Power Electronics

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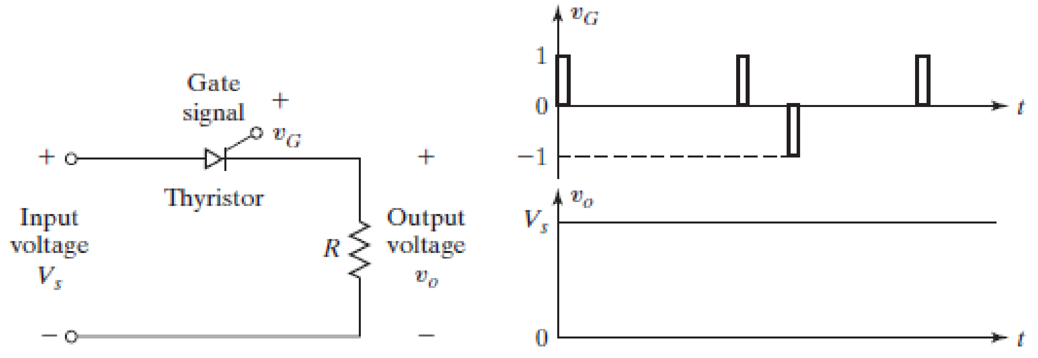
Choices	Low Power	Medium Power	High Power
Power Range	Up to 2 kW	2 to 500 kW	More than 500 kW
Usual Converter Topologies	ac-dc, dc-dc	ac-dc, dc-dc, dc-ac	ac-dc, dc-ac
Typical Power Semiconductors	MOSFET	MOSFET, IGBT	IGBT, IGCT, thyristor
Technology Trend	High power density High efficiency	Small volume and weight Low cost and high efficiency	High nominal power of the converter High power quality and stability
Typical Applications	Low-power devices Appliances	Electric vehicles Photovoltaic roofing	Renewable energy Transportation Power distribution Industry

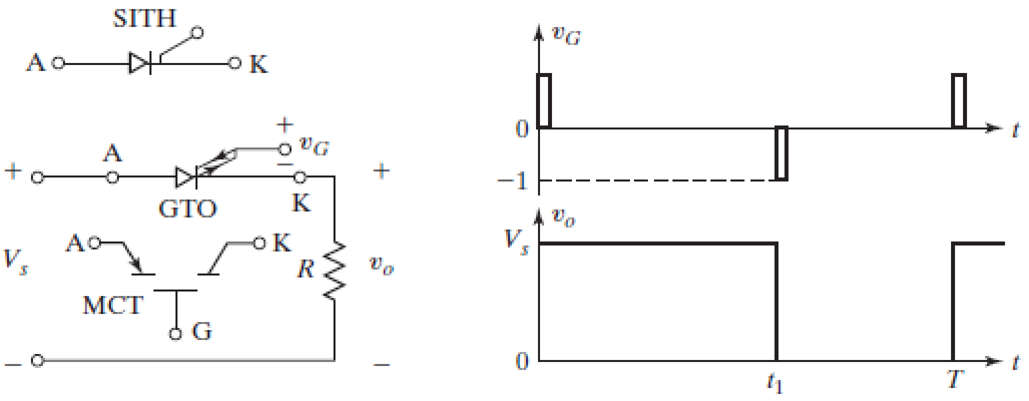
TABLE 1.5 Switching Characteristics of Power Semiconductors

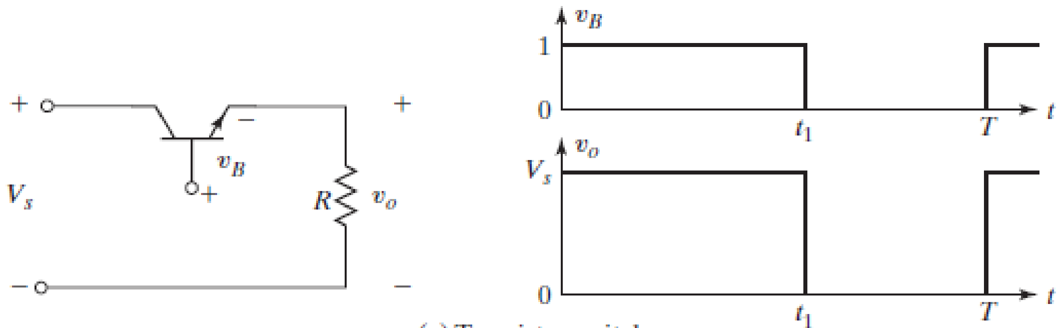
Device Type	Device	Continuous Gate	Pulse Gate	Controlled Turn-On	Controlled Turn-Off	Unipolar Voltage	Bipolar Voltage	Unidirectional Current	Bidirectional Current
Diodes	Power diode					x		x	
Transistors	BJT	x		x	x	x		x	
	MOSFET	x		x	x	x			x
	COOLMOS	x		x	x	x			x
	IGBT	x		x	x	x		x	
	SIT	x		x	x	x		x	
Thyristors	SCR		x	x			x	x	
	RCT		x	x			x		x
	TRIAC		x	x			x		x
	GTO		x	x	x		x	x	
	MTO		x	x	x		x	x	
	ETO		x	x	x		x	x	
	IGCT		x	x	x		x	x	
	SITH		x	x	x		x	x	
	MCT	x		x	x		x	x	

Examples

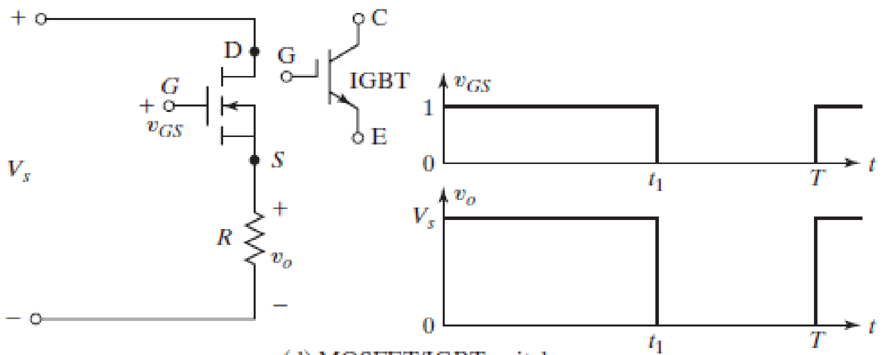


(a) Thyristor switch





(c) Transistor switch



(d) MOSFET/IGBT switch

Semiconductor Basics

- Most commonly used semiconductors are silicon and germanium
- Silicon materials cost less than germanium materials and allow diodes to operate at higher temperatures
- A pure silicon material is known as an *intrinsic semiconductor* with resistivity that is too low to be an insulator and too high to be a conductor
- Process of adding impurities is called *doping*, which involves a single atom of the added impurity per over a million silicon atoms
- When the silicon is lightly doped with an impurity such as phosphorus (Group V element), the doping is denoted as *n-doping*
- When it is heavily doped, it is denoted as *n*+ doping
- Each atom of the *dopant* forms leaves a loose electron and greatly increase the conductivity of the material.

- If pure silicon is doped with a small amount of a Group III element (boron, gallium) a vacant location called a *hole* is introduced into the silicon lattice.
- holes greatly increase the conductivity of the material.
- When it is heavily doped, it is denoted as *p*+ doping
- In a *p*-type material, the holes are called the majority carriers and electrons are called the minority carriers
- fundamental challenge in power semiconductor design is obtaining a high breakdown voltage, while maintaining low forward voltage drop and on-resistance.
- Another related issue is the longer switching times of high-voltage low on-resistance devices.

- The breakdown voltage of a reverse-biased p-n junction and its depletion region is a function of doping level

- high breakdown voltage requires low doping concentration, and hence high resistivity

- high-voltage devices have higher on-resistance than low-voltage devices.

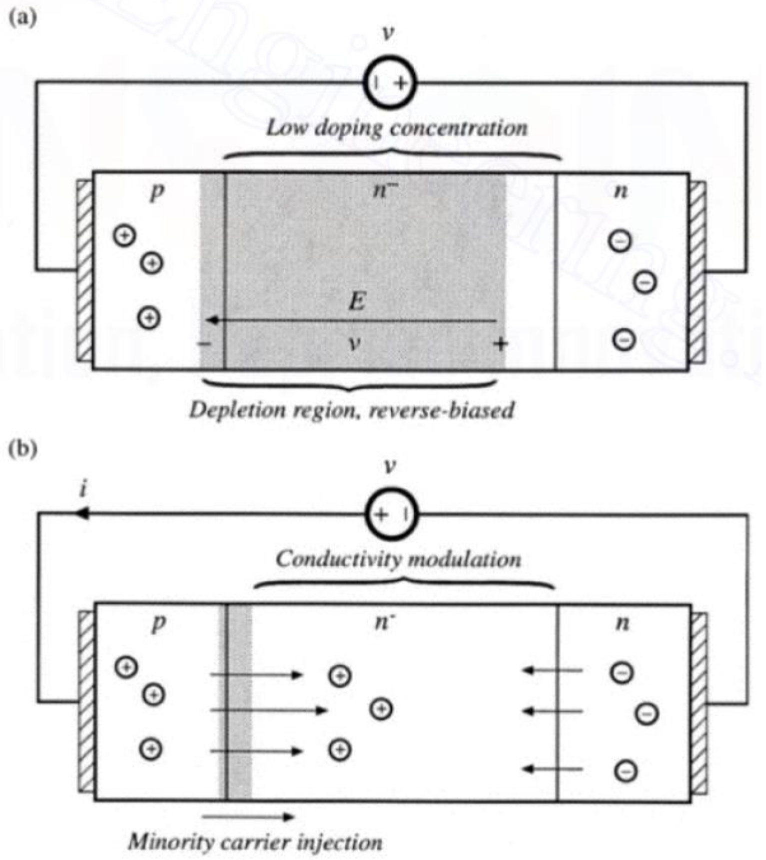
- In majority carrier devices (MOSFET and Schottky diode) there is a first-order dependence of on-resistance on rated voltage.

- For minority carrier devices (diffused-junction diode, BJT, IGBT, and the thyristor family SCR, GTO) exhibit phenomenon known as conductivity modulation.

- Minority-carrier devices exhibit lower on-resistances and lower switching speed than majority-carrier devices.

- Majority carrier devices used at low voltage level applications compared to the other

Power diode



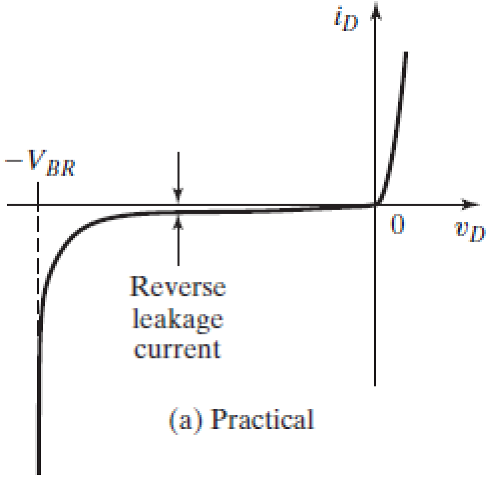
- The diffused-junction p-n diode contains a lightly doped or intrinsic high-resistivity region, which allows a high breakdown voltage to be obtained.

- During off state, the **p-n$^-$** junction is under reverse-biased condition, essentially all of the applied voltage appears across the depletion region inside the **n$^-$** region

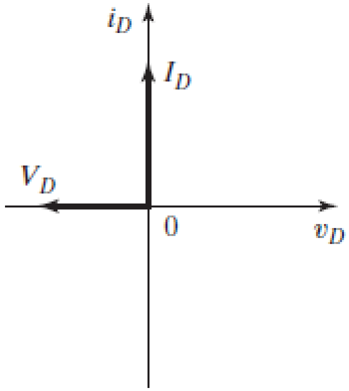
- During on state, holes are injected across the forward-biased junction, and become minority carriers in the **n$^-$** region

- minority carriers reduce the apparent resistivity of the **n-** region via conductivity modulation.

- When anode potential is positive w.r.t the cathode - forward biased - diode conducts
- Small forward voltage drop during conduction(depends on manufacturing process & junction temperature)
- cathode potential is positive w.r.t the anode, the diode is reverse biased
- Under reverse-biased conditions, a small reverse current (*leakage current*) in the range of micro- or milliampere flows
- leakage current increases slowly in magnitude with the reverse voltage until the avalanche breakdown

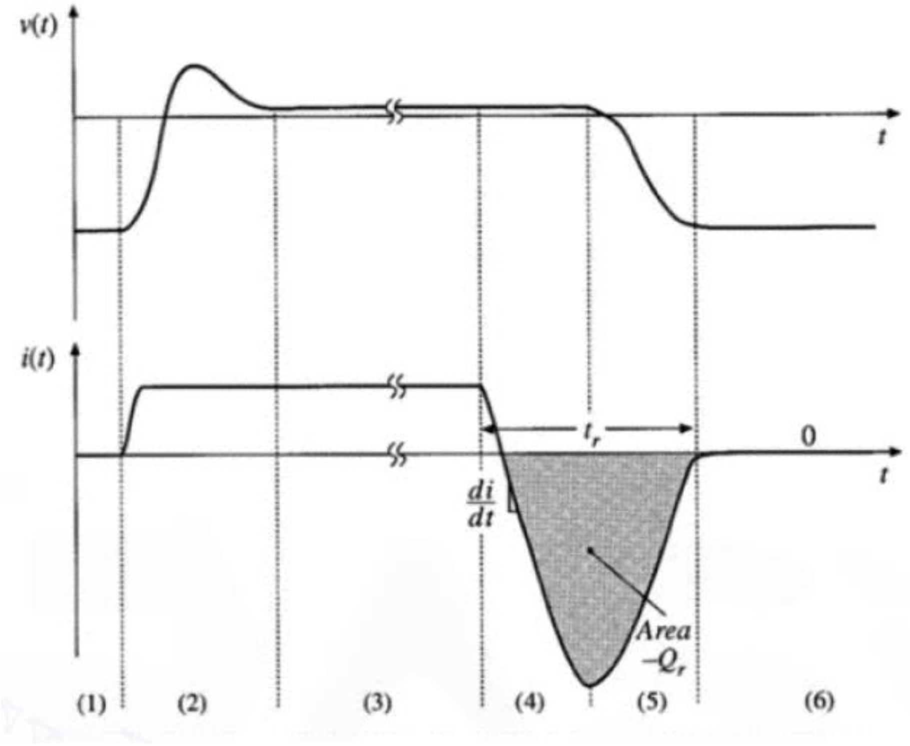


(a) Practical



(b) Ideal

Switching characteristics



Interval (1) : the diode operates in the off state with zero current and negative voltage

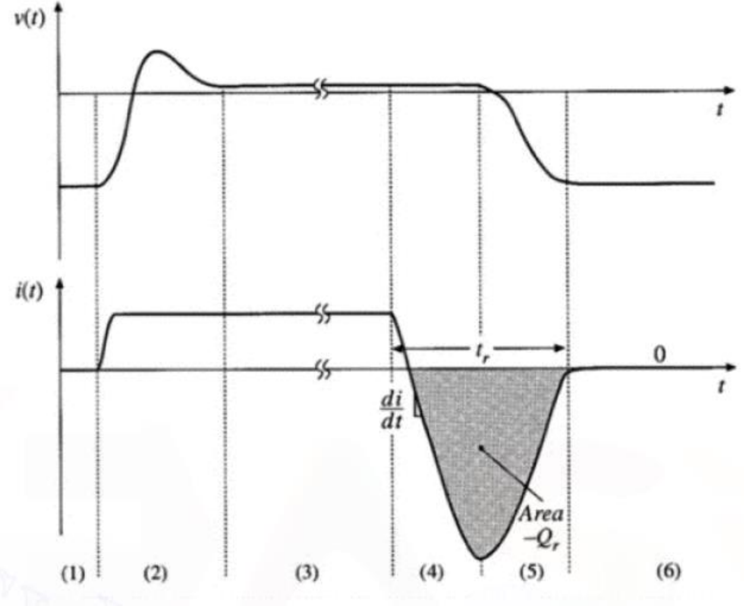
Interval (2) : the current increases to some positive value. This current charges the effective capacitance of the reverse-biased diode, supplying charge to the depletion region and increasing the voltage v(t).

Eventually, the voltage becomes positive, and the diode junction becomes forward-biased.

The voltage may rise to a peak value, (large resistance of lightly doped n^- region)

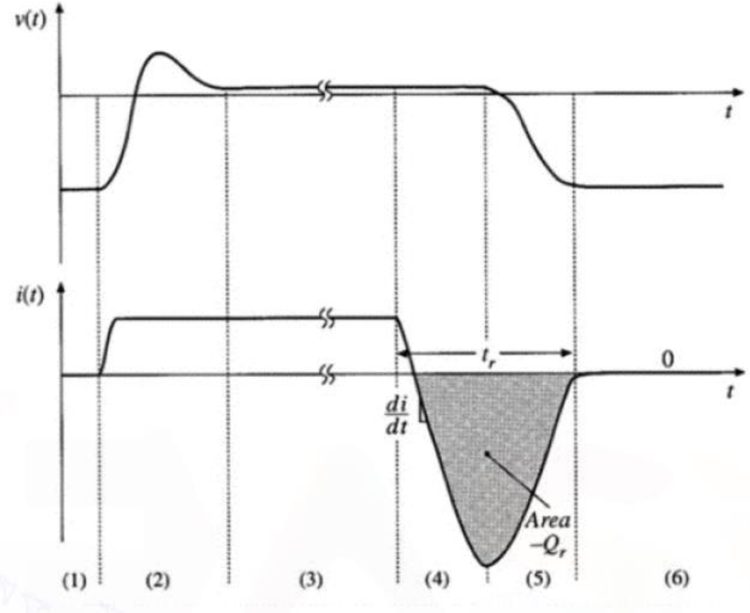
The forward-biased junction continues to inject minority charge into n^- region -- conductivity modulation of the n^- region -- effective resistance decrease -- forward voltage drop v(t) also decreases -- reaches equilibrium, in which minority carrier injection rate = recombination rate

Interval (3) : the diode operates in the on state, with forward voltage drop given by the diode static characteristic.



<u>Interval (4)</u>

- turn-off transient initiated
- remains forward biased - minority charge is present in the vicinity of pn-junction
- Reduction of the stored minority charge -- active method via negative terminal current, or passive method via recombination
- The charge Qr contained in the negative portion of the diode turn-off current waveform is called the recovered charge
- The portion of Qr occurring during interval (4) is actively-removed minority charge,
- Stored minority charge at the vicinity of p-n^{-} junction removed such that the diode junction becomes reverse-biased and is able to block negative voltage.



Interval (5)

- The depletion region effective capacitance is charged to the negative off-state voltage.
- The portion of Qr occurring during (5) is charge supplied to the depletion region, as well as minority charge that is actively removed from remote areas of the diode.
- The diode is able to block the entire applied reverse voltage.
- The length of intervals (4) and (5) is called the reverse recovery time (t_r or t_{rr})

Interval (6)

- the diode operates in the off state

- The t_{rr} consists of two components, t_a and t_b

- t_a is due to charge storage in the depletion region of the junction (time between the zero crossing and the peak reverse current I_{RR})

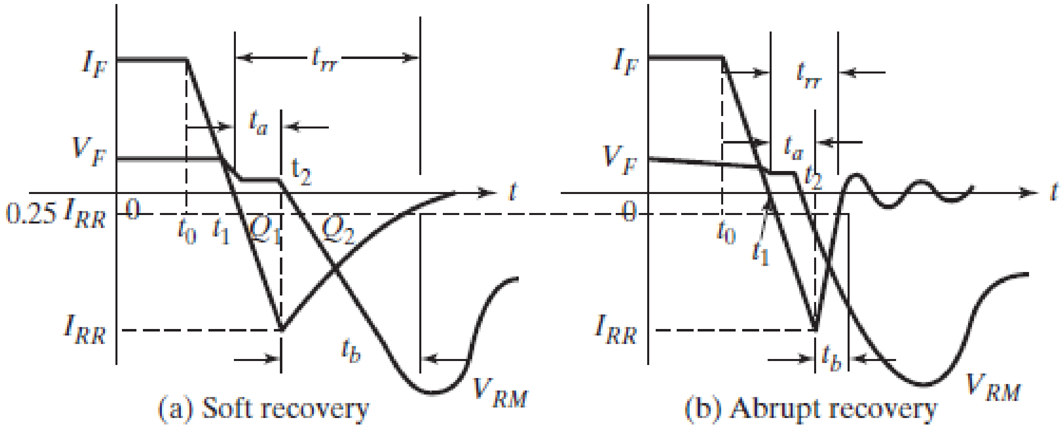
- t_b is due to charge storage in the bulk semiconductor material

- The ratio t_b/t_a is known as the *softness factor*

- There are two types of recovery: soft and hard (or abrupt)

- total recovery time t_{rr} and peak value of the reverse current I_{RR}

$$t_{rr} = t_a + t_b \qquad I_{RR} = t_a \frac{di}{dt}$$



- *Reverse recovery charge (Q_{RR})* - amount of charge carriers that flows across the diode in the reverse direction due to changeover from forward conduction to reverse blocking condition

- $\boldsymbol{t_{rr}}$ **-**time interval between the instant the current passes through zero (during the changeover from forward conduction to reverse blocking condition) and the moment the reverse current has decayed to 25% of its peak reverse value $\boldsymbol{I_{RR}}$

- Depending on the recovery characteristics and manufacturing techniques, the power diodes can classified into the following three categories:

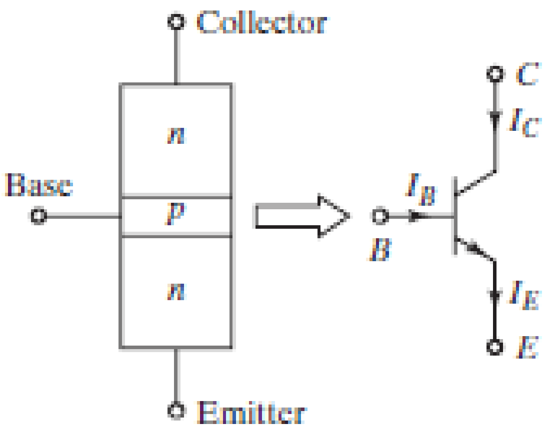
1. Standard or general-purpose diodes (available up to 6000 V, 4500A)

2. Fast-recovery diodes (high-frequency switching)

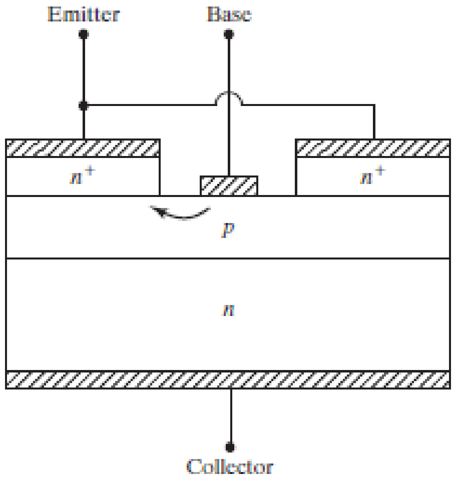
3. Schottky diodes (low on-state voltage and a very small recovery time)

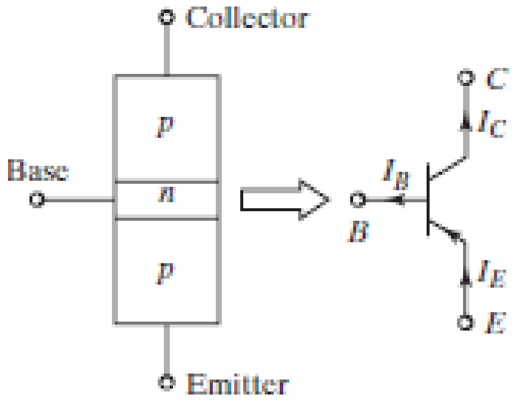
<u>Bipolar Junction Transistors</u>

- Current controlled device
- formed by adding a second *p*- or *n*-region to a *pn*-junction diode
- two *n*-regions and one *p*-region, two junctions are formed (*NPN-transistor)*
- *Two p*-regions and one *n*-region (*PNP-transistor*) two junctions
- *collector, emitter*, and *base*
- Junctions: a collector–base junction (CBJ) and a base–emitter junction (BEJ)

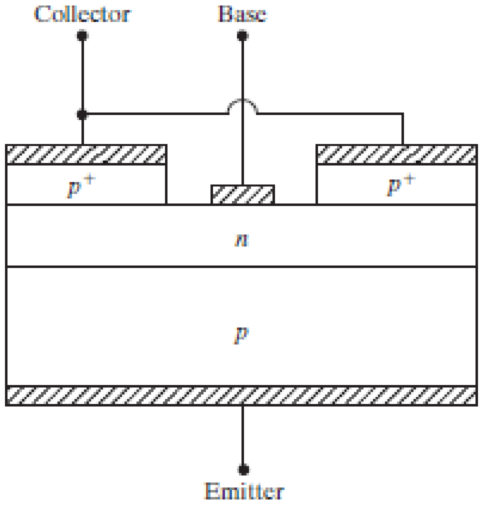


(a) *NPN*-transistor

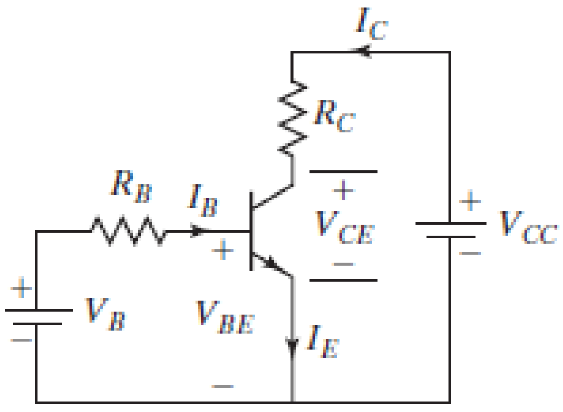




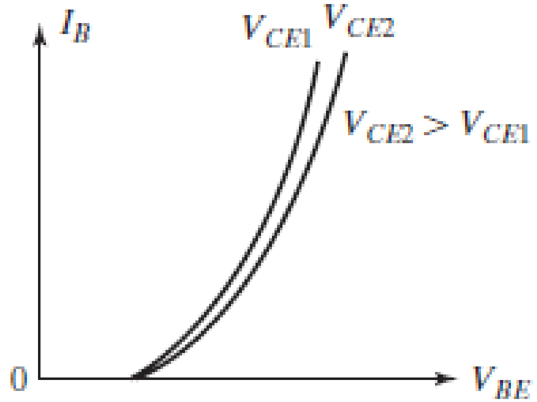
(b) *PNP*-transistor



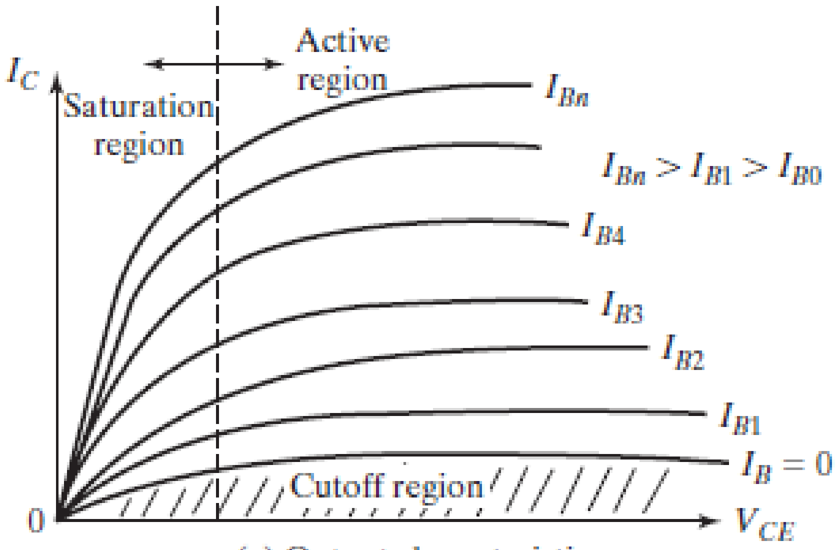
- Typical input characteristics of base current I_B against base–emitter voltage V_{BE}
- Typical output characteristics of collector current I_C against collector–emitter voltage V_{CE}



(a) Circuit diagram



(b) Input characteristics

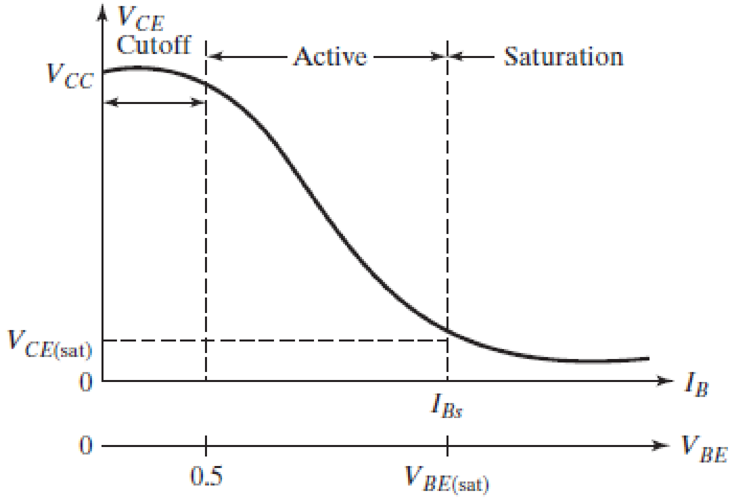


(c) Output characteristics

- three operating regions of a transistor: cutoff, active, and saturation.
- cutoff region -- the transistor is off (base current is not enough to turn it on) and both junctions are reverse biased
- saturation region -- the base current is sufficiently high so that the V_{CE} is low, and the transistor acts as a switch. Both junctions (CBJ and BEJ) are forward biased.

- Transfer chara:- is a plot of V_{CE} against I_B

$$I_E = I_C + I_B \qquad \beta_F = h_{FE} = \frac{I_C}{I_B}$$

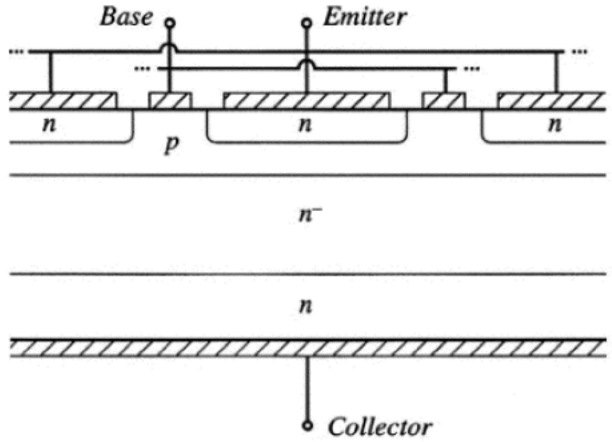


- The base current is effectively the input current and the collector current is output current.
- The ratio of the collector current I_C to base current I_B is known as the forward *current gain (very small for power BJT)*

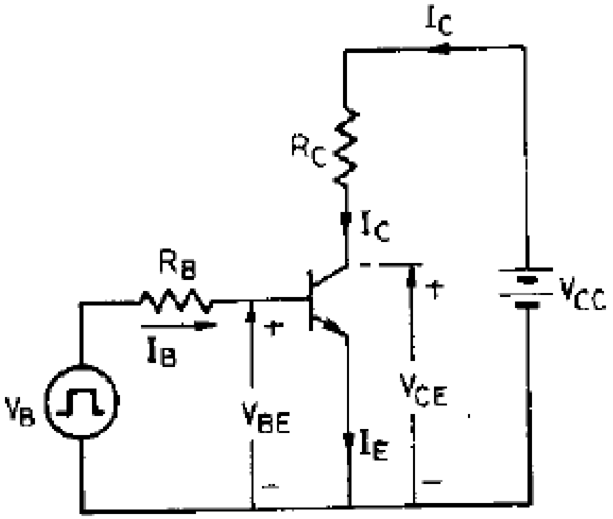
$$I_C = \beta_F I_B + I_{CEO}$$

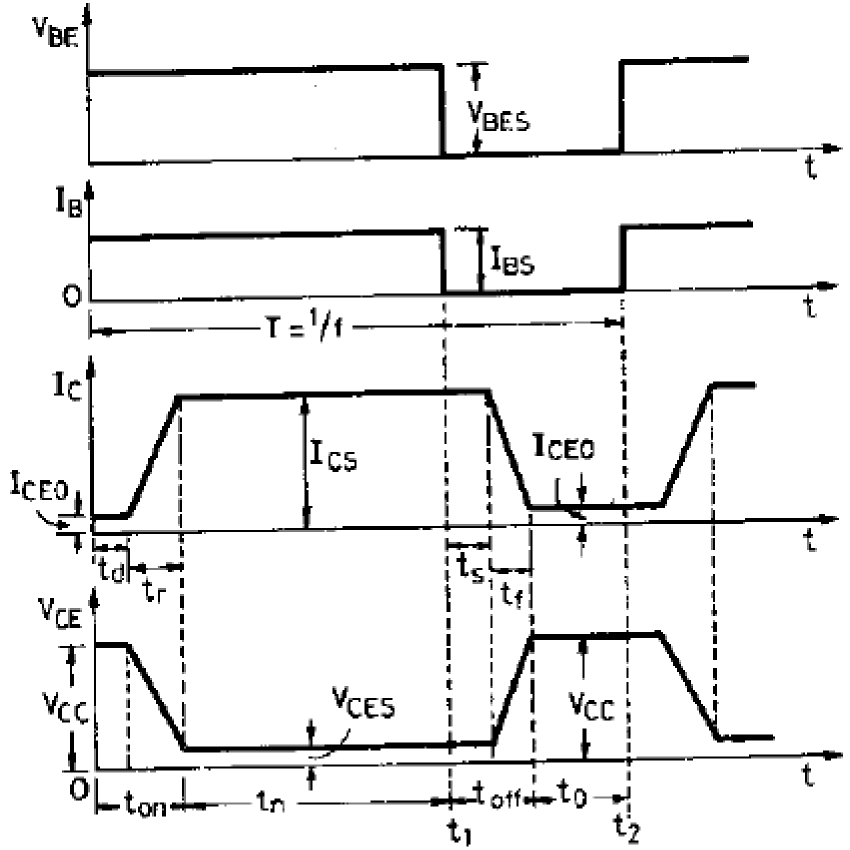
Power BJT structure

- A lightly doped **n**$^-$ region is inserted in the collector, to obtain the desired voltage breakdown rating.
- operates in the off state (cutoff) when p-n BEJ and the p-n$^-$ BCJ are reverse-biased
- applied collector-to-emitter voltage then appears essentially across the depletion region of the p-n$^-$ junction.



- Operates in on state (saturation) when both junctions are forward-biased
- substantial minority charge is present in the p and n^{-} regions.
- This minority charge causes the n- region to exhibit a low on-resistance due to conductivity modulation

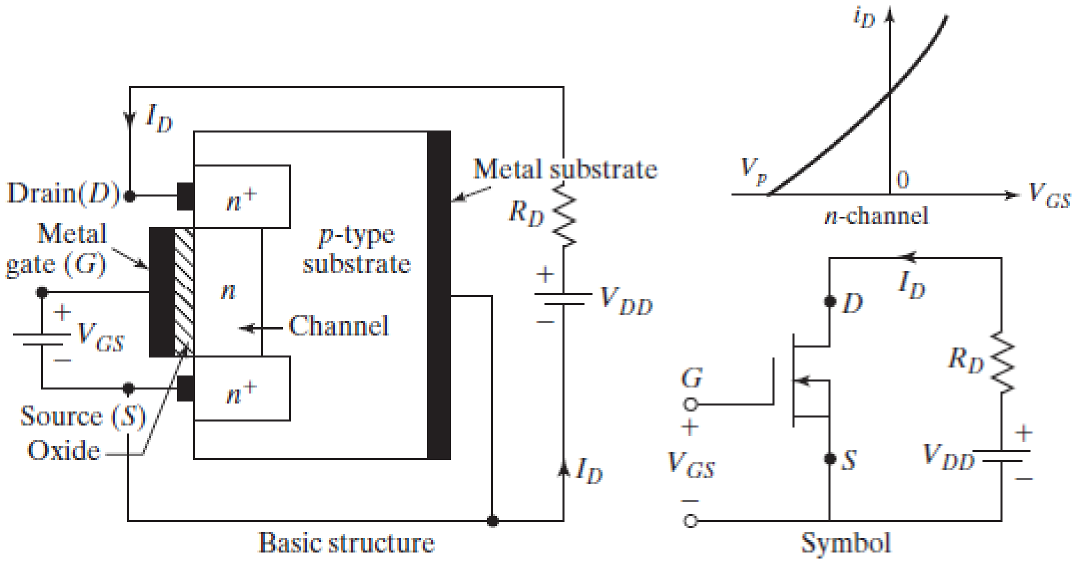




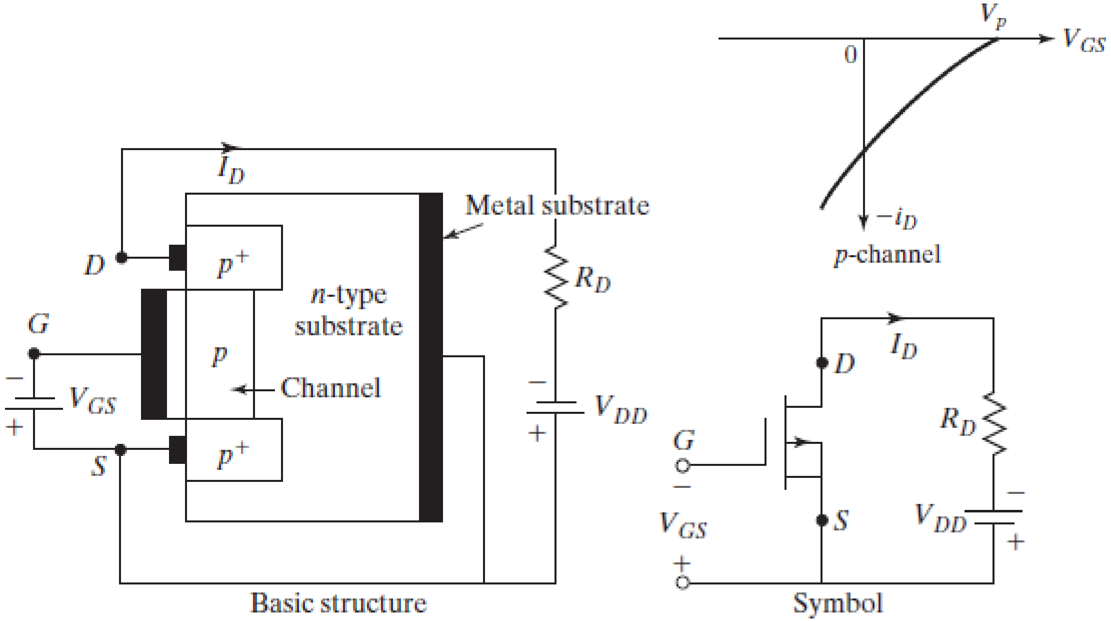
- **Second breakdown (SB).** The SB, which is a destructive phenomenon, results from the current flow to a small portion of the base, producing localized hot spots. If the energy in these hot spots is sufficient, the excessive localized heating may damage the transistor. Thus, secondary breakdown is caused by a localized thermal runaway, resulting from high current concentrations. The current concentration may be caused by defects in the transistor structure. The SB occurs at certain combinations of voltage, current, and time. Because the time is involved, the secondary breakdown is basically an energy-dependent phenomenon.

Power MOSFET

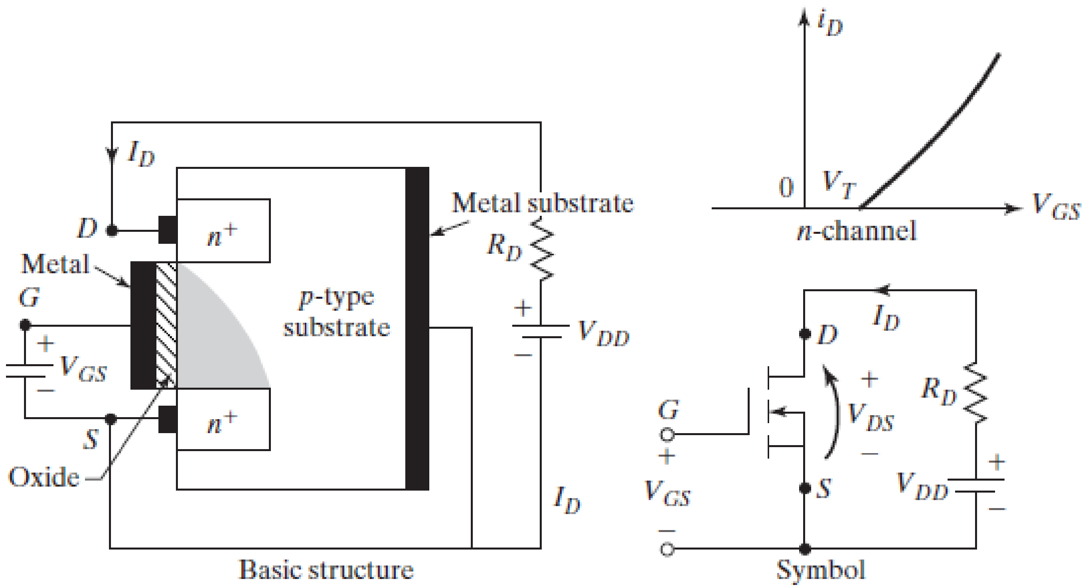
- voltage-controlled device and requires only a small input current
- switching times = order of nanoseconds (high switching speed)
- Application: low-power high-frequency converters
- MOSFETs have problems of electrostatic discharge but no issue of second breakdown phenomena
- Two types of MOSFETs -- depletion MOSFETs and enhancement MOSFETs
- The three terminals are called *gate, drain*, and *source*
- *n*-channel depletion-type MOSFET is formed on a *p*-type silicon substrate with two heavily doped *n*+ silicon sections for low resistance connections.
- gate is isolated from the channel by a thin oxide layer



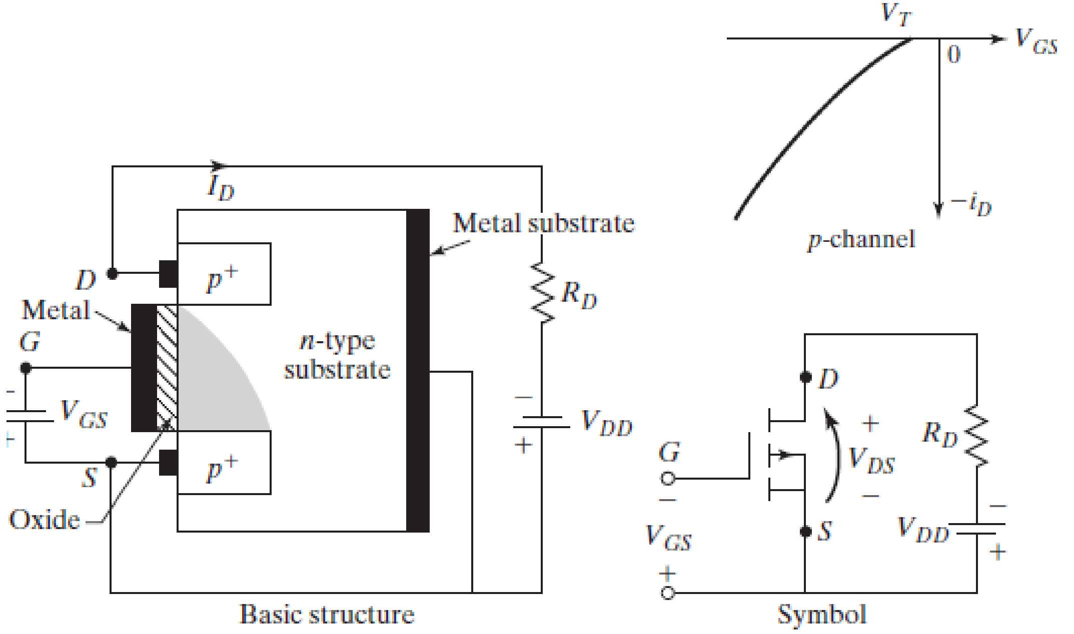
(a) *n*-Channel depletion-type MOSFET



(b) *p*-Channel depletion-type MOSFET



(a) *n*-Channel enhancement-type MOSFET

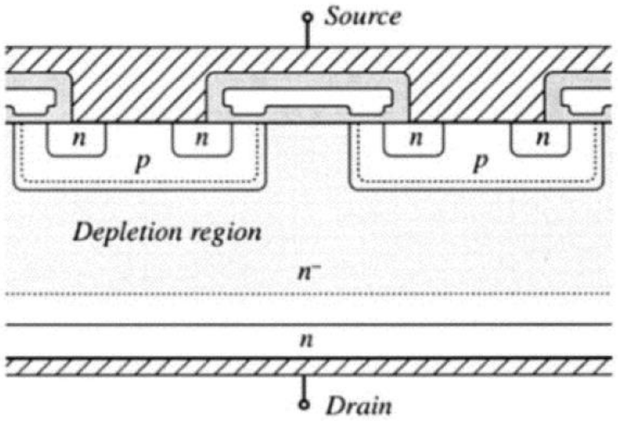


(b) *p*-Channel enhancement-type MOSFET

- The substrate is normally connected to the source
- Gate-to-source voltage V_{GS} -- positive or negative
- Consider *n*-channel depletion-type MOSFET, if V_{GS} is negative, some of the electrons in the *n*-channel area are repelled and depletion region is created below the oxide layer
- Leads to 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}
- no current flows from the drain to source (occurs when V_{GS}- pinchoff voltage)
- if V_{GS} is made positive, the channel becomes wider, and I_{DS} increases due to reduction in R_{DS}

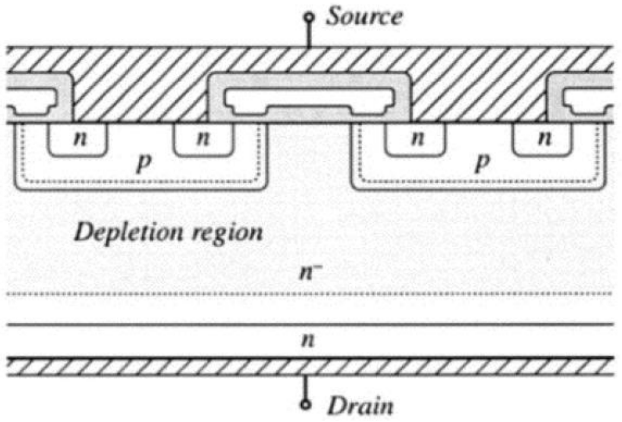
Power MOSFET structure

- The power device comprised of many small parallel-connected enhancement-mode MOSFET cells



- Current flows vertically through the silicon wafer
- Metallized drain connection is made on the bottom of the chip
- Metallized source connection and polysilicon gate are on the top surface
- Under normal operating conditions, in which V_{ds} >= 0, both the p-n and p-$\mathbf{n}^-$ junctions are reverse-biased
- The applied drain-to-source voltage then appears across the depletion region of the p-$\mathbf{n}^-$ junction
- The $\mathbf{n}^-$ region is lightly doped, such that the desired breakdown voltage rating is attained.

- Operation in on state occurs with sufficiently large positive gate-to-source voltage
- A channel forms at the surface of the p region, underneath the gate.
- The drain current flows through the **n^-** region, channel, n region, and out through the source contact.
- The on- resistance of the device is the sum of the resistances of the n region, the channel, the source and drain contacts, etc.
- As the breakdown voltage is increased, the on-resistance becomes dominated by the resistance of the n- region.
- Since there are no minority carriers to cause conductivity modulation, the on-resistance increase rapidly as the breakdown voltage is increased



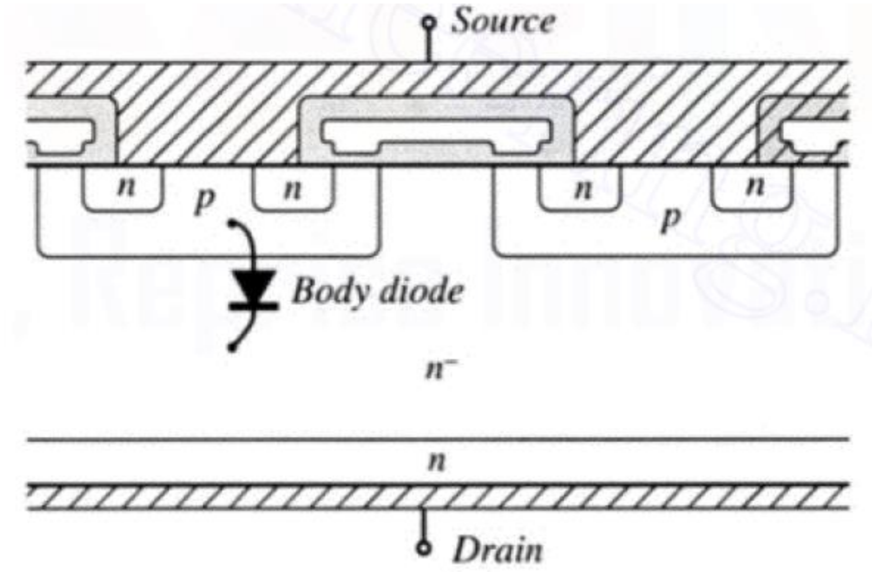
- The **pn⁻** junction is called the body diode (junction forms an effective diode in parallel with MOSFET channel)

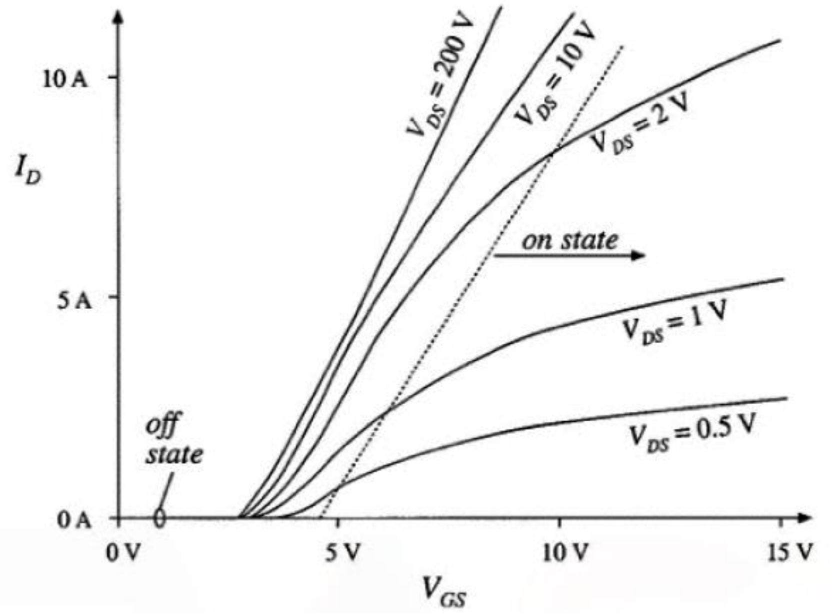
- The body diode can become forward-biased when the drain-to-source voltage is negative.

- This diode is capable of conducting the full rated current of MOSFET.

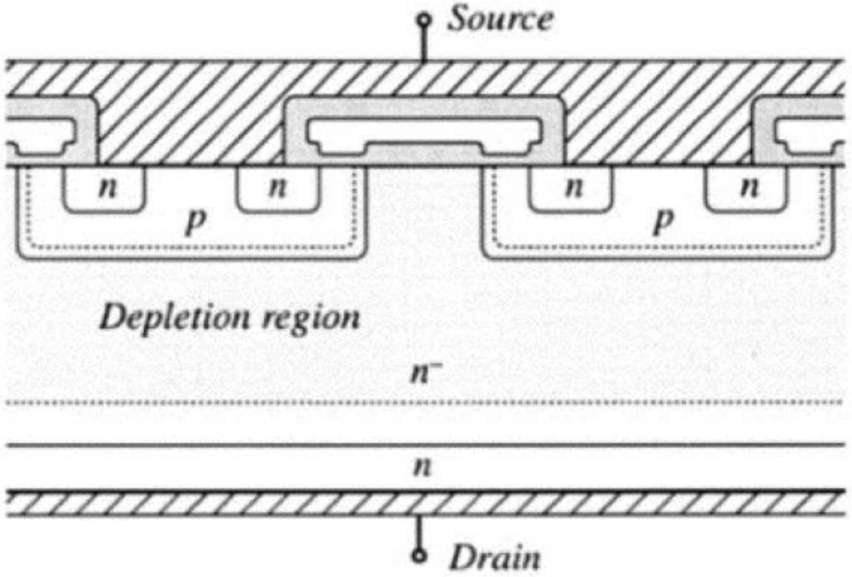
- But large peak currents that flow during the reverse recovery transition of the body diode can cause device failure.

- Therefore, several manufacturers produce MOSFETs that contain fast recovery body diode

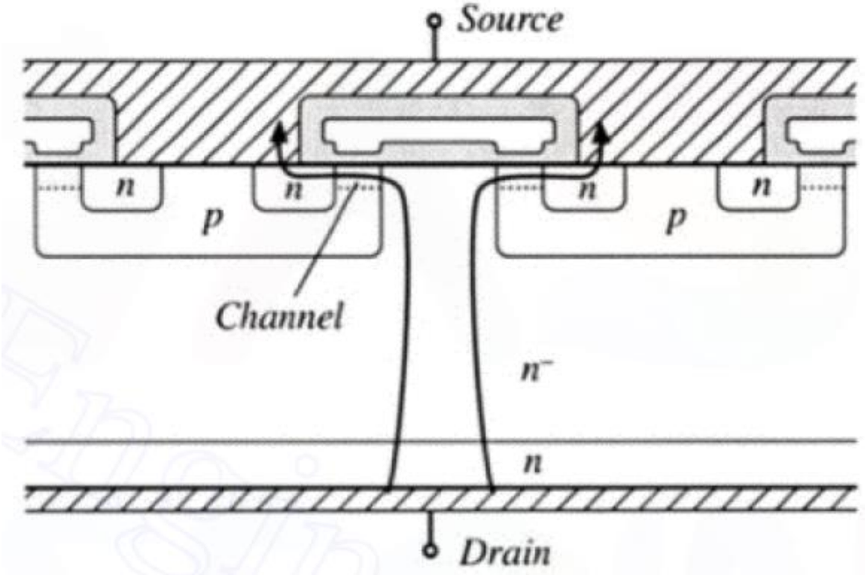




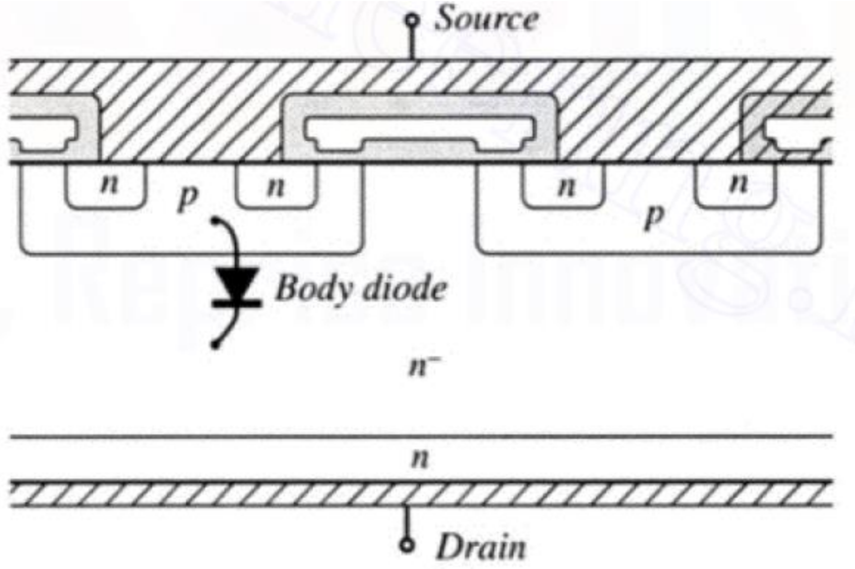
- The drain current is plotted as a function of the gate-to-source voltage (V_{GS}), for various values of drain-to-source voltage (static switch characteristics)
- When V_{GS}< threshold voltage V_{TH} (approx. 3 V), the device operates in off state
- When the V_{GS} > 6 or 7 V, the device operates in the on state
- typically, the gate is driven to 12 or 15 V to ensure minimization of the forward voltage drop
- High current MOSFET modules are available containing several parallel connected chips



in the off state, V_{ds} appears across the depletion region in the n^- region

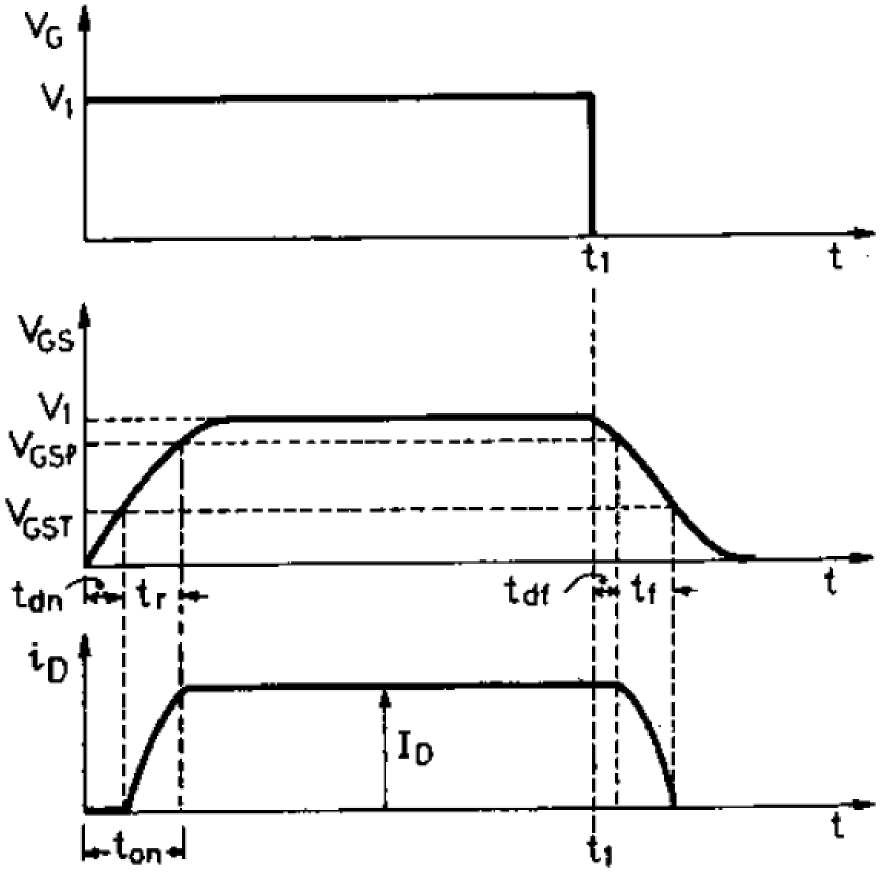


current flow through the conducting channel in the on state



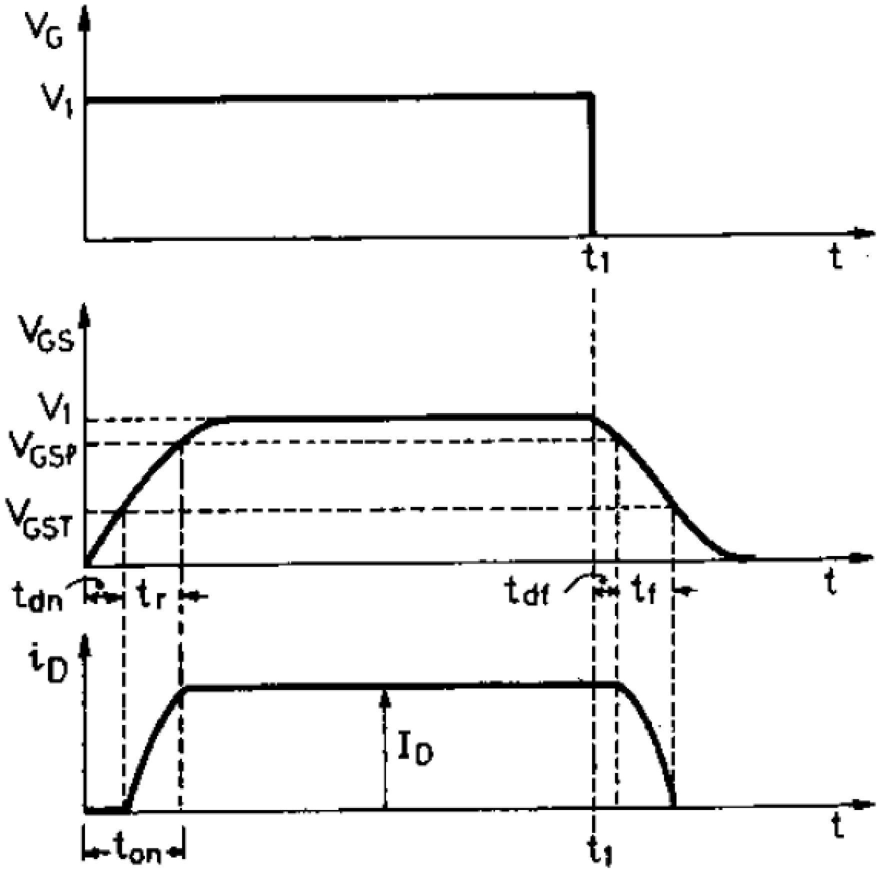
body diode due to the pn^- junction

Switching characteristics



- The switching chara. influenced by internal capacitance of device and internal impedance of gate drive circuit.
- At turn-on, t_{dn} is turn-on delay time during which input capacitance charges to gate threshold voltage V_{GST}
- **t_r** called rise time, during which gate voltage rises to V_{GSP}, voltage sufficient to drive the MOSFET into on state
- During tr, drain current rises from zero to full on current I_D
- **$T_{on} = t_{dn} + t_r$**
- The turn-on time can be reduced by using low-impedance gate drive source.

Switching characteristics

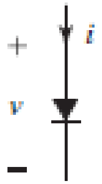
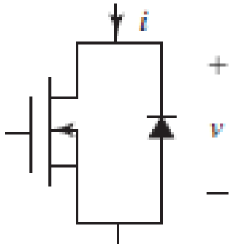
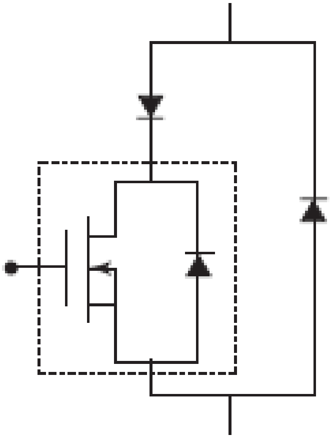


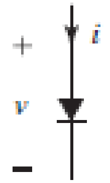
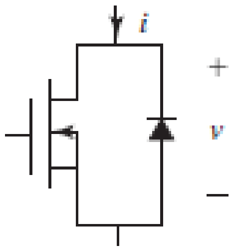
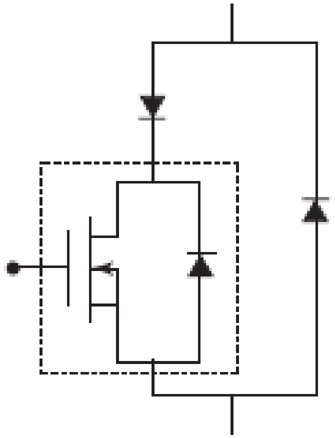
- MOSFET is a majority carrier device, turn-off process is initiated soon after removal of gate voltage at t_1
- T_{df} (turn off delay time) is the time during which input capacitance discharges from overdrive gate voltage V_1 to V_{GSP}.
- The fall time, t_f is the time during which input capacitance discharges from V_{GSP} to threshold voltage
- During t_f, drain current falls from I_D to zero
- So when V_{GS}< $=V_{GST}$, MOSFET turn-off is complete
- Power MOSFETs are very popular in switched mode power supplies

Comparisons of Transistors

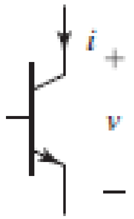
- A diode is one quadrant uncontrolled device
- BJT or an IGBT is one-quadrant controlled device
- A transistor with an antiparallel diode allows withstanding bidirectional current flows
- A transistor in series with a diode allows withstanding positive and negative voltages
- Due to internal diode, MOSFET is a two-quadrant device that allows bidirectional current flow
- Any transistor (MOSFETs, BJTs, IGBTs) in combination with diodes can be operated in four quadrants

Switch Type	Base/Gate Control Variable	Control Characteristic	Switching Frequency	On-State Voltage Drop	Max. Voltage Rating V_s	Max. Current Rating I_s	Advantages	Limitations
MOSFET	Voltage	Continuous	Very high	High	1 kV $S_s = V_s I_s$ $= 0.1$ MVA	150 A $S_s = V_s I_s$ $= 0.1$ MVA	Higher switching speed Low switching loss Simple gate-drive circuit Little gate power Negative temperature coefficient on drain current and facilitates parallel operation	High on-state drop, as high as 10 V Lower off-state voltage capability Unipolar voltage device
COOLMOS	Voltage	Continuous	Very high	Low	1 kV	100 A	Low gate-drive requirement and low on-state power drop	Low-power device Low voltage and current ratings
BJT	Current	Continuous	Medium 20 kHz	Low	1.5 kV $S_s = V_s I_s$ $= 1.5$ MVA	1 kA $S_s = V_s I_s$ $= 1.5$ MVA	Simple switch Low on-state drop Higher off-state voltage capability High switching loss	Current controlled device and requires a higher base current to turn-on and sustain on-state current Base drive power loss Charge recovery time and slower switching speed Secondary breakdown region High switching losses Unipolar voltage device
IGBT	Voltage	Continuous	High	Medium	3.5 kV $S_s = V_s I_s$ $= 1.5$ MVA	2 kA $S_s = V_s I_s$ $= 1.5$ MVA	Low on-state voltage Little gate power	Lower off-state voltage capability Unipolar voltage device
SIT	Voltage	Continuous	Very high	High			High-voltage rating	Higher on-state voltage drop Lower current ratings

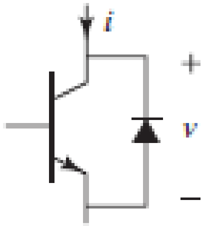
Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Diode					
MOSFET					
MOSFET with two external diodes					

Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Diode		x	x		
MOSFET	x		x	x	
MOSFET with two external diodes	x		x	x	

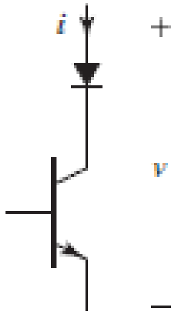
BJT/IGBT

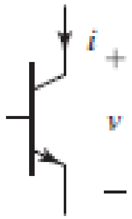
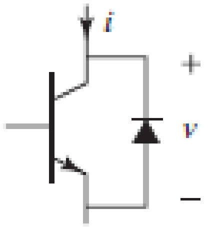
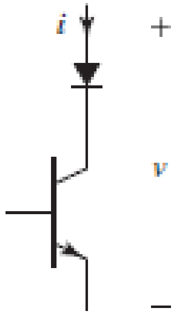


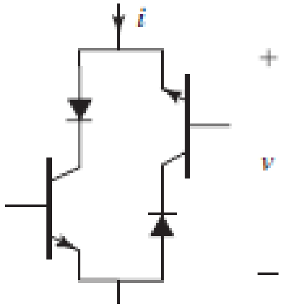
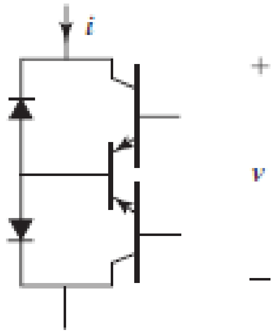
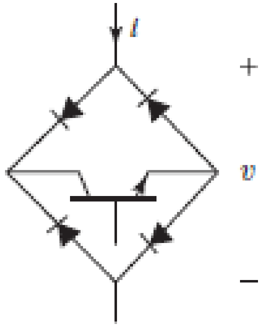
BJT/IGBT with
an antiparallel
diode

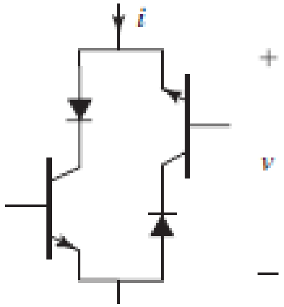
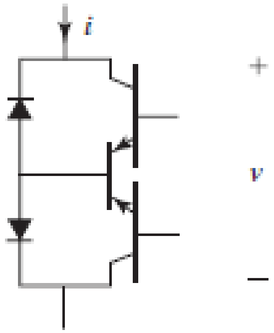


BJT/IGBT with
a series diode



BJT/IGBT	x		x		
BJT/IGBT with an antiparallel diode	x		x	x	
BJT/IGBT with a series diode	x	x	x		

Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Two BJTs/ IGBTs with two series diodes					
Two BJTs/ IGBTs with two antiparal-lel diodes					
BJT/IGBT with four bridge-connected diodes					

Devices	Positive Voltage Withstanding	Negative Voltage Withstanding	Positive Current Flow	Negative Current Flow	Symbol
Two BJTs/ IGBTs with two series diodes	x	x	x	x	
Two BJTs/ IGBTs with two antiparal-lel diodes	x	x	x	x	
BJT/IGBT with four bridge-connected diodes	x	x	x	x