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E- Content

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Title : Power Devices- II

- ## IGBT

An insulated-gate bipolar transistors (IGBTs) combines the BJTs and MOSFETs. An IGBT has high input impedance like MOSFETs and low on-state conduction losses like BJTs.

The other names to this device are insulated gate transistor (IGT) and bipolar mode MOSFET or bipolar MOS transistor. IGBTs are finding increasing applications in medium-power applications such as dc and ac motor drives, power supplies, solid state relays and contactors.

Structure of IGBT:-

The vertically oriented structure of IGBT is as shown in fig 1(a) (IGBT uses the vertically oriented structure in order to maximize the area available for the current flow). This will reduce the resistance offered to the current flow and hence the on state power loss taking place in the device.

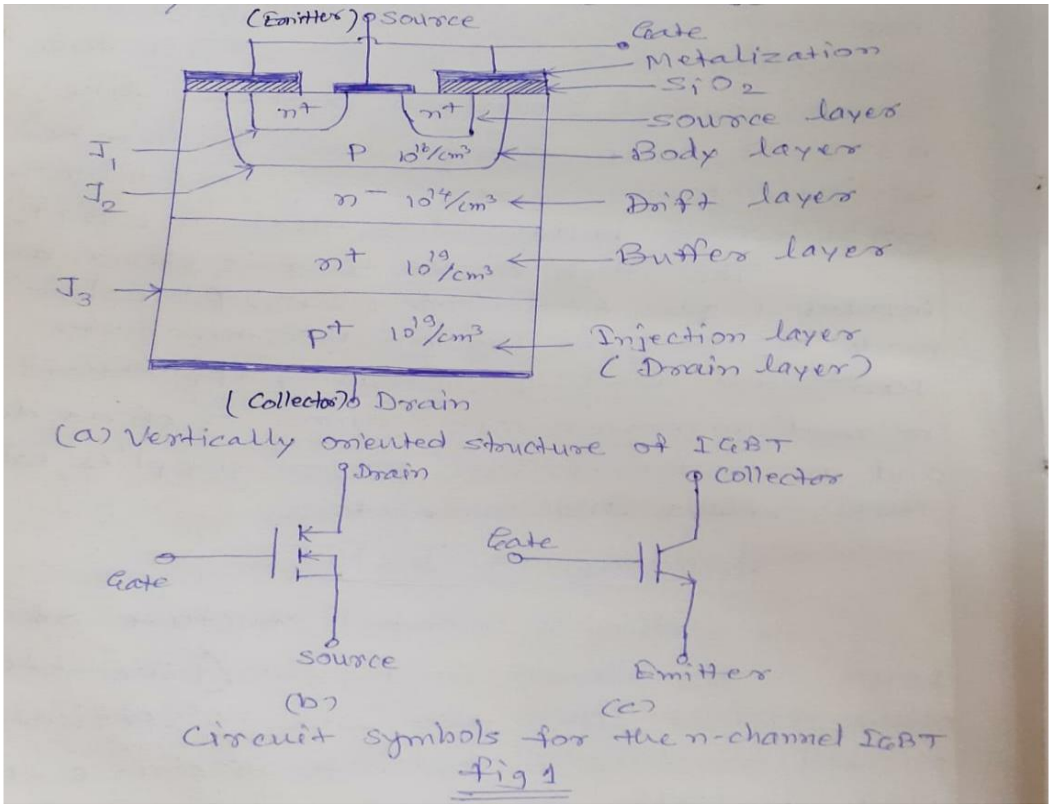


Fig 1(a): Structure of IGBT

Fig 1(b): Circuit Symbols of IGBT

The doping levels used in different layers of IGBT are as shown. The main difference in the structure of IGBTs compared to that of MOSFET is the existence of p+ layer that forms the drain of the IGBT. This device also uses the n- type drift layer which improves its breakdown voltage capacity (this is same as that in case of power MOSFETs).

The n+ buffer layer (is not essential for the operation of IGBT this layer) improves the operation of IGBT in two important aspects: (i) It reduces the on state voltage drop across the device and (ii) It shortens the turn-off time But the drawback is that presence of the buffer layer greatly reduces the reverse blocking capacity of the IGBT.

<u>Circuit Symbol for IGBT</u>:-

The circuit symbols for an n-channel IGBT are shows in fig 1 (b) & (c).The symbol shown in figure 1(c) is used if IGBT is considered to be basically a BJT with MOSFET gate input.

- ## <u>IGBT I-V Characteristics:</u>

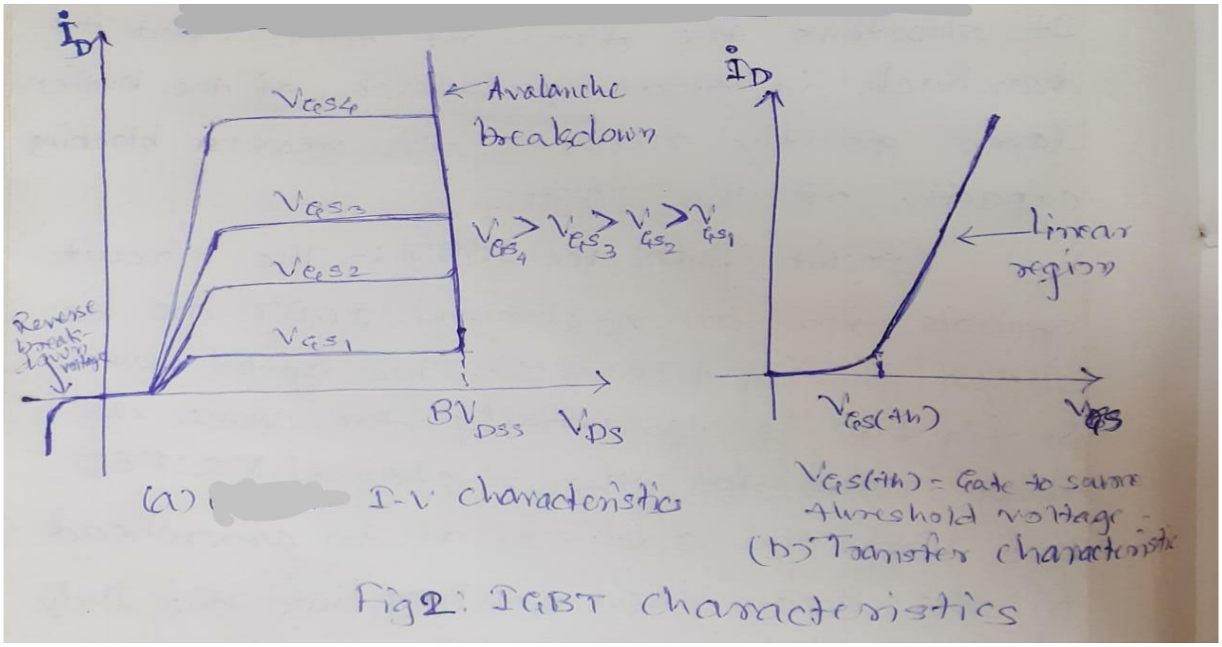


Fig. 2(a): IGBT I-V Characteristics
Fig. 2(b): Transfer Characteristics

The I-V characteristics of IGBT is as shown in figure 2(a). In the forward direction they are similar to those of the transistor, the only difference is that the controlling parameter is the gate to source voltage. Thus IGBT is a voltage controlled device with an insulated gate. The IGBT possesses all the advantages of MOSFET due to the insulated gate. It also has all the advantages of the BJT due to bipolar conduction. As seen from the fig 2 (b) the transfer characteristics is fairly linear, over most of the range when the drain current is higher. The curve becomes nonlinear for low values of drain current.

As seen from the fig2 (a), the drain current (or the collector current) increases with increase in the voltage between gate and source (V_{GS}). Also the gate to source voltage V_{GS} is positive. BV_{DSS} is the forward breakdown voltage. This is the voltage at which the avalanche breakdown takes. At this point the voltage across the device and current through it both are high. Therefore the power dissipation in the device will be very large and will damage it. The device must be therefore operated below this voltage.

The transfer characteristics relates the output parameter that is being controlled (I_D) in this case and the controlling parameter on the input side (V_{GS}) in this case. As seen from this characteristics, it is linear above the threshold value of gate to source voltage $V_{GS(th)}$. Therefore in order to operate the IGBT in the linear portion of these characteristics, it is necessary to apply V_{GS} greater than $V_{GS(th)}$.

- **Operation of IGBT**

The principle of operation of IGBT is similar to that of a MOSFETs. The operation can be divided into 2 parts

1. Creation of inversion layer and
2. Conductivity modulation

1. Creation of inversion layer:

The operation of IGBT is based on the principle of creation of inversion layer. If the gate voltage is increased further, the number of electrons below the SiO_2 layer will be greater than the number of holes. Thus the conductivity or a part of p layer close to SiO_2layer will change from positive to negative. That means of an n-type of sub-layer is formed below the SiO_2 layer. This process is known as creation of the inversion layer.

Due to the formation of n-type of layer in the p type body layer, a channel is formed (n+ n n-) which helps to establish the Current as shown in fig 1(a). The only difference between the MOSFET and IGBT is that there is no conductivity modulation of drift layer in MOSFET (Therefore the on state resistance $R_{DS(on)}$ and hence the state power loss is very high in MOSFET). However in IGBT the conductivity modulation takes place.

2. Conductivity modulation in IGBT:

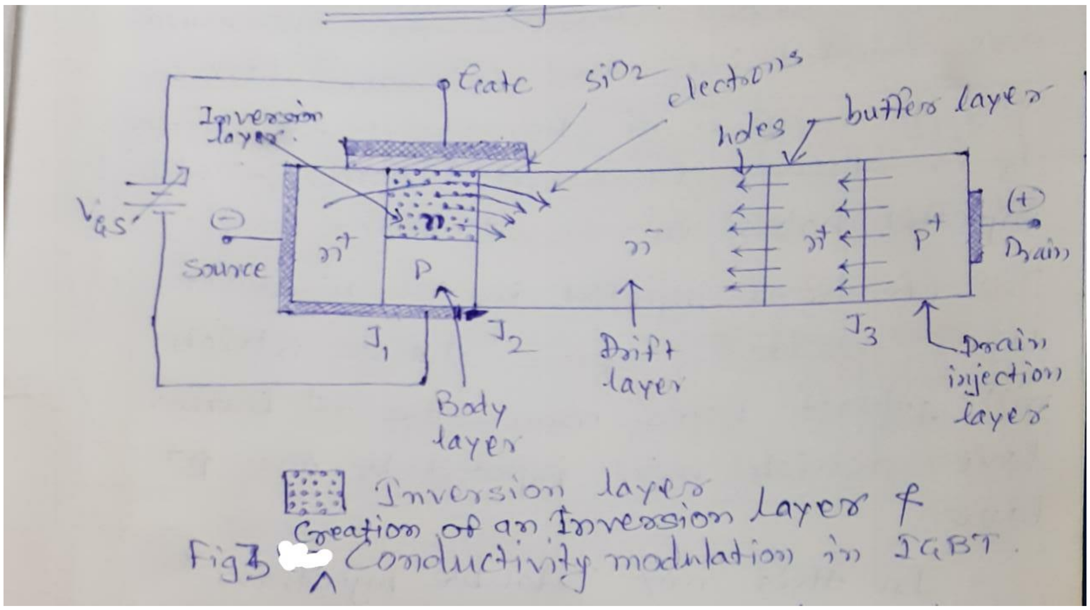


Fig. 3: Creation of an Inversion Layer and Conductivity Modulation in IGBT

In IGBT the conductivity modulation of the n- drift layer takes place. The effect of conductivity modulation is reduction in the on state resistance and hence the on state power loss. Therefore the on state losses in IGBT are less than in MOSFETs.

The conductivity modulation in the n- drift layer can be explained with the help of figure 3. Due to application of forward voltage between drain collector and source emitter the junction J_3 is forward biased. Due to the creation of inversion layer, electrons from the source are injected into the n- drift player via the n+ n n- channel. As the junction J_3 is already forward biased, it will injected holes in the n+ buffer layer. The electrons injected in the n- drift layer create a space charge which will attract holes from the n+ buffer layer which were injected by the p+ layer.

In this way double injection takes place into the n- drift region from both sides as shown. This increases the conductivity of the drift region and reduces the resistance to its minimum. So the conductivity modulation will reduce the on state voltage across the IGBT

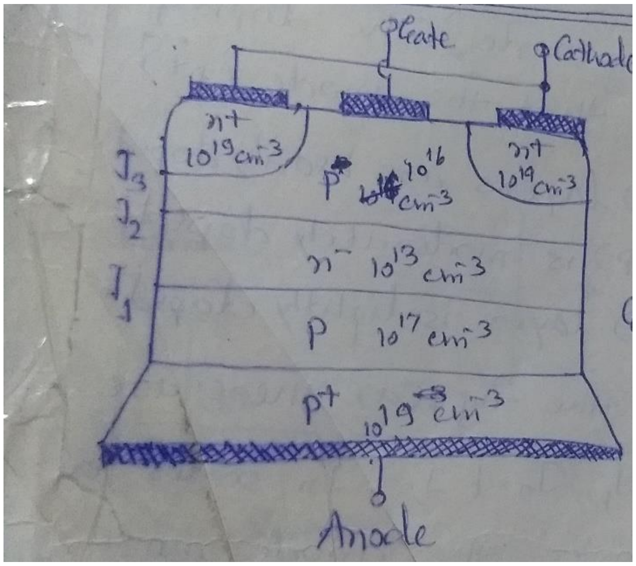
- **Comparison of Power BJT, MOSFET and IGBT:**

Sr. No.	Parameter	Power BJT	Power MOSFET	IGBT
1	Operating frequency	10 kHz	100kHz	10kHz
2.	Trigger circuit	Current controlled needs continuous base drive	Voltage control needs continuous gate drive	Voltage control needs continuous gate drive
3.	On state voltage drop	< 2 volts	4-5 volts	3 volts
4.	Snubbers	Necessary polarized	Snubber can be eliminated. If used a polarized snubber is used	Snubber can be eliminated. If used a polarized snubber is used
5.	Maxing V-I ratings	2kV/1000 A	600V/200A	1500V/400A
6.	Applications	UPS, SMPS, AC motor control	AC motor control, SMPS	SMPS, UPS, AC motor control

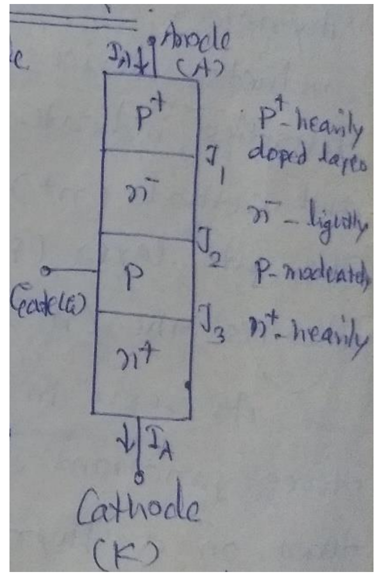
- **Thyristors**

The thyristors sometimes termed silicon controlled rectifiers (SCRs) are one of oldest types of solid state power device. The thyristors have the highest power handling capacity of all the power semiconductor devices. The special construction features of thyristors ensure the highest power handling capacity.

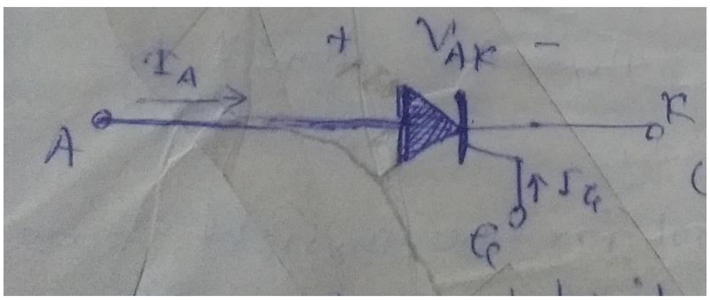
- **Structure of SCR: -**



(a) Vertical cross-section of SCR



(b) Basic structure of SCR



(c) Circuit symbol of a thyristor

Fig 1: Structural details of Thyristor

The basic structure of thyristor is as shown in fig 1(b). It is a four layer PNPN device, with three terminals brought out for the users, they are anode, and cathode and gate. The gate terminal is the control terminal that can turn on the device whenever required. The vertical cross section of a thyristor is as shown in fig 1 (a).The doping densities indicate that the anode (p^+) and cathode (n^+) layers are heavily doped. The gate layer (P) is moderately doped whereas the (n^-) layer is lightly doped. As seen in the Fig 1(a) there are three junctions J_1, J_2, J_3.In order to turn on a thyristor, the anode must be at higher positive potential than cathode i.e. the thyristor should be forward biased. The symbol for the thyristors as shown in fig 1(c). (1t is essentially the symbol of rectifying diode with a third control terminal, the gate added to it.) (The directions of forward anode current, voltage across SCR and the direction of conventional gate current are as shown.) The directions of anode and gate current in fig 1(C) are conventional current directions. It clearly indicates that SCR is a unidirectional device and also that gate current can be positive only.

- **<u>I-V Characteristics of SCR:-</u>**

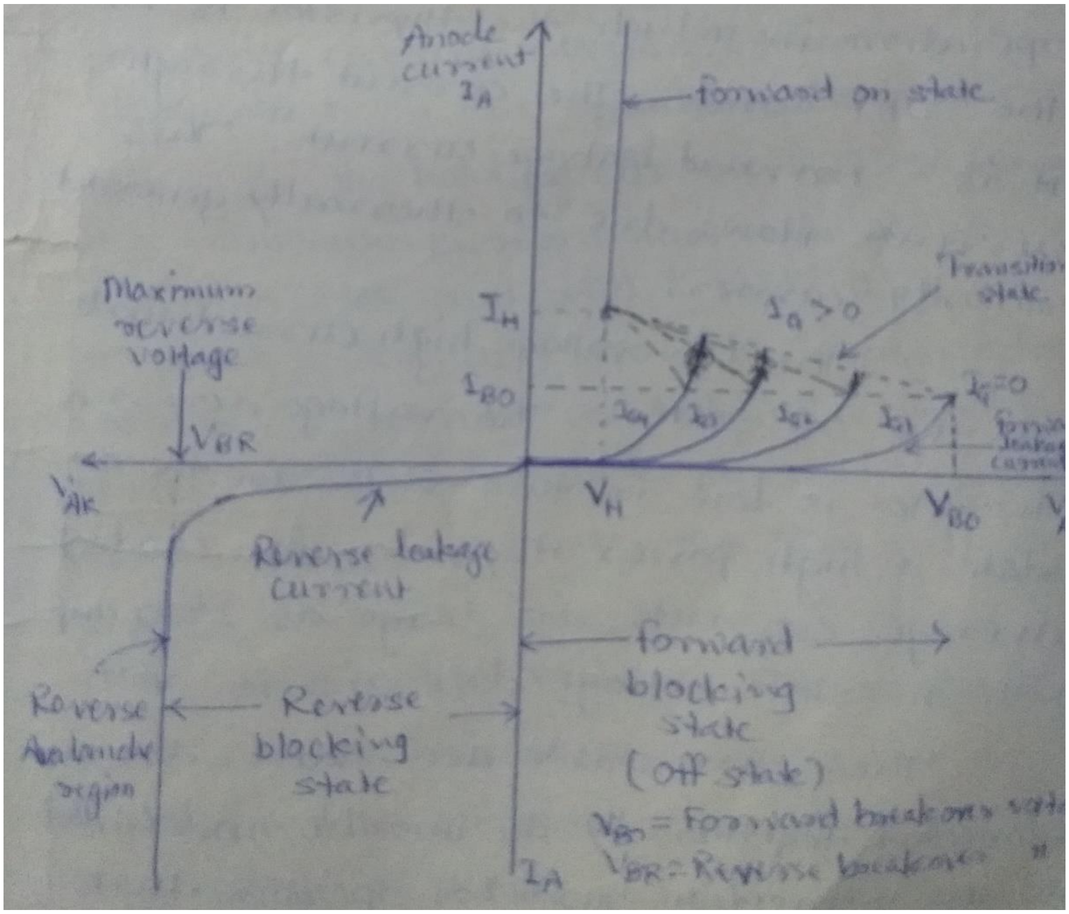


Fig. 2: I-V Characteristics of SCR

The graph of anode current I_A versus the anode to cathode voltage V_{AK} of a thyristor is as shown in fig.2.The characteristics in the reverse direction is similar to a reverse biased diode. For lower reverse voltage a small reverse leakage current flows until the avalanche breakdown takes place at reverse break over voltage V_{BR}.

The forward characteristics has two stable states or modes of operation

1. Forward blocking state (mode):- This is the high voltage low current mode of operation in which the thyristor is in the “Off" state. The current through it is "Forward leakage current”. This current flows due to thermally generated minority carriers.

2. The low voltage high current mode or on state:-

The voltage across a thyristor is low in this state. In the on state a high power thyristor can conducts average currents as large as 2000 amp with on state voltage drop of a few volts.

These two stable states are connected together by an unstable mode (called as the transition mode) of operation that appears as a negative resistance on the I-V Characteristics (dotted line in fig 2)

The important voltage & current terms in the-V characteristics are as follows:-

1. The forward breakover voltage V_{B0}: -This is the maximum forward voltage that can be applied between anode and cathode, without initiating forward conduction

(This voltage is defined for a zero gate current. In short this is the maximum forward voltage across the the SCR in its off state.)

2. The forward leakage current: - The small current flowing in the forward direction in the off state of the device. (This current is generated due to minority Current carriers and therefore is dependent on the operating temperature.)

3. The holding current I_H: - It represents the minimum current that can flow through the thyristor and still "hold" it in the on state. The accompanying (corresponding) voltage is termed as holding voltage V_H.
(If the forward anode current is reduced below holding current, the SCR will be turned off.)

4. On state voltage: - The voltage across the SCR in its on state is very low as compared to the off state voltage. (The on state voltage is equal to drop across one junction) (If of the order of 1 to 1.5 volts)

- **Operation of SCR:**

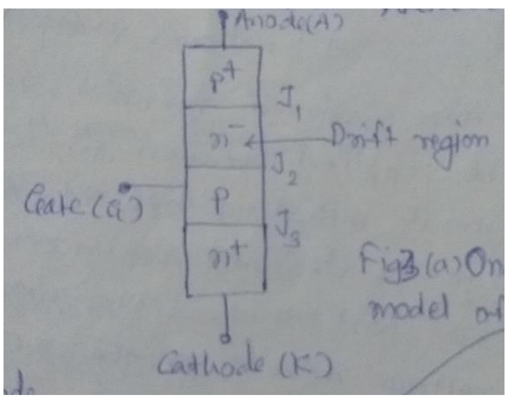


Fig. 3(a): One dimensional model of a thyristor

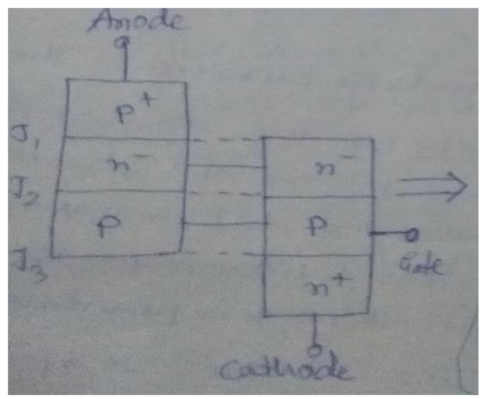


Fig. 3(b): Transistor equivalent circuit

The operation of a thyristor can be explained with the help of the one dimension model as shown in fig 3(a). (The device is considered to be an ideal device). A low frequency equivalent circuit made up of a pnp and npn transistor is as shown in fig 3(b).

Operation in the reverse blocking state:-
In the reverse blocking state, anode is biased negative with respect to cathode. Therefore the junctions J_1 and J_3 are reverse biased and the junction J_2 is forward biased. Out of the two reverse biased junctions J_1 and J_3 the lower junction I has allow breakdown voltage due to the heavy

doping on both sides of it. Therefore the reverse blocking capacity depends entirely on junction J_1.The reverse blocking capacity of junction J_1 is usually decided by the length of n^- region.

Operation in the forward blocking state: -

In the forward blocking state, the thyristor has to block a forward voltage because anode is biased positive with respect to cathode. Therefore the junctions J_1 and J_3 are forward biased and junction J_2 is reverse biased. The junction J_2 has to block the entire anode to cathode voltage. In order to achieve this n^-layer is lightly doped and made wide enough. The depletion region of the reverse biased J_2 junction appears in this layers. Thus this region decides the forward blocking voltage.

Reverse voltage rating is higher than forward Voltage rating:-

The reverse voltage rating of the device is the sum of ratings of J_1 and J_3, while the forward voltage rating is the rating of J_2 junction. Since the layer is lightly doped and narrower than anode layer, the voltage blocking capacity of J_1 is larger than that of J_2. Also this means rating of $(J_1 + J_3)$ is even larger than that of J_2. Hence for a thyristor the reverse voltage rating is usually greater than its forward voltage rating. Therefore the forward voltage is used as a criteria while designing thyristorised circuits.

(The forward and reverse blocking voltages are dependent on the junction temperature. They reduce with increase in junction temperature beyond 150°C.

Therefore most manufactures specify the maximum junction temperature for their thyristors at 125°c).

- <u>**Two Transistor Analogy (Equivalent Circuit): -**</u>

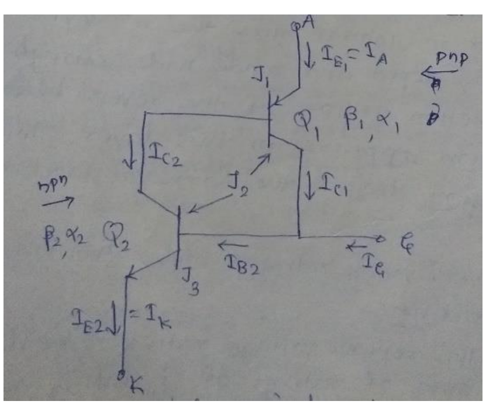


Fig 4:- Two transistor equivalent circuit of a thyristor

Assume that both the transistors Q_1 and $Q_2$are in the active region. The transistor common base and common emitter current gains are α_1, α_2 and $ß_1$, $ß_2$ respectively as shown in fig 4 above.

A bipolar transistor (Q_1 and Q_2) at low frequencies by the Ebers-Moll equations are

$Ic_1 = \alpha_1 IE_1 + Ico_1$ ---------------------------------- (1)

And $Ic2 = \alpha_2 IE_2 + Ico_2$ -------------------------------- (2)

Where the leakage current is given by

$I_{co} = I_{cs} (1- \alpha_f \alpha_r)$ -------------------------- (3)
Where Ics - Reverse saturation current of collector
to base diode with emitter open.

α_f = forward active mode base transport coefficient

α_r = reverse active mode base transport coefficient

$\alpha = \beta / 1 + \beta$-------------------- (4)

If $I_A = I_{E1}$ and $I_k = I_{E2} = I_A + I_G$ and setting the sum of all the currents into one of the transistors to zero.

From the fig 4 above

$I_{E2} = I_{c2} + I_{B2}$ ---------------------------------- (5)

But $I_{E2} = I_A + I_G$

$I_A + I_G = I_{c2} + I_{B2}$ .... (6)

But $I_{B2} = I_{c1} + I_G$

$I_A + I_G = I_{c2} + I_{C1} + I_G$ -------------- (7)

But $I_{c2} = \alpha_2 I_{E2} + I_{co2}$ and $I_{c1} = \alpha_1 I_{E1} + I_{co1}$

$I_A = \alpha_2 I_{E2} + I_{co2} + \alpha_1 I_{E1} + I_{co1}$.................................(8)

But $I_{E2} = I_A + I_G$ and $I_{E1} = I_A$

Therefore equation (8) can be written as

$I_A = \alpha_2 (I_A + I_G) + I_{co2} + \alpha_1 (I_A) + I_{co1}$-------------------------- (9)

Therefore, $I_A - \alpha_2 I_A - \alpha_1 I_A = \alpha_2 I_G + I_{co1} + I_{co2}$

Therefore $I_A = (\alpha_2 I_G + I_{co1} + I_{co2}) / \ 1 - (\alpha_1 + \alpha_2)$ ------------ (10)

In the off state the sum of $(\alpha_1 + \alpha_2)$ must be much less than unity. So anode current I_A can be kept quite small.

If $(\alpha_1 + \alpha_2)$ approaches unity, the denominator of the equation no. 10 will be very small and the thyristor will be at the break down point, ready to enter into the transition state. The current gains of the two transistors Q_1 and Q_2 would be high, then the collector current of one transistor acts as base current for other one. The base current of first is collector current of second. This cumulative current multiplication, soon increase the anode current, so that SCR will be in ON state .This is the turn-on process of thyristor.

(As the forward anode- cathode voltage is increased, the depletion region of junction J_2grows into the n^- layer (base layer of PNP).

The effective thickness of base region reduces and hence $\alpha_1$increases.Similarly the extension of depletion region (base of npn) will cause increase in value of $\alpha 2$.)

- **<u>SCR Turn On Process:-</u>**

A thyristor turns on when forward anode to cathode voltage is increased.

1. When the gate drive is applied, it injects holes in the gate layer. These holes acts as the base drive to the pnp transistor.
2. The space charge of the injected holes will attract electrons from the n^+ layer i.e. cathode to flow towards the edge of the depletion layer due to both drift and diffusion.
3. These elections are swept into the drift layer (n^-) due to electric field created by the depletion region of the reverse biased junction J_2 These elections now acts as base current for the pnp transistor.

4. The space charge of the excess electrons in the drift layer (n^-) will attract holes from are anode layer (p+), which will flow towards the edge of the depletion layer by both drift and diffusion.
5 The electric field is in such a direction that any holes in the vicinity of the depletion layer will be swept into the gate layer (P).
6. These swept holes into gate layer acts as base drive to the npn transistor.
Thus the action is cumulative and can continue even without the gate drive once the anode current exceeds the "Latching current". When the SCR is conducting, all the four layers are flooded with free carriers and the reverse biased junction J_2no longer exists, and the SCR remains in the on state without the gate drive

$V_{AK(on)} = V_{J1} - V_{J2} + V_{J3} + Vn^-$ -------------------- (1)

Where V_{J1}, V_{J2}, V_{J3} are the voltages across the three junctions J_1, J2 and J_3 and Vn^-as voltage of o.l V. The value of the other on state voltage a thyristor is approx. one junction drop)

- **SCR Turn Off Process: -**

Once a thyristor is turned on, it gets latched into its on state of acts like a closed switch. The gate terminal looses control over the thyristor it even though the gate pulses are removed the thyristor remains in the on state. A conducting SCR can be turned off with the help of an external circuit, by reducing the anode current below its holding current for a minimum specified time.
During this time, the stored change inside the device will be removed due to internal recombination and carries sweepont. Due to this, the transistors Q_1 and Q_2 in the equivalent circuit, come out of saturation and enter into active region. The values of $\alpha_1$and α2will decrease, the recombination will decrease of the conducting SCR will turn off.
The minimum time required for the recombination of carrier sweepont should be provided before the device is turned on again. This is necessary fire the successful turn off of a thyristor.

- **Thyristor Ratings:-**

All semiconductor devices have definite limits to their capability and exceeding these even for short times will result in failure, loss of control or damage (All thyristors therefore have to be used within their limits and this must include extreme conditions as many
exist during their circuit faults and it must take into account load, supply system, temperature and environmental variations.) Therefore, the reliable operation of the device can be ensured only if its ratings are not exceeded under all operating conditions.

1. **Voltage Ratings:-** (It is essential that the voltage capability of a thyristor is not exceeded during operation even for a very short period of time),

a) Working peak reverse voltage: -This is the maximum instantaneous value of the reverse voltage that occurs across the device excluding all transient voltages.
b) On state voltage: - This is the voltage drop between anode and cathode with specified forward ON state current & junction temperature, its value is of the order of 1 to 1.5 V.
c) Grade trigger voltage: -This is the minimum gate voltage required to produce are gate trigger current.
d) Forward dv / dt rating:-The dv / dt at rating of a thyristors indicates the maximum sate of rise of anode voltage that will not triggers the device without any gate signal. (It also depends on the junction temperature, higher the junction temperature, lower the dv / dt of the device.)

2. **Current Rating: -**The current carrying ability of the thyristor is determined by the temperature at its junction. Hence even for short overs currents, the junction temperature may exceed the rated value and the device maybe damaged.

a) Average on state current: - As the forward voltage drop across conducting SCR is very low, the power loss in an SCR depends mainly on forward average on state current. The current rating is the maximum junction temperature. (This rating varies with case temperature),

b) Surge current: - The surge current rating indicates the maximum possible non-repetitive or surge current, the device can withstand and this may occur due to non-repetitive faults or short circuit during the life span of a thyristor.

c) di / dt rating :- The di / dt rating of a thyristor indicates the maximum rate of rise in anode to cathode current. The maximum rate of change of current that the device can withstand during its ON state is called its critical rate of rise of current.

(The di / dt depends upon the level of the gate current used to trigger the thyristor, within limits, the higher the gate current, the higher the di / dt capability),

d) Holding current: - It may be defined as the minimum value of anode current below which the device stops conducting to returns to its off state.

e) Latching current - The latching current of a device may be defined as the minimum on state current required to keep the device in the on state after the triggering pulse has been removed.

f) Gate current: - The current which is applied to the gate of the thyristors for control purposes, is known as its gate current.

3. Power Rating: -

a) Forward conduction loss: - The average anode current multiplied by the forward voltage drop across the SCR is the average power dissipated in the thyristor.

b) Turn-on losses: - Since the switching process takes a finite time, there is a relatively high voltage across the thyristor while a current flows. Therefore, this loss is higher than the turn-off loss, higher the turn off loss.

c) Turn-off losses: - The turn off power losses arises during the time of decay of reverse current, according to the product of instantaneous values of reverse current& reverse voltage.

d) Gate power loss: - The gate power is the mean power power loss due to gate current, & between the gate & main terminals. Gate losses are negligible for pulse type triggering signals.

4. Thermal Ratings:-

a) Junction temperature: - A thyristor's ability to block forward voltage applied to can only be maintained within a specific junction temperature limit. This is usually the deciding factor in controlling the maximum current that can be carried by the thyristor for any significant period of time.(The operating junction temperature range of thyristors varies for the individual types).

b) Transient thermal impedance: - This is the resistance between the junction of aThyristor and its cooling surfaces. It is invariably expressed as degree centigrade temperature difference per watt of energy dissipated. (The larger of the thyristor, the smaller will be its thermal resistance value).

- **<u>SCR Protection Circuits:-</u>**

1. **Concept of di/dt Protection :-** The SCR requires a minimum time to spread the current conduction uniformly throughout the junctions. If the rate of rise of anode current (di/dt) is very fast compared to the spreading velocity of a turn on process, a localized "hot-spot" heating will occur due to high current density and the device may fail (damage),as a result of excessive temperature.

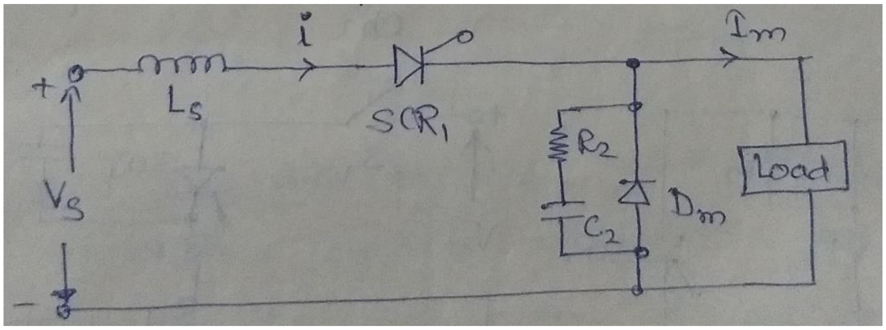


Fig. 1:- di/dt Protection Circuit

The practical devices must be protected against high di/dt. Let us consider the circuit in fig.1; gives the chopper circuit with di/dt limiting inductors. Under steady-state operation diode Dm conducts when SCR_1 is off. If SCR1 is fired when Dm is still conducting, di/dt can be very high and limited only by the stray inductance of the circuit.
In practice, the di/dt is limited by adding a series, inductor Ls, as shown.
The forward di/dt is Vs = Ls di/dt
Therefore, di/dt = Vs/Ls------------------ (1)
Where Ls is the series inductance including any stray inductance.

2. Concept of dv/dt Protection:-

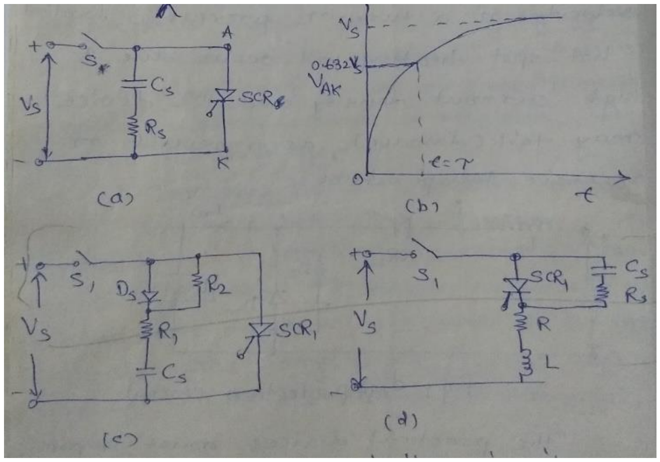


Fig. 2 dv/dt protection circuits

Fig 2 gives the dv/dt protection circuit for the SCR. If switch so closed at time t=0, a step voltage will be applied across SCR, and dv/dt may be high enough to turn on the device. The dv/dt can be limited by connecting capacitor Cs. When SCR is turned on the discharge current of capacitor is limited by resistor
Rs as shown in fig 2 (a).

With RC circuit known as a snubber circuit, the voltage across SCR. will rise exponentially shown in fig 2 (b) and the circuit dv/dt can be found approximately from
dv/dt = 0.632 Vs / T = 0.632 Vs / Rs Cs --------------------------- (1)
The value of snubber time constant T=Rs Cs can be determined from equation number (1) for a known value of dv/dt. (The value of Rs is found from the discharge current I_{TD}.

Rs = Vs/I_{TD}-- (2)

It is possible to use more than one resistor for dv/dt and discharging as shown in fig.2(c). The dv/dt is limited by R_1 and Cs. (R_1+ R_2) limits the discharging current such that

I_{TD} = Vs / R_1 + R_2-- (3)

The damping factor α = Rs + R / 2(Ls + L)
And the resonant frequency Wo = 1 / (Ls + L) Cs ---------------------- (4)
. The damping ratio of a second order equation is

δ = α / Wo = [Rs + R / 2(Ls + L)] x [(Ls + L) Cs]

= [(Rs + R) /2)] [Cs / (Ls + L)] ------------------------- (5)
Where Ls is the stray inductance and L and R are the load inductance and resistance respectively.)

To limit the peak voltage overshoot applied across the SCR, the damping ratio of R and C in the range 0.5 to 1.0 is used. The circuits of fig 2 above should be fully analyzed to determine the required value of damping ratio to limit the dv/dt to the desired value.

- **TRIAC:-**

(The major drawback of an SCR is it can conduct current in one direction only. However in an ac system, it is often desirable and necessary to exercise control over both positive and negative half cycles. For this purpose, a semiconductor device called triac is used).
The triac semiconductor switching device which can control alternating current in a load.

- **Construction: -**

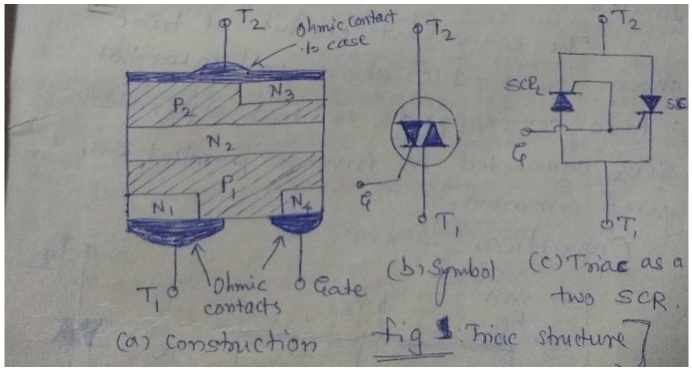


Fig2: Triac Structure

Fig.2 (a) gives the construction of triac while fig 2(b) gives its circuit symbol. The triac three terminal five-layer semiconductor device that acts as a power switch to control the flow of alternating current. In fig.2 (b) the two arrowheads show the direction of conventional current flow. (Thus we see current may flow in either direction between switch terminals T_1 and T_2)
The triac is therefore classified as a bidirectional or bilateral device. Terminal T_1 is the reference terminal from which all voltages are measured. Terminal T_2 is usually case or header to which a heat sink is attached.(The remaining gate terminal exercises limited control over the switching terminals.)
(The equivalent circuit of triac shown in fig 1(c) above indicates that a triac corresponds to two separate SCRs connected in inverse parallel with gates common.)

- **Operation:-**

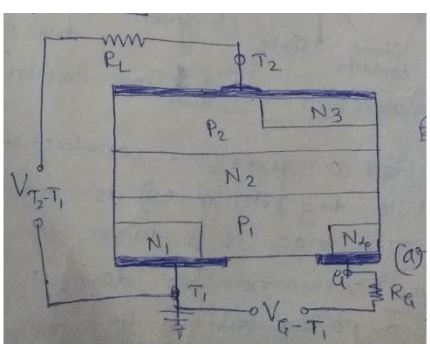


Fig. 2 (a): Triac Circuit

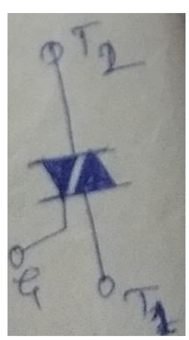


Fig. 2 (b): Circuit symbol

Fig. 2

Fig.2 shows the triac circuit to trigger the triac into forward and reverse conduction by the gate current. When sufficient positive or negative voltage is applied between gate and

terminalT_1, the triac's switch terminal conduct current (on-state) in a direction determined by the external circuit
When the terminal T_2 is positive w.r.t. T_1then current flows from $T_2$to T_1withinthe triac is designated as positive or forward conduction, while current flow from T_1toT_2 is designated as negative or reverse conduction.(The polarities agrees with the potential of T_2 with respect to T_1 when the triac conducts.) The direction of current flow in positive conduction is through the equivalent positive SCR-$P_2N_2P_1N_1$.The triac has negative conduction through equivalent SCR-$P_1N_2P_2N_3$.

- **<u>Characteristics:-</u>**

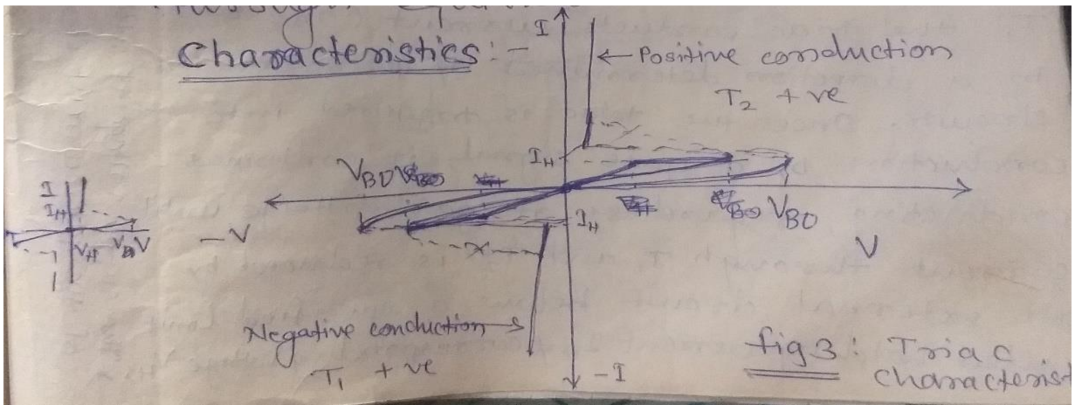


Fig3: Triac Characteristics

Fig.3 gives the volt-ampere characteristic of a triac. Because the triac essentially consists of two SCRs of opposite orientation fabricated in the same crystal, its operating characteristics I and III quadrant are the same except for the direction of applied voltage and current flows. When the switch terminal T_2 is positive w.r.t.T_1then the I-V characteristic curve fall in the first quadrant if the positive conduction. The positive conduction is also called mode I (mode one) operation, to correspond with the quadrant Current direction and voltage from $T_2$to T_1 is reversed for negative conduction and negative I-V characteristic would fall in the third quadrant. Thus negative conduction operation is represented by the shorthand notation mode III (mode three).
When sufficient positive or negative voltage is applied between gate and terminal $T_{1,}$ the triac conducts current (on-state) in a direction determined by the external
circuit. Once the triac is triggered into conduction by a gate signal, it continues conducting, regardless of gate voltage, until current through T_1 and T_2 is reduced by the external circuit below a specified limit called holding current I_H and corresponding voltage V_H . The supply voltage at which the triac is turned on depends upon the value of the gate current i.e. the breakover voltage.

- **<u>MOS Controlled Thyristor:-</u>**

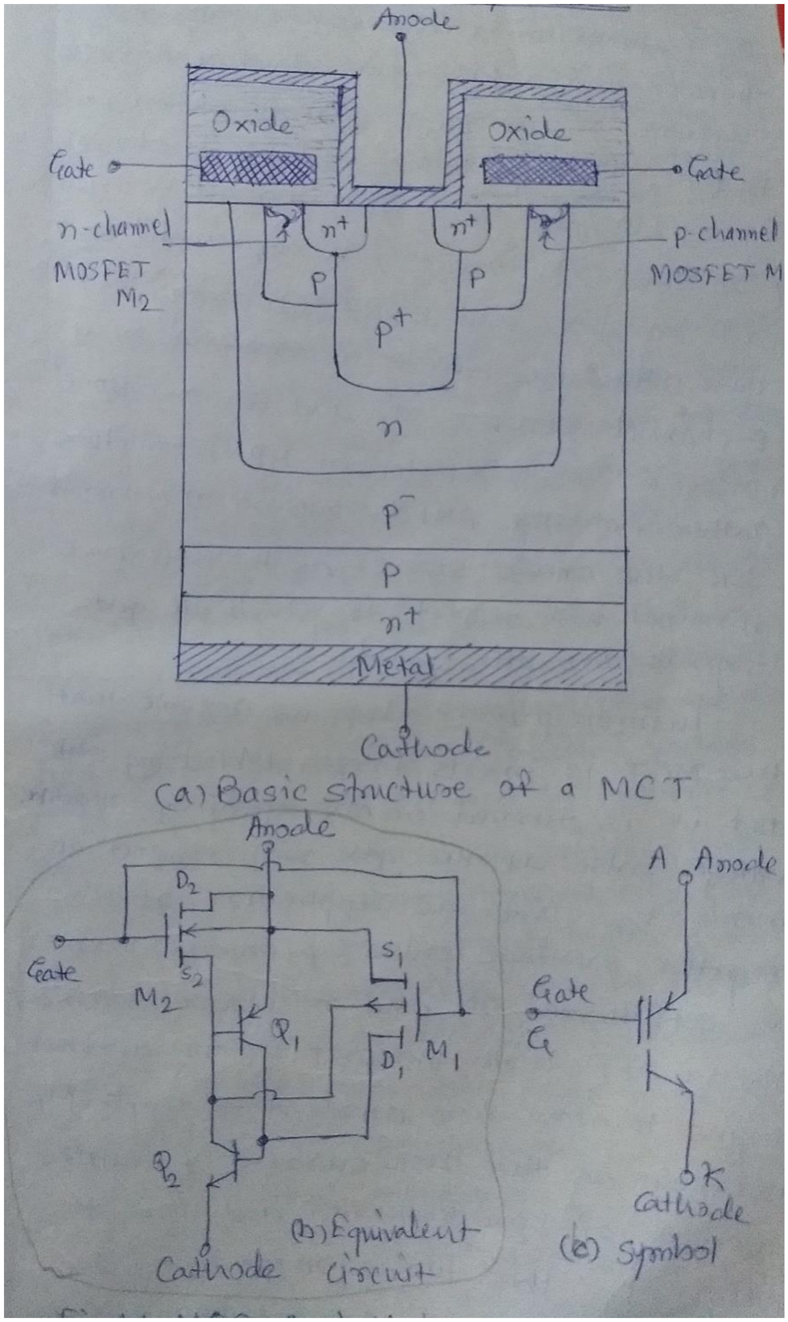


Fig 1: MOS controlled thyristor

A MOS. controlled thyristor (MCT) combines the features of a regenerative four-layer thyristors and a MOS-gate structure, A basic MCT cell is shown inFig.1 (a), (The equivalent circuit is shown in fig 1(b)) and the circuit symbol in figi.1(c).(The NPNP structure may be represented by an NPN-transistor and a PNP transistor.) The MOS-gate structure can be represented by a p-channel MOSFET M_1 and an n channel MOSFET M_2. Due to an NPNP structure rather than the PNPN structure of a normal SCR, the anode serves as the reference terminal with respect to which all gate signals are applied.

Turn-on Process: -Let us assume that the MCT is in its forward blocking state and it is turned on by applying a negative voltage pulse at the gate with respect to anode V_{GA}. With the application of this negative voltage pulse, p-channel MOSFETM_1 gets turned on and n channel

MOSFETM_2 is off. With MOSFET M_1, on, current begins to flow from anode A, through M_1 and then as the base current & emitter current of npn transistor) and then to cathode K.This turns on npn transistor. As a result, collector current begins to flow npn transistor. As channel MOSTETM_2 is off, this collector current of npn transistor acts as base current of pnp transistor. Subsequently pnp transistor is also turned on.
(Note that a channel MOSFET M_1 and pnp transistor are in parallel when thyristor is in conduction state. During the time MCT is on, base current flows mainly through pnp transistor because of its better conducting property.)

Turn-off Process: - Let us assume that the MCT is in its conduction state and for turning off the MCT, n-channel MOSFET$M_2$is energized by positive voltage pulse at the gate. With the application of positive voltage pulse, M_2 is turned on and M_1 is turned off. After M_2 is turned on, emitter base terminals of pnp transistor are short circuited by M_1. So now anode current begins to flow through M_1& therefore base current of pnp begins to decrease. Further collector current of pnp transistor that forms the base current of npn transistor also begins to decrease. As a consequence base currents of both transistors begin to decay/decreases. This regenerative action eventually turns off the MCT.

An MCT has the following merits:

(i) A low forward voltage drop during conduction.
(ii) A fast turn-on time (e.g. 0.4μs) and a fast turn off time (e.g. 1.25μs)
(iii) Low switching losses and
(iv) Low reverse voltage blocking capability and
(v) A high gate input impedance

An MCTs potential / main applications include dc & ac motor drives, UPS systems, induction heating, dc-dc converters, Power line conditioners etc.

Q.1 Select correct alternative.

1. ... is a unidirectional device.

a) SCR b) Triac c) IGBT d) Diac

2. -----------------modulation is a process where holes and electrons both are injected into the drift layer.

a) Resistivity b) amplitude c) phase d) conducting

3. Power transistor is the higher breakdown………………. Than conventional transistors due to the presence of the drift layer.

a) Current b) voltage and current c) voltage d) none

4. ----------- is a voltage controlled device.

a) SCR b) BJT c) BJT and MOSFET d) MOSFET

5. --------------- structure is obtained by adding an insulated gate to the power transistor and a p+ layer.

a) IGBT b) BJT c) SCR d) MOSFET

6. Which of the following device has the terminals collector, emitter and gate?

a) MOSFET b) IGBT c) BJT d) Triac

7. The effect of drift layer in power diode is the increase in the reverse -------------

a) current b) current and voltage c) breakdown voltage d) none

8. The process of conductivity modulation results in the reduction in the ---------------

a) current b) voltage c) power d) on state loss

9. The conductivity modulation in power BJT reduces the on state --------------------

a) voltage drop b) current c) power d) current and voltage

10. Power MOSFET is a -------------- carrier device.

a) minority b) majority c) minority and majority d) bipolar

11. A power diode uses a vertically oriented structure, as it reduces the on state --------------

a) voltage drop b) current c) power d) none

12. Leakage current is generated due to ----------------------

a) forward voltage b) reverse voltage c) temperature d) pressure

13. The typical value of current gain of a power transistor is -------------------

a) 1000 b) 100 c) 10 d) 1

14. Power transistor has a ------------breakdown voltage than conventional transistor due to the presence of the drift layer.

a) lower b) smaller c) moderate d) higher

15. The on state voltage drop across the MOSFET is -----------than that across a BJT.

a) greater b) less c) equal d) none

16. The width of the drift layer is always compromise between ---------------

a) On state losses and breakdown voltage. b) On state voltage and switching losses.
c) Low on state voltage drop and high breakdown voltage. d) On state current and switching losses.

17. The forward break over voltage of SCR. ---------------

a) Decreases with increase in gate current. b) Increases with increase in gate current.
c) Does not depend on the gate current. d) None of these

18. The holding current is------------

a) Less than latching current b) greater than latching current.
c) equal to the latching current d) greater than the anode current

19. A TRIAC is equivalent to-------------

a) two diodes in antiparallel b) one thyristor and one diode in parallel.

c) two thyristor in parallel d) two thyristor in antiparallel.

20. An inductance is connected in series with the SCR to protect it against--------

a) damage due to high dv/dt b) damage due to high power

c) damage due to high di/dt d) damage due to large forward current

21. The holding current is ....the latching current.

a) equal to b) greater than c) less than d) none of this

22. If the firing angle of SCR is 30 degree then its conduction angle is .... degree.

a) 60 b) 90 c) 120 d) 150

23. An IGBT has three terminals called as ....

a) drain, source, base b) collector, emitter, base

c) drain, source, gate d) collector, emitter, gate

24. The power BJT is a ....controlled device

a) voltage b) current c) current & voltage d) none of these

25. If the firing angle of SCR is 45 degree then its conduction angle is...........degree.

a) 30 b) 45 c) 90 d) 135

26. ....is a unidirectional device with three terminals.

a) SCR b) Diac c) Triac d) None of these

27. It is possible to turn off a conducting SCR by-----------------

a) Applying a positive gate voltage

b) Applying a negative gate voltage

c) Reducing the forward anode current below the holding current

d) Removing the gate drive to the SCR

Q. 2 Attempt any Two (Eight marks each)

1. Explain the construction and working of I-V characteristics of a thyristor.
2. Explain the basic structure of a power MOSFET and give principle of operation of it.
3. Explain the basic structure and operation of an IGBT.
4. Explain the operation of SCR with transistor analogy and obtain the anode current equation.
5. With the help of two transistor analogy explain the working of SCR and derive the expression of its anode current.

Q.3 Attempt any Four (Four marks each)

1. Explain the basic structure of a power transistor.
2. Give the principle of operation of MOSFET.
3. Explain the operation of series connected diode.
4. Give the principle of operation of IGBT.
5. Explain the operation of parallel connected diode.
6. Explain the basic structure of IGBT.
7. Describe the SPICE diode model.
8. Explain the characteristics or SCR.

9. Write short note on dv/dt rating of SCR
10. Explain the operation of series connected diodes.
11. Explain the operation of TRIAC.
12. Explain the operation of Power transistor.
13. Explain of operation of TRIAC.
14. Compare SCR and TRIAC.
15. Compare power MOSFET and BJT.
16. Draw the forward and reverse current voltage characteristics of SCR. Show I, I, V Bo and VBR on the characteristics.