G. PULLAIAH COLLEGE OF ENGINEERING AND TECHNOLOGY
Accredited by NAAC with 'A' Grade of UGC, Approved by AICTE, New Delhi
Permanently Affiliated to JNTUA, Ananthapuramu
(Recognized by UGC under 2(f) and 12(B) & ISO 9001:2008 Certified Institution)
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Department of Electrical and Electronics Engineering

Bridge Course
On
POWER ELECTRONICS

1. INTRODUCTION TO POWER ELECTRONICS:

Power Electronics is a field which combines Power (electric power), Electronics and Control systems. Power engineering deals with the static and rotating power equipment for the generation, transmission and distribution of electric power. Electronics deals with the study of solid state semiconductor power devices and circuits for Power conversion to meet the desired control objectives (to control the output voltage and output power). Power electronics may be defined as the subject of applications of solid state power semiconductor devices (Thyristors) for the control and conversion of electric power. Power electronics deals with the study and design of Thyristorised power controllers for variety of application like Heat control, Light/Illumination control, Motor control - AC/DC motor drives used in industries, High voltage power supplies, Vehicle propulsion systems, High voltage direct current (HVDC) transmission.

1.1 BRIEF HISTORY OF POWER ELECTRONICS:

The first Power Electronic Device developed was the Mercury Arc Rectifier during the year 1900. Then the other Power devices like metal tank rectifier, grid controlled vacuum tube rectifier, ignitron, phanotron, thyratron and magnetic amplifier, were developed & used gradually for power control applications until 1950. The first SCR (silicon controlled rectifier) or Thyristor was invented and developed by Bell Lab's in 1956 which was the first PNPN triggering transistor. The second electronic revolution began in the year 1958 with the development of the commercial grade Thyristor by the General Electric Company (GE). Thus the new era of power electronics was born. After that many different types of power semiconductor devices & power conversion techniques have been introduced.The power electronics revolution is giving us the ability to convert, shape and control large amounts of power.

1.2 SOME APPLICATIONS OF POWER ELECTRONICS

Advertising, air conditioning, aircraft power supplies, alarms, appliances - (domestic and industrial), audio amplifiers, battery chargers, blenders, blowers, boilers, burglar alarms, cement kiln, chemical processing, clothes dryers, computers, conveyors, cranes and hoists, dimmers (light dimmers), displays, electric door openers, electric dryers, electric fans, electric vehicles, electromagnets, electro mechanical electro plating, electronic ignition, electrostatic precipitators, elevators, fans, flashers, food mixers, food warmer trays, fork lift trucks, furnaces, games, garage door openers, gas turbine starting, generator exciters, grinders, hand power tools, heat controls, high frequency lighting, HVDC transmission, induction heating, laser power supplies, latching relays, light flashers, linear induction motor controls, locomotives, machine tools, magnetic recording, magnets, mass transit railway system, mercury arc lamp ballasts, mining, model trains, motor controls, motor drives, movie projectors, nuclear reactor control rod, oil well drilling, oven controls, paper mills, particle accelerators, phonographs, photo copiers, power suppliers, printing press, pumps and compressors, radar/sonar power supplies, refrigerators, regulators, RF amplifiers, security systems, servo systems, sewingmachines, solar power supplies, solid-state contactors, solid-state relays, static circuit breakers, static relays, steel mills, synchronous motor starting, TV circuits, temperature controls, timers and toys, traffic signal controls, trains, TV deflection circuits, ultrasonic generators, UPS, vacuum cleaners, VAR compensation, vending machines, VLF transmitters, voltage regulators, washing machines, welding equipment.

1.3 POWER ELECTRONIC APPLICATIONS COMMERCIAL APPLICATIONS

Heating Systems Ventilating, Air Conditioners, Central Refrigeration, Lighting, Computers and Office equipments, Uninterruptible Power Supplies (UPS), Elevators, and Emergency Lamps. DOMESTIC APPLICATIONS Cooking Equipments, Lighting, Heating, Air Conditioners, Refrigerators & Freezers, Personal Computers, Entertainment Equipments, UPS. INDUSTRIAL APPLICATIONS Pumps, compressors, blowers and fans. Machine tools, arc furnaces, induction furnaces, lighting control circuits, industrial lasers, induction heating, welding equipments. AEROSPACE APPLICATIONS Space shuttle power supply systems, satellite power systems, aircraft power systems. TELECOMMUNICATIONS Battery chargers, power supplies (DC and UPS), mobile cell phone battery chargers. TRANSPORTATION Traction control of electric vehicles, battery chargers for electric vehicles, electric locomotives, street cars, trolley buses, automobile electronics including engine controls. UTILITY SYSTEMS High voltage DC transmission (HVDC), static VAR compensation (SVC), Alternative energy sources (wind, photovoltaic), fuel cells, energy storage systems, induced draft fans and boiler feed water pumps.

2. POWER SEMICONDUCTOR DEVICES :

- Power Diodes.
- Power transistors (BJT's).
- Power MOSFETS.
- IGBT's.

Thyristors

Thyristors are a family of p-n-p-n structured power semiconductor switching devices SCR's (Silicon Controlled Rectifier) The silicon controlled rectifier is the most commonly and widely used member of the thyristor family. The family of thyristor devices include SCR's, Diacs, Triacs, SCS, SUS, LASCR's and so on.

2.1 POWER SEMICONDUCTOR DEVICES USED IN POWER ELECTRONICS

The first thyristor or the SCR was developed in 1957. The conventional Thyristors (SCR's) were exclusively used for power control in industrial applications until 1970. After 1970, various types of power semiconductor devices were developed and became commercially available. The power semiconductor devices can be divided broadly into five types

- Power Diodes.
- Thyristors.
- Power BJT's.
- Power MOSFET's.
- Insulated Gate Bipolar Transistors (IGBT's).

- Static Induction Transistors (SIT's).

The Thyristors can be subdivided into different types

- Forced-commutated Thyristors (Inverter grade Thyristors)
- Line-commutated Thyristors (converter-grade Thyristors)
- Gate-turn off Thyristors (GTO).
- Reverse conducting Thyristors (RCT's).
- Static Induction Thyristors (SITH).
- Gate assisted turn-off Thyristors (GATT).
- Light activated silicon controlled rectifier (LASCR) or Photo SCR's.
- MOS-Controlled Thyristors (MCT's).

3. POWER DIODES

Power diodes are made of silicon p-n junction with two terminals, anode and cathode. P-N junction is formed by alloying, diffusion and epitaxial growth. Modern techniques in diffusion and epitaxial processes permit desired device characteristics.

The diodes have the following advantages:

- High mechanical and thermal reliability
- High peak inverse voltage
- Low reverse current
- Low forward voltage drop
- High efficiency
- Compactness.

4. POWER TRANSISTORS

Power transistors are devices that have controlled turn-on and turn-off characteristics. These devices are used a switching devices and are operated in the saturation region resulting in low on-state voltage drop. They are turned on when a current signal is given to base or control terminal. The transistor remains on so long as the control signal is present. The switching speed of modern transistors is much higher than that of thyristors and are used extensively in dc-dc and dc-ac converters. However their voltage and current ratings are lower than those of thyristors and are therefore used in low to medium power applications. Power transistors are classified as follows

- Bipolar junction transistors(BJTs)
- Metal-oxide semiconductor filed-effect transistors(MOSFETs)
- Static Induction transistors(SITs)
- Insulated-gate bipolar transistors(IGBTs)

4.1 BIPOLAR JUNCTION TRANSISTORS:

The need for a large blocking voltage in the off state and a high current carrying capability in the on state means that a power BJT must have substantially different structure than its small signal equivalent. The modified structure leads to significant differences in the I-V characteristics and switching behavior between power transistors and its logic level counterpart.

POWER TRANSISTOR STRUCTURE:

If we recall the structure of conventional transistor we see a thin p-layer is sandwiched between two n-layers or vice versa to form a three terminal device with the terminals named as Emitter, Base and Collector. The difference in the two structures is obvious. A power transistor is a vertically oriented four layer structure of alternating p-type and n-type. The vertical structure is preferred because it maximizes the cross sectional area and through which the current in the device is flowing. This also minimizes on-state resistance and thus power dissipation in the transistor. The doping of emitter layer and collector layer is quite large typically 1019 cm-3 . A special layer called the collector drift region (n-) has a light doping level of 1014 . The thickness of the drift region determines the breakdown voltage of the transistor. The base thickness is made as small as possible in order to have good amplification capabilities, however if the base thickness is small the breakdown voltage capability of the transistor is compromised. Practical power transistors have their emitters and bases interleaved as narrow fingers as shown. The purpose of this arrangement is to reduce the effects of current crowding. This multiple emitter layout also reduces parasitic ohmic resistance in the base current path which reduces power dissipation in the transistor.

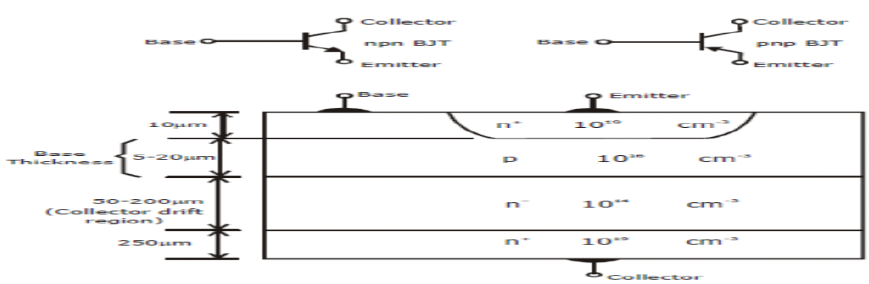

Fig 4.1 : structure of power transistor

Fig: 4.2

STEADY STATE CHARACTERISTICS

Figure 4(a) shows the circuit to obtain the steady state characteristics.
Figure 4(b) shows the input characteristics of the transistor which is a plot of I_B versus V_{BE}.
Figure 4(c) shows the output characteristics of the transistor which is a plot I_C versus V_{CE}.
The characteristics shown are that for a signal level transistor.

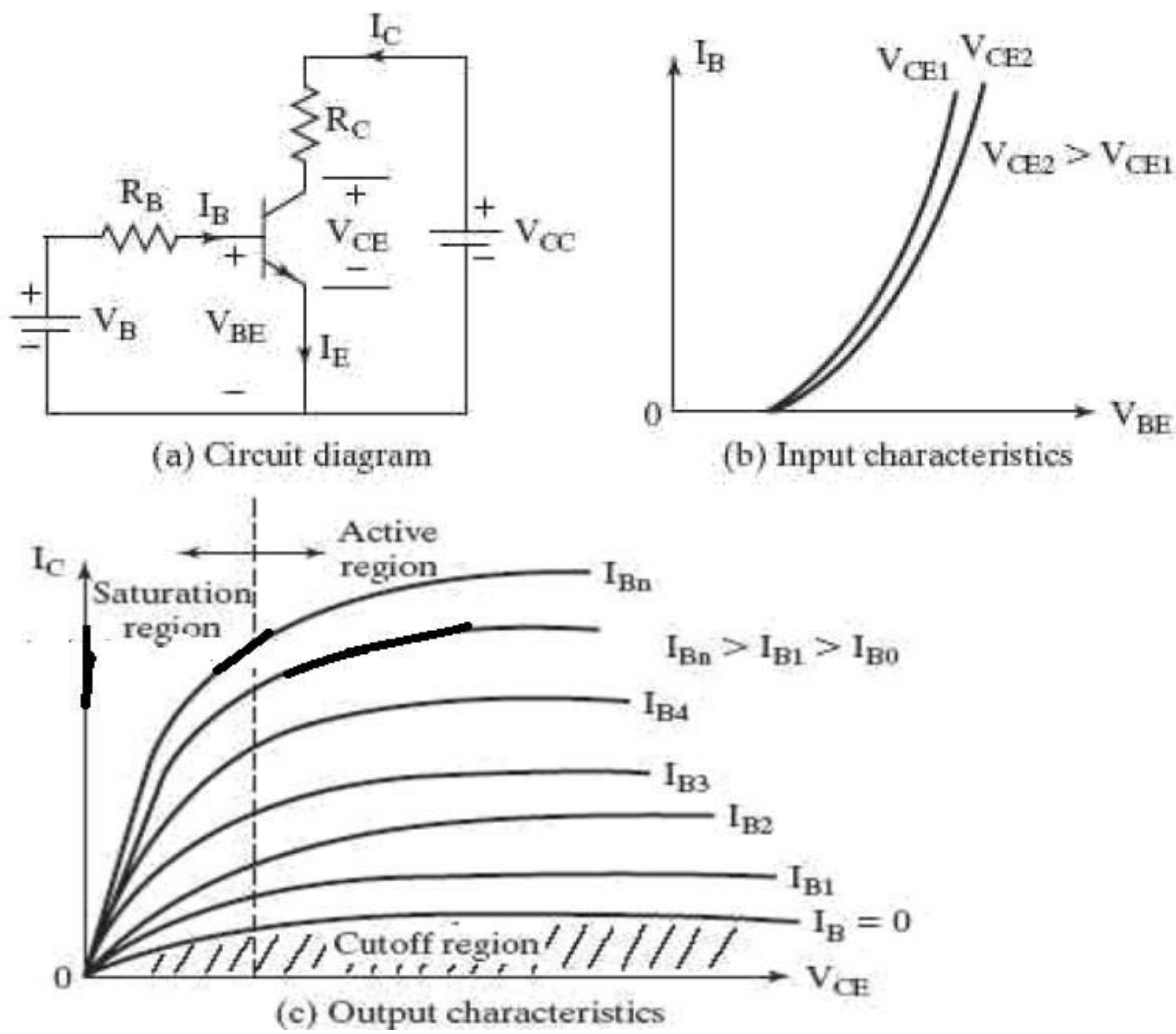

Fig4.3: charecteristics of NPN Transistor

The power transistor has steady state characteristics almost similar to signal level transistors except that the V-I characteristics has a region of quasi saturation as shown by figure 4There are four regions clearly shown: Cutoff region, Active region, quasi saturation and hard saturation. The cutoff region is the area where base current is almost zero. Hence no collector current flows and transistor is off. In the quasi saturation and hard saturation, the base drive is applied and transistor is said to be on. Hence collector current flows depending upon the load. The power BJT is never operated in the active region (i.e. as an amplifier) it is always operated between cutoff and saturation. The *BVSUS* is the maximum collector to emitter voltage that can be sustained when BJT is carrying substantial collector current. The *BVCEO* is the maximum collector to emitter breakdown voltage that can be sustained when base current is zero and *BVCBO* is the collector base breakdown voltage when the emitter is open circuited

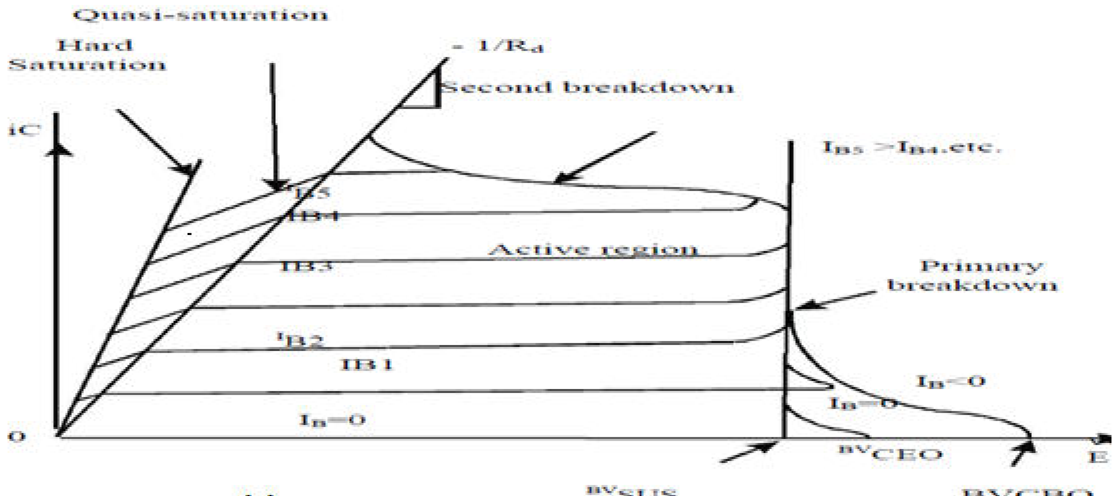

Fig. 4.4 Characteristics of NPN Power Transistors

The primary breakdown shown takes place because of avalanche breakdown of collector base junction. Large power dissipation normally leads to primary breakdown.The second breakdown shown is due to localized thermal runaway

TRANSFER CHARACTERISTICS

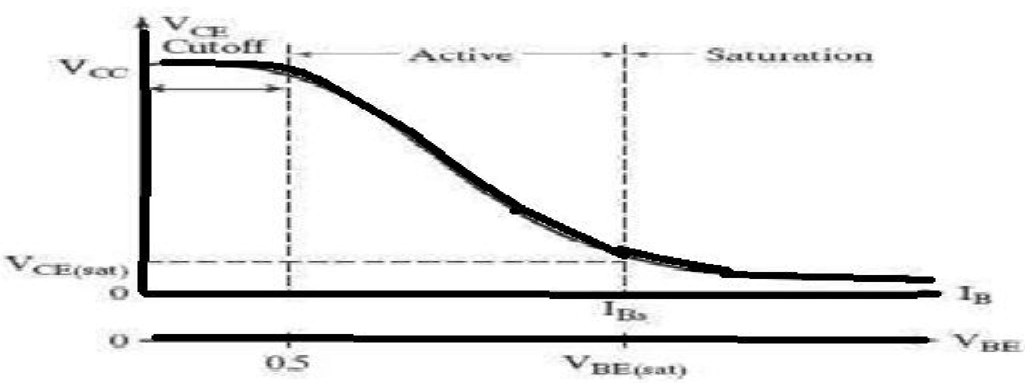

Fig 4.5: Transfer Characteristics

TRANSISTOR AS A SWITCH

The transistor is used as a switch therefore it is used only between saturation and cutoff. From fig. 5 we can write the following equations

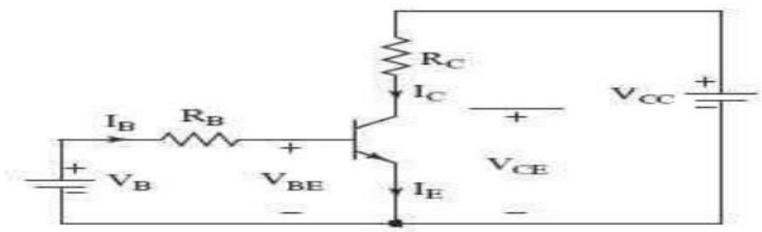

Fig. 4.6: Transistor Switch

If the base current is increased above *I BM* ,*VBE* increases, the collector current increases and *VCE* falls below*VBE* . This continues until the CBJ is forward biased with *VBC* of about 0.4 to 0.5V, thetransistor than goes into saturation. The transistor saturation may be defined as the point above which anyincrease in the base current does not increase the collector current significantly.

In saturation, the collector current remains almost constant. If the collector emitter voltage is *VCE sat* the collector current is *VBE* increases due to increased base current resulting in increased power loss. Once the transistor is saturated, the CE voltage is not reduced in relation to increase in base current. However the power is increased at a high value of ODF, the transistor may be damaged *I B vsIBS* may operate in active region, *VCE* increases resulting in increased power loss.

SWITCHING CHARACTERISTICS

A forward biased p-n junction exhibits two parallel capacitances; a depletion layer capacitance and a diffusion capacitance. On the other hand, a reverse biased p-n junction has only depletion capacitance. Under steady state the capacitances do not play any role. However under transient conditions, they influence turn-on and turn-off behavior of the transistor.

TRANSIENT MODEL OF BJT

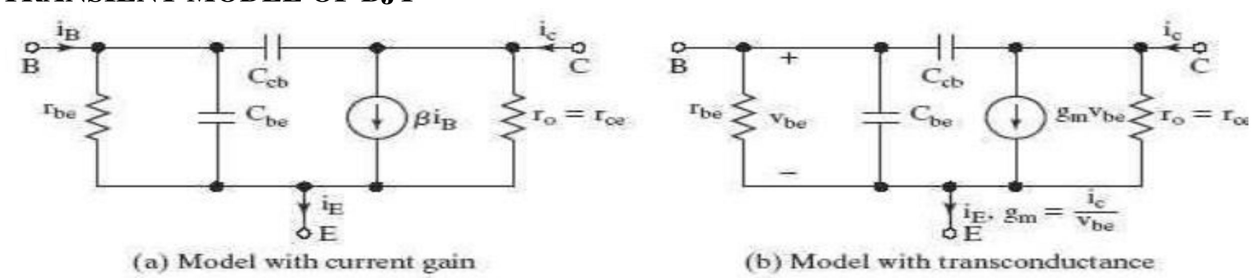

Fig. 4.7: Transient Model of BJT

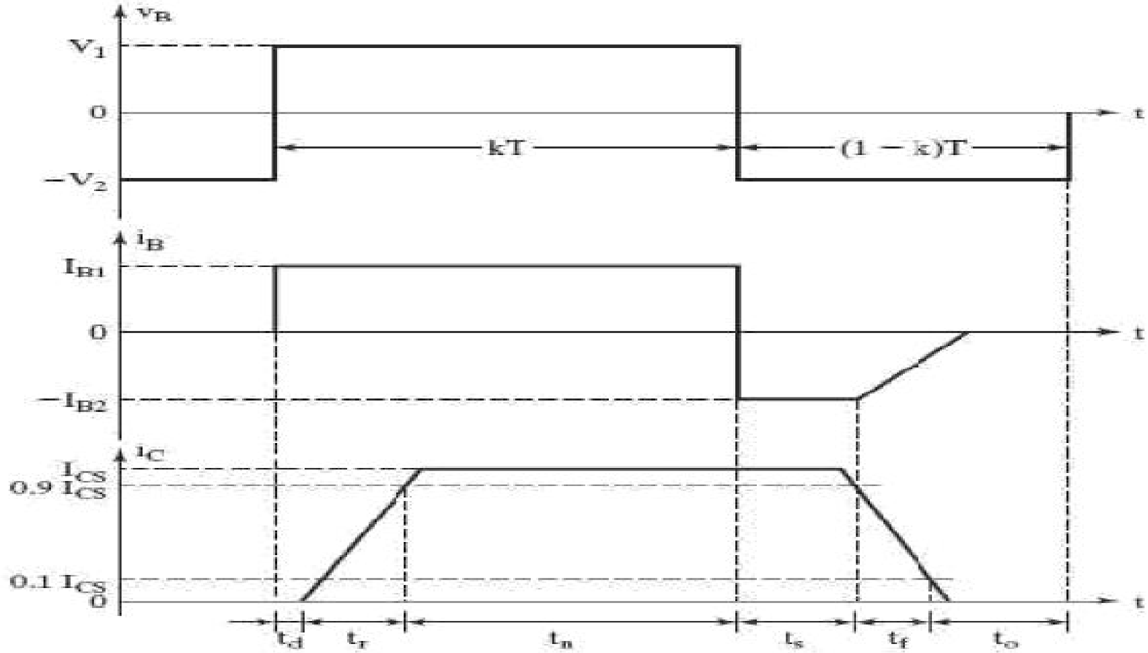

Fig. 4.8: Switching Times of BJT

Due to internal capacitances, the transistor does not turn on instantly. As the voltage VB rises from zero to V1 and the base current rises to IB1, the collector current does not respond immediately. There is a delay known as delay time td, before any collector current flows. The delay is due to the time required to charge up the BEJ to the forward bias voltage VBE(0.7V). The collector current rises to the steady value of I CS and this time is called rise time tr.

The base current is normally more than that required to saturate the transistor. As a result excess minority carrier charge is stored in the base region. The higher the ODF, the greater is the amount of extra charge stored in the base. This extra charge which is called the saturating charge is proportional to the excess base drive.

This extra charge which is called the saturating charge, is proportional to the excess base drive and the corresponding current Ie.

When the input voltage is reversed from V1 to -V2, the reverse current –IB2 helps to discharge the base. Without –IB2 the saturating charge has to be removed entirely due to recombination and the storage time ts would be longer.

Once the extra charge is removed, BEJ charges to the input voltage –V2 and the base current falls to zero. tf depends on the time constant which is determined by the reverse biased BEJ capacitance.

Turn-on time *ton* : The turn-on time can be decreased by increasing the base drive for a fixed value of collector current. *td* is dependent on input capacitance does not change significantly with *IC* . However tr increases with increase in *IC* .

Turn off time *toff* :The storage time ts is dependent on over drive factor and does not change significantly with IC.tf is a function of capacitance and increases with ic.tf is a function of capacitance and increases with ic ts andtf can be reduced by providing negative base drive during turn off tf is less sensitive to negative base drive

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5. POWER MOSFETS

5.1 INTRODUCTION TO FET'S

FET's use field effect for their operation. FET is manufactured by diffusing two areas of p-type into the n-type semiconductor as shown. Each p-region is connected to a gate terminal; the gate is a p-region while source and drain are n-region. Since it is similar to two diodes one is a gate source diode and the other is a gate drain diode.

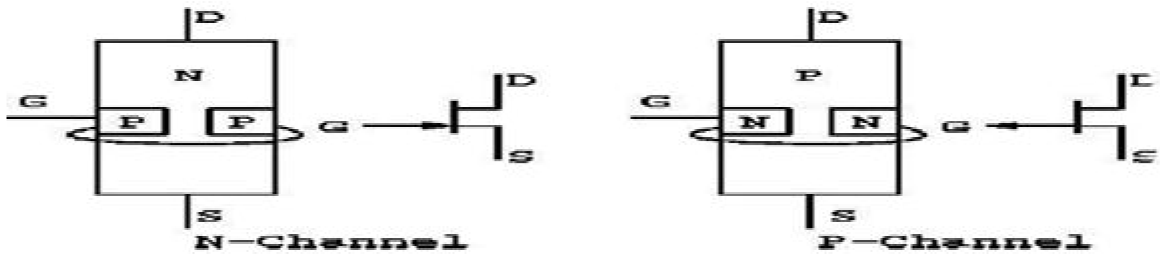


Fig: 5.1 Schematic symbol of JFET

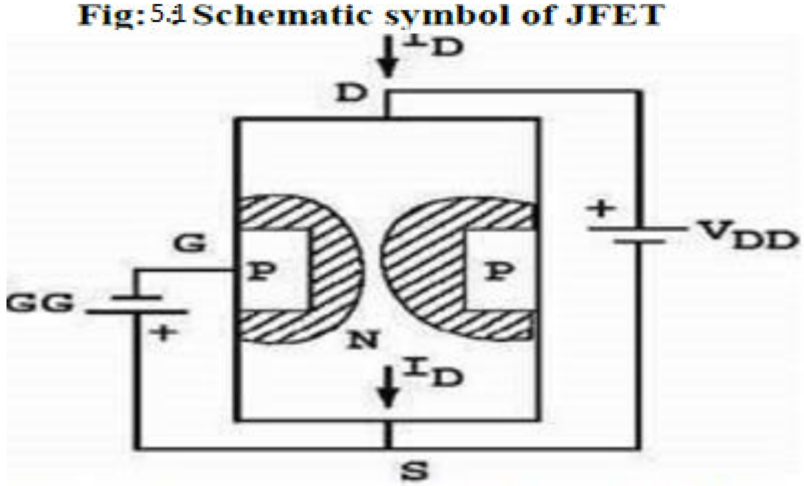


Fig. 5.2 Structure of FET with biasing

In BJT's we forward bias the B-E diode but in a JFET, we always reverse bias the gate-source diode. Since only a small reverse current can exist in the gate lead. Therefore *IG* 0 , therefore *Rin ideal* The term field effect is related to the depletion layers around each p-region as shown. When the supply voltage *VDD* is applied as shown it forces free electrons to flow from source to drain. With gate reverse biased, the electrons need to flow from source to drain, they must pass through the narrow channel between the two depletion layers. The more the negative gate voltage is the tighter the channel becomes. Therefore JFET acts as a voltage controlled device rather than a current controlled device. JFET has almost infinite input impedance but the price paid for this is loss of control over the output current, since JFET is less sensitive to changes in the output voltage than a BJT.

JFET CHARACTERISTICS

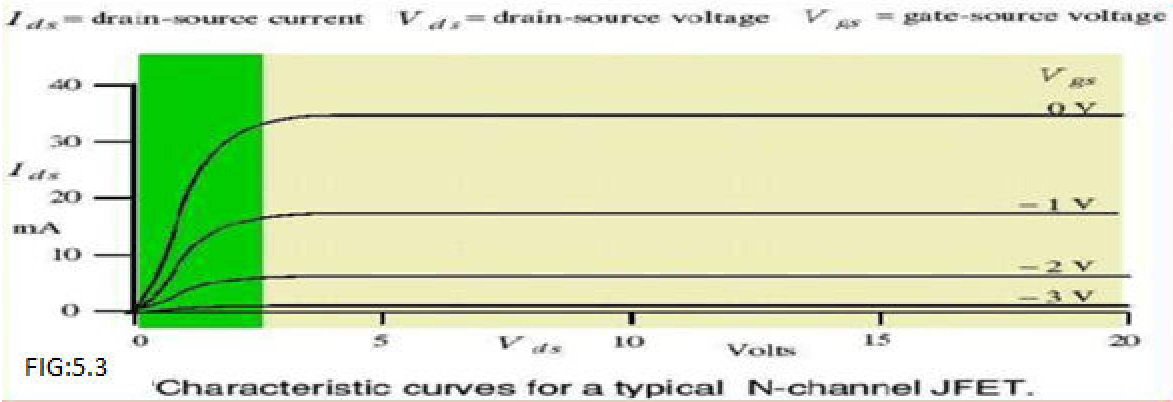


FIG:5.3

Characteristic curves for a typical N-channel JFET.

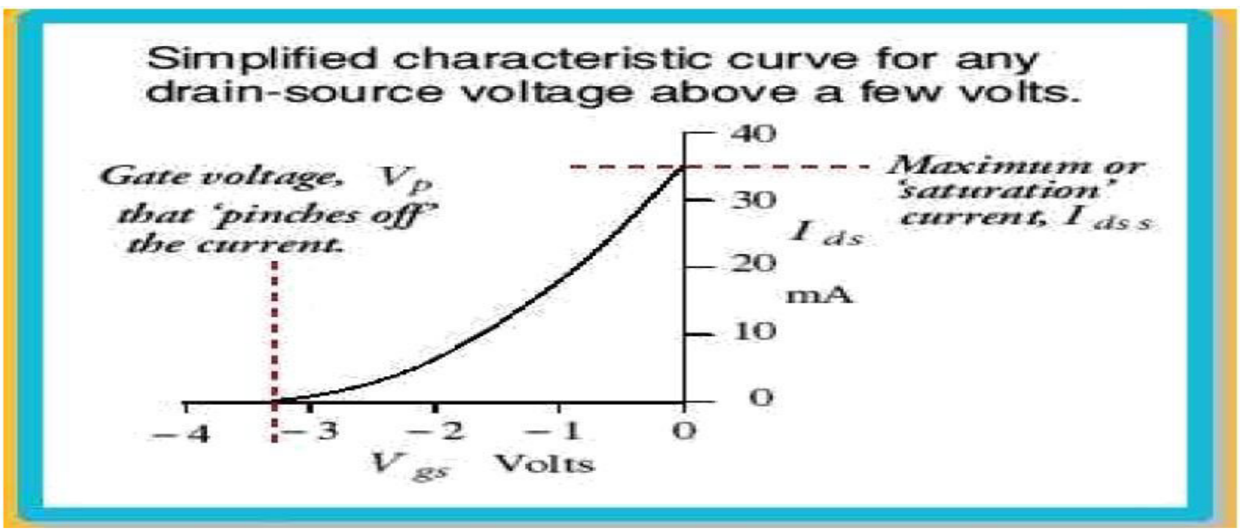


FIG:5.4

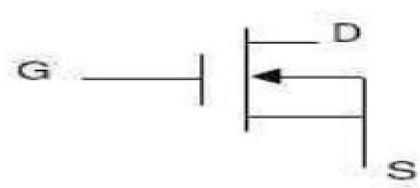
The maximum drain current out of a JFET occurs when *VGS VDS* is increased for 0 to a few volts, the current will increase as determined by ohms law. As *VDS* approaches *VP* the depletion region will widen, carrying a noticeable reduction in channel width. If *VDS* is increased to a level where the two depletion region would touch a pinch-off will result. *ID* now maintains a saturation level *IDSS* . Between 0 volts and pinch off voltage *VP* is the ohmic region. After *VP* , the regions constant current or active region.If negative voltage is applied between gate and source the depletion region similar to those obtained with *VGS VDS* . Therefore saturation level is reached earlier.

6. Classification of MOSFET

MOSFET stands for metal oxide semiconductor field effect transistor. There are two types of MOSFET
Depletion type MOSFET
Enhancement type MOSFET

6.1 DEPLETION TYPE MOSFET

CONSTRUCTION



Symbol of n-channel depletion type MOSFET

It consists of a highly doped p-type substrate into which two blocks of heavily doped n-type material are diffused to form a source and drain. A n-channel is formed by diffusing between source and drain. A thin layer of *SiO*2 is grown over the entire surface and holes are cut in *SiO*2 to make contact with n-type blocks. The gate is also connected to a metal contact surface but remains insulated from the n-channel by the *SiO*2 layer

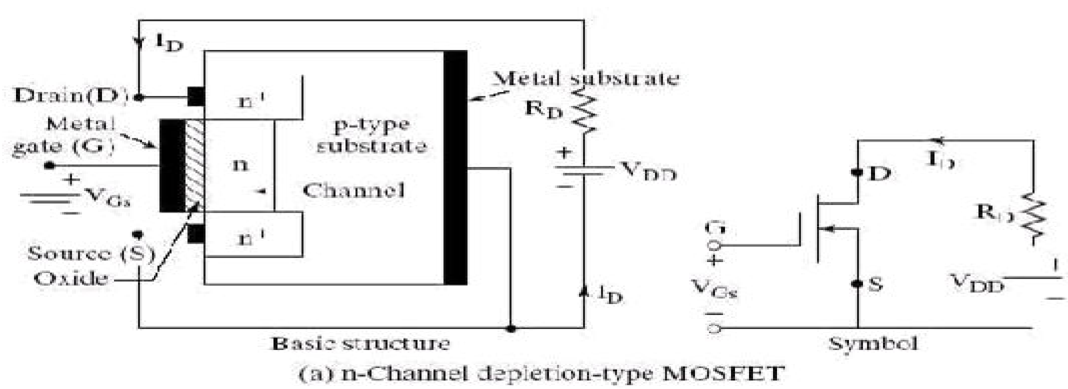


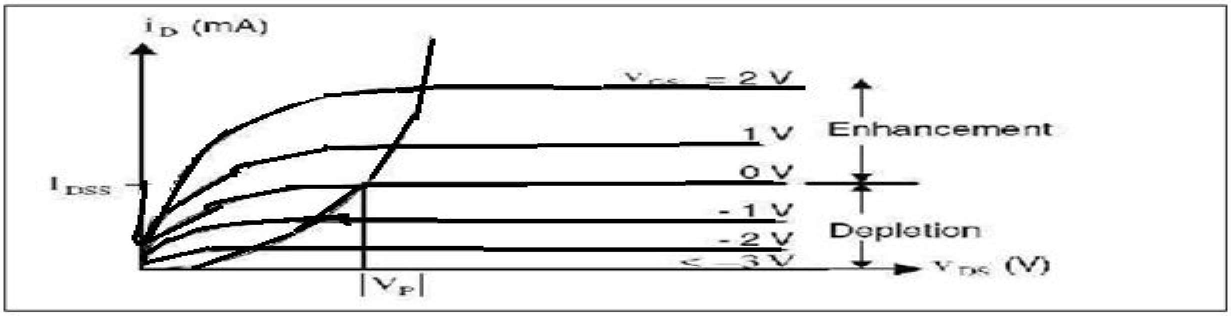
fig. 6.1: Structure of n-channel depletion type MOSFET

OPERATION

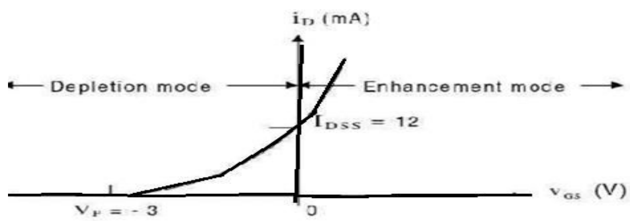
When *VGS V* and *VDS* is applied and current flows from drain to source similar to JFET. When *VGS V* , the negative potential will tend to pressure electrons towards
the p-type substrate and attracts hole from p-type substrate. Therefore recombination occurs and will reduce the number of free electrons in the n-channel for conduction. Therefore with increased negative gate voltage *ID* reduces.
For positive values,*Vgs* , additional electrons from p-substrate will flow into the

channel and establish new carriers which will result in an increase in drain current with positive gate voltage.

DRAIN CHARACTERISTICS



TRANSFER CHARACTERISTICS



7 ENHANCEMENT TYPE MOSFET

Here current control in an n-channel device is now affected by positive gate to source voltage rather than the range of negative voltages of JFET's and depletion type MOSFET.

BASIC CONSTRUCTION

A slab of p-type material is formed and two n-regions are formed in the substrate. The source and drain terminals are connected through metallic contacts to n-doped regions, but the absence of a channel between the doped n-regions. The SiO_2 layer is still present to isolate the gate metallic platform from the region between drain and source, but now it is separated by a section of p-type material.

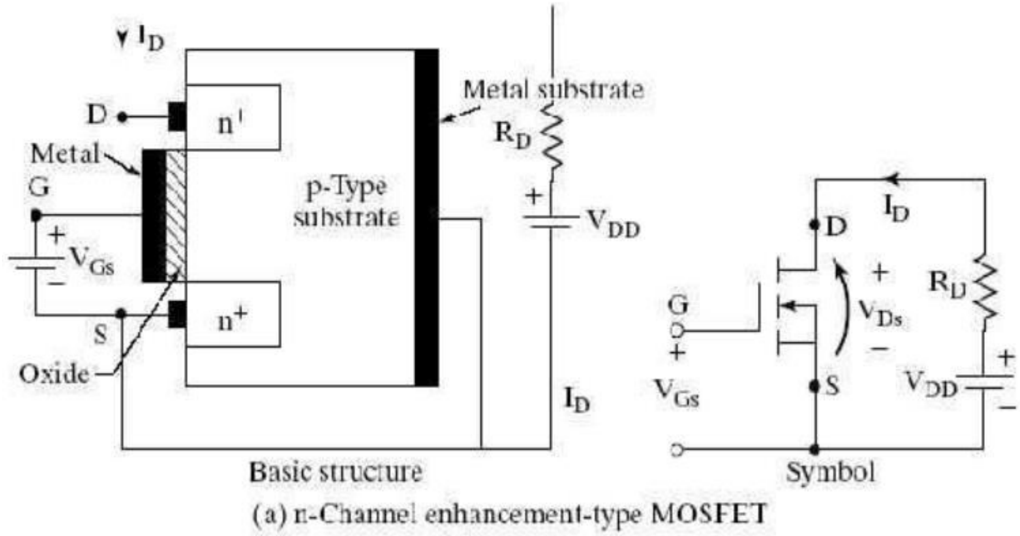


Fig. 7.1 : Structure of n-channel enhancement type MOSFET

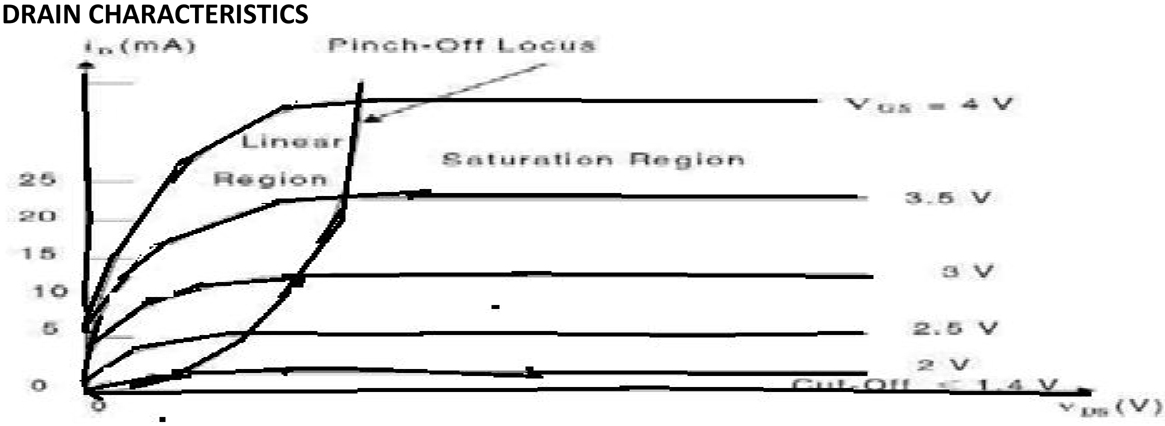
OPERATION

If *VGS V* and a voltage is applied between the drain and source, the absence of a n-channel will result in a current of effectively zero amperes. With *VDS* set at some positive voltage and *VGS* set at 0V, there are two reverse biased p-n junction between the n-doped regions and p substrate to oppose any significant flow between drain and source.

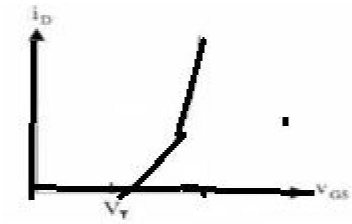
If both *VDS* and *VGS* have been set at some positive voltage, then positive potential at the gate will pressure the holes in the p-substrate along the edge of SiO_2 layer to leave the area and enter deeper region of p-substrate. However the electrons in the p-substrate will be attracted to the positive gate and accumulate in the region near the surface of the SiO_2 layer. The negative carriers will not be absorbed due to insulating SiO_2 layer, forming an inversion layer which results in current flow from drain to source.

The level of *VGS* that results in significant increase in drain current is called threshold voltage *VT* . As *VGS* increases the density of free carriers will increase resulting in increased level of drain current. If *VGS* is constant *VDS* is increased; the drain current will eventually reach a saturation level as occurred in JFET.

DRAIN CHARACTERISTICS



TRANSFER CHARACTERISTICS



8 MOSIGT OR IGBT

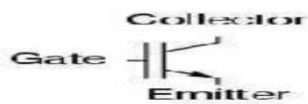


FIG: 8.1

The metal oxide semiconductor insulated gate transistor or IGBT combines the advantages of BJT's and MOSFET's. Therefore an IGBT has high input impedance like a MOSFET and low-on state power loss as in a BJT. Further IGBT is free from second breakdown problem present in BJT.

IGBT BASIC STRUCTURE AND WORKING

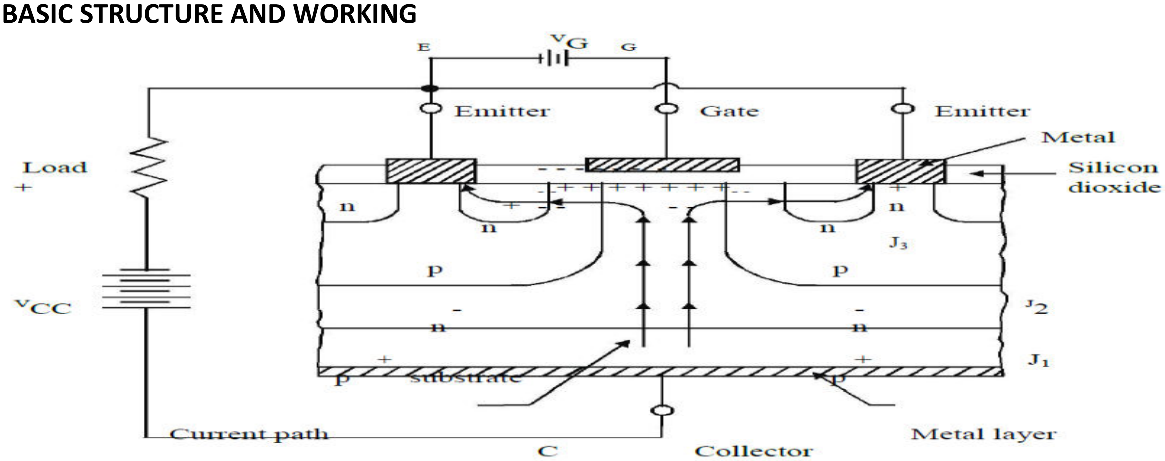


FIG: 8.2

It is constructed virtually in the same manner as a power MOSFET. However, the substrate is now a *p* layer called the collector. When gate is positive with respect to positive with respect to emitter and with gate emitter voltage greater than *VGSTH* , an n channel is formed as in case of power MOSFET.

This *n* channel short circuits the *n* region with *n* emitter regions.

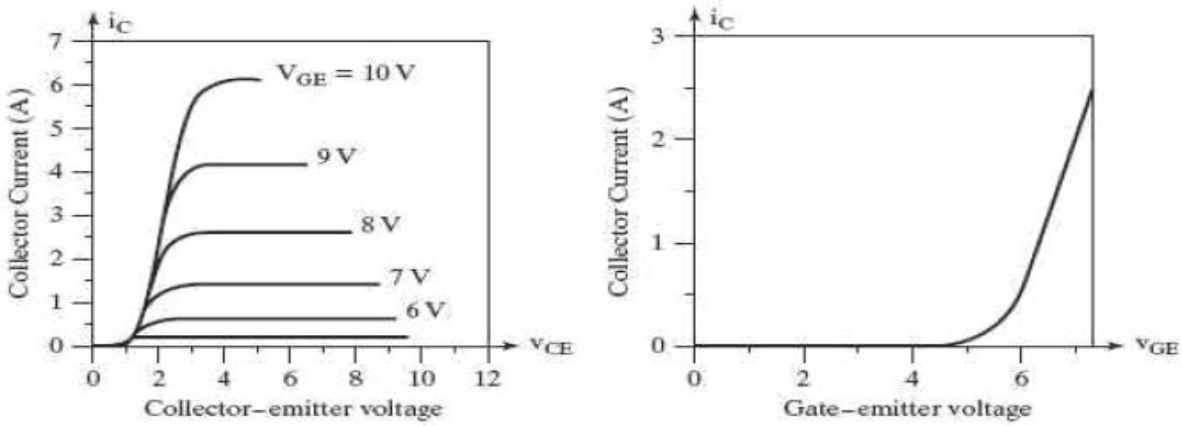
An electron movement in the *n* channel in turn causes substantial hole injection from *p* substrate layer into the epitaxially *n* layer. Eventually a forward current is established.

MOSFET is formed with input gate, emitter as source and *n* region as drain. Equivalent circuit is as shown below.

Also *p* serves as collector for PNP device and also as base for NPN transistor. The two PNP and NPN is formed as shown. is formed as shown. When gate is applied VGS *VGSth* mosfet turn on. This gives the basic drive to T1. Therefore *T*1 starts conducting. The collector of *T*1 is base of *T*2 . Therefore regenerative action takes place and large number of carriers are injected into the *n* drift region. This reduces the ON-state loss of IGBT just like BJT.

When gate drive is removed IGBT is turn-off. When gate is removed the induced channel will vanish and internal MOSFET will turn-off. Therefore *T*1 will turn-off it.*T*2 turns off.
Structure of IGBT is such that *R*1 is very small. If *R*1 small *T*1 will not conduct therefore IGBT's are different from MOSFET's since resistance of drift region reduces when gate drive is applied due to *p* injecting region. Therefore ON state IGBT is very small.

IGBT CHARACTERISTICS



STATIC CHARACTERISTICS

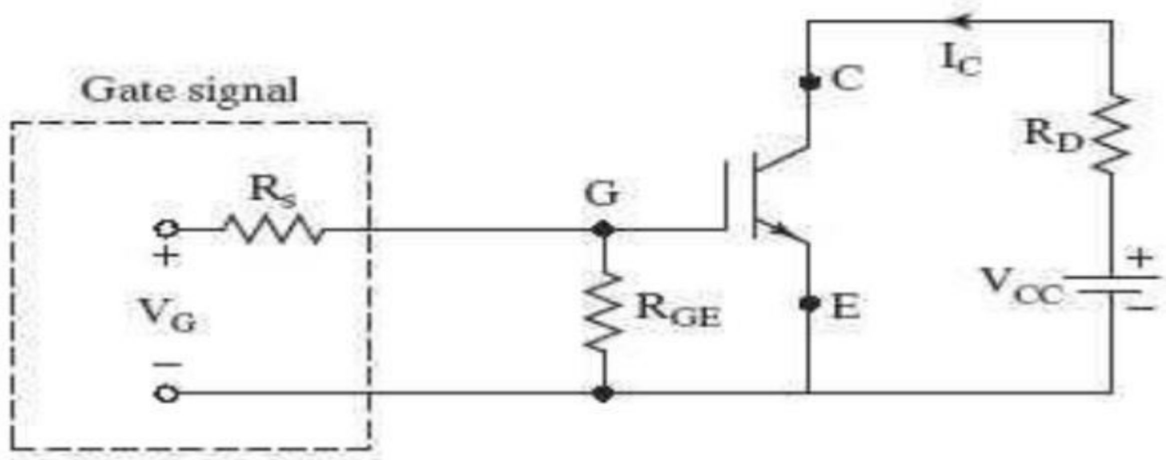


Fig 8.3: IGBT bias circuit

Static V-I characteristics (*IC* **versus** *VCE* **)** :Same as in BJT except control is by *VGE* . Therefore IGBT is a voltage controlled device.
Transfer Characteristics (*IC* **versus** *VGE* **)** :Identical to that of MOSFET. When *VGE, VGET* , IGBT is in off-state.

APPLICATIONS

Widely used in medium power applications such as DC and AC motor drives, UPS systems, Power supplies for solenoids, relays and contractors. Though IGBT's are more expensive than BJT's, they have lower gate drive requirements, lower switching losses. The ratings up to 1200V, 500A.

9 Diode Rectifier Circuits:

Diode :

Diodes allow electricity to flow in only one direction. Diodes are the electrical version of a valve and early diodes were actually called valves. The schematic symbol of a diode is shown below. The arrow of the circuit symbol shows the direction in which the current can flow. The diode has two terminals, a cathode and an anode as shown in Figure 1.

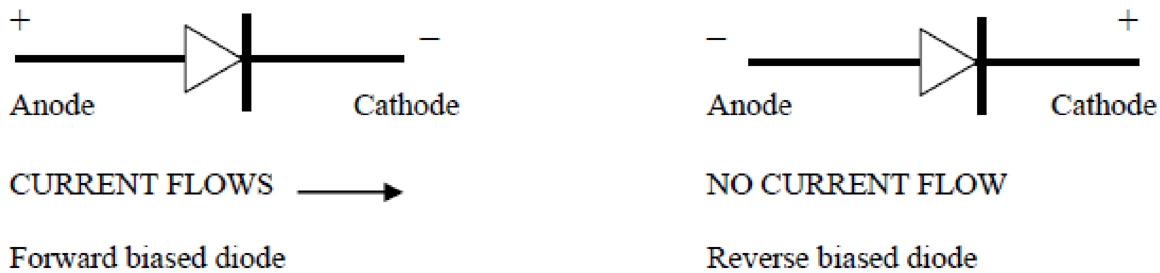


Figure 9.1: Diode operation

If a negative voltage is applied to the cathode and a positive voltage to the anode, the diode is forward biased and conducts. The diode acts nearly as a short circuit. If the polarity of the applied voltage is changed, the diode is reverse biased and does not conduct. The diode acts very much as an open circuit. Finally, if the voltage V_D is more negative than the Reverse Breakdown voltage (also called the Zener voltage, VZ), the diode conducts again, but in a reverse direction. The voltage versus current characteristics of a silicon diode is shown in Figure 2.

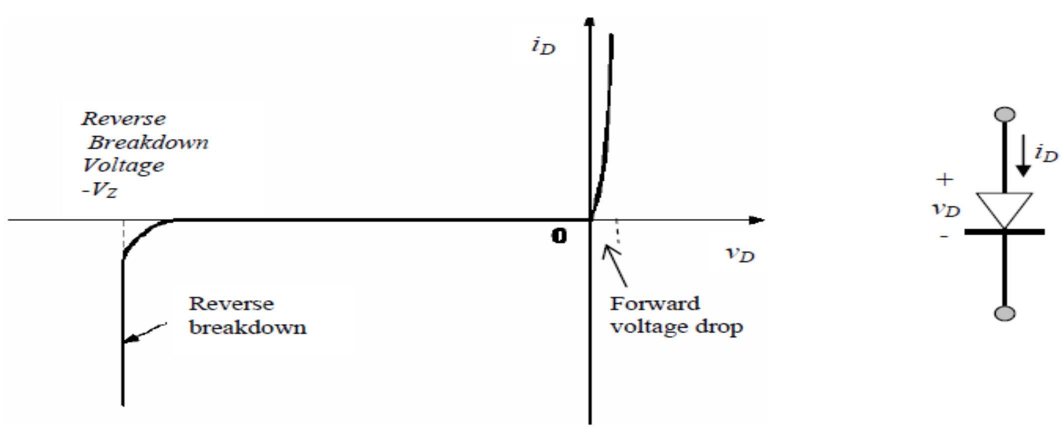


Figure 9.2: Voltage-current characteristics of a Silicon diode

Ideal Diode

For most practical applications, the operating voltage is high, and the forward voltage drop is negligible in comparison. The voltage-current characteristics of a diode (shown in figure 3) suggest that we can use the following model of an ideal diode for all practical purposes (i.e., ignoring the forward voltage drop). The ideal diode acts as a short circuit for forward currents and as an open circuit with reverse voltage applied.

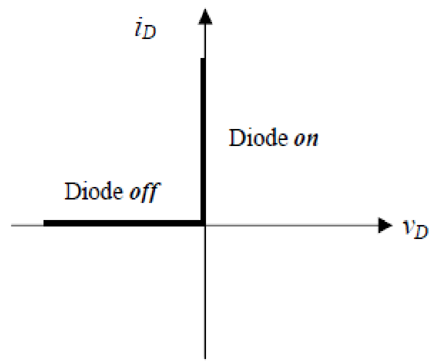


Figure 9. 3: Ideal characteristics

10 Diode Rectifier Circuits

One of the important applications of a semiconductor diode is in rectification of AC signals to DC. Diodes are very commonly used for obtaining DC voltage supplies from the readily available AC voltage.

There are many possible ways to construct rectifier circuits using diodes. The three basic types of rectifier
circuits are:

- The Half Wave Rectifier
- The Full Wave Rectifier
- The Bridge Rectifier

Half-wave Rectifier

The easiest rectifier to understand is the half wave rectifier. A simple half-wave rectifier using an ideal diode and a load is shown in Figure 9.5

Circuit operation:

Let's look at the operation of this single diode rectifier when connected across alternating voltage source *vs*.
Since the diode only conducts when the anode is positive with respect to the cathode, current will flow only during the positive half cycle of the input voltage.

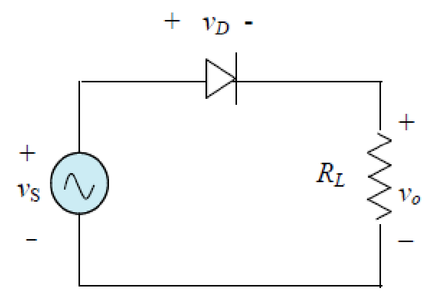


Figure 10.1: Simple half-wave rectifier circuit

During the positive half cycle of the source, the ideal diode is forward biased and operates as a closed switch. The source voltage is directly connected across the load. During the negative half cycle, the diode is reverse biased and acts as an open switch. The source voltage is disconnected from the load. As no current flows through the load, the load voltage *vo* is zero. Both the load voltage and current are of one polarity and hence said to be rectified. The waveforms for source voltage *v*S and output voltage *vo* are shown in figure9.6.

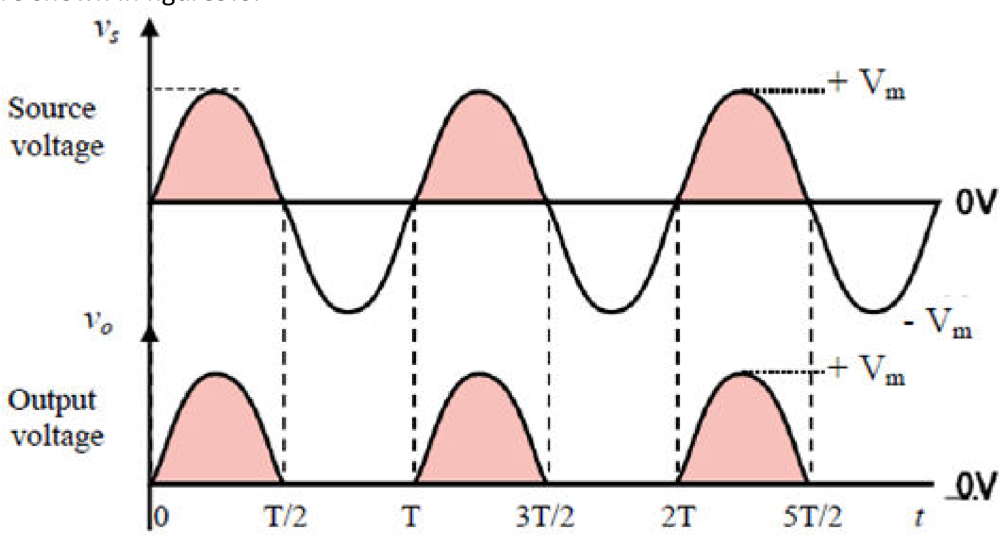


Fig 10.2 *: Source and output voltages*

We notice that the output voltage varies between the peak voltage *Vm* and zero in each cycle. This variation is called “ripple”, and the corresponding voltage is called the peak-to-peak ripple voltage, *Vp-*
The output voltage waveform and average voltage are shown in figure 10.3

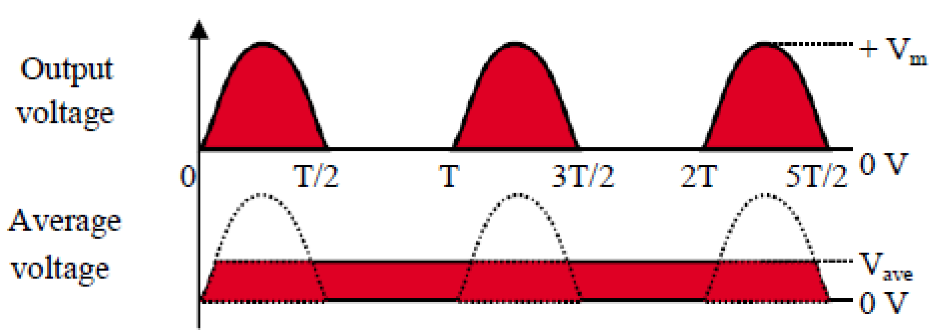


Figure10.3: Output voltage and average voltage for half-wave rectifier

The output *vo* may be viewed as a DC voltage plus a ripple voltage. As we can see, the output has a large amount of ripple.

The Full-Wave Rectifier

The full wave rectifier consists of two diodes and a resister as shown in Figure 12.

The transformer has a centre-tapped secondary winding. This secondary winding has a lead attached to the centre of the winding. The voltage from the centre tap to either end terminal on this winding is equal to one half of the total voltage measured end-to-end.

Circuit Operation

Figure 10.4 shows the operation during the positive half cycle of the full wave rectifier. Note that diode D1 is forward biased and diode D2 is reverse biased. Note the direction of the current through the load.

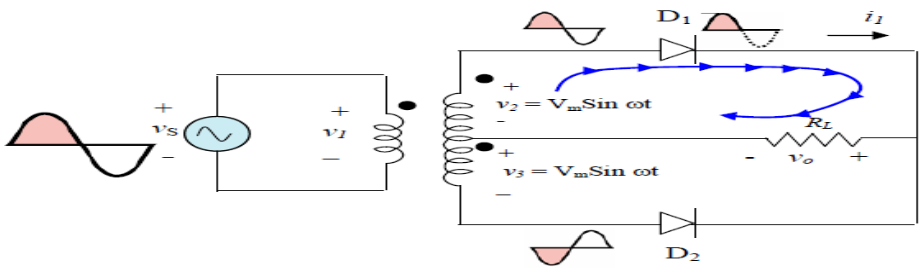


Figure 10.4 : Full-wave rectifier- Circuit operation during positive half cycle

During the negative half cycle, (figure 13) the polarity reverses. Diode D2 is forward biased and diode D1 is reverse biased. Note that the direction of current through the load has not changed even though the secondary voltage has changed polarity. Thus another positive half cycle is produced across the load.

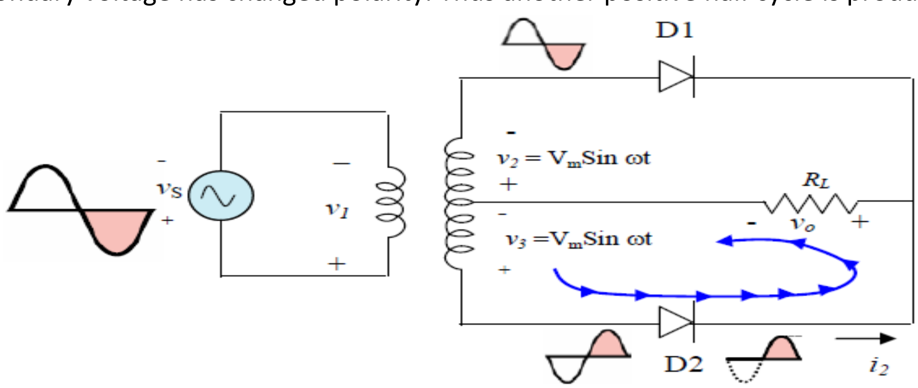


Figure 10.5: Full-wave rectifier – circuit operation during negative half cycle

Figure 10.6 below illustrates the average dc voltage for a full wave rectifier.

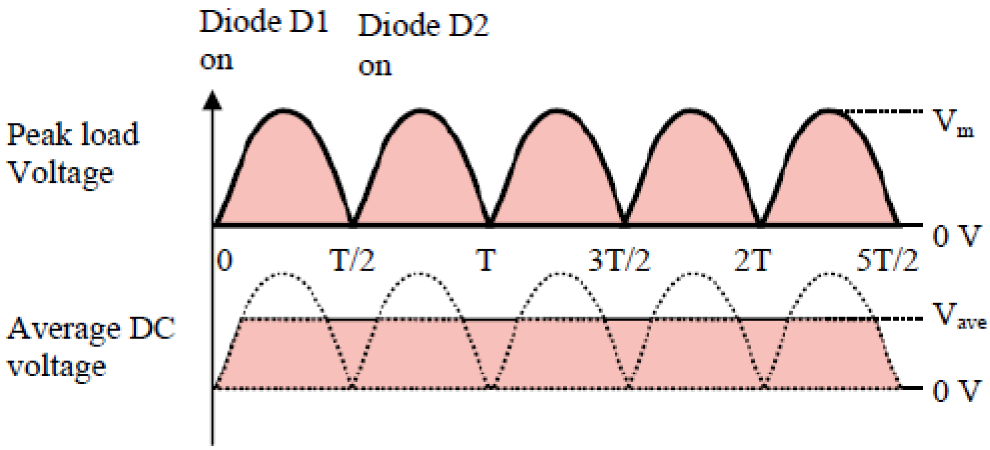


Figure 10.6: Average DC Voltage for a Full Wave Rectifier

The Full Wave Bridge Rectifier
In many power supply circuits, the bridge rectifier (Figure 17) is used. The bridge rectifier produces almost double the output voltage as a full wave center-tapped transformer rectifier using the same secondary voltage.The advantage of using this circuit is that no center-tapped transformer is required.

Basic Circuit Operation:

During the positive half cycle (Figure 10.7) , both D3 and D1 are forward biased. At the same time, both D2 andD4 are reverse biased. Note the direction of current flow through the load.During the negative half cycle (Figure 18) D2 and D4 are forward biased and D1 and D3 are reverse biased. Again note that current through the load is in the same direction although the secondary winding polarity has reversed.

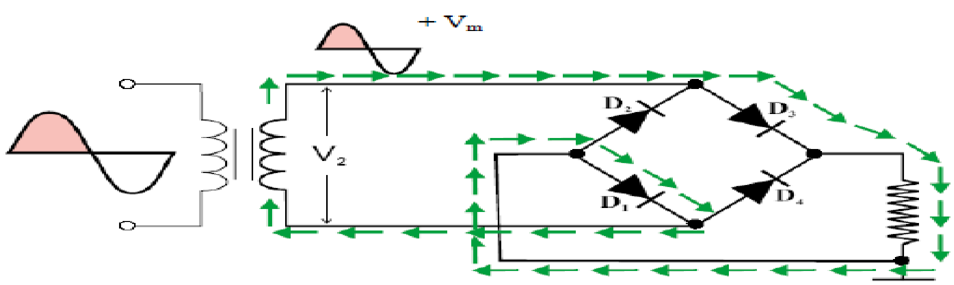


Figure 10.7: Operation during positive half cycle

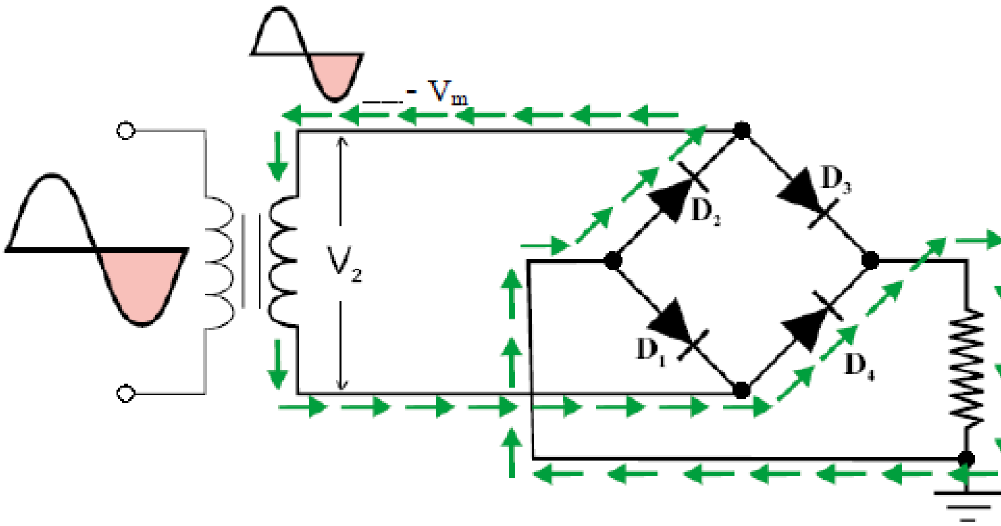


Figure 10.8: Operation during negative half cycle