## Ten- twelve weeks

## SERIES OPERATION OF THYRISTOR

For high voltage application, two or more thyristor connected in series the voltage rating. The characteristics of the same type of thyristor are not identical. This mean thyristors of the same class to be connected in series. T he characteristics of two thyristors of same make and rating are never same and this leads to the following two major problems during series connection of the devices.

1- Unequal distribution of voltage across devises
2- Difference in reverse- recovery characteristics

When the thyristors of identical are connected in series, variations in their forward and reverse blocking characteristics cause unequal distribution of voltage in steady- state. The maximum voltage to two SCRs string can block is only ($V_1+V_2$) and not the rate blocking voltage 2V. Hence, in order to force equal sharing of voltage across the two SCRs under steady, external resistors R have to be connected in parallel with each thyristor such that the parallel combination has the same resistance. The second problem of unequal voltage sharing among the series connected SCRs, due to difference in reverse- recovery characteristics of two SCRs unmatched SCRs, of the same type. If SCR $T_1$ is assumed to have less reverse – recovery time than that of SCR $T_2$. As result, SCR $T_1$ recovers faster than SCR $T_2$ and it limits the reverse – current. Hence unequal voltage distribution occurs due to difference in the reverse- recovery current of SCRs of the same time. Voltage equalization under these condition can be achieved by connecting capacitors. The capacitor charge during SCR is turn ON, and the capacitor discharge heavy current through this SCR. To limit discharge current is used in series resistor with each capacitor.

A uniform voltage distribution can be achieved by connecting a suitable resistance across each SCR, such that each parallel combination has the same resistance. To obtain uniform voltage distribution is to connect the same value of resistance in parallel with each SCR.

Let $n_s$ be the number of thyristor connected in series. If the range of blocking current is defined as $I_{b(max)}-I_{b(min)}=\Delta I_b$, it is observed that the maximum unbalance in blocking voltage to SCRs of a series string occurs when one devise has a blocking $I_{b(min)}$ and all remaining SCRs have $I_{b(max)}$.

$I_{b(max)}+I_2= I_{b(min)}+I_1$

$I_{b(max)}-I_{b(min)}=I_1-I_2=\Delta I_b$

Let $V_D$ be the maximum permissible blocking voltage, then

$V_D=I_1.R$ (1)

Now, we can write string voltage $V_s$ as

$V_s= V_D+(n_s-1)R.I_2$ (2)

$I_2=I_1-\Delta I$ (3)

Sub eq. (3)(2)

$V_s= V_D+(n_s-1)R.( I_1-\Delta I)$

$V_s= V_D+(n_s-1)R.I_1- (n_s-1)R. \Delta I$ (4)

Sub eq.(1) in (4)

$V_s= V_D + (n_s-1)V_D - (n_s-1)R. \Delta I$

$$R = \frac{n_s V_D - V_s}{(n_s - 1)\Delta I_b}$$

$$V_D = \frac{V_S + (n_S - 1)\, R\, \Delta I_D}{n_S}$$

Let $\Delta Q_{max}$ be the maximum permissible difference between reverse-recovery charge of SCRs of the same time and $\Delta V_{max}$ be the maximum difference in voltage

$$\Delta V_{max} = \frac{\Delta Q_{max}}{C}$$

If the $V_D$ is the maximum permissible blocking voltage of SCR $T_{1,}$ then voltage across remaining ($n_s$-1) SCRs will be ($V_D-\Delta V_{max}$)

$V_s= V_D+(n_s-1).( V_D-\Delta V_{max})$

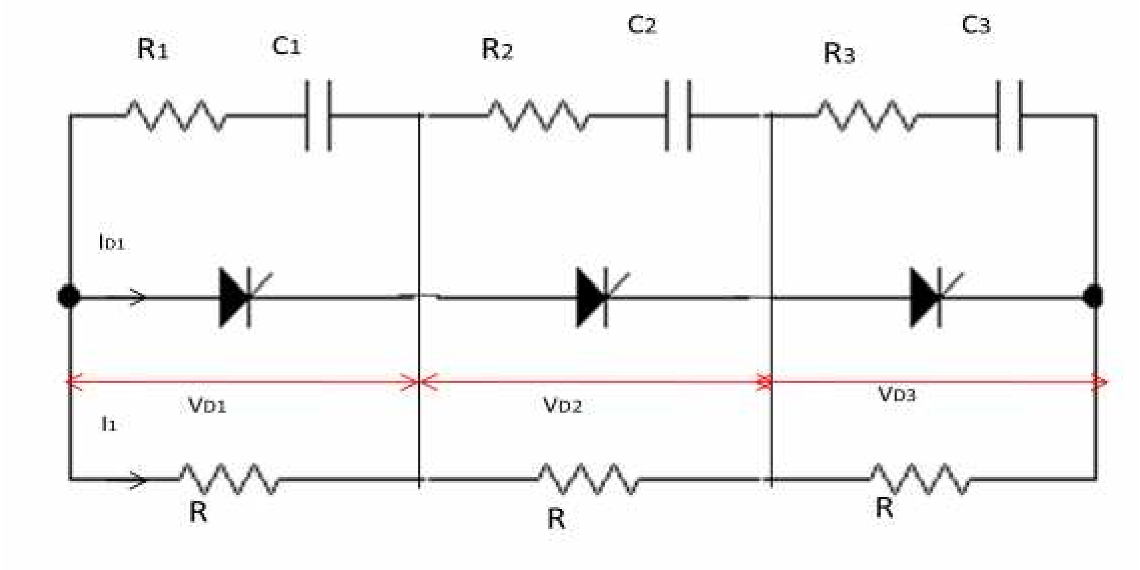
$V_s = V_D + n_s V_D - V_D - n_s \Delta V_{max} + \Delta V_{max}$

$n_s \Delta V_{max} - \Delta V_{max} = n_s V_D - V_s$

$(n_s - 1) \Delta V_{max} = n_s V_D - V_s$

$(n_s - 1) \frac{\Delta Q_{max}}{C} = n_s V_D - V_s$

$$C = \frac{(n_s - 1)\Delta Q_{max}}{ns\ VD - Vs}$$



## PARALLEL OPERATION OF THYRISTOR

When the load current of the single thyristor, thyristors are connected in parallel to increase the overall current capability. Thyristors can be connected directly in parallel with each other if they have identical forward V-I characteristics. Contrary to what might be expected, the load current is not shared equally between the thyristors. Total rated current of parallel unit is $(I_1+I_2)$ instead of 2I.

This unequal distribution of current in parallel connected thyristor leads to a thermal-runaway problem which mean, the thyristor carrying the higher current would dissipate more power and this increase the junction temperature in turn and hence decrease the internal resistance. The thermal- runaway may be prevented by a common heat- sink to ensure the thyrisyors are operating at the same temperature. The unequal distribution of current in parallel caused by the inductive effect of current carrying conductors. When the thyristors are arranged unsymmetrically, as shown in figure (1-a), the middle thyristor will have less current as compared to outer two SCRs. This unequal distribution can be avoided by mounting the SCRs symmetrically on heat- sink as shown in figure (1-b)

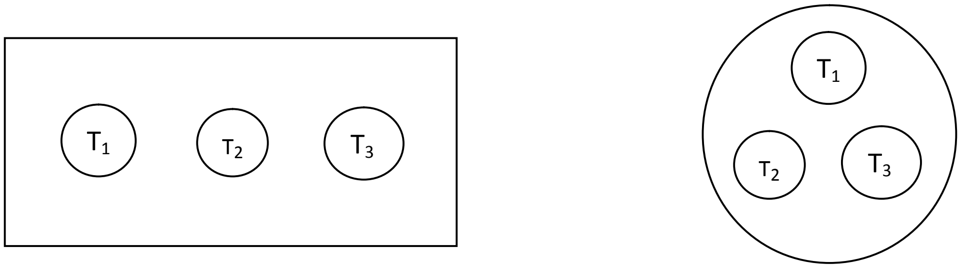
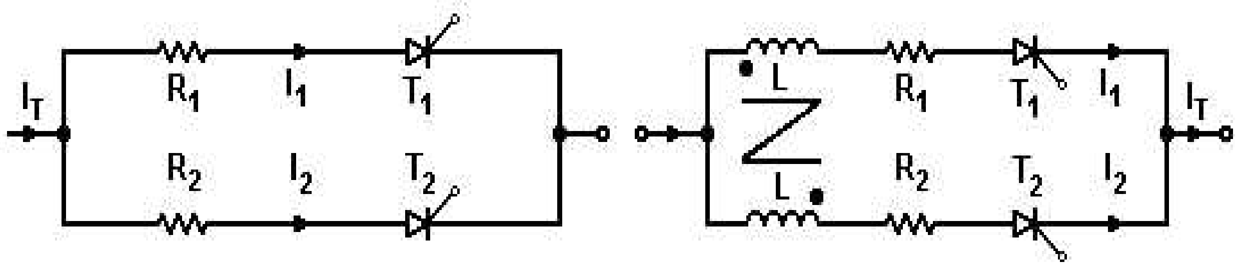


Fig. 1-a

Fig. 1-b

Figure 1-unsymmetrically and symmetrically in parallel connection

Equal current sharing could be accomplished with the use of a small resistor or inductor in series with each thyristor as shown in figure 2



(a) Static current sharing

(b) Dynamic current sharing

## STRING EFFICIENCY

For series or parallel connected SCRs, it should be ensured that each SCR rating is fully utilization and system operation is satisfactory. Therefore, sting efficiency is a trem that usedfor measuring the degree of utilization of SCRs in string. String efficiency of SCRs connected in series or parallel is defined as

Series efficiency $=\frac{V_s}{n_s V_D} \times 100\%$

Parallel efficiency $=\frac{I_m}{n_s I_b} \times 100\%$

## DERATING

In order to improve the reliability of the series and parallel connection, an extra device may be added so that the voltage/ current applied to each device will be lower than its normal rating. Thus, there is an inherent derating of the devices connected in series and parallel

Series derating $=1- \frac{V_s}{n_s V_D} \times 100\%$

Parallel derating $= 1- \frac{I_m}{n_s I_b} \times 100\%$

## THYRISTOR TYPES

The thyristor are manufactured almost by diffusion. The anode current required a finite time to propagate to the whole area of the junction from the point near the gate. The manufactured used various gate structures to control di/dt, turn on and turn off time depending on the physical construction of the device. Thyristor could classify into:

1. Phase Controlled Thyristor. (**SCR**)
2. Fast Switching Thyristor. (**ASCR**)
3. Gate Turn Off thyristor. (**GTO**)
4. Bidirectional Thyristor. (**TRIAC**)
5. Reverse Conduction Thyristor. (**RCT**)
6. Static Induction Thyristor. (**SITH**)
7. Light Activated Silicon Controlled Rectifier. (**LASCR**)
8. FET Controlled Thyristor. (**FET-CTH**)
9. MOS Controlled Thyristor. (**MCT**)
10. Silicon Controlled Switch (**SCS**)
11. Programmable Unijunction Thyristor (**PUT**)
12. Silicon Unilateral Switch (**SUS**)

## PHASE CONTROLLED THYRISTOR. (SCR)

This thyristor generally operate at line frequency and turn off by “natural commutation” and do not have special fast switching. The turn off time $t_q$, is about 50 - 100μs and the conduction voltage vary from 1.5V for 600V device, 2.5V for 4000V device and 1.25 for 1200V device. The phase control thyristors are enhancement of dynamic dv/dt capability and the improvement of the gate sensitivity. To improve dynamic dv/dt capabilities and high temperature by the use of emitter shorting structure which provide shunting path for current that hence from rise the voltage applied in conjunction with device capacitance at the end of the turn off interval, this current can turn on the device if sufficiently high. The modern thyristor use an amplifying gate. When an auxiliary $T_A$ is gated ON an amplified output applied to gate of main thyristor $T_m$. The amplifying gate permits high dynamic characteristics with a typical dv/dt of 1000V/μs and di/dt of 500A/μs as shown in figure below.

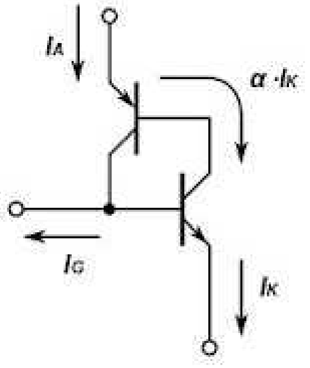
## FAST SWITCHING THYRISTOR (ASCR)

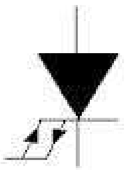
This type used for high speed switching applications with forced commutation. It has fast turn off time (5-50μs) depending on the voltage range and permits operation at switching frequency of 20KHz or more with high efficiency. This thyristor called “asymmetrical thyristor”. The ON-state forward drop varies as invertors function of the turn off time $t_q$, it has high dv/dt (1000V/μs) and high di/dt (1000A/μs). The fast turn off and high dv/dt very important to reduce the size and weight of commutation circuit.

## GATE TURN- OFF THYRISTOR (GTO)

Thyristors can only be turned ON and cannot be turned OFF. Thyristors are switched ON by a gate signal, but even after the gate signal is de-asserted (removed), the thyristor remains in the ON-state until any turn-off condition occurs (which can be the application of a reverse voltage to the terminals, or when the current flowing through (forward current) falls below a certain threshold value known as the "holding current"). The GTO can be turned-on by a gate signal, and can also be turned-off by a gate signal of negative polarity.

Turn on is accomplished by a "positive current" pulse between the gate and cathode terminals. As the gate-cathode behaves like PN junction, there will be some relatively small voltage between the terminals. The turn on phenomenon in GTO is however, not as reliable as an SCR (thyristor) and small positive gate current must be maintained even after turn on to improve reliability. Turn off is accomplished by a "negative voltage" pulse between the gate and cathode terminals.





## ADVANTAGES

The prime design goal of GTO devices are to achieve fast turn off time and high current turn off capability and to enhance the safe operating area during turn off. The GTO's turn off occurs by removal of excess holes in the cathode base region by reversing the current through the gate terminal. . It has advantage **than** SCR like

- Eliminate of the commutation circuit component then reducing cost.
- Reduction in acoustic and electromagnetic noise due to eliminate of chokes.
- Fast turn off so, high switching frequency.
- Improve efficiency of converter.

In low power application GTO has advantage **than** bipolar transistor:

- Higher blocking voltage capability.
- High ratio of peak controllable current to average current.

- High ratio of surge current to average current.
- High ON-state gain.
- Pulsed gate signal of short duration

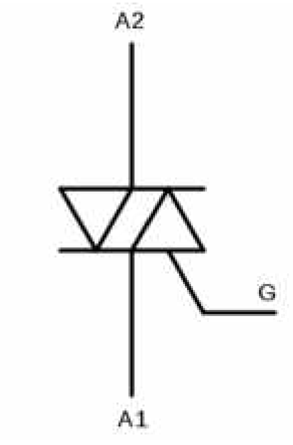
## DISADVANTAGES

Compared to a conventional thyristors, the device has the following disadvantages

1. Low gain duration off-state
2. High negative current pulse
3. High ON-state voltage

## BIDIRECTIONAL TRIODE THYRISTOR (TRIAC)

A TRIAC can conduct in both direction and normally used in AC phase controlled. TRIACs are part of the thyristor family and are closely related to silicon-controlled rectifiers (SCR). However, unlike SCRs, which are unidirectional devices (that can conduct current only in one direction), TRIACs are bidirectional and so current can flow in either direction. Another difference from SCRs is that TRIAC current flow can be enabled by either a positive or negative current applied to its *gate* electrode, whereas SCRs can be triggered only by positive current going into the gate. To create a triggering current, a positive or negative voltage has to be applied to the gate with respect to the MT1 terminal (otherwise known as A1). If $MT_2$ positive with respect to $MT_1$ TRIAC can turn on by positive gate signal between gate and $MT_1$, and vice versa.



To explain how TRIACs work, one has to individually analyze the triggering in each one of the four quadrants. The four quadrants are illustrated in Figure below, according to the voltage on the gate and the MT2 terminals with respect to the MT1 terminal. The MT1 and MT2 terminals are also commonly referred to as A1 and A2, respectively.

The relative sensitivity depends on the physical structure of a particular triac, but as a rule, quadrant I is the most sensitive (least gate current required) and quadrant IV is the least sensitive (most gate current required)

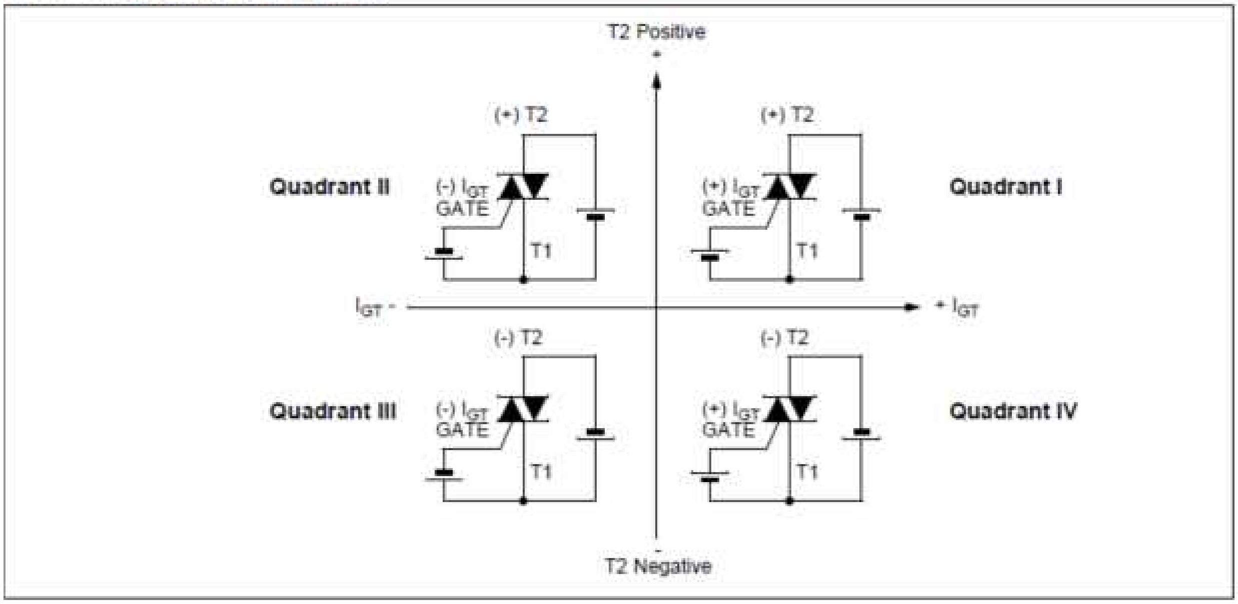
Quadrant I operation occurs when the gate and MT2 are positive with respect to MT1.

Quadrant II operation occurs when the gate is negative and MT2 is positive with respect to MT1

Quadrant III operation occurs when the gate and MT2 are negative with respect to MT1

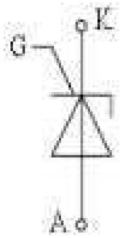
Quadrant IV operation occurs when the gate is positive and MT2 is negative with respect to MT1.

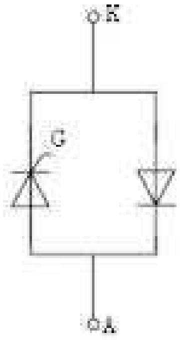
**Quadrant Definitions for a Triac**



## REVERSE CONDUCTION THYRISTOR (RCT)

It is compromise between device characteristics and circuit requirement. It is connect anti-parallel with diode and this thyristor turn off by passing a current pulse through the diode part on the chip. The forward blocking voltage varies from 400-2000 V and current about 500 A the ratio of forward current to reverse current is fixed, so the application will be limited to a specific circuits. Isolation of thyristor and diode function is important to ensure that charge carriers present in the diode during commutation do not diffuse into thyristor part of the chip to cause retriggering when forward voltage is reapplied.





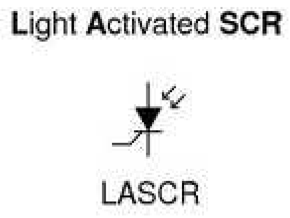
## STATIC INDUCTION THYRISTOR (SITH)

It is similar to MOSFET, turn on by applying positive gate signal and turn off by applying negative gate signal. It is minority carrier device so has low on state resistance. It has fast switching speed (1-6μs) and high dv/dt and high di/dt.

## LIGHT ACTIVATED SILICON CONTROLLED THYRISTOR (LASCR)

LASCR is turn on by direct radiation of light on the silicon wafer. The electron-hole pair produces triggering the gate. It is design to be sensitive to light triggering. This sensitivity can be varied by connecting a variable resistor between gate and cathode.

LASCR used in high voltage and current application, because it provide complete isolation between the light triggering and switching device. Voltage rate 4KV for 1500 A and light triggering power 100mw.



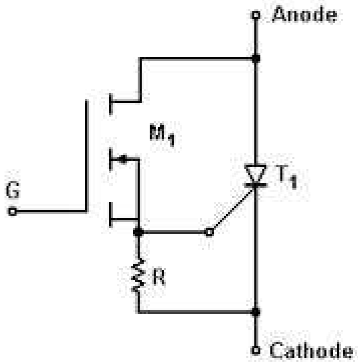
## FET CONTROLLED THYRISTOR (FET-TH)

It is combining of MOSFET and thyristor in parallel connection. If a sufficient voltage applied to gate MOSFET a triggering current generated internally for the thyristor. It has high switching speed, dv/dt and di/dt. Turn off done by applying optical firing to provide electrical isolation between input or control signal and switching device.

## MOS CONTROLLED THYRISTOR (MCT)

It is combines the advantages of MOSFET and the thyristor and it is with insulated gate terminal. MCT has low on- state losses and high current capabilities of thyristor and simpler drive characteristics and fast switching speed of MOSFET. The main features are:

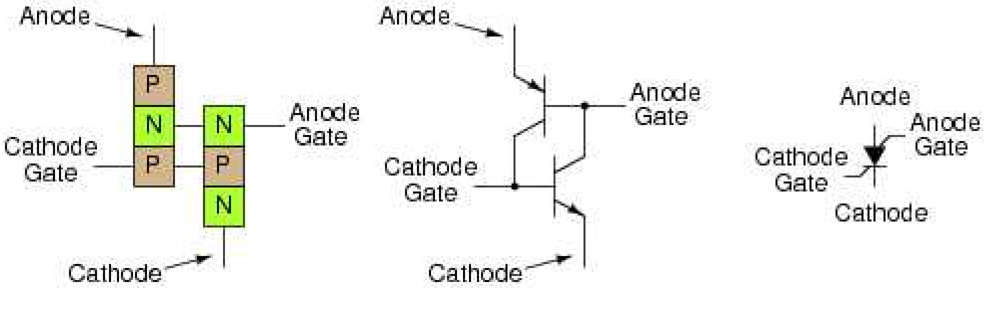
1- Fast turn on time typically 0.4µsec and fast turn off 1.25µsec
2- MCTs can easily be connected in series and parallel combination for higher power requirement, Device with maximum voltage capability of 2KV-3KV and current capability of 200 A are presently available.
3- Low switching losses
4- High gate input impedance
5- Low reverse voltage blocking
6- Low forward voltage drop during conduction.



## SILICON CONTROLLED SWITCH (SCS)

A silicon-controlled switch (SCS) is a device similar to an SCR. When a positive voltage/input current pulse is applied to an additional anode gate lead. The device also can be triggered into conduction by applying a negative voltage/output current pulse to the same lead. In other words, it can be turn on by applying a positive pulse at cathode gate and can also be turn on by applying a negative pulse at the anode gate. The SCS can turn off by applying a positive pulse at the anode gate or negative pulse at cathode gate. The SCS behaves like an SCR. It has many features

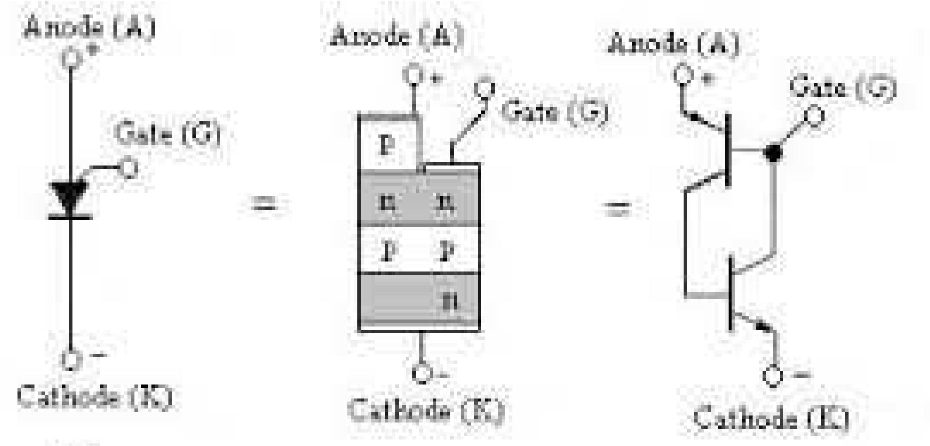
1- Low turn off gain
2- Low current device so design to low current application.
3- It is used mainly in low power circuits, limiting and counting circuits and digital logic circuits.



*Physical diagram* *Equivalent schematic* *Schematic symbol*

## PROGRAMMABLE UNIJUNCTION THYRISTOR (PUT)

It is a PNPN device like the SCR, but the gate connected to N-type near the anode. Thus, the anode and gate constitute P-N junction which controls the ON and OFF state of the PUT. The gate is positively bias relative to the cathode by amount $V_g$. When the anode voltage less than $V_g$ the anode- gate junction reverse biased and the device is in the off-state. When the anode voltage exceeds $V_g$ by about 0.7 V, the anode gate junction conduct causing the device to turn on state.



รูปที่ 15 Programmable Unijunction Transistor (PUT)

## SILICON UNILATERAL SWITCH (SUS)

It is similar to the PUT with an inbuilt low voltage avalanche diode between gate and cathode. Because of the anode of SUS turn on for a fixed anode- cathode voltage unlike other types, this required a trigger voltage.

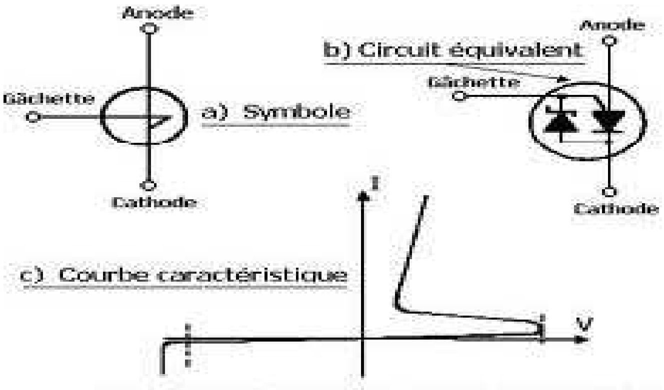


Fig. 27. - COMMUTATEUR UNILATÉRAL SUS.

## Power transistor

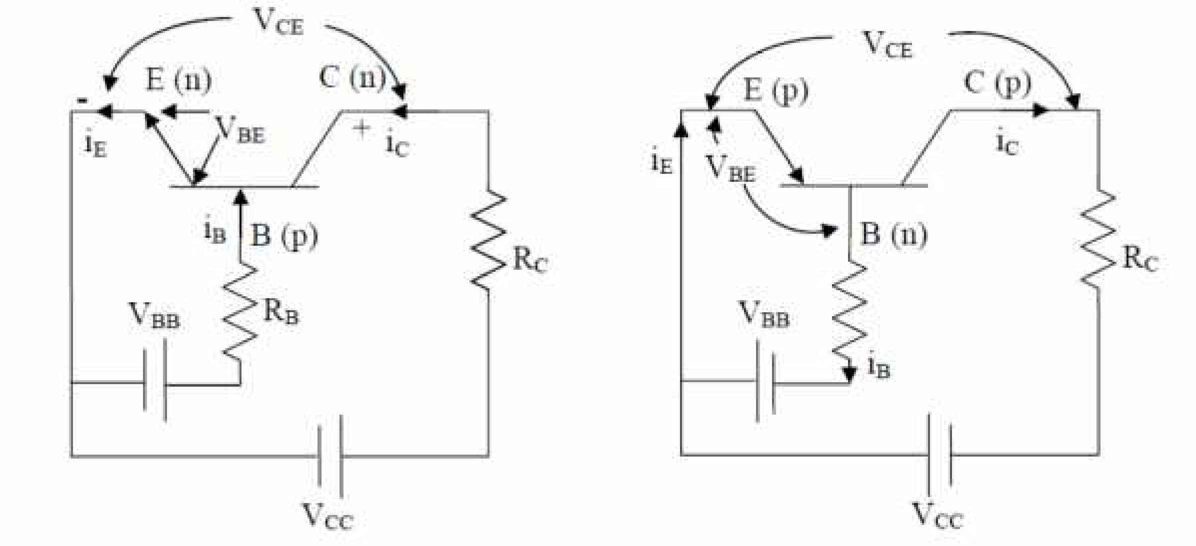
Power transistor has controlled characteristics, it turn on when the current signal given to the control terminal and stay at this case as signal found.

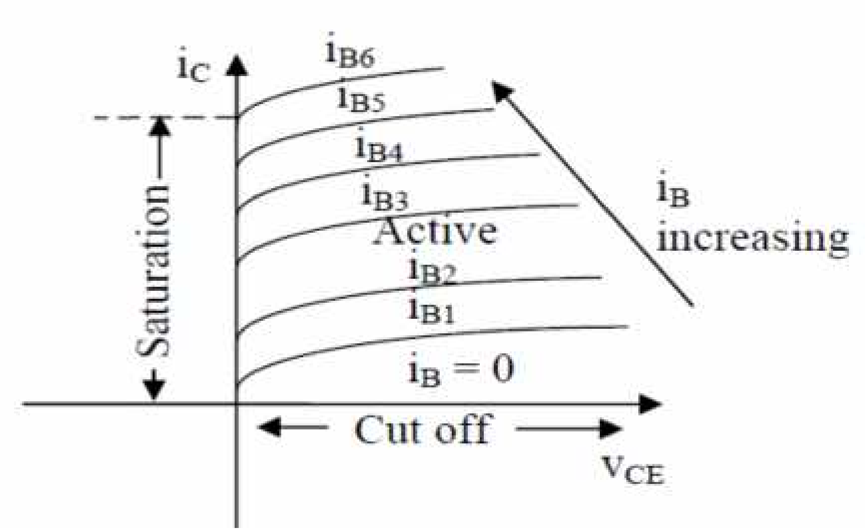
It has four types:

1- Bipolar junction transistor
2- Metal oxide semiconductor field effect transistor.
3- Insulated gate bipolar transistor
4- Static induction transistor

## Bipolar junction transistor

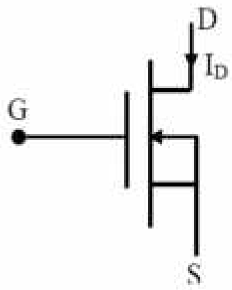
Power Bipolar Junction Transistor (BJT) is the first semiconductor device to allow full control over its Turn on and Turn off operations. It simplified the design of a large number of Power Electronic circuits that used forced commutated thyristors at that time and also helped realize a number of new circuits. It is three layers, two junctions pnp or npn, the term bipolar denotes that the current flow in the devices due to the movement the electrons and holes. It has three terminals, emitter, collector and base.



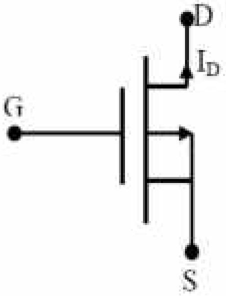


## Metal oxide semiconductor field effect transistor.

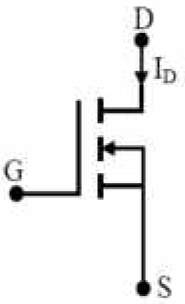
The operating principle a MOSFET is a voltage controlled majority carrier device. The movement of majority carriers in a MOSFET is controlled by the voltage applied on the control electrode (called gate) which is insulated by a thin metal oxide layer from the bulk semiconductor body. The electric field produced by the gate voltage modulates the conductivity of the semiconductor material in the region between the main current carrying terminals called the Drain (D) and the Source (S). Power MOSFETs can be of two types (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. Figure below shows the circuit symbol of these four types of MOSFETs.



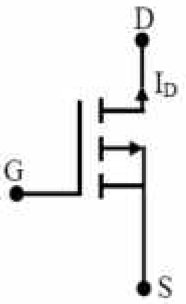
n-channel depletion type MOSFET



p-channel depletion type MOSFET

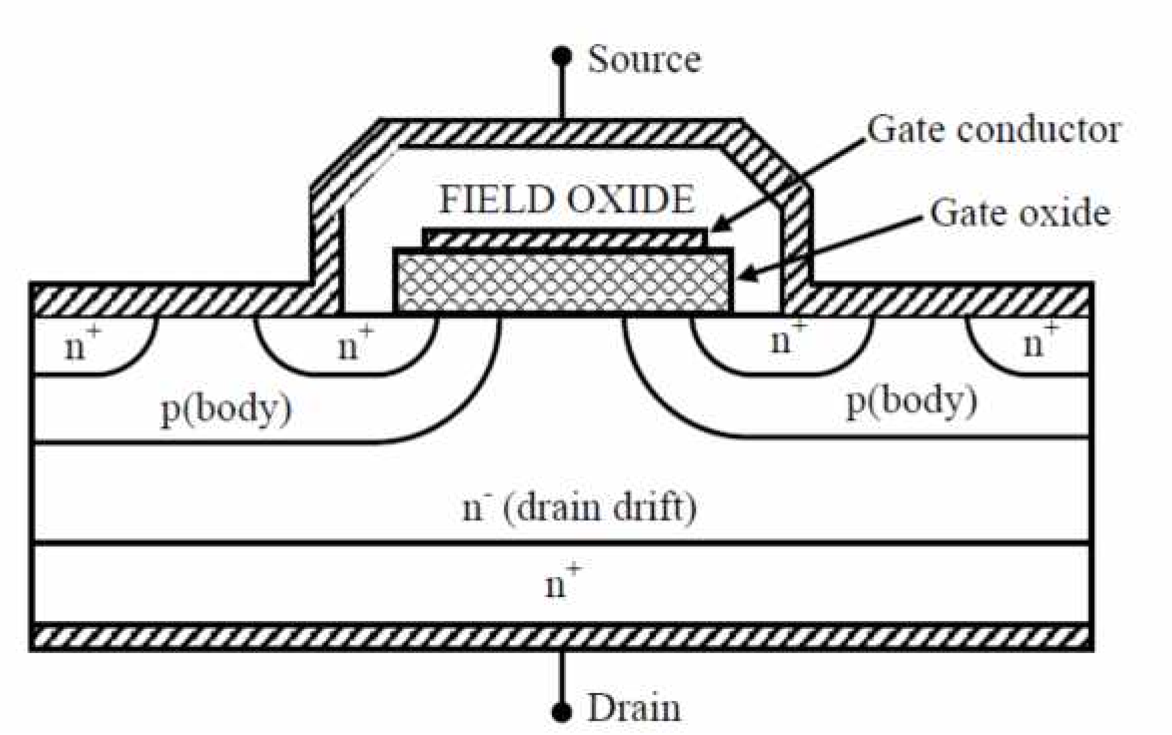


n-channel enhancement type MOSFET



p-channel enhancement type MOSFET

It can be concluded that depletion type MOSFETs are normally ON type switches, with the gate terminal open a nonzero drain current can flow in these devices. 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 which shown in figure below

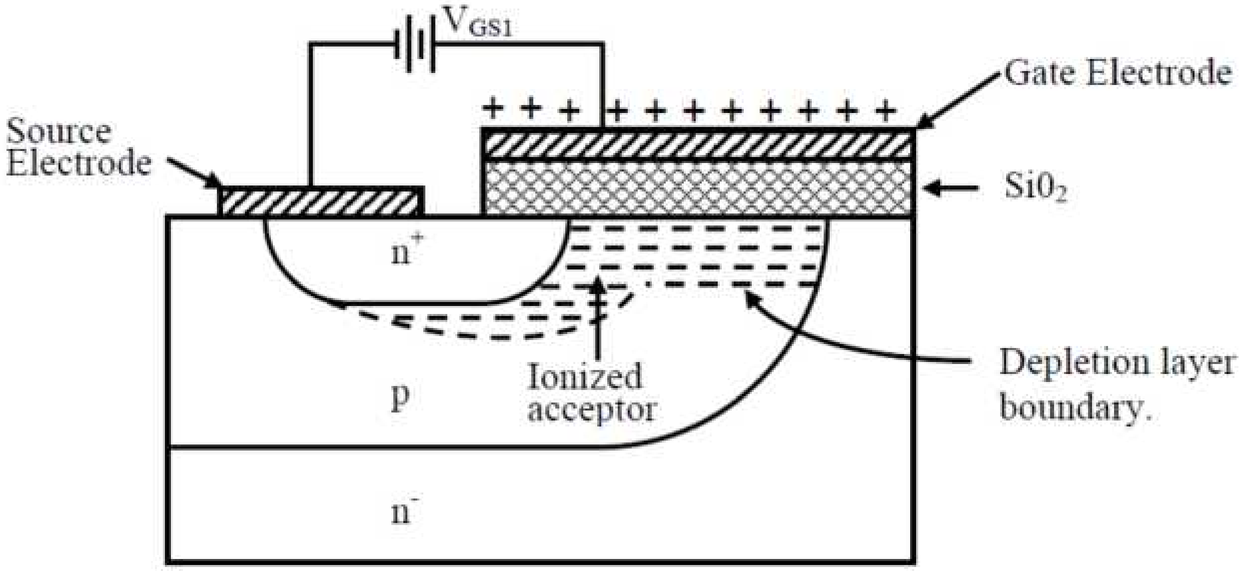


The two $\mathbf{n}^+$ end layers labeled “Source” and “Drain” are heavily doped to approximately the same level. The **p** type middle layer is termed the body (or substrate) and has moderate doping level. The $\mathbf{n}^-$ drain drift region has the lowest doping density. Thickness of this region determines the breakdown voltage of the device. The gate terminal is placed over the $\mathbf{n}^-$ and **p** type regions of the cell structure and is insulated from the semiconductor body be a thin layer of silicon dioxide (also called the gate oxide). The source and the drain region of all cells on a wafer are connected to the same metallic contacts to form the Source and the Drain terminals of the complete device

There is no path for any current to flow between the source and the drain terminals since at least one of the **p n** junctions (source – body and body-Drain) will be reverse biased for either polarity of the applied voltage between the source and the drain. The gate (silicon) oxide layer and the p-body silicon forms a high quality capacitor. When a small voltage is gate terminal positive with respect to the source, a depletion region forms at the interface between the $SiO_2$ and the silicon.

When gate is made positive with respect to source, an electric field is established and negative charge “electron” in p-substrate (below $SiO_2$) formed, and construct an n- channel and current can flow from drain to source. If $V_{GS}$ increase will causes the depletion layer to grow in thickness. At the same time the electric field at the oxide-silicon interface gets larger and begins to attract free electrons. The source of electron is electron-hole generation by thermal ionization.

The disadvantage of n-channel : conducting between the source and drain give large ON-state resistance and high power dissipation. This planner MOSFET construction replace with vertical flow of electron from drain to source. Power MOSFET is very loss device at high current application, it could used in high switching application.



Comparison between PMOSFET and PBJT

1-MOSFET is unipolar, BJT is bipolar

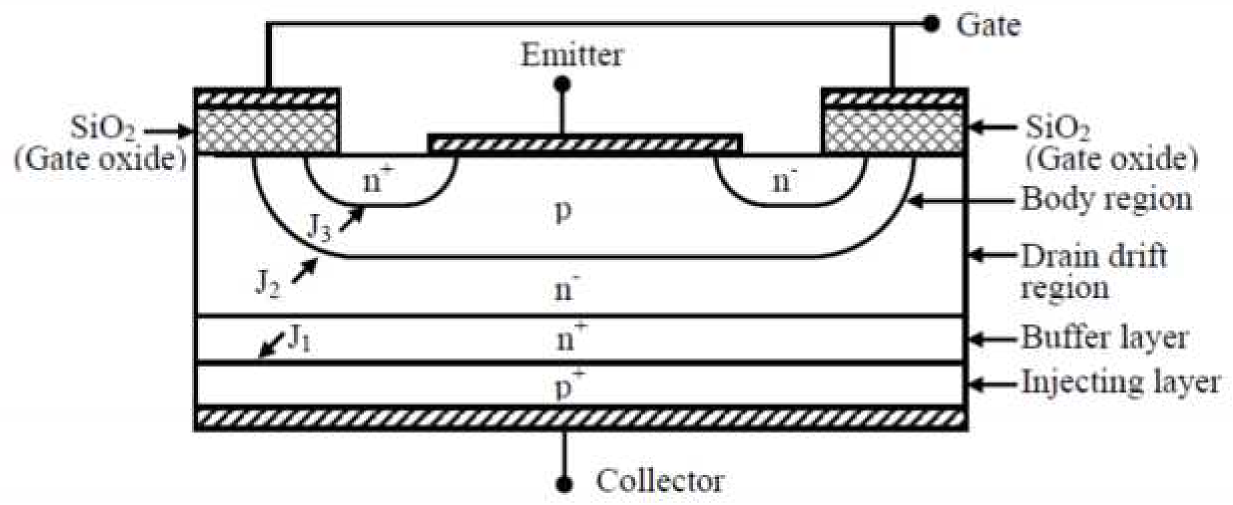
2-MOSFET has low switching losses but conduction losses is high, BJT has high switching losses but lower conduction losses

3-MOSFET has high input impedance, BJT has low input impedance.

4-MOSFET is voltage controlled, BJT is current controlled.

## Insulated Gate Bipolar Transistor (IGBT)

The insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch and in newer devices is noted for combining high efficiency and fast switching. The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low-saturation-voltage capability of bipolar transistors. The IGBT combines an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is a semiconductor device with four alternating layers (P-N-P-N) that are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action. An IGBT cell is constructed similarly to a n-channel vertical construction power MOSFET except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP bipolar junction transistor.



## Static Induction Transistor (SIT)

Static induction transistor (SIT) is a high power, high frequency device. It is a vertical structure device with short multichannel. Being a vertical device, the SIT structure offers advantages in obtaining higher breakdown voltages than a Field-effect transistor (FET). For the SIT, it is not limited by the surface breakdown between gate and drain, and can operate at a very high current and voltage.

Characteristics of SIT

- short channel length
- low gate series resistance
- low gate-source capacitance
- small thermal resistance
- low noise
- low distortion
- high audio frequency power capability
- short turn-on and turn-off time, typically 0.25 μs