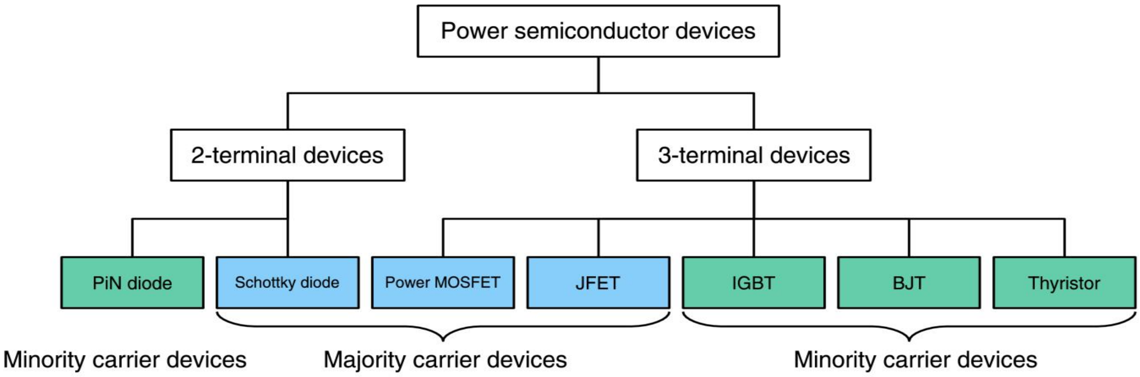
Power Semiconductor Switching Devices

2.1 Classification of power semiconductor switches

- **Power devices are divided into terms of their number of terminals:**
  - The two-terminal devices (diodes), whose state is completely dependent on the external power circuit they are connected to;
  - The three-terminal devices, whose state is not only dependent on their external power circuit, but also on the signal on their driving terminal (gate or base).
- **A second classification has to do with the type of charge carriers they use:**
  - Some devices are *majority carrier devices* (Schottky diode, MOSFET, JFET) - use only one type of charge carriers (i.e., either electrons or holes)
  - Others are *minority carrier devices* (p-n diode, Thyristor, BJT, IGBT) - use both charge carriers (i.e. electrons and holes).
- **A third classification is based on the degree of controllability:** uncontrollable switches (diodes), semi-controllable switches (thyristors), and fully-controllable switches (BJT, MOSFET, JFET, IGBT, GTO, MCT)



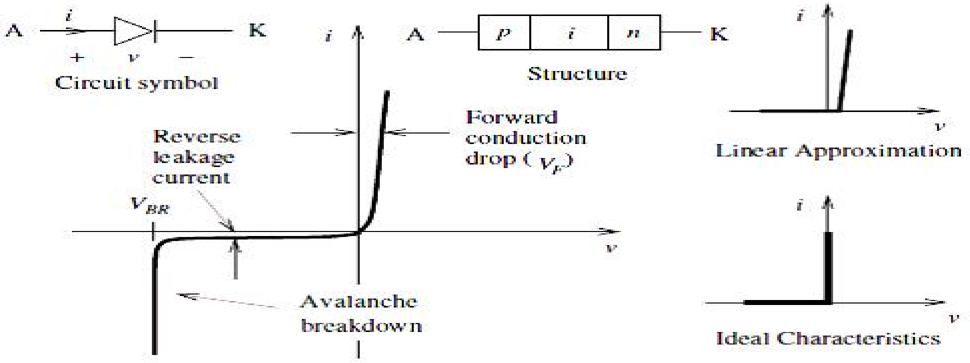
2.2 Brief History

- Power semiconductor devices first appeared in 1952 with the introduction of the power diode.
- The thyristor appeared in 1957. Thyristors are able to withstand very high reverse breakdown voltage and are also capable of carrying high current. One disadvantage of the thyristor for switching circuits is that once it is 'latched-on' in the conducting state it cannot be turned off by external control.
- The first bipolar transistors devices with substantial power handling capabilities were introduced in the 1960s. These components overcame some limitations of the thyristors because they can be turned on or off with a control signal.
- With the improvements of the Metal Oxide Semiconductor technology, power MOSFETs became available in the late 1970s. These devices allow operation at higher frequency than bipolar transistors, but are limited to the low voltage applications.
- The Insulated Gate Bipolar Transistor (IGBT) developed in the 1980s became widely available in the 1990s. This component has the power handling capability of the bipolar transistor, with the advantages of the isolated gate drive of the power MOSFET.

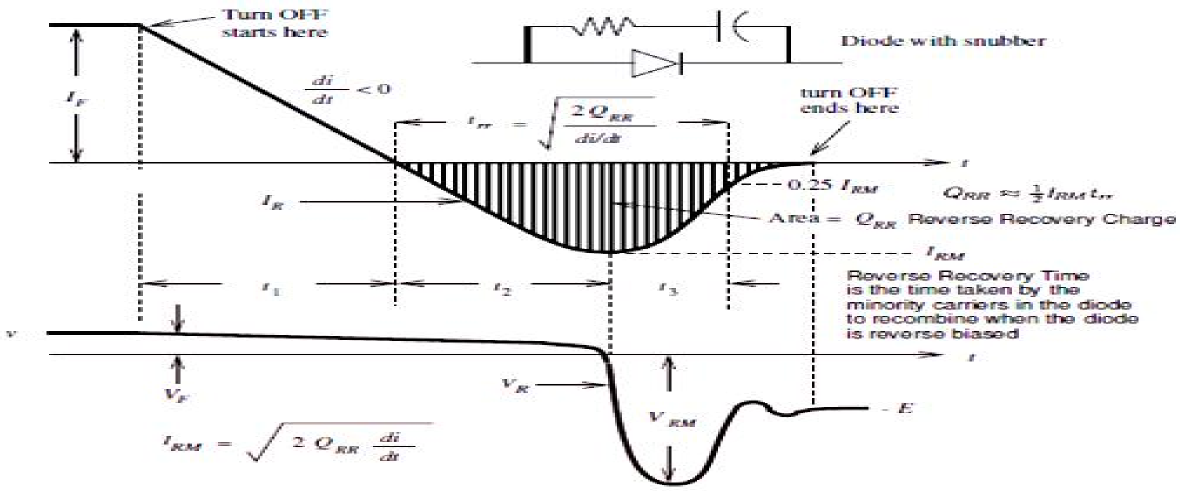
2.3 Power Diodes

- An ideal diode should have the following characteristics:
  - When forward-biased, the voltage across the end terminals of the diode should be zero, whatever the current that flows through it (on-state);
  - When reverse-biased, the leakage current should be zero, whatever the voltage (off-state).

- The transition between on and off states should be instantaneous.
  - The i-v curve of a practical diode is shown below
  - On and off states controlled by the power circuit



2.3.1 Reverse Recovery Characteristics of Power Diodes



2.3.2- Important Specifications of Power diodes:

- Reverse Blocking Voltage (V_{RRM}).
- Forward Average Current ($I_{F(AVE)}$).
- Forward RMS Current ($I_{F(RMS)}$).
- Surge Current Rating (I_{FSM}).
- Maximum On-state Voltage Drop (V_{FM}).
- I2t Rating.
- Reverse Recovery Time (t_{rr}).
- The maximum allowable junction and case temperatures
  (θ_{JM} and θ_{CM}).
- Junction-to-case and case-to-sink thermal resistances
  (R_{qJC} and R_{qCS}).

2.3.3 Types of Power Diodes

1. **Standard Recovery Diodes (general purpose diodes)**

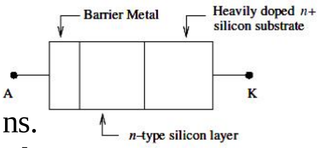
- $t_{rr} \approx 25$ms.
- Leakage current in the OFF-state is of the order of few mA.

- Have lower ON-state voltage drop.
- Available with ratings of several kV and kA.
  Typically used in rectifiers at power frequencies i.e., at 50Hz or 60 Hz.

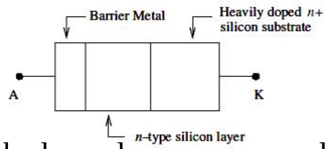
2. Fast Recovery Diodes

- $t_{rr} \leq 5\mu s$.
- Have relatively higher ON-state voltage drop.
- Typically used in D.C.-to-D.C. converters and inverters operating at higher frequencies as freewheeling diodes.

3. Schottky Diodes



- t_{rr} is typically around few ns.
- Have very low ON-state voltage drop of the order of 0.15-0.45 V and consequently very low PON.
- Typically available in voltage ratings in the range 50-200 V.
- Used in circuits having very low output voltages like switched mode power supplies.

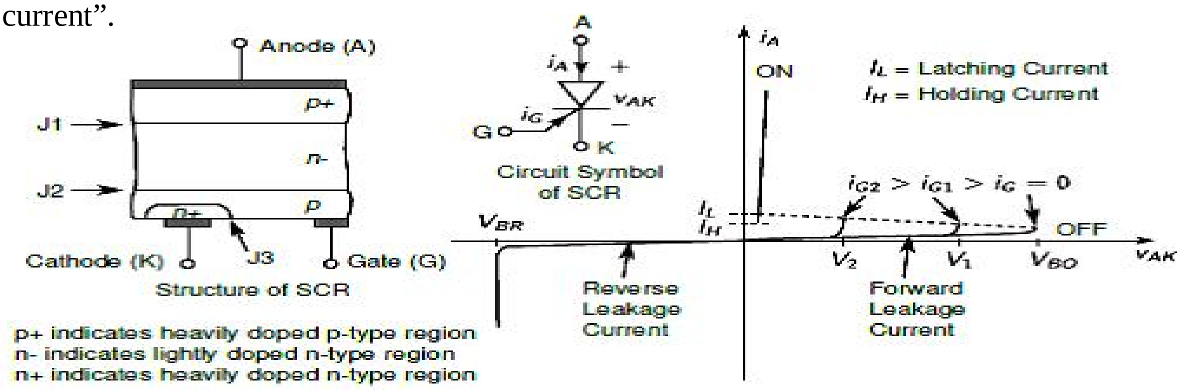


4. **Silicon Carbide Diodes.**

- These are Schottky diodes constructed from silicon carbide.
- Have very low power loss.
- Have extremely fast switching behavior with very-low t_{rr} .
- Can operate at junction temperatures > 225°C.
- Switching behavior is independent of ON-state forward current and temperature.
- Have much lower reverse leakage current than silicon Schottky diodes, and higher reverse voltage rating.
- Very expensive as compared to Si Schottky diodes.

2.4 . Thyristor (SCR)

- A thyristor is a semi-controlled, three-terminal device with four layers of semiconductor material.
- Thyristors have three states:
  1. Reverse blocking mode : Voltage is applied in the direction that would be blocked by a diode
  2. Forward blocking mode: Voltage is applied in the direction that would cause a diode to conduct, but the thyristor has not yet been triggered into conduction.
  3. Forward conducting mode: The thyristor has been triggered into conduction and will remain conducting until the forward current drops below a threshold value known as the "holding current".



2. 4.1- Two Transistor Model of SCR

In Fig.(c) shown on the right, by applying KCL to the device we get

$$I_K = I_A + I_G \quad \text{and} \quad I_A = I_{C1} + I_{C2} \qquad (1)$$

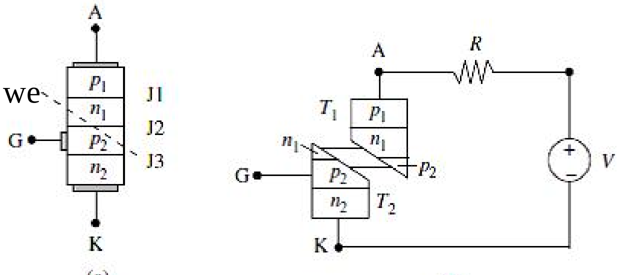
Considering each transistor we have

$$I_{C1} = \alpha_1 I_A + I_{CBO1} \quad \text{and} \quad I_{C2} = \alpha_2 I_K + I_{CBO2} \qquad (2)$$

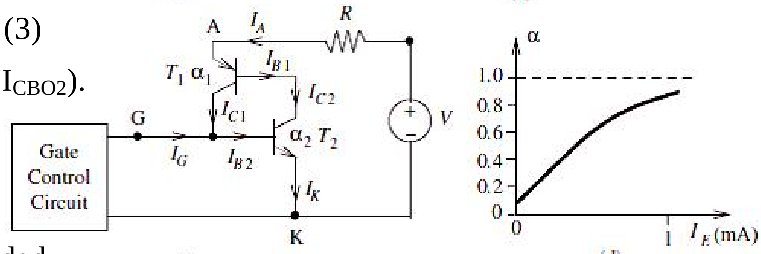
Substituting Eq.(2) in (1) and by rearranging terms we get

$$I_A = \frac{\alpha_2 I_G + (I_{CBO1} + I_{CBO2})}{[1-(\alpha 1+\alpha 2)]} \qquad (3)$$

When $(\alpha 1 + \alpha 2) << 1$ the device is OFF as $I_A \approx (I_{CBO1} + I_{CBO2})$.
When $(\alpha 1 + \alpha 2) \rightarrow 1$ the device turns ON since $I_A \rightarrow \infty$.



(a) (b)



(c) (d)

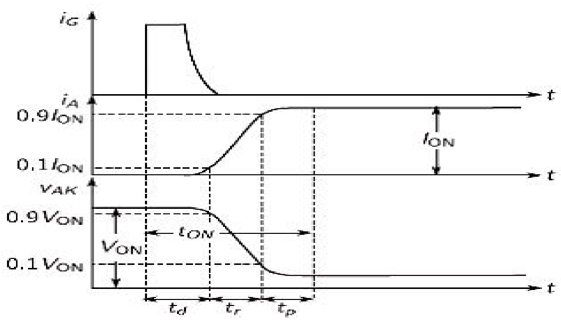
2. 4.2-Factors Causing Turn ON of SCR

- Forward voltage $v_{AK} > V_{BO}$. This should be avoided Since it may permanently damage the device.
- Rise in device temperature can cause unwanted turn ON and hence should be avoided by cooling the device.
- By injecting positive gate current I_G until $I_A = I_L$ where I_L is the latching value. This is the preferred method of turning ON the device.
- Forward dv_{AK}/dt > rated value causes undesirable turn ON and should prevented by connecting a snubber circuit across the SCR.
- Light radiation of specific wavelength incident on junctions of SCR turns ON the device. LASCR's are turned ON by this method.

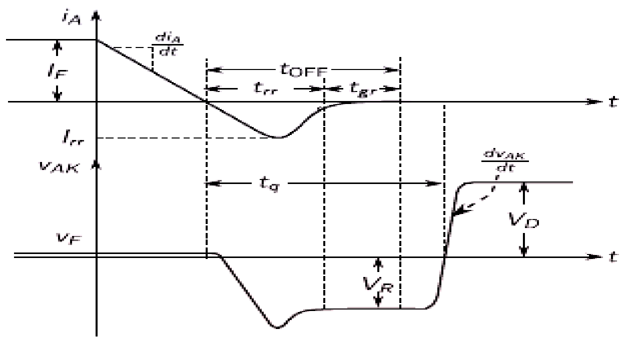
2.4.3- Turn OFF of SCR

- Gate current has no control over the SCR after it turns ON.
- I_A should be reduced below the holding value I_H in order to make $(\alpha 1 + \alpha 2) \rightarrow 0$ to stop the internal regenerative action to turn OFF the device.
- After I_A drops to zero, the device should be reverse biased for a duration $t_q > t_{OFF}$ where t_{OFF} is known as the device turn OFF time and t_q is known as the circuit turn-off time.

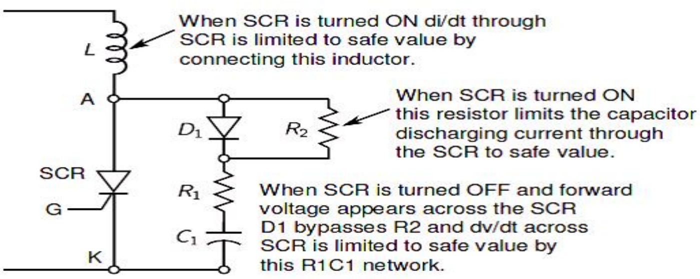
SCR Turn ON Characteristics



SCR Turn OFF Characteristics



Snubber Circuit for SCR



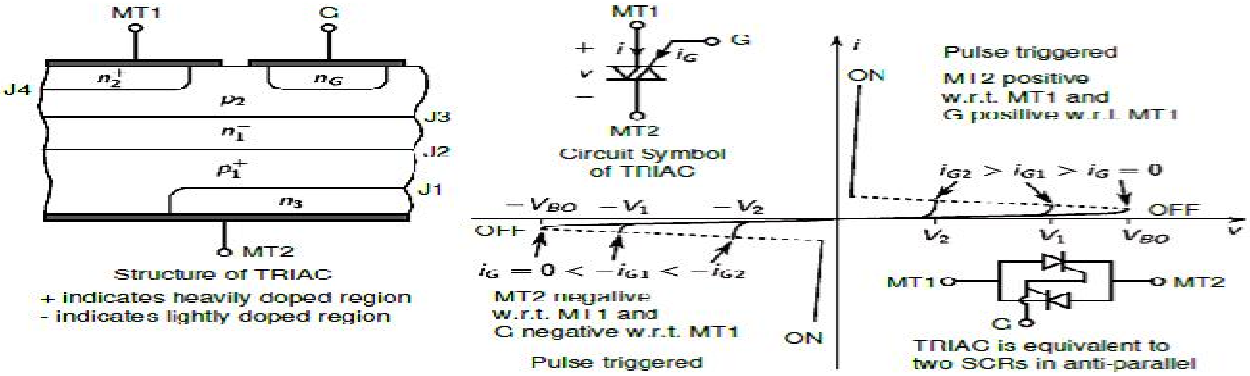
A	–	Anode, ambient	J	–	Junction
(AV)	–	Average	K	–	Cathode
(BO)	–	Breakover	M, m	–	Maximum
(BR)	–	Breakdown	Q, q	–	Turn off
D	–	Off state or non-trigger	R, r	–	Reverse, repetitive
d	–	Delay time	(RMS)	–	RMS value
F, f	–	Forward, falltime	rr	–	Reverse recovery
H	–	Holding	S	–	surge, nonrepetitive
G, g	–	Gate terminal	T, t	–	On-state, trigger

2.5 Triac

•A Tirac belongs to the thyristor (or SCR) family. However, unlike SCRs, which are unidirectional devices (i.e. can conduct current only in one direction), a Triac is bidirectional and so current can flow through them in either direction.

•Another difference from SCRs is that TRIACs can be triggered by either a positive or a negative current applied to its *gate* electrode, whereas SCRs can be triggered only by currents going into the gate.

•Once triggered, the device continues to conduct until the current drops below a certain threshold, called the "holding current".

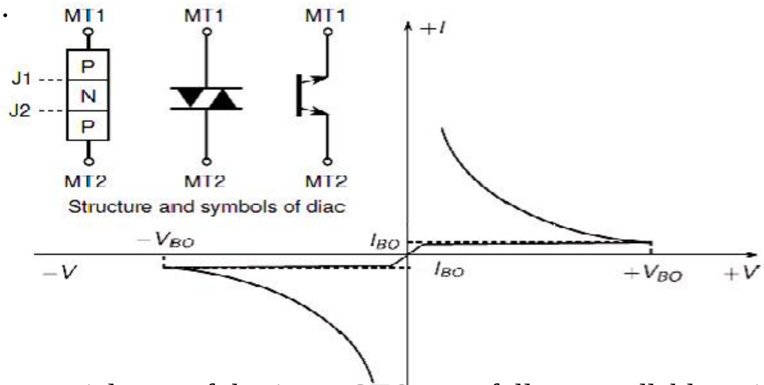


2.5.1 Limitations of TRIAC as Compared to SCRs

- Has lower dv/dt rating.
- Requires well designed R-C snubber connected across it to limit dv/dt.
- Has longer turn-off time.
- Has lower power handling capability.
- Typically used in small motor speed regulators, temperature control, illumination control, liquid level
  control, phase control circuits, power switches.
- Cannot be used in A.C. systems of frequency more than 400 Hz.

2.6 Diac

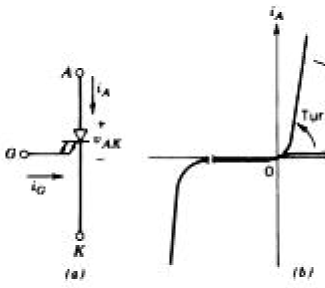
- Diacs are typically used to trigger TRIACS in ceiling fan regulators and light dimming circuits.

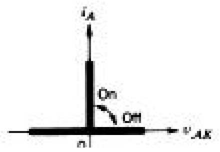


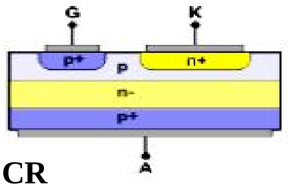
2.7 Gate Turn-Off Thyristor (GTO)

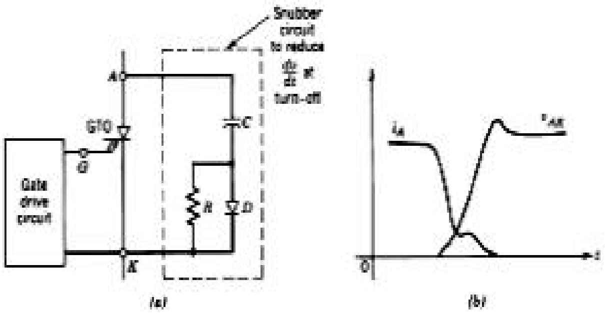
- A **gate turn-off thyristor (GTO)** is a special type of thyristor. GTOs, are fully controllable switches which can be turned on and off by switching the polarity of the gate signal.
  – Turn on is accomplished by a "positive current" pulse between the gate and cathode terminals.
  – Turn off is accomplished by a "negative current" pulse between the gate and cathode terminals.

- Slow switching speeds. Used at very high power levels. Requires elaborate gate control circuitry (needs a turn-off snubber circuit).







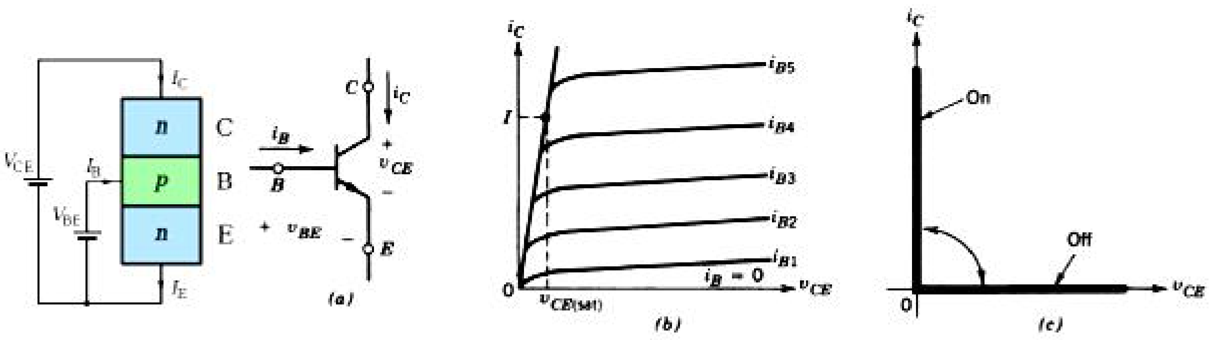


2.7.1 GTO Compared with SCR

GTO	SCR
Fully-controlled	Semi-controlled
$V_{ON} = 3\text{-}4$ V	$V_{ON} = 1.5\text{-}2$ V
Higher I_L and I_H	I_L and I_H very low compared to GTO
Assymetric GTO has very low V_{BR}	Has $V_{BR} \approx V_{BO}$
Typically $dv/dt = 1000$ V/μs	Typically $dv/dt = 200\text{-}500$ V/μs
Turn-off Current Gain: 6-15	Not applicable
Max. operating frequency: 1-4 kHz	Typcally operated at 50 or 60 Hz

2.8 Bipolar Junction Transistor (BJT)

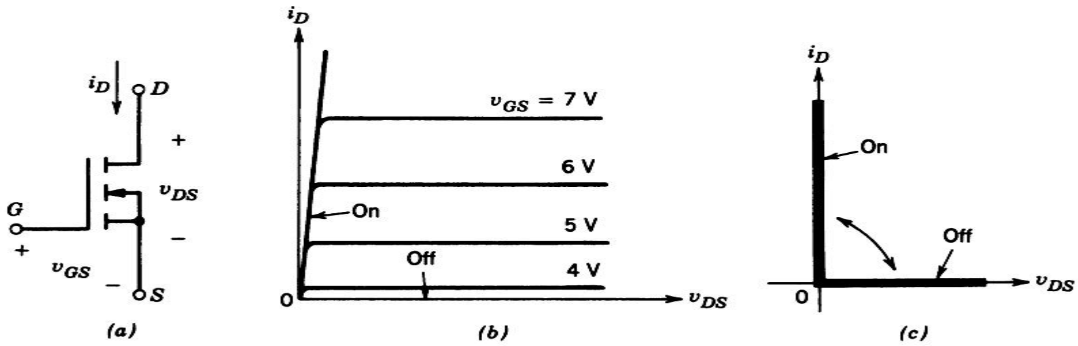
- A BJT is a current-controlled switch that can be considered as two diodes with a shared anode.
- A sufficiently large base current results in the device fully on ($i_B > I_C/h_{FE}$, where h_{FE} is the dc current gain).
- The base current must be supplied continuously to keep the switch turned on.
- Used commonly in the past (now used in specific applications). Being replaced by MOSFETs and IGBTs.



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

2.9 Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET)

- A MOSFET (type of FET) is a voltage-controlled device - easy to control. It uses an electric field to control the shape and hence the conductivity of a channel of majority-charge-carriers in a semiconductor material.
- MOSFETS have *gate*, *drain*, and *source* terminals that correspond roughly to the *base*, *collector*, and *emitter* of BJTs.
- Optimal for low-voltage operation at high switching f7requencies.
- On-state requires continuous application of gate-source voltage of appropriate magnitude



N-channel MOSFET: (*a*) symbol, (*b*) *i–v* characteristics, (*c*) idealized characteristics.

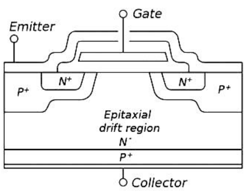
2.10 IGBT

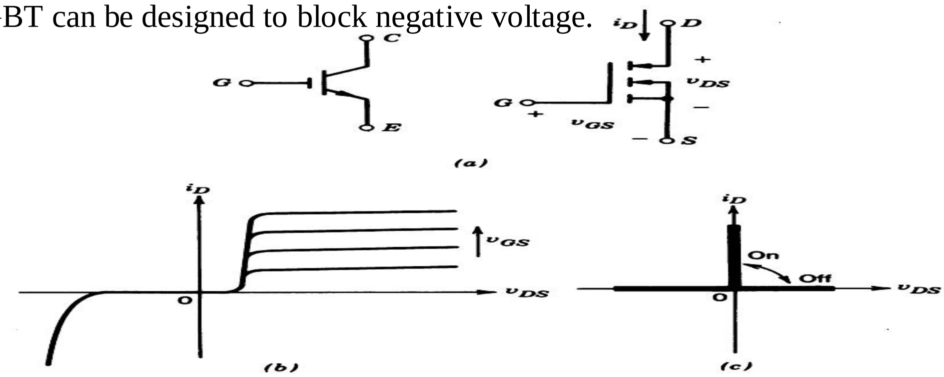
•Advantages over MOSFET, BJT and GTO:

– Similar to the MOSFET, the IGBT has a high impedance gate, thus requires only a small amount of energy to switch the device.

– Like the BJT, the IGBT has a small on-state voltage.

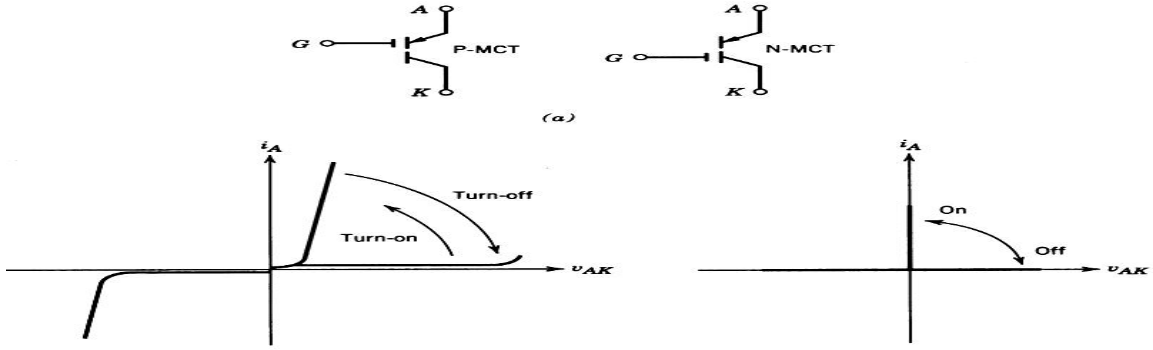
– Similar to the GTO, IGBT can be designed to block negative voltage.





2.11 MOS-CONTROLLED THYRISTOR (MCT)

- An MCT is a relatively 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.
- In an MCT, anode is the reference with respect to which the gate signal is applied. In a conventional SCR, cathode is the reference terminal for the gate signal.



2.12 Summary of Switching Device Capabilities (in terms of voltage, current and frequency)