region into the drift region. Some of the holes combine with the electrons in the drift region.

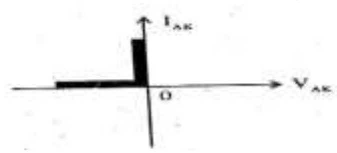
The injected holes are more, they attract electrons from the n^+ layer. Hence resistance of the drift region reduces significantly (considerable). Thus, diode current goes on increasing, but drift region resistance remains almost constant.

V-I characteristics:





- When anode of diode is positive with respect to cathode, diode is said to be forward biased, increases of source voltage V_s from zero value, initially diode current is zero, from $V_s = 0$ to cut in voltage, the forward current is very small. Beyond cut in voltage anode current increases linearly with voltages because of ohmic resistance present in the n^- layer. A forward bias of 0.8 to 1Volt is sufficient to trigger diode into conduction. Cut in voltage is also known as threshold voltage or turn ON voltage.
- When the cathode potential is positive with respect to the anode, the diode is said to be reverse bias under reverse biased condition. A small reverse current (leakage current) increases rapidly. Hence large power dissipation (power losses) takes place in the diode and it is damaged. Therefore, power diode must be operated below V_{BD} (Reverse breakdown voltage).
- The ideal characteristics of power diode is shown in below figure.



Types of Power Diodes:

Power Diodes are classified in to three types depending upon their reverse recovery characteristics.

1) **General Purpose Diodes:**

These diodes have high reverse recovery time (The time taken by a diode to switch from forward biased (ON) condition to OFF state) of about 25μsec. Hence this diode is used in low speed applications such as rectifiers and converters.

General purpose diodes operate up to 1 KHz & their ratings are from 1A/50V to 1000A/5000V.

Applications:

- Battery charging.
- UPS.
- Electroplating
- Electric traction
- Welding.

2) **Fast recovery Diodes:**

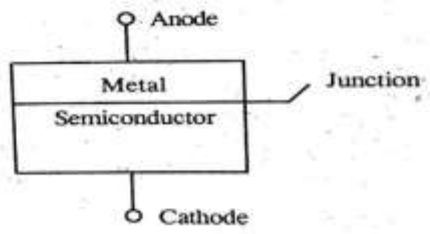
These diodes have less reverse recovery time of about less than 5μsec. Hence these diodes are used in high speed applications such as choppers and inverters.

Fast recovery diodes have rating from 1A/50V to 100A/3KV.

Applications:

- Choppers.
- SMPS (switch mode power supply).
- Induction heating.
- Commutation circuits.

3) **Schottky Diodes:**



Schottky diodes have metal to semiconductor junction for rectification purpose, instead of p-n junction.

- A thin metal is placed directly on the semiconductor as shown in the above figure. The metal is anode and semiconductor is cathode. Metal is made up of aluminium & semiconductor is made up of silicon.
- No Pn junction in the schottky diode, the storage time is absent hence turn off time is very small, hence schottky diodes have high switching frequencies.
- Schottky diodes Breakdown voltage rating is less than 100V and forward current ratings vary from 1A to 300A.

Applications:

- Low voltage converters.
- Freewheeling diodes.
- Switching power supply.
- High frequency instrumentation.

Applications of Power Diodes:

- Power Diodes are used in uncontrolled rectifiers.
- Power diodes are used in Feedback and freewheeling operations in choppers, inverters and controlled converters.
- Used in half controlled converters and half bridge inverters.
- Used in commutating (Turn-off) circuits for SCR's.

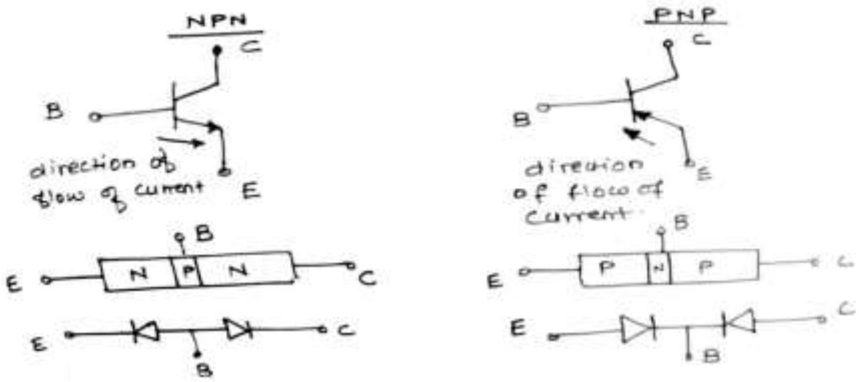
POWER TRANSISTORS:

Power transistors are three terminal semiconductor electronic device that can be used as amplifier, switches for electronic signals & electrical power.

- Power transistors is a controlled device, power transistors are turned ON when a suitable current signal is applied to base or control terminal.
- The transistor remains in the ON state as long as control signal is present. Once the control signal is removed the power transistor gets turned OFF.
- Power transistors are mainly classified into four types, they are
  i. BJT (Bipolar junction transistor)
  ii. MOSFET (Metal oxide semiconductor field effect transistor)
  iii. IGBT (Insulated gate bipolar transistor)
  iv. SIT (Static induction transistor)

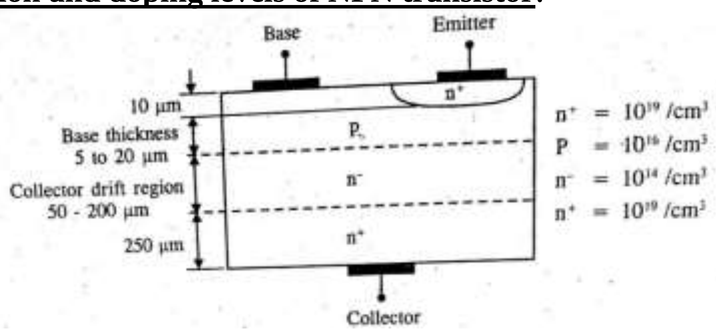
BJT:

- Bipolar junction transistor is a current controlled device & it requires large gate current to turn ON the device.
- BJT is solid state device, in which the current flow between two terminals (collector & emitter) is controlled by the amount of current that flows through a third terminal (Base).
- Bipolar junction transistor is a three terminal (Emitter (E), Base (B), collector (C)), three layer (PNP or NPN), and two junction semiconductor device.
- Bipolar junction transistor uses both electrons and holes as charge carriers. The term Bipolar denotes that the current flow in the device is due to the movement of both holes and electrons.
- Bipolar junction transistor blocks high voltage in the OFF state and has high current carrying capacity in the ON state.
- BJT are available both in NPN and PNP format but NPN transistor having high current and voltage operating ratings, so NPN transistor is used in large applications.
- BJT operated in three configurations, common base, common emitter & common collector.
- Circuit Symbol of NPN and PNP BJT is shown in below figure.



- When a transistor is used as a switch to control power from the source to the load.
- Terminals Collector & Emitter are connected in series with the main power circuit and terminals Base & Emitter are connected to a driving circuit that controls the ON and OFF of the circuit.

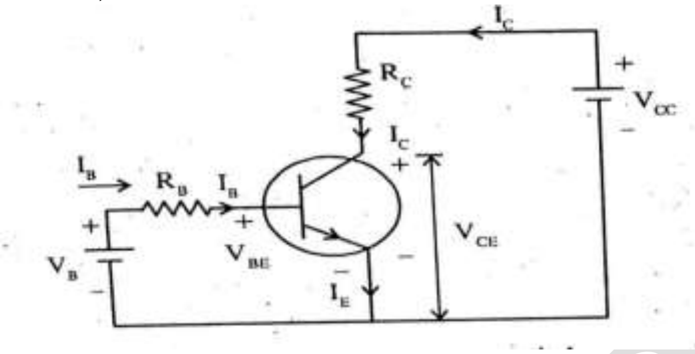
Schematic Construction and doping levels of NPN transistor.



- The emitter is heavily doped n^+ with doping level $10^{19}/cm^3$.
- Base is doped P with $10^{16}/cm^3$. The collector is split in to two regions, the n^- region is called drift region and has light doping level of $10^{14}/cm^3$. The width of this layer decides the breakdown voltage of power transistor. The n^+ region doping same as emitter.

Operation of NPN transistor:

Below figures shows the circuit diagram (common emitter), steady state V-I characteristics (I_C verses V_{CE}) of the NPN transistor.



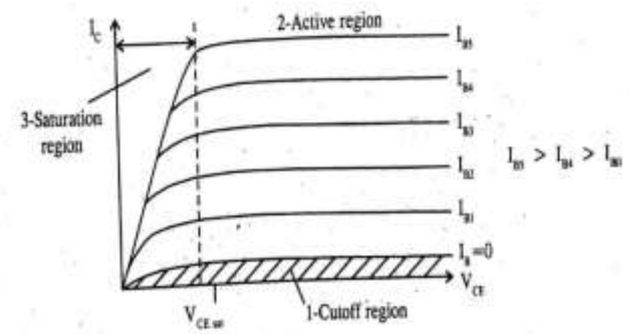


fig: Transistor switching circuit **fig: Steady state V-I characteristics (output char)**

- From the circuit diagram, total current equation is $I_E = I_C + I_B$………………(1)
- The base current is the input current & collector current is the output current. The ratio of collector current (I_C) to base current (I_B) is forward current gain (β)

$$\beta = I_C / I_B \text{……………….(2)}$$

- Collector current has two components $I_C = \beta I_B + I_{CE0}$………………………...(3)
  Where, I_{CE0} is collector to emitter leakage current with base open circuit & is negligibly small.
- The transistor is operated in cut-off region, saturation region & active region.

Cut-off region: (E>B<C)

When base current I_B is zero, both the junction's emitter-base junction & collector-base junctions are reverse biased, then the transistor is in off state (cut-off condition of power transistor). $I_B=0$ & I_C is negligibly small, only small leakage current flows.

$$V_{CE} = V_{CC} - I_C R_C \text{…………..(4)} \quad \text{[from Kirchhoff's voltage law]}$$

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

Active region: (E<B<C)

Base emitter junction is forward bias, while collector base junction is reverse bias. Then the active region is used for amplification and is avoid the switching application.

$$I_E = I_C + I_B$$

Saturation region: (E<B>C)

When emitter-base junction is forward biased & collector-base junction is also forward biased, then the transistor is in ON state or saturation region.

When the base current I_B is increased, collector current I_C increases & V_{CE} decreases.

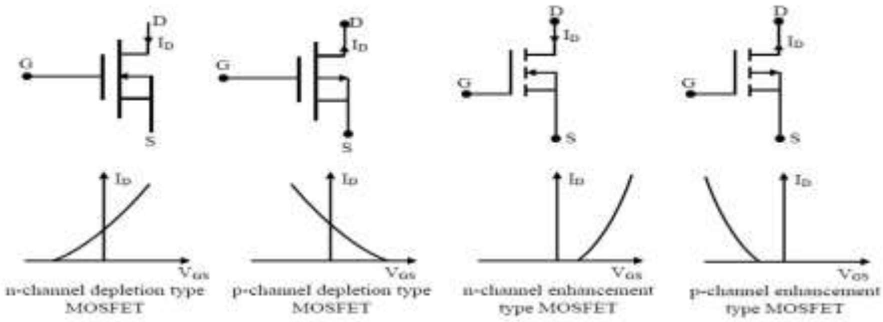
Region	Emitter Base Junction	Collector Base Junction	State
Cutoff	Reverse bias	Reverse bias	Transistor is OFF
Active	Forward bias	Reverse bias	Transistor is amplifier
Saturation	Forward bias	Forward bias	Transistor is ON

Applications of power BJT:

- Signal processing.
- Static switches in power electronic converters and choppers.
- Switch mode power supply.
- Used in low and medium power applications because voltage and current ratings are lower than the thyristors.

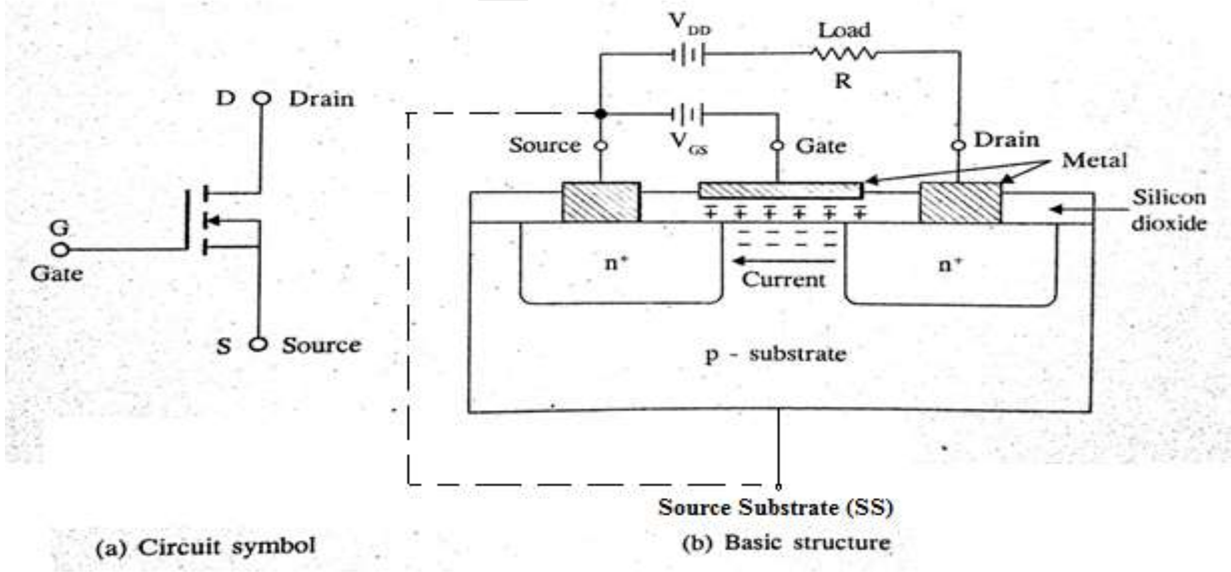
MOSFET:

- Power MOSFET is a voltage controlled device & it requires small input gate current to turn ON the device.
- MOSFET is a voltage-controlled majority carrier device. As the name suggests, movement of majority carriers in a MOSFET is controlled by the voltage applied on the control electrode (called gate) which is insulated by a thin metal oxide layer (dielectric) from the bulk semiconductor body.
- MOSFET has three terminals device with Drain (D), Source (S), and Gate (G). Drain and source are power terminals of the switch and the gate is control terminal.
- Power MOSFET is unipolar device, because operation depends only on flow of majority carriers & switching speed is very high (nano seconds).
- MOSFET is widely used for switching and amplifying electronic signals in electronic devices.
- The gate voltage controls the conductivity of the main current carrying terminals (Drain and Source).
- Power MOSFET can be classified in to two types, they are (i) Depletion type and (ii) Enhancement type. Both of these can be either **n-** channel type or **p**-channel type depending on the nature of the bulk semiconductor. Below Fig shows the circuit symbol of four types of MOSFETs along with their drain current v/s gate-source voltage characteristics (transfer characteristics).



- Above figure concluded that Depletion type MOSFETs are normally ON type switches i.e, Depletion MOSFET remains ON at zero gate voltage it is normally called ON MOSFET. This is not convenient in many power electronic applications. Therefore, the Enhancement type MOSFETs (particularly of the n-channel variety) is more popular for power electronics applications.
- Power MOSFET is turned ON by applying drain to source voltage and small current across the gate terminal.
- The MOSFET can be turned OFF by removing the gate to source voltage.

N-Channel Enhancement Power MOSFET:



- Power MOSFET is a voltage controlled device.

Construction:

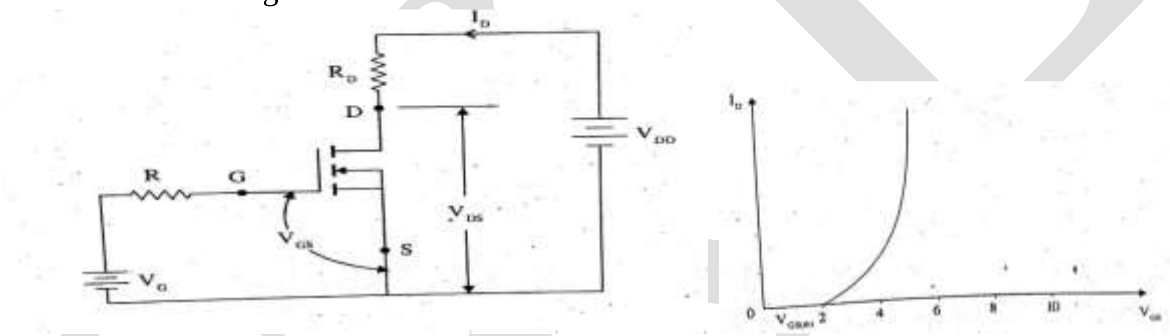
- A simplified structure of N-channel enhancement MOSFET is shown in above fig (b) and symbol in fig (a).
- In N-channel enhancement MOSFET a lightly doped p-type substrate forms the body of the device and source and drain regions are heavily doped with n-type impurities. An insulating layer of silicon dioxide (Sio_2) is placed on the surface.
- n^+ regions makes contact with source and drain terminals through insulating layer and layer of metal.
- A layer of metal is also deposited on Sio_2 to form gate terminal.

Working:

- When gate circuit is open, junction between n^+ region and p-substrate is reverse biased by input voltage V_{DD}. So, no current flows from drain to source and load.
- When gate is made +ve with respect to source, an electric field is established as shown in figure (b). It induces –ve charges in p-substrate below Sio_2 layer and forms electron channel called induced n-channel between two n^+ regions and current can flow from drain to source as shown by the arrow.
- If V_{GS} made more +ve, more current flows from drain to source.
- The drain current I_D is enhanced (increase) by gradual increases of gate voltage hence it is called as n-channel enhancement MOSFET.

Transfer (V-I) characteristics of MOSFET:

- The basic circuit diagram & transfer characteristics of n-channel MOSFET is shown in below fig.



- Power MOSFET is operated in two state, they are OFF state and ON state.

Off state:

If the drain terminal is made positive with respect to the source without gate voltage. NO current can flow from the drain to the source because the junction between n^+ and p region is reverse bias.

On state:

A positive voltage applied to the gate with respect to the source, it's creates an electric field in between the drain and source. (N channel makes a path for flow of current from drain to source).

- The minimum gate-to-source voltage that is required to create a conducting path between the source and drain terminals is called **THRESHOLD VOLTAGE.**
- Any gate input given to above the threshold voltage, it creates voltage drop in the gate region.
- MOSFET is used as a switch, its basic function is to control the drain current by the gate voltage.
- The transfer characteristics shows the drain current is "0" until the threshold voltage given to the gate.

Applications of MOSFET:

- As static switches.
- High frequency and low power inverter and choppers.
- High frequency SMPS.
- Low power AC and DC drives.
- Analog and digital signal processing circuits.
- Used in analog devices.

IGBT:

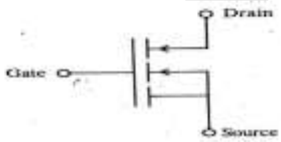
- Insulated gate bipolar transistor is a voltage control switch. Its having low ON state conduction losses & fast switching action.
- If BJT have lower conduction losses but have longer switching times. MOSFET can be turned OFF and ON much faster but their ON state conduction losses are high. So, IGBT combined the advantages of BJT's and MOSFET's. It's having low ON state conduction losses and fast switching action.
- IGBT consists of three terminals, they are collector (Drain), emitter (source), and gate.

Symbol and basic structure of IGBT:

Below figure shows the symbol of IGBT which is combination of BJT and MOSFET.

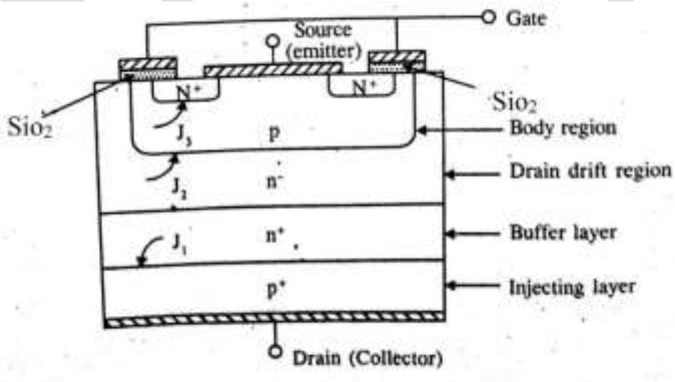
Symbol of IGBT

Some times IGBT are also indicated by following symbol as shown in the below fig.



Symbol of IGBT (N-type)

Structure of IGBT shown in the below figure, is similar to n-channel MOSFET with an additional P^+ layer called collector or drain.

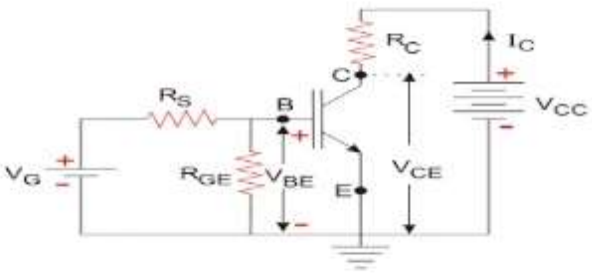


Structure of IGBT

- The adjacent n^+ and n^- layers adjacent to P^+ layers are treated as a single N layer. The P^+ substrate is called injection layer because it injects holes into n layer and forms pn junction J_1.
- The n^+ layer is called buffer layer and n^- layer is drain or drift region, n^- layer determines the voltage blocking capability of IGBT.
- P layer is called body region of IGBT, which forms junction J_2 and J_3.
- Collector and emitter are the power terminals of IGBT switch, the base terminal of BJT is replaced by the insulated gate terminal in the IGBT.
- Switching control voltage is applied across the gate and emitter and this controls the switching of IGBT.

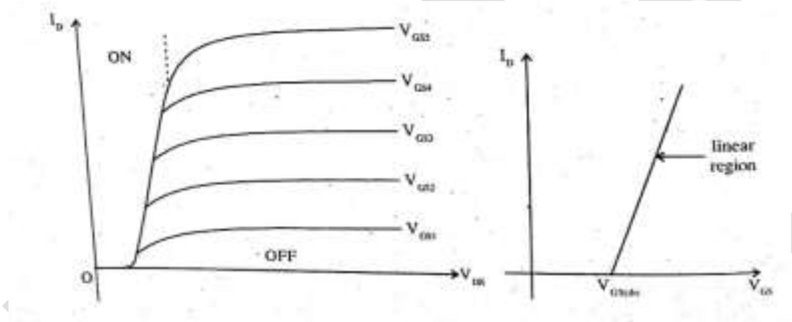
Operation of the IGBT:

- Basic circuit diagram of an N-type IGBT is shown in the below figure.



- Operation of the IGBT is similar to that of MOSFET.
- A positive voltage is applied to the collector with respect to the emitter and a positive gate voltage is applied to the gate, then gate will turn ON the device when the gate voltage exceeds the threshold voltage.
- IGBT is turn-off by simply removing the gate emitter voltage.

V-I Characteristics of IGBT:



- V-I characteristics of n type IGBT as shown in the above figure, it shows the plot of drain (collector) current V/S drain to source (collector to emitter) voltage.
- When there is no voltage applied to the gate, IGBT is in the OFF state and drain (base) current is zero.
- Gate voltage (V_G) is greater than the threshold voltage applied to the gate, then the device turns ON and allows current (I_D) to flow.

Applications of IGBT:

- IGBT's are widely used as switches in static power converters.
- DC to DC converters (choppers).
- UPS system.
- Inverters.
- Solid relays.

Comparison of BJT, MOSFET and IGBT:

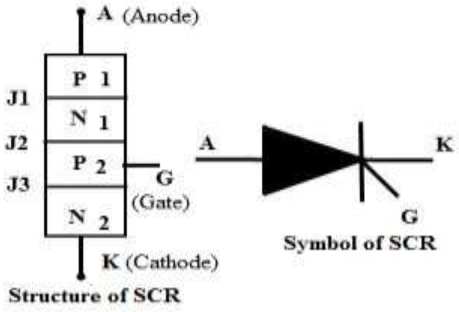
Sl. no	BJT	MOSFET	IGBT
1	It is current controlled device	It is voltage controlled device	It is voltage-controlled device
2	It requires sufficient base current for keeping it in ON state	It requires negligible current at its control terminal to maintain it in ON state	A small current is required at its control terminal to maintain it in the ON state
3	Bipolar device	Unipolar device	Bipolar device
4	Switching speed is lower than MOSFET	Switching speed is very high	Switching speed is high
5	Additional power diode necessary for freewheeling action	Freewheeling possible without any additional diode	Additional power diode necessary for freewheeling action
6	Current and voltage ratings are higher than MOSFET	Current and voltage ratings are low	Current and voltage ratings are higher than MOSFET
7	ON state voltage drop is lower than that of POWER MOSFET (<2 Volts)	ON state voltage drop is high (4 - 6 Volts)	ON state voltage drop is maximum of 3.3 Volts.
8	Used in DC to AC converters, induction motor drives, UPS, SMPS, Choppers.	Used in DC Choppers, low power UPS, SMPS, Brushless DC motor drives.	Used in DC to AC Converters, AC motor drives, UPS, Choppers, SMPS.

POWER THYRISTORS:

- Thyristor is a solid-state semiconductor device with four layers of alternating P & N type materials. Thyristor starts to conducting when the gate receives a current (triggering signal) & conduct until the voltage across the device is reversed biased or voltage is remove.
- Thyristors are the oldest power semiconductor devices used for power control applications.
- Thyristors are classified into two types, they are
    1. **UNIDIRECTIONAL THYRISTORS:** Unidirectional thyristors conduct in forward direction only. Ex: SCR, LASCR (Light activated SCR).
    2. **BIDIRECTIONAL THYRISTORS:** Bidirectional thyristors conduct in both forward and reverse direction. Ex: TRIAC.
- The thyristors require a control signal to switch from non-conducting to conducting state.
- The devices which generate control signals are called triggering devices. They are DIAC (Diode AC switch), UJT (Unijunction transistor).
- The commonly used device from thyristor family is silicon-controlled rectifier (SCR).

SCR: (Silicon controlled rectifier)

- SCR is one of the most important semiconductor devices in the field of power electronics used as a controlled switch to perform a variety of functions. Such as rectification (AC to DC), inversion (DC to AC) and power control.
- SCR provide very low resistance in forward conduction and very high resistance in the reverse direction.
- SCR is a four-layer semiconductor device of PNPN structure shown in below figure



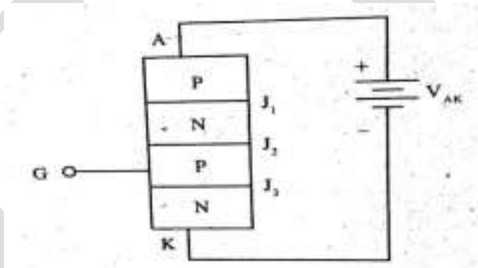
- SCR having 3 PN junctions namely J_1, J_2 & J_3, with three terminals Anode (A), Cathode (K) & Gate (G).
- The Anode terminal (A) is taken out from the P_1 layer, cathode terminal (K) is taken out from the layer N_2 and Gate terminal (G) from the layer P_2.
- The gate terminal is used to turn ON the device.

<u>SCR operation:</u>

SCR operate in two conditions; they are Forward bias condition and Reverse bias condition.

1. **<u>Forward bias:</u>**

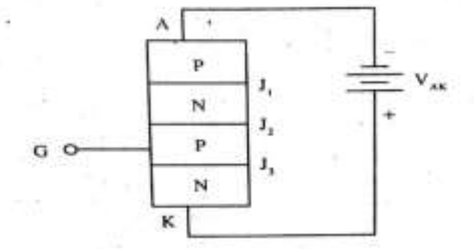
- When anode is positive with respect to cathode, SCR is said to be forward biased. As shown in below figure.



- In this mode junctions J_1, J_3 are forward biased and junctions J_2 is reverse biased.
- Small current present in the junction J_2, this current is called <u>forward leakage current</u>, because SCR is forward biased with a very small voltage and this mode is called Forward blocking mode.
- The applied forward voltage V_{AK} is increased to a certain critical value called forward break over voltage (V_{BO}). Then junction J_2 breaks down.
- SCR having a very small resistance of about 0.1 to 1Ω and voltage drop is also low.
- In the ON state the current through the SCR is very large and is controlled by the applied voltage and external resistance.

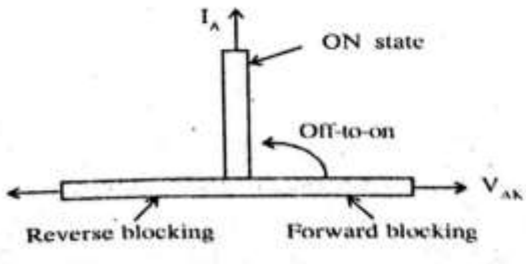
2. **<u>Reverse bias:</u>**

- When anode is made negative with respect to cathode SCR is said to be reverse biased as shown in below fig.



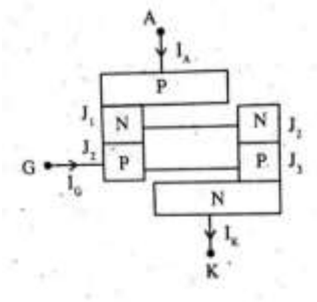
- In this mode junctions J_1 & J_3 are reverse biased and J_2 is forward biased, there is no current except reverse leakage current flow through SCR. This mode is called reverse blocking mode.
- If reverse voltage applied V_{AK} is increased to a certain value called reverse breakdown voltage, then the junction J_1 will breakdown due to sudden increase of movement of electrons.

- Reverse breakdown voltage causes a large current to flow through the SCR, hence SCR get damage in the reverse bias condition after breakdown of junction J_1.
- Ideal characteristics of SCR is shown in below fig.

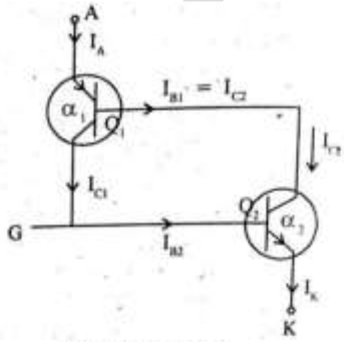


Two Transistor Model of SCR (Ideal latch of SCR):

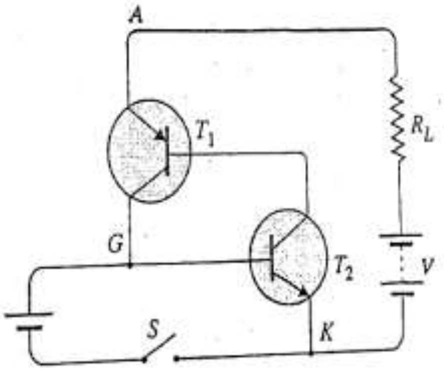
- A thyristor can be considered as two complementary transistors one PNP transistor Q_1 and other NPN transistor Q_2 as shown in below fig.



Basic Structure



Equivalent Circuit



- The base of transistor Q_1 is connected to collector of Q_2. Similarly, base of Q_2 is connected to collector of Q_1. The collector of each transistor is coupled to the base of the other there by making + Ve feedback loop.
- These transistors are in common base (B) configuration, in general the relationship between collector current 'I_C', emitter current 'I_E' & leakage current 'I_{CB0}' of a transistor is $I_C = \alpha I_E + I_{CB0}$
  Where, α (common base current gain) = I_C / I_E
- The two-transistor model of SCR or Ideal latch of a SCR is operating in two states.

ON state:

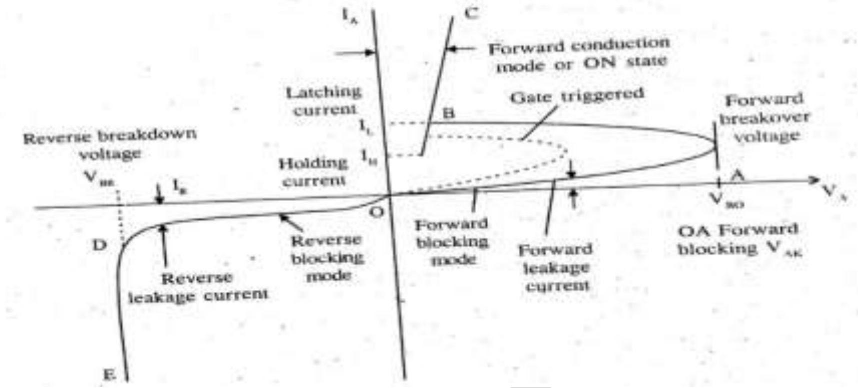
- The base current of transistor Q_2 increases, the collector current of transistor Q_2 will also increase.
- It causes more base current through transistor Q_1 due to which collector current of transistor Q_1 increases.
  $\mathbf{I_{C1} = \alpha_1 I_A + I_{CB01}}$ where I_{CBO} = Reverse leakage current between collector and base.
  $\mathbf{I_{C2} = \alpha_2 I_K + I_{CB02}}$ $\alpha = (I_C / I_E)$
  $\mathbf{I_A = I_{C1} + I_{C2}}$
  $\mathbf{I_K = I_A + I_G}$
- This action will continue till both the transistors are driven into saturation. In the saturation region SCR acts like an ON switch and it will pass current from anode to cathode.

OFF state:

- Base current of transistor Q_2 decreases, the collector current of transistor Q_2 will also decrease. It causes reduced base current through transistor Q_1 due to which the collector current of transistor Q_1 decreases.
- This action will continue till both the transistors are driven into cut-off.
- In this case SCR acts like an OFF switch and hence it will block the current from anode to cathode.

V-I Characteristics of SCR:

The V-I characteristics of SCR are shown in below fig. it's having three modes of operation, they are Forward blocking mode, Forward conduction mode and reverse blocking mode.



i. **Forward blocking mode:**

- When a forward voltage is applied to a SCR a small forward leakage current flows until forward voltage equals forward break over voltage (V_{BO}).
- The junctions J_1 & J_3 are forward bias and junction J_2 is reverse bias.
- The thyristor is forward biased but it does not turn ON and is called forward blocking mode or OFF state. Under this condition SCR having high resistance.
- Region OA is called forward blocking mode, SCR blocks the forward anode to cathode voltage. So thyristor is an open switch even in forward bias.
- The rated voltage at which the SCR is switched from forward blocking mode to ON position is known as Forward break over voltage (V_{BO}).

ii. **Forward conduction mode:**

- When the anode to cathode forward voltage (V_{AK}) reaches or exceeds V_{BO}, the thyristor turns ON. Hence large anode current starts flowing through the thyristor and anode to cathode voltage falls to a very small value is shown across the point B.
- The anode current must be more than a latching current (I_L). It maintains the required amount of carrier flow across the junction, otherwise device comeback to blocking condition.
- The minimum anode current is requires to keeping turned ON SCR after removing gate signal is known as Latching current (I_L). In the presence of latching current in the SCR, gate signal has been removed.
- The minimum anode current to maintain the SCR in ON state is known as Holding current (I_H). ($I_H < I_L$)
- When anode current reduces below holding current SCR turns OFF.

iii. **Reverse blocking mode (OFF state):**

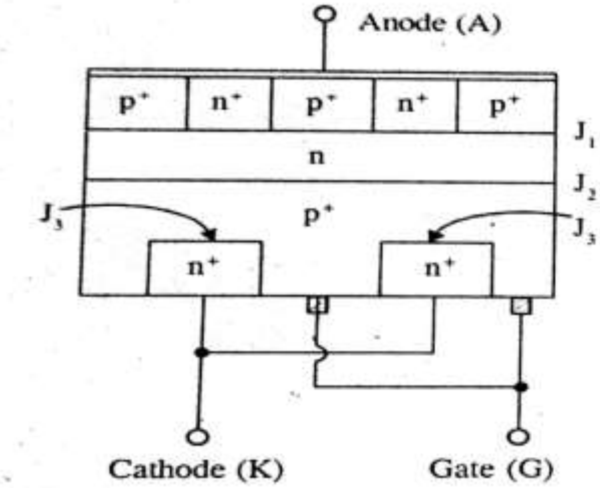
- When cathode is made positive with respect to anode. The junction J_2 is forward bias but junctions J_1&J_3 are reverse bias this mode of operation is called reverse blocking mode.
- The reverse leakage current (I_R) flows through the device until the applied reverse voltage reaches breakdown voltage (V_{BR}), region OD shows the reverse biasing region in the above fig.
- Applied voltage is increased above breakdown voltage, the reverse current (I_R) increases more rapidly, it's may damage the device.

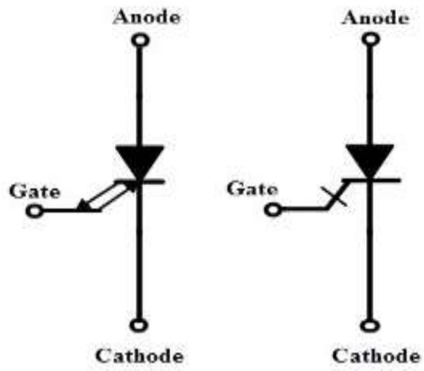
Applications of SCR:

- SCR's are suitable for controlled rectifier.
- AC regulators.
- Battery charger.
- Inverters.
- Protective circuits, relay control, time delay circuits, regulated power supplies.
- Motor, phase & heat control.

GTO (Gate Turn-Off Thyristors):

- GTO is a semiconductor PNPN device, it can be turned ON by giving a positive gate current and turned OFF by giving a negative gate current at its gate cathode terminal.
- It's having three terminals, Anode (A), cathode (K) and gate (G) as shown in below symbol.
- Double arrow on the gate indicates that bidirectional current flows through the gate, the rest of the symbol is similar to SCR.





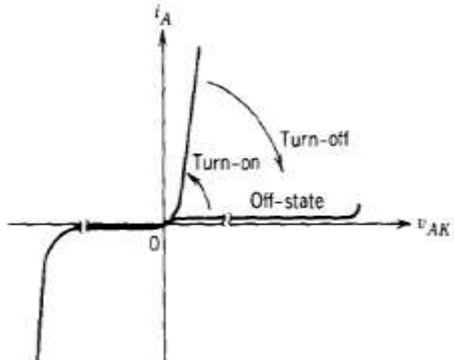
Gate Turn-Off Thyristor Symbols

- Basic structure of GTO having four layers of $p^+np^+n^+$ and three junctions of J_1, J_2 and J_3.

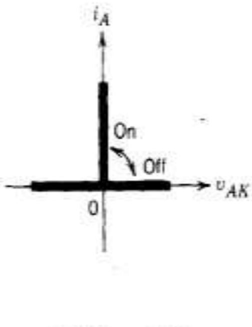
Operation:

- A GTO is turned ON by applying a positive gate current (I_G) in between the gate and cathode, it behaves like PN junction. As GTO is in forward biased condition the regenerative processes (combining of holes and electrons) starts and saturation level is reached and GTO is turned ON.
- When GTO is in reverse bias condition, the GTO has no blocking capability, because anode has shorted with p^+ and n^+ layers.
- GTO is turned OFF by applying a negative gate current across gate and cathode terminal.

V-I characteristics:



V-I characteristics



Ideal characteristics

Above figure shows the V-I characteristics and Ideal characteristics of GTO. In V-I characteristics GTO turned ON only in forward biased condition, is shown in above fig.

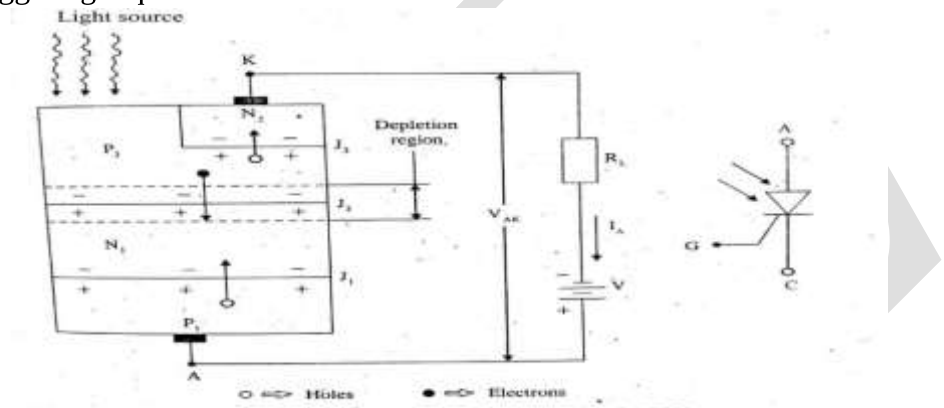
GTO turned ON by positive current applied to the gate and turned OFF by negative current (signal) applied to the gate. Otherwise GTO is in OFF state.

Applications:

- Rolling mills, robotics and machine tools, used in traction purposes because of their lighter weight, used in adjustable frequency inverter drives.

LASCR (Light Activated SCR) (Photo thyristor):

- A light activated silicon-controlled rectifier is a semiconductor device which turns ON, when the gate is expose to light.
- The light is focussed on the gate junction area which acts as a trigger pulse and device is turned ON.
- The structure and symbol are as shown in below fig. it consists of 4 layers of semiconductors which forms PNPN structure with 3 junctions J_1, J_2 & J_3 and 3 terminals anode (A), cathode (K) and gate (G).
- The operation of LASCR is similar to ordinary SCR except that its gate can be triggered by light. It can be turned OFF only by reducing current through it below its holding current. But does not turn OFF when light source is removed.
- Sometimes a combination of both light source and gate signal is used to trigger an SCR.
- These devices are available up to the rating of 6 KV and 3.5 KA, with ON-state voltage drop of about 2V and light-triggering requirements of 5 mw.

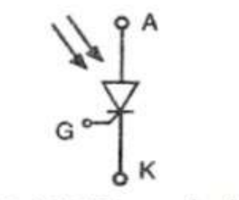


Structure and symbol of a photo SCR (LASCR)

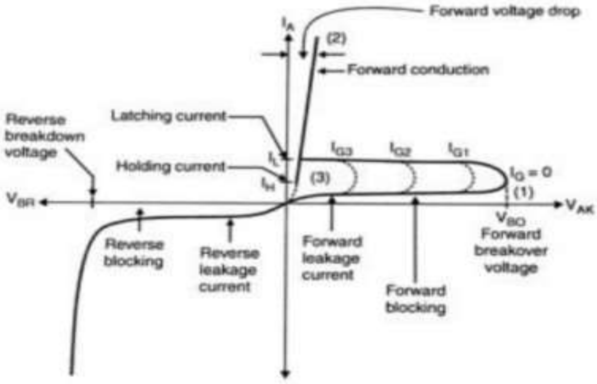
Operation:

- The LASCR works on the principle of photoconduction.
- With proper bias, photons (light source) incident on the P_2 base region, it create electron-hole pairs in the P_2 region.
- When forward bias voltage is applied to the LASCR, the junction J_1 & J_3 become forward bias, while the junction J_2 become reverse bias. In in the forward bias condition, apply a clock pulse (light source) at the gate terminal, the junction J_2 become forward bias & the LASCR start to conduct.
- The LASCR turn ON & OFF very quickly, at the OFF state the LASCR provide infinity resistance & in ON state, it offers very low resistance in the range of 0.01 Ω to 1Ω.

V-I Characteristics of LASCR:



LASCR symbol



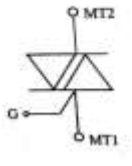
V-I Characteristics of SCR

Applications of LASCR:

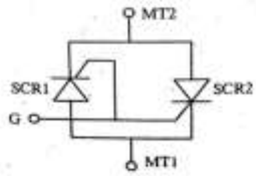
- Used in high voltage & high current application, HVDC transmission, optical light control, phase control, motor control, solid state relay.

TRIAC:

- TRIAC is a bilateral, bidirectional switching device with three terminal namely main terminal 1 (MT1), main terminal 2 (MT2) & gate (G).
- TRIAC can be triggered by either a positive or a negative pulse irrespective of the polarity of the voltage applied across its main terminals.
- The symbol of TRIAC and equivalent circuit of TRIAC is has shown in the below figure.

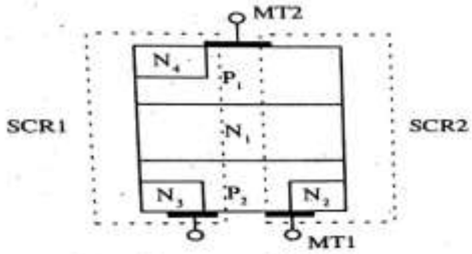


Triac Symbol



Equivalent circuit

- Equivalent circuit consists of two SCR’s connected in antiparallel with common gate.
- Below figure shows the structure of TRIAC, it consists of two four-layer switches in parallel. These switches $P_1N_1P_2N_2$ and $P_2N_1P_1N_4$ as shown by the broken lines in the figure.

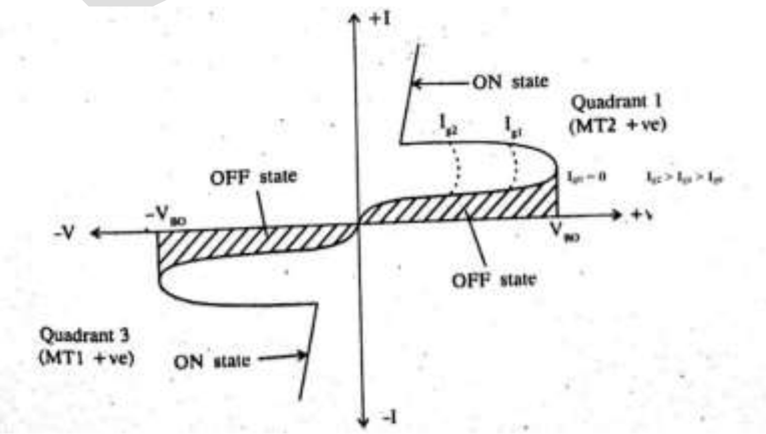


Structure of TRIAC

- The Tri & AC indicates the three terminal alternating current control. An additional N_3 region acts as a gate controller.
- The gate terminal makes contact with both P_2 & N_3 type materials for allowing either a positive or a negative pulse as trigger currents.

Operation and V-I characteristics of TRIAC:

- TRIAC is said to be positively biased when terminal 2 (MT2) is positive with respect to the main terminal 1 (MT1). This leads to the operation in quadrant 1 and current flows from MT2 to MT1.
- TRIAC in OFF state until the applied voltage greater than the break over voltage (V_{BO}).
- The TRIAC operates in quadrant 3, when MT2 is negative with respect to MT1 and then current flows in reverse direction.
- The TRIAC can be turned ON in each half cycle of the applied voltage by applying a positive or negative voltage to the gate with respect to terminal MT1.
- Even with NO gate current, the TRIAC will be turned ON by providing supply voltage equals to break over voltage (V_{BO}). But normal way to turn ON the TRIAC is by introducing the proper gate current.

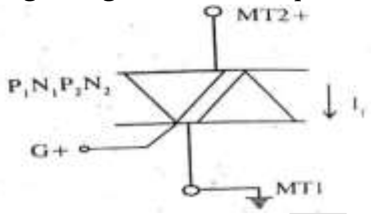


Gate Triggering Modes of TRIAC:

TRIAC has 4 modes of turn-on depending upon the polarity of voltage across its main terminal and gate terminal.

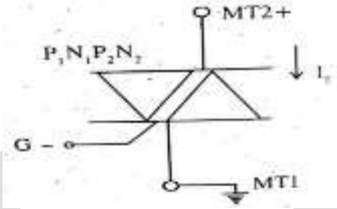
Mode-1:

MT_2 is positive and gate is positive. In this mode the current flows through the switch $P_1N_1P_2N_2$ from MT_2 to MT_1 as shown in the below fig. the gate current required for triggering is less.



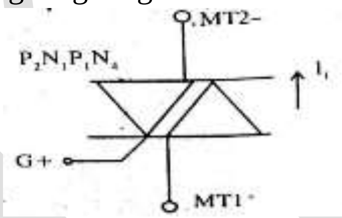
Mode-2:

MT_2 is positive and gate is negative. In this mode the current flows through the switch $P_1N_1P_2N_2$ from MT_2 to MT_1 as shown in the below fig. Higher gate current is required for triggering.



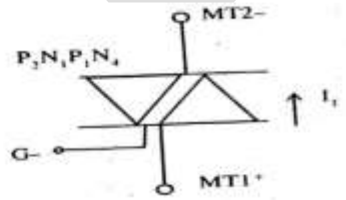
Mode-3:

MT_2 is negative and gate is positive. In this mode the current flows through the switch $P_2N_1P_1N_4$ from MT_1 to MT_2 as shown in the below fig. Higher gate current is required for triggering.



Mode-4:

MT_2 is negative and gate is negative. In this mode the current flows through the switch $P_2N_1P_1N_4$ from MT_1 to MT_2 as shown in the below fig. Less gate current is required for triggering.



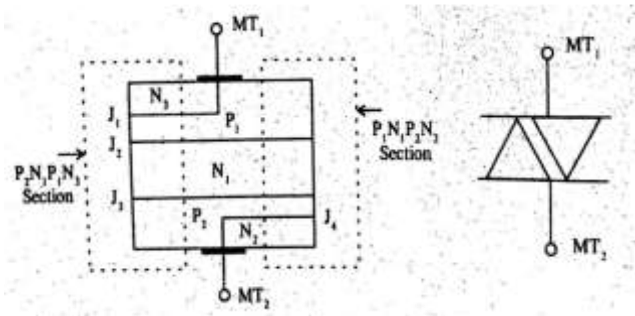
Mode	MT2	Gate	Quadrant	Required gate current Ig
1	+	+	1	5 - 10 mA
2	+	–	1	10 - 20 mA
3	–	+	3	>40 mA
4	–	–	3	7 - 15 mA

Applications of TRIAC:

- Triggering devices for SCR.
- Control of AC power.
- Speed control of AC motors.
- Illumination (light) control.
- Time delay relay.
- Temperature control of furnaces.

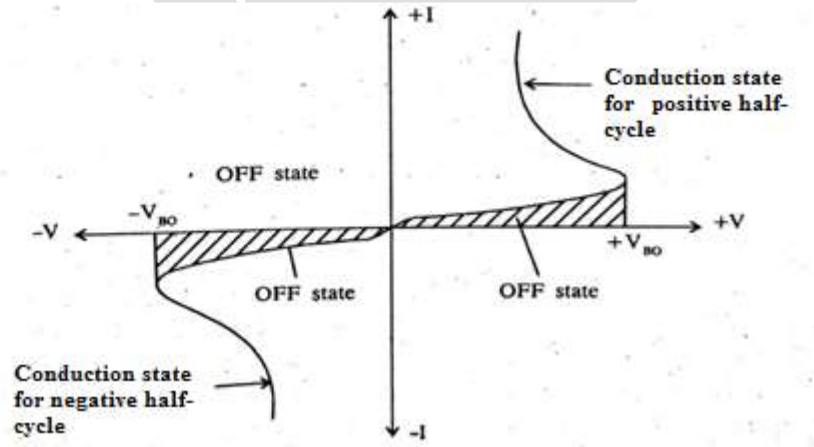
DIAC :(Trigger diode)

- A DIAC is a two terminal bidirectional triggering device which can be switched from OFF state to ON state during both half cycles (+ve & -ve) of AC input signal.
- The device consists of two PNPN sections in antiparallel order as shown in the below fig. It has no gate terminal.



Operation & V-I characteristics of DIAC:

- The section $P_1N_1P_2N_2$ has junctions J_2, J_3 & J_4 and $P_2N_1P_1N_3$ has junctions J_3, J_2 & J_1.
- When a positive voltage is applied at MT_1 with respect to MT_2, junctions J_2 and J_4 are forward biased, whereas J_3 is reverse biased and junction J_1 is also reverse biased so no current flows through it.
- For a small applied voltage, the current through the device is also small called leakage current due to minority carrier flows in the DIAC and device remains in OFF state.
- When the voltage across the DIAC has increased to $+V_{BO}$ (Break over voltage), sudden break down occurs at the reverse biased junction J_3.
- The current through the DIAC increases rapidly and the device is said to be in the ON state.
- When MT_2 is made positive, a similar action takes place and current flows from MT_2 to MT_1 through left hand portion of device $P_2N_1P_1N_3$ as shown in above fig.
- The forward & reverse characteristics of the device are identical because its construction is absolutely symmetrical.



Applications:

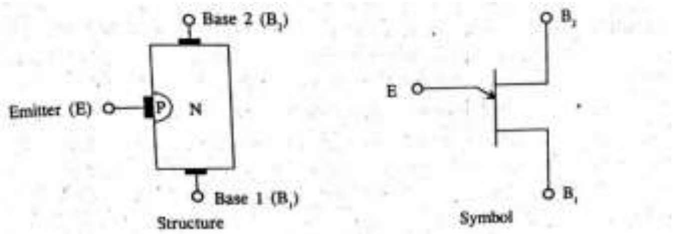
- Light control.
- Motor speed control.
- Fan regulator.
- Heat control.

UJT :(Unijunction transistor)

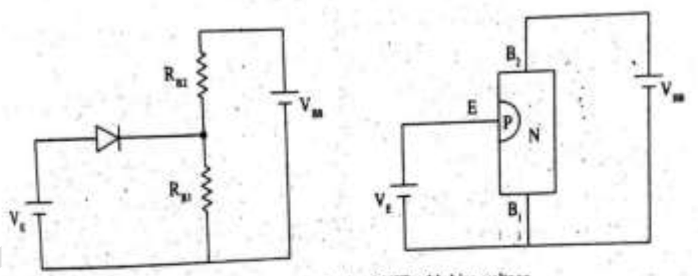
- UJT is a three terminal semiconductor device with only one junction & two layer (P-N) switching device.

Construction:

- UJT consists of n-type semiconductor silicon bar which acts as the base as shown in below fig.
- The base region is lightly doped & the resistivity of base region is very high.
- The emitter section is highly doped p-type material is deposited between B_1 and B_2 regions. The emitter junction or p-type material is placed at a point closer to B_2 then B_1.
- The symbol and structure of UJT is shown in below fig.



Operation:



Equivalent circuit of UJT with bias voltage

- The diode represents PN junction and R_{BB} is the inter base resistance of N-type substrate.

$$\mathbf{R_{BB} = R_{B1} + R_{B2}}$$

- The intrinsic standoff ratio (η) is the ratio of R_{B1} to R_{B2}.

$$\eta = \frac{R_{B1}}{R_{B0}} \quad \text{i.e.,} \quad \frac{R_{B1}}{R_{B1} + R_{B2}}$$

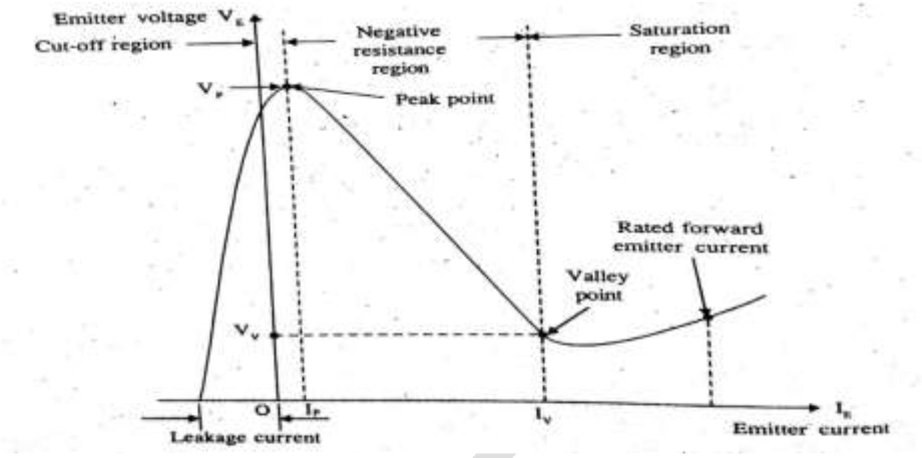
- When the emitter voltage is small the emitter junction is reverse biased. The voltage across the emitter junction increases the emitter current flows and holes get injected from emitter in to N-type. It creates only path in between emitter and base 1. The large current starts flows in between E & B_1.
- E & B_1 region resistance R_{B1} decreases due to the increase of charge carriers, this phenomenon is called as <u>conductivity modulation.</u>
- The minimum current required for triggering the UJT is called <u>peak-point emitter current.</u>
- The base 2 is used for applying external voltage (V_{BB}). The terminals emitter and base 1 (B_1) are active terminals.
- UJT gets triggered by applying a positive pulse to the emitter and it can be turned OFF by applying a negative trigger pulse.

Applications:

- Triggering devices for SCR & TRIAC.
- Delay timer circuits.
- Energising relays.

V-I characteristics:

- UJT emitter current I_E versus emitter voltage V_E characteristics curve is as shown in below fig.



- Emitter voltage (V_E) increases up to peak point voltage (V_P), current I_E increases up to I_P peak point.
- Beyond peak point, current increases from I_P to I_V as voltage decreases from V_P to V_V. The region between peak point and valley point (lowest or minimum voltage point) is called <u>negative resistance region</u>.
- The resistance of R_{B1} is lowest at valley point.
- The increase in emitter current I_E is due to decrease in resistance R_{B1}, therefore this region is called <u>negative resistance region.</u>
- The region beyond valley point, the UJT behaves as a forward biased diode and UJT is turned into ON state is known as <u>saturation region.</u>
- The emitter voltage remains almost constant with increasing emitter current.
- Emitter and B_1 is reverse biased and there is no emitter current in the left of peak point (V_P) is called <u>cut off region</u>. In this region UJT remains in OFF state.

Applications:

- Delay timer circuit.
- Energising relays.
- Triggering devices for SCR and TRIAC's.
- Used in phase control & timing circuits.