Unit 6: Power Transistors

Module 22: IGBT: structure with equivalent circuit, Static and dynamic characteristics; Comparison between Power BJT, Power MOSFET and IGBT.

Introduction:

An insulated-gate bipolar transistor (IGBT) is a three-terminal power semiconductor device primarily used as an electronic switch, which, as it was developed, came to combine high efficiency and fast switching. It consists of four alternating layers (P–N–P–N) that are controlled by a metal–oxide–semiconductor (MOS) gate structure.

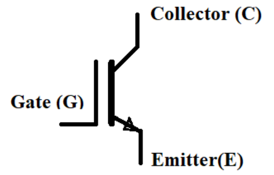
Although the structure of the IGBT is topologically the same as a thyristor with a "MOS" gate (MOS-gate thyristor), the thyristor action is completely suppressed, and only the transistor action is permitted in the entire device operation range. It is used in switching power supplies in high-power applications: variable-frequency drives (VFDs), electric cars, trains, variable-speed refrigerators, lamp ballasts, arc-welding machines, and air conditioners.

Since it is designed to turn on and off rapidly, the IGBT can synthesize complex waveforms with pulse-width modulation and low-pass filters, so it is also used in switching amplifiers in sound systems and industrial control systems. In switching applications modern devices feature pulse repetition rates well into the ultrasonic-range frequencies, which are at least ten times higher than audio frequencies handled by the device when used as an analog audio amplifier. As of 2010, the IGBT is the second most widely used power transistor, after the power MOSFET.

IGBT

IGBT stands for insulated-gate bipolar transistor. It is a bipolar transistor with an insulated gate terminal. The IGBT combines, in a single device, a control input with a MOS structure and a bipolar power transistor that acts as an output switch. IGBTs are suitable for high-voltage, high-current applications. They are designed to drive high-power applications with a low-power input.

IGBT is a three-terminal device. The three terminals are Gate (G), Emitter (E) and Collector (C). The circuit symbol of IGBT is shown below.



Construction of IGBT:

An IGBT is constructed on a p+ layer substrate. On p+ substrate, a high resistivity n- layer is epitaxially grown. As in other semi-conductor devices, the thickness of n- layer determines the voltage blocking capability of IGBT. On the other side of p+ substrate, a metal layer is deposited to form the Collector (C) terminal. Now, p regions are diffused in the epitaxially grown n- layer. Further, n+ regions are diffused in p region. A basic construction structure of IGBT is shown in figure below.

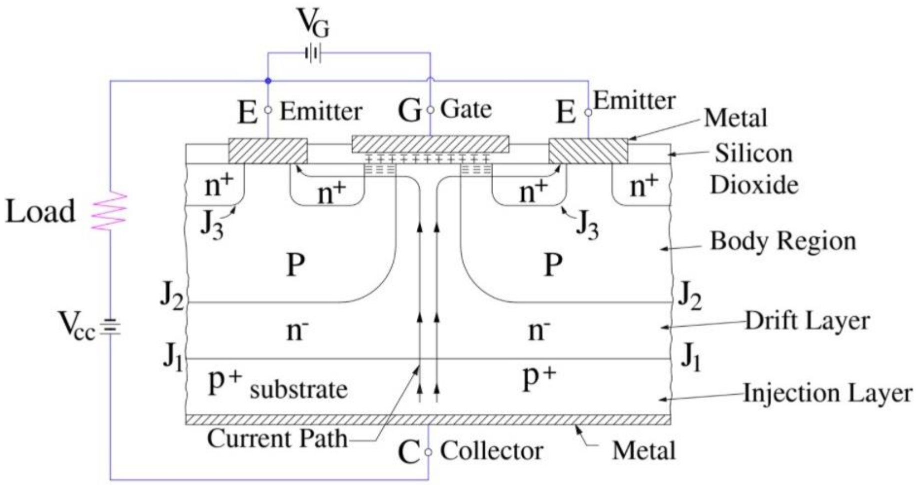


Fig 1: Construction of IGBT

Now, an insulating layer of Silicon Dioxide (SiO2) is grown on the surface. This insulating layer is etched in order to embed metallic Emitter and Gate terminals.

The p+ substrate is also called injector layer because it injects holes into n- layer. The n- layer is called drift region. The next p layer is called the body of IGBT. The n- layer in between the p+ & p region serves to accommodate the depletion layer of pn- junction i.e. J2.

Equivalent Circuit:

The approximate equivalent circuit of IGBT comprises of MOSFET and p+n-p transistor (Q1). To account for resistance offered by the n- drift region, resistance Rd has been incorporated in the circuit. This is shown below.

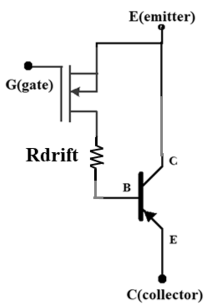
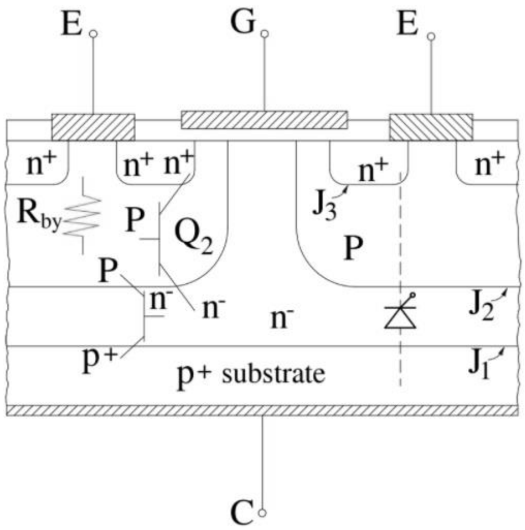
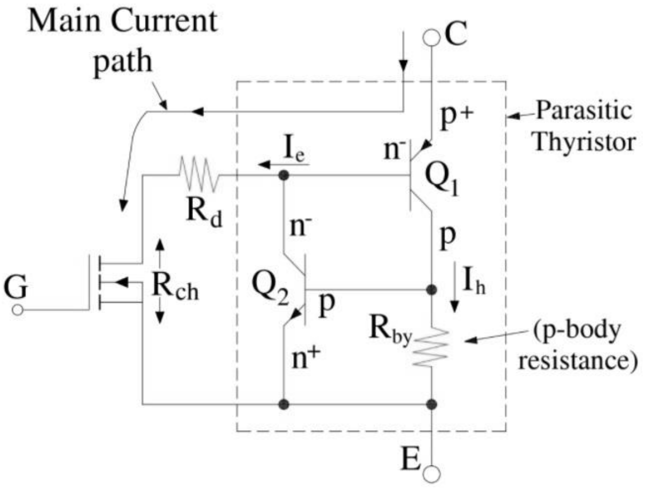


Fig 2: Approximate equivalent circuit of IGBT

The exact equivalent circuit of IGBT can be drawn by careful examination of the IGBT construction structure shown below.





R_{by} in this circuit is the resistance offered by p region to the flow of hole current.

Fig 3: Exact equivalent circuit of IGBT

Working Principle of IGBT:

The working principle of IGBT is based on the biasing of Gate to Emitter terminals and Collector to Emitter terminals. When collector is made positive with respect to emitter, IGBT gets forward biased. With no voltage between Gate and Emitter, two junctions between n-region & p region i.e., junction J_2 are reversed biased. Therefore, no current flows from collector to emitter. You may refer figure-1 for better understanding.

When Gate is made positive with respect to Emitter by some voltage V_G (this voltage should be more than the threshold voltage V_{GET} of IGBT), an n-channel is formed in the upper part of the p-region just beneath the Gate. This n-channel is called the inversion layer. This n-channel short circuits the n- region with n+ emitter region. Electrons from n+ emitter begins to flow to n- drift region through n-channel.

As IGBT is forward biased with collector positive and emitter negative, p+ collector region injects holes into n- drift region. Thus, n- drift region is flooded with electrons from p-body region and holes from p+ collector region. With this, the injection carrier density in n- drift region increases considerably and subsequently, conductivity of n- region enhances. Therefore, IGBT gets turned ON and begins to conduct forward current I_C.

Current I_C or I_E comprises of two current components:

Hole current I_h due to injection of holes from collector p+, p+ n–p transistor Q1, p-body region resistance R_{by} and emitter.

Electronic current Ie due to injected electrons flowing from collector, injection layer p+, drift region n-, n-channel resistance R_{ch}, n+ and emitter.

Therefore, the collector, or load current

$$
\begin{aligned}
I_C &= \text{Emitter Current} \\
&= I_E \\
&= I_h + I_e
\end{aligned}
$$

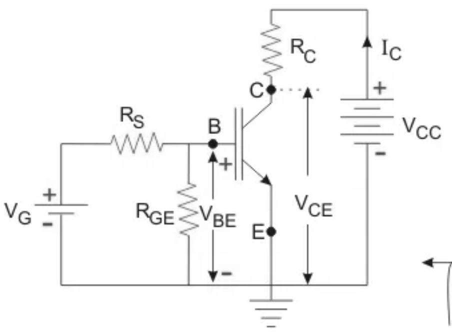
Major current of collector current is electronic current I_e i.e., main current path for collector, or load, current is through p+, n-, drift resistance R_d and n-channel resistance R_{ch}. This is shown in exact equivalent circuit.

The voltage drops in an IGBT during its ON condition consists of voltage drop in n-channel, voltage drop across drift n- region, voltage drop across forward biased p+ n- junction J_1. The voltage drop across junction J_1 is very small of the order of 0.7 to 1V. The ON state voltage drop of IGBT is very small and hence ON state losses are also low.

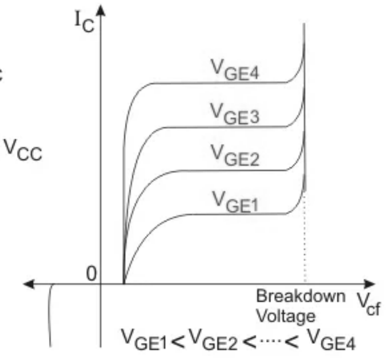
Characteristics of IGBT

Static I-V Characteristics of IGBT

The figure below shows static i-v characteristics of an n-channel IGBT along with a circuit diagram with the parameters marked.



Circuit Diagram

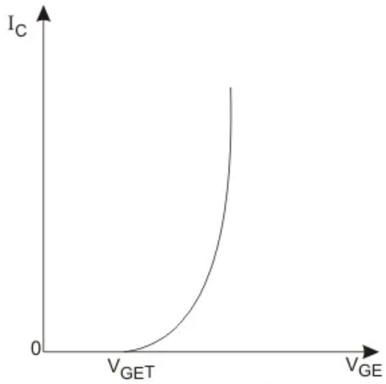


Static I - V Characteristics

The graph is similar to that of a BJT except that the parameter which is kept constant for a plot is V_{GE} because IGBT is a voltage-controlled device unlike BJT which is a current controlled device. When the device is in OFF mode (V_{CE} is positive and $V_{GE} < V_{GET}$) the reverse voltage is blocked by J_2 and when it is reverse biased, i.e., V_{CE} is negative, J_1 blocks the voltage.

Transfer Characteristics of IGBT

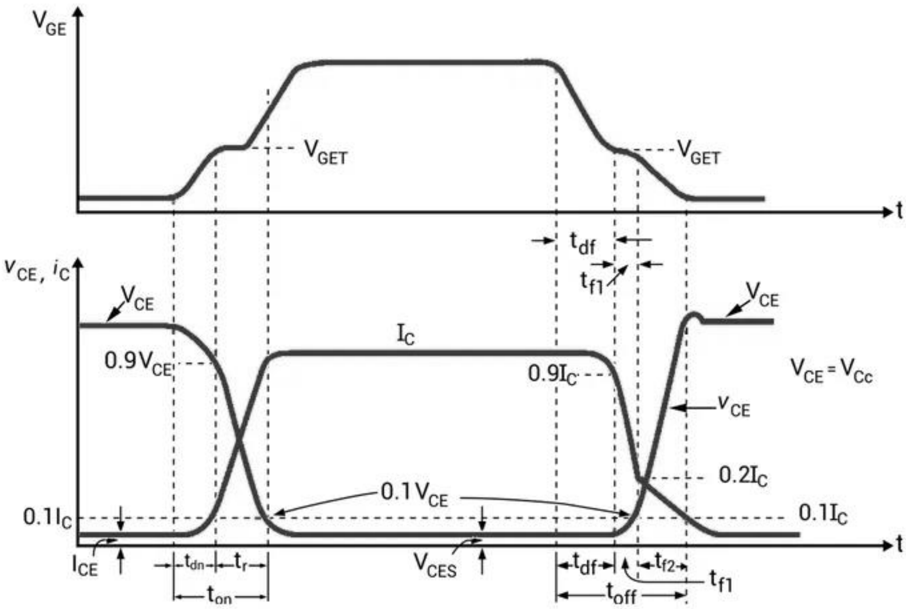
Figure below shows the transfer characteristic of IGBT, which is exactly same as P- type MOSFET. The IGBT is in ON-state only after V_{GE} is greater than a threshold value V_{GET}.



Transfer Characteristics

Switching Characteristics of IGBT

The figure below shows the typical switching characteristic of IGBT.



Typical Switching Characteristic of IGBT

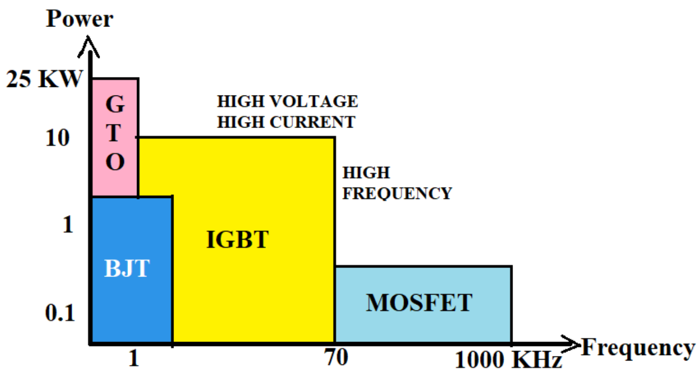
Turn on time t_{on} is composed of two components as usual, delay time (t_{dn}) and rise time (t_r). Delay time is defined as the time in which collector current rises from leakage current I_{CE} to 0.1 I_C (final collector current) and collector emitter voltage falls from V_{CE} to $0.9V_{CE}$. Rise time is defined as the time in which collector current rises from 0.1 I_C to I_C and collector emitter voltage falls from $0.9V_{CE}$ to 0.1 V_{CE}.

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

The turn off time t_{off} consists of three components, delay time (t_{df}), initial fall time (t_{f1}) and final fall time (t_{f2}). Delay time is defined as time when collector current falls from I_C to 0.9 I_C and V_{CE} begins to rise. Initial fall time is the time during which collector current falls from 0.9 I_C to 0.2 I_C and collector emitter voltage rises to 0.1 V_{CE}. The final fall time is defined as time during which collector current falls from 0.2 I_C to 0.1 I_C and $0.1V_{CE}$ rises to final value V_{CE}.

$$t_{off} = t_{df} + t_{f1} + t_{f2}$$

IGBT – OPERATION AREAS



Applications of IGBT

- SMPS(switch mode power supply).
- UPS(uninterrupted power supply).
- Power control circuits like inverters, choppers, etc.
- Inductive heating applications.
- Audio amplifiers in speakers.
- Motor drives in locomotives.
- IGBT are best alternative as power transistors in medium switching applications.

Advantages and Disadvantages of IGBT

Advantages:

- Lower gate drive requirements
- Low switching losses
- Small snubber circuitry requirements
- High input impedance
- Voltage controlled device
- Temperature coefficient of ON state resistance is positive and less than PMOSFET, hence less On-state voltage drop and power loss.
- Enhanced conduction due to bipolar nature
- Better Safe Operating Area

Disadvantages:

- Cost
- Latching-up problem
- High turn off time compared to PMOSFET

Comparison between Power BJT, Power MOSFET and IGBT

IGBT comparison table

Device characteristic	Power bipolar	Power MOSFET	IGBT
Voltage rating	High <1 kV	High <1 kV	Very high >1 kV
Current rating	High <500 A	High >500 A	High >500 A
Input drive	Current ratio h_{FE} ~ 20–200	Voltage V_{GS} ~ 3–10 V	Voltage V_{GE} ~ 4–8 V
Input impedance	Low	High	High
Output impedance	Low	Medium	Low
Switching speed	Slow (μs)	Fast (ns)	Medium
Cost	Low	Medium	High