Module 2

Power Transistors

Power Transistors: *Introduction, Bipolar Junction Transistors – Steady State Characteristics, Switching Characteristics, Switching Limits, Power MOSFETs – Steady State Characteristics, Switching Characteristics, IGBTs; BJT Base Drive, MOSFET Gate Drive, Isolation of Gate and Base Drives, Pulse transformers and Optocouplers.*

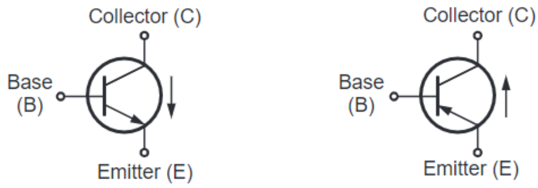
Introduction:

These devices have fully controlled turn-on and turn-off behavior. They do not need external commutation components. BJT, IGBT and MOSFETs are widely used in switched-mode power supplies and P WM inverters. These devices have fully controlled turn-on and turn-off behavior. They do not need external commutation components. Due to developments in solid-state manufacturing technology, it is possible to manufacture devices having high operating frequencies, low on-state losses and higher current/ voltage ratings.

Power transistors are classified as follows:

1. Bipolar Junction Transistors (BJT's)
2. Metal – Oxide – Semiconductor Field Effect Transistor (MOSFET's)
3. Static Induction Transistors (SIT's)
4. Insulated Gate Bipolar Transistor (IGBT)

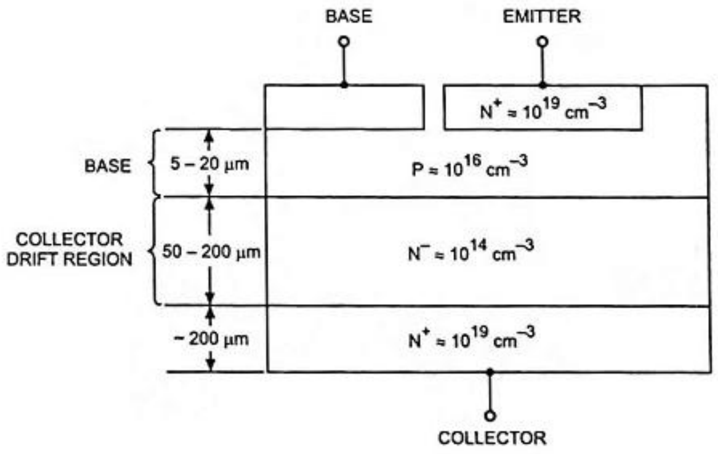
Power BJT:



(a) npn BJT **(b) pnp BJT**

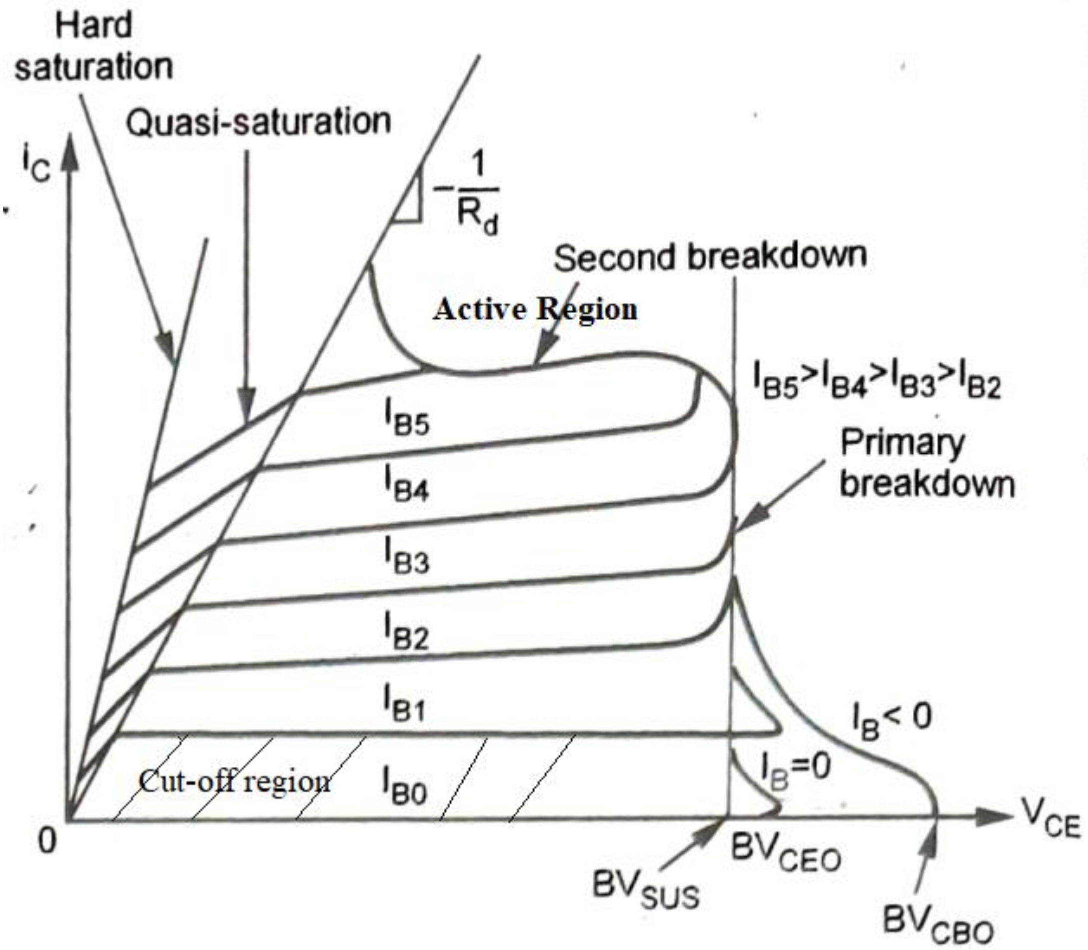
The power BJT is a bipolar device it is also called as power transistor in general. The BJTs are of two types : npn and pnp.BJT has collector (C) base (B) and emitter (E). In the npn BJT, when the base-emitter junction is forward biased to saturation, the transistor turns 'on' and current flows from collector to emitter. When the BJT turns 'on', the collector-emitter drop becomes negligible. The BJT turns-off as soon as base-emitter drive is removed. Similarly in pnp BJT, when base-emitter junction is forward biased to saturation, the transistor turns 'on' and current flows from emitter to collector. The transistor turns off as soon as base emitter drive is removed. Thus the drive has full control over the conduction of BJT. No commutating components are required by BJT for turn off.

Structure of BJT: The power BJT is a vertical oriented 4 layer structure of p-type and n-type. The vertical structure maximizes the cross-sectional area through which the current in the device is flowing. Because of this, the on-state resistance and power dissipation in the transistor is reduced. In the above structure, observe that there is highly doped emitter region (about 10^{19} per cm^{-3}). The emitter region has the thickness of about 10 μm. The base has moderate doping of the order of 10^{16} per cm^{-3}. The thickness of the base can vary from 5 to 20 μm. Small base good thickness provides amplification capabilities. But breakdown voltage capability of the transistor is reduced for small base regions. The collector is split into two regions. These two regions are (with 10^{14} per cm^{-3}) and n + (with 10^{19} per cm^{-3}). The n -region has light doping and it is called collector drift region.The thickness of n -layer determines the breakdown voltage capability of the transistor. The n + region has high doping intensity. It's doping is similar to that of emitter. The n + region serves as collector contact for external circuits. In the practical power transistors, the emitters and bases are interleaved. This reduces the effects of current crowding and hence possibility of second breakdown.



Cross Section of Typical Vertical NPN Power BJT

Steady State Characteristics of BJT:



V-l characteristics of npn power BJT and different regions of operation

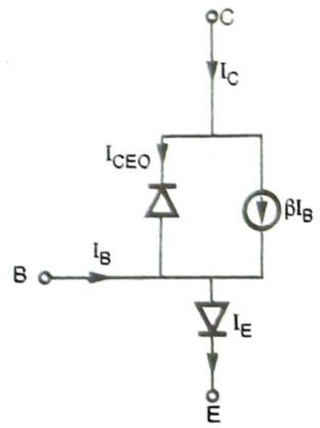
- Fig shows the output characteristics of the transistor which is a plot I_C versus V_{CE}. There are four regions clearly shown in the figure Cut-off region, Active region, quasi-saturation and hard saturation.
- The cut-off region is the area where the base current is almost zero. Hence no collector current flows and the transistor is 'off'.
- In the quasi-saturation and hard saturation, the base drive is applied and the transistor is said to be 'on'. hence collector current flows depending upon the load.

- BJT is never operated in the active region (as an amplifier) and it is operated in cut-off and saturation Thus BJT acts as a switch.
- The BV_{SUS} is the maximum collector-to-emitter voltage that can be sustained when BJT is carrying substantial collector current.
- BV_{CEO} is the maximum collector to emitter breakdown voltage that can be sustained when base current is zero.
- BV_{CBO} is the collector base breakdown voltage when the emitter is open-circuited.

Primary breakdown: The primary breakdown in BJT takes place because of avalanche breakdown of the collector-base junction. The large power dissipation normally leads to primary breakdown.

Second breakdown: At the large collector currents, the collector-emitter voltage drops. Due to this voltage drop, the collector current increases Here there is a substantial increase in power power dissipation is not evenly spread across the entire volume of the device. But it is dissipation. This concentrates on the highly localized regions. In these regions, the local temperature grows very rapidly and the BJT is damaged.

Mathematical Analysis:



The current gain (β) of the transistor is,

$$\beta = h_{FE} = \frac{I_C}{I_B}$$

The collector, emitter and base currents are related as,

$$I_E = I_C + I_B$$

Normally I_{CEO} is very small and it can be neglected. Hence $I_c = \beta I_B$. Putting for Ic in above equation,

$$I_E = \beta I_B + I_B = (\beta + 1) I_B$$

$$I_B = \frac{I_C}{\beta}, \text{ hence above equation will be,}$$

$$I_E = \frac{\beta + 1}{\beta} I_C$$

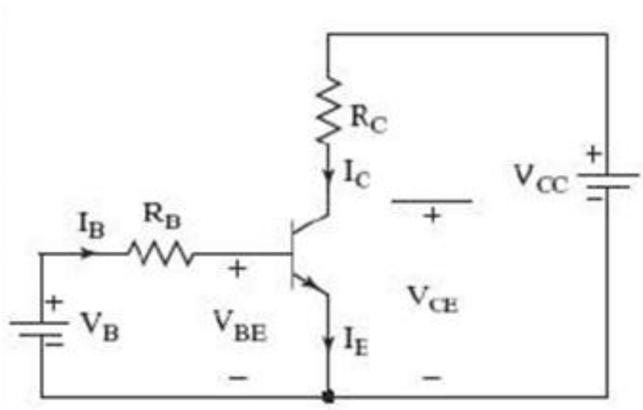
The collector and emitter currents are related by other equations also. i.e,

$$I_C = \alpha I_E$$

$$\alpha = \frac{\beta + 1}{\beta}$$

Transistor as a Switch:

The transistor is used as a switch therefore it is used only between saturation and cutoff.



Transistor as a Switch

From the above circuit we have

$$I_B = \frac{V_B - V_{BE}}{R_B}$$
$$V_C = V_{CE} = V_{CC} - I_C R_C$$
$$V_C = V_{CC} - \beta \frac{R_C \ V_B - V_{BE}}{R_B}$$
$$V_{CE} = V_{CB} + V_{BE}$$
$$V_{CB} = V_{CE} - V_{BE} \qquad \text{.... (1)}$$

As long as V_{CB} is positive the base collector junction is reverse biased and transistor will be in active region. As the base current is increased, Ic increases and V_{CE} starts reducing. At particular point $V_{CE} = V_{BE}$ and $V_{CB} = 0$ as per equation (1). At this point transistor goes from the active region to the saturation region. Hence maximum collector current of active region is obtained when $V_{CE} = V_{BE}$. It is denoted by $I_{Cmax(active)}$

$$I_{Cmax\,(active)} = \frac{V_{CC} - V_{CE}}{R_C} = \frac{V_{CC} - V_{BE}}{R_C}$$

And the maximum base current will be,

$$I_{Bmax\,(active)} = \frac{I_{Cmax\,(active)}}{\beta}$$

As the base current is increased, the transistor comes out of active region and goes on saturation mode $V_{CE} < V_{BE}$ and base collector junction will be forward biased. Further increase-in-base-current--does not increase collector current and collector emitter voltage becomes less than 0.3 to 0.4 V. The collector current in saturation is given

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C}$$

The base current will be, $I_{B(sat)} = \frac{I_{C(sat)}}{\beta}$

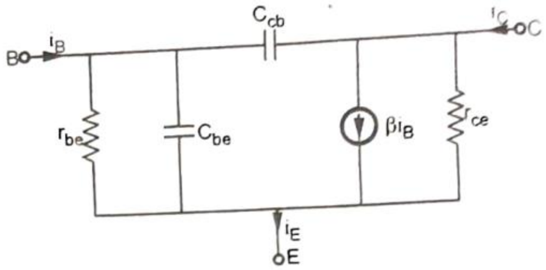
But the actual base current is always higher than $I_{B(sat)}$. Let this actual base current be I_B. Then the ratio of I_B to $I_{B(sat)}$ is called overdrive factor (ODF) i.e,

$$\text{Overdrive factor (ODF)} = \frac{I_B}{I_{B(sat)}}$$

The ratio of $I_{C(sat)}$ to I_B is called forced β or β_{forced} i.e.,

$$\text{Forced } \beta \text{ or } \beta_{forced} = \frac{I_{C(sat)}}{I_B}$$

Switching Characteristics of BJT:



Fig(1)

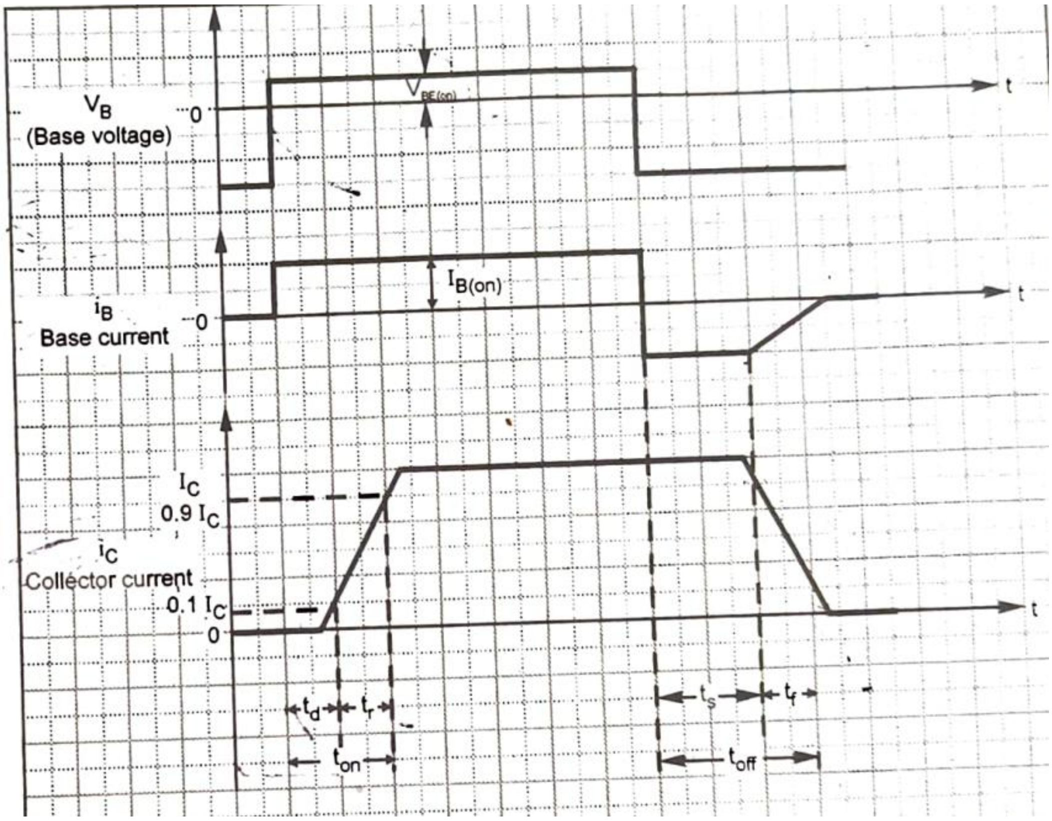


Fig (2)

Consider the model of the npn transistor shown in Fig. The equivalent collector-base-junction capacitance (C_{cb}) and base-emitter junction capacitances (C_{be}) play significant role during turn on and turn off. The effect of these capacitances can be neglected under steady-state conditions. But turn on and turn off are affected due to internal capacitances of BJT. The value of internal capacitances depend upon junction voltage and physical construction of BJT.

Fig (2) shows the switching waveforms of the BJT. The base-emitter voltage is made positive to turn on the BJT. This voltage is $V_{BE(on)}$. As the base voltage becomes positive, the base current also starts flowing. The value of base current is $I_{B(on).}$

In figure(2) observe that collector current does not start flowing as soon as base drive is applied. This is because, the collector-base junction capacitance (C_{be}) starts charging when base drive is applied.

The delay time (t_d) is the time delay involved when collector current starts increasing after base drive is applied. When C_{be} charges to forward bias voltage of 0.7 volts, collector current reaches to its steady state value. The BJT is then said to be turned on fully. The rise time (t_r) is the time required to raise collector current to its steady state value. The turned on time (t_{on}) of the BJT is equal to sum of delay time and rise time.

$$t_{on} = t_d + t_r$$

To turn off the transistor, base voltage is made negative. Hence, the base current is also negative. But the collector current does not change for time t_s. This is called storage time. During this period, the saturating charge is removed from the base.

After the stored charges are removed, the base current starts reducing and collector current also starts falling. The stored charge is removed because of the negative bas3 current. Once the stored charge in base is removed, C_{be} is charged to a negative base voltage and base current becomes zero. The decay of collector current depends upon the stored charge and hence on C_{be}. The turn-off time of the transistor is equal to sum of storage time and fall time (t_f).

$$t_{off} = t_s + t_f$$

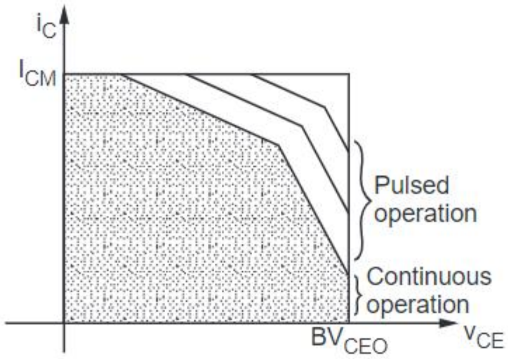
Switching Limits:

Second Breakdown

It is a destructive phenomenon that results from the current flow to a small portion of the base, producing localized hot spots. If the energy in these hot spots is sufficient the excessive localized heating may damage the transistor. Thus secondary breakdown is caused by a localized thermal runaway. The SB occurs at certain combinations of voltage, current, and time. Since time is involved, the secondary breakdown is basically an energy-dependent phenomenon.

Forward Biased Safe Operating Area FBSOA

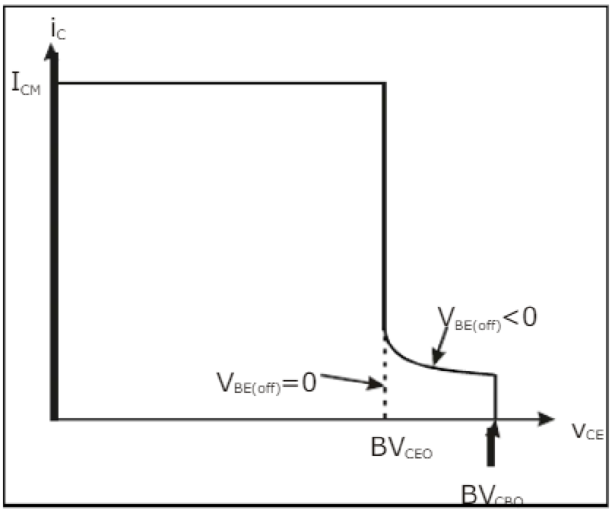
During turn-on and on-state conditions, the average junction temperature and second breakdown limit the power handling capability of a transistor. The manufacturer usually provides the FBSOA curves under specified test conditions. FBSOA indicates the Ic – Vce limits of the transistor and for reliable operation the transistor must not be subjected to greater power dissipation than that shown the FBSOA curve.



The dc FBSOA is shown as shaded area and the expansion of the area for pulsed operation of the BJT with shorter switching times which leads to larger FBSOA. The second break down boundary represents the maximum permissible combinations of voltage and current without getting into the region of ic vce plane where second breakdown may occur.

The final portion of the boundary of the FBSOA is breakdown voltage limit BV_{CEO}.

Reverse Biased Safe Operating Area RBSOA



During turn-off, a high current and high voltage must be sustained by the transistor, in most cases with the base-emitter junction reverse-biased. The collector-emitter voltage must be held to a safe level at or below a specified value of collector current. The manufacturer provides Ic -Vce during reverse-biased turn off as reverse-biased safe area (RBSOA).

The area encompassed by the RBSOA is somewhat larger than FBSOA because of the extension of the area of higher voltages than BV_{CEO} up to BV_{CBO} at low collector currents.

This operation of the transistor up to higher voltage is possible because the combination of low collector current and reverse base current has made the beta so small that breaks down voltage rises towards BV_{CBO}

.

Power Derating

The thermal equivalent is shown. If the total average power loss is P_T ,

The case temperature is $T_c = T_j – P_T T_{jc}$

The sink temperature is $T_S = T_C - P_T R_{CS}$

The ambient temperature is $T_A = T_S – P_T R_{SA}$

And $T_J – T_A = P_T (R_{JC} + R_{CS} + R_{SA})$

R_{JC} = Thermal resistance from junction to case, ^{0}C/w

R_{CS} = Thermal resistance from case to sink, ^{0}C/w

R_{SA} = Thermal resistance from sink to ambient, ^{0}C/w

The maximum power dissipation is P_T is specified at $T_C = 25^0$ C

Breakdown Voltages:

The breakdown voltage is defined as the absolute maximum voltage between two terminals with the third terminal open, shorted or biased in either forward or reverse direction.

BV_{SUS}: The maximum voltage between the collector and emitter that can be sustained across the transistor when it is carrying substantial collector current
BV_{CEO}: The maximum voltage between the collector and emitter terminal with a base open circuited.
BV_{CBO}: This is the collector to base break down voltage when the emitter is open-circuited.

Base Drive Control: This is required to optimize the base drive of the transistor sufficient base current is required to drive BJT is saturation. Storage time determines turn-on and turn-off times of BJT.
Some common types of optimizing base drives of transistors are
1. Turn on Control
2. Turn off Control
3. Proportional Base Control
4. Anti-Saturation Control

Turn on Control:

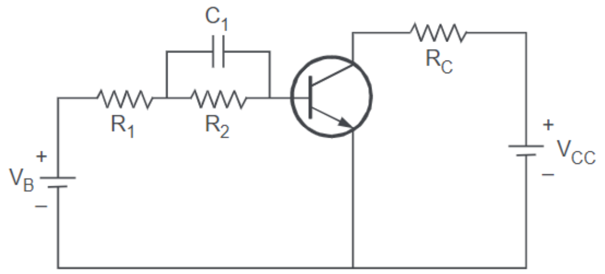


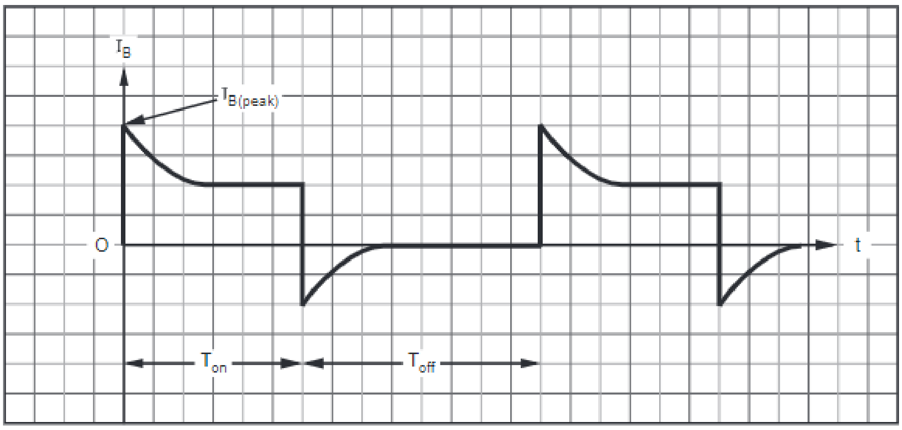
Fig. shows the base drive circuit for turn-on of a transistor. Due to this circuit, the 't_{on}' time is reduced.
As shown in this circuit, when base drive V_B is applied, the capacitor C_1 acts as a short. Hence R_2 is virtually bypassed. Therefore an initial value of base current is only limited by R_1 and it is given as,

$$I_{B(peak)} = \frac{V_B - V_{BE}}{R_1}$$

Drive circuit to make base current high at beginning of t_{on}

This heavy base current drives transistor into saturation for quick turn on. Once the transistor is turned on, there is no need of such large base current. This is taken care-off by R_2C1 circuit. The capacitor Cl starts charging and base current starts falling. This is shown in Fig. 2.2.14. Observe that there is peaking of base current at the beginning of turn on. Then the current reduces to,

$$I_B = \frac{V_B - V_{BE}}{R_1 + R_2}$$



Base current peaking at the beginning of turn on

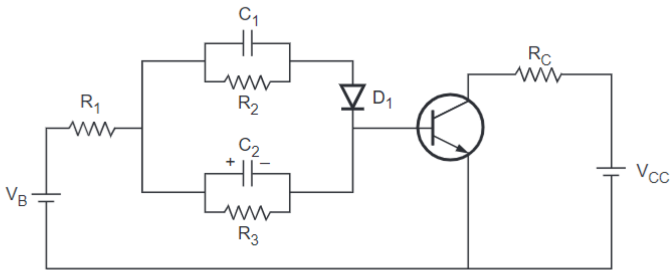
To turn-off the transistor, base voltage is made zero. Therefore capacitor voltage appears as negative voltage across base-emitter. Hence suddenly base current is reversed as shown in above Fig.. This current slowly decays to zero after the stored charge in base region is removed. The capacitor C_1 then discharges through R_2. This discharge time constant is,

$$\tau_2 = R_2 C_1$$

The charging time constant of the capacitor is,

$$\tau_1 = \frac{R_1 R_2 C_1}{R_1 + R_2}$$

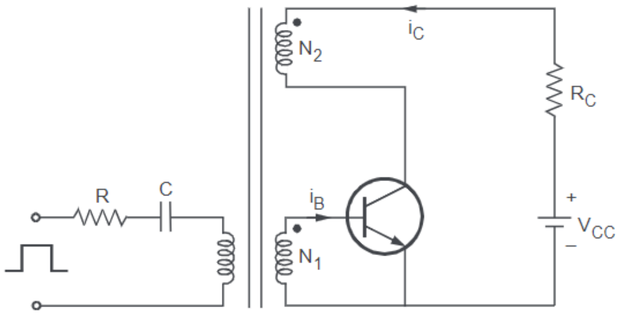
Turn-off Control:



Base drive circuit for positive and negative peaking of base current

If the input voltage is changed to during turn-off, the capacitor voltage V_C is added to as reverse voltage across the transistor. There will be base current peaking during turn-off. As the capacitor C_1 discharges, the reverse voltage will be reduced to a steady state value, if different turn-on, turn-off characteristics are required a turn-off circuit using R_3 and R_4 may be added. The diode D_1 isolates the forward base drive circuit from the reverse base drive circuit during turn-off.

Proportional Base Control:



Proportional base drive control

The collector current changes as the load changes. If the load is reduced, then collector current reduces. Then the base current should also be reduced to avoid excess carries in the base region. Hence proportional base control can be used.
A short-duration pulse is applied to turn on the transistor. The transistor turns on and collector current starts flowing. The collector current passes through the coil magnetically coupled to the base coil. Hence collector current induces the current in the base coil also. This current acts as base drive to the BJT. The RC time constant determines the duration of the pulse to be applied externally to drive BJT into saturation. The turns ratio must be,

$$\frac{N_2}{N_1} = \frac{I_C}{I_B} = \frac{\beta I_B}{I_B} = \beta$$

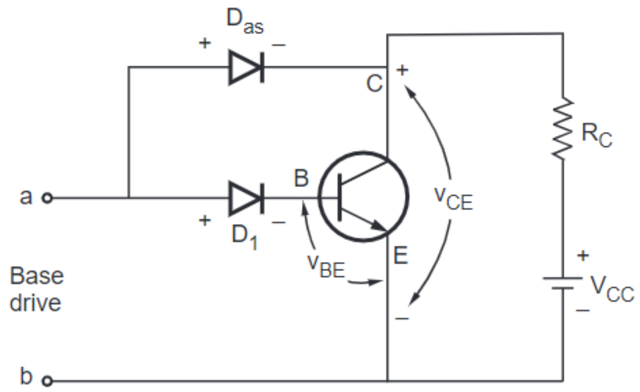
The base current then varies according to variations in the collector current. The transistor can be turned off by applying negative pulse through RC circuit. This makes base current negative and BJT turns off.

Anti saturation Control: Excess base current increases storage time of the BJT. Hence the turn off time increases. Such excess or heavy base drive is called hard saturation. Therefore transistor must be operated in soft saturation. This means base must be given the carriers which are sufficient to drive the transistor in just saturation (quasi saturation).
Fig. shows the circuit diagram to achieve quasi saturation. In this circuit the base drive is applied at terminals a-b. We can write following equation for loop consisting of a - D_l - B -E - b,

$$v_{a\text{-}b} = v_{D1} + v_{BE}$$

Similarly for loop a - D_{as} - C - E we can write,

$$v_{a\text{-}b} = v_{Das} + v_{CE}$$



Base drive with antisaturation diode

Hence equating the two equations,

$$v_{D1} + v_{BE} = v_{Das} + v_{CE}$$

Normally $v_{Das} = v_{D1}$. Hence above equation becomes,

$$v_{CE} = v_{BE}$$

This shows that the collector-emitter voltage will be equal to base-emitter voltage.
When BJT is turned on, the base-emitter voltage is nearly 0.7 and the collector-emitter saturation voltage is 0.3. Because of anti saturation diode (VD_{as}), the collector emitter voltage is raised to V_{BE} i.e 0.7V. Hence the BJT is no longer in saturation. The collector-emitter voltage can be further increased by putting additional diode in series of D_1.

Disadvantage of antisaturation diode
The collector-emitter voltage is increased. This increases the on-state losses in BJT.

Merits, Demerits and Applications of BJT:

Merits of BJT:
1. BJTs have small turn-on and turn-off times, hence their switching frequencies are higher.
2. BJTs have small turn-on losses.
3. The base drive has full control over the operation of BJT.
4. BJ Ts do not require commutation circuits.
5. BJT is a bipolar device.
6. BJTs are available easily with much-reduced costs.

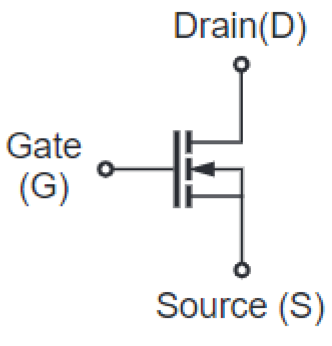
Demerits of BJT:
1. Drive circuit of BJ T is complex.
2. Storage charge in base reduces switching frequencies.
3. Negative temperature coefficient creates problems in the paralleling of BJTs.

Applications of BJT:
1. Switched Mode Power Supplies
2. Bridge inverters
3. DC to DC converter (choppers)
4. Power factor correction techniques.

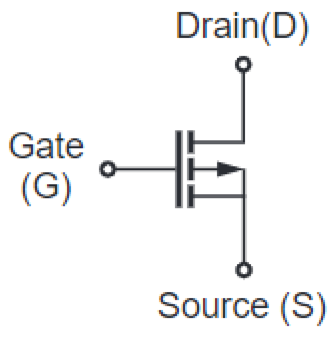
Comparison of BJT and SCR:

Sr. No.	SCR	BJT
1.	Four layer (PNPN) device.	Three layer (PNP or NPN) device.
2.	Turns on by regeneration.	No regeneration exists.
3.	Gate has no control once SCR is turned on.	Base has full control over the operation of BJT.
4.	External circuits are required to turn off the SCR.	No external circuits are required. BJT turns off if base drive is removed.
5.	Switching frequencies are low.	Switching frequencies are high.
6.	False triggering takes place if dv/dt is exceeded.	BJT is damaged if dv/dt is exceeded.
7.	Used for controlled rectifiers, AC regulators and DC motor drives.	Used for inverters, UPS, AC motor drives and SMPS.

Power MOSFET: A metal-oxide semiconductor field effect transistor (MOSFET) is a device developed by combining the areas of field effect concept and MOS technology.
The MOSFET has three terminals gate (G), drain (D) and source (S).
When the MOSFET is turned 'on' the current flows from drain to source. The voltage is applied between gate-source to turn 'on' the MOSFET. Very small current flows from gate to source. Only voltage is to be applied to turn on the MOSFET. The MOSFET can be turned off by removing the gate to source voltage. Thus gate has full control over the conduction of the MOSFET. The turn-on and turn off times of MOSFETs are very small. Hence they operate at very high frequencies. Hence MOSFETs are preferred in applications such as choppers and inverters. Since only voltage drive (gate-source) is required, the drive circuits of MOSFETs are very simple. The paralleling of MOSFETs is easier due to their positive temperature coefficient (PTC). MOSFETs have high on-state resistance, RDS (on). Hence for higher currents, losses in the MOSFETs are substantially increased. Hence MOSFETs are mainly used for low power applications.



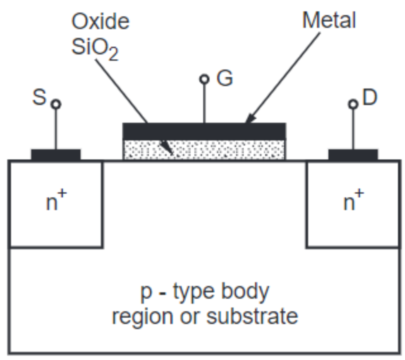
(a) n-channel



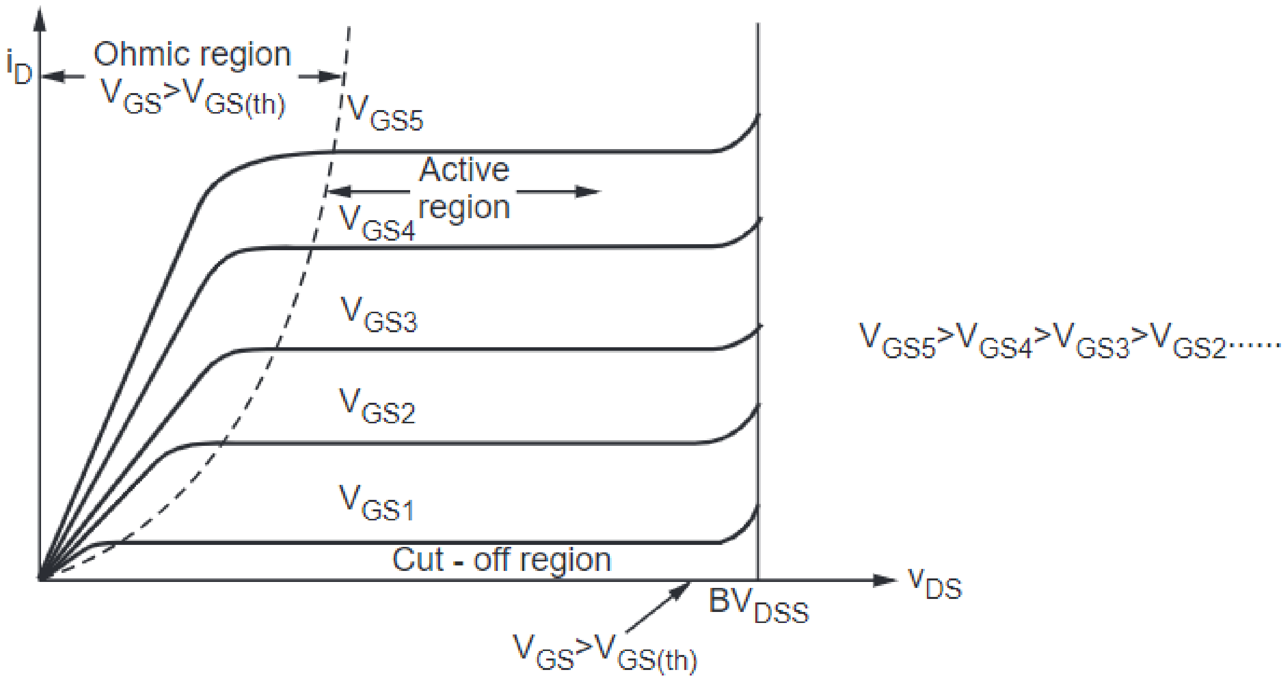
(b) p-channel

Structure of MOSFET:

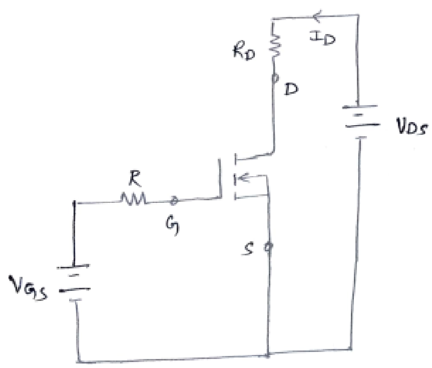
There are two types of MOSFETs depletion type MOSFET and enhancement type MOSFET. In both of these types the MOSFETs can be n - channel or p-channel. Fig. shows the structure of n-channel enhancement type MOSFET. The source and drain are connected n + regions. These regions are heavily doped with the intensity of 10^{19} per cm^3. The p-type body region forms the channel between drain and source. The body region has the doping level of 10^{16} per cm3. The gate is not directly connected to the p-type region. There is an insulating oxide (Si02) layer between gate metal and p-type layer.



Static Characteristics of MOSFET:



V-I characteristics of n-channel power MOSFET



- Fig.shows the V-I characteristics of n-channel power MOSFET. The drain current i_D is plotted with respect to drain to source voltage v_{DS}. These characteristics are plotted for various values of gate source voltages (V_{GS}).
- In Fig. we observe that there are three regions in the characteristics : **Ohmic region, active region and cut-off region.**

- In the cut-off region, the drain current is negligible and the MOSFET is said to be in 'OFF' state. The MOSFET is driven in cut-off region by applying $V_{GS} < V_{GS}$ (th). Here V_{GS} is the threshold gate source voltage. When gate to source voltage is less than threshold gate source voltage, MOSFET is off, i.e. in cut-off region.
- The MOSFET is driven into ohmic region when $V_{GS} >> V_{GS}$(th). In the ohmic region, the MOSFET conducts heavily. Hence it is said to be 'on' in the ohmic region. Thus by applying heavy gate to source voltage, MOSFET can be turned on.
- In the power electronic applications, MOSFET is never operated in the active region. In active region it acts as an amplifier. For switching applications, MOSFET is operated only in ohmic and cut-off regions.
- The BV_{DSS} is the drain to source breakdown voltage, when the gate is open circuited. The MOSFET is damaged if drain to source voltage is increased above BV_{DSS}.

Switching Characteristics of MOSFET:

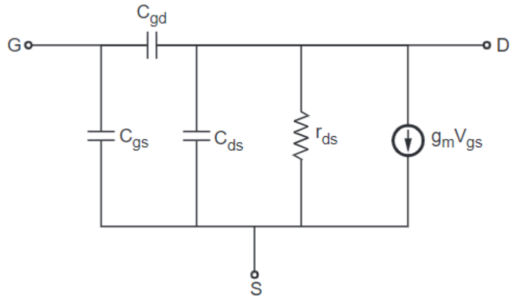


Fig1 Switching model of MOSFET

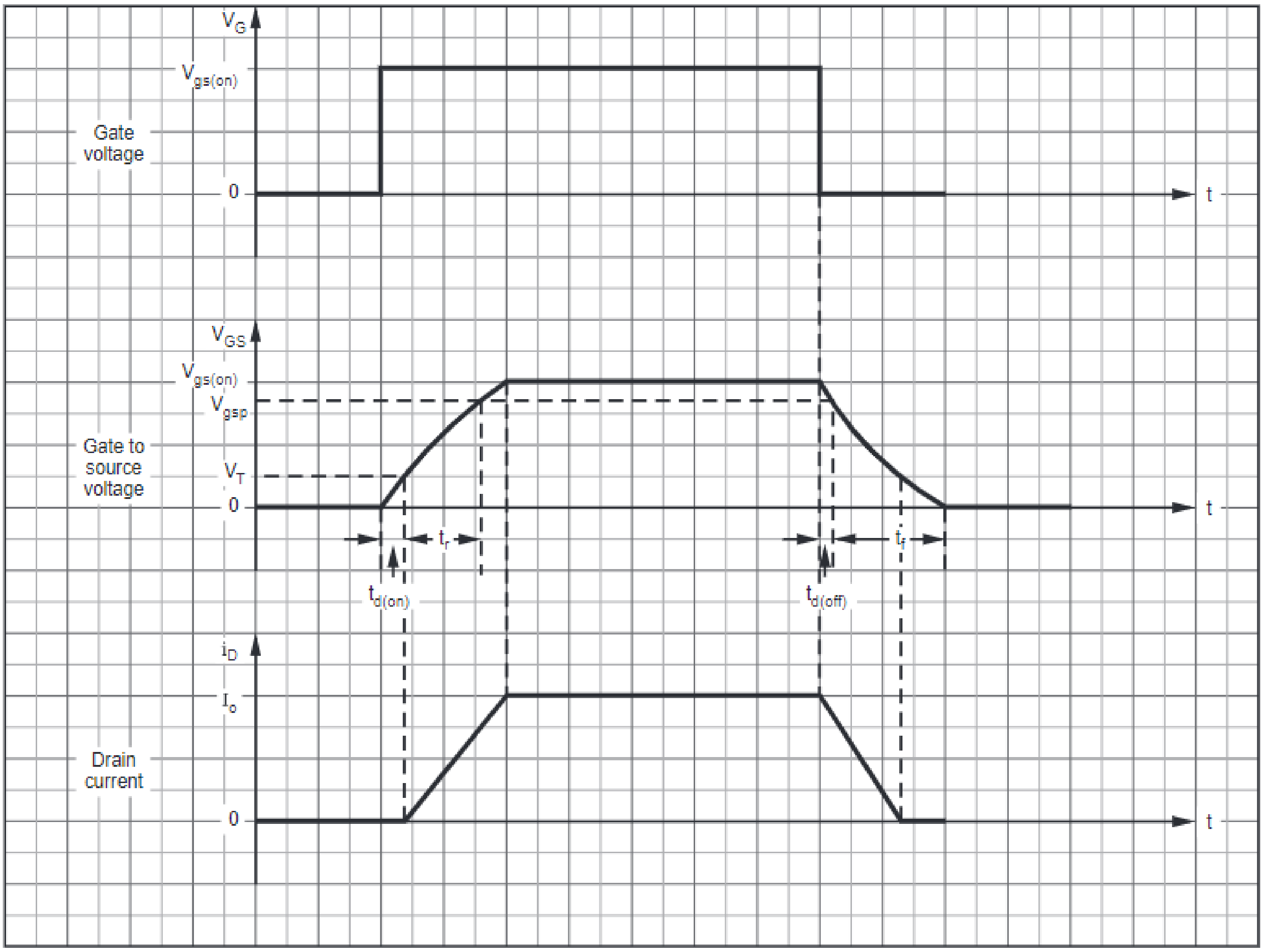


Fig 2 Switching characteristics of MOSFET

The internal capacitances of MOSFET affect the turn on and turn off times of MOSFETs. These capacitances have no effect during steady state. Fig.1 shows the switching model of MOSFET.In the above figure Cgs is the parasitic gate to source capacitance and C_{gd} is the gate to drain parasitic capacitance. The MOSFET can be turned on by applying positive gate voltage as shown in Fig 2.

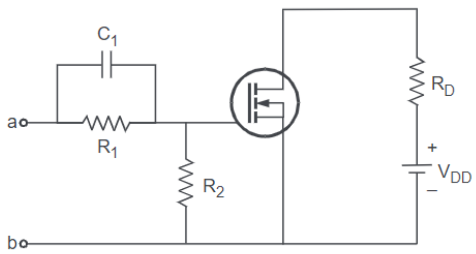
When the gate voltage is applied, the gate to source capacitance C_{gs} starts charging. The turn on delay ($t_{d(on)}$) is the time required to charge C_{gs} to threshold voltage (V_T). After this voltage, the drain current (i_D) starts rising. The C_{gs} charges from threshold voltage to full gate voltage (v_{gsp}). The time required for this charging is called rise time (t_r). Observe that during this period, the drain current rises to its full value, i.e. I_0. The MOSFET is then said to have fully turned on. Thus, the total turn on time of the MOSFET is,

$$t_{on} = t_{d(on)} + t_r$$

To turn off the MOSFET, the gate voltage is made negative or zero. The gate to source voltage then reduces from $v_{gs(on)}$ to v_{gsp}. That is, C_{gs} discharges from overdrive to pinch-off region gate voltage. The time required for this discharge is called turn off delay time ($t_{d(off)}$). The drain current also start reducing. The C_{gs} keeps on discharging and its voltage becomes equal to threshold voltage (V_T). The time required to discharge C_{gs} from v_{gsp} to VT is called fall time (t_f). The drain current becomes zero when $v_{GS} \leq VT$. The MOSFET is then said to have turned off. The C_{gs} then discharges to zero voltage. The turn off time of the MOSFET is equal to sum of turn off delay time and fall time. i.e.,

$$t_{off} = t_{d(off)} + t_f$$

Gate Drive:



Gate drive circuit

The gate drive circuit for MOSFET should satisfy the following requirements :

1. The gate-source input capacitance should be charged quickly.
2. MOSFET turns on when gate-source input capacitance is charged to sufficient level.
3. To turn off MOSFET quickly, the negative gate current should be sufficiently high to discharge gate-source input capacitance.

Fig. shows the gate drive as per the above requirements. The gate drive is applied across the terminal a-b. Initially, the resistance R_1 is bypassed by C_1 and full drive voltage is applied to the gate. This charges the gate-source capacitance quickly. As the capacitor C_l charges, the gate current reduces. Once the MOSFET is turned on required gate current is very small. When MOSFET is to be turned off, the voltage V_{a_b} is made zero. This applies capacitor voltage across gate-source in a negative direction. Therefore charge on the gate-source capacitance is removed quickly. C_l then discharges through R_1. The resistance R_2 provides an additional discharge path for gate-source capacitance.

Merits, Demerits and Applications of MOSFETs:

Merits of MOSFETs:

1. MOSFETs are majority carrier devices.
2. MOSFETs have positive temperature coefficient, hence their paralleling is easy.
3. MOSFETs have very simple drive circuits.
4. MOSFETs have short turn on and turn off times, hence they operate at high frequencies.
5. MOSFETs do not require commutation circuits.
6. Gate has full control over the operation of MOSFET.

Demerits of MOSFET:

1. On-state losses in MOSFETs are high.
2. MOSFETs are used only for low power applications.
3. MOSFETs suffer from static charge.

Applications of MOSFETs:

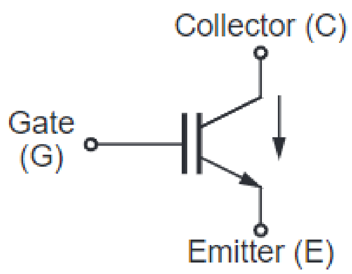
1. High frequency and low power inverters.
2. High frequency SMPS.
3. High frequency inverters and choppers.
4. Low power AC and DC drives.

Comparison of BJT and MOSFET:

Sr. No.	BJT	MOSFET
1.	This is bipolar device.	This is majority carrier device.
2.	Controlled by base.	Controlled by gate.
3.	Current controlled device.	Voltage controlled device.
4.	Negative temperature coefficient.	Positive temperature coefficient.
5.	Paralleling of BJTs is difficult.	Paralleling of MOSFETs is simple.
6.	Losses are low.	Losses are higher than BJTs.
7.	Drive circuit is complex.	Drive circuit is simple.
8.	Switching frequency is lower than MOSFET.	Switching frequency is high.
9.	BJTs are suitable for high power applications.	MOSFETs are suitable for low power application.
10.	BJTs are available with higher voltage and current ratings.	MOSFETs have less voltage and current ratings.

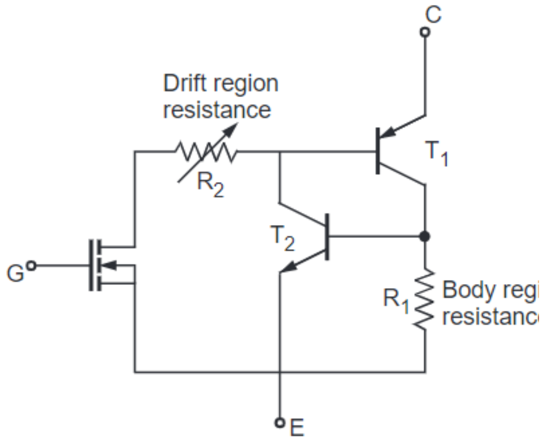
Power IGBT:

The Insulated Gate Bipolar Transistor (IGBT) is the latest device in power electronics. It is obtained by combining the properties of BJT and MOSFET. We know that BJ T has lower on-state losses for high values of collector current. But the drive requirement of BJT is little complicated. The drive of MOSFET is very simple (i.e. only voltage is to be applied between gate and source). But MOSFET has high on-state losses. The gate circuit of MOSFET and collector-emitter circuits of BJ T are combined together to form a new device. This device is called IGBT. Thus IGBT has advantages of both the BJT and MOSFETs. Fig. shows the symbol of IGBT. Observe that the symbol clearly indicates combination of MOSFET and BJT.



The IGBT has three terminals : Gate (G), collector (C) and emitter (E). Current flows from collector to emitter whenever a voltage between gate and emitter is applied. The IGBT is said to have turned 'on'. When gate emitter voltage is removed, IGBT turns off. Thus gate has full control over the conduction of IGBT. When the gate to emitter voltage is applied, very small (negligible) current flows. This is similar to the gate circuit of MOSFET. The on-state collector to emitter drop is very small like BJT.

Structure of IGBT:



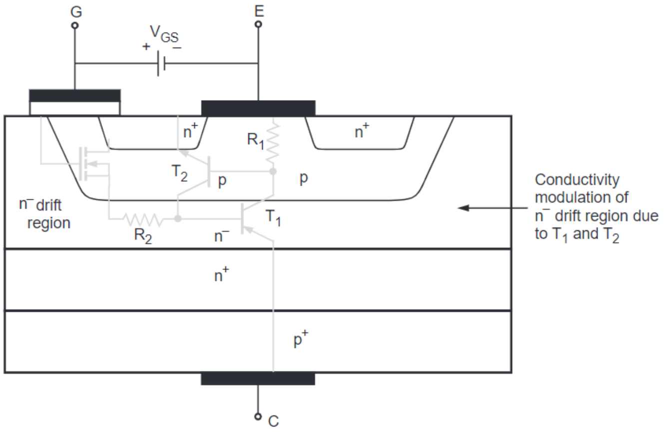


Fig 1. **Equivalent circuit of IGBT** **Fig 2 Structure of IGBT**

The structure of IGBT is similar to that of MOSFET. Fig. 2. shows the vertical cross-section of IGBT. In this structure observe that there is an additional p+ layer. This layer is the collector (Drain) of IGBT.

This p+ injecting layer is heavily doped. It has a doping intensity of 10^{19} per cm^3. The doping of other layers is similar to that of MOSFET. n+ layers have 10^{19} per cm^3. p-type body region has a doping level of 1016 per cm3. The n- drift region is lightly doped (10^{14} per cm^3).

With n^+ buffer layer

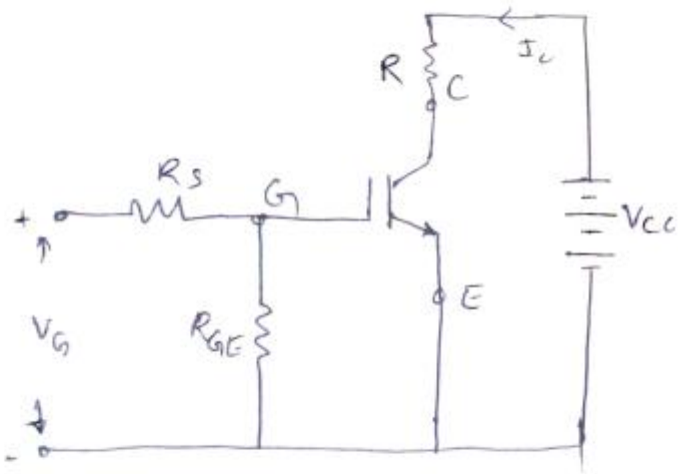
- Punch through IGBT: Asymmetric voltage blocking capabilities and faster turn-off time. Used in choppers and inverters
- Non punch through IGBT: Symmetric voltage blocking capability. Used in rectifiers.

When gate is positive with respect to emitter and with gate emitter voltage(V_{GE}) more than the threshold voltage of IGBT, an n-channel is formed in the p-region as in a power MOSFET.

This n-channel short circuits the n^- region with n^+ emitter region. An electron movement in the n-channel in turn cause substantial hole injection from p^+ substrate layer into the epitaxial n-layer. Eventually, a forward current is established as shown in fig 1.

The two pnp and npn transistors can be connected as shown in fig 2 to give the equivalent circuit of an IGBT.

Steady State (V-I) characteristics of IGBT:



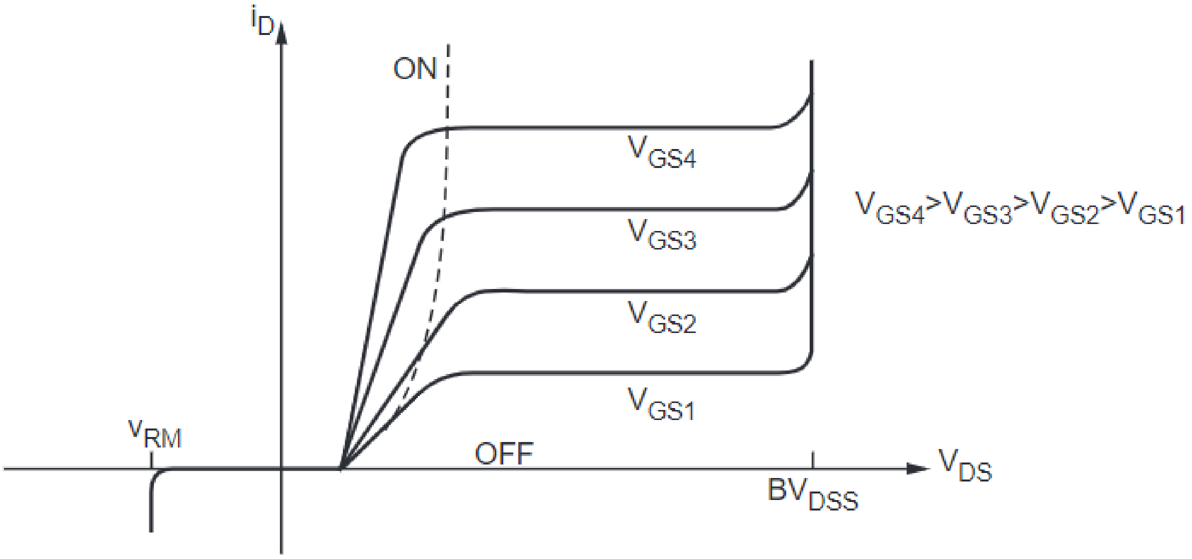
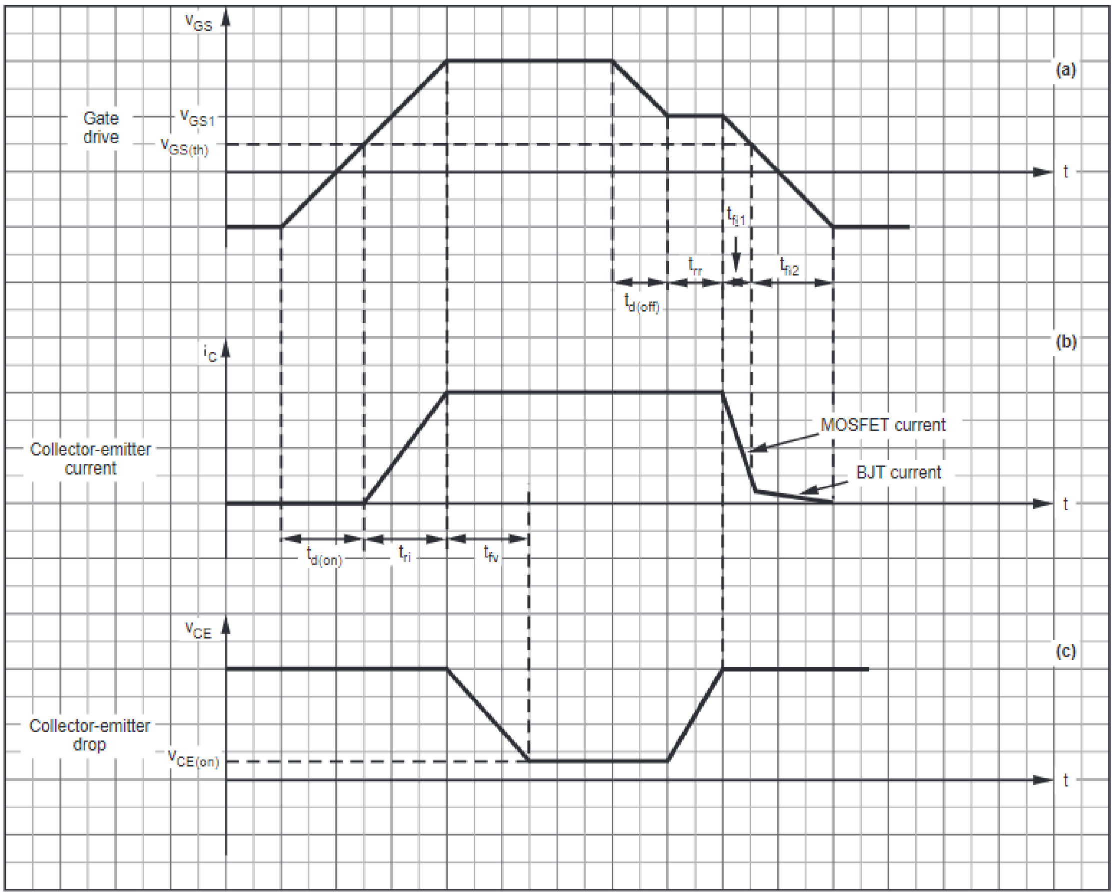


Fig. shows the V-I characteristics of n-channel IGBT. Sometimes the collector is also called drain and emitter is also called source. The above characteristics are plotted for drain (collector) current i_D with respect to drain source (collector emitter) voltage V_{DS}. The characteristics are plotted for different values of gate to source (V_{GS}) voltages. When the gate to source voltage is greater than the threshold voltage $V_{GS(th)}$, then IGBT turns on. The IGBT is off when VGS is less than $V_{GS(th)}$. Fig. shows the 'on' and 'off' regions of IGBT. The BV_{DSS} is the breakdown drain to source voltage when gate is open circuited. The IGBT is the popular device now-a-days. IGBT has simplest drive circuit and it has low on-state losses.

Switching Characteristics of IGBT:



Switching characteristics of IGBT

Fig. shows the switching characteristics of IGBT. The gate to source voltage is normally negative. This voltage is made positive to turn on the IGBT. When $V_{GS} > V_{GS(th)}$, the collector current starts increasing. Turn on delay, $t_{d(on)}$ is the delay when gate drive is applied and i_c starts increasing. When i_c increases to its full value, collector-emitter voltage starts falling. t_{ri} is the rise time of collector and t_{fr} is the fall time of voltage. Thus, turn on time of IGBT is,

$$t_{on} = t_{d(on)} + t_{ri} + t_{fv}$$

The turn-off of the IGBT is initiated by reducing the gate voltage. When gate voltage falls to the value equal to v_{GS1}, v_{CE} starts rising. v_{GS1} is the voltage where IGBT comes out of saturation. Turn off delay, $t_{d(off)}$ is the delay time when gate voltage is reduced and VCE starts increasing. When reaches to supply voltage, i_c starts reducing. ic reduces fast till VGS reaches to $V_{GS(th)}$. This fast decay in i_c is basically due to internal MOSFET. Then goes to zero and becomes negative. But i_c keeps on flowing for some time. This is internal BJT current. This current flows due to stored carriers in the drift region. Hence, turn-off time of IGBT is higher than IGBT. The turn off time of IGBT will be,

$$t_{off} = t_{d(off)} + t_{rv} + t_{fi1} + t_{fi2}$$

Here, t_{rv} is voltage rise time

t_{fi1} is MOSFET current fall time.

t_{fi2} is BJT current fall time.

Merits, Demerits and Applications of IGBT:

Merits of IGBT

1. Voltage controlled device. Hence drive circuit is very simple.
2. On-state losses are reduced.
3. Switching frequencies are higher than thyristors.
4. No commutation circuits are required.
5. Gate have full control over the operation of IGBT.
6. IGBTs have approximately flat temperature coefficient.

Demerits of IGBT

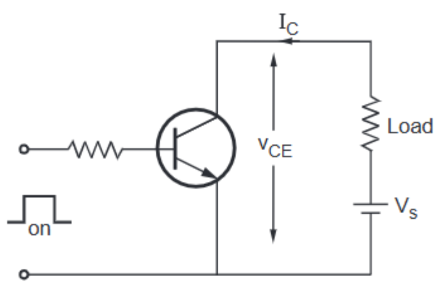
1. IGBTs have static charge problems.
2. IGBTs are costlier than BJTs and MOSFETs.

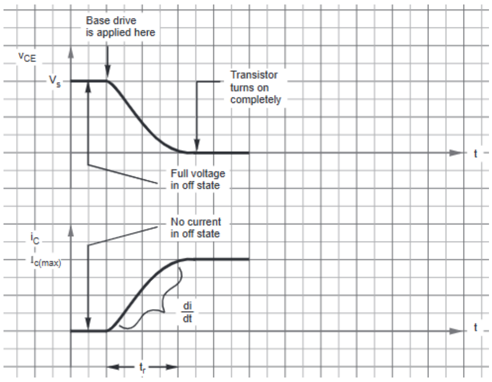
Applications of IGBTs

1. AC motor drives, i.e. inverters.
2. DC to DC power supplies, i.e choppers.
3. UPS systems.
4. Harmonic compensators.

di/dt and dv/dt Limitations:

Definition of di/dt: When the power semiconductor device is off, then full voltage appears across its terminals. Zero current flows through it. Fig. shows an example of power BJT going from off to on state. Its collector-emitter voltage and collector current is also shown.



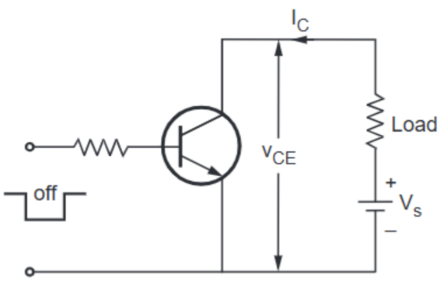


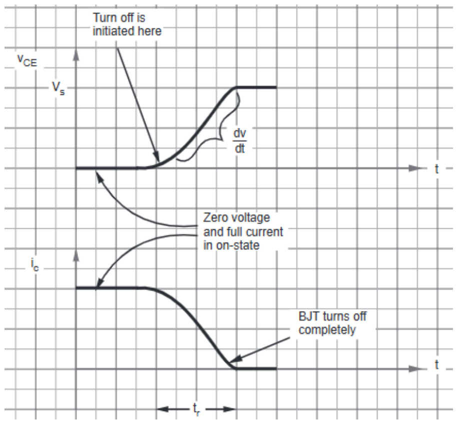
In the above figure observe that V_{CE} = Vs, i_c = 0 when BJT is off. When base drive is applied, then V_{CE} starts falling and i_c, starts increasing. The rate of change of collector di/dt. The fast rate of rise of collector current causes local heating of the BJT and it can be damaged. Hence di/dt rating of the transistor should not be exceeded. In the Fig. observe that i_c changes from 0 to $I_{c(max)}$ during times tr . Hence

$$\frac{di}{dt} = \frac{I_{c(\max)}}{t_r}$$

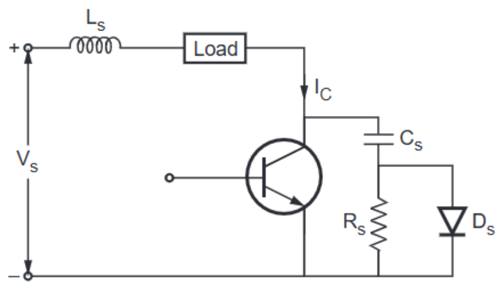
Definition of dv/dt : Consider the case when BJT is on-state. Voltage across collector emitter will be zero. Full load current will be flowing when the base drive is removed, then collector current starts reducing and collector-emitter voltage starts rising. The rate of change of voltage across the device during turn off is called dv/dt. A fast rate of rise of collector-emitter voltage may damage the BJT. Hence it should not be exceeded. In the Fig. observe that the collector-emitter voltage changes from zero to Vs during time 't_f'. Hence,

$$\frac{dv}{dt} = \frac{V_s}{t_f}$$





Protection Against di/dt and dv/dt:



As shown in above circuit, the series inductance (Ls) reduces the fast rise in collector current. It protects the device against di/dt. The value of this inductance can be obtained as,

$$\frac{di}{dt} = \frac{V_s}{L_s}$$

$$\frac{I_{c(\max)}}{t_r} = \frac{V_s}{L_s}$$

$$L_s = \frac{V_s t_r}{I_{c(\max)}}$$

When the BJT turns off the fast rise across collector-emitter is reduced by Cs and Ds. Observe that Cs virtually acts as a short through Ds, when collector-emitter voltage tries to suddenly rise. The capacitor slowly charges and reduces the rate of rise of voltage across collector-emitter. When BJT turns on, the capacitor discharges through BJT and Rs. Here Rs is used to limit the discharge current of Cs. For this circuit we can write,

$$\frac{dv}{dt} = \frac{I_c}{C_s}$$

$$\frac{V_s}{t_f} = \frac{I_c}{C_s}$$

$$\therefore \quad C_s = \frac{I_c t_f}{V_s}$$

And the value of R_s can be calculated as,

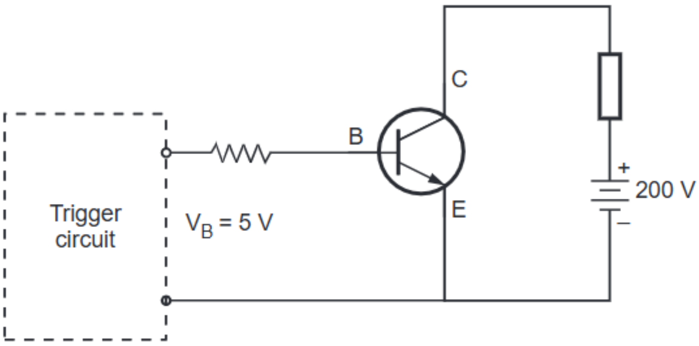
$$R_s = 2\sqrt{\frac{L_s}{C_s}}$$

$$\text{or} \quad R_s = \frac{1}{3 f_s C_s}$$

Here it is assumed that the discharge time constant RsCs must be less than one third of the switching time of the device.

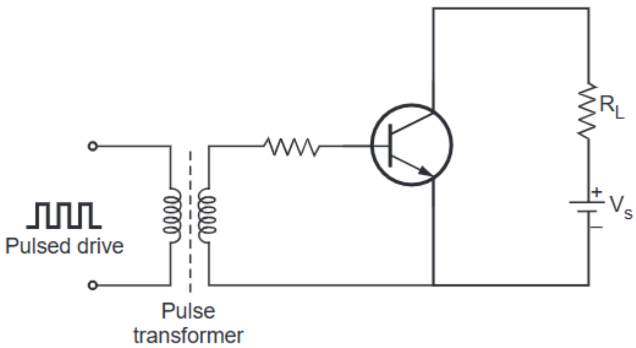
Isolation of Base and Gate Drive:

Necessity of Isolation: Driver circuits operate at very low power levels. Normally the signal levels are 3 to 12 volts. The gate and base drives are connected to power devices that operate at high power levels. Fig. shows this situation. Observe that the collector of BJT can have voltages of 200 V. But base is connected to trigger circuit with voltages of 5V. If BJ T is damaged and collector base gets shorted, then high voltage will get connected to trigger circuit. This will damage the trigger circuit also. This means trigger circuit is damaged due to device damage. Therefore there must be some electric isolation between the control and power circuit.



Isolation using Pulse Transformer:

Pulse transformer has one primary and one or more secondary windings. It is normally used for pulsed mode of triggering Fig. shows the isolation using pulse transformer. In the above circuit, observe that the triggering circuit is electrically isolated from BJT. Hence if there is any electric damage to BJT, there will be no effect on triggering circuit.



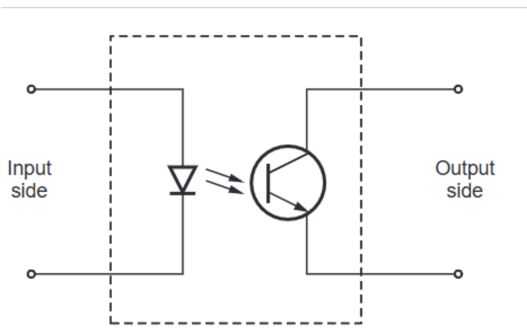
Advantages

1. Pulse transformer does not need external power for its operation.
2. It is very simple to use.

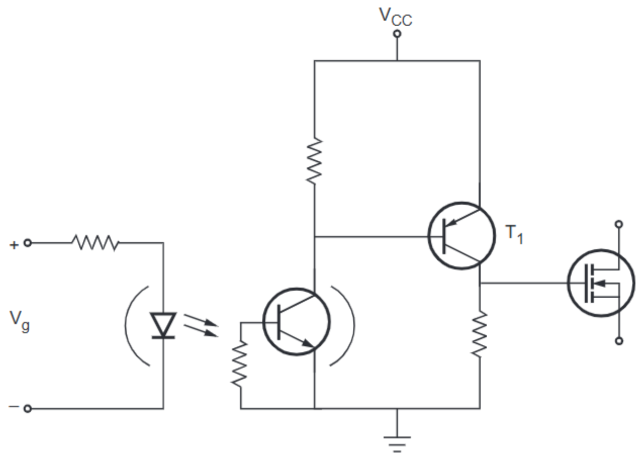
Disadvantages

1. Pulse transformer saturates at low frequencies hence it can be used only for high frequencies.
2. Due to magnetic coupling, the signal is distorted.

Isolation using Optocouplers:



Optocoupler



MOSFET triggering circuit using optocoupler

Optocoupler consists of a pair of infrared LED and phototransistor Fig.a shows the symbol of optocoupler. When the signal is applied to the infrared LED, it turns on. It's light falls on phototransistor. Therefore phototransistor also starts conducting. There is no electric connection between LED and phototransistor.

Fig. b shows the triggering circuit that uses an optocoupler. In this circuit, the triggering pulses are given to the input (LED) of the optocoupler. When 'Vg' is positive, LED turns on. Light falls phototransistor. It's on Hence it turns on Therefore base of T_l is connected to zero volts through phototransistor. Due to this, T_l turns on. Therefore the voltage vcc is applied to gate of the MOSFET. Hence MOSFET turns on. When Vg = (), the LED turns off, therefore phototransistor also turn off. Therefore base drive of Tl goes to VCC and it turn off. When Tl turns off, MOSFET gate voltage becomes zero. Therefore MOSFET turns off. Thus gate drive circuit using optocoupler works.

Advantages

1. Very good response at low frequencies.
2. Compact and cheaper optocoupler devices are available.

Disadvantages

1. Optocoupler need, external biasing voltage for their operation.
2. High frequency response is poor.

Applications

Inverters, SMPS, Choppers, AC motor drives use optocouplers.