

UNIVERSITY OF Hilla		LECTURE : 2
ENGINEERING FACULTY		SUBJECT : power Electronics
Medical Device Technology Engineering		LECTURE'S TITLE Power Semiconductor devices
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Power Semiconductor devices

Diodes

- 1- General purpose
- 2- High speed
- 3- Schottky

Transistors

- 1- BJT
- 2- MOSFET
- 3- IGBT
- 4-SIT

Thyristors

- 1- SCR
- 2- TRIAC
- 3- GTO
- 4- RCT
- 5-GATT
- 6- LASCR
- 7- MCT
- 8- SITH
- 9- UJT

1. Power Diodes

These are two terminal switches, as shown in Fig. 1 –a. The diode characteristic consists of two regions, as shown in Fig. 1 –b. Ideally, the diode is represented by a short circuit when forward biased and as an open circuit when reversed biased with the ideal characteristic shown in Fig. 1-c.

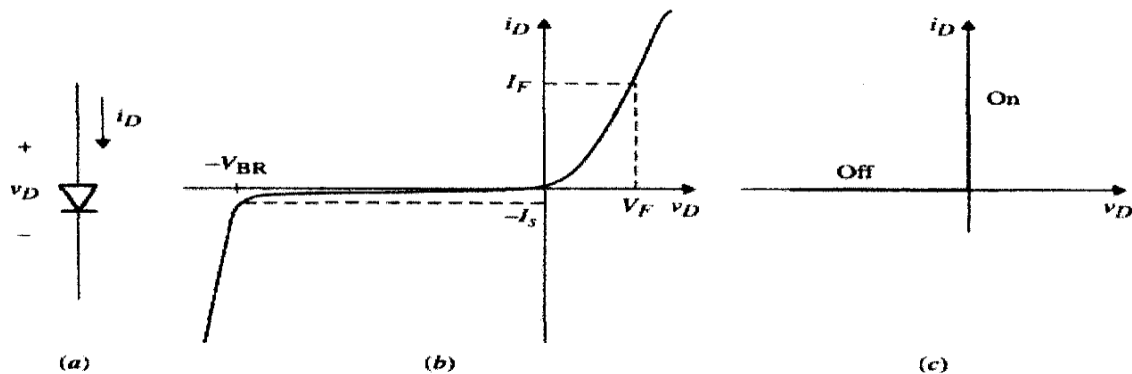


Fig. 1 Diode: a) symbol, b) characteristic, and c) ideal characteristic

Types of Power Diodes:

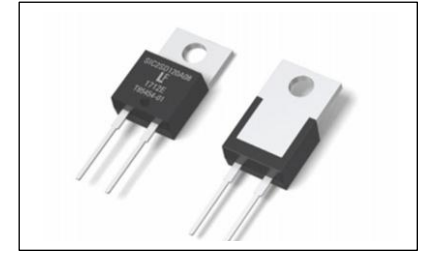
1. Line frequency (general purpose)

- on state voltage very low (below 1 V) ,
- large reverse recovery time t_{rr} (about 25 μ s) .
- Ratings are from 1A/50V to 1000 A/500V
- They can operate up to 1kHz
- used in line-frequency (50/60Hz) applications such as rectifiers.
- Slow recovery



2. Fast recovery

- very low t_{rr} ($<1 \mu s$).
- power levels at several hundred volts and several hundred amps.
- Ratings are from 1A/50V to 100A/3KV
- used in high frequency ,high speed applications
Such as choppers & inverters



3. Schottky

The pn junction is eliminated.

A thin film of metal is placed directly on the semiconductor
Aluminum is deposited on n type & semiconductor as p type.

The storage time is absent. t_{off} is very small (high switching frequency).

- very low forward voltage drop (typical 0.3V) (on state losses are very low)
- limited blocking voltage (50-100V) .
- used in low voltage, high current applications such as SMPSs and freewheeling diodes

Applications of power diodes

- 1- Uncontrolled rectifiers
- 2- Feedback & freewheeling operations in choppers, inverters & controlled converters
- 3- Almost the commutating circuits for SCRs
- 4- Half controlled converters and half bridge inverters .

Type of diode	Voltage –current ratings	Maximum frequency	On state voltage drop
General purpose	4KV/3.5KA	2KHz	1-2 V
High speed	2KV/1KA	12KHz	1-1.5V
Schottky	50V/50A	20KHz	0.5-1V

Table(1) ratings of power diodes

Switching Characteristics of Power Diodes

Current through diode before reversed biased

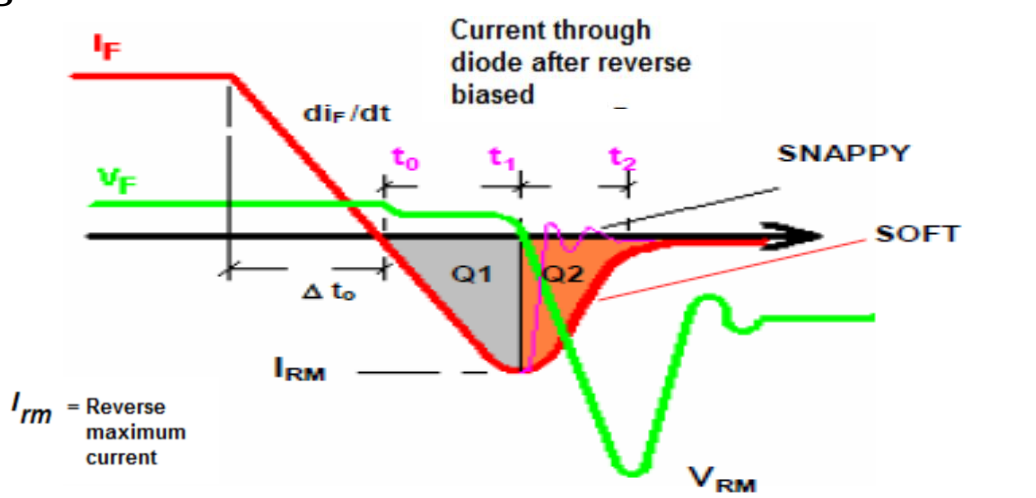


Fig.2 Switching Characteristics of Power Diodes

As shown in fig.2 Power Diodes take finite time to make transition from reverse bias to forward bias condition (**switch ON**) and vice versa (**switch OFF**).

Behavior of the diode current and voltage during these switching periods are important due to the following reasons.

- Severe over voltage / over current may be caused by a diode switching at different points in the circuit using the diode.
- Voltage and current exist simultaneously during switching operation of a diode. Therefore, every switching of the diode is associated with some energy loss. At high switching frequency this may contribute significantly to the overall power loss in the diode.

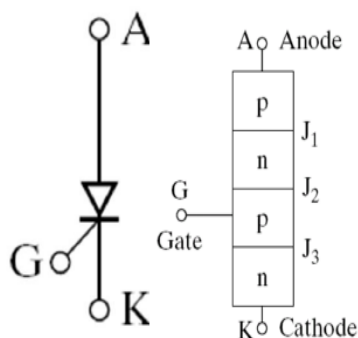
2. Power Thyristor

The modern power electronics area truly began with advent of thyristors. One of the first developments was the publication of the P-N-P-N transistor switch concept in 1956 by J.L. Moll and others at Bell Laboratories, probably for use in **Bell's Signal application**. However, engineers at **General Electric** quickly recognized its significance to power conversion and control and within nine months announced the first commercial Silicon Controlled Rectifier in 1957. This had a continuous current carrying capacity of 25A and a blocking voltage of 300V. Thyristors (also known as the **Silicon Controlled Rectifiers or SCRs**) have come a long way from this modest beginning and now high power light triggered SCRs with blocking voltage in excess of 6kv and continuous current rating in excess of 4kA are available. They have reigned supreme for two entire decades in the history of power electronics **fig.4.A** illustrates the graphics of SCR. **Fig.4.B** illustrates SCR circuit symbol

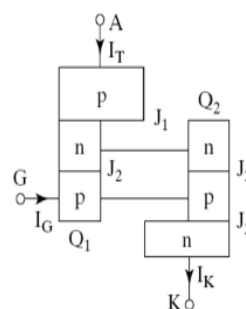
SCR or Thyristor, is a **four-layer, three terminal** switching semiconductor device, with each layer consisting of an alternately N or P-type material, for example N-P-N-P as shown in fig 4.C &D. that can handle **high currents and high voltages**, with better switching speed and improved breakdown voltage . The main terminals, labeled **anode** and **cathode**, are across the full four layers, and the control terminal, called the **gate**, is attached to one of the middle layers .



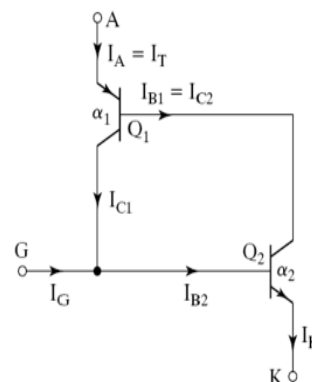
A



B



C



D

Fig.3 a) graphic b) circuit symbol c) layers' construction d) transistors equivalent circuit

-The name '**thyristor**', is derived by a combination of the capital letters from **THYR**atron and **transISTOR**.

-**Thyristor** has characteristics similar to a **thyatron** tube which is a type of gas filled tube used as a high energy electrical switch and controlled rectifier.

-This means that the **thyristor** is a solid state device like a transistor and has characteristics similar to that of a **thyatron** tube.

-Have the highest power handling capability. They have a rating of 5000V / 6000A with switching frequencies ranging from 1KHz to 20KHz.

-Is inherently a slow switching device compared to BJT or MOSFET.

-Used as a latching switch that can be **turned on by the control terminal** but **cannot be turned off by the gate**.

From the construction and operational point of view a thyristor is **minority carrier** semi-controlled device. It can be turned on by a current signal but can not be turned off without interrupting the main current. It can block voltage in both directions but can conduct current only in one direction. During conduction it offers very low forward voltage drop due to an internal latch-up mechanism. Thyristors have longer switching times (measured in tens of μs) compared to a BJT. This, coupled with the fact that a thyristor can not be turned off using a control input, have all but **eliminated thyristors in high frequency switching applications** involving a DC input (i.e, choppers, inverters). However in power frequency ac applications where the current naturally goes through zero, thyristor remain popular due to its low conduction loss its reverse voltage blocking capability and very low control power requirement. **In fact, in very high power (in excess of 50 MW) AC – DC (phase controlled converters) or AC – AC (cyclo-converters) converters, thyristors still remain the device of choice.**

SCR is a controllable switch that usually required to be latched to conduct. This latching (triggering) process is carried out by injecting current to the gate terminal (i_g), at the required latching instant provided that the device is forward biased (v_{AK} is positive).

Practically, **SCR characteristic has three main regions** as shown in Fig.4.A & B

- I- **The Conduction Region** where the thyristor is operating in its ON state,
- II- **The Forward Blocking Region** where the thyristor is forward biased but not yet triggered or the voltage didn't reach the forward breakover voltage.
- III- **The Reverse Region** that consists of the reverse blocking region and the reverse avalanche region similar to the diode characteristic.

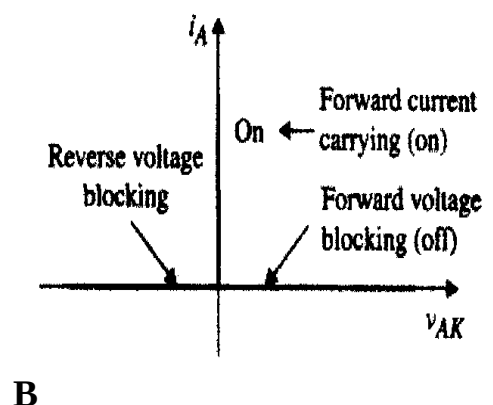
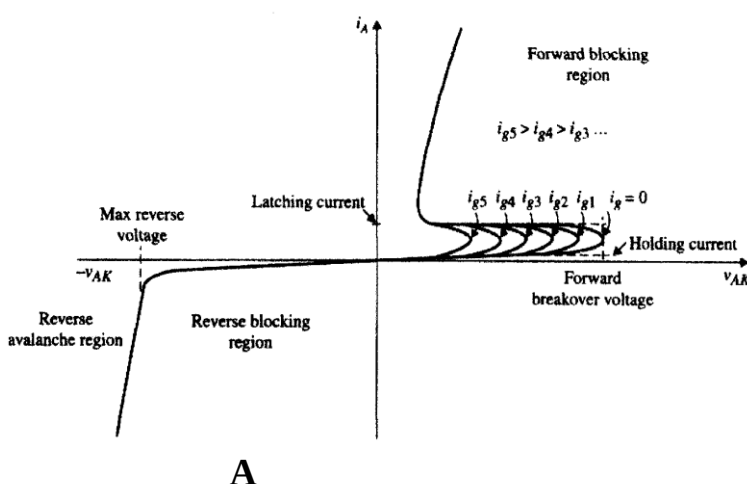


Fig.4 characteristics of thyristors A) practical B) Ideal

SCR can only be turned on with three conditions

- I- The device must be forward biased, i.e. the anode should be more positive than the cathode.
- II-A positive gate current (I_g) should be applied at the gate.
- II-the current through the SCR should be more than the **latching current**

The parameters of the SCR characteristic:

- I- **Latching Current (I_L)**: This is the minimum current required to turn on the SCR device and convert it from the Forward Blocking State to the ON State.
- II- **Holding Current (I_H)**: This is the minimum forward current flowing through the SCR to keep it in forward condition mode. when I_F reduces below holding current, SCR turns off.
- III- **Forward Break over Voltage (V_{BRF})**: This is the forward voltage required to be applied across the SCR to turn it ON without the gate signal application.
- IV- **Max Reverse Voltage (V_{BRR})**: This is the maximum reverse voltage to be applied across the SCR before the reverse avalanche occurs.

Ideally, SCRs are represented by a **short circuit when operating within the conduction region** and as an **open circuit when operating within the blocking region**. The ideal characteristic is shown in Fig. 4-B. It is also worth mentioning that once the SCR is triggered and turned ON the gate signal can be removed without turning it OFF. SCRs are turned OFF when reversing the terminal voltage and current.

Static output i-v characteristics of a thyristor

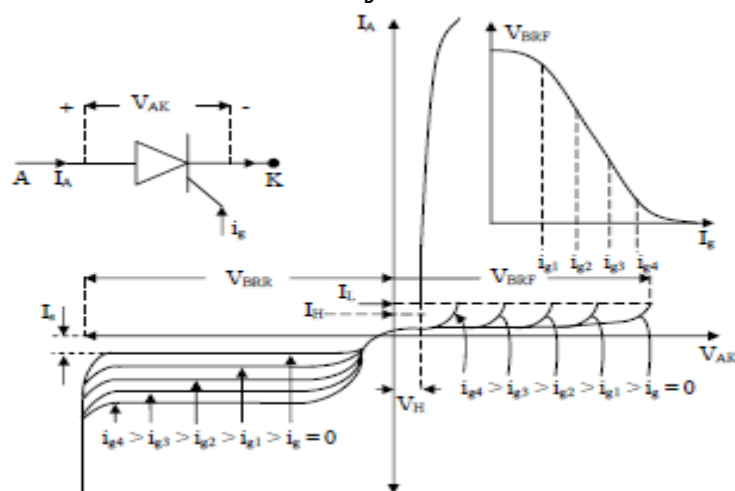


Fig. 5: Static output characteristics of a SCR

As shown in fig.5 the circuit symbol in the left hand side inset defines the polarity conventions of the variables used in this figure. With $i_g = 0$, V_{AK} has to increase up to voltage V_{BRF} before significant anode current starts flowing. However, at V_{BRF} takes place

and the voltage across the SCR drops to V_H (holding voltage). Beyond this point voltage across the SCR (V_{AK}) remains almost constant at V_H (1-1.5v) while the anode current is determined by the external load.

The magnitude of (I_g) has a very strong effect on the value of the break over voltage as shown in the figure. The right hand side figure in the inset shows a typical plot of the (V_{BRF}) as a function of the gate current

After “Turn ON” the SCR is no more affected by the (I_g). Hence, any current pulse (of required magnitude) which is longer than the min. needed for “Turn ON” is sufficient to effect control. **The min. gate pulse width is decided by the external circuit and should be long enough to allow the anode current to rise above the (I_L) level.**

The left hand side of Fig. 5 shows the reverse i-v characteristics of the SCR. Once the SCR is ON the only way to turn it OFF is by bringing the SCR current below (I_H). The gate terminal has no control over the turn OFF process. In ac circuits with resistive load this happens automatically during negative zero crossing of the supply voltage. This is called “natural commutation” or “line commutation”. However, in dc circuits some arrangement has to be made to ensure this condition. This process is called “forced commutation.”

During reverse blocking if $i_g = 0$ then only reverse saturation current (I_s) flows until the reverse voltage reaches reverse break down voltage (V_{BRR}). At this point current starts rising sharply. Large reverse voltage and current generates excessive heat and destroys the device. If $i_g > 0$ during reverse bias condition the reverse saturation current rises as explained in the previous section. This can be avoided by removing the gate current while the thyristor is reverse biased.

Thyristor Gate Characteristics

The gate circuit of a thyristor behaves with high on state voltage drop and low reverse break down voltage. This characteristic usually is not unique even within the same family of devices and shows considerable variation from device to device.

Therefore, manufacturer’s data sheet provides the upper and lower limit of this characteristic as shown in Fig 6.

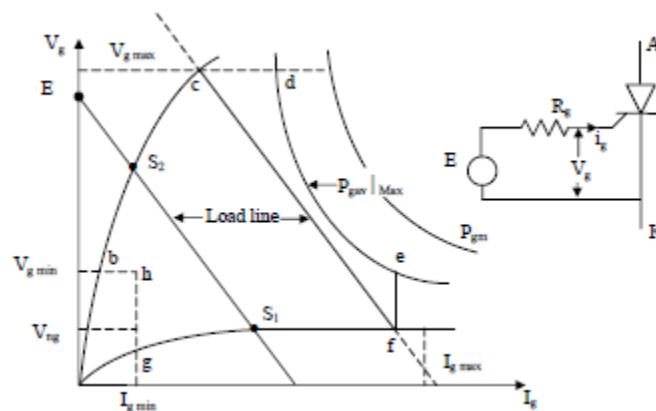


Fig. 6: Gate characteristics of a thyristor.

It is however customary to trigger a SCR using pulsed voltage & current. Maximum power dissipation curves for pulsed operation (P_{gm}) allows higher gate current to flow which in turn reduces the turn on time of the SCR. The value of P_{gm} depends on the pulse width (T_{ON}) of the gate current pulse. **T_{ON} should be larger than the turn on time of the SCR.** The magnitude

of the gate voltage and current required for triggering a SCR is inversely proportional to the junction temperature.

The gate cathode junction also has a maximum reverse (i.e, gate negative with respect to the cathode) voltage specification. If there is a possibility of the reverse gate cathode voltage exceeding this limit a reverse voltage protection using diode as shown in Fig. 7 should be used.

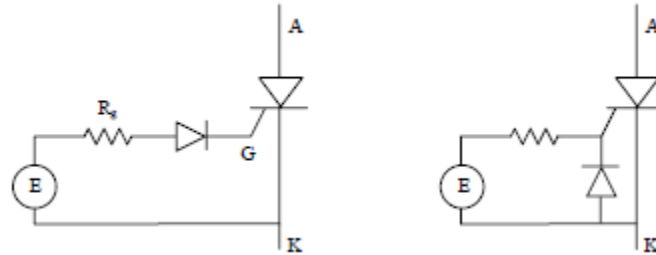


Fig. 7: Gate Cathode reverse voltage protection circuit.

Thyristor ratings

1- Voltage ratings

- Peak Working Forward OFF state voltage (V_{DWM}),
- Peak repetitive off state forward voltage (V_{DRM}),
- Peak non-repetitive off state forward voltage (V_{DSM}),
- Peak working reverse voltage (V_{DWM}),
- Peak repetitive reverse voltage (V_{RRM}),
- Peak non-repetitive reverse voltage (V_{RSM}) &
- Maximum Forward voltage drop (VF)

2- Current ratings

- Maximum RMS current (I_{rms}),
- Maximum average current (I_{av}),
- Maximum Surge current (I_{SM}),
- Maximum Squared Current integral ($\int i^2 dt$),
- Latching Current (I_L),
- Holding Current (I_H) &
- Average power dissipation (P_{av})

Turning on/off (Switching Characteristics of a Thyristor)

1- Turn on characteristics

Fig. 8 shows the waveforms of the gate current (i_g), anode current (i_A) and anode cathode voltage (V_{AK}) in an expanded time scale during Turn on. The reference circuit and the associated waveforms are shown in the inset. The total switching period being much smaller compared to the cycle time, i_A and V_{AK} before and after switching will appear flat.

As shown in Fig.8 there is a transition time " t_{ON} " from forward off state to forward on state. This transition time is called the thyristor turn of time and can be divided into three separate intervals namely,

- (i) delay time (t_d)
- (ii) rise time (t_r)
- (iii) spread time (t_p).

These times are shown in Fig .8 for a resistive load.

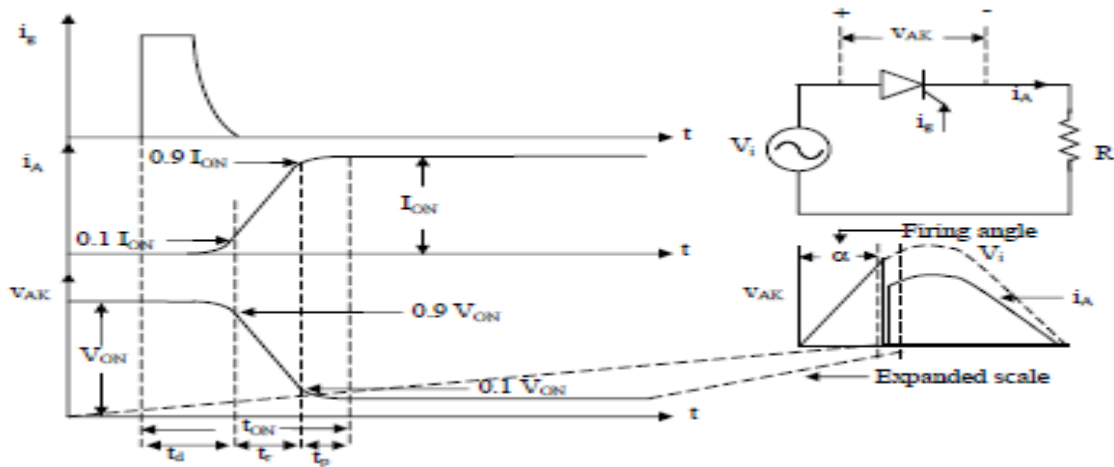


Fig. 8: Turn on characteristics of a thyristor.

Delay time (t_d)

If I_g and I_a represent the final value of gate current and anode current. Then the delay time can be explained as time during which the gate current attains $0.9 I_g$, the instant anode current reaches $0.1 I_a$ or the anode current rises from forward leakage current to $0.1 I_a$.

1. Anode voltage falls from V_a to $0.9V_a$.
2. Anode current rises from forward leakage current to $0.1 I_a$.

Rise time (t_r)

Time during which

1. Anode current rises from $0.1 I_a$ to $0.9 I_a$
2. Forward blocking voltage falls from $0.9V_a$ to $0.1V_a$. V_a is the initial forward blocking voltage.

Spread time (t_p)

1. Time taken by the anode current to rise from $0.9 I_a$ to I_a .
 2. Time for the forward voltage to fall from $0.1V_o$ to on state voltage drop of 1 to 1.5V.
- During turn on, SCR is considered to be a charge controlled device. A certain amount of charge is injected in the gate region to begin conduction. So higher the magnitude of gate current it requires less time to inject the charges. Thus turn on time is reduced by using large magnitude of gate current.

Different turn ON methods for SCR

1. Forward voltage triggering
2. Gate triggering
3. $\frac{dv}{dt}$ triggering
4. Light triggering
5. Temperature triggering

1. Forward voltage triggering

A forward voltage is applied between anode and cathode with gate circuit open.

- Junction $J1$ and $J3$ is forward biased.
- Junction $J2$ is reverse biased.
- As the anode to cathode voltage is increased breakdown of the reverse biased junction $J2$ occurs. This is known as avalanche breakdown and the voltage at which this phenomena occurs is called forward break over voltage.
- The conduction of current continues even if the anode cathode voltage reduces below V_{BO} till I_a will not go below I_h . Where I_h is the holding current for the thyristor.

2. Gate triggering

This is the simplest, reliable and efficient method of firing the forward biased SCRs. First SCR is forward biased. Then a positive gate voltage is applied between gate and cathode. In practice the transition from OFF state to ON state by exceeding V_{BO} is never employed as it may destroy the device. The magnitude of V_{BO} , so forward break over voltage is taken as final voltage rating of the device during the design of SCR application.

First step is to choose a thyristor with forward break over voltage (say 800V) higher than the normal working voltage. The benefit is that the thyristor will be in blocking state with normal working voltage applied across the anode and cathode with gate open. When we require the turning ON of a SCR a positive gate voltage between gate and cathode is applied. The point to be noted that cathode n- layer is heavily doped as compared to gate p-layer. So when gate supply is given between gate and cathode gate p-layer is flooded with electron from cathode n-layer. Now the thyristor is forward biased, so some of these electron reach junction $J2$. As a result width of $J2$ breaks down or conduction at $J2$ occur at a voltage less than V_{BO} . As I_g increases V_{BO} reduces which decreases then turn ON time. Another important point is duration for which the gate current is applied should be more then turn ON time. This means that if the gate current is reduced to zero before the anode current reaches a minimum value known as holding current, SCR can't turn ON.

In this process power loss is less and also low applied voltage is required for triggering.

3. dv/dt triggering

This is a turning ON method but it may lead to destruction of SCR and so it must be avoided. When SCR is forward biased, junction $J1$ and $J3$ are forward biased and junction $J2$ is reversed biased so it behaves as if an insulator is place between two conducting plate. Here $J1$ and $J3$ acts as a conducting plate and $J2$ acts as an insulator. $J2$ is known as junction capacitor. So if we increase the rate of change of forward voltage instead of increasing the magnitude of voltage. Junction $J2$ breaks and starts conducting. A high value of changing current may damage the SCR. So SCR may be protected from high $\frac{dv}{dt}$.

$$q = cv$$

$$I_a = c \frac{dv}{dt}$$

$$I_a \propto \frac{dv}{dt}$$

4-Temperature triggering

During forward biased, J_2 is reverse biased so a leakage forward current always associated with SCR. Now as we know the leakage current is temperature dependant, so if we increase the temperature the leakage current will also increase and heat dissipation of junction J_2 occurs. When this heat reaches a sufficient value J_2 will break and conduction starts. Disadvantages of this type of triggering causes local hot spot and may cause thermal run away of the device. This triggering cannot be controlled easily. It is very costly as protection is costly.

5. Light triggering

First a new recess niche is made in the inner p-layer. When this recess is irradiated, then free charge carriers (electron and hole) are generated. Now if the intensity is increased above a certain value then it leads to turn ON of SCR. Such SCR are known as Light activated SCR (LASCR).

2- Turn off characteristics

Once the thyristor is on, and its anode current is above the latching current level the gate loses control. It can be turned off only by reducing the anode current below holding current.

The turn off time (t_q) : is defined as the time between the instant anode current becomes zero and the instant the thyristor regains forward blocking capability. If forward voltage is applied across the device during this period the thyristor turns on again.

During turn off time, excess minority carriers from all the four layers of the thyristor must be removed. Accordingly t_q is divided in to two intervals,

(a) The reverse recovery time (t_{rr})

(b) The gate recovery time (t_{gr}).

Fig. 9 shows the variation of anode current and anode cathode voltage with time during turn off operation on an expanded scale.

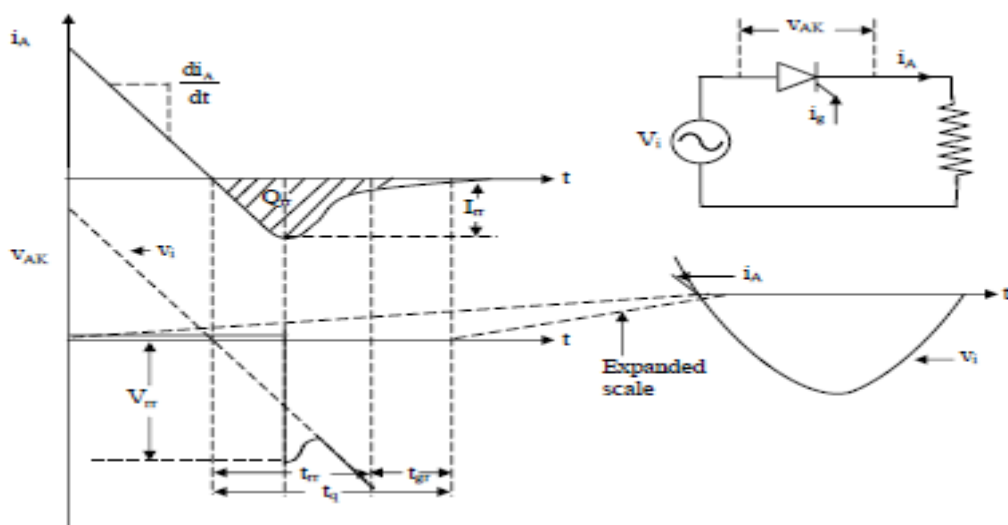


Fig. 9: Turn off characteristics of a thyristor.

Thyristor turn off means it changed from ON to OFF state. Once thyristor is ON there is no role of gate. As we know thyristor can be made turn OFF by reducing the anode current below the latching current. Here we assume the latching current to be zero ampere. If a forward voltage is applied across the SCR at the moment it reaches zero then SCR will not be able to block this forward voltage. Because the charges trapped in the 4-layer are still favourable for conduction and it may turn on the device. So to avoid such a case, SCR is reverse biased for some time even if the anode current has reached to zero.

So now the turn off time can be different as the instant anode current becomes zero to the instant when SCR regains its forward blocking capability.

$$t_q = t_{rr} + t_{qr}$$

Where, t_q is the turn off time, t_{rr} is the reverse recovery time, t_{qr} is the gate recovery time

At t_1 anode current is zero. Now anode current builds up in reverse direction with same dv/dt slope. This is due to the presence of charge carriers in the four layers. The reverse recovery current removes the excess carriers from J_1 and J_3 between the instants t_1 and t_3 . At instant t_3 the end junction J_1 and J_3 is recovered. But J_2 still has trapped charges which decay due to recombination only so the reverse voltage has to be maintained for some more time. The time taken for the recombination of charges between t_3 and t_4 is called gate recovery time t_{qr} . Junction J_2 recovered and now a forward voltage can be applied across SCR.

The turn off time is affected by:

1. Junction temperature
2. Magnitude of forward current $\frac{di}{dt}$ during commutation.

Turn off time decreases with the increase of magnitude of reverse applied voltage.

Thyristor turn off Methods

The process of turning OFF SCR is defined as "Commutation". Thyristor cannot be turned off by applying negative gate current. It can only be turned off if the current I through it goes negative (reverse). In all commutation techniques, a reverse voltage is applied across the thyristor during the turn OFF process.

There are two methods by which a thyristor can be turned OFF.

i. Natural Commutation

In AC circuit, the current always passes through zero for every half cycle. As the current passes through natural zero, a reverse voltage will simultaneously appear across the device. This will turn OFF the device immediately. This happens when negative portion of the of sine-wave occurs. This process is called as "**natural commutation**" since no external circuit is required for this purpose.

ii. Forced Commutation

Another method of turning off is known as "**forced commutation**". The anode current is "diverted" to another circuitry. To turn OFF a thyristor, the forward anode current should be brought to zero for sufficient time to allow the removal of charged carriers. In case of DC circuits the forward current should be forced to zero by means of some external circuits.

Thyristor protection

1-Over Voltage Protection

Over voltage occurring during the switching operation causes the failure of SCR.

2-Internal Over voltage

It is due to the operating condition of SCR. During the commutation of SCR, when the anode current decays to zero anode current reverses due to stored charges. First the reverse current rises to peak value, then reverse current reduces abruptly with large di/dt . During series inductance of SCR large transient large voltage i.e $L di/dt$ is generated.

3- External Overvoltage

This is due to external supply and load condition. This is because of

- a. The interruption of current flow in an inductive circuit.
- b. Lightning strokes on the lines feeding the thyristor systems.

Suppose a SCR converter is fed from a transformer, voltage transient occur when transformer primary will energise or de-energised.

This overvoltages cause random turn ON of a SCR.

The effect of overvoltage is minimized using

- a. RC circuits
- b. Non linear resistor called voltage clamping device.

Voltage clamping device is a non linear resistor. It is connected between cathode and anode of SCR. The resistance of voltage clamping device decreases with increasing voltages. During normal working condition Voltage clamping (V.C) device has high resistance, drawing only leakage current. When voltage surge appears voltage clamping device offers a low resistance and it creates a virtual short circuit across the SCR. Hence voltage across SCR is clamped to a safe value. When surge condition over voltage clamping device returns to high resistance state. e.g. of voltage clamping device

1. Selenium thyrector diodes
2. Metal Oxide varistors
3. Avalanche diode suppressors

Over Current protection

Long duration operation of SCR, during over current causes the

1. junction temp. of SCR to rise above the rated value, causing permanent damage to device.

SCR is protected from overcurrent by using

1. Circuit breakers
2. Fast acting fuses

Proper co-ordination is essential because

1. fault current has to be interrupted before SCR gets damaged.
2. only faulty branches of the network has to be replaced.

In stiff supply network, source has negligible impedance. So in such system the magnitude and rate of rise of current is not limited. Fault current hence junction temp rises in a few milliseconds.

Points to be noted

1. Proper coordination between fast acting fuse and thyristor is essential.
2. The fuse is always rated to carry marginal overload current over definite period.
3. The peak let through current through SCR must be less than sub cycle rating of the SCR.
4. The voltage across the fuse during arcing time is called arcing or recovery voltage and is equal to sum of the source voltage and emf induced in the circuit inductance during arcing time.
5. On abrupt interruption of fuse current, induced emf would be high, which results in high arcing voltage.

2-The Triac

The triac is a two thyristors connected back – to – back, used for high or medium power control for both a.c and d.c applications, as shown in Fig.10. Either of the electrodes MT1 and MT2 can act as anode and either is cathode. The device can be triggered by either positive or negative voltage on the gate with respect to MT1. This device is effectively two thyristors (SCRs) back- to- back in construction with an external n-region which is the gate.

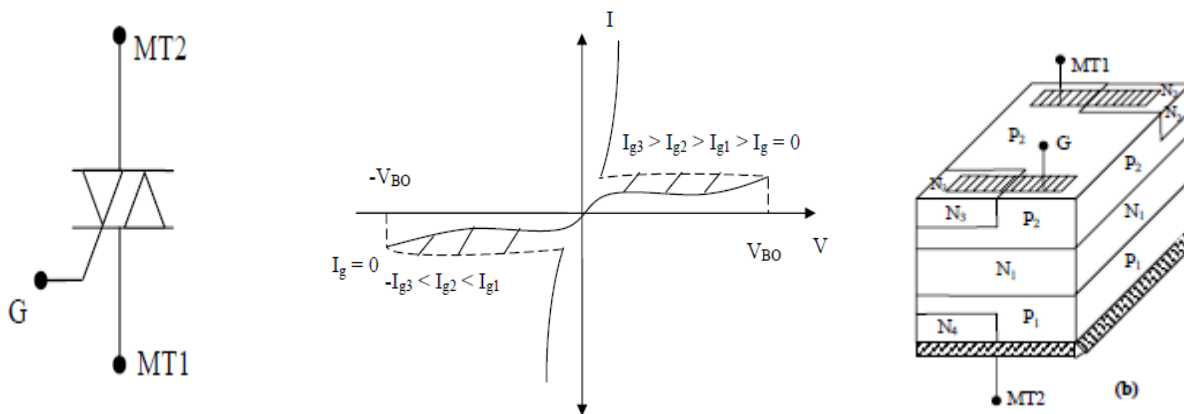


Fig. 10: TRIAC circuit symbol, characteristics & construction

The four possible modes of operation of triac are

- (a) MT2 +, G + (both relative to MT1) Gate current flows into gate terminal.
- (b) MT2+, G – Gate current opposite to (a).
- (c) MT2-, G + Gate current as (a)
- (d) MT2-, G – Gate current as (b)

Unlike a thyristor a triac gets limited time to turn off due to bidirectional conduction. As a result the triacs are operated only at power frequency. Switching characteristics of a triac is similar to that of a thyristor. However, turn off of a triac is extremely sensitive to temperature variation and may not turn off at all if the junction temperature exceeds certain limit. Problem may arise when a triac is used to control a lagging power factor load. At the current zero instant (when the triac turns off) a reverse voltage will appear across the triac since the supply

voltage is negative at that instant. The rate of rise of this voltage is restricted by the triac junction capacitance only. The resulting dv/dt may turn on the triac again. Similar problem occurs when a triac is used to control the power to a resistive element which has a very low resistance before normal working condition is reached. If such a load (e.g. incandescent filament lamp) is switch on at full supply voltage very large junction capacitance charging current will turn ON the device. To prevent such condition an R-C snubber is generally used across a triac.

The triac should be triggered carefully to ensure safe operation. For phase control application, the triac is switched on and off in synchronism with the mains supply so that only a part of each half cycle is applied across the load. To ensure 'clean turn ON' the trigger signal must rise rapidly to provide the necessary charge. A rise time of about $1\ \mu s$ will be desirable. Such a triac gate triggering circuit using a "diac" and an R-C timing network is shown in Fig .12.

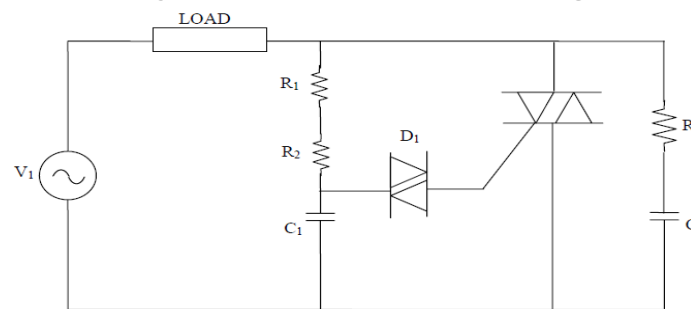


Fig. 12: Triac triggering circuit using a diac.

3-Gate Turn Off Thyristors (GTO Thyristors),

GTO behaves like normal thyristor, but can be turned off using gate signal. However turning off is difficult. Need very large reverse gate current (normally $1/5$ of anode current).GTO symbol and characteristics are shown in Fig.13

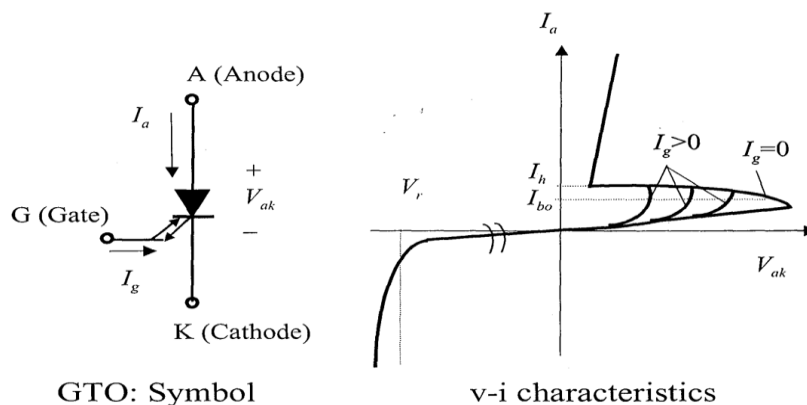


Fig. 13 GTO symbol & characteristics

Ratings: Voltage: $V_{ak} < 6kV$, Current: $I_a < 2\ kA$ -

Frequency $< 5\ kHz$.

Gate drive design is very difficult. Need very large reverse gate current to turn off.

GTO normally requires snubbers. High power snubbers are expensive.

In very high power region ($> 6kV$, $> 2kA$), development in gate-controlled thyristor (GCT) may effectively end the future of GTO.

4-MCTs (MOS Controlled Thyristor)

An effort to combine the advantages of bipolar junction and field-effect structures has resulted in hybrid devices:

The IGBT is an improvement over a BJT .

The MCT is an improvement over a thyristor.

MCT characteristics

- MCT can be switched on or off by negative or positive gate voltage, respectively.
 - It has fast TURN-ON and then OFF times, with high-speed switching capability.
 - Low conduction losses, low switching losses, and high current density.
 - The gating requirements of an MCT are easier than those of the GTO since it needs smaller gate turn-off current due to its high gate input impedance.
 - Compared with the power MOSFET, it has higher current density and lower forward drop .
- It has great potential in high-power, high-voltage applications. A peak power of 1 MW can be switched off in 2 ns by a single MCT.

Therefore, the MCT overcomes several of the limitations of the existing power devices and promises to be a better switch for the future. The MCT symbol and equivalent circuit are shown in Fig.2.15. The MCT characteristics are shown in Fig. 17.

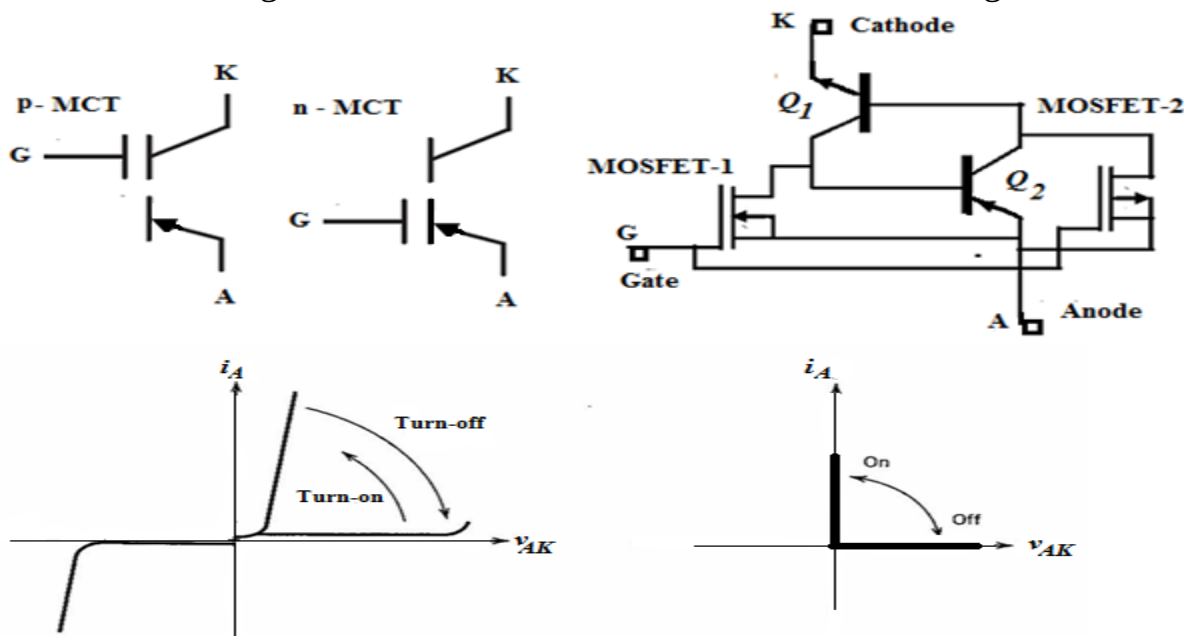


Fig. 17 MCT symbol & characteristics

New Emerging Devices

The Power Silicon Carbide Semiconductors

Silicon Carbide (SiC) semiconductors are a new option for power electronic designers looking to improve system efficiency, its features are:

Extremely low Switching losses

High Power Density

High thermal conductivity

Reduced Sink requirements

High temperature operation

power transistor

Can be turned "ON" and "OFF" by relatively very small control signals.

Operated in SATURATION and CUT OFF modes only. No "linear region" operation is allowed due to excessive power loss.

Traditional devices: Bipolar junction transistors (BJT), Metal oxide silicon field effect transistor (MOSFET), Insulated gate bipolar transistors (IGBT).

Emerging (new) devices: Gate controlled thyristors (IGCT).

Bipolar Junction Transistor(BJT)

Ratings: Voltage: $V_{CE} < 1600 \text{ V}$, Current $I_C < 1000 \text{ A}$.

- Switching frequency up to 5 kHz
- Low on-state voltage V_{CE} : 2-3V, hence low on – state loss.
- Low current gain (β) Need high base current to obtain reasonable I_C .
- Expensive and complex base drive circuit.
- Not popular in new products.

BJT Power Transistor Characteristics

- To turn on/off the device, a base drive circuit is connected to the base and emitter terminal.
- To turn on, current is injected into the base terminal. When turned on, conventional current passes from collector to emitter.
- To turn-off, the base current is removed.
- The current gain of a BJT ends to be low when operated in the saturated ON condition. $\beta < 10$ is common. It deteriorates as voltage ratings increases.
- It is normal to use Darlington connection for higher current gain.

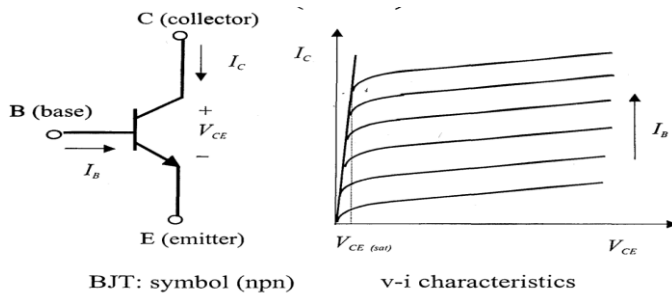


Fig. 14 BJT symbol , characteristics & graphics

ii-Metal Oxide Semiconductor Field Effect Transistors “MOSFETs”

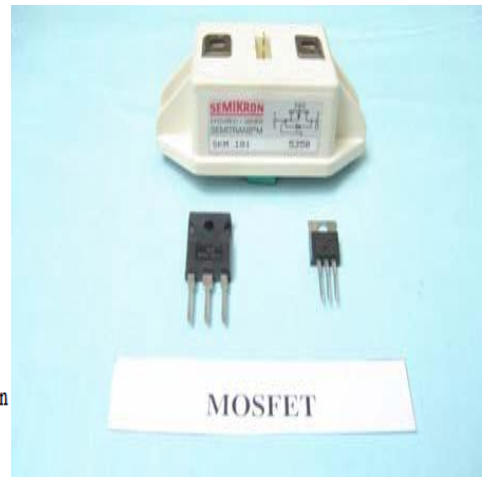
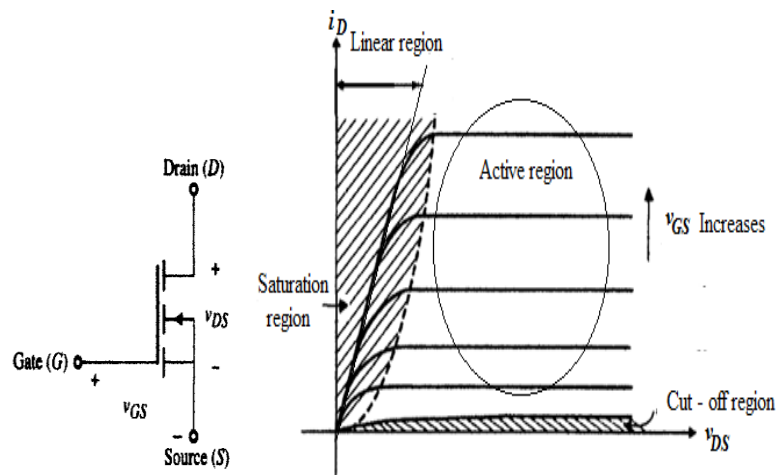


Fig. 15 MOSFET symbol , characteristics & graphics

These are three terminal switches as shown in Fig.15

This is considered the fastest power switching device (200 kHz) for rating voltages $< 500V$, current $I_{DS} < 300A$, or at 100 kHz, $< 1500 V$, 300 A .

MOSFET characteristics

- Turning on and off is very simple. Only need to provide $V_{GS} = +15V$ to turn on and 0V to turn off. Gate drive circuit is simple.
- Basically low voltage device. High voltage device are available up to 600V but with limited current. Can be paralleled quite easily for higher current capability.
- Dominant in high frequency application (>100 kHz). Biggest application is in switched-mode power supplies.
- On state loss relatively high. $V_{DS} > 3 V$.

Practically, MOSFET's characteristic consists of three regions, as shown in Fig.2.13 :

- Cut OFF region (OFF state) when $V_{GS} < V_{Th}$.
- Linear region when $V_{DS} < V_{GS} - V_{Th}$, and
- Active region when $V_{DS} > V_{GS} - V_{Th}$. Ideally, MOSFETs are represented by a short circuit when operating within the ON State and as an open circuit when operating within the OFF State.

iii- Insulated Gate Bipolar Transistor (IGBT)

This is also a three terminal switch as shown in Fig. 16. Its operation modes and characteristics are almost similar to those for MOSFETs. .

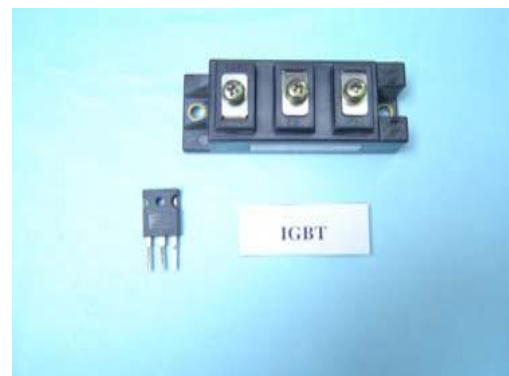
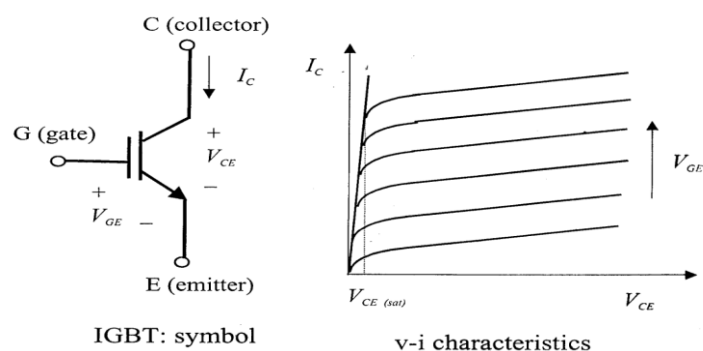


Fig. 16 IGBT symbol , characteristics & graphics •

Gate behavior similar to MOSFET - easy to turn on and off.

- Low losses like BJT due to low on-state Collector-Emitter voltage $V_{CE} = (2-3V)$.
- Ratings: Voltage: $V_{CE} < 6000V$, Current 2500A currently available.
- Good switching capability (up to 100 kHz) for newer devices.
- Typical application, IGBT is used at 20-50 kHz.
- For very high power devices and applications, frequency is limited to several kHz -
- Very popular in new products; practically replacing BJT in most new applications
- „Snubberless” operation is possible. Most new IGBTs do not require snubber.