EE8552 Power Electronics

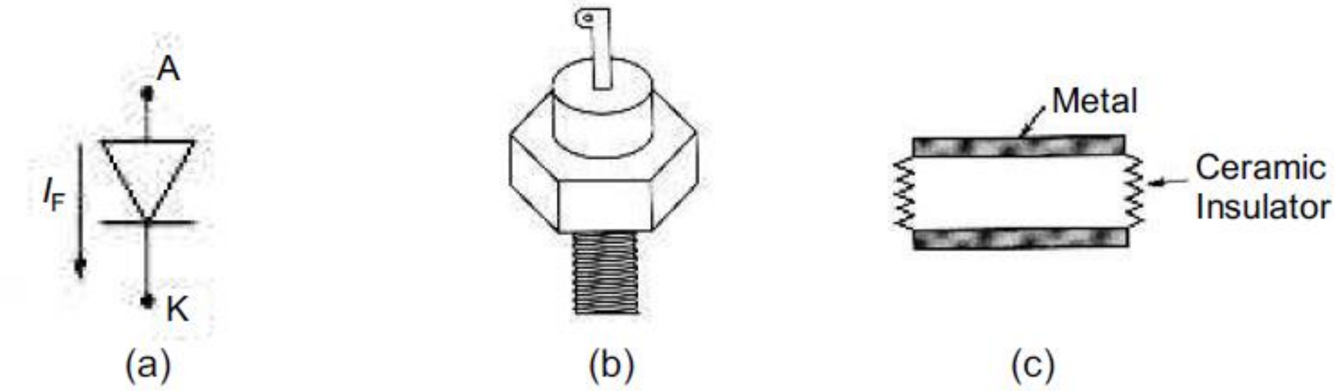
TOPICS COVERED

- SEMICONDUCTOR DEVICES
- CONTROLLED RECTIFIERS
- DC CHOPPERS
- INVERTERS
- AC CHOPPERS

SEMICONDUCTOR DEVICES

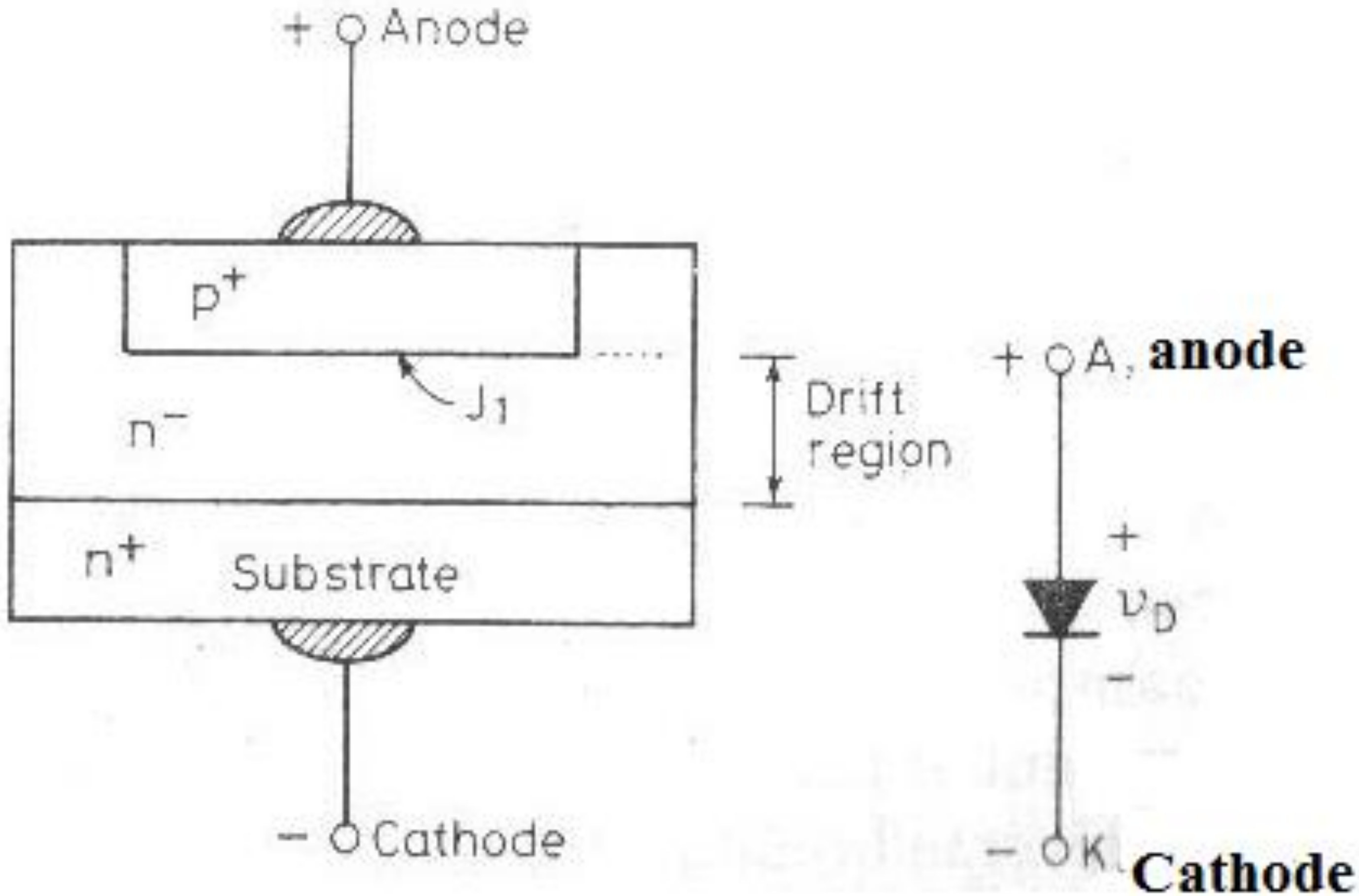
- POWER DIODE
- POWER TRANSISTORS
  - POWER BJT
  - POWER MOSFET
  - IGBT
  - SIT
- THYRISTORS
  - SCR
  - TRIAC
  - GTO
  - SITH
  - MCT

POWER DIODE

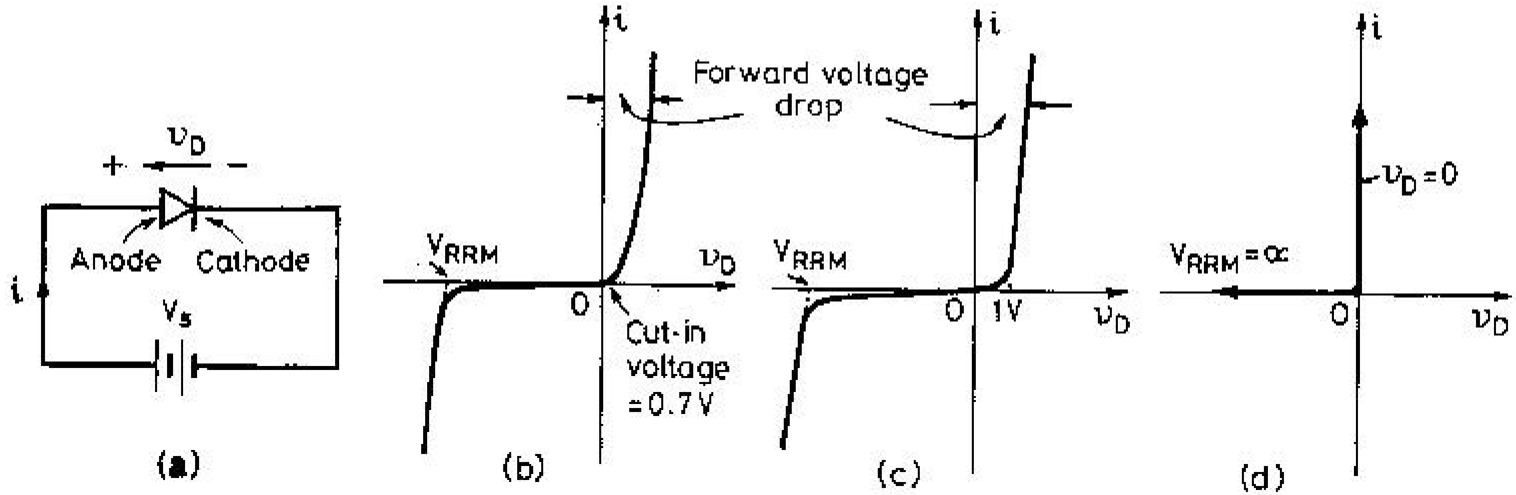


Power diode: (a) symbol; (b) and (c) types of packaging.

STRUCTURAL FEATURES OF POWER DIODE AND ITS SYMBOL



V-I CHARACTERISTICS OF SIGNAL DIODE, POWER DIODE AND IDEAL DIODE



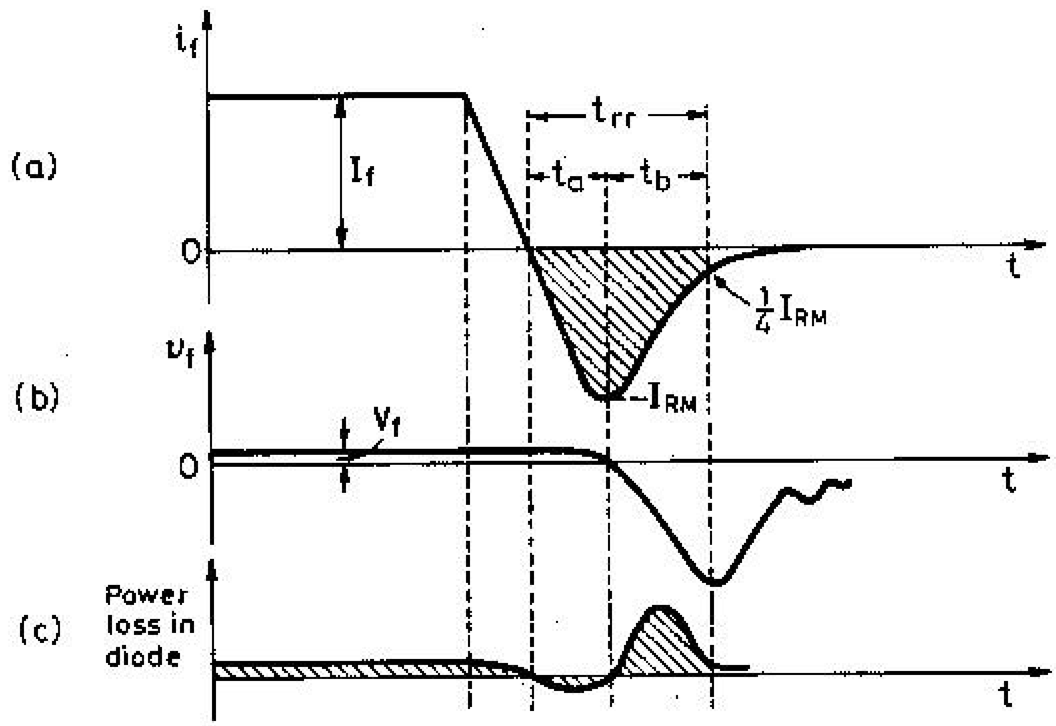
(a) Forward biased Power Diode

(b) V-I Charateristics of Signal Diode

(c) V-I Characteristics of Power Diode

(d)V-I Characteristics of Ideal Diode

REVERSE RECOVERY CHARACTERISTICS



(a)Variation of Forward Current If (b) Forward Voltage DropVf (c) Power loss in the Diode

POWER TRANSISTORS

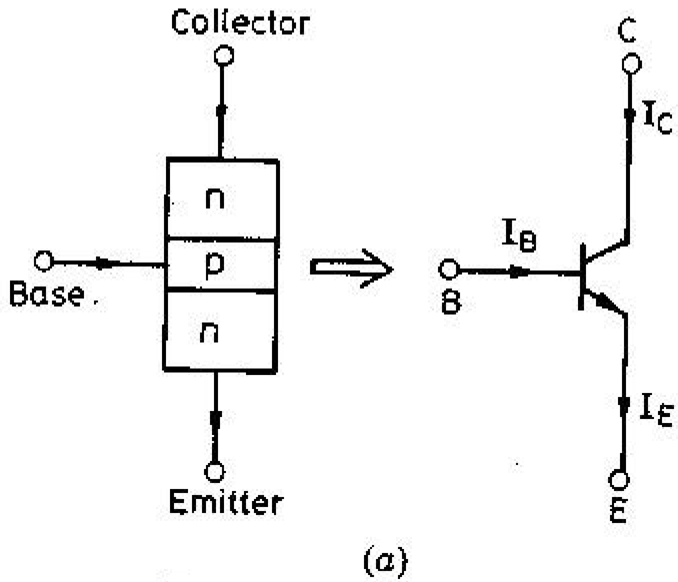
FOUR TYPES

- Bipolar junction Transistor(**BJT**)
- Metal Oxide Semiconductor Field Effect Transistor(**MOSFET**)
- Insulated Gate Bipolar Transistors(**IGBT**) and
- Static Induction Transistor (**SIT**)

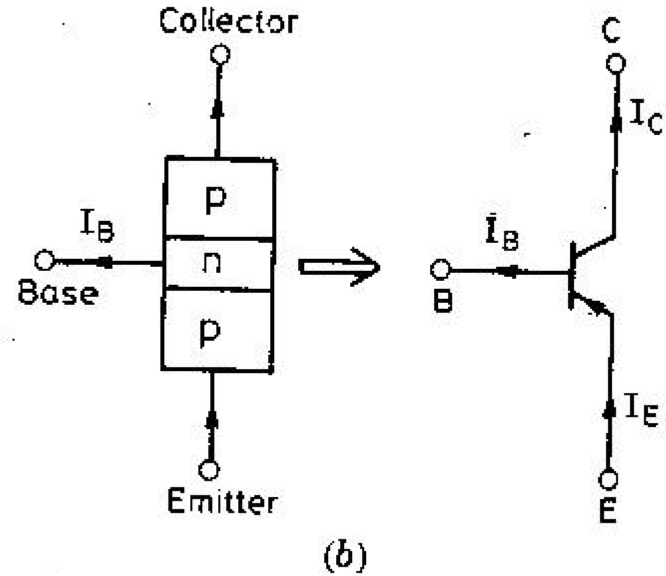
POWER BJT

- **Three layer ,Two Junction** npn or pnp type
- **Bipolar** means current flow in the device is due to the movement of BOTH holes and Electrons.

POWER BJT

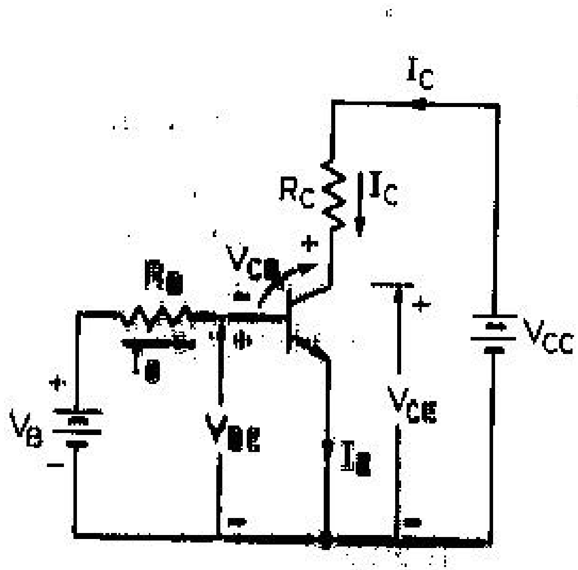


(a) npn type

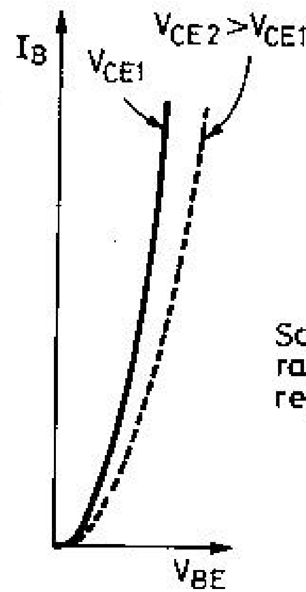


(b) pnp type

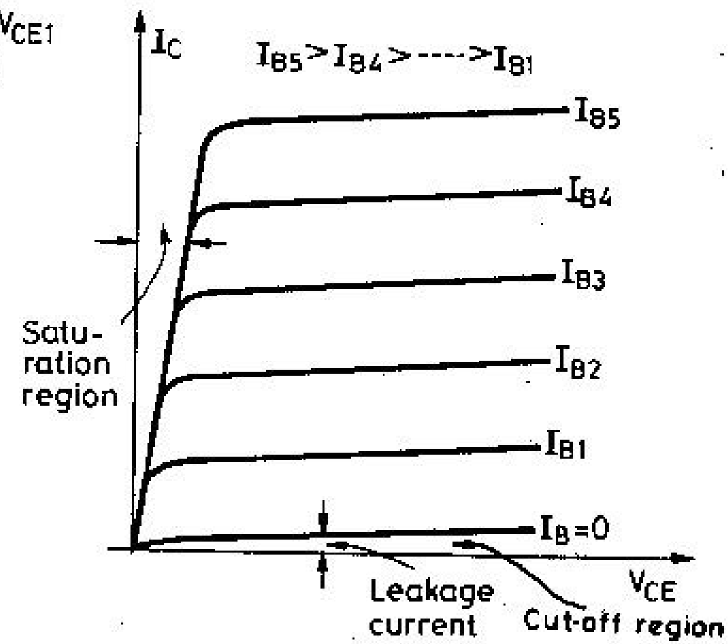
V-I CHARACTERISTICS OF POWER BJT



(a)npn Transistor circuit

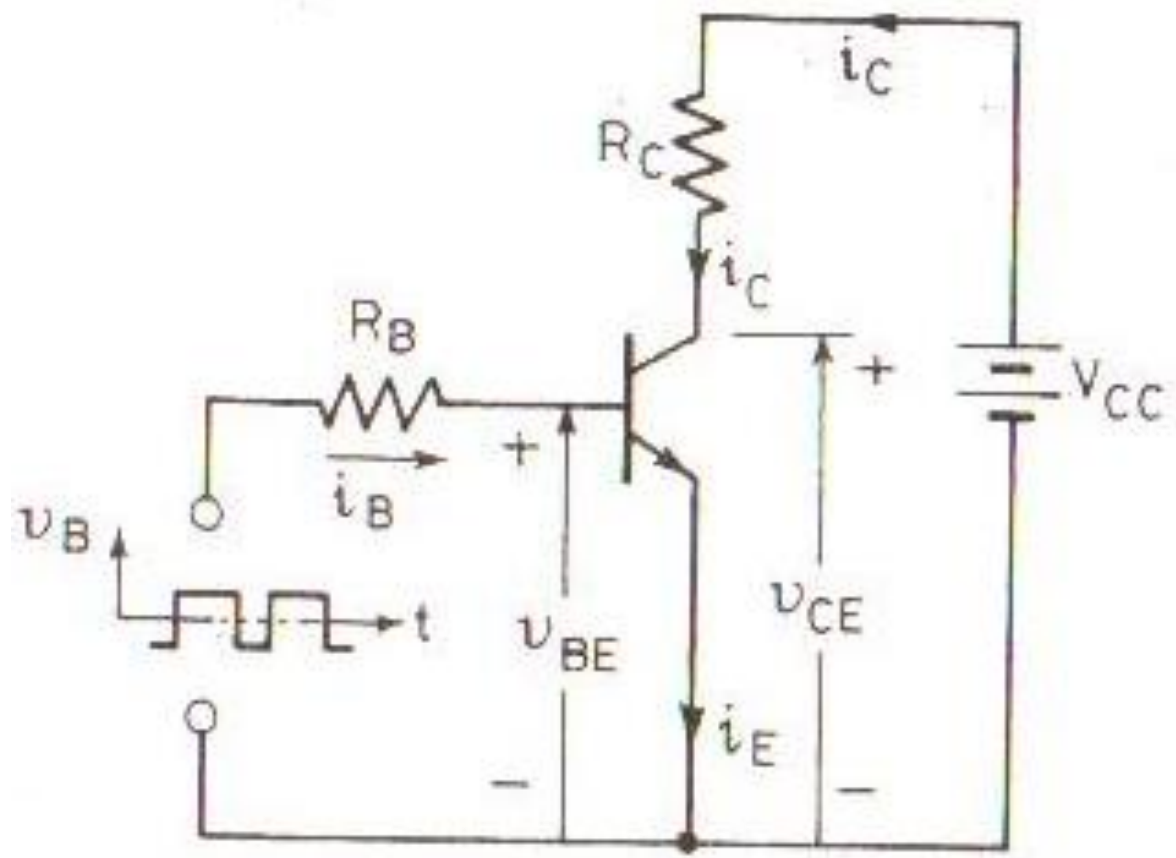


(b) Input Charateristics



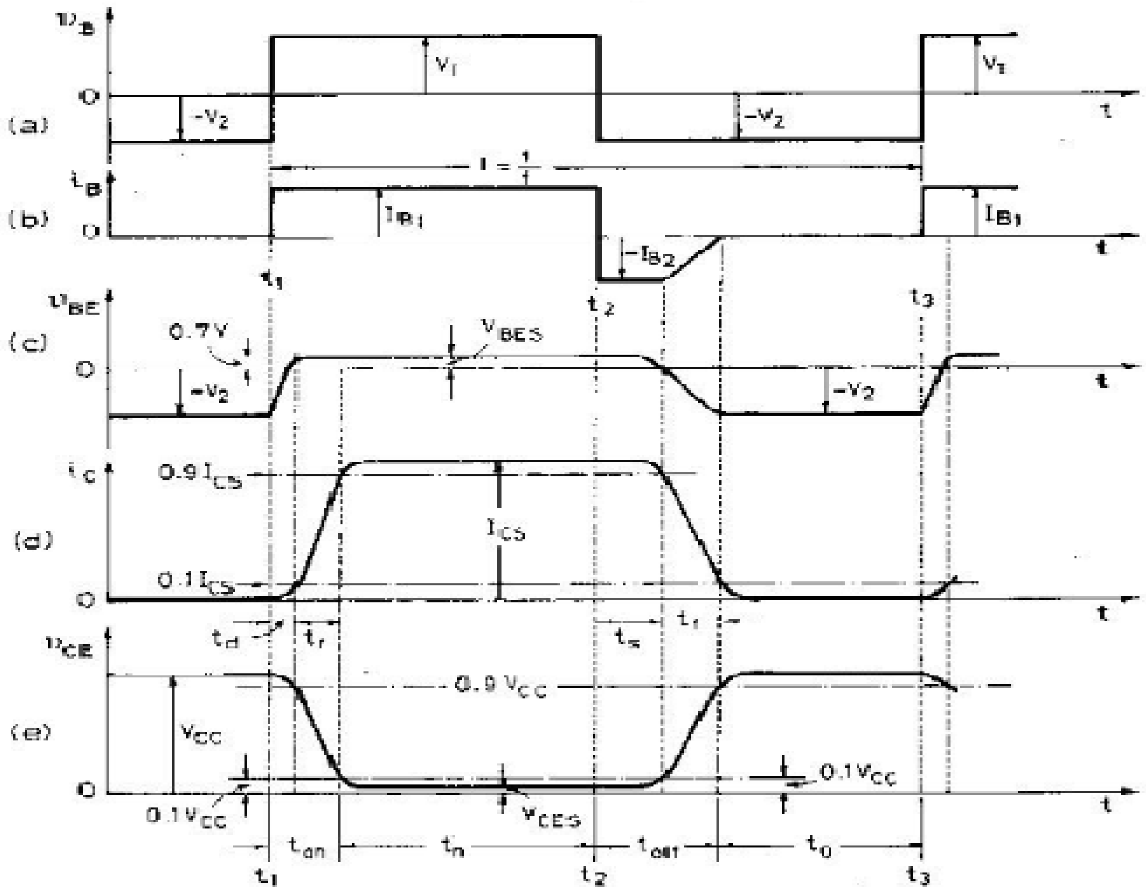
(c)Output Characteristics

SWITCHING CHARACTERISTICS CIRCUIT FOR BJT



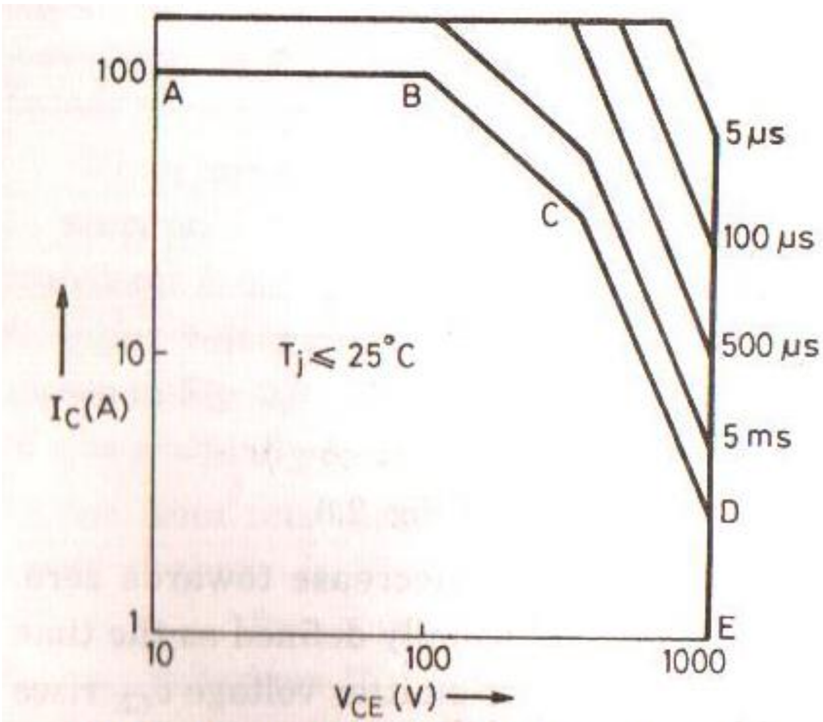
npn transistor with resistive load

SWITCHING CHARACTERISTICS OF POWER BJT

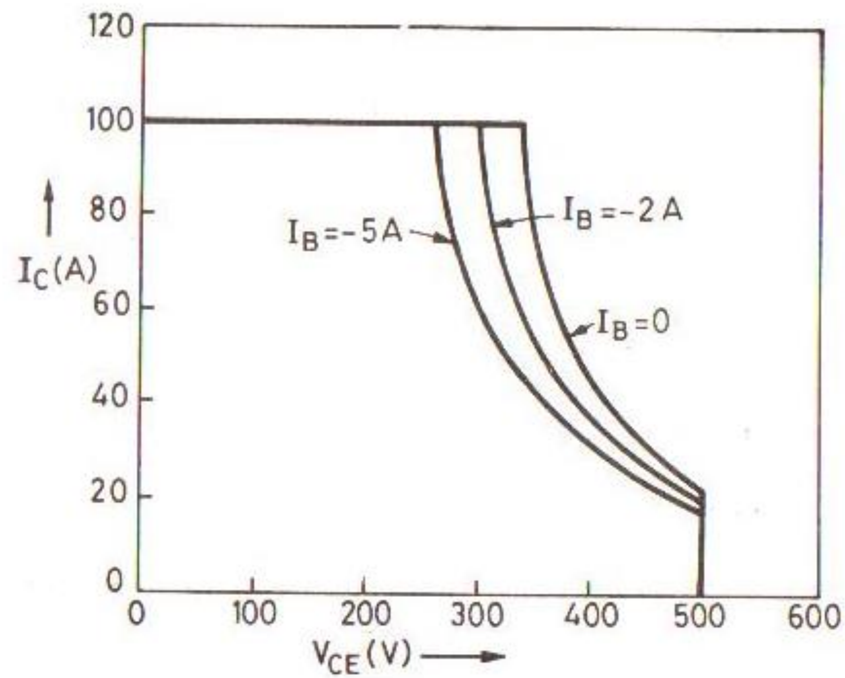


Switching waveforms of Power BJT

SAFE OPERATING AREA FOR POWER BJT

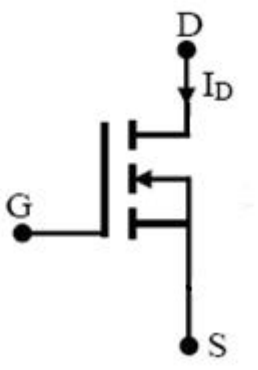


FBSOA-Forward biased Safe Operating Area



RBSOA-Reverse Block Safe Operating Area

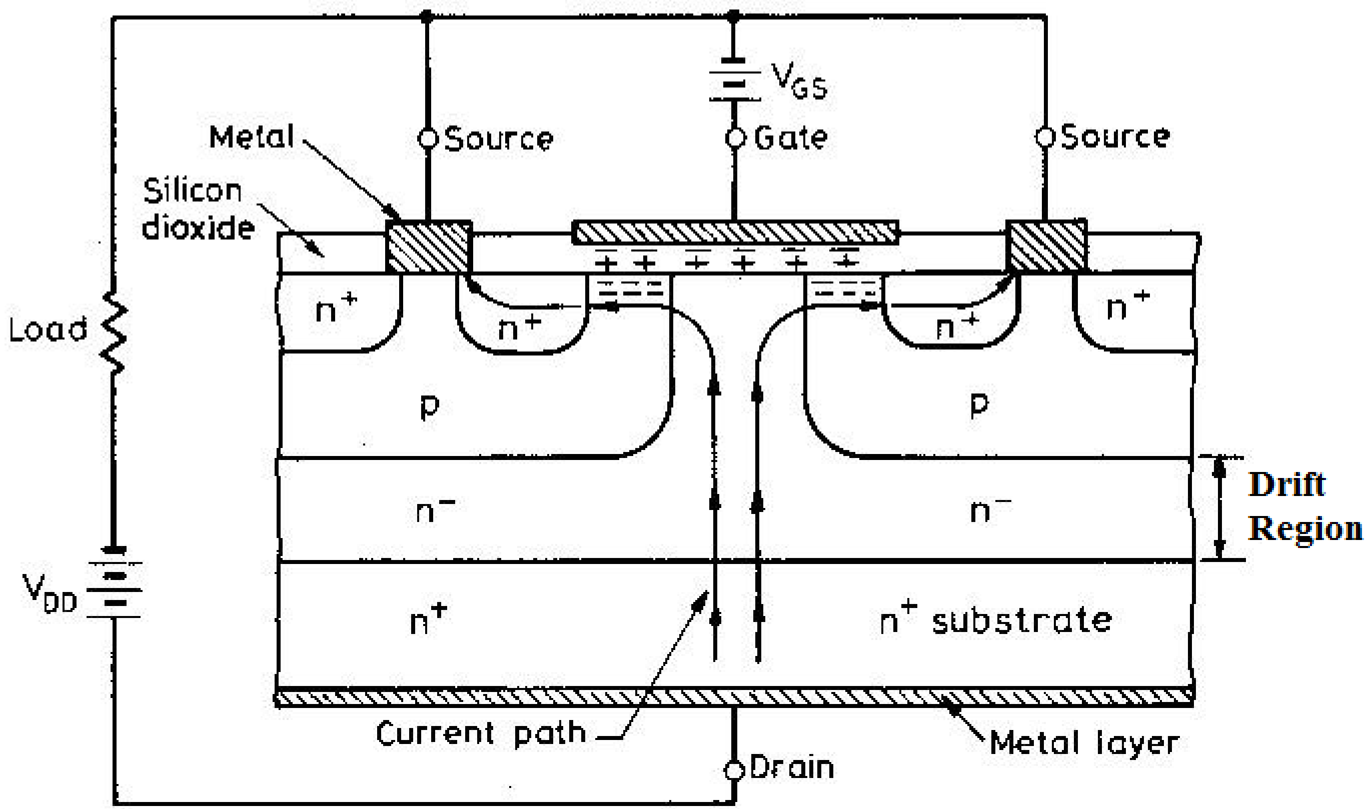
POWER MOSFET



POWER MOSFET

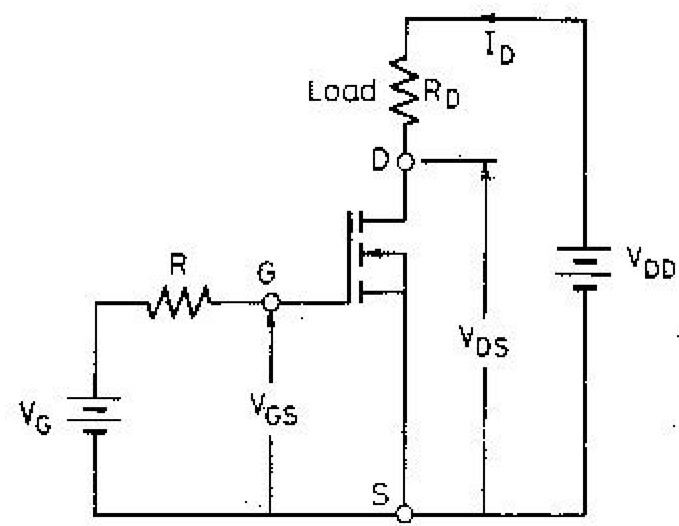
- THREE TERMINALS – DRAIN,SOURCE AND GATE
- VOLTAGE CONTROLLED DEVICE
- GATE CIRCUIT IMPEDANCE IS HIGH (OF THE ORDER OF MEGA OHM).HENCE GATE CAN BE DRIVEN DIRECTLY FROM MICROELECTRONIC CIRCUITS.
- USED IN LOW POWER HIGH FREQUENCY CONVERTERS,SMPS AND INVERTERS

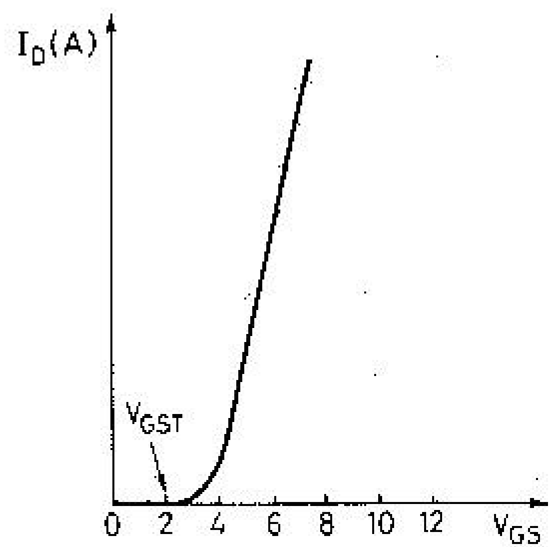
BASIC STRUCTURE OF n-CHANNEL POWER MOSFET



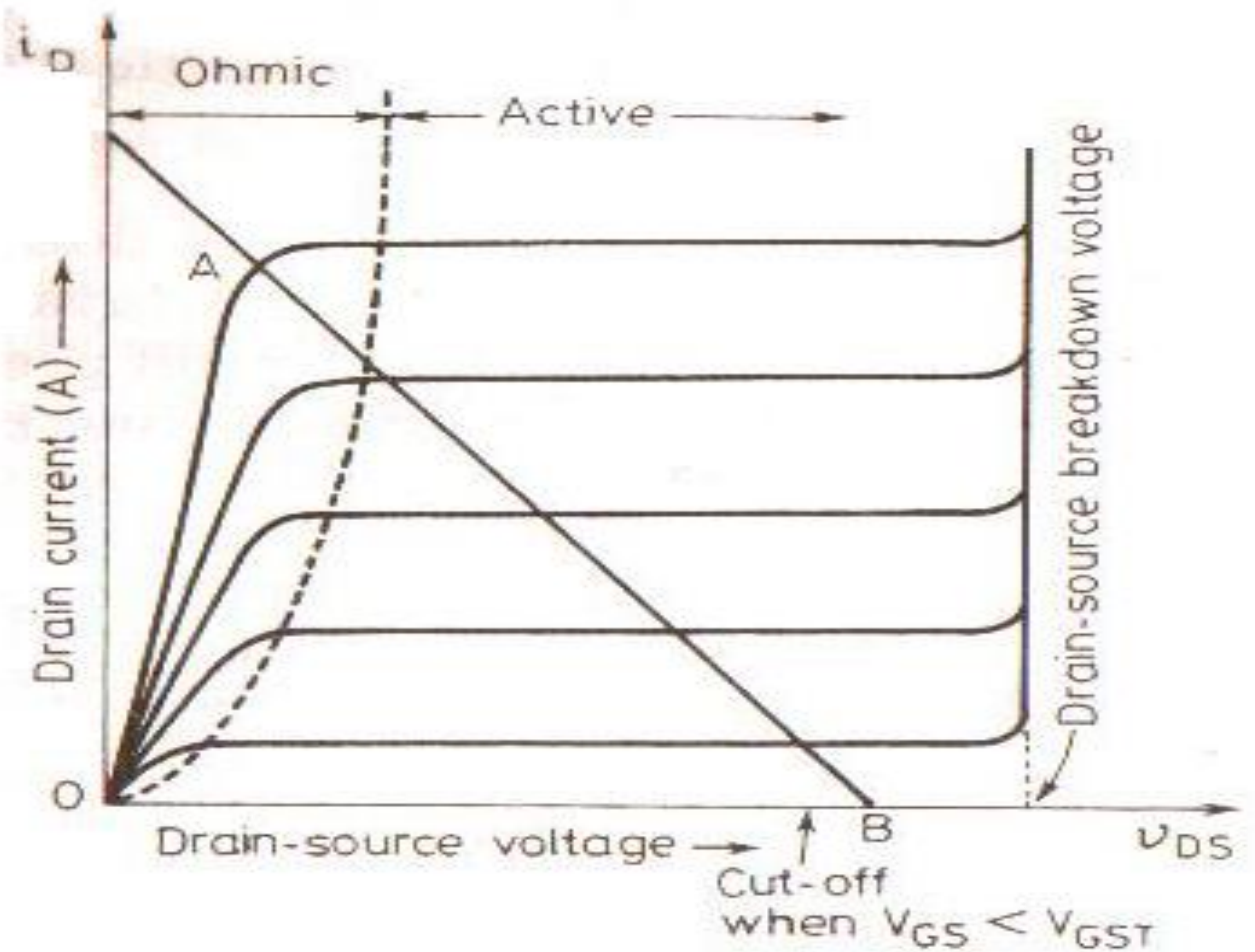
BASIC STRUCTURE OF n-CHANNEL POWER MOSFET

MOSFET TRANSFER CHARACTERISTICS

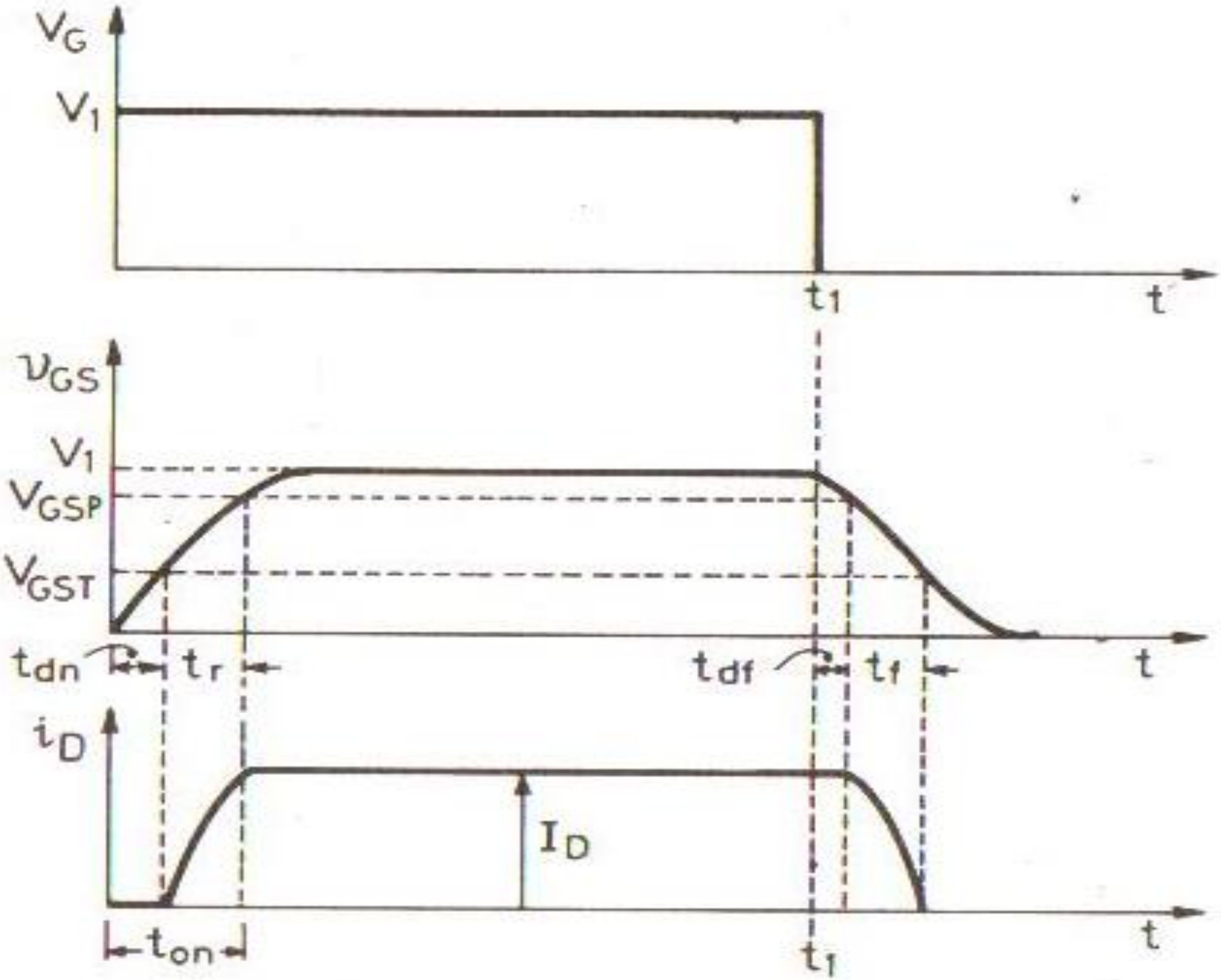




MOSFET OUTPUT CHARACTERISTICS



MOSFET SWITCHING CHARACTERISTICS



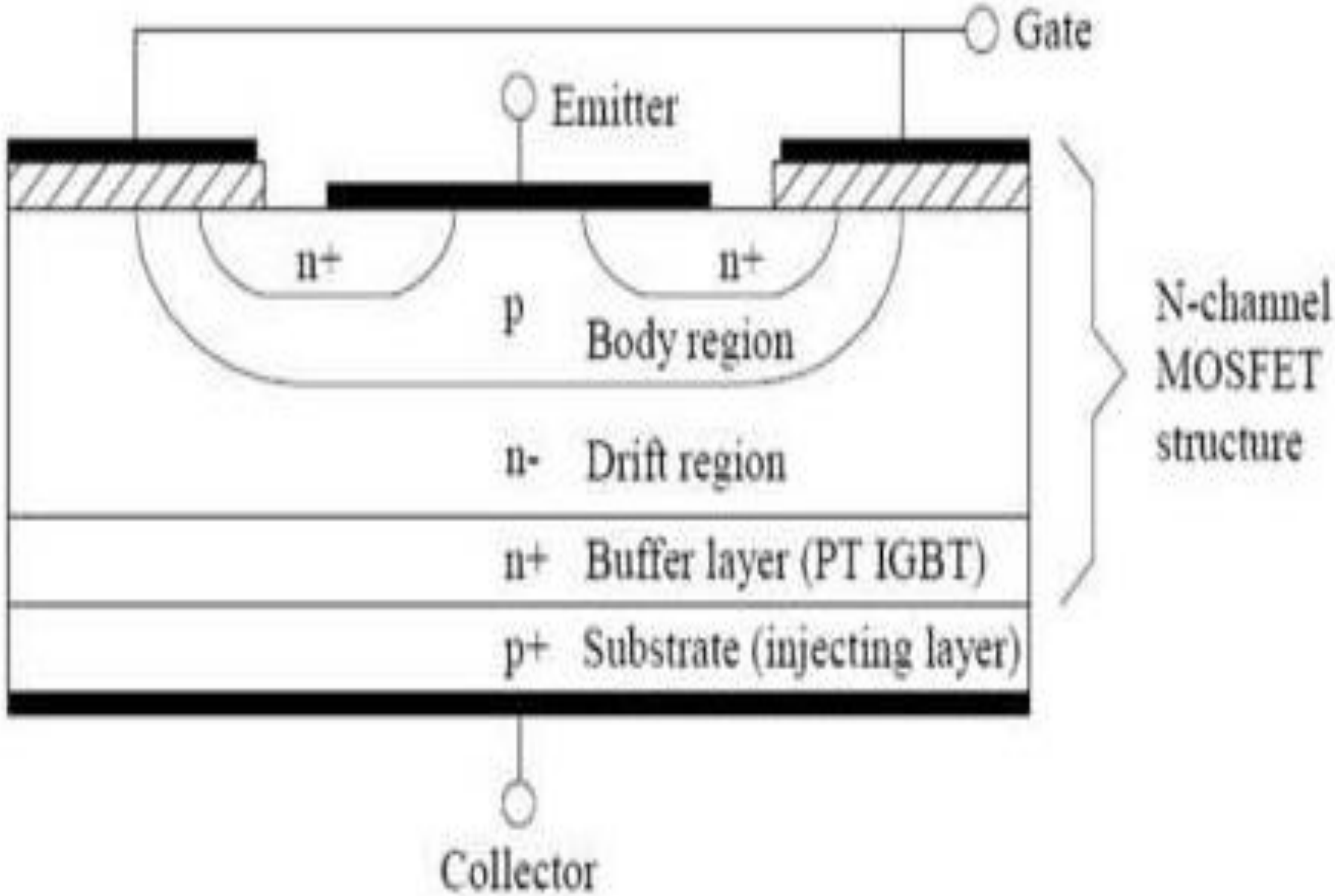
COMPARISON OF BJT AND MOSFET

S.No	BJT	MOSFET
1	BIPOLAR DEVICE	UNIPOLAR DEVICE
2	LOW INPUT IMPEDANCE(KILO OHM)	HIGH INPUT IMPEDANCE (MEGA OHM)
3	HIGH SWITCHING LOSSES BUT LOWER CONDUCTION LOSSES	LOWER SWITCHING LOSSES BUT HIGH ON-RESISTANCE AND CONDUCTION LOSSES
4	CURRENT CONTROLLED DEVICE	VOLTAGE CONTROLLED DEVICE
5	NEGATIVE TEMPERATURE COEFFICIENT OF RESISTANCE.PARALLEL OPERATION IS DIFFICULT.CURRENT SHARING RESISTORS SHOULD BE USED.	POSITIVE TEMPERATURE COEFFICIENT OF RESISTANCE. PARALLEL OPERATION IS EASY
6	SECONDARY BREAKDOWN OCCURS.	SECONDARY BREAKDOWN DOES NOT OCCUR.
7	AVAILABLE WITH RATINGS 1200V,800A	AVAILABLE WITH RATINGS 500V,140A

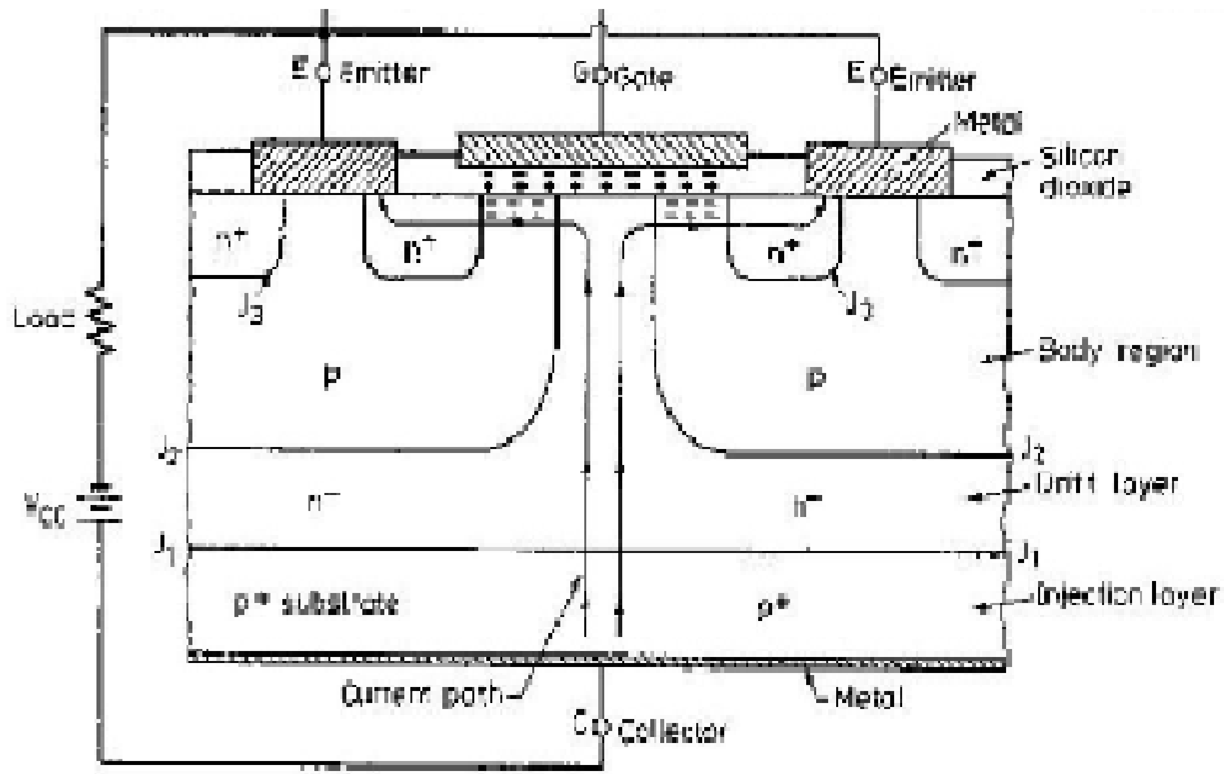
INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

- COMBINES THE BEST QUALITIES OF BOTH **BJT** AND **MOSFET**
- HAS HIGH INPUT IMPEDANCE AS MOSFET AND HAS LOW ON-STATE POWER LOSS AS IN BJT
- OTHER NAMES
  - ✓ **MOSIGT** (METAL OXIDE INSULATED GATE TRANSISTOR),
  - ✓ **COMFET** (CONDUCTIVELY-MODULATED FIELD EFFECT TRANSISTOR),
  - ✓ **GEMFET** (GAIN MODULATED FIELD EFFECT TRANSISTOR),
  - ✓ **IGT** (INSULATED GATE TRANSISTOR)

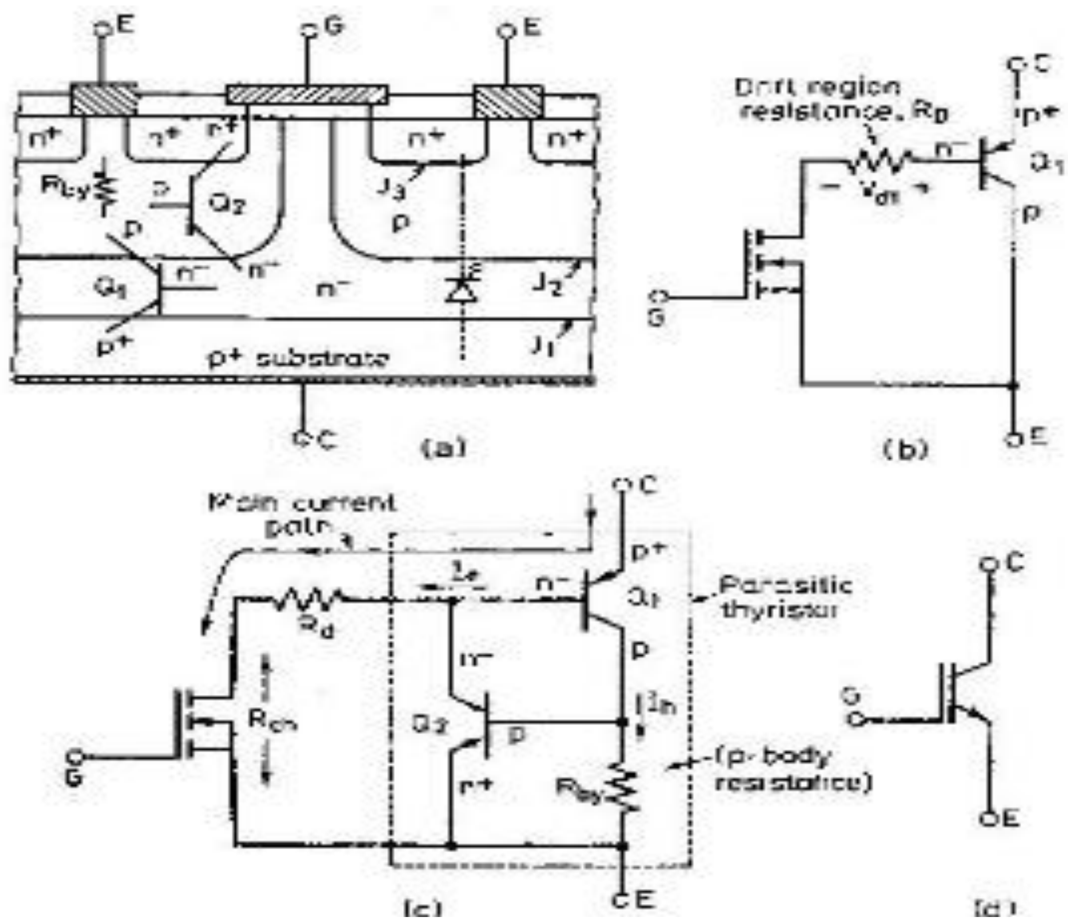
BASIC STRUCTURE OF IGBT



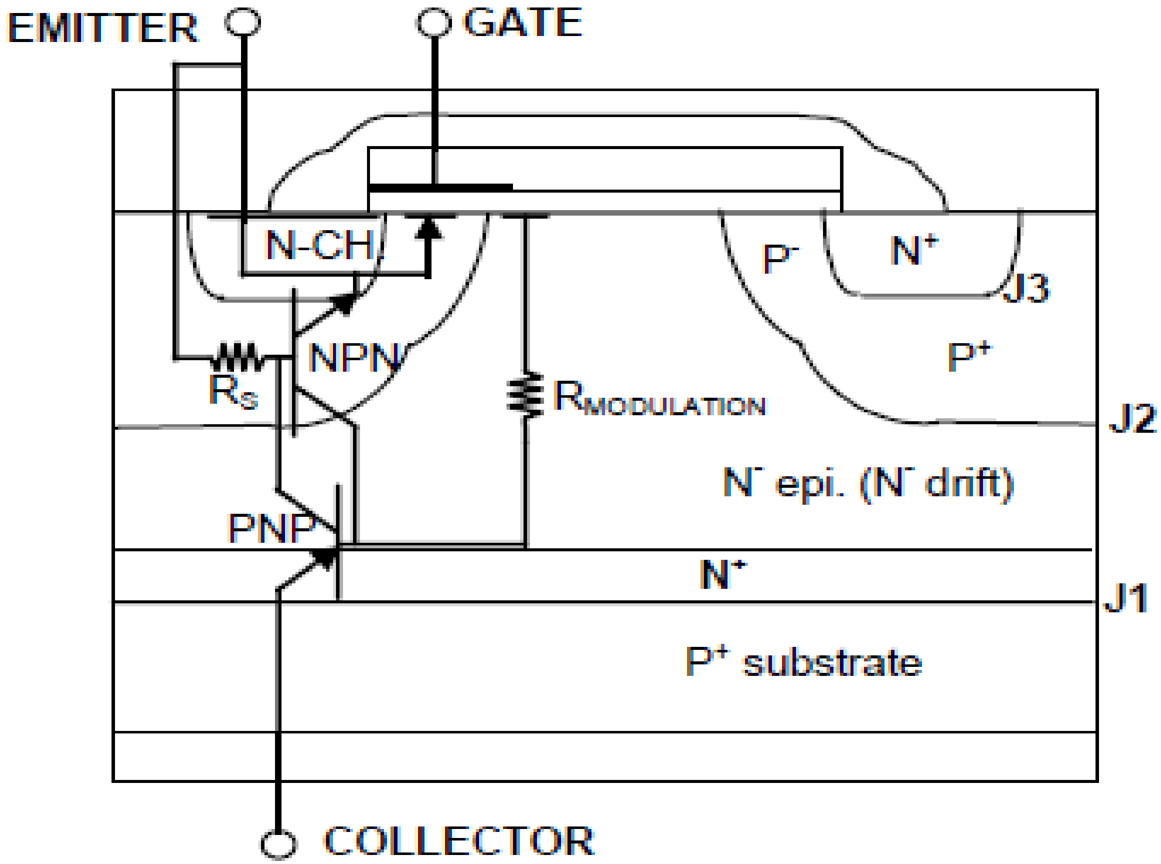
BASIC STRUCTURE OF IGBT



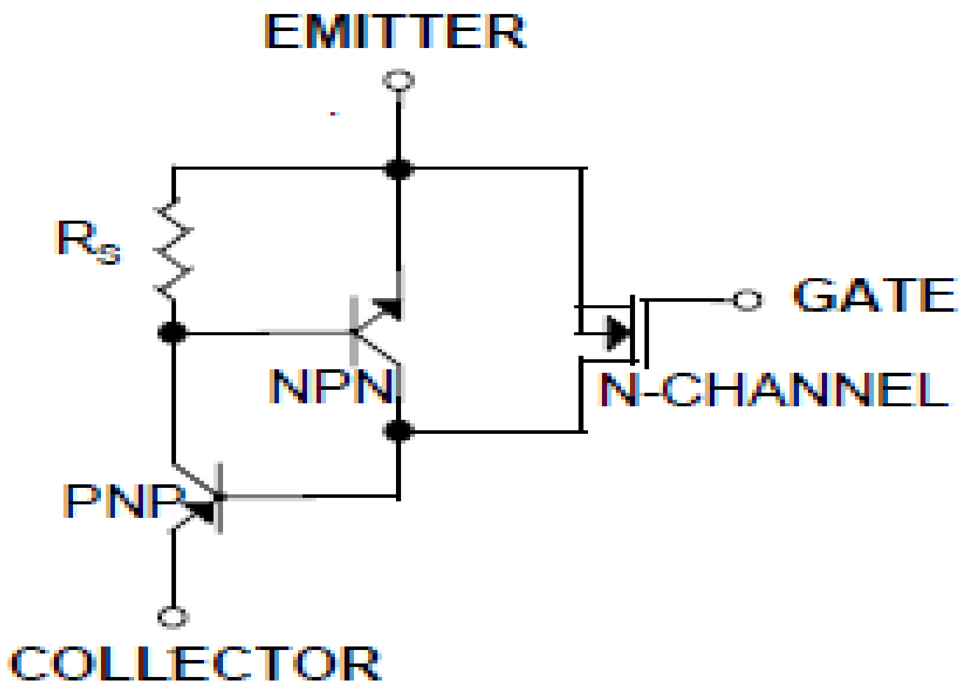
EQUIVALENT CIRCUIT OF IGBT



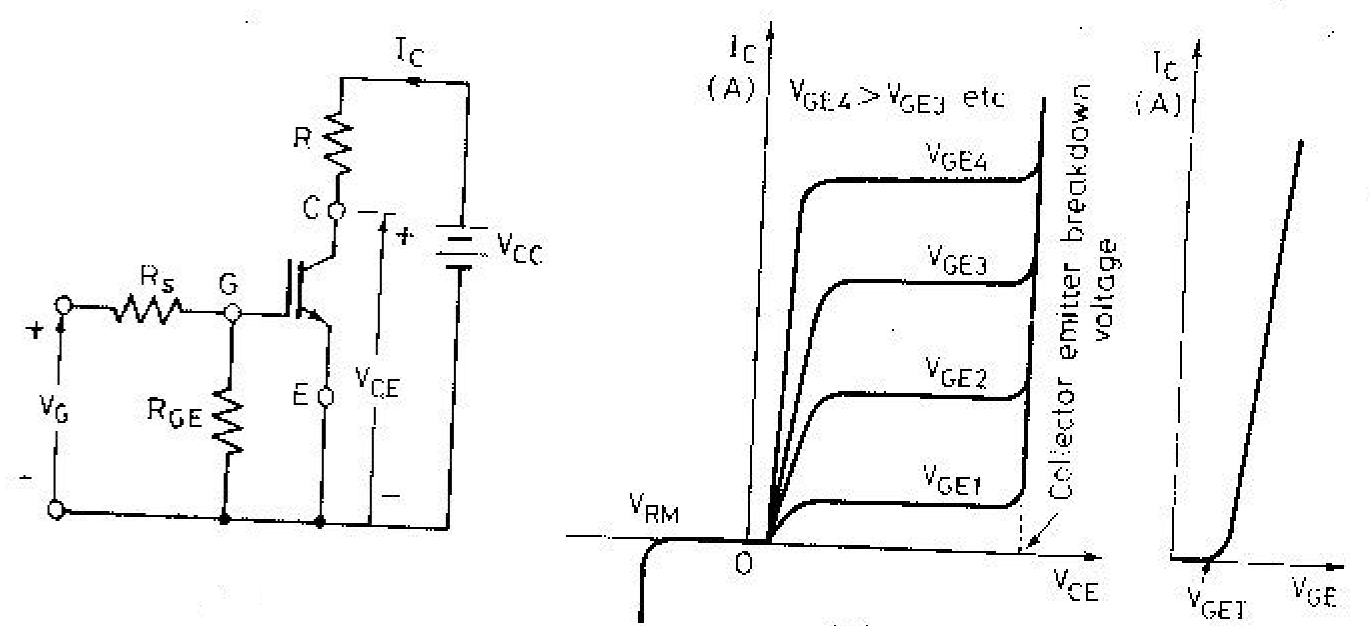
BASIC STRUCTURE OF IGBT



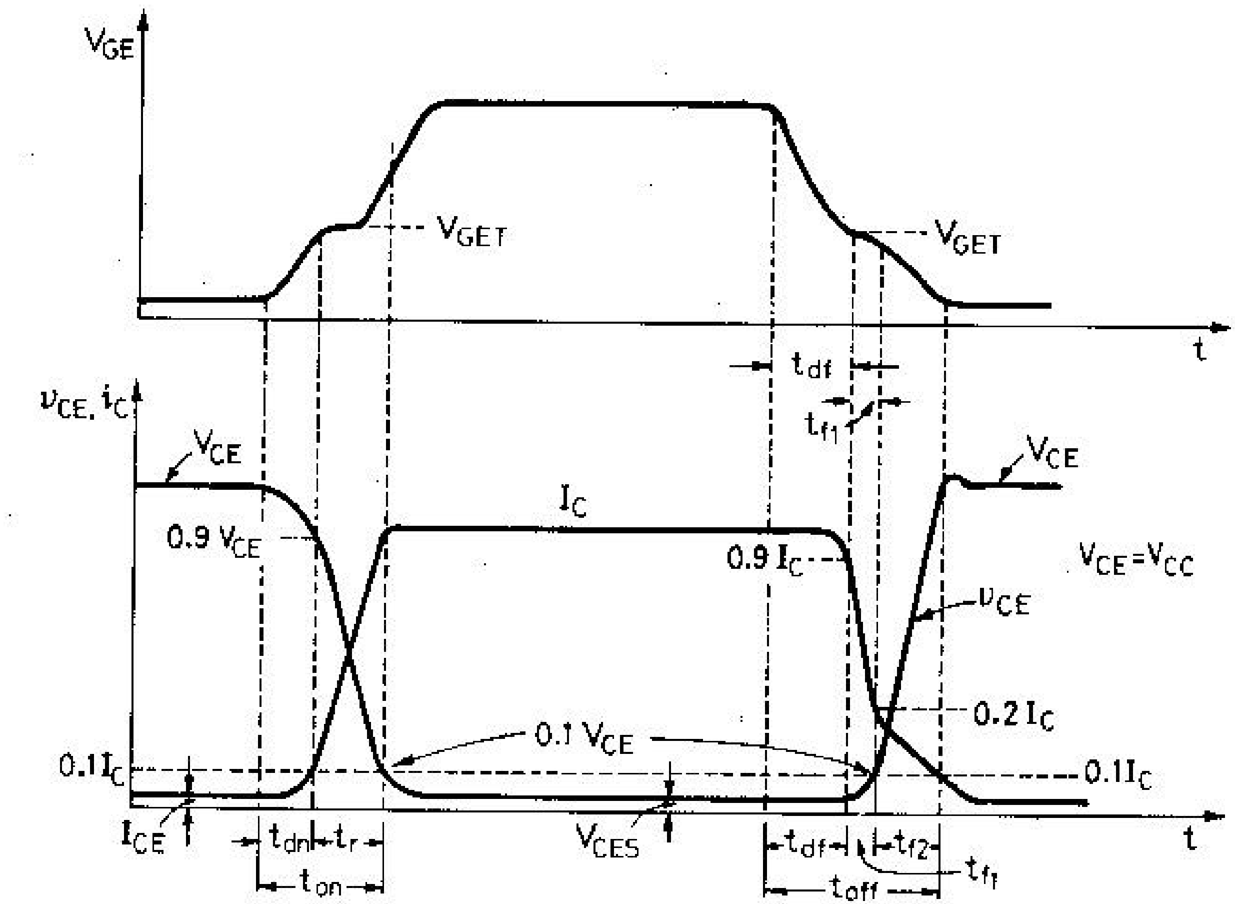
EQUIVALENT CIRCUIT OF IGBT



V-I AND TRANSFER CHARACTERISTICS OF IGBT



SWITCHING CHARACTERISTICS OF IGBT



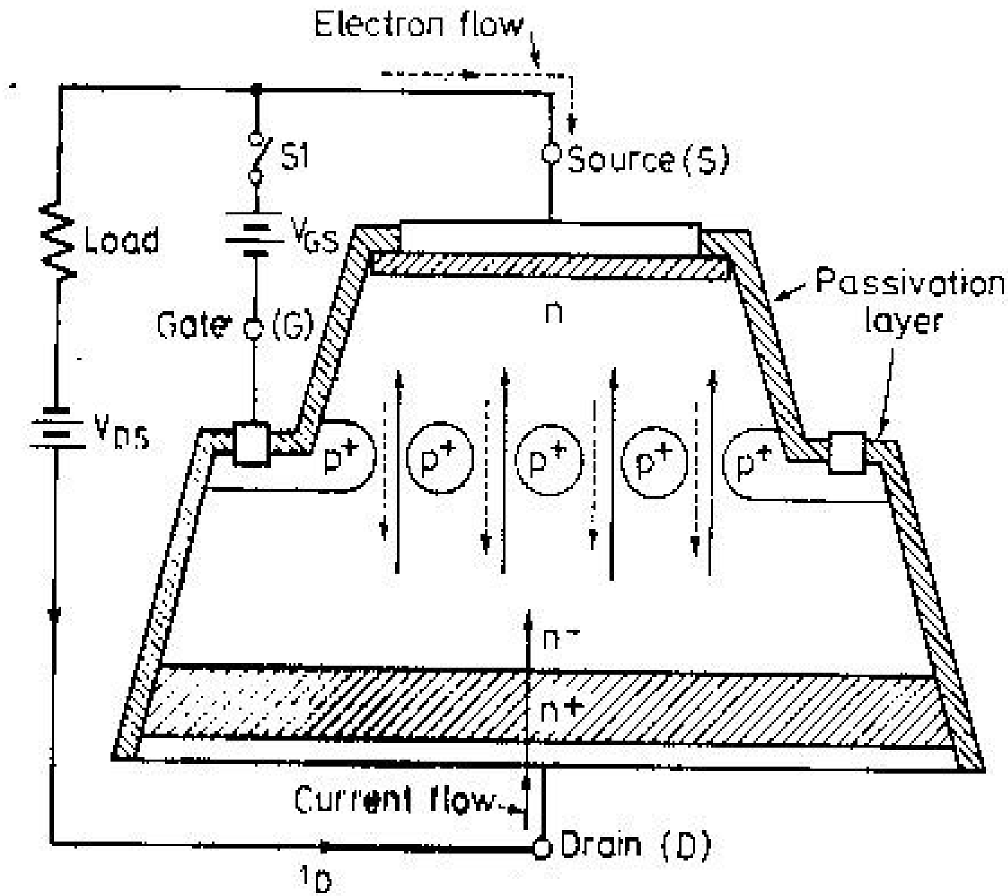
APPLICATIONS OF IGBT

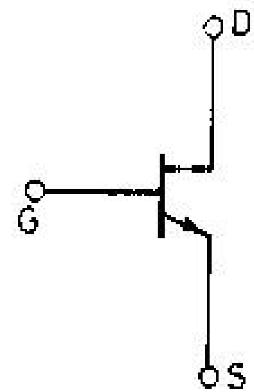
- DC AND AC MOTOR DRIVES
- UPS SYSTEMS,POWER SUPPLIES
- DRIVES FOR SOLENOIDS,RELAYS AND CONTACTORS

COMPARISON OF IGBT WITH MOSFET

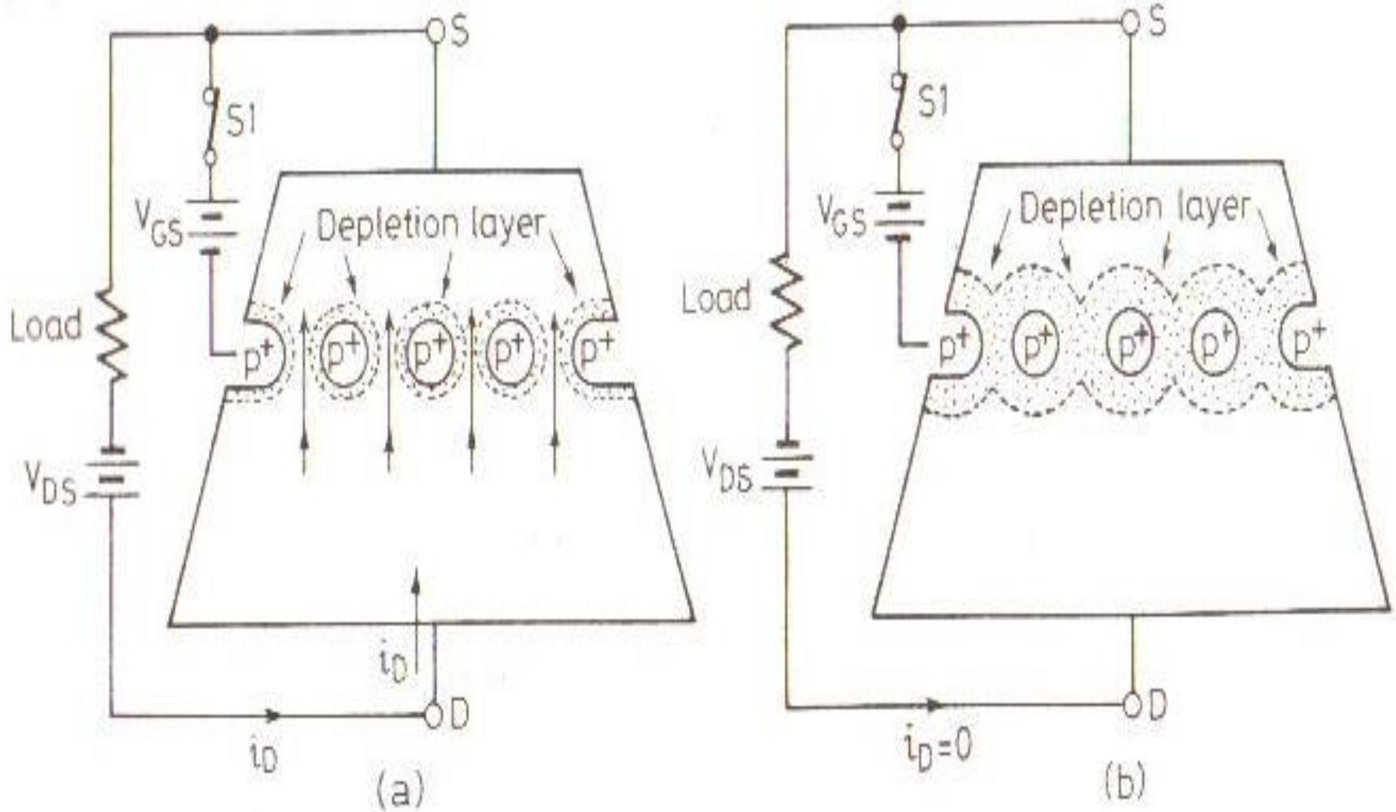
S.No	MOSFET	IGBT
1.	THREE TERMINALS ARE GATE,SOURCE AND DRAIN	THREE TERMINALS ARE GATE,EMITTER AND COLLECTOR
2.	HIGH INPUT IMPEDANCE	HIGH INPUT IMPEDANCE
3.	VOLTAGE CONTROLLED DEVICE	VOLTAGE CONTROLLED DEVICE
4.	RATINGS AVAILABLE UPTO 500V,140A	RATINGS AVAILABLE UPTO 1200V,500A
5.	OPERATING FREQUENCY IS UPTO I MHz	OPERATING FREQUENCY IS UPTO 50KHz
6.	WITH RISE IN TEMPERATURE,THE INCREASE IN ON-STATE RESISTANCE IN MOSFET IS MORE PRONOUNCED THAN IGBT.SO, ON-STATE VOLTAGE DROP AND LOSSES RISE RAPIDLY IN MOSFET THAN IN IGBT ITH RISE IN TEMPERATURE.	
7.	WITH RISE IN VOLTAGE,THE INCREMENT IN ON-STATE VOLTAGE DROP IS MORE DOMINANT IN MOSFET THAN IT IS IN IGBT.THIS MEANS IGBTs CAN BE DESIGNED FOR HIGHER VOLTAGE RATINGS THAN MOSFETs.	

BASIC STRUCTURE OF STATIC INDUCTION TRANSISTOR(SIT)





WORKING OF SIT



(a)Lower reverse bias,load current is reduced due to depletion layer
(b) Higher reverse bias,expanded depletion layer stops current flow

WORKING OF SIT

- SIT IS A NORMALLY ON DEVICE
- IF V_{GS} =0 AND V_{DS} IS PRESENT ,ELECTRONS WOULD FLOW FROM SOURCE TO n,P^+,n^-, n^+ AND REACH DRAIN.DRAIN CURRENT FLOWS FROM D TO S.
- IF V_{GS} = NEGATIVE, P^+n^- JUNCTIONS GET REVERSE BIASED.DEPLETION REGION IS FORMED AROUND P+ ELECTRODES AND THIS REDUCES THE CURRENT FLOW FROM ITS VALUE WHEN V_{GS} =0.
- AT SOME HIGHER VALUE OF REVERSE BIAS VOLTAGE V_{GS} ,THE DEPLETION LAYER WOULD GROW TO SUCH AN EXTENT AS TO CUT OFF THE CHANNEL COMPLETELY AND LOAD CURRENT WOULD BE ZERO.

STATIC INDUCTION TRANSISTOR(SIT)

- IT IS A HIGH POWER,HIGH FREQUENCY DEVICE.
- LARGE DROP IN SIT MAKES IT UNSUITABLE FOR GENERAL POWER ELECTRONIC APPLICATIONS.
- A 1500V,180A SIT HAS A CHANNEL RESISTANCE OF 0.5 Ω GIVING 90V CONDUCTION DROP AT 180A.AN EQUIVALENT THYRISTOR OR GTO DROP MAY BE AROUND 2V.
- TYPICAL T_{ON} AND T_{OFF} TIMES ARE VERY LOW AROUND 0.35μs.
- HIGH CONDUCTION DROP WITH VERY LOW TURN-ON AND TURN-OFF TIMES RESULT IN LOW ON-OFF ENERGY LOSSES.THIS MAKES SIT SUITABLE FOR HIGH POWER,HIGH FREQUENCY APPLICATIONS.

APPLICATIONS OF SIT

- AM/FM TRANSMITTERS
- INDUCTION HEATERS
- HIGH VOLTAGE LOW CURRENT POWER SUPPLIES
- ULTRASONIC GENERATORS
- TYPICAL RATINGS AVAILABLE -1200V,300AWITH TURN ON AND TURN OFF TIMES AROUND 0.25 TO 0.35 μs AND 100KHz OPERATING FREQUENCY.

THYRISTORS
SILICON CONTROLLED RECTIFIER (SCR)

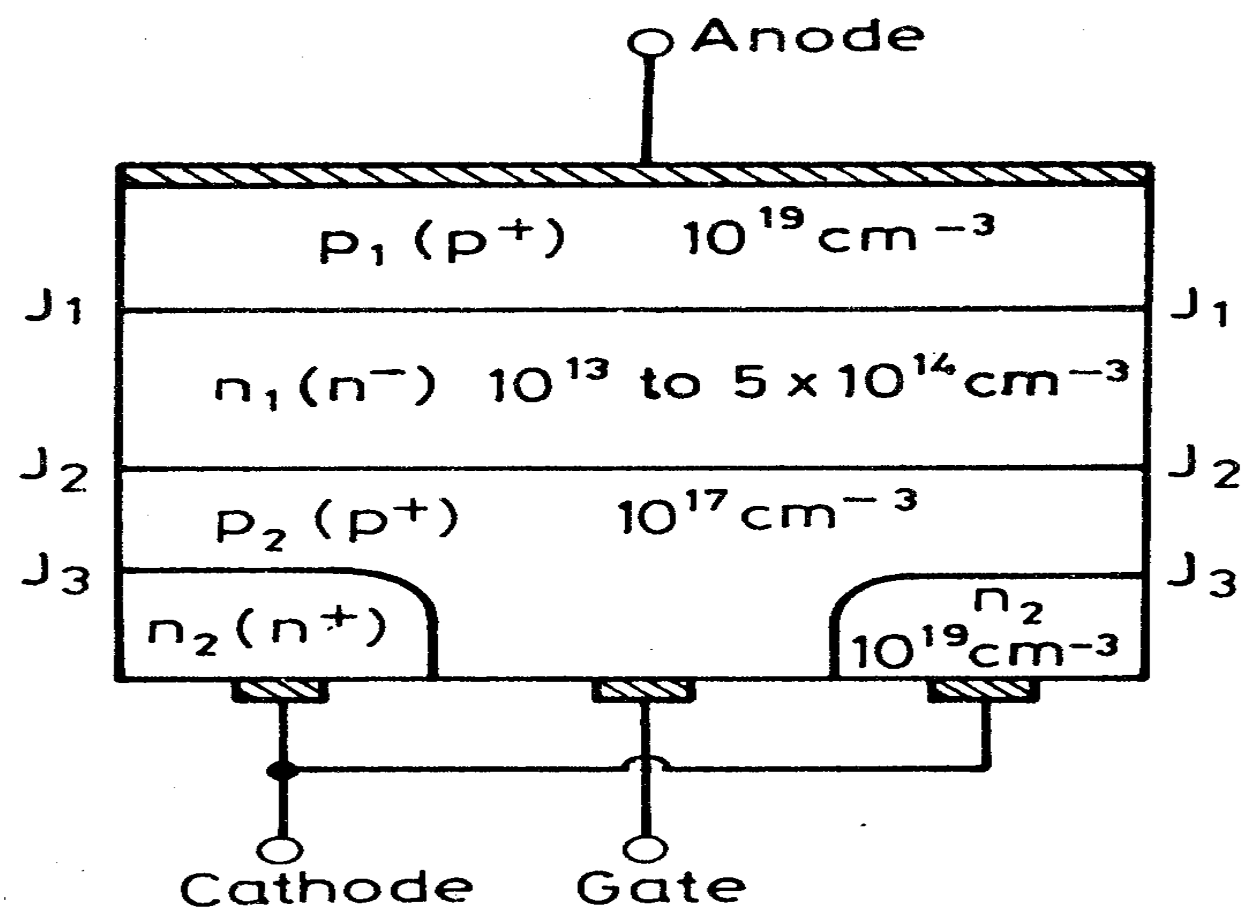
- Three terminal, four layers (P-N-P-N)
- Can handle high currents and high voltages, with better switching speed and improved breakdown voltage .
- Name 'Thyristor', is derived by a combination of the capital letters from **THYRatron** and **transISTOR**.
- Has characteristics similar to a thyratron tube

  But from the construction view point belongs to transistor (pnp or npn device) family.

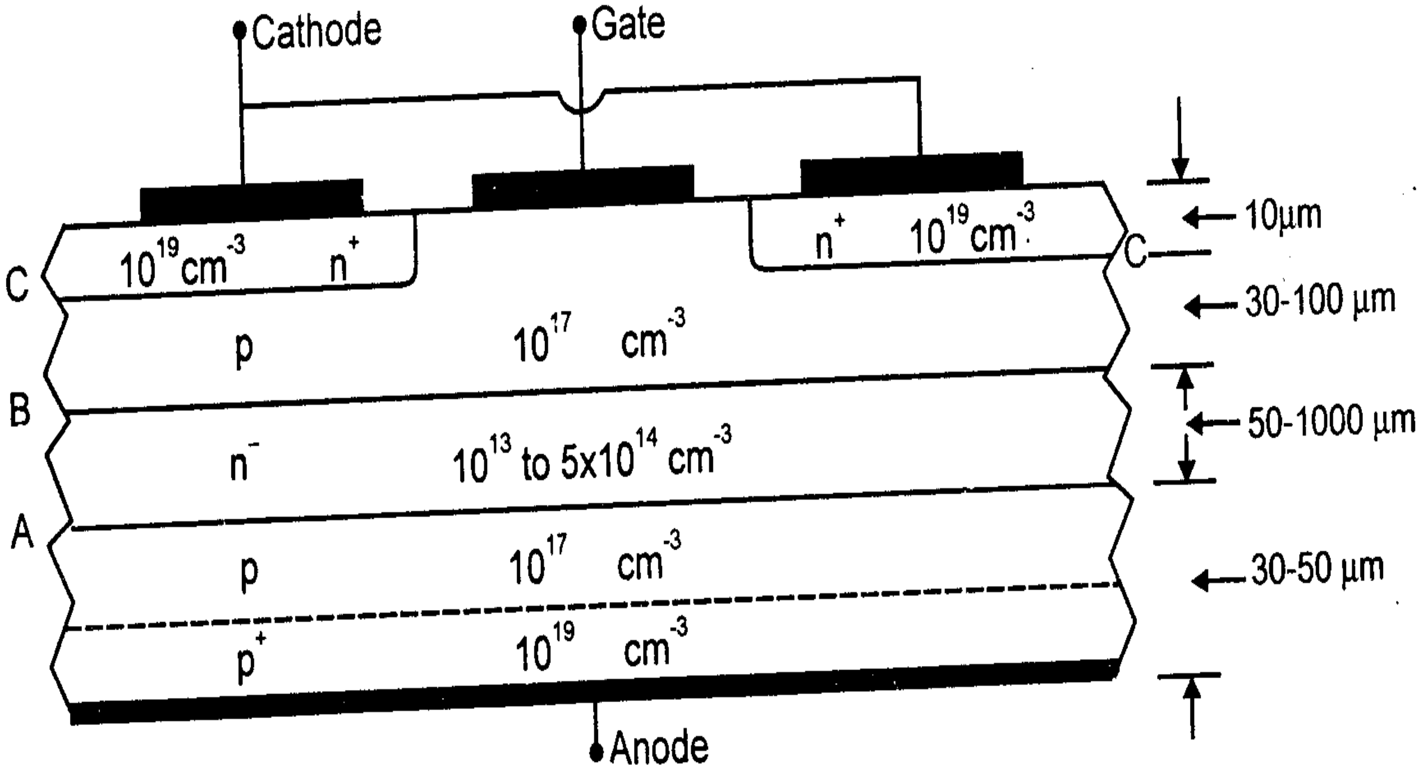
THYRISTORS

- TYPICAL RATINGS AVAILABLE ARE 1.5KA & 10KV WHICH RESPONDS TO 15MW POWER HANDLING CAPACITY.
- THIS POWER CAN BE CONTROLLED BY A GATE CURRENT OF ABOUT 1A ONLY.

BASIC STRUCTURE OF SCR



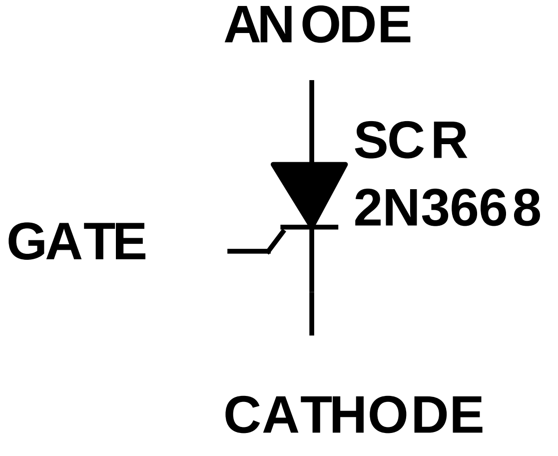
BASIC STRUCTURE OF SCR CONTD…



(a) Vertical cross-section of thyristor

SCR / Thyristor

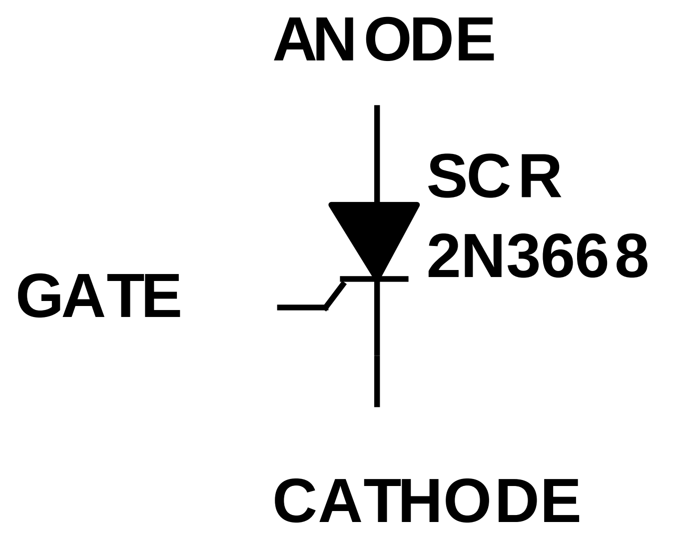
- Circuit Symbol and Terminal Identification



SCR / Thyristor

- Anode and Cathode terminals as conventional pn junction diode

- Gate terminal for a controlling input signal



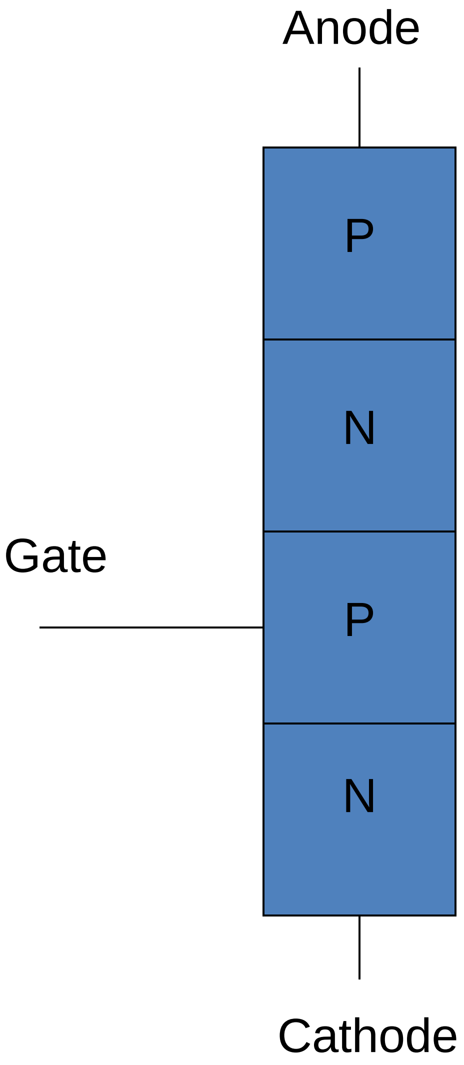
SCR/ Thyristor

- An SCR (Thyristor) is a “controlled” rectifier (diode)
- Control the conduction under forward bias by applying a current into the Gate terminal
- Under reverse bias, looks like conventional pn junction diode

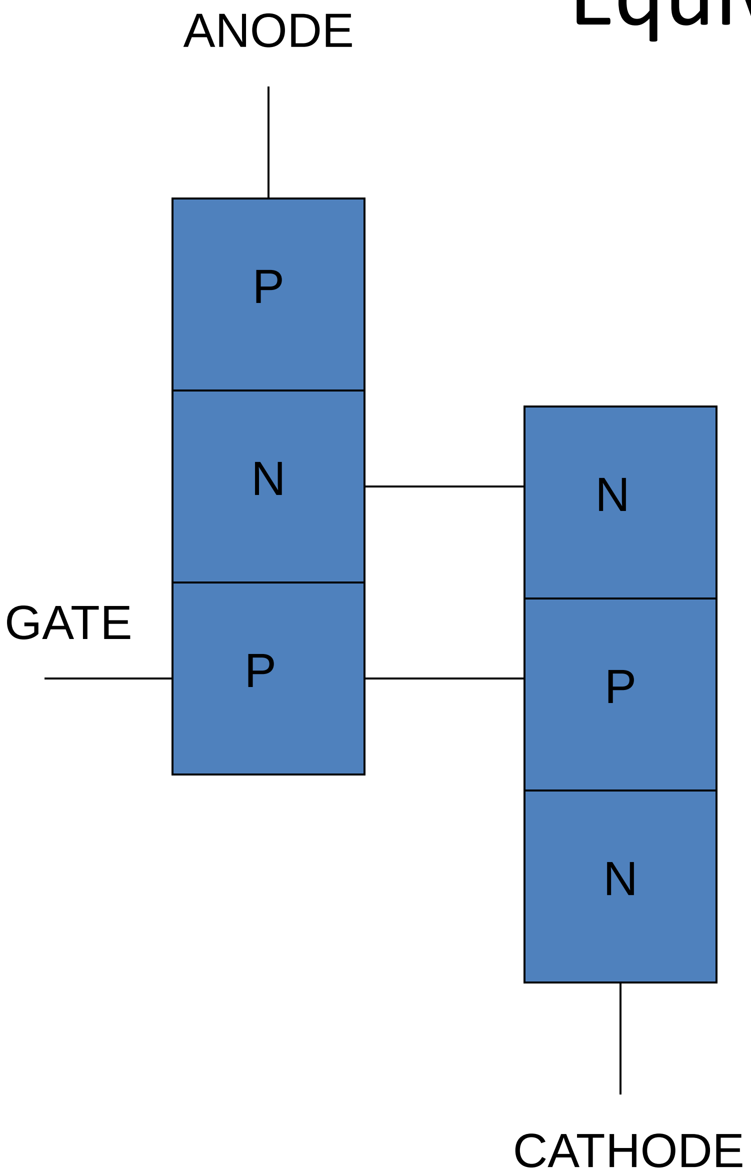
SCR / Thyristor

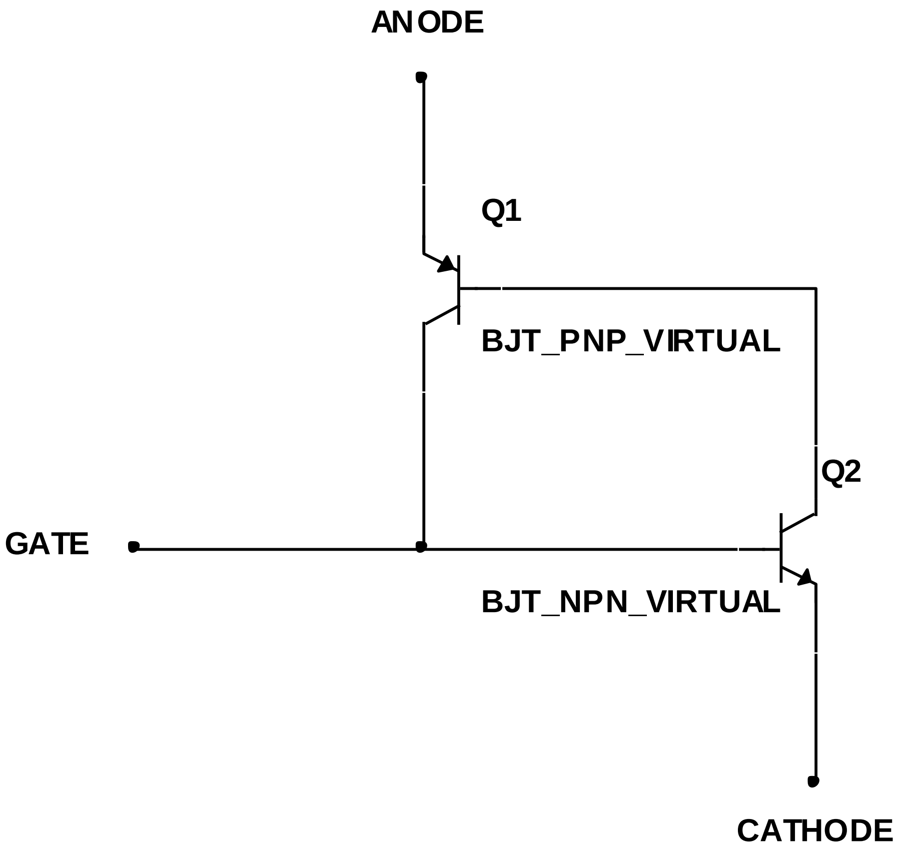
- 4-layer (pnpn) device
- Anode, Cathode as for a conventional pn junction diode

- Cathode Gate brought out for controlling input



Equivalent Circuit

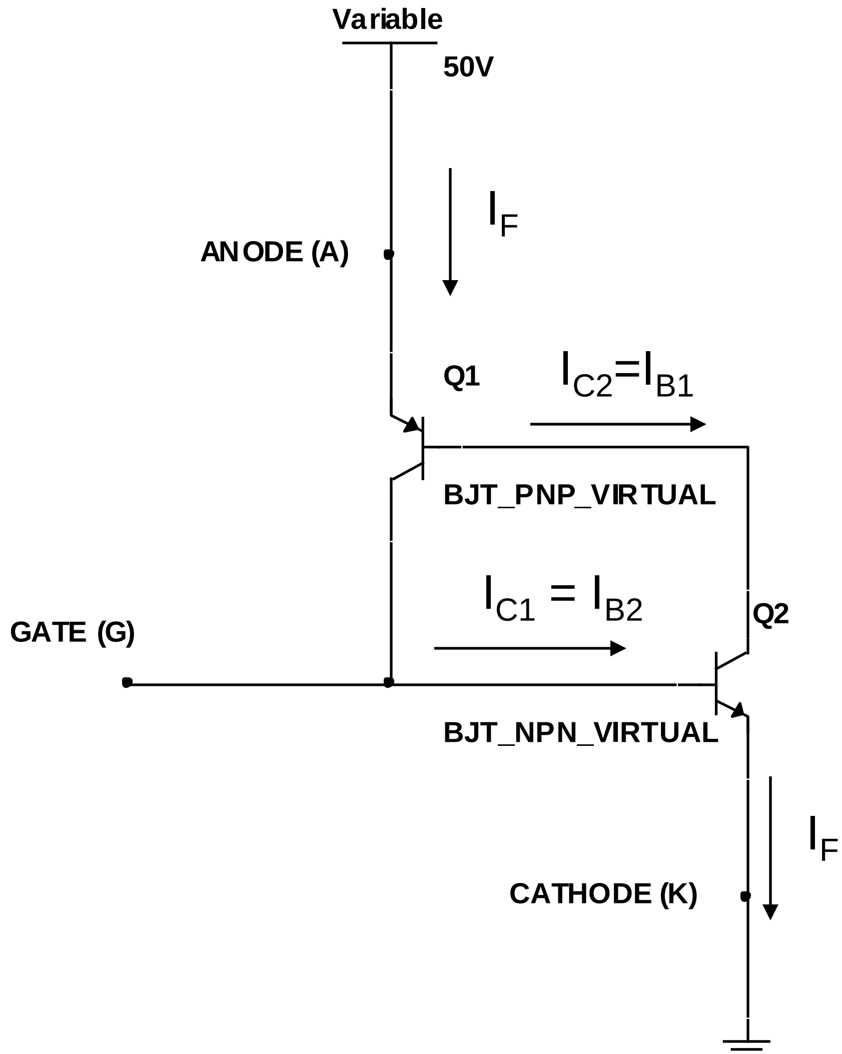




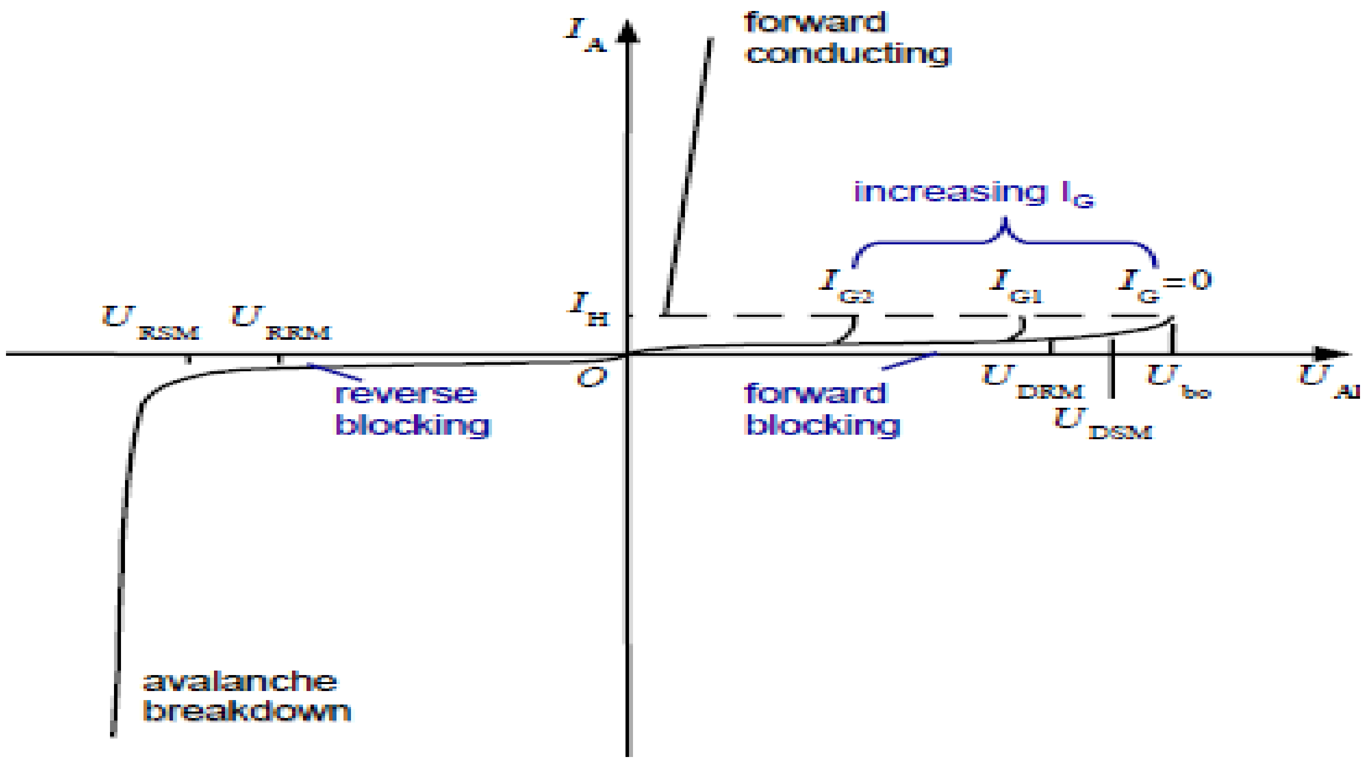
Apply Biasing

With the Gate terminal OPEN, both transistors are OFF. As the applied voltage increases, there will be a “breakdown” that causes both transistors to conduct (saturate) making $I_F > 0$ and $V_{AK} = 0$.

$V_{Breakdown} = V_{BR(F)}$



V-I CHARACTERISTICS OF SCR



Apply a Gate Current

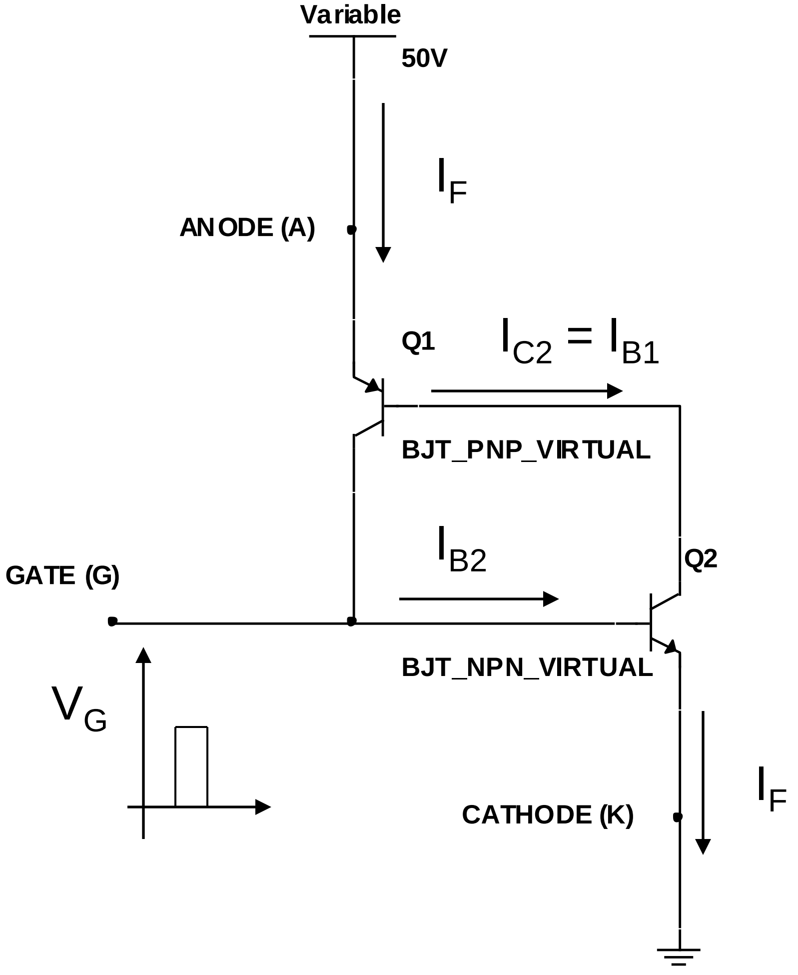
For $0 < V_{AK} < V_{BR(F)}$,

Turn Q_2 ON by applying a current into the Gate

This causes Q_1 to turn ON, and eventually both transistors SATURATE

$V_{AK} = V_{CEsat} + V_{BEsat}$

If the Gate pulse is removed, Q_1 and Q_2 still stay ON!

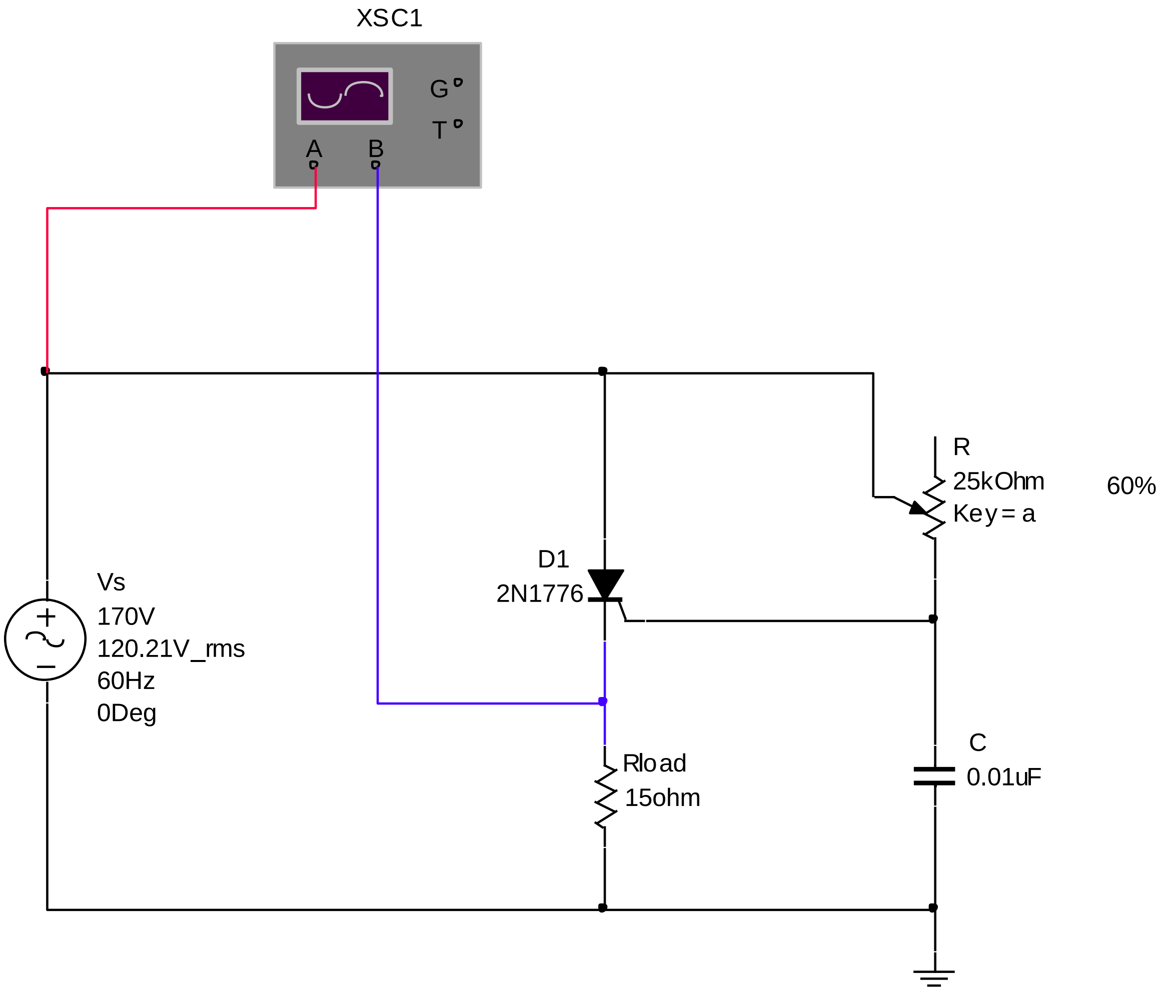


How do you turn it OFF?

- Cause the forward current to fall below the value if the “holding” current, I_H

- Reverse bias the device

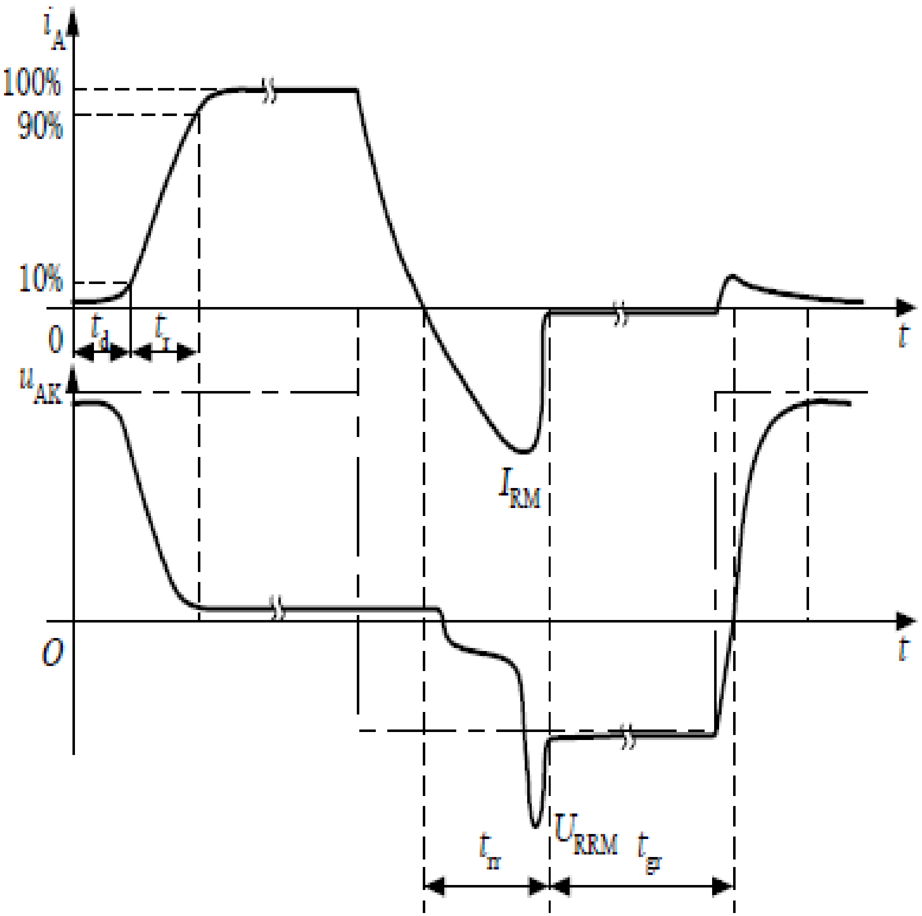
SCR Application – Power Control



When the voltage across the capacitor reaches the "trigger-point" voltage of the device, the SCR turns ON, current flows in the Load for the remainder of the positive half-cycle.

Current flow stops when the applied voltage goes negative.

SWITCHING CHARACTERISTICS OF SCR



Turn-on transient

- Delay time t_d
- Rise time t_r
- Turn-on time t_{gt}

Turn-off transient

- Reverse recovery time t_{rr}
- Forward recovery time t_{gr}
- Turn-off time t_q

SCR OPERATING MODES

FORWARD BLOCKING MODE: Anode is positive w.r.t cathode, but the anode voltage is less than the break over voltage (VBO) .

only leakage current flows, so thyristor is not conducting .

FORWARD CONDUCTING MODE: When anode voltage becomes greater than VBO, thyristor switches from forward blocking to forward conduction state, a large forward current flows.

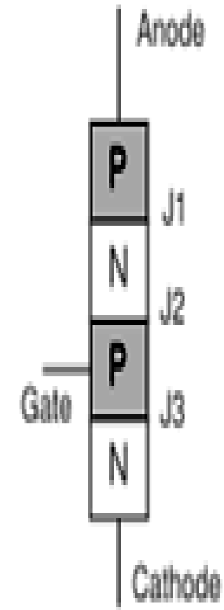
If the IG=IG1, thyristor can be turned ON even when anode voltage is less than VBO.

- The current must be more than the latching current (IL).
- If the current reduced less than the holding current (IH), thyristor switches back to forward blocking state.

REVERSE BLOCKING MODE: When cathode is more positive than anode , small reverse leakage current flows. However if cathode voltage is increased to reverse breakdown voltage , Avalanche breakdown occurs and large current flows.

Thyristor- Operation Principle

- Thyristor has three p-n junctions (J1, J2, J3 from the anode).
- When anode is at a positive potential (VAK) w.r.t cathode with no voltage applied at the gate, junctions J1 & J3 are forward biased, while junction J2 is reverse biased.
  - As J2 is reverse biased, no conduction takes place, so thyristor is in forward blocking state (OFF state).
  - Now if *V*AK (forward voltage) is increased w.r.t cathode, forward leakage current will flow through the device.
  - When this forward voltage reaches a value of breakdown voltage (*V*BO) of the thyristor, forward leakage current will reach saturation and reverse biased junction (J2) will have avalanche breakdown and thyristor starts conducting (ON state), known as forward conducting state .
- If Cathode is made more positive w.r.t anode, Junction J1 & J3 will be reverse biased and junction J2 will be forward biased.
- A small reverse leakage current flows, this state is known as reverse blocking state.
- As cathode is made more and more positive, stage is reached when both junctions A & C will be breakdown, this voltage is referd as reverse breakdown voltage (OFF state), and device is in reverse blocking state



TRIGGERING METHODS

- THYRISTOR TURNING ON IS ALSO KNOWN AS **TRIGGERING**.
- WITH ANODE POSITIVE WITH RESPECT TO CATHODE, A THYRISTOR CAN BE TURNED ON BY ANY ONE OF THE FOLLOWING TECHNIQUES :
  - FORWARD VOLTAGE TRIGGERING
  - GATE TRIGGERING
  - DV/DT TRIGGERING
  - TEMPERATURE TRIGGERING
  - LIGHT TRIGGERING

Forward Voltage Triggering

- When breakover voltage (VBO) across a thyristor is exceeded than the rated maximum voltage of the device, thyristor turns ON.
- At the breakover voltage the value of the thyristor anode current is called the latching current (IL) .
- Breakover voltage triggering is not normally used as a triggering method, and most circuit designs attempt to avoid its occurrence.
- When a thyristor is triggered by exceeding VBO, the fall time of the forward voltage is quite low (about 1/20th of the time taken when the thyristor is gate-triggered).
- However, a thyristor switches faster with VBO turn-ON than with gate turn-ON, so permitted di/dt for breakover voltage turn-on is lower.

dv/dt triggering

- With forward voltage across anode & cathode of a thyristor, two outer junctions (A & C) are forward biased but the inner junction (J2) is reverse biased.
- The reversed biased junction J2 behaves like a capacitor because of the space-charge present there.
- As p-n junction has capacitance, so larger the junction area the larger the capacitance.
- If a voltage ramp is applied across the anode-to-cathode, a current will flow in the device to charge the device capacitance according to the relation:

$$i_C = C.\frac{dv}{dt}$$

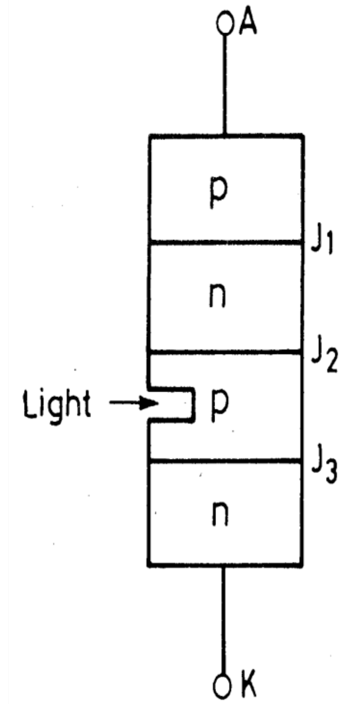
- If the charging current becomes large enough, density of moving current carriers in the device induces switch-on.
- This method of triggering is not desirable because high charging current (Ic) may damage the thyristor.

Temperature Triggering

- During forward blocking, most of the applied voltage appears across reverse biased junction J2.
- This voltage across junction J2 associated with leakage current may raise the temperature of this junction.
- With increase in temperature, leakage current through junction J2 further increases.
- This cumulative process may turn on the SCR at some high temperature.
- High temperature triggering may cause Thermal runaway and is generally avoided.

Light Triggering

- In this method light particles (photons) are made to strike the reverse biased junction, which causes an increase in the number of electron hole pairs and triggering of the thyristor.
- For light-triggered SCRs, a slot (niche) is made in the inner p-layer.
- When it is irradiated, free charge carriers are generated just like when gate signal is applied b/w gate and cathode.
- Pulse light of appropriate wavelength is guided by optical fibers for irradiation.
- If the intensity of this light thrown on the recess exceeds a certain value, forward-biased SCR is turned on. Such a thyristor is known as light-activated SCR (LASCR).
- Light-triggered thyristors is mostly used in high-voltage direct current (HVDC) transmission systems.



Thyristor Gate Control Methods

- An easy method to switch ON a SCR into conduction is to apply a proper positive signal to the gate.
- This signal should be applied when the thyristor is forward biased and should be removed after the device has been switched ON.
- Thyristor turn ON time should be in range of 1-4 micro seconds, while turn-OFF time must be between 8-50 micro seconds.
- Thyristor gate signal can be of three varieties.
  - **D.C Gate signal**
  - **A.c Gate Signal**
  - **Pulse**

Thyristor Gate Control Methods

D.C Gate signal: Application of a d.c gate signal causes the flow of gate current which triggers the SCR.

- Disadvantage is that the gate signal has to be continuously applied, resulting in power loss.
- Gate control circuit is also not isolated from the main power circuit.

A.C Gate Signal: In this method a phase - shifted a.c voltage derived from the mains supplies the gate signal.

- Instant of firing can be controlled by phase angle control of the gate signal.

Pulse: Here the SCR is triggered by the application of a positive pulse of correct magnitude.

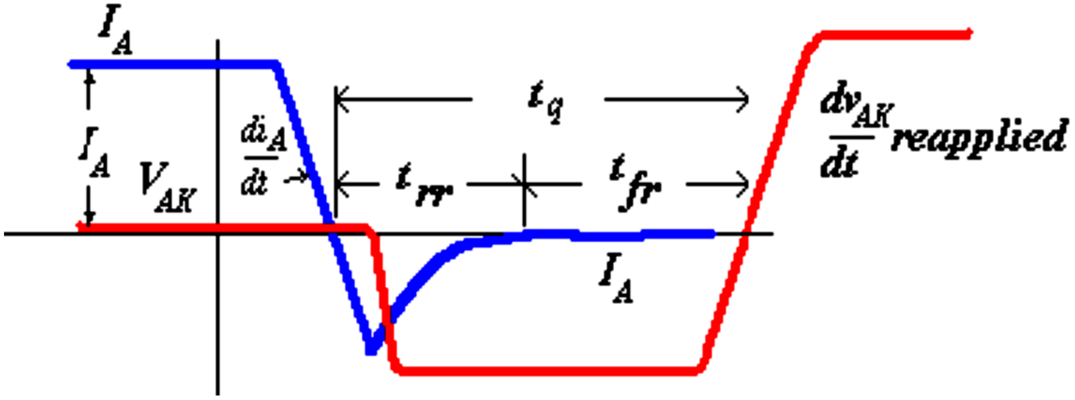
- For Thyristors it is important to switched ON at proper instants in a certain sequence.
- This can be done by train of the high frequency pulses at proper instants through a logic circuit.
- A pulse transformer is used for circuit isolation.
- Here, the gate looses are very low because the drive is discontinuous.

Thyristor Commutation

- Commutation: Process of turning off a conducting thyristor
  - Current Commutation
  - Voltage Commutation
- A thyristor can be turned ON by applying a positive voltage of about a volt or a current of a few tens of milliamps at the gate-cathode terminals.
- But SCR cannot be turned OFF via the gate terminal.
- It will turn-off only after the anode current is negated either naturally or using forced commutation techniques.
- These methods of turn-off do not refer to those cases where the anode current is gradually reduced below Holding Current level manually or through a slow process.
- Once the SCR is turned ON, it remains ON even after removal of the gate signal, as long as a minimum current, the Holding Current (IH), is maintained in the main or rectifier circuit.

Thyristor Turn-off Mechanism

- In all practical cases, a negative current flows through the device.
- This current returns to zero only after the reverse recovery time (*trr)* , when the SCR is said to have regained its reverse blocking capability.
- The device can block a forward voltage only after a further *tfr*, the forward recovery time has elapsed.
- Consequently, the SCR must continue to be reverse-biased for a minimum of *tfr + trr = tq*, the rated turn-off time of the device.
- The external circuit must therefore reverse bias the SCR for a time *toff > tq*.
- Subsequently, the reapplied forward biasing voltage must rise at a dv/dt < dv/dt (reapplied) rated. This dv/dt is less than the static counterpart.



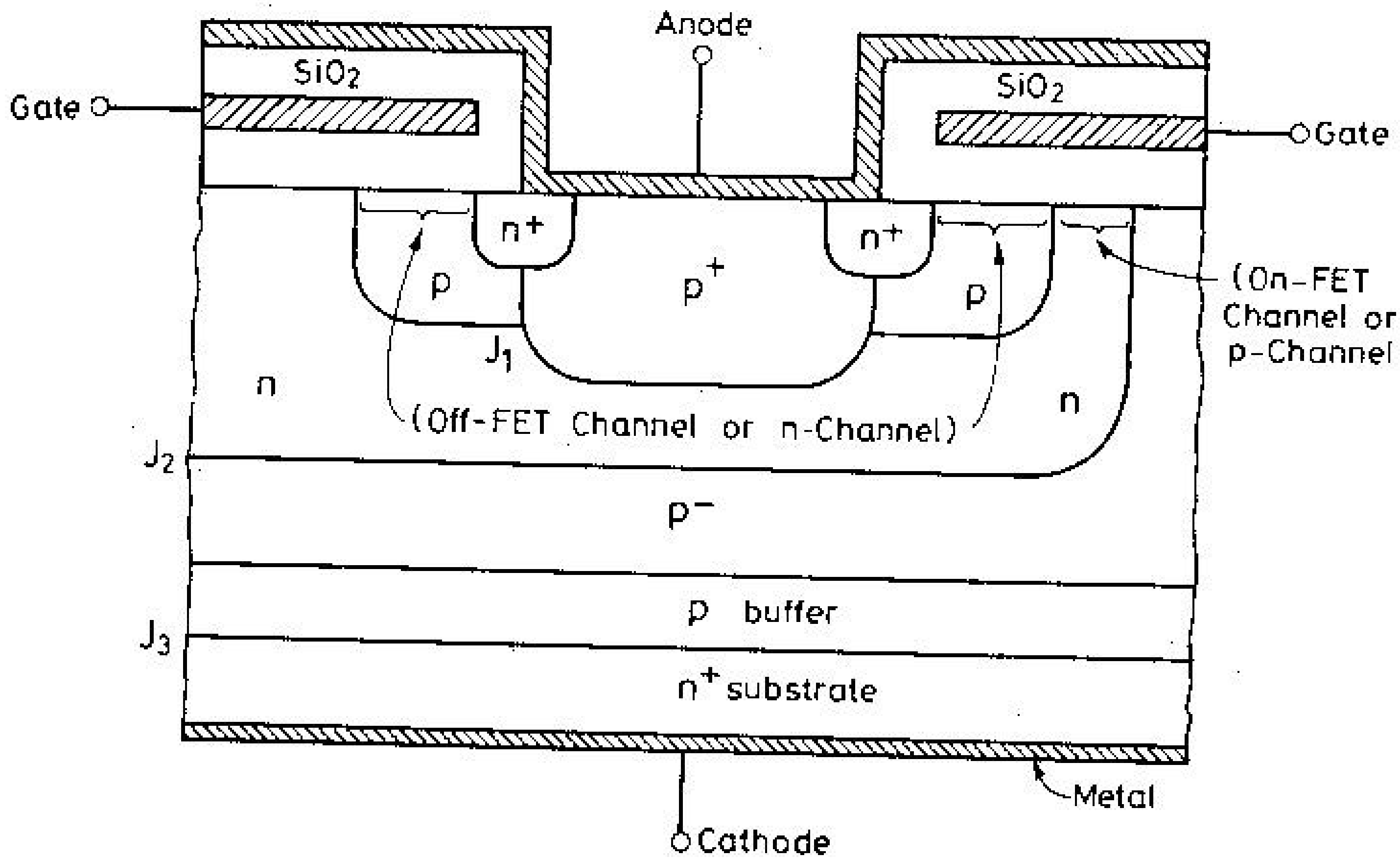
Thyristor Commutation Classification

- Commutation can be classified as
  - Natural commutation
  - Forced commutation

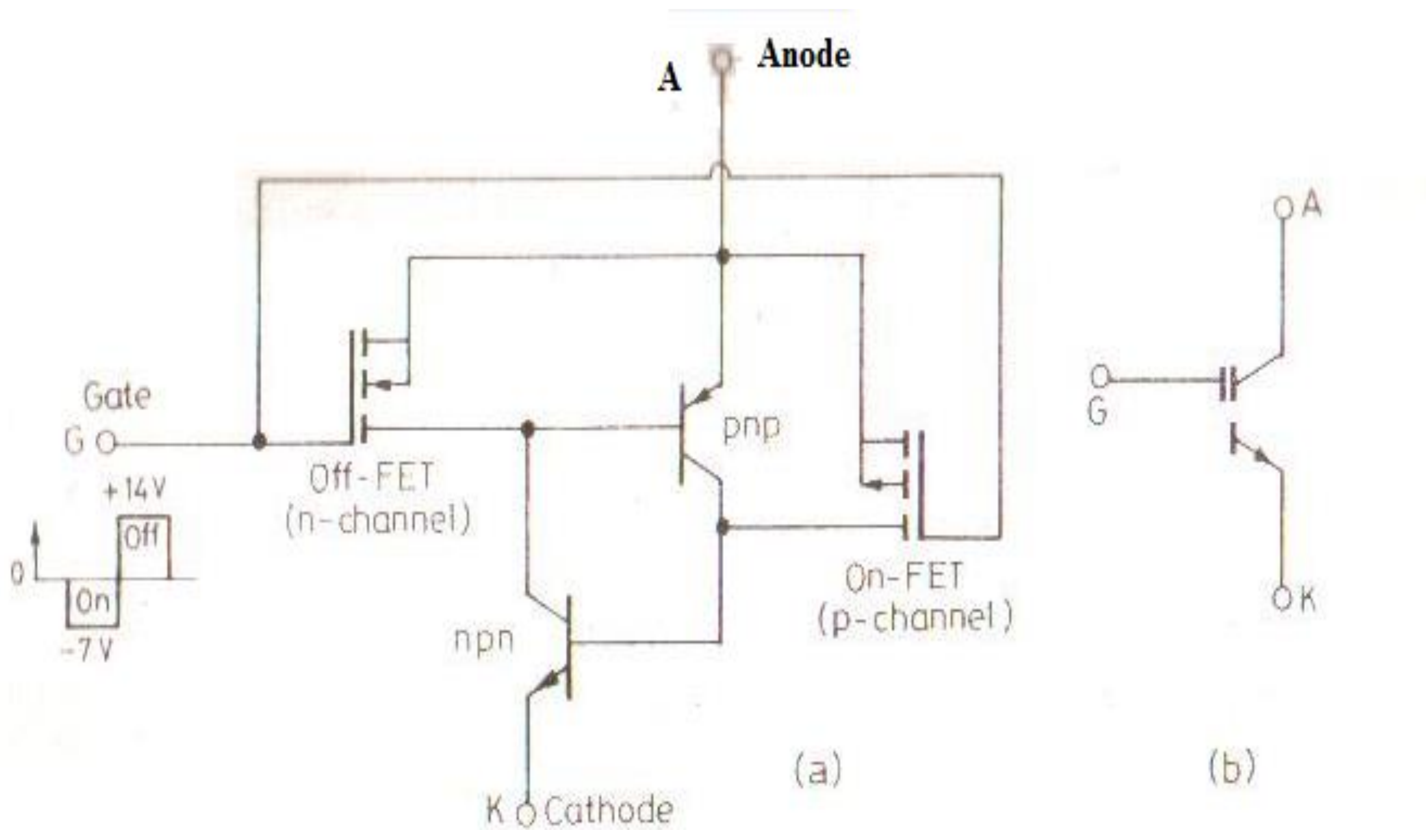
MOS CONTROLLED THYRISTOR (MCT)

- IT IS BASICALLY A THYRISTOR WITH TWO MOSFETS BUILT INTO THE GATE STRUCTURE
- ONE MOSFET IS USED TO TURN ON THE MCT AND THE OTHER FOR TURNING OFF OF MCT.
- IT IS A HIGH FREQUENCY,HIGH POWER,LOW CONDUCTION DROP SWITCHING DEVICE.
- IN A MCT, THE ANODE IS THE REFERENCE W.R.TO WHICH ALL THE GATE SIGNALS ARE APPLIED. IN A SCR,CATHODE IS THE REFERENCE SIGNAL TO THE GATE SIGNAL.

BASIC STRUCTURE OF MCT



EQUIVALENT CIRCUIT OF MCT

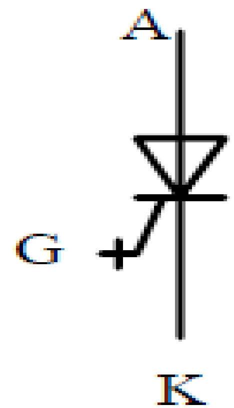


MERITS OF MCT

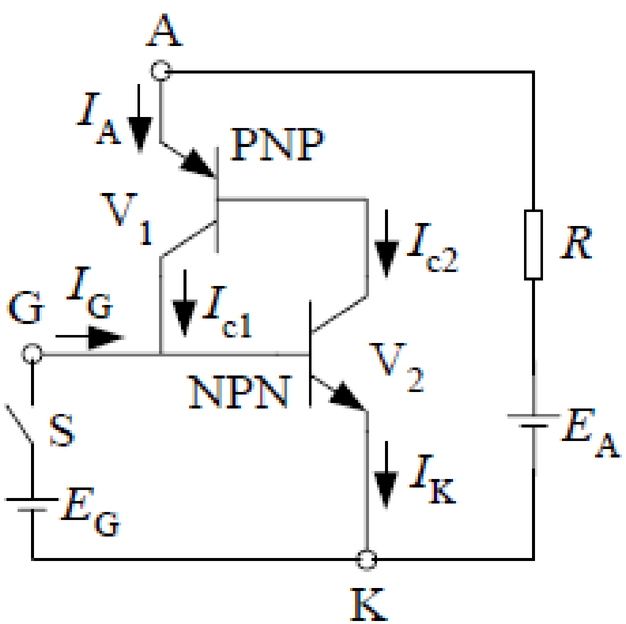
- LOW FORWARD CONDUCTION DROP
- FAST TURN AND TURN OFF TIMES
- LOW SWITCHING LOSSES
- HIGH GATE INPUT IMPEDANCE

- LOW REVERSE VOLTAGE BLOCKING CAPABILITY IS THE MAIN **DISADVANTAGE** OF MCT

GATE TURN OFF THYRISTORS (GTO)



PRINCIPLE OF OPERATION



The basic operation of GTO is the same as that of the conventional thyristor.

The principal differences lie in the modifications in the structure to achieve gate turn-off capability.

- Large α_2
- $\alpha_1+\alpha_2$ is just a little larger than the critical value 1.
- Short distance from gate to cathode makes it possible to drive current out of gate.

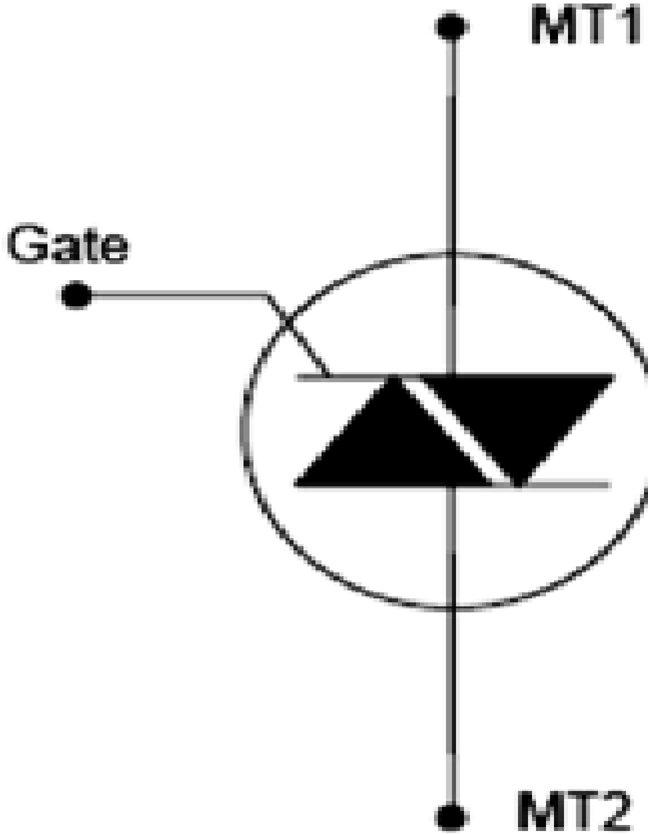
TRIAC
(TRIODE FOR ALTERNATING CURRENT)

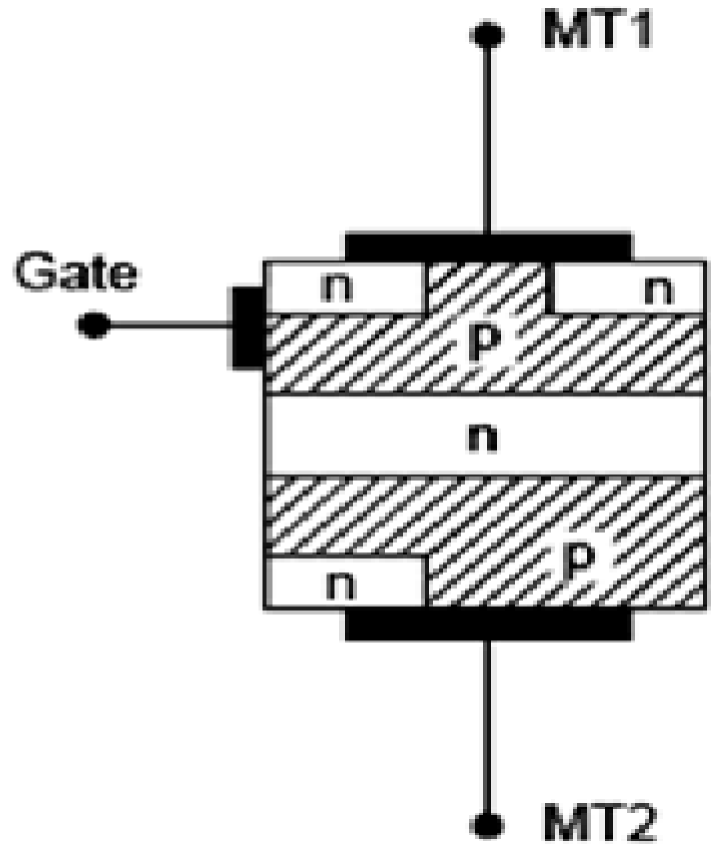
- TRIAC is five layer device that is able to pass current bidirectionally and therefore behaves as an a.c. power control device.
- The main connections are simply named main terminal 1 (MT1) and main terminal 2 (MT2).
- The gate designation still applies, and is still used as it was with the SCR.

TRIAC (CONTD….)

- it not only carries current in either direction, but the gate trigger pulse can be either polarity regardless of the polarity of the main applied voltage.
- The gate can inject either free electrons or holes into the body of the triac to trigger conduction either way.
  - So triac is referred to as a "four-quadrant" device.
- Triac is used in an ac environment, so it will always turn off when the applied voltage reaches zero at the end of the current half-cycle.
- If a turn-on pulse is applied at some controllable point after the start of each half cycle, we can directly control what percentage of that half-cycle gets applied to the load, which is typically connected in series with MT2.
- USED for light dimmer controls and motor speed controls.

TRIAC SYMBOL AND BASIC STRUCTURE





TRIAC OPERATION

- TRIAC can be considered as two thyristors connected in antiparallel .The single gate terminal is common to both thyristors.
- The main terminals MT1 and MT2 are connected to both p and n regions of the device and the current path through the layers of the device depends upon the polarity of the applied voltage between the main terminals.
- Device polarity is usually described with reference to MT1, where the term MT2+ denotes that terminal MT2 is positive with respect to terminal MT1.

Thank You