UPPSC-AE 2020

Uttar Pradesh Public Service Commission

Combined State Engineering Services Examination

Assistant Engineer

Electrical Engineering

Power Electronics and Drives

Well Illustrated **Theory** *with*

Solved Examples and **Practice Questions**

MADE EASY Publications

Power Electronics and Drives

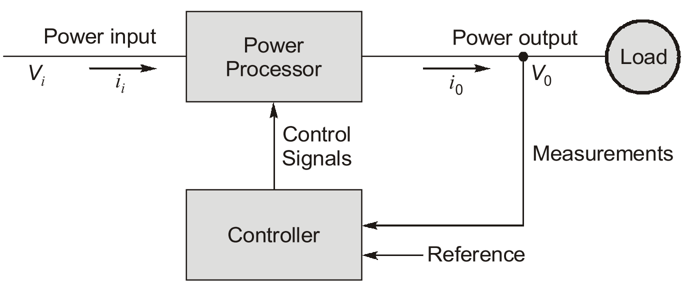
Contents

CHAPTER 1 Basics of Power Electronics Devices

1.1 Introduction

The task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads.

Block Diagram of Power Electronic Systems:



Power electronics may be defined as the application of solid state electronics for the control and conversion of electric power.

1.2 Scope and Applications of Power Electronics

- The development of computers, communication equipment and consumer electronics, all of which require regulated dc power supplies and often uninterruptible power supplies.
- Adjustable speed motor drives, load proportional, capacity modulated heat pumps and air conditioners are examples of applying power electronics to achieve energy conservation.
- In many countries, electric trains have been in widespread use for a long time. Now, there is also a possibility of using electric vehicles in large metropolitan areas to reduce smog and pollution. Electric vehicles would also require battery chargers that utilize power electronics.
- These include equipment for welding, electroplating, and induction heating.
- One such application is in transmission of power over high voltage dc (HVDC) lines.

1.3 Types of Power Electronic Circuits

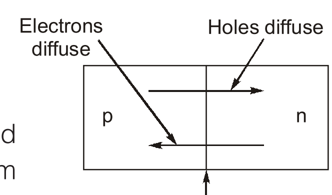
1. **AC to DC converters :**
   - A diode rectifier (uncontrolled rectifier) circuit converts ac input voltage into a fixed dc voltage.
   - Phase controlled rectifier convert constant ac voltage to variable dc output voltage. Phase-controlled converters may be fed from single-phase or three-phase source. These are used in dc drives, metallurgical and chemical industries, excitation systems for synchronous machines etc.

2. **DC to DC converters (DC Choppers):** A dc chopper converts fixed dc input voltage to a controllable dc output voltage. The chopper circuits require forced, or load, commutation to turn-off the thyristors.
3. **DC to AC converters (Inverters):** An inverter converts fixed dc voltage to a variable ac voltage. The output may be a variable voltage and variable frequency. These converters use line, load or forced commutation for turning-off the thyristors.
4. **AC to AC converters:**
   - These convert fixed ac input voltage into variable ac output voltage.These are of two types as under:
     - **AC voltage controllers (AC voltage regulators):** These converter circuits convert fixed ac voltage directly to a variable ac voltage at the same frequency.
     - **Cycloconverters:** These circuits convert input power at one frequency to output power at a different frequency through one-stage conversion. Line commutation is more common in these converters, though forced and load commutated cycloconverters are also employed.
   - The power semiconductor devices can operate as static switches or contactors. Static switches possess many advantages over mechanical and electromechanical circuit breakers. Depending upon the input supply, the static switches are called ac static switches or dc static switches.

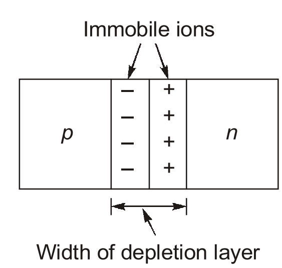
1.4 The p-n Junction

- A p-n junction is formed when p-type semicondutor is brought in metallurgical, or physical, contact with n-type semiconductor.
- A p-region has greater concentration of holes whereas n-region has more electron-concentration.
- In p-region, free holes are called majority carriers and free electrons ***minority carriers***.
- In n-region, free electrons are called majority carriers whereas free holes are called minority carriers.
- In general, p^+ indicates highly doped p-region, n^- lightly doped n-region.

1.4.1 Depletion Layer



Direction of holes and electrons diffusion



Depletion region

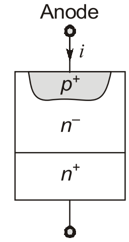
- When physical contact between p and n regions is made, free electrons in n-material diffuse across the junction into p material.
- Diffusion of each electron from n to p, leaves a positive charge behind in the n-region near the junction. Similarly, diffusion of each hole from p to n, leaves a negative charge behind in the p region near the junction.
- As a result of this diffusion, n-region near the junction becomes positively charged and p region in the vicinity of junction becomes negatively charged.
- These charges establish an electric field across the junction. When this field grows strong enough, it stops further diffusion and charge carriers don't move. As a consequence, opposite charges on each side of the junction produce immobile ions.
- The region extending into both p and n semiconductor layers is called ***depletion region***.
- The width of depletion region, or depletion layer, is of the order of 5×10^{-4} mm.
- There is a potential difference of 0.7 V across the depletion region in silicon and it is 0.3 V in germanium. This potential is called ***barrier potential***.

NOTE

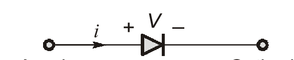
- The barrier potential depends on width of the depletion layer and it decreases with rise in junction temperature.
- A junction with lightly doped layer on its one side requires large breakdown voltage.
- A junction with highly doped layers on its both sides requires low breakdown voltage.

1.5 Power Diodes

- A high-power diode, called power diode, is also a pn-junctiondevice but with constructional features somewhat different from a signal diode.
- The voltage, current and power ratings of power diodes are much higher than the corresponding ratings for signal diode.
- Power diode operate at lower switching speeds whereas signal diodes operate at higher switching speeds.
- Power diodes consists of heavily doped n^+ substrate. On this, a lightly doped n^- layer is exptexially grown. Now heavily doped p^+ layer is diffused into n^- layer to form the anode.



(a)
Structural features of power diode

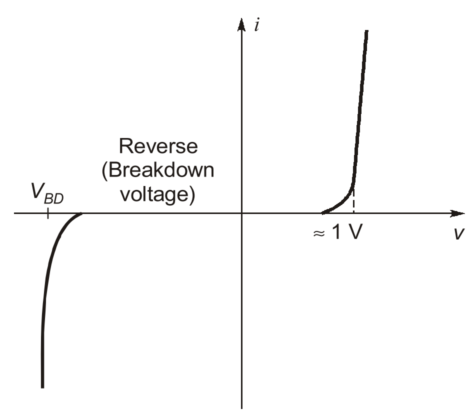


(b)
Circuit symbol

- The break-down voltage needed in a power diode governs the thickness of n^- layer. Greater the breakdown voltage, more the n^- layer thickness.
- The drawback of n^- layer is to add significant ohmic resistance to the diode when it is conducting a forward current.

1.5.1 V.I. Characteristics of Power Diodes

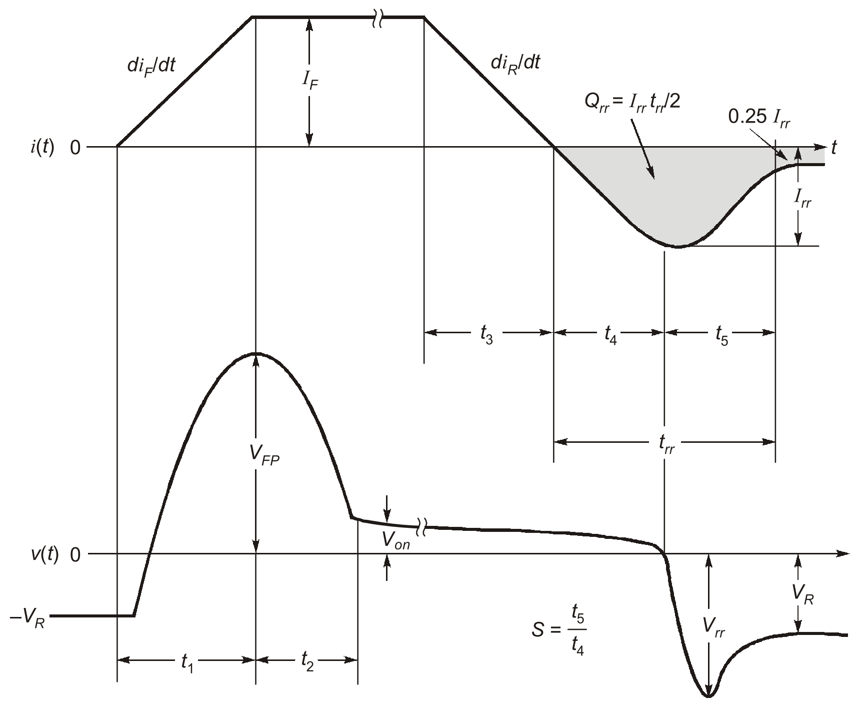
- With increase of the source voltage V_s from zero to cut-in voltage, the forward-diode current is very small.
- Cut-in voltage is also known as ***threshold voltage*** or ***turn-on voltage.***
- Beyond cut-in voltage, the diode current rises rapidly and the diode is said to conduct.
- For silicon diode, the cut-in voltage is around 0.7 V. When diode conducts, there is a forward voltage drop of the order of 0.8 to 1 V.



- For low-power diodes, current in the forward direction increases first exponentially with voltage and then becomes almost linear as shown in figure. For power diodes, the forward current grows almost linearly with voltage.
- In the reverse biased condition, a small reverse current called ***leakage current***.
- The leakage current is almost independent of the magnitude of reverse voltage until this voltage reaches breakdown voltage. At this reverse breakdown, voltage remains almost constant but reverse current becomes quite high-limited only by the external circuit resistance.
- Reverse breakdown must be avoided by operating it below the peak reverse repetitive voltage V_{RRM}.
- **Peak Inverse Voltage** is the largest reverse voltage to which a diode may be subjected during its working. PIV is the same as V_{RRM}.

1.5.2 Reverse Recovery Characteristics

- After the forward diode current decays to zero, the diode continues to conduct in the reverse direction because of the pressure of stored charges in the depletion region and the semiconductor layers.



- The diode regains its blocking capability unit reverse recovery current decays to zero.
- The time from forward diode current is zero to reverse recovery current decays to 25% of its reverse peak value I_{RM} is known as reverse recovery time.
- The reverse recovery time is composed of two segments of time t_a and t_b (i.e. t_{rr} = t_a and t_b), as shown in above figure and time t_a is the time between zero crossing of forward current and peak reverse current I_{RM}.

NOTE

- During the time t_a, charge stored in depletion layer is removed.
- During t_b, charge from the semiconductor layers is removed.

- The shaded area in above figure represents the stored charge, or reverse recovery charge, Q_R which must be removed during the reverse recovery time t_{rr}.
- The ratio t_b/t_a is called the softness factor or S-factor. It is a measure of the voltage transients that occur during the time diode recovers.
- If S-factor is small, diode has large oscillatory over voltages.
- A diode with S-factor equal to one is called *soft-recovery diode* and a diode with S-factor less than one is called *fast-recovery diode*.
- The product of v_f and i_f gives the power loss in a diode and average value gives the total power loss.
- Major power loss in a diode occurs during the period t_b.

Example - 1.1 A power diode is in the forward conduction mode and the forward current is now decreased. The reverse recovery time of the diode is t_r and the rate of fall of the diode current is di/dt. What is the stored charge?

(a) $\left(\frac{di}{dt}\right)\cdot t_r$ (b) $\left(\frac{di}{dt}\right)\cdot t_r$

(c) $\left(\frac{di}{dt}\right)\cdot t_r^2$ (d) $\frac{1}{2}\left(\frac{di}{dt}\right)\cdot t_r$

Solution: (b)

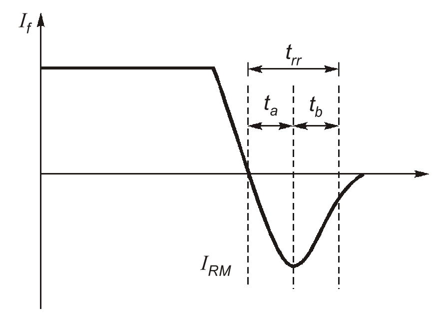
From figure, $I_{RM} = t_a \frac{di}{dt}$

Assuming reverse recovery characteristics to be triangular, storage charge Q_R

$$Q_R = \frac{1}{2} I_{RM}\, t_{srr} = \frac{1}{2}\left(t_a \frac{di}{dt}\right) t_{rr}$$

If $t_a \approx t_{rr}$

$$Q_R = \frac{1}{2}\left(\frac{di}{dt}\right) t_{rr}^2$$



Reverse Recovery Characteristic

1.5.3 Peak Inverse Current and Storage Charge

- Assume the reverse recovery characteristics is triangular in shape.
- Peak inverse current; $I_{RM} = t_a \frac{di}{dt}$

  where $\frac{di}{dt}$ is the rate of change of reverse current.
- Storage charge; $Q_R = \frac{1}{2} I_{RM}\cdot t_{rr}$

  If $t_{rr} \cong t_a$ then $t_{rr} = \left[\frac{2Q_R}{(di/dt)}\right]^{1/2}$

  and $I_{RM} = \frac{2Q_R}{t_{rr}} = \left[2Q_R\left(\frac{di}{dt}\right)\right]^{1/2}$
- Reverse recovery time t_{rr} and peak inverse current I_{RM} depends on storage charge and rate of change of current di/dt.
- The storage charge depends upon the forward diode current I_f.

1.5.4 Classification of power diodes

Diodes are classified according to their reverse recovery characteristics. These are three types.

General Purpose Diodes:

- These diodes have relatively high reverse recovery time, of the order of about 25 μs.
- Current ratings vary from 1 A to several thousand amperes.
- Voltage rating vary form 50 V to about 5 kV.

  Application: Battery charging, electric traction, electroplating and welding.

Fast-recovery Diodes:

- Low reverse recovery time, of about 5 μs or less.
- Current rating vary from about 1A to several thousand amperes.
- Voltage rating vary from 50 V to about 5 kV.

Application: These are used in choppers, commutation circuits, switching mode power supplies, induction heating etc.

NOTE

- For voltage ratings below about 400 V, the epitaxial process is used for diode fabrication. These diodes have fast recovery time, as low as 50 ns.
- For voltage ratings above 400 V, diffusion techniques used for the fabrication of diodes.
- To shorten the reverse-recovery time, platinum or gold doping is carried out, but this doping may increase the forward voltage drop in a diode.

Schottky Diodes:

- This class of diodes use metal to semi-conductor junction for rectification purpose instead of p-n junction.
- These are characterized by very fast recovery time and low forward voltage drop.
- Their reverse voltage ratings are limited to about 100 V and forward current ratings vary from 1 A to 300 A.
- When Schottky diode is forward biased, free electrons in n material move towards the Al-n junction and then travel through the metal (aluminium) to constitute the flow of forward current.
- Forward current in schottky diodes is due to the movement of electrons only.
- As the metal has no holes, there is no storage charge and no-reverse recovery time.
- As compared to p-n junction diode, a Schottky diode has
  - lower cut-in voltage
  - higher reverse leakage current
  - higher operating frequency.

Application: High frequency instrumentation and switching power supplies.

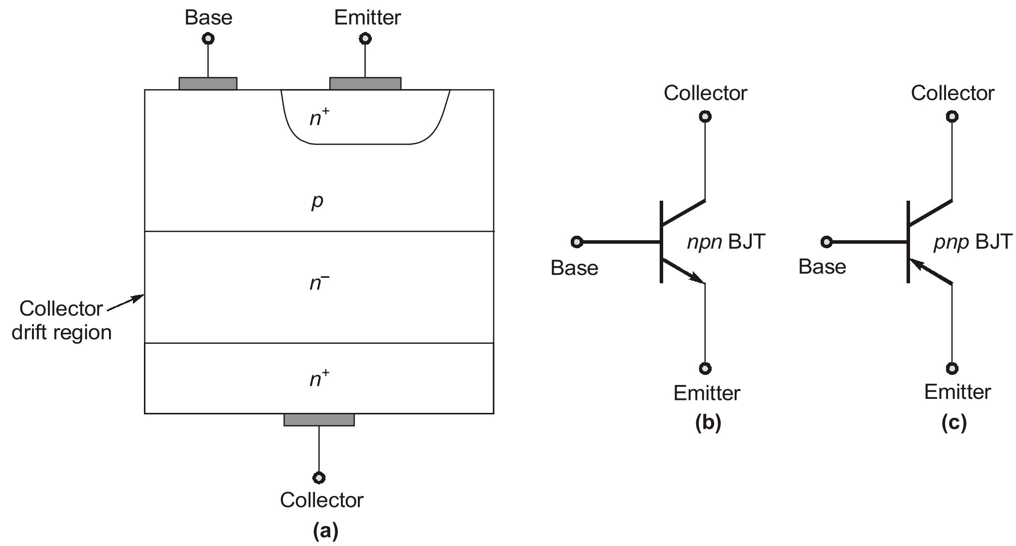
1.6 Power Transistors

- Power transistors have controlled characteristics while power diodes are uncontrolled devices.
- Power transistors are turned-on when a current signal is given to base, or control terminal. The transistor remains in the on-state so long as control signal present. When this control signal is removed, a power transistors is turned-off.

NOTE: Power transistors, used as a switching device in power-electronic circuit, must operate in the saturation region in order that their on-state voltage drop is low. Their applications as switching elements include dc choppers and inverters.

1.7 Bipolar Junction Transistors

- A bipolar transistor is a three-layer, two junction *n-p-n* or *p-n-p* semiconductor device.

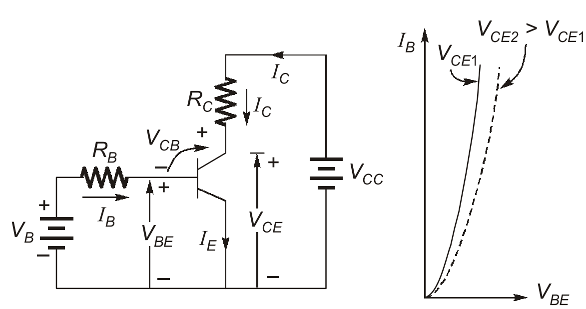


- Term bipolar means the current flows in the device is due to movement of both holes and electrons.
- A BJT has three terminals named collector (C), emitter (E) and base (B).
- In n-p-n Transistor one p-region is sandwitched by two n-regions.
- In p-n-p Transistor one n-region is sandwitched by two p-region.
- An emitter is indicated by an arrowhead indicating the direction of emitter current.
- Power transistors of npn type are easy to manufacture and are cheaper also.
- Use of power npn transistors is very wide in high-voltage and high-current applications.

1.7.1 Steady State Characteristics

Input characteristics:

- A graph between base current I_B and base emitter voltage V_{BE} gives input characteristics of a transistor.
- As the base-emitter junction of a transistor is like a diode, I_B versus V_{BE} graph resembles a diode curve.

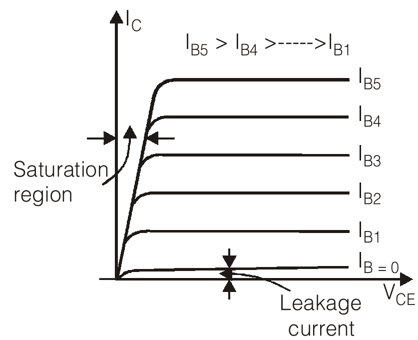


Common emitter circuit *Input characteristics*

- When collector-emitter voltage V_{CE2} is more than V_{CE1}, base current, for the same V_{BE}, decreases.

Output characteristics:

- A graph between collector current I_C and collector-emitter voltage V_{CE} gives output characteristics of a transistor.

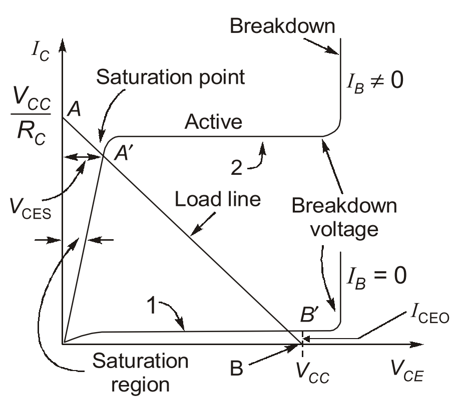


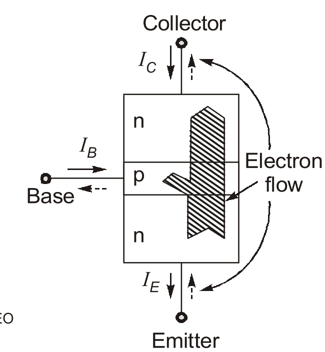
Output characteristics

- For zero base current, as V_{CE} is increased, a small leakage (collector) current exists as shown figure. As base current is increased from $I_B = 0$, the collector current also increases.

Analysis of Output Characteristics:

- We sketch two of the output characteristics curves, one for $I_B = 0$ and other for $I_B \neq 0$.





Output Characteristics and load line *Electron flow in an npn transistor*

- The initial port of curve 2, characterised by low V_{CE}, is called the ***Saturation region***. In this region the transistor acts like a switch.
- The flat part of curve 2, indicated by increasing V_{CE} and almost constant I_C, is the ***active region***. A load line is a locus of all possible operating point.
- Almost vertically rising curve is the ***breakdown region*** which must be avoided at all costs. In this region, transistor acts like an amplifier.
- Ideally, when transistor is on, V_{CE} is zero and $I_C = V_{CC}/R_C$.
- When the transistor is off, or in the cut-off region, V_{CC} appears across collector-emitter terminals and there is no collector current.
- Most of the electrons, proportional to I_E, given out by emitter reach the collector as shown in electron flow diagram.
- Collector current I_C, is almost equal to I_E.

- Forward current gain; $\alpha = \dfrac{I_C}{I_E}$.
- Value of α varies from 0.95 to 0.99.
- Current gain; $\beta = \dfrac{I_C}{I_B}$
- β is much more than unity; its value varies from 50 to 300.
- Emitter current is the largest of the three currents, collector current is almost equal to, but less than, emitter current. Base current has the least value.
- Relation between α and β

$$\beta = \frac{\alpha}{1-\alpha} \text{ and } \alpha = \frac{\beta}{1+\beta}$$

1.7.2 Transistor Operation as a Switch

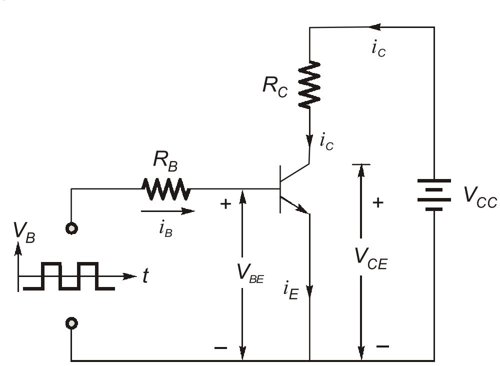
- Transistor operates either in the saturation region as closed or in the cut-off region as open switch and nowhere else on the load line.
- In practice, the large base current will cause the transistor to work in the saturation region at point A′ with small saturation voltage V_{CES}. Voltage V_{CES} represents on-state voltage drop of the transistor which is of the order of about 1 V.
- When the control, or base, signal is reduced to zero, the transistor is turned-off and its operation shifts to B′ in the cut-off region.
- A small leakage current I_{CEO} flows in the collector circuit when the transistor is off.
- If base current is less than I_{BS}, the transistor operates in the active region.
- If base current is more than I_{BS}, V_{CES} is almost zero and collector current I_{CS} is V_{CC}/R_C. i.e. collector current at saturation remains substantially constant even if base current is increased.
- The total power loss in the two junctions of a transistor

$$P_T = V_{BE}I_B + V_{CE}I_C$$

NOTE: Under saturated conditions both junctions in a power transistor are forward biased.

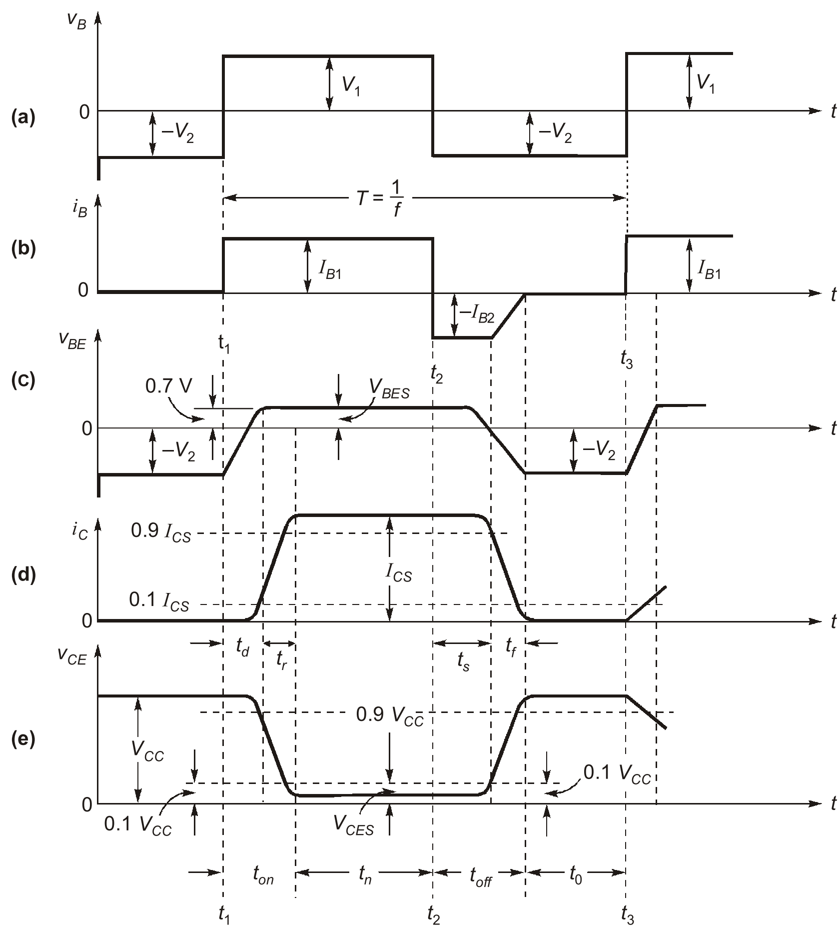
1.7.3 BJT Switching Performance

- When base current is applied, a transistor does not turn-on instantly because of the presence of internal capacitances.



npn transistor with resistive load

- Various switching waveforms for above circuits are shown below.



Switching waveforms

Delay Time (t_d): It is defined as the time during which the collector current rises from zero to 0.1 I_{CS} and collector-emitter voltage falls from V_{CC} to 0.9 V_{CC}, which depends upon transistor junction capacitances.

Rise Time (t_r):

- It is defined as the time during which collector current rises from 0.1 I_{CS} to 0.9 I_{CS} and collector-emitter voltage falls from 0.9 V_{CC} to 0.1 V_{CC}.
- Total turn-on time ($t_{on} = t_d + t_r$) is of the order of 30 to 300 nano seconds.

Storage time (t_s):

- The time required to remove these excess carriers is called storage time.
- Transistor comes out of saturation only after t_s.
- After t_s, collector current begins to fall and collector-emitter voltage starts building up.

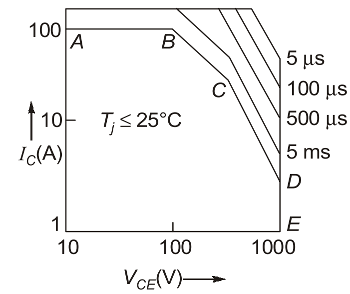
Fall Time (t_f): It is defined as the time during which collector current drops from 0.9 I_{CS} to 0.1 I_{CS} and collector-emitter voltage rises from 0.1 V_{CC} to 0.9 V_{CC}.

1.7.4 Safe Operating Area

- The safe operating area of a power transistor speicfies the safe operating limits of collector current I_C versus collector-emitter voltage V_{CE}.
- For reliable operation of the transistor, the collector current and voltage must always lie within this area.

Forward Biased Safe Operating Area (FBSOA)

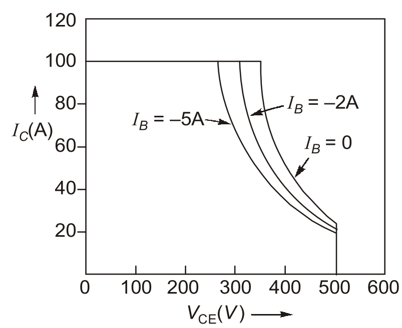
- Pertains to the transistor operation when base-emitter junction is forward biased to turn-on the transistor.
  Boundary AB: Maximum limit for dc and continuous current.
  Boundary BC: To limit the junction temperature to safe value.
  Boundary CD: Secondary breakdown limit.
  Boundary DE: Maximum voltage capability.



FBSOA for power transistor (logarithmic scale)

Reverse Block Safe Operating Area (RBSOA)

- A plot of collector current versus collector-emitter voltage, when base-emitter junction is reverse biased to turn-off the transistor.



RBSOA for power transistor (logarithmic scale)

- Specifies the limits of transistor operation at turn-off when the base current is zero or when the base-emitter junction is reverse biased.
- With increased reverse bias, area of RBSOA decreases in size.

Example - 1.2 Turn-on and turn-off times of transistor depend on

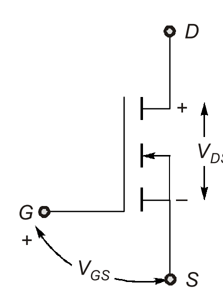
(a) static characteristic (b) junction capacitances
(c) current gain (d) none of the above

Solution: (b)

Turn-on and turn-off times of transistor depend on junction capacitance. Because of charging and discharging of junction capacitance a transistor does not turn-on and turn off instantly.

1.8 Power MOSFETS

- A metal-oxide-semiconductor field-effect transistor MOSFET = MOS Technology + Field effect concept.
- A MOSFET has three terminals called drain, source, and gate.
- Power MOSFET is a **voltage controlled device**.
- As its operation depends upon the flow of majority carriers only, MOSFET is a **unipolar device**.
- Gate circuit impedance in MOSFET is extremely high, of the order of $10^9\ \Omega$.
- Power MOSFET are now finding increasing application in low power high frequency converters.
- *n*-channel enhancement and *p*-channel enhancement MOSFET are two types of MOSFETS, *n*-channel enhencements MOSFET is more common because of higher mobility.



Circuit symbol

1.8.1 Constructional Features of MOSFET

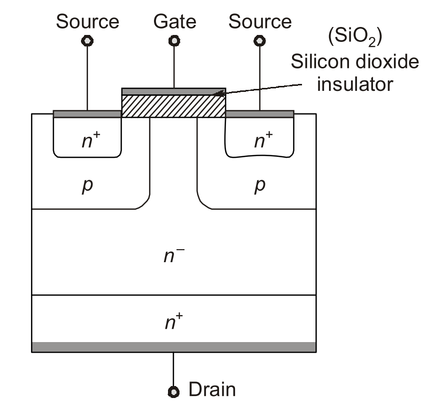
For Low Power Rating:

- For n-channel, two heavily doped n^+ regions are diffused on p-substrate as shown.
- An insulating layer of silicon dioxide (SiO_2) etched in order to embed metallic source and drain terminals.

NOTE

- n^+ region make contact with source and drain terminals.
- A layer of metal is also deposited on SiO_2 layer so as to form the gate of MOSFET.

- When gate circuit is open junction between n^+ region below drain and p-substrate is reverse biased by input voltage V_{DD}. Therefore, no current flows from drain to source and load.
- When gate is made positive with respect to source, an electric field is established as shown in figure. Eventually, induced negative charges in the p-substrate below SiO_2 layer are formed thus causing the p-layer below gate to become an induced n-layer.
- These negative charges, called electrons, form n-channel between two n^+ regions and current can flow from drain to source as shown by the arrow.

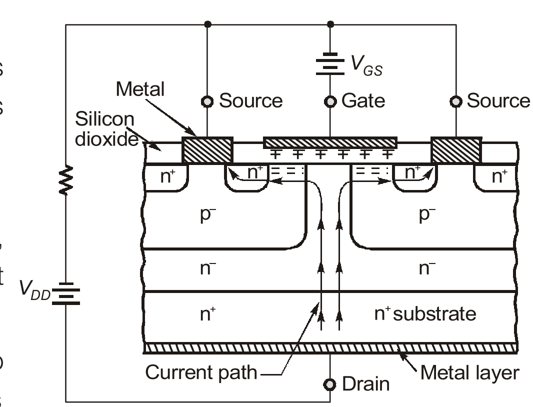


N-channel enhancement power MOSFET, Its basic structure

High Power Rating MOSFET:

- On n^+ substrate, high resistivity n^- layer is epitaxially grown.
- The thickness of n^- layer determines the voltage blocking capability of the device.
- On the other side of n^+ substrate, a metal layer is deposited to form the drain terminal. Now p regions are diffused in the epitaxially grown n^- layer.

  Further, n^+ regions are diffused in p regions.
- When gate circuit voltage is zero, and V_{DD} is present, $n^- - p^-$ junctions are reverse biased and no current flows from drain to source.
- When gate terminal is made positive with respect to source, an electric-field is established and electrons from n-channel in the p^- regions as shown. So a current from drain to source is established as indicated by arrows.

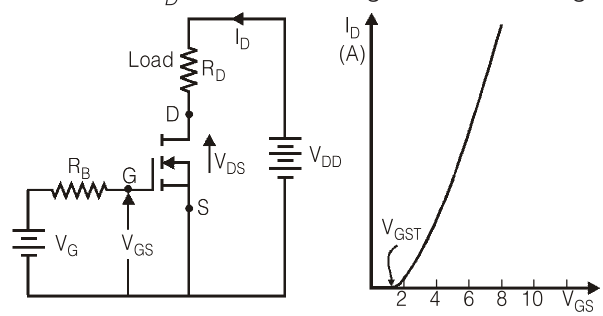


- MOSFET is a majority carrier device. Hence, time delays caused be removal or recombination of minority carriers are eliminated during the turn-off process of this device.

1.8.2 Characteristics of MOSFET

Transfer Characteristics:

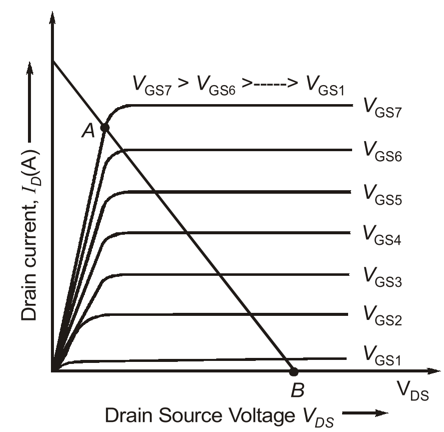
- The variation of drain current I_D as a function of gate-source voltage V_{GS}.



- V_{GST} is the minimum positive voltage between gate and source to induce n-channel. Thus for threshold voltage below V_{GST}, device is in the off-state. Magnitude of V_{GST} is of the order of 2 to 3 V.

Output Characteristics:

- The variation of drain current I_D as a function of drain-source voltage V_{DS}, with gate-source voltage V_{GS} as a parameter.
- For low value of V_{DS}, the graph between I_D-V_{DS} is almost linear, this indicates a constant value of on-resistance R_{DS} (= V_{DS}/I_D).
- A load line intersects the output characteristics at A and B. Here A indicates fully-on condition and B fully off state.
- Power MOSFET operates as a switch either at A or at B just like BJT.



Output characteristics of MOSFET

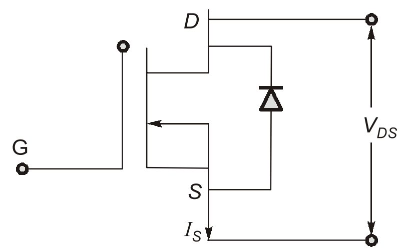
MOSFET Applications:

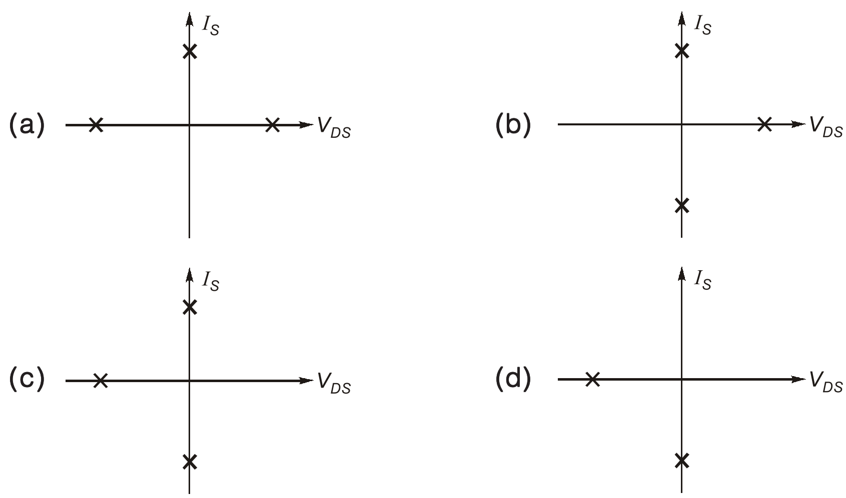
- High-frequency switching applications.
- Switched-mode power supplies and inverters.

1.8.3 Comparison of PMOSFET with BJT

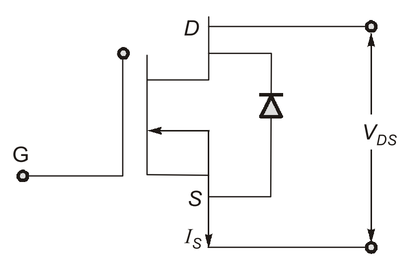
- BJT is a bipolar device whereas MOSFET is a unipolar device.
- A MOSFET has high input impedance (mega ohm) whereas input impedance of BJT is low (a few kilo-ohm).
- MOSFET has lower switching losses but its on-resistance and conduction losses are more. A BJT has higher switching losses but lower conduction loss. So, at high frequency applications, MOSFET is the obvious choice. But at lower operating frequencies (less than about 10 to 20 kHz), BJT is superior.
- MOSFET is voltage controlled device whereas BJT is current controlled device.
- MOSFET has positive temperature coefficient for resistance. This makes parallel operation of MOSFETs easy.
- A BJT has negative temperature coefficient, so current sharing resistors are necessary during parallel operation of BJTs.
- In MOSFETs, secondary breakdown does not occur, because it has positive temperature coefficient.
- MOSFETs in higher voltage ratings have more conduction loss.

Example - 1.3 Figure shows a MOSFET with an integral body diode. It is employed as a power switching device in the ON and OFF states through appropriate control. The ON and OFF states of the switch are given on the $V_{DS} - I_s$ plane by





Solution: (b)



When reverse current flows through diode *D*.

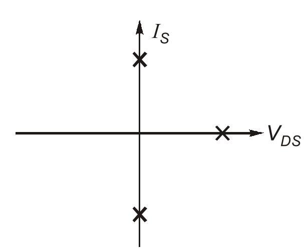
So, $I_S < 0$ and $V_{DS} = 0$

When MOSFET is in ON state

$I_S > 0$ and $V_{DS} = 0$

When MOSFET is in OFF state

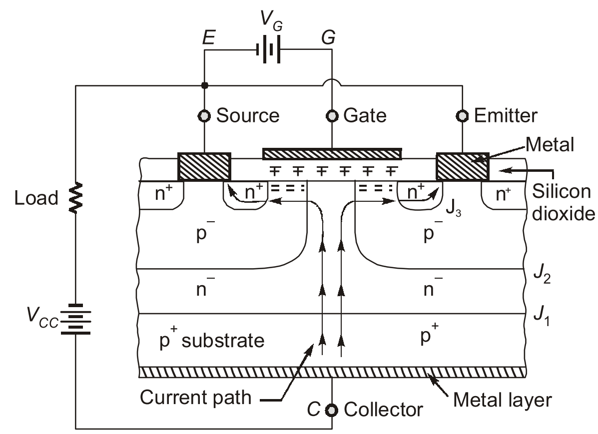
$I_S = 0$ and $V_{DS} > 0$



1.9 Insulated Gate Bipolar Transistor

- An IGBT have best qualities of both BJT and MOSFET.
- It possesses high input impedance like a MOSFET and has low on-state power loss as in a BJT.
- It is free from second breakdown problem present in BJT.

Basic Structure:



Basic structure of an IGBT

- It is constructed virtually in the same manner as a power MOSFET. There is, however, a major difference in the substrate. The n^+ layer substrate at the drain in MOSFET is now substituted in the IGBT by a p^+ layer substrate called collector.
- p^+ substrate is called injection layer because it injects holes into n^- layer. Then n^- layer is called drift region.
- Thickness of n^- layer determines the voltage blocking capability of IGBT.
- The n^- layer in between p^+ and p regions serves to accommodate the depletion layer of pn^- junction.

1.9.1 IGBT Characteristics

V-I Characteristics:

- The plot of collector current I_c versus collector-emitter voltage V_{CE} for various values of gate-emitter voltages.
- In the forward direction, the shape of the output characteristics is similar to that of BJT. But here the controlling parameter is gate-emitter voltage V_{GE} because I_{GBT} is a voltage-controlled device.
- When the device is off, junction J_2 blocks forward voltage and in case reverse voltage appears across collector and emitter, junction J_1 blocks it.
- V_{RM} is the maximum reverse breakdown voltage.

Transfer Characteristics:

- A plot of collector current I_C versus gate-emitter voltage V_{GE}.
- Identical to that of power MOSFET
- When V_{GE} is less than the threshold voltage V_{GET}, IGBT is in the off-state.

1.9.2 Switching Characteristics

- The turn-on time is defined as the time between the instants of forward blocking to forward on-state. It is composed of delay time t_{dn} and rise time t_r, i.e. $t_{on} = t_{dn} + t_r$.
- *The turn-off time*
- Consists of three intervals: (i) delay time, t_{df} (ii) initial fall time, t_{f1} and (iii) final fall time t_{f2}; i.e. $t_{off} = t_{df} + t_{f1} + t_{f2}$.
- *Delay time*
- Time during which gate voltage falls from V_{GE} to threshold voltage V_{GET}.
- The ***first fall time*** t_{f1} is defined as the time during which collector current falls from 90 to 20% of its initial value I_C.
- The ***final fall time*** t_{f2}.
- Time during which collector current falls from 20 to 10% of I_C, or the time during which collector-emitter voltage rises from 0.1 V_{CE} to final value V_{CE}.