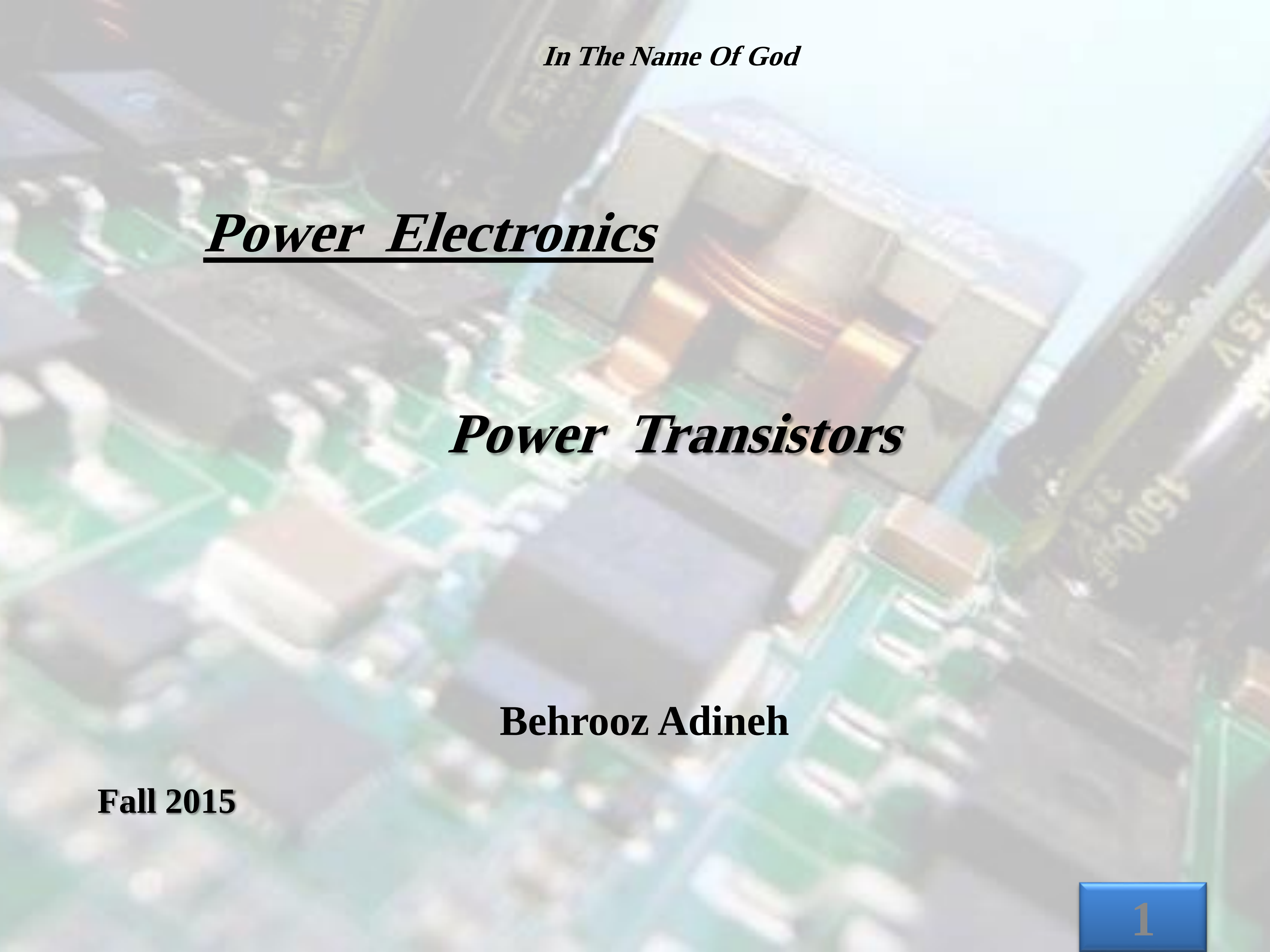


In The Name Of God

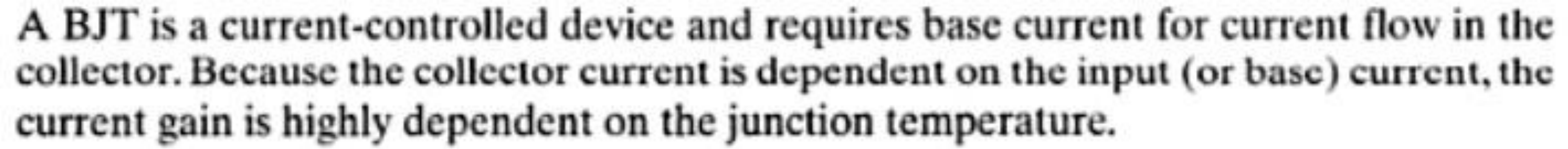
Power Electronics

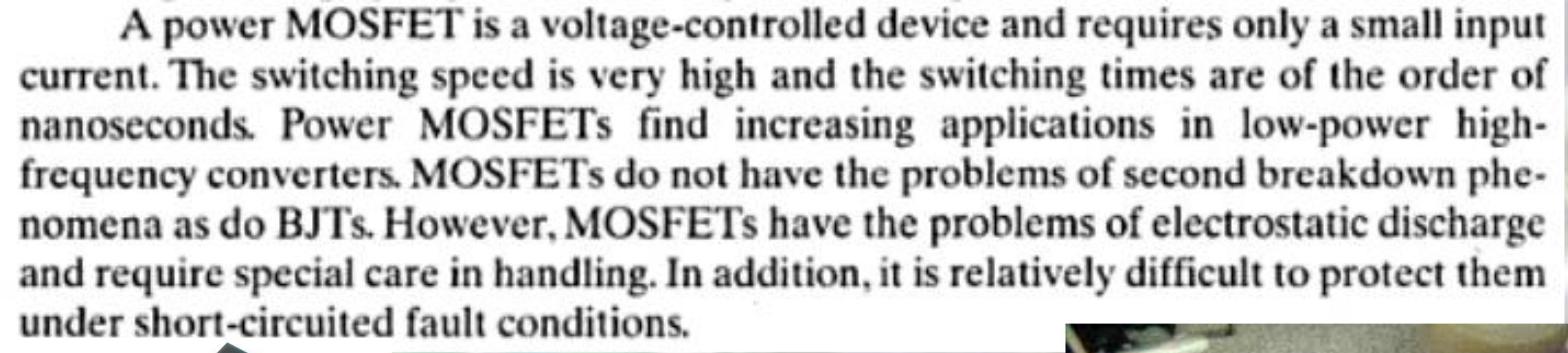
Power Transistors

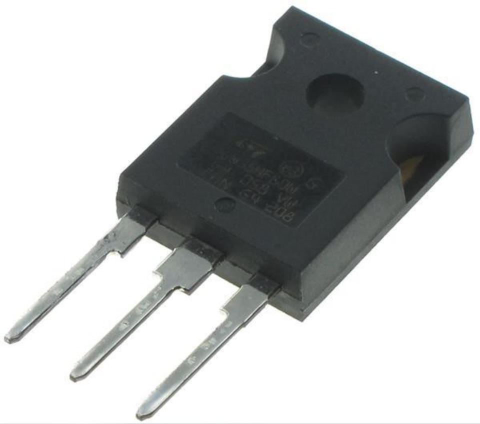
Behrooz Adineh

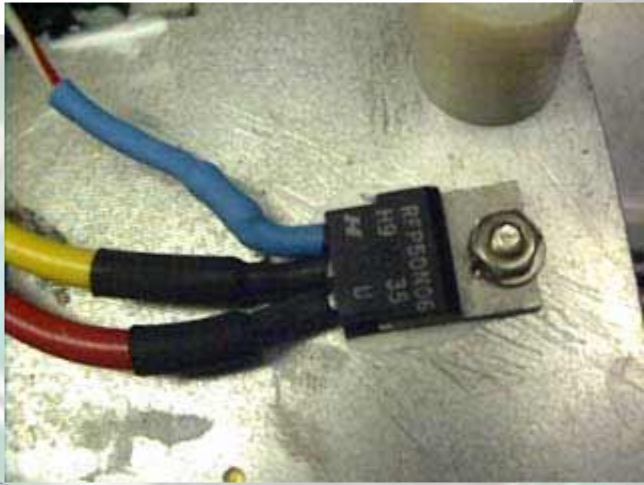
Fall 2015

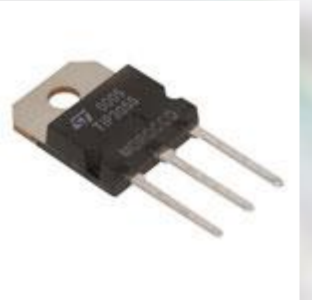
Power MOSFETs

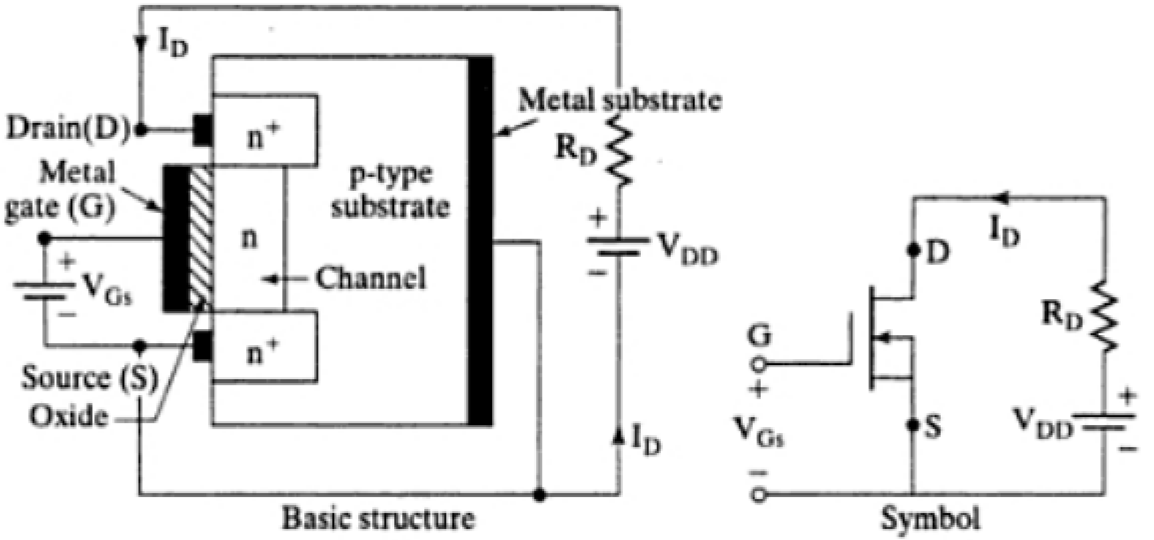

A BJT is a current-controlled device and requires base current for current flow in the collector. Because the collector current is dependent on the input (or base) current, the current gain is highly dependent on the junction temperature.


A power MOSFET is a voltage-controlled device and requires only a small input current. The switching speed is very high and the switching times are of the order of nanoseconds. Power MOSFETs find increasing applications in low-power high-frequency converters. MOSFETs do not have the problems of second breakdown phenomena as do BJTs. However, MOSFETs have the problems of electrostatic discharge and require special care in handling. In addition, it is relatively difficult to protect them under short-circuited fault conditions.





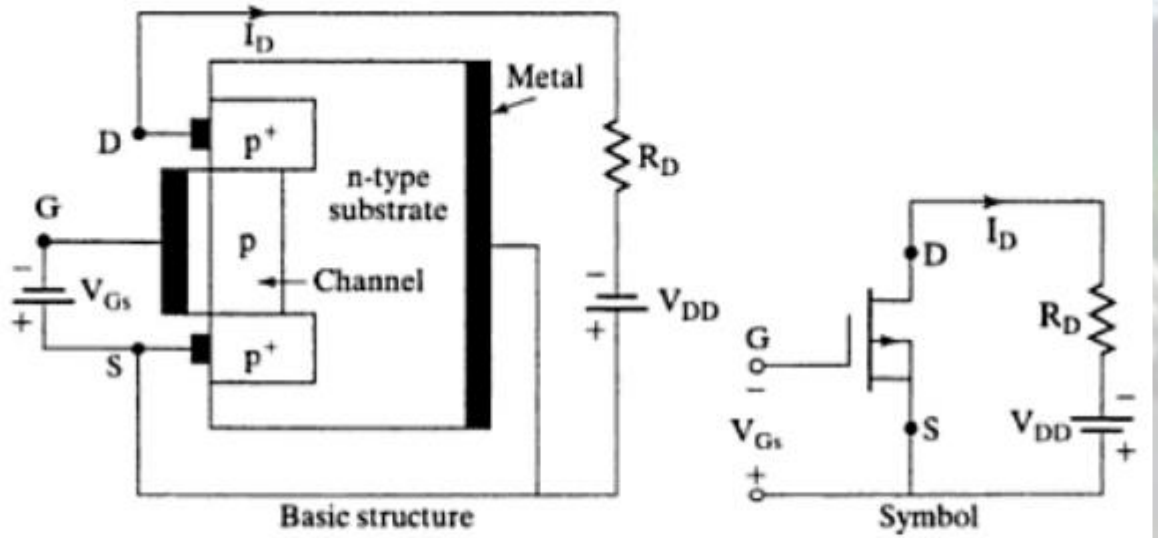




Basic structure

Symbol

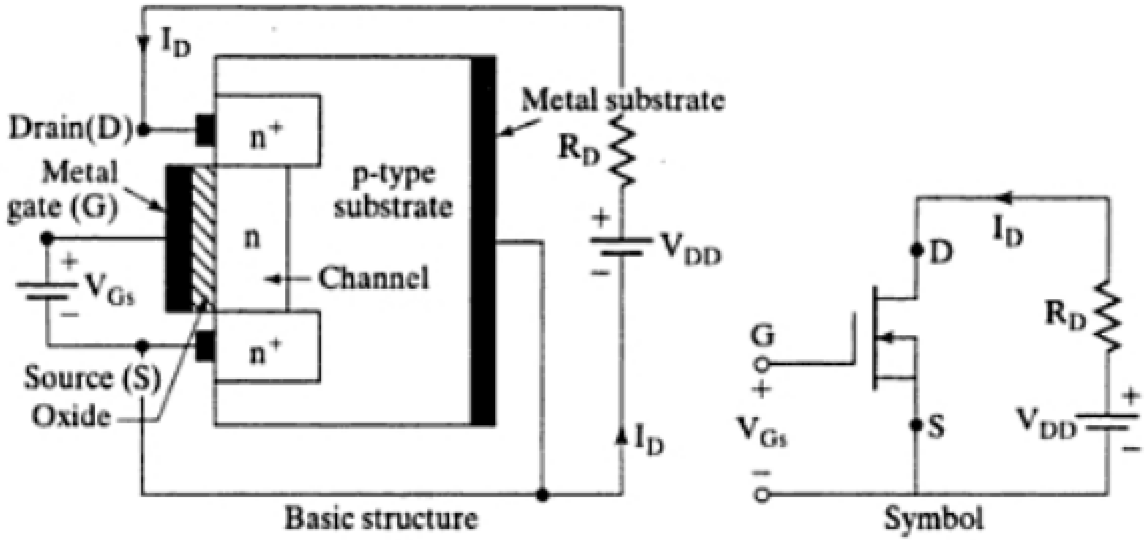
(a) n-Channel depletion-type MOSFET



Basic structure

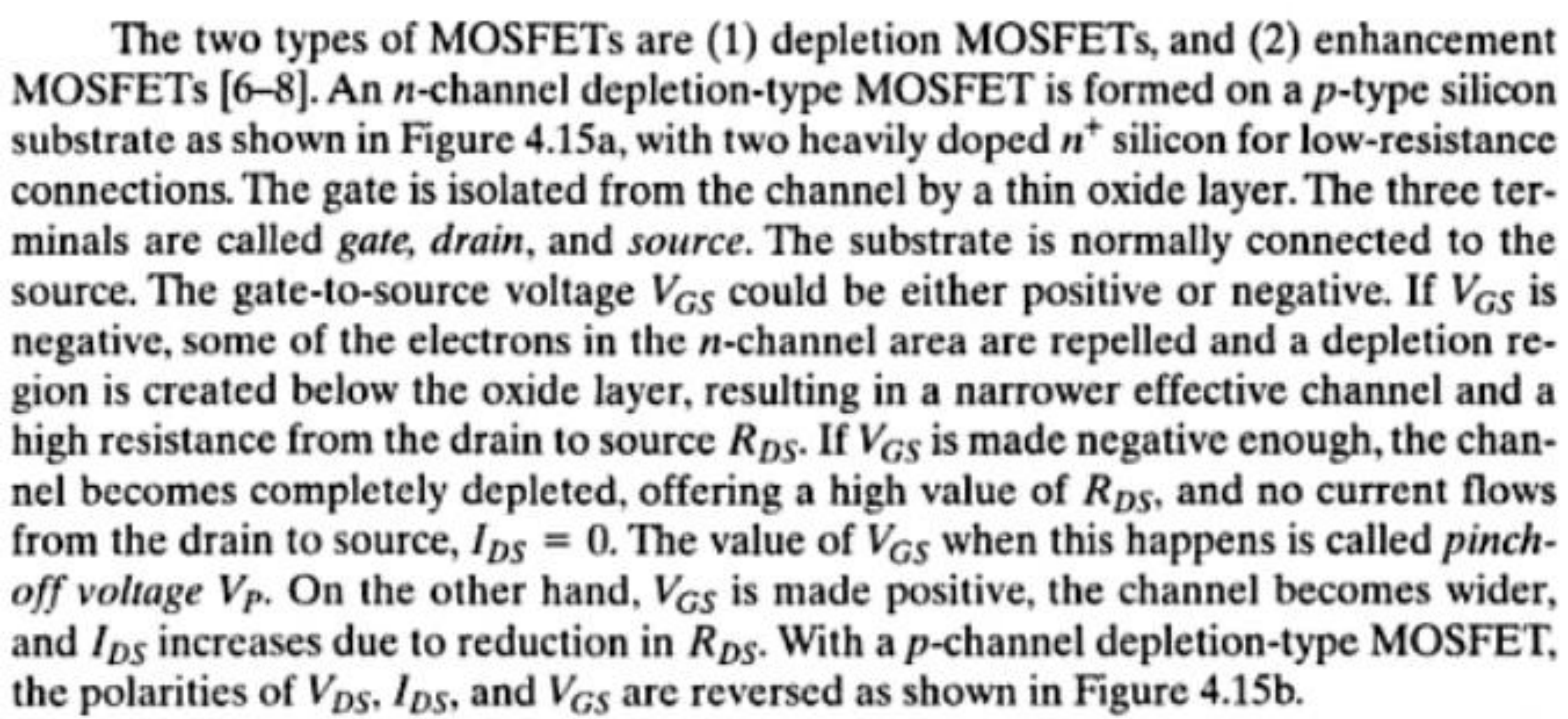
Symbol

(b) p-Channel depletion-type MOSFET

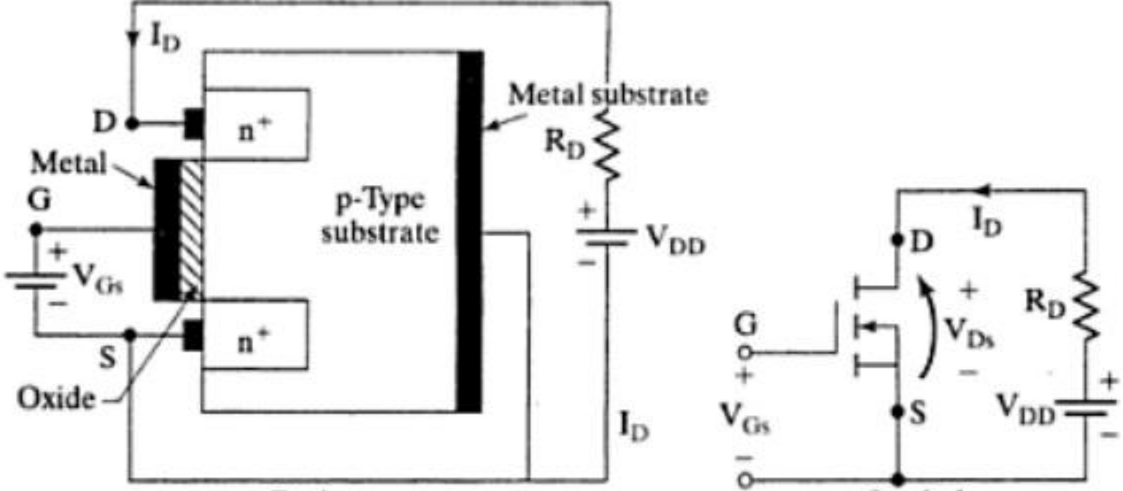


Basic structure Symbol

(a) n-Channel depletion-type MOSFET



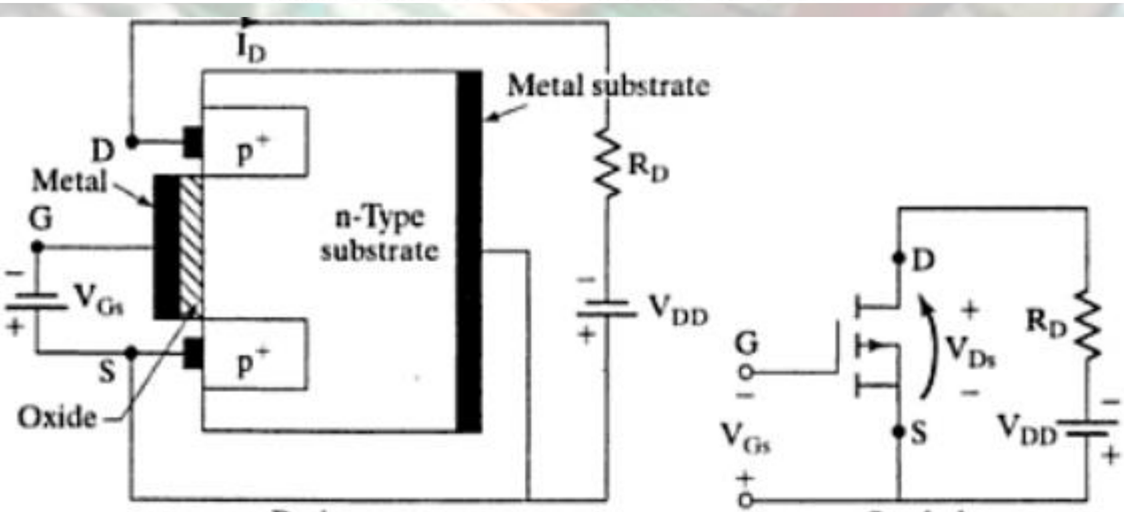
The two types of MOSFETs are (1) depletion MOSFETs, and (2) enhancement MOSFETs [6–8]. An *n*-channel depletion-type MOSFET is formed on a *p*-type silicon substrate as shown in Figure 4.15a, with two heavily doped n^+ silicon for low-resistance connections. The gate is isolated from the channel by a thin oxide layer. The three terminals are called *gate, drain*, and *source*. The substrate is normally connected to the source. The gate-to-source voltage V_{GS} could be either positive or negative. If V_{GS} is negative, some of the electrons in the *n*-channel area are repelled and a depletion region is created below the oxide layer, resulting in a narrower effective channel and a high resistance from the drain to source R_{DS}. If V_{GS} is made negative enough, the channel becomes completely depleted, offering a high value of R_{DS}, and no current flows from the drain to source, $I_{DS} = 0$. The value of V_{GS} when this happens is called *pinch-off voltage* V_P. On the other hand, V_{GS} is made positive, the channel becomes wider, and I_{DS} increases due to reduction in R_{DS}. With a *p*-channel depletion-type MOSFET, the polarities of V_{DS}, I_{DS}, and V_{GS} are reversed as shown in Figure 4.15b.



Basic structure

Symbol

(a) n-Channel enhancement-type MOSFET

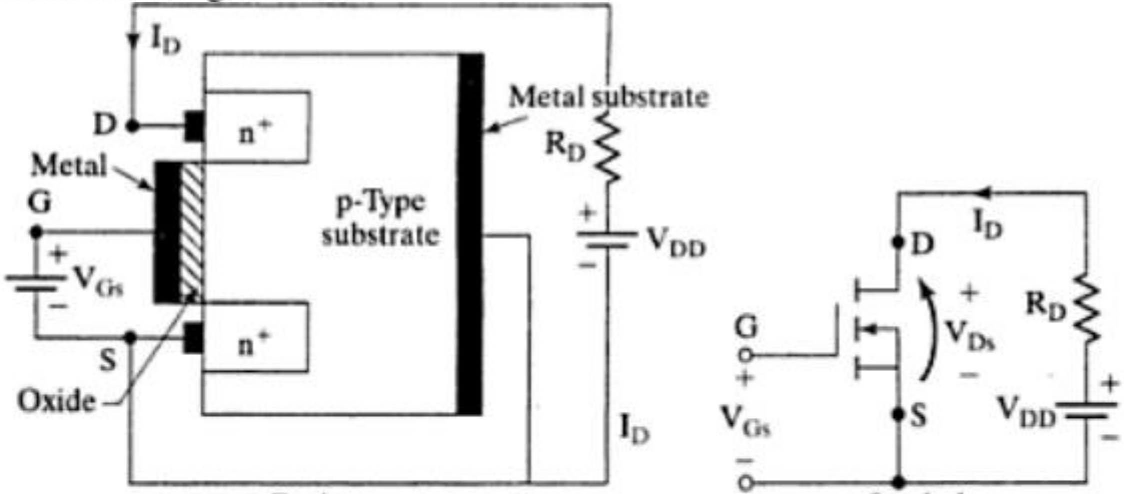


Basic structure

Symbol

(b) p-Channel enhancement-type MOSFET

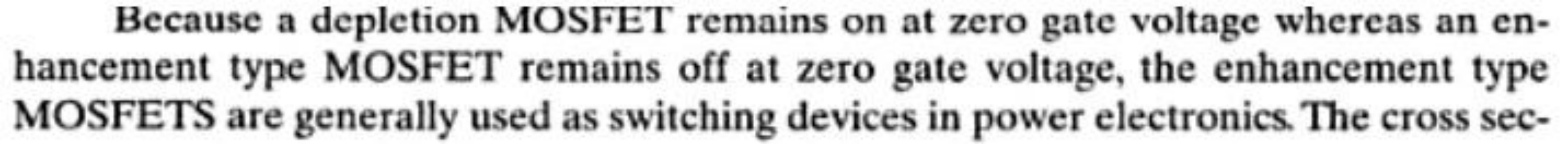
An n-channel enhancement-type MOSFET has no physical channel, as shown in Figure 4.16a. If V_{GS} is positive, an induced voltage attracts the electrons from the p-substrate and accumulate them at the surface beneath the oxide layer. If V_{GS} is greater than or equal to a value known as *threshold voltage* V_T, a sufficient number of electrons are accumulated to form a virtual n-channel and the current flows from the drain to source. The polarities of V_{DS}, I_{DS}, and V_{GS} are reversed for a p-channel enhancement-type MOSFET as shown in Figure 4.16b. Power MOSFETs of various sizes are shown in Figure 4.17.



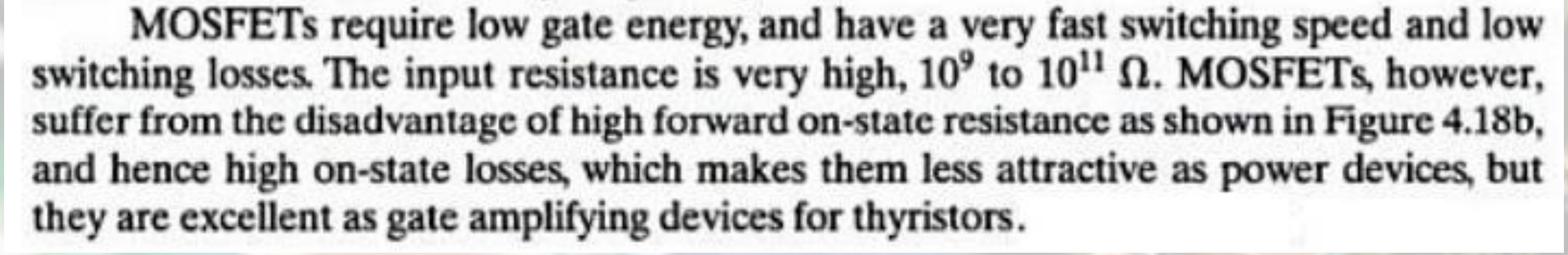
Basic structure

Symbol

(a) n-Channel enhancement-type MOSFET

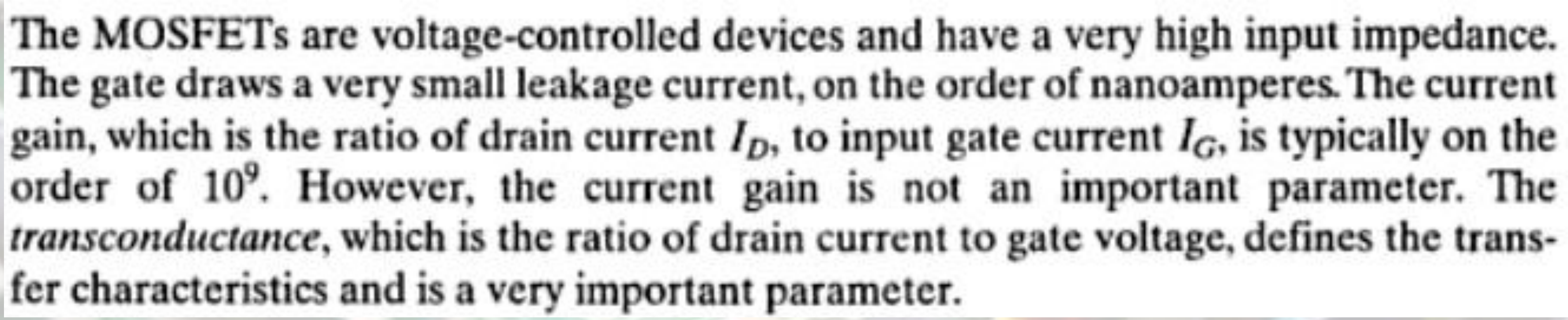


Because a depletion MOSFET remains on at zero gate voltage whereas an enhancement type MOSFET remains off at zero gate voltage, the enhancement type MOSFETS are generally used as switching devices in power electronics. The cross sec-

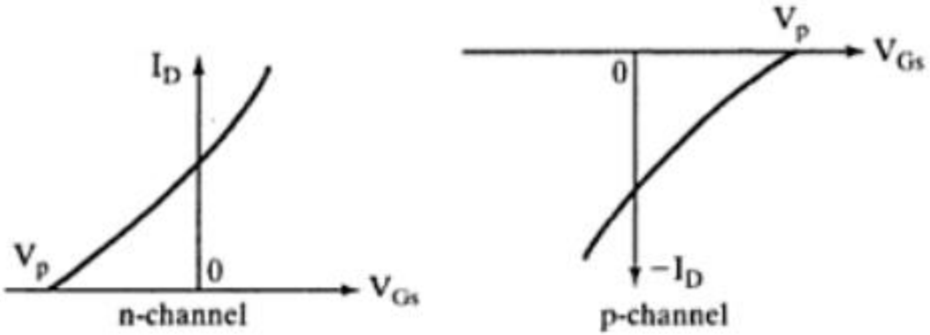


MOSFETs require low gate energy, and have a very fast switching speed and low switching losses. The input resistance is very high, 10^9 to 10^{11} Ω. MOSFETs, however, suffer from the disadvantage of high forward on-state resistance as shown in Figure 4.18b, and hence high on-state losses, which makes them less attractive as power devices, but they are excellent as gate amplifying devices for thyristors.

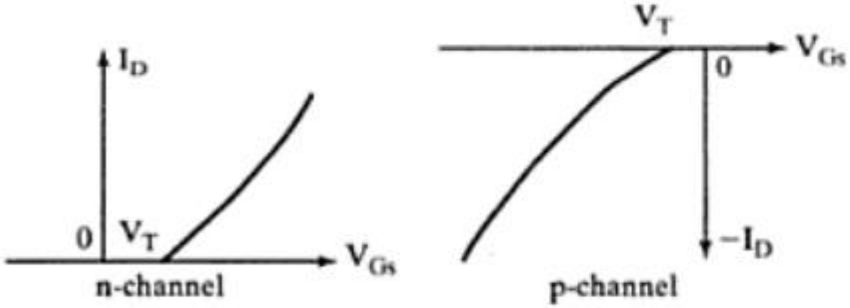
Steady- State Characteristics



The MOSFETs are voltage-controlled devices and have a very high input impedance. The gate draws a very small leakage current, on the order of nanoamperes. The current gain, which is the ratio of drain current I_D, to input gate current I_G, is typically on the order of 10^9. However, the current gain is not an important parameter. The *transconductance*, which is the ratio of drain current to gate voltage, defines the transfer characteristics and is a very important parameter.



(a) Depletion-type MOSFET

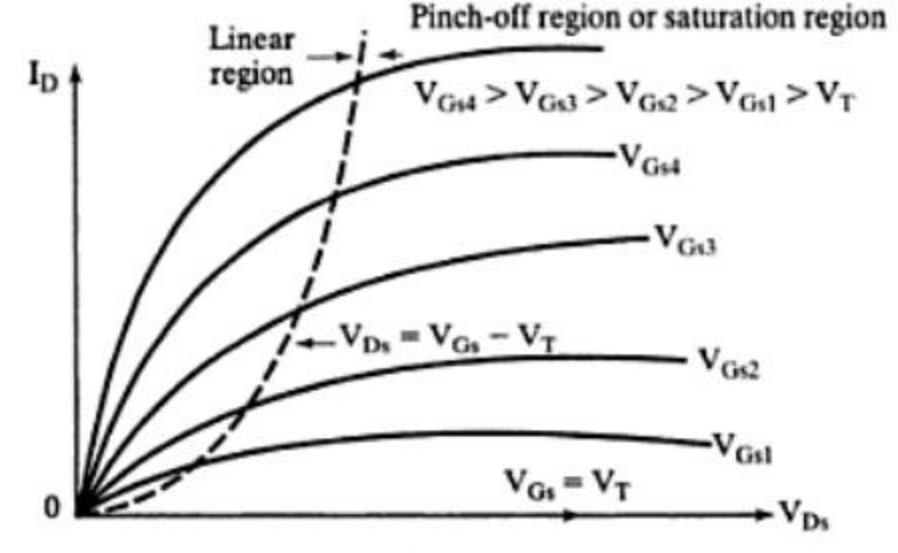


(b) Enhancement-type MOSFET

Transfer characteristics of MOSFETs.

There are three regions of operation: (1) cutoff region, where $V_{GS} \leq V_T$; (2) pinch-off or saturation region, where $V_{DS} \geq V_{GS} - V_T$; and (3) linear region, where $V_{DS} \leq V_{GS} - V_T$. The pinch-off occurs at $V_{DS} = V_{GS} - V_T$. In the linear region, the drain current I_D varies in proportion to the drain–source voltage V_{DS}. Due to high drain current and low drain voltage, the power MOSFETs are operated in the linear region for switching actions. In the saturation region, the drain current remains almost constant for any increase in the value of V_{DS} and the transistors are used in this region for voltage amplification. It should be noted that saturation has the opposite meaning to that for bipolar transistors.

$$g_m = \left.\frac{\Delta I_D}{\Delta V_{GS}}\right|_{V_{DS}=\text{constant}}$$



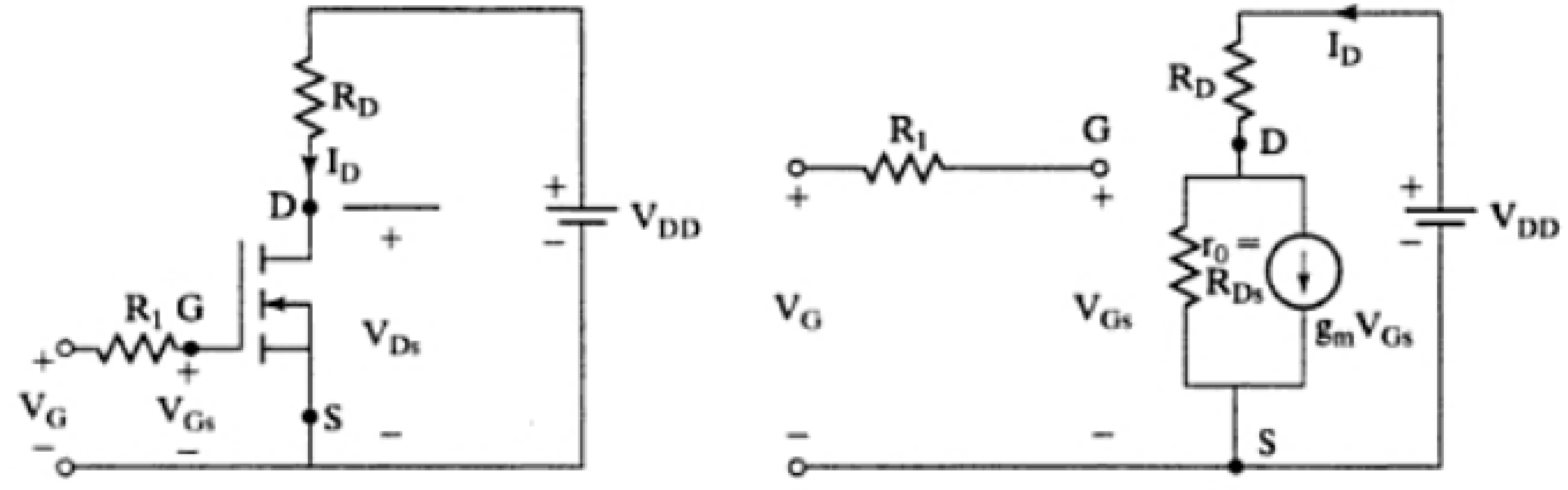
Output characteristics of enhancement-type MOSFET.

The output resistance, $r_o = R_{DS}$, which is defined as

$$R_{DS} = \frac{\Delta V_{DS}}{\Delta I_D}$$

is normally very high in the pinch-off region, typically on the order of megohms and is very small in the linear region, typically on the order of milliohms.

For the depletion-type MOSFETs, the gate (or input) voltage could be either positive or negative. However, the enhancement-type MOSFETs respond to a positive gate voltage only. The power MOSFETs are generally of the enhancement type. However, depletion-type MOSFETs would be advantageous and simplify the logic design in some applications that require some form of logic-compatible dc or ac switch that would remain on when the logic supply falls and V_{GS} becomes zero. The characteristics of depletion-type MOSFETs are not discussed further.



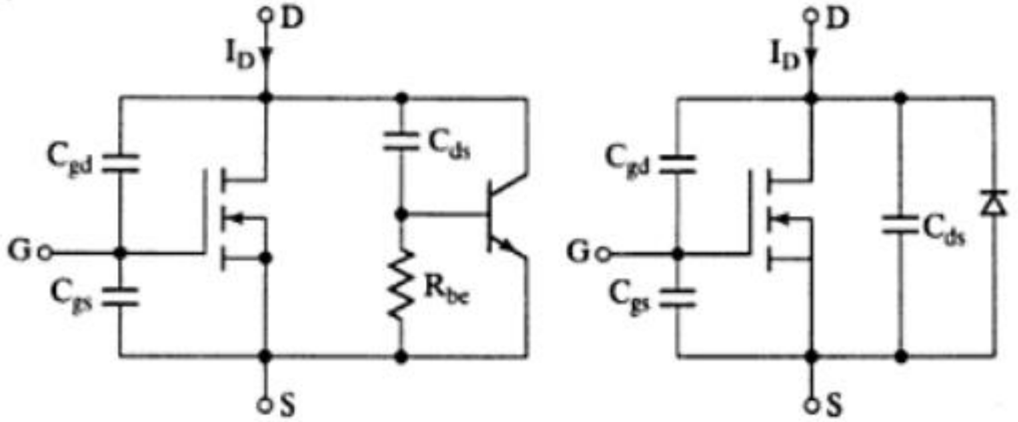
(a) Circuit diagram

(b) Equivalent circuit

Steady-state switching model of MOSFETs.

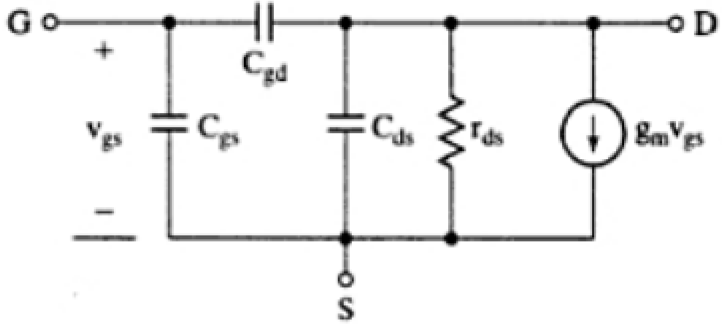
Switching Characteristics

Without any gate signal, an enhancement-type MOSFET may be considered as two diodes connected back to back or as an *NPN*-transistor. The gate structure has parasitic capacitances to the source, C_{gs}, and to the drain, C_{gd}. The *npn*-transistor has a reverse-bias junction from the drain to the source and offers a capacitance, C_{ds}.

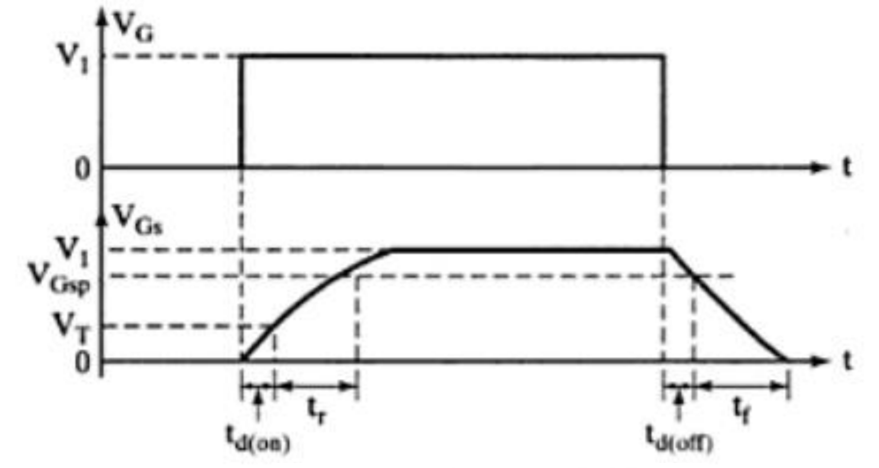


(a) Parasitic biploar (b) Internal diode

Parasitic model of enhancement of MOSFETs.



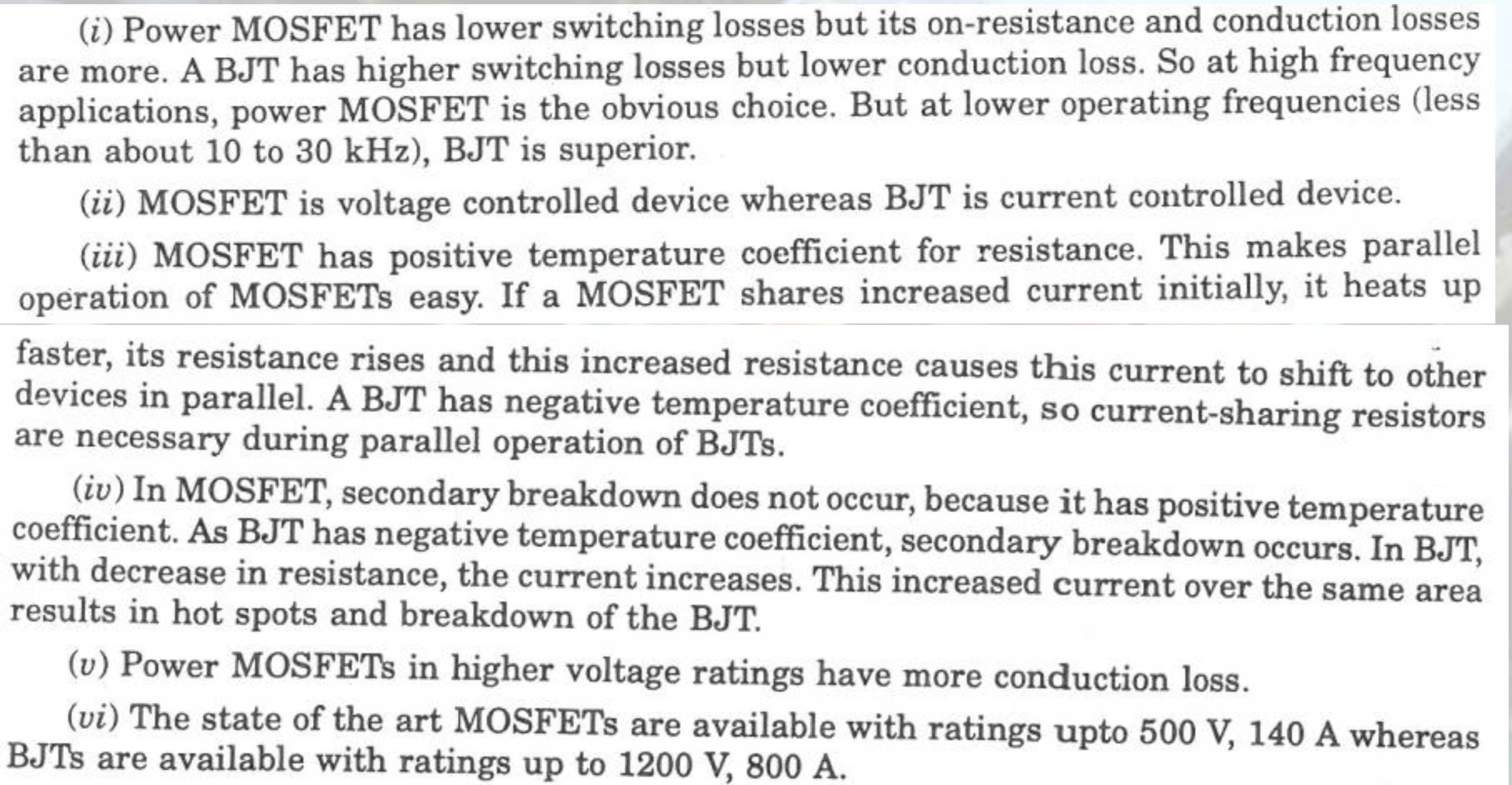
Switching model of MOSFETs.



Switching waveforms and times.

The *turn-on delay* $t_{d(on)}$ is the time that is required to charge the input capacitance to threshold voltage level. The *rise time* t_r is the gate-charging time from the threshold level to the full-gate voltage V_{GSP}, which is required to drive the transistor into the linear region. The *turn-off delay time* $t_{d(off)}$ is the time required for the input capacitance to discharge from the overdrive gate voltage V_1 to the pinch-off region. V_{GS} must decrease significantly before V_{DS} begins to rise. The *fall time* t_f is the time that is required for the input capacitance to discharge from the pinch-off region to threshold voltage. If $V_{GS} \le V_T$, the transistor turns off.

Comparison of MOSFET with BJT



(*i*) Power 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, power MOSFET is the obvious choice. But at lower operating frequencies (less than about 10 to 30 kHz), BJT is superior.

(*ii*) MOSFET is voltage controlled device whereas BJT is current controlled device.

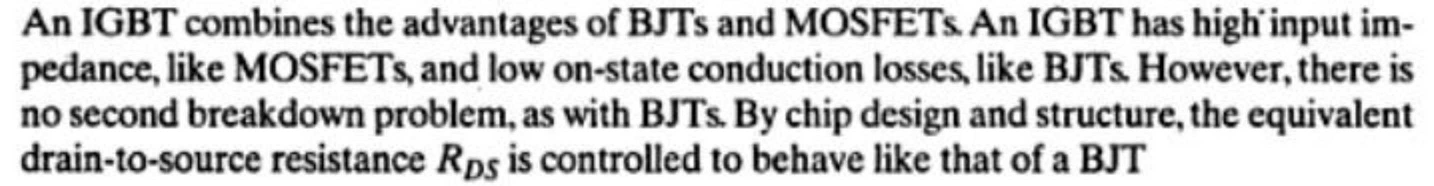
(*iii*) MOSFET has positive temperature coefficient for resistance. This makes parallel operation of MOSFETs easy. If a MOSFET shares increased current initially, it heats up faster, its resistance rises and this increased resistance causes this current to shift to other devices in parallel. A BJT has negative temperature coefficient, so current-sharing resistors are necessary during parallel operation of BJTs.

(*iv*) In MOSFET, secondary breakdown does not occur, because it has positive temperature coefficient. As BJT has negative temperature coefficient, secondary breakdown occurs. In BJT, with decrease in resistance, the current increases. This increased current over the same area results in hot spots and breakdown of the BJT.

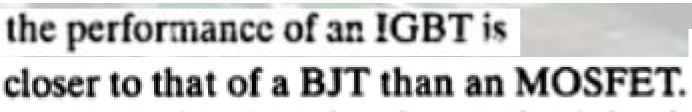
(*v*) Power MOSFETs in higher voltage ratings have more conduction loss.

(*vi*) The state of the art MOSFETs are available with ratings upto 500 V, 140 A whereas BJTs are available with ratings up to 1200 V, 800 A.

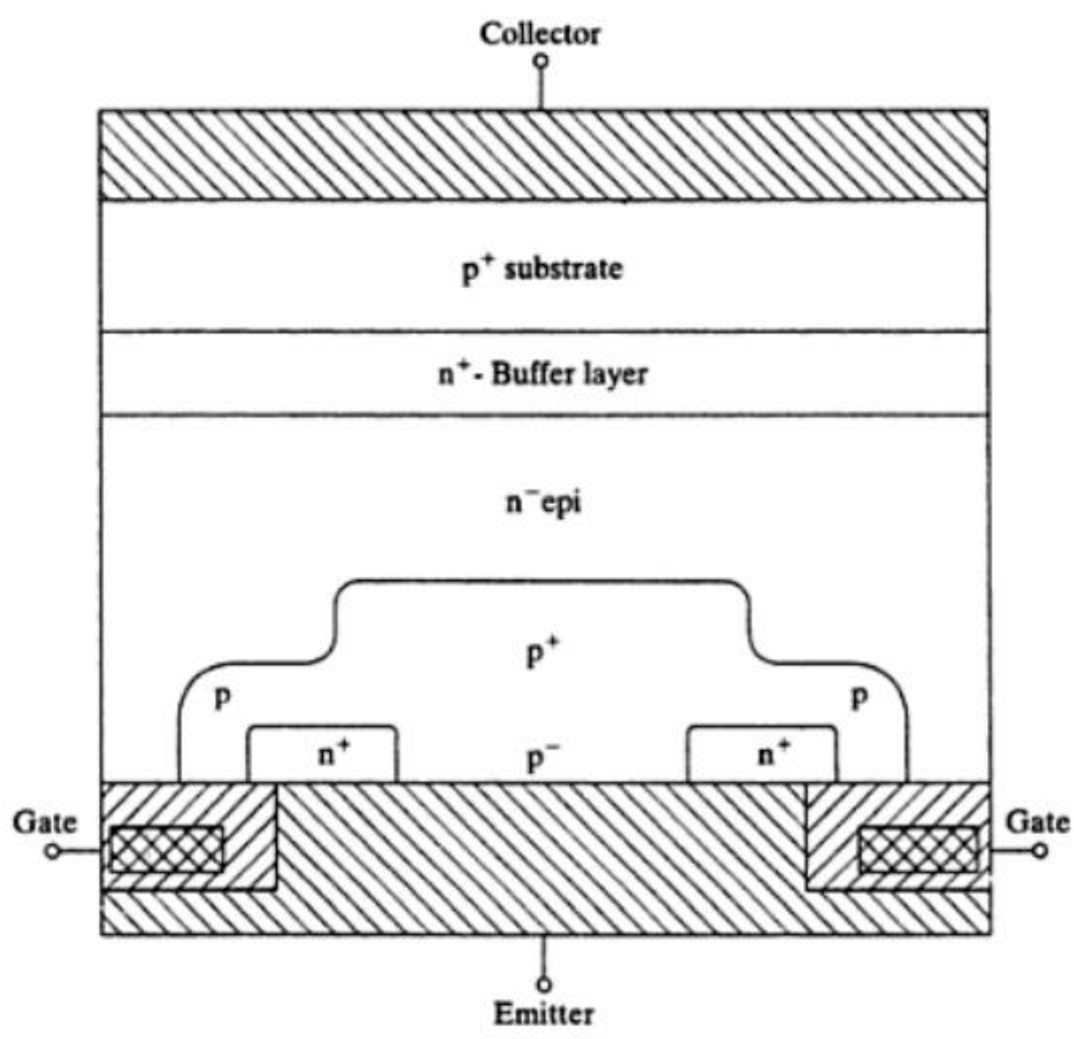
Insulated Gate Bipolar Transistor (IGBT)



An IGBT combines the advantages of BJTs and MOSFETs. An IGBT has high input impedance, like MOSFETs, and low on-state conduction losses, like BJTs. However, there is no second breakdown problem, as with BJTs. By chip design and structure, the equivalent drain-to-source resistance R_{DS} is controlled to behave like that of a BJT

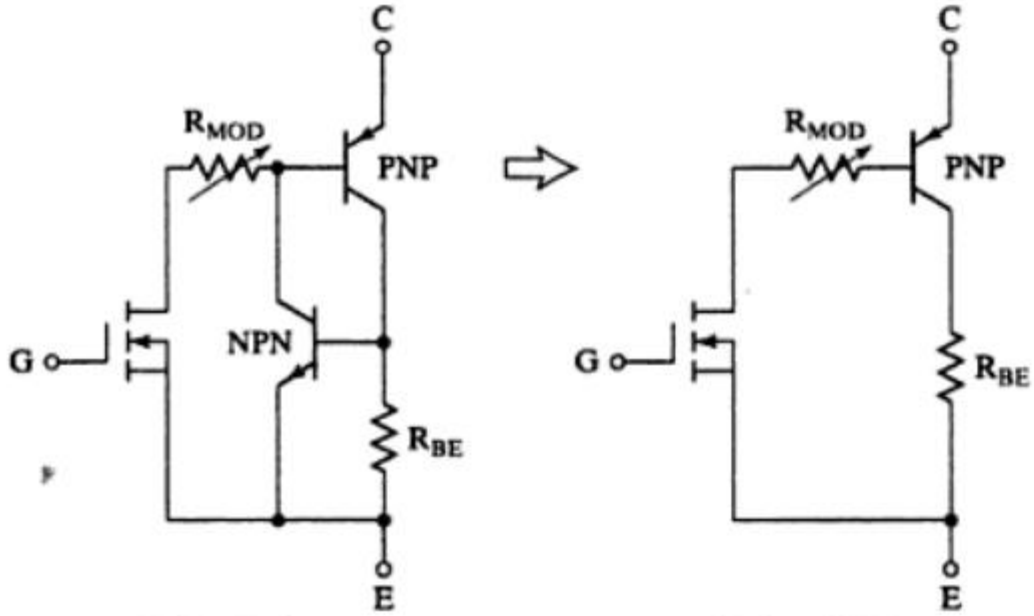


the performance of an IGBT is closer to that of a BJT than an MOSFET.



(a) Cross section

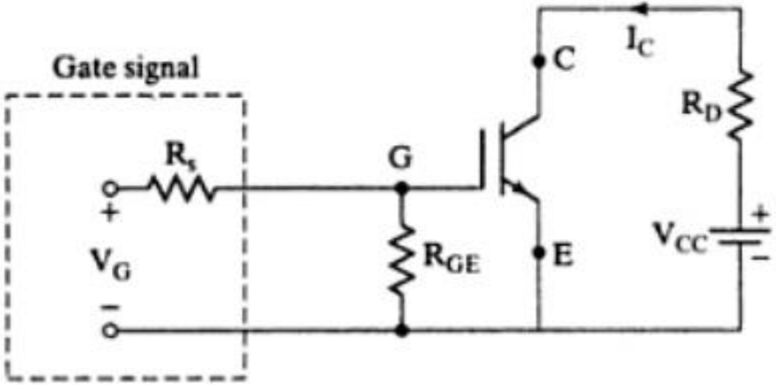
An IGBT is made



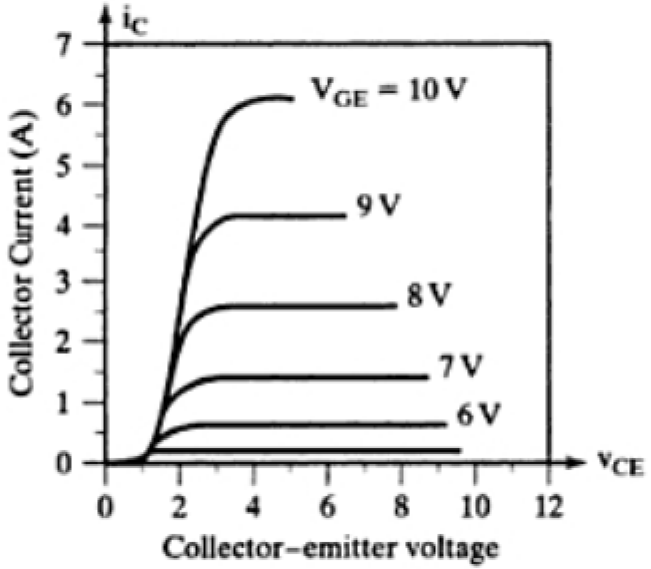
(b) Equivalent

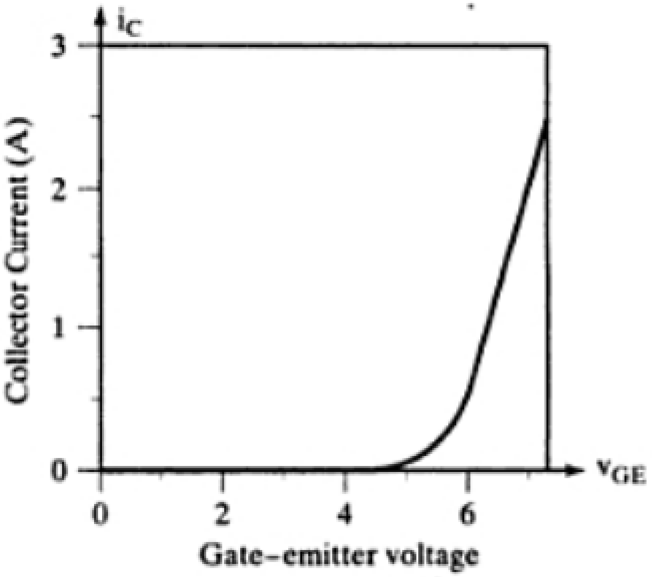
(c) Simplified circuit

of four alternate *PNPN* layers, and could latch like a thyristor given the necessary condition: $(\alpha_{npn} + \alpha_{pnp}) > 1$. The n^+-buffer layer and the wide epi base reduce the gain of the *NPN*-terminal by internal design, thereby avoiding latching. IGBTs have two structures of IGBTs: punch-through (PT) and nonpunch through (NPT). In the PT IGBT structure, the switching time is reduced by use of a heavily doped *n*-buffer layer in the drift region near the collector. In the NPT structure, carrier lifetime is kept more than that of a PT structure, which causes conductivity modulation of the drift region and reduces the on-state voltage drop. An IGBT is a voltage-controlled device similar to a power MOSFET. Like an MOSFET, when the gate is made positive with respect to the emitter for turn-on, *n* carriers are drawn into the *p*-channel near the gate region; this results in a forward bias of the base of the *npn*-transistor, which thereby turns on. An IGBT is turned on by just applying a positive gate voltage to open the channel for *n* carriers and is turned off by removing the gate voltage to close the channel. It requires a very simple driver circuit. It has lower switching and conducting losses while sharing many of the appealing features of power MOSFETS, such as ease of gate drive, peak current, capability, and ruggedness. An IGBT is inherently faster than a BJT. However, the switching speed of IGBTs is inferior to that of MOSFETs.



Symbol and circuit for an IGBT.

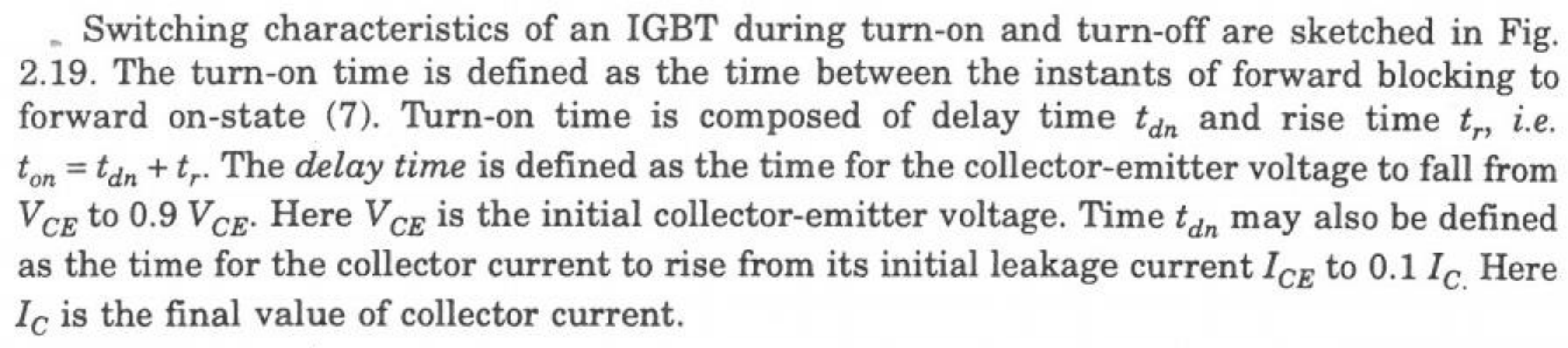




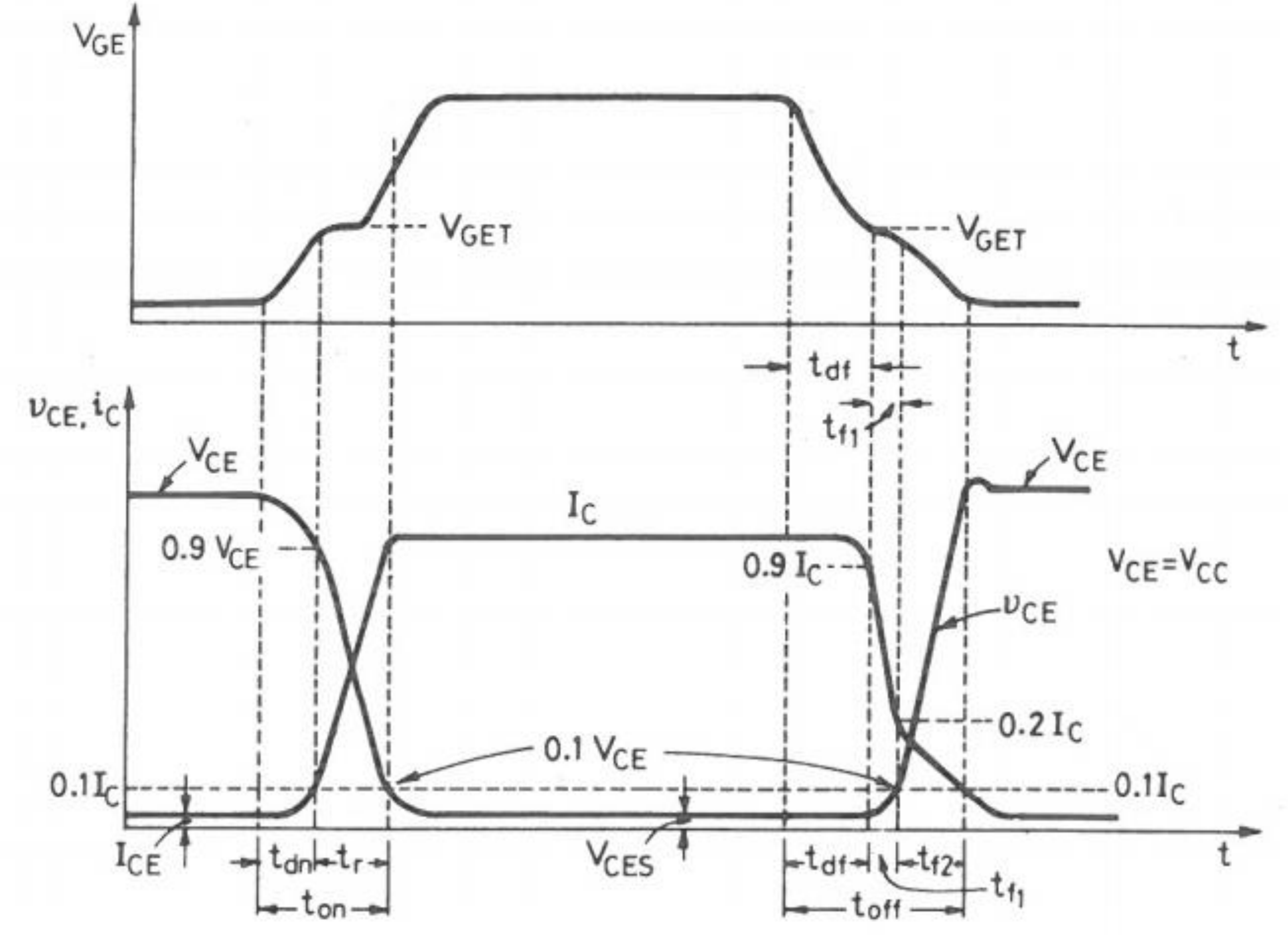
The current rating of a single IGBT can be up to 1200 V, 400 A, and the switching frequency can be up to 20 kHz. IBGTs are finding increasing applications in medium-power applications such as dc and ac motor drives, power supplies, solid-state relays, and contractors.

As the upper limits of commercially available IGBT ratings are increasing (e.g., as high as 6500 V and 2400 A), IGBTs are finding and replacing applications where BJTs and conventional MOSFETs were predominantly used as switches.

Switching Characteristics



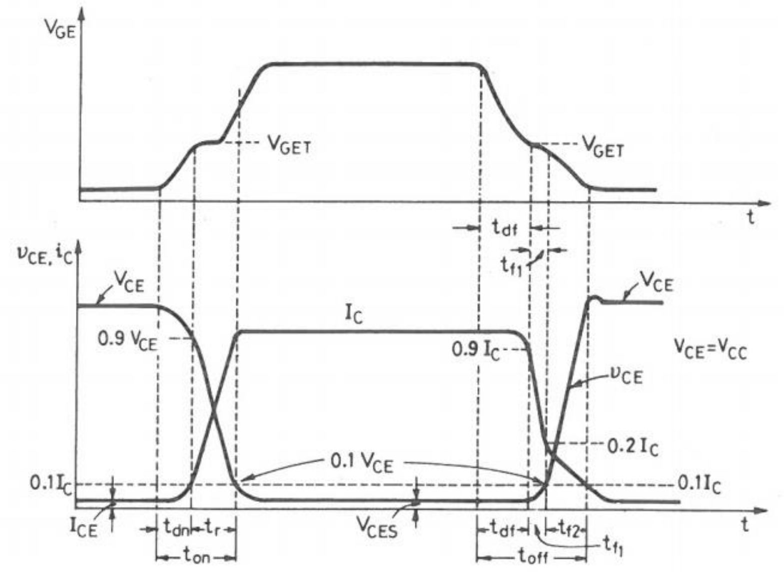
Switching characteristics of an IGBT during turn-on and turn-off are sketched in Fig. 2.19. The turn-on time is defined as the time between the instants of forward blocking to forward on-state (7). Turn-on time is composed of delay time t_{dn} and rise time t_r, *i.e.* $t_{on} = t_{dn} + t_r$. The *delay time* is defined as the time for the collector-emitter voltage to fall from V_{CE} to 0.9 V_{CE}. Here V_{CE} is the initial collector-emitter voltage. Time t_{dn} may also be defined as the time for the collector current to rise from its initial leakage current I_{CE} to 0.1 $I_{C.}$ Here I_C is the final value of collector current.



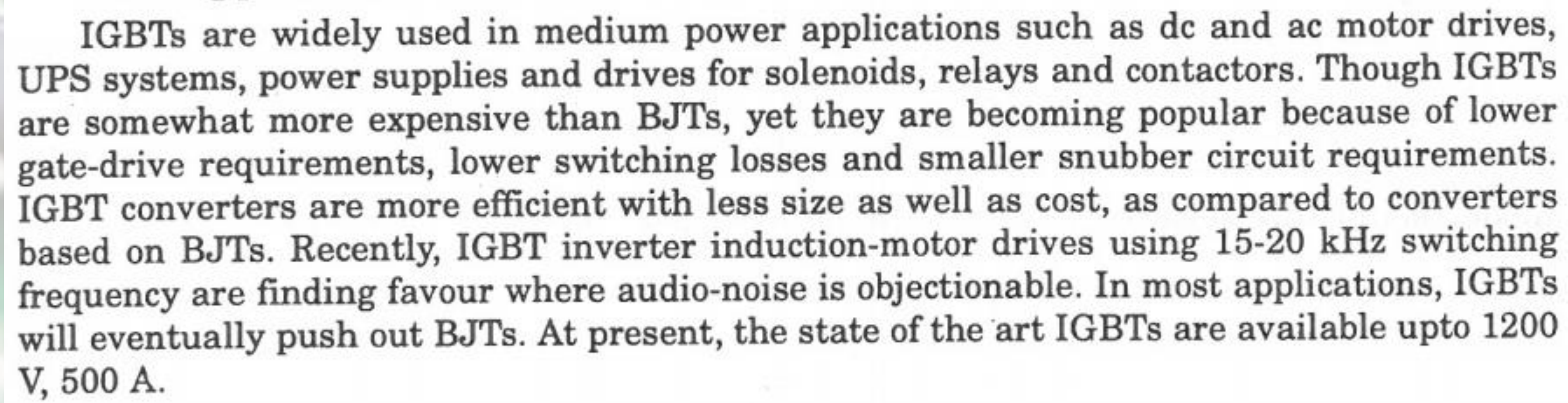
The *rise time* t_r is the time during which collector-emitter voltage falls from 0.9 V_{CE} to 0.1 V_{CE}. It is also defined as the time for the collector current to rise from 0.1 I_C to its final value I_C. After time t_{on}, the collector current is I_C and the collector-emitter voltage falls to small value called conduction drop = V_{CES} where subscript S denotes saturated value.

The turn-off time is somewhat complex. It consists of three intervals : (*i*) delay time, t_{df} (*ii*) initial fall time, t_{f1} and (*iii*) final fall time, t_{f2} ; *i.e.* $t_{off} = t_{df} + t_{f1} + t_{f2}$. The delay time is the time during which gate voltage falls from V_{GE} to threshold voltage V_{GET}. As V_{GE} falls to V_{GET} during t_{df}, the collector current falls from I_C to 0.9 I_C. At the end of t_{df}, collector-emitter voltage begins to rise. 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, or the time during which collector-emitter voltage rises from V_{CES} to 0.1 V_{CE}.

The final fall time t_{f2} is the 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}, see Fig. 2.19.

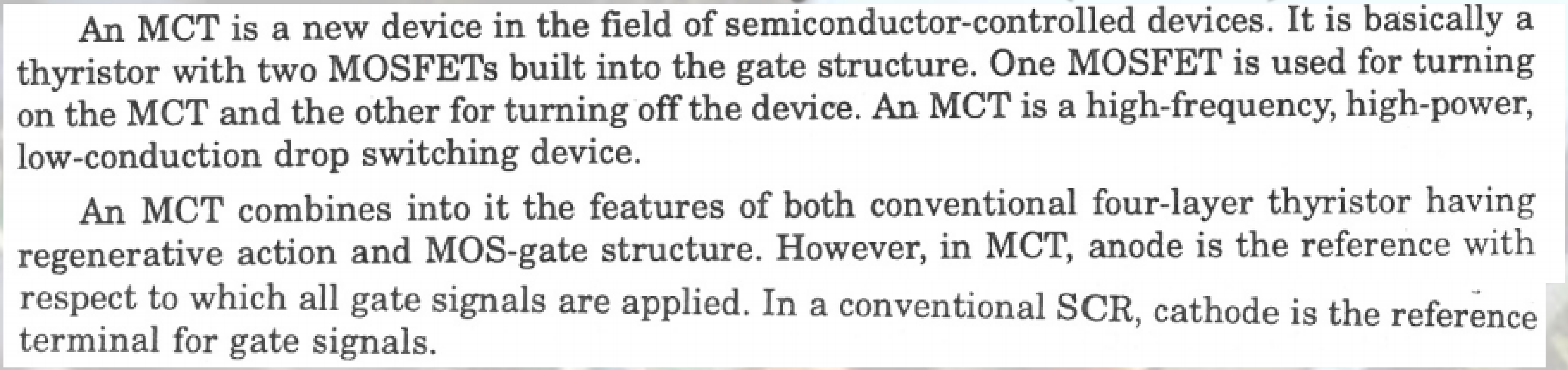


Application of IGBT



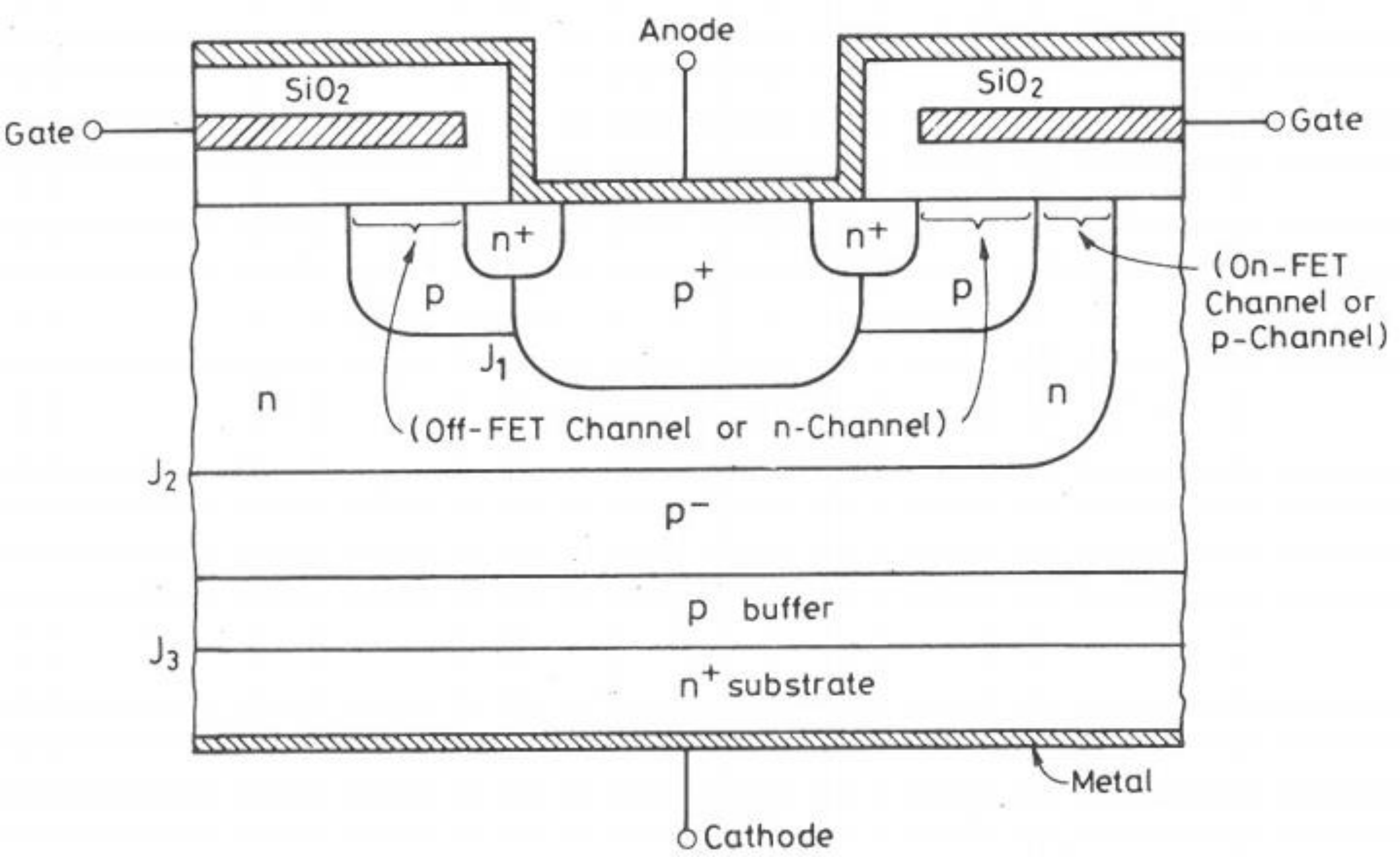
IGBTs are widely used in medium power applications such as dc and ac motor drives, UPS systems, power supplies and drives for solenoids, relays and contactors. Though IGBTs are somewhat more expensive than BJTs, yet they are becoming popular because of lower gate-drive requirements, lower switching losses and smaller snubber circuit requirements. IGBT converters are more efficient with less size as well as cost, as compared to converters based on BJTs. Recently, IGBT inverter induction-motor drives using 15-20 kHz switching frequency are finding favour where audio-noise is objectionable. In most applications, IGBTs will eventually push out BJTs. At present, the state of the art IGBTs are available upto 1200 V, 500 A.

MOS-Controlled Thyristor (MCT)



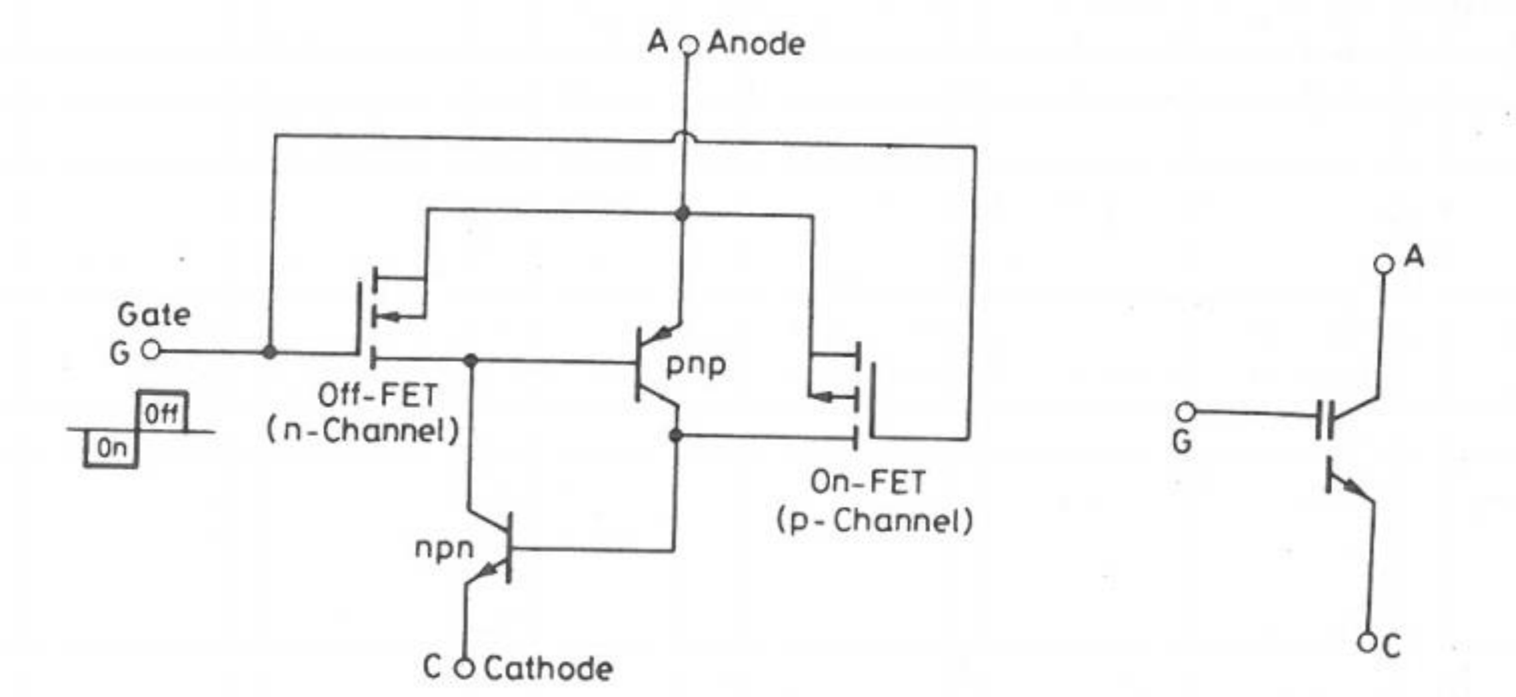
An MCT is a new device in the field of semiconductor-controlled devices. It is basically a thyristor with two MOSFETs built into the gate structure. One MOSFET is used for turning on the MCT and the other for turning off the device. An MCT is a high-frequency, high-power, low-conduction drop switching device.

An MCT combines into it the features of both conventional four-layer thyristor having regenerative action and MOS-gate structure. However, in MCT, anode is the reference with respect to which all gate signals are applied. In a conventional SCR, cathode is the reference terminal for gate signals.



The equivalent circuit of MCT is shown in Fig It consists of one on-FET, one off-FET and two transistors. The on-FET is a p-channel MOSFET and off-FET is an n-channel MOSFET. An arrow towards the gate terminal indicates n-channel MOSFET and the arrow away from the gate terminal as the p-channel MOSFET. The two transistors in the equivalent circuit indicate that there is regenerative feedback in the MCT just as it is in an ordinary thyristor.

An MCT is turned-on by a negative voltage pulse at the gate with respect to the anode and is turned-off by a positive voltage pulse.



Turn-on process. As stated above, MCT is turned on by applying a negative voltage pulse at the gate with respect to anode. In other words, for turning on MCT, gate is made negative with respect to anode by the voltage pulse between gate and anode. With the application of this negative voltage pulse, on-FET gets turned-on and off-FET is off. With on-FET on, current begins to flow from anode *A*, through on-FET and then as the base current and emitter current of *npn* transistor and then to cathode C. This turns on *npn* transistor. As a result, collector current begins to flow in *npn* transistor. As off-FET is off, this collector current of *npn* transistor acts as the base current of *pnp* transistor. Subsequently, *pnp* transistor is also turned on. Once both the transistors are on, regenerative action of the connection scheme takes place and the thyristor or MCT is turned on.

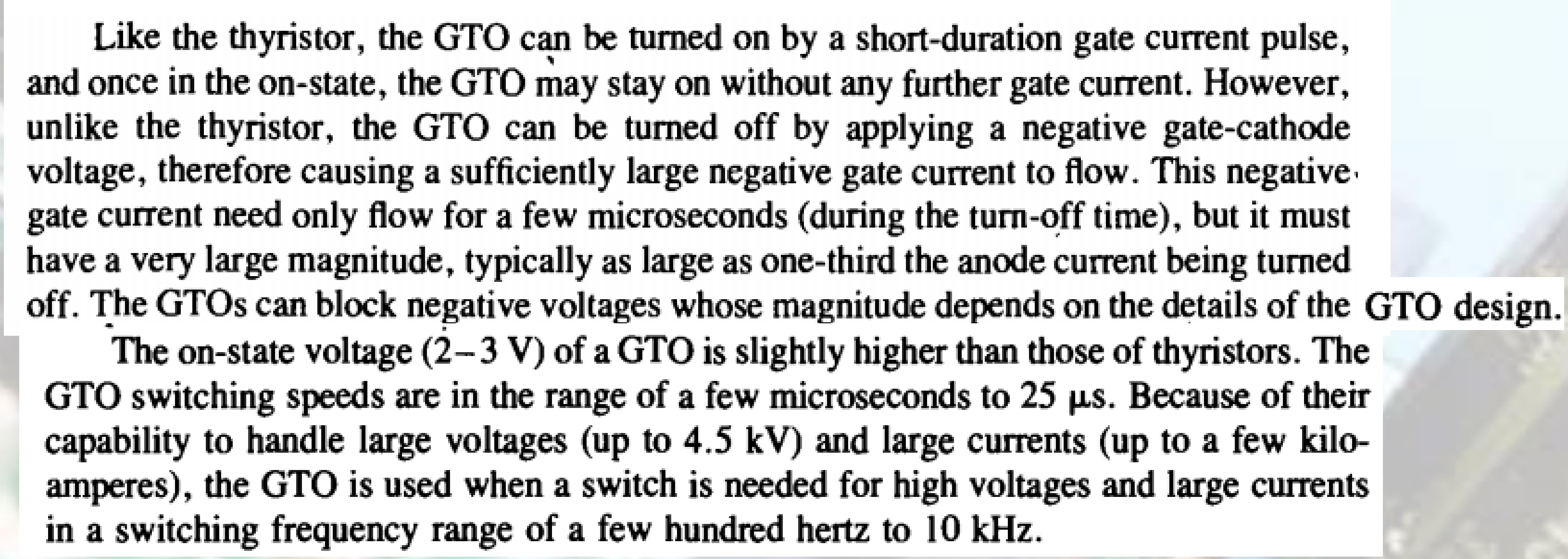
Note that on-FET and *pnp* transistor are in parallel when thyristor is in conduction state. During the time MCT is on, base current of *npn* transistor flows mainly through *pnp* transistor because of its better conducting property.

Turn-off process. For turning-off the MCT, off-FET (or *n* -channel MOSFET) is energized by positive voltage pulse at the gate. With the application of positive voltage pulse, off-FET is turned on and on-FET is turned off. After off-FET is turned on, emitter-base terminals of *pnp* transistor are short circuited by off-FET. So now anode current begins to flow through off-FET and therefore base current of *pnp* transistor begins to decrease. Further, collector current of *pnp* transistor that forms the base current of *npn* transistor also begins to decrease. As a consequence, base currents of both *pnp* and *npn* transistors, now devoid of stored charge in their *n* and *p* bases respectively, begin to decay. This regenerative action eventually turns off the MCT.

An MCT has the following merits :

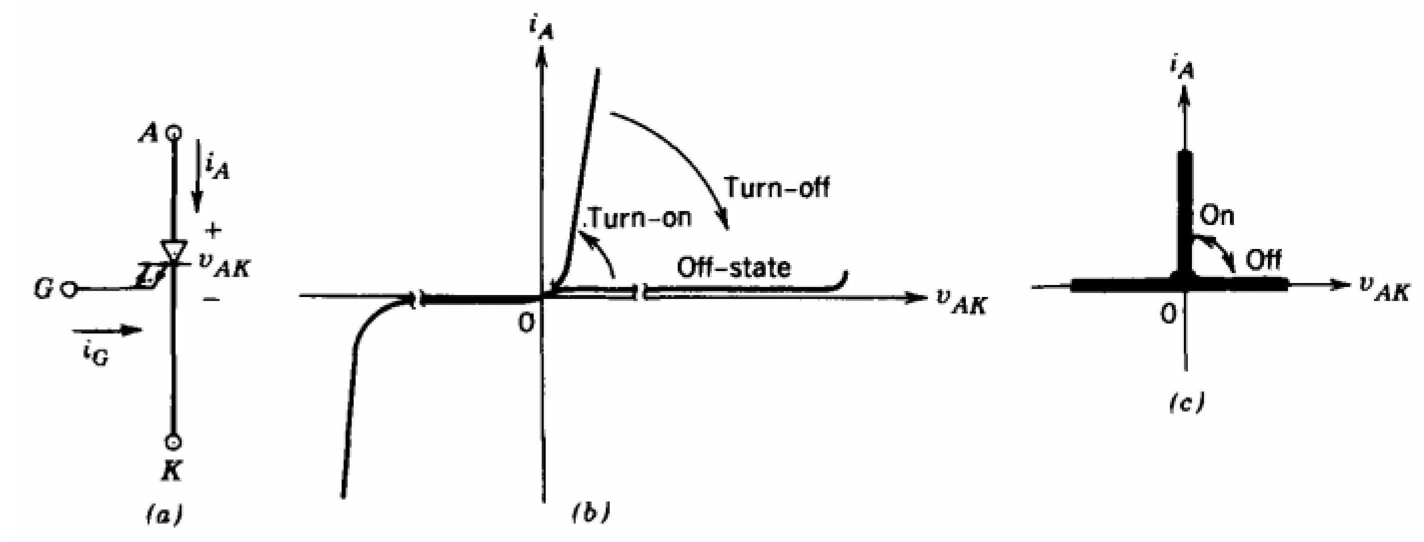
(*i*) Low forward conduction drop,
(*ii*) fast turn-on and turn-off times,
(*iii*) low switching losses and
(*iv*) high gate input impedance, which allows simpler design of drive circuits.

Gate-Turn-Off Thyristor (GTO)



Like the thyristor, the GTO can be turned on by a short-duration gate current pulse, and once in the on-state, the GTO may stay on without any further gate current. However, unlike the thyristor, the GTO can be turned off by applying a negative gate-cathode voltage, therefore causing a sufficiently large negative gate current to flow. This negative gate current need only flow for a few microseconds (during the turn-off time), but it must have a very large magnitude, typically as large as one-third the anode current being turned off. The GTOs can block negative voltages whose magnitude depends on the details of the GTO design.

The on-state voltage (2–3 V) of a GTO is slightly higher than those of thyristors. The GTO switching speeds are in the range of a few microseconds to 25 μs. Because of their capability to handle large voltages (up to 4.5 kV) and large currents (up to a few kiloamperes), the GTO is used when a switch is needed for high voltages and large currents in a switching frequency range of a few hundred hertz to 10 kHz.



A GTO: (*a*) symbol, (*b*) *i*–*v* characteristics, (*c*) idealized characteristics.

Comparison of Controllable Switches

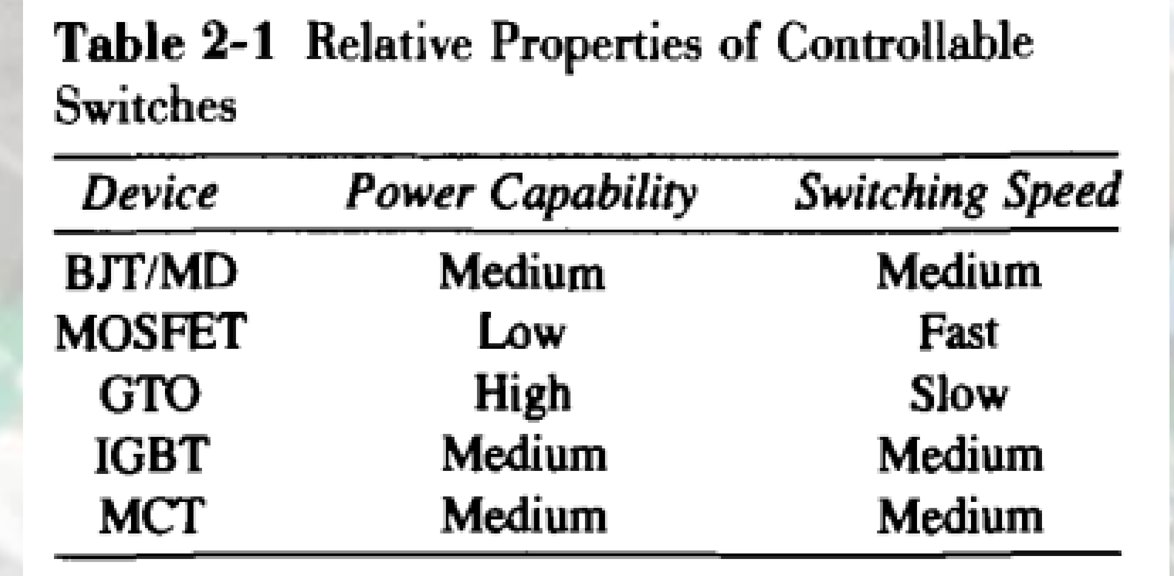


Table 2-1 Relative Properties of Controllable Switches

Device	*Power Capability*	*Switching Speed*
BJT/MD	Medium	Medium
MOSFET	Low	Fast
GTO	High	Slow
IGBT	Medium	Medium
MCT	Medium	Medium