PART I: POWER ELECTRONICS
CHAPTER ONE

POWER ELECTRONICS FUNDAMENTALS

1.1 INTRODUCTION

The first electronics revolution began in 1948 with the invention of the bipolar silicon transistor at Bell Telephone Laboratories by Bardeen, Brattain, and Schockley. This invention leads to the most recent advanced in electronic technologies seen today. Also, modern microelectronics has evolved over the years from these silicon semiconductors. In 1957, the second electronics revolution started with the development of the four-layer high power commercial thyristor by the General Electric Company in USA. The invention of this device and its later applications in energy processing and motor control fields has initiated a new era of power electronics.

From the early 1960s until quite recently, the thyristor and its family was almost universally used as the high power semiconductor switch which leads to introduction of many different types of energy conversion techniques. The energy conversion using power electronics achieves conversion of electric power from one form to another, using a combination of high-power semiconductor devices and passive components, mainly transformers, inductors, and capacitors. The input and output may be alternating current (a.c.) or direct current (d.c.) and may differ in magnitude and/or frequency. The end goals of a power electronic converter are to achieve high efficiency of conversion, minimize size and weight, and achieve desired regulation of the output.

Power electronic converters can be classified into four different types on the basis of input and output, dc-dc, dc-ac, ac-dc, and ac-ac, named with the first part referring to the input and the second to the output. Development of power semiconductors with very high voltage and current ratings has enabled the use of power electronic converters in many
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industrial and utility applications. The range of applications continues to expand in areas such as power supplies, motor speed control, factory automation, transportation, energy storage, industrial drives, and electric power transmission and distribution. Applications in power transmission include high-voltage d.c. (HVDC) converter stations, flexible a.c. transmission system (FACTS), and static-var compensators. Almost all new electrical or electromechanical equipment, from household air conditioners and computer power supplies to industrial motor controls, contain power electronic circuits and/or systems. Also, engineers involved in conversion and control of power and energy, working in applications ranging from several hundred voltages at a fraction of an ampere for display devices to about 1000 kV at high-voltage d.c. transmission should have a working knowledge of power electronics.

In general these applications require an efficient conversion of voltage and frequency including driving an a.c. electric motor with variable speed requiring in principle constant V/Hz in most industrial applications or variable voltage in d.c. motors in transportation applications as used in electric/hybrid vehicles, electric trains/trams, submarines and ships. Also in utility application to connect various sources of energy (mostly renewable such as wind where wind generator is driven with variable speed /frequency to maximize energy capture and PV where power is generated as d.c. and the voltage available changes heavily with the illumination and proximity to maximum power point) to the a.c. grid (directly or via long high voltage d.c. transmission lines). In addition, in communication engineering, mobile applications may impose additional restrictions regarding size/weight which means higher power densities are required and that can only be achieved (for similar functionality) by power electronics.

By definition, Power Electronics relates power semiconductor devices circuitry, its design and role includes the techniques of converting and processing high power electrical energy. The role of power electronics is shown in Fig.1.1.

![Fig.1.1 The role of power electronics.](image)
Power semiconductor devices are used, such as power diodes, thyristors and power transistors. These power semiconductor devices are so important in modern power control. They are used in switching applications where they compete with “mechanically-operated" or “electrically-operated” switches and they give the following advantages:

1. Faster in operation by a factor of at least a hundred times.
2. Need no routine maintenance.
3. Do not stick, bounce or wear.
4. Give no sparking on break.
5. Have a very long life expectancy when used properly.
6. Are physically small.
7. Are relatively cheap.

The main goal of electronic power conversion systems is to convert electrical energy from one form to another, from the source to the load using power semiconductor devices with, high efficiency, high availability, high reliability, small size, light weight and low cost. Hence, in addition to the simple on-off applications of power semiconductor devices their speed of operation and life expectancy, which are independent of the number of switching actions, make them possible to arrange for smooth control of the mean power from zero to maximum in most applications.

1.2 POWER ELECTRONICS APPLICATIONS

The main fields of applications are in Energy Processing and Drive Technology. Power semiconductor devices are interconnected in a variety of ways to form power control units. These units can be classified in a variety of ways, one of the simplest being to classify them according to their input/output requirements, thus, referring to Fig.1.2.

![Power Electronics Applications Diagram](image)

**Fig.1.2** Power or energy processing through power electronics converters.
(1) **AC-DC (Rectifiers)**: Circuits for converting a.c. voltage to d.c. voltage or transfer of power from an alternating current (a.c.) supply to direct current (d.c.) form. These circuits can be of two main types:
   (a) AC-DC (Uncontrolled)
   (b) AC-DC (Controlled)

(2) **DC-AC (Inverters)**: Circuits for converting a d.c. voltage to an alternating one or transfer of power from a direct current supply to alternating current form. The output power can be at any desired voltage and/or frequency.

(3) **DC-DC Converters**: Circuits change a fixed d.c. voltage into a variable d.c. supply, i.e. transfer of power from a direct current supply directly into a direct current load of different voltage level. These types of converters are usually called d.c. choppers.

(4) **AC-AC Converters**: Circuits change a fixed a.c. voltage into a variable a.c. supply, i.e. transfer of power from an alternating current supply directly into an alternating current load of different voltage level at fixed frequency or variable frequency. These converters are usually of two types:
   (a) AC voltage controllers: Change the a.c. supply voltage magnitude only keeping the frequency unchanged.
   (b) Cycloconverters or matrix converters: Change the a.c. supply directly to a variable a.c. supply both in magnitude and frequency (also called static frequency changers).

### 1.3 POWER SEMICONDUCTOR DEVICES

Power electronics evolution is a result of the evolution of power semiconductor devices. The Power semiconductor switches are the workhorses of power electronics (PE). There are several power semiconductor devices currently involved in several industrial applications. PE switches work in two states only: Fully on (conducting), and fully off (blocking). Switches are very important and crucial components in power electronic systems. The ideal or good switch must have the following characteristics:

- Very low or negligible power loss during turning ON or OFF.
- Switching times between ON and OFF states should be very low.
- Small power required to turn it ON or OFF.
- Bidirectional and voltage blocking capability.
- Adequate voltage and current ratings.

Practical power semiconductor switches are not perfect. They usually have a very low on-state resistance that result in conduction voltage drop
across the switch itself. In the off-state, these switches possess a very high resistance which results leakage current in both the forward and reverse directions depending on the polarity of the applied voltage. However, the ratings of the power switch in practical case shall include:

- Ratings: blocking voltage and carrying current.
- Speed: any real device requires a definite time to switch.
- Second-order ratings: \(di/dt, dv/dt\), momentary capabilities.
- Power loss.
- Thermal ratings: need for heat sinks.
- Control ratings: method of operation of the switch.

### 1.4 TYPES OF POWER SEMICONDUCTOR SWITCHES

The main types of power semiconductor switches are:

1. Power Diodes

2. Thyristor devices
   a. Silicon controlled rectifier (SCR)
   b. Triac (Triode ac switch)
   c. Gate turn-off thyristor (GTO)
   d. MOS controlled thyristor (MCT)
   e. Integrated gated-commutated thyristor (IGCTs)
   f. Static induction thyristor (SITH)

3. Power transistors
   a. Bipolar junction transistor (BJT)
   b. Metal oxide semiconductor field effect transistor (MOSFET and COOLMOS)
   c. Insulated gate bipolar transistor (IGBT)
   d. Static induction transistor (SIT)

4. Power integrated circuit and power modules
   a. Monolithic integration : power integrating circuit
      (i) High voltage integrated circuit (HVIC)
      (ii) Smart power integrated circuit (SPIC)
   b. Packaging integration: power modules
      (i) Ordinary power module: power devices packaged together
      (ii) Intellegent power module (IPM): power devices, drive circuit, protection circuit
      (iii) Integrated power electronics module (IPEM): power devices, drive circuit, protection circuit, control circuit.
These devices are based on the mature and very well established silicon technology. However, Si exhibits some important limitations regarding its voltage blocking capability, operation temperature and switching frequency. In some industrial applications where electronic systems based on traditional Si power devices cannot operate, a new generation of power devices based on Wide Band Gap Semiconductors such as silicon carbide SiC and gallium nitrate GaN are used. These new devices present high-voltage blocking capability, high-temperature operation and high switching frequencies. Therefore, the power switching devices may also be divided into high voltage devices (mostly IGBTs), low voltage devices (mostly discrete MOSFETs), wide band gap devices (GaN and SiC MOSFETs and diodes), and integrated power (also sometimes known as smart power).

1.4.1 Power Diode

Power diode is usually used as a switch; it is the simplest one among other power electronics switches. It is a two terminal device formed of a PN junction as shown in Fig.1.3(a). Terminal A known as the anode and terminal K known as the cathode. It is not controllable and its operating states are determined by the circuit operating point. When diode is forward biased, i.e. terminal A becomes at a higher potential compared to terminal K, it conducts current \( i_D \) in the direction as shown, i.e. a forward positive voltage \( V_F \) will turn it on. When it reversed biased (a reverse negative current from cathode to anode) will turn it off. With forward biasing a small voltage drop \( V_D \) will appear across it typically it ranges from 0.6 to 1.0 V for currents in the normal range, which under ideal conditions is usually ignored. However, when a diode is reverse biased, it does not conduct and the diode then experiences a small current \( I_s \) flowing in the reverse direction called the leakage current. Both forward voltage drop and leakage current are ignored in an ideal diode or in power electronics applications.

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Fig.1.3 Power diode: (a) Symbol, (b) Characteristic, and (c) Ideal characteristic.
Practically, the diode characteristic consists of two regions, as shown in Fig.1.3(b):

(a) A forward bias region (on-state) where both $v_D$ and $i_D$ are positive and the current in this region increases exponentially with the increase in the voltage, and,

(b) A reversed bias region (off-state) where both $v_D$ and $i_D$, are negative and very small leakage current (μA to mA) flows through the diode until the applied reverse voltage reaches the diode’s breakdown voltage limit $V_{BR}$.

Ideally, the diode is represented by a short circuit when forward biased and as an open circuit when reversed biased with the ideal characteristic shown in Fig.1.3(c). In general, for each diode, there is a small delay in going from off-state to on-state due to the time required for the carriers to build up. During turn-off, the excess carriers in the drift region have to be removed. Thus, for a short time, the diode conducts in the reverse direction with a high voltage across it. This phenomenon, known as reverse recovery, leads to significant power loss and becomes one of the limiting factors in high-frequency circuits.

### 1.4.1.1 Diode parameters

1. **DC diode parameters**

The most important parameters of a power diode are the following:

- Forward voltage $V_F$ is the voltage drop of a diode across A and K at a defined current level when it is forward biased.
- Breakdown voltage $V_{BR}$ is the voltage drop across the diode at a defined current level when it is beyond reverse-biased level. This is known as avalanche.
- Reverse current $I_R$ is the current at a particular voltage, and which is below the breakdown voltage.

2. **AC diode parameters**

- Forward recovery time $t_{FR}$ is the time required for the diode voltage to drop to a particular value after the forward current starts to flow.
- Reverse recovery time $t_{rr}$ is the time interval between the application of reverse voltage and the reverse current dropped to 0.25 of $I_{rm}$ (reverse maximum current), as shown in Fig. 1.4.
1.4.1.2 Classifications of power diode

PN junction type power diodes are classified as:

1. Line frequency diodes: For low frequency rectifications.
   - On-state voltage very low (below 1V).
   - Large reverse recovery time $t_{rr}$ (about 25 µs).
   - Very high current (up to 6 kA) and voltage (8 kV) ratings.
   - Used in line-frequency (50/60 Hz) applications such as rectifiers.
   - Slow recovery, as illustrated in Fig.1.4.

2. Fast and ultra-fast recovery diode: For high frequency rectifications.
   - Very low $t_{rr}$ (< 1 µs).
   - Power levels at several hundred volts and several hundred amperes.
   - Normally used in high frequency circuits.

3. Schottky diode: These are based on metal-semiconductor junctions. These junctions have a lower junction potential leading to a lower forward voltage drop.
   - Silicon-based Schottky power diodes have forward voltage drop ranging from 0.3 to 0.6 V,
   - Can withstand reverse voltages up to 200 V. As opposed to PN junction diodes, Schottkys are majority carrier devices, so they do not have any reverse recovery.
   - They are used in low voltage, high current application such as switched-mode power supplies.

4. SiC Schottky diode: Recently, SiC-based Schottky diodes have been replaced the Si-based diodes due to their thermal capabilities.
1.4.2 Thyristors (Silicon Controlled Rectifiers “SCRs”)

The thyristor, it is also called silicon controlled rectifier (SCR), is a four-layer, three terminal switching semiconductor device, with each layer consisting of an alternately N or P-type material, for example N-P-N-P. The main terminals, labeled anode A and cathode K, are across the full four layers, and the control terminal, called the gate G, is attached to one of the middle layers. The thyristor symbol and its two-transistor analogy is shown in Fig.1.5. In contrast to the linear relation that exists between load and control currents in a transistor, the thyristor is bistable. The anode and cathode terminals are connected in series with the load to which power is to be controlled. The gate electrode which is the control terminal may be connected to an integrated and complex structure as part of the device.

![Thyristor Symbol and Two-Transistor Analogy](image)

Fig.1.5 The thyristor and its equivalent two-transistor analogue.

Thyristors are mainly used where high currents and voltages are involved, and are often used to control alternating currents, where the change of sign of the current causes the device to automatically switch off. Like a diode, a thyristor conducts only in one direction and used to approximate ideal closed (no voltage drop between anode and cathode) or open (no anode current flow) switch for control of power flow in a circuit. All thyristor types are controllable in switching from a forward blocking state (positive voltage applied to the anode with respect to the cathode) into a forward-conduction state (large forward anode current flowing with a small anode-cathode voltage drop).

Ideally, SCRs are represented by a short circuit when operating within the conduction region and as an open circuit when operating within the blocking region. The ideal characteristic is shown in Fig.1.6(a). After switching from a forward-blocking state into the forward-conduction state, most thyristors have the characteristic that the gate signal can be
Fig. 1.6 (a) Thyristor ideal characteristic, (b) Thyristor gate circuit.

removed and the thyristor will remain in its forward-conduction mode. This means that once the thyristor is turned-on, the gate loses control. This property, called “latching”, is an important distinction between thyristors and other types of power electronic devices. This latching (triggering) process is carried out by injecting current to the gate terminal \(i_g\) or applying a low voltage, short duration pulse \(v_g\) to the gate (typically 4 V, 100 µs), Fig.1.6(b), at the required latching instant provided that the device is forward biased \(v_{AK}\) is positive).

1.4.2.1 Static Characteristics of the Thyristor

Practically, the static thyristor characteristic or the Current-Voltage curves for thyristors has three main regions as shown in Fig.1.7.

Fig.1.7 Static volt-ampere characteristics of a thyristor.
• The Conduction Region where the thyristor is operating in its on-state,
• The Forward Blocking Region where the thyristor is forward biased but not yet triggered or the voltage did not reach the forward breakover voltage, and
• The Reverse Region that consists of the reverse blocking region and the reverse avalanche region similar to the diode characteristic.

The operation of thyristors is as follows: When a positive voltage is applied to the anode (with respect to a cathode), the thyristor is in its forward-blocking state. The center junction $J_2$ (see Fig.1.5) is reverse-biased. In this operating mode the gate current is held to zero (open-circuit). As long as the forward applied voltage does not exceed the value necessary to cause excessive carrier multiplication in the depletion region around $J_2$ (avalanche breakdown), the thyristor remains in an off-state (forward blocking). If the applied voltage exceeds the maximum forward blocking voltage of the thyristor, it will switch to its on-state. However, this mode of turn-on causes non-uniformity in the current flow, is generally destructive, and should be avoided.

When a positive gate current is injected into the device, it becomes forward-biased and electrons are injected from the n-emitter into the p-base. Some of these electrons diffuse across the p-base and are collected in the n-base. This collected charge causes a change in the bias condition of $J_1$. This change will cause holes to be injected from the p-emitter into the n-base. These holes diffuse across the n-base and are collected in the p-base. The addition of these collected holes in the p-base acts the same as gate current. The entire process is regenerative and will cause the increase in charge carriers until $J_2$ also becomes forward biased and the thyristor is latched in its on-state (forward-conduction). The regenerative action will take place as long as the gate current is applied in sufficient amount and for a sufficient length of time. This mode of turn-on is considered to be the desired one as it is controlled by the gate signal.

This switching behavior can also be explained in terms of the two-transistor analog shown in Fig. 1.5. The two transistors are regeneratively coupled so that if the sum of their forward current gains ($\alpha$'s) exceeds unity, each drives the other into saturation. However, Thyristor can only be turned on with three conditions:

1. The device must be forward biased, i.e. the anode should be more positive than the cathode.
2. A positive gate current ($i_g$) should be applied at the gate.
3. The current through the thyristor should be more than or equal to the latching current.
Once conducting, the anode current is LATCHED (continuously flowing).

1.4.2.2 Thyristor Parameters

The important points for the thyristor characteristic which can be considered as the thyristor parameters are,

**Latching Current:** This is the minimum current required to turn on the SCR device and convert it from the Forward Blocking State to the ON State.

**Holding Current:** This is the minimum forward current flowing through the thyristor in the absence of the gate triggering pulse.

**Forward Breakover Voltage:** This is the forward voltage required to be applied across the thyristor to turn it on without the gate signal application.

**Max Reverse Voltage:** This is the maximum reverse voltage to be applied across the thyristor before the reverse avalanche occurs.

**Peak Inverse Voltage:** It is the maximum voltage which the device can safely withstand in its off-state.

**ON-State Voltage:** The voltage which appears across the device during its on-state is known as its on-state voltage.

**Rate of rise of voltage \( \frac{dv}{dt} \):** The rate at which the voltage across the device rises without triggering the device is known as its rate of rise of voltage.

**Current Rating:** The current carrying capacity of the device is known as its current rating.

It is also worth mentioning that once the SCR is triggered and turned ON the gate signal can be removed without turning it OFF. SCRs are turned OFF when reversing the terminal voltage and current. The thyristor turning ON and OFF mechanisms are illustrated in the following subsections.

1.4.2.3 Thyristor Turning ON Mechanism

In reverse-biased mode, the SCR behaves like a diode. It conducts a small leakage current which is almost dependent of the voltage, but increases with temperature. When the peak reverse voltage is exceeded, avalanche breakdown occurs, and large current will flow. In the forward biased mode, with no gate current present (i.e. in the untriggered state, the device exhibits a leakage current. If the forward breakover voltage \( V_{Bo} \) is exceeded, the SCR “self-triggers” into the conducting state and the voltage collapses to the normal forward volt-drop, typically 1.5-3 V. The presence of any gate current \( i_g \) will reduce the forward breakover voltage and will trigger the thyristor at any required instant (\( \alpha \)), also called firing angle, see Fig.1.8.
Methods of turning ON the thyristor

The turning on process of the thyristor is known as “Triggering”. There are several methods to turn on the thyristor and change its state from Forward-Blocking state to Forward-Conduction state. These methods can be summarized as:

(a) GateTriggering

This is the most general (practical) method to turn on the thyristor by applying positive voltage between the gate and the cathode to a forward biased thyristor. In this case charge carriers are injected in the inner p-layer, thereby reducing the depletion layer thickness. This will increase the anode current and regenerative action starts. Once the thyristor is turned on, there will be no need to the gate voltage or current, thus, in gate triggering method, instead of applying continuous signal, pulse triggering is preferable.

(b) High Forward Voltage Triggering

In this mode, an additional forward voltage is applied between anode and cathode. When the anode terminal is positive with respect to cathode ($V_{AK}$), Junction $J_1$ and $J_3$ is forward biased and junction $J_2$ is reverse biased. No current flows due to depletion region in $J_2$ is reverse biased (except leakage current). As $V_{AK}$ is further increased, at a voltage $V_{BO}$ (Forward Break Over Voltage) the junction $J_2$ undergoes avalanche breakdown and so a current flows and the device tends to turn ON (even when gate is open).
(c) Thermal (or) Temperature Triggering

The width of depletion layer of SCR decreases with increase in junction temperature. Therefore in SCR when $V_{AR}$ is very near its breakdown voltage, the device is triggered by increasing the junction temperature. By increasing the junction temperature the reverse biased junction collapses thus the device starts to conduct.

(d) Radiation Triggering (or) Light Triggering

For light triggered SCRs a special terminal niche is made inside the inner p-layer instead of gate terminal. When light is allowed to strike this terminal, free charge carriers are generated. When intensity of light becomes more than a normal value, the thyristor starts conducting. This type of thyristors are called as Light Activated SCR “LASCR”.

(e) $dv/dt$ Triggering:

When the device is forward biased, $J_1$ and $J_3$ are forward biased, $J_2$ is reverse biased. Junction $J_2$ behaves as a capacitor, due to the charges existing across the junction. If voltage across the device is $V$, the charge is represented by $Q$ and capacitance by $C$ then,

$$i_c = dQ/dt$$

$$Q = CV$$

$$i_c = d(CV)/dt$$

$$= C. dV/dt + V. dC/dt$$

as $dC/dt = 0$

$$i_c = C.dV/dt$$

Therefore when the rate of change of voltage across the device becomes large, the device may turn on, even if the voltage across the device is small.

1.4.2.4 Thyristor Turning OFF Mechanism (Thyristor Commutation)

The process of turning off a thyristor is defined as "Commutation". Thyristor cannot be turned off by applying negative gate current. It can only be turned off if the current $I$ through it goes negative (reverse). In all commutation techniques, a reverse voltage is applied across the thyristor during the turn off process.

There are two methods by which a thyristor can be turned off.

(a) Natural Commutation
(b) Forced Commutation
For natural commutation, in a.c. circuit, the current always passes through zero for every half cycle. As the current passes through natural zero, a reverse voltage will simultaneously appear across the device. This will turn off the device immediately. This happens when negative portion of the sine-wave occurs. This process is called as "natural commutation" since no external circuit is required for this purpose.

In forced commutation, the anode current is "diverted" to another circuitry. To turn off a thyristor, the forward anode current should be brought to zero for sufficient time to allow the removal of charged carriers. In case of d.c. circuits the forward current should be forced to zero by means of some external circuits. One typical thyristor commutation circuit is shown in Fig.1.9. Thyristor $T_m$ is the main thyristor through which the flow of power is controlled. Capacitor C and the four thyristors ($T_1, T_2, T_3, T_4$) is the commutation circuit. The function of the commutation circuit is to switch off the main thyristor at the end of each on period. During on period of the thyristor, the two auxiliary thyristors $T_2$ and $T_4$ are triggered so that the capacitor C is charged such as plate $a$ is positive. To switch off, thyristors ($T_1, T_3$) are triggered on. This results in applying reverse polarity voltage across $T_m$ and hence it will be switched off. Also the capacitor polarity will be reversed; i.e. plate $b$ will now be positive. Thyristor $T_m$ is switched on for the next on period, and now to switch off $T_m$, thyristors ($T_2, T_4$) are switched on, and so the cycle is repeated (see Appendix B for more details about forced commutation circuits).

Fig.1.9 Typical forced commutation circuit for a thyristor.

1.4.2.5 Types of Thyristors

1. Phase Controlled
   - Rectifying line frequency voltage and current for a.c. and d.c. motor drives.
   - Large voltage (up to 7 kV) and current (up to 5 kA) type-1 capability.
   - Low on-state voltage drop (1.5 to 3 V).
2. **Inverter Grade**
   - Used in inverter and chopper
   - Quite fast, can be turned-off using “force commutation” method.

3. **Light Activated (Photo Activated)**
   - Similar to phase controlled, but triggered by pulse of light. This is mainly used with optocoupler or optoisolator.
   - Normally very high power ratings.

SCR ratings for voltage and current approach those of diodes. Devices for high-voltage d.c. (HVDC) conversion have been built with simultaneous 12 kV and 6 kA type-2 ratings. Fig. 1.10 shows photograph for different types of thyristors used in practice.

![Photo of power semiconductor switches (thyristors).](image)

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**1.4.3 The Triac**

The triac, also called ‘**Bidirectional Thyristor**’, is a two thyristors connected back-to-back, used for high or medium power control for both a.c. and d.c. applications, as shown in Fig.1.11. Either of the electrodes MT1 and MT2 can act as anode and either is cathode. The device can be triggered by either positive or negative voltage on the gate with respect to MT1. This device is effectively two thyristors (SCR s) back-to-back in construction with an external n-region which is the gate. Both SCRs are mounted within an encapsulated enclosure and there is one gate terminal. The application of positive anode voltage with positive gate pulse to an inert device causes switch-on in the forward direction. If the anode voltage is reversed, switch-off occurs when the current falls below its holding value, as for an individual SCR. Voltage blocking will then occur in both directions until the device is gated again, in either polarity, to obtain conduction in the desired direction. Hence, the four possible modes of operation of a triac can be summarized as:
Power electronics and drives

Fig. 1.11 The Triac.

(a) MT2 +, G +: (both relative to MT1) Gate current flows into gate terminal.
(b) MT2 +, G −: Gate current opposite to (a)
(c) MT2 −, G +: Gate current as (a)
(d) MT2 −, G −: Gate current as (b)

Compared with individual SCRs, the triac combination is a low-voltage, lower power, and low-frequency switch with applications usually restricted below 400 Hz. The triac v-i characteristics is shown in Fig.1.12.

Fig. 1.12 Triac characteristic.

1.4.4 Gate Turn off Thyristors (GTO)

A gate turn-off thyristor (known as a GTO) is a three-terminal power semiconductor device that belongs to a thyristor family with a four-layer structure. They also belong to a group of power semiconductor devices that have the ability to fully control on and off states via the control terminal (gate). The design, development, and operation of the GTO are easier to understand if we compare it to the conventional thyristor. Like a
thyristor, applying a positive gate signal to its gate terminal can turn on a GTO. Unlike a standard thyristor, a GTO is designed to turn off by applying a negative gate signal.

There are two types of GTOs: asymmetrical and symmetrical. The asymmetrical GTOs are the most common type on the market. This type is normally used with an anti-parallel diode and hence do not have high reverse-blocking capability. Reverse conducting is accomplished with an anti-parallel diode integrated onto the same silicon wafer. The symmetrical GTOs have equal forward and reverse-blocking capability.

GTO behaves like normal thyristor, but can be turned off using gate signal. The turning off process is difficult, needs very large reverse gate current (normally 1/5 of anode current). It means a 2000 A rating GTO requires 400 A gate current pulse to switch it off but for very short time. Therefore, the gate pulse duration and the power loss due to the gate pulse is small and it can be supplied by low voltage power MOSFETs. The GTO symbol and characteristics are shown in Fig. 1.13. The basic structure of a GTO, a four-layer p-n-p-n semiconductor device, is very similar in construction to a thyristor. It has several design features that allow it to be turned on and off by reversing the polarity of the gate signal.

Fig. 1.13 Gate turns off (GTO) thyristor.

The turn-on mode is similar to that of a standard thyristor. The injection of the hole current from the gate forward biases the cathode p-base junction, causing electron emission from the cathode. These electrons flow to the anode and induce hole injection by the anode emitter. The injection of holes and electrons into the base regions continues until charge multiplication effects bring the GTO into conduction. This is shown in Fig. 1.14(a). The GTO structure is also shown in Fig. 1.14(b).
As with a conventional thyristor, only the area of cathode adjacent to the gate electrode is turned on initially and the remaining area is brought into conduction by plasma spreading. However, unlike the thyristor, the GTO consists of many narrow cathode elements, heavily interdigitated with the gate electrode, and therefore the initial turned-on area is very large and the time required for plasma spreading is small. The prime design goal of GTO devices are to achieve fast turn off time and high current turn off capability. The GTO's turn off occurs by removal of excess holes in the cathode base region by reversing the current through the gate terminal. The ratings, merits and demerits of the device are,

- **Ratings:** Voltage $V_{ak} < 6 \text{ kV}$ (4500 V), Current $I_a < 3 \text{ kA}$.
- Frequency $< 5 \text{ kHz}$.
- Gate drive design is very difficult, need very large reverse gate current to turn off.
- GTO normally requires snubbers: A GTO normally requires a $dv/dt$ snubber circuit to conduct actual turn-off operation under high voltage and high current condition. High power snubbers are expensive.
- A reverse conducting GTO has been fabricated that can block 6 kV in the forward direction, interrupt a peak current of 3 kA, and has a turn-off gain of 5.
- In very high power region ($> 6 \text{ kV}$, $> 3 \text{ kA}$), a modified GTO structure, called a gate commutated thyristor (GCT), has been designed and manufactured that commutates all of the cathode current away from the cathode region and diverts it out the gate contact. The GCT is similar to a GTO in structure except that it has a low-loss n-buffer region between the n-base and p-emitter; see Fig.1.14. Development in gate-controlled thyristor (GCT) may effectively end the future of GTO.
The Advantages and Disadvantages of GTO are:

Advantages of the GTO include:
1. High current-voltage capability.
2. Low conduction loss.
3. Low cost.

Disadvantages
1. Non-uniform turn-off and $dv/dt$ snubber required.
2. Non-uniform turn-on $di/dt$ snubber required.
3. Current control-high gating power.
4. Long switching time-long storage time, minimum on-time and off-time requirements.
5. No current limitation capability.

1.4.5 Power Transistors

There are many different types of Power Transistor include MOSFETs ranging from 500V to 1500V, silicon carbide (SiC) MOSFETs featuring the industry’s highest temperature rating of 200 °C, IGBTs with breakdown voltages ranging from 350 V to 1300 V and a wide range of power bipolar transistors. These devices can be turned “ON” and “OFF” by relatively very small control signals, operated in SATURATION and CUT-OFF modes only. No “linear region” operation is allowed due to excessive power loss.

1.4.5.1 Bipolar Junction Transistor (BJT)

Power bipolar junction transistors (BJTs) play a vital role in power circuits. Like most other power devices, power transistors are generally constructed using silicon. The use of silicon allows operation of a BJT at higher currents and junction temperatures, which leads to the use of power transistors in a.c. applications where ranges of up to several hundred kilowatts are essential.

The power transistor is part of a family of three-layer devices. The three layers or terminals of a transistor are the base, the collector, and the emitter. Effectively, the transistor is equivalent to having two $pn$-diode junctions stacked in opposite directions to each other. The two types of a transistor are termed $nnp$ and $pnp$. The $nnp$-type transistor has a higher current-to-voltage rating than the $pnp$ and is preferred for most power conversion applications. Fig. 1.15 shows the symbol of a BJT $nnp$-type transistor and its V-I characteristics.
With zero base current the transistor behaves like an open switch. With high base current the device saturates and switches into conduction with a low forward voltage drop. Hence, to turn on/off the device, a base drive circuit is connected to the base and emitter terminal. To turn on, current is injected into the base terminal. When turned on, conventional current passes from collector to emitter; current is injected into the base terminal. To turn-off, the base current is removed (made zero value). The current gain $\beta$ of a BJT ends to be low when operated in the saturated ON condition, $\beta < 10$ is common. It deteriorates as voltage ratings increases.

**Safe Operating Area (SOA) of BJT**

The safe operating area (SOA) is defined as the voltage and current conditions over which the transistor or any power semiconductor switch can be expected to operate without self-damage. This characteristic is also called the dynamic breakdown characteristics. The dynamic behavior of a power transistor is bounded by three main parameters:

- **$FBSOA$:** Forward Bias Safe Operating Area
- **$RBSOA$:** Reverse Bias Safe Operating Area
- **$BV_{sus}$:** Breakdown Sustaining

The designer of a given application must carefully check that, under no circumstances, the transistor will operate out of the curves provided in the data sheet: severe damage, or destruction, occurs if the operating point moves outside the specified limits.

The data provided for the $FBSOA$ curve are based on a maximum junction temperature, and is bounded by four points as shown in Fig.1.16:
Chapter 1: Fundamentals of power electronics

**Fig. 1.16** Forward biased SOA as the voltage and current.

$BV_{CEO}$: maximum collector to emitter voltage when base is open circuited

$I_{CM}$: maximum allowable collector current

$P_m$: maximum power dissipation

$PW$: pulse width

**RBSOA**

The RBSOA curves are used to define the maximum current /voltage a transistor can sustain under Base-Emitter reverse bias. These characteristics can be found by special test circuit and depicted in Fig. 1.17. The RBSOA parameter is essentially an analysis of the breakdown, under dynamic condition, when the device is loaded by an inductor. The RBSOA is usually larger than FBSOA because of $BV_{CBO}$ at low collector current.

**Fig. 1.17** The RBSOA of a BJT.
Ratings, Merits and Demerit of BJT

i. Ratings: Voltage $V_{CE} < 1600$ V, Current $I_C < 1000$ A.

ii. BJT has small turn-on and turn-off times, hence its switching frequency is higher, up to 5 kHz.

iii. Low on-state voltage $V_{CE}$: 2-3 V, hence low on-state loss.

iv. Low current gain ($\beta$): Need high base current to obtain reasonable $I_C$.

v. BJT does not require commutation circuits. It is a bipolar device.

vi. The base drive circuit of the BJT is relatively expensive and complex.

1.4.5.2 Metal Oxide Semiconductor Field Effect Transistors “MOSFETs”

Unlike the bipolar junction transistor (BJT) which uses both types of carriers in conduction, the MOSFET device is a unipolar device, because it uses only one type of the majority carriers in conduction (either holes or electrons). The development of metaloxide-semiconductor (MOS) technology for microelectronic circuits opened the way for development of the power metal oxide semiconductor field effect transistor (MOSFET) device in the early 1970s. Since its invention, it has gone through several evolutionary steps. Now days, power MOSFETs are commonly used as switches in power electronics applications.

The invention of the power MOSFET was partly driven by the limitations of bipolar power transistors which, until recently, were the devices of choice in power electronics applications. Although it is not possible to define absolutely the operating boundaries of a power device, we will loosely refer to the power device as any device that is capable of switching at least 1A. The bipolar power transistor is a current-controlled device and a large base drive current as high as one fifth of the collector current is required to keep the device in the on state.

Also, higher reverse base drive currents are required to obtain fast turn-off. Despite the very advanced state of manufacturability and lower costs of bipolar power transistors, these limitations have made the base drive circuit design more complicated and hence more expensive. There are two further limitations to the bipolar power transistor. First, both electrons and holes contribute to conduction in BJTs. Presence of holes with their higher carrier lifetime causes the switching speed to be several orders of magnitude slower than for a power MOSFET of similar size and voltage rating. Secondly, the BJTs suffer from thermal runaway.

The forward voltage drop of a BJT decreases with increasing temperature causing diversion of current to a single device when several devices are paralleled. Power MOSFETs, on the other hand, are majority carrier devices with no minority carrier injection. They are superior to the BJTs in high-frequency applications where switching power losses are impor-
tant and can withstand simultaneous application of high current and voltage without undergoing destructive failure due to second breakdown. Power MOSFETs can also be paralleled easily since the forward voltage drop increases with increasing temperature, ensuring an even distribution of current among all components. However, at high breakdown voltages (>200V) the on-state voltage drop of the power MOSFET becomes higher than that of a similar size bipolar device with a similar voltage rating, making it more attractive to use the bipolar power transistor at the expense of worse high-frequency performance.

Fig. 1.18 shows the present current-voltage limitations of power MOSFETs and BJTs. New materials, structures and processing techniques are expected to push these limits out over time. A relatively new device

![Power MOSFET structure](image)

Fig. 1.18 Power MOSFET structure.

which combines the high-frequency advantages of the MOSFET with the low on-state voltage drop of high voltage BJTs is the insulated-gate-bipolar transistor (IGBT). The power MOSFETs are also three terminals switches as shown in Fig. 1.19 constructed either with electrons as the majority carriers (n-channel type) or with holes as the majority carriers (p-channel type).

![Power MOSFET symbol](image)

Fig. 1.19 Power MOSFET symbol (a) p-channel, and (b) n-channel.
MOSFET is considered the fastest power switching device (200 kHz) for rating voltages < 500 V, current $I_{DS} < 300$ A, or 100 kHz, < 1500 V, 300 A.

MOSFET characteristics
- Turning on and off is very simple. Only need to provide $V_{GS} = +15$V to turn on and 0.0 V to turn off. Gate drive circuit is simple.
- Basically low voltage device. High voltage device are available up to 600 V but with limited current. Can be paralleled quite easily for higher current capability.
- Dominant in high frequency application (>100 kHz). Biggest application is in switched-mode power supplies.
- On-state loss relatively high, $V_{DS} > 3$ V.

Practically, MOSFET’s characteristic consists of three regions, as shown in Fig.1.20:
- Cut OFF region (OFF state) when $V_{GS} < V_{Th}$.
- Linear region when $V_{DS} < V_{GS} - V_{Th}$, and
- Active region when $V_{DS} > V_{GS} - V_{Th}$.

Ideally, MOSFETs are represented by a short-circuit when operating within the ON state and as an open-circuit when operating within the OFF state.

![Power MOSFET characteristics](image)

Fig.1.20 Power MOSFET characteristics.

A new power device called COOLMOS is now available which is an improvement of the conventional MOSFET. It is capable of handling 2 to 3 times output power compared with that of a standard MOSFET and its conduction losses are less by a factor of five.
1.4.5.3 Insulated Gate Bipolar Transistor “IGBT”

When the development of power MOSFETs encountered difficulty in increasing their current-handling capability, the idea of a MOS-controlled bipolar device was developed to overcome the problem. This effort led to today’s insulated gate bipolar transistor (IGBT). This device, which is also a three terminal switch, combines the high-frequency advantages of the MOSFET with the low on-state voltage drop of high voltage BJTs. Its operation modes and characteristics are almost similar to those for MOSFETs, except for the operating ranges. The IGBT symbol and characteristics are shown in Fig.1.21.

![IGBT symbol](image)

**IGBT: symbol**

**v-i characteristics**

**Fig.1.21** The IGBT power transistor.

The IGBT fundamentally changes the BJT current control into voltage control while maintaining the advantages of the BJT. In addition, the use of a wide-base *pnp* transistor in the IGBT structure results in a much improved conductivity modulation effect than a conventional BJT, pushing the voltage rating of the IGBT toward the level of GTOs. The internal *pnp* structure also does not have the second breakdown problem as a conventional *nnp* structure because the high voltage is supported by the base region of the *pnp* transistor instead of by the collector region as is the case for a conventional *npp* transistor. IGBTs also have excellent RBSOA and FRSOA. Having undergone several years of development, IGBTs have become the best device for applications in the range of 600 to 3000 V.

The above trend shows that when the power level moves higher, power semiconductor devices limit the maximum system switching frequency, hence the performance of the system, especially at the GTO level. To meet the increasing demand for better performance in high-power systems, many efforts have been made to improve the performance
of high-power semiconductor devices. Among them, one effort is to push the IGBT toward higher power ratings based on the module concept. With its good dynamic performance, high-power systems equipped with IGBTs can operate at a much higher switching frequency and have many benefits compared with a conventional GTO system. The state-of-the-art IGBT rating is currently 3.3 kV/1.2 kA, which is at the low end of that of the GTO.

IGBT Structure and Operation

The name insulated gate bipolar transistor stems from its operation based on an internal interaction between an insulated-gate FET (IGFET) and a bipolar transistor. It has previously been called an IGT (insulated-gate transistor), an IGR (insulated-gate rectifier), a COMFET (conductivity-modulated field effect transistor), a GEMFET (gain-enhanced MOSFET), a BiFET (bipolar FET), and an injector FET. IGBTs have been successfully used since they were first demonstrated in 1982 and are currently the most widely used power semiconductor switches with applications from several kilowatts to a few megawatts. A cross section of the planar junction-based IGBT structure introduced in the 1980s is shown in Fig. 1.22.

![IGBT structure](image)

The IGBT structure is similar to that of a planar power MOSFET except the difference in the substrate doping type. The fabrication of the IGBT therefore is almost the same as a power MOSFET. This makes manufacturing relatively easy immediately after conception, and its ratings have grown at a rapid pace as a result of the ability to scale up both the current and the blocking voltage ratings. IGBT has a combination of BJT and MOSFET characteristics, compromises include:

i. Gate behavior similar to MOSFET - easy to turn on and off.
ii. Low losses like BJT due to low on-state Collector-Emitter voltage $V_{CE}$ (2-3 V).
i. Ratings: Voltage $V_{CE} < 6000$ V, Current 2500A currently available.

iv. Good switching capability (up to 100 kHz) for newer devices.

v. Typical application, IGBT is used at 20-50 kHz.

vi. For very high power devices and applications, frequency is limited to several kHz.

vii. Very popular in new products; practically replacing BJT in most new applications.

viii. “Snubberless” operation is possible. Most new IGBTs do not require snubber.

1.4.5.4 MOS-Controlled Thyristor (MCT Thyristor)

An effort to combine the advantages of bipolar junction and field-effect structures has resulted in hybrid devices:

- The IGBT is an improvement over a BJT.
- The MCT is an improvement over a thyristor.

The IGBT power transistor has been discussed in the previous subsection. In this section, the MOS-controlled thyristor MCT will be discussed and investigated.

MCT can be switched on or off by negative or positive gate voltage, respectively. It has fast turn-on and then off times, with high-speed switching capability, low conduction losses, low switching losses, and high current density. The gating requirements of an MCT are easier than those of the GTO since it needs smaller gate turn-off current due to its high gate input impedance. Compared with the power MOSFET, it has higher current density and lower forward drop. It has great potential in high-power, high-voltage applications. A peak power of 1 MW can be switched off in 2 ns by a single MCT. Therefore, the MCT overcomes several of the limitations of the existing power devices and promises to be a better switch for the future. The MCT symbol and equivalent circuit are shown in Fig. 1.23. The MCT characteristics are shown in Fig. 1.24.

**MCT Working Principle**

The P-MOS helps turn on the MCT. To it turn on, it needs:

- Forward bias.
- Applying a negative pulse to its gate with respect to the anode.
- The regenerative action within $Q_1$ and $Q_2$ turns the MCT on into full conduction within a very short time and maintains it even after the gate pulse is removed.
MCT will remain in the on-state until the device current is reversed or a turn-off pulse is applied to its gate. With a positive pulse the n-MOS helps turn the MCT off by diverting $Q_2$ current and breaking the latching action of the SCR. The highest current that can be turned off with the application of a gate bias is called the “maximum controllable current”. The MCT can be gate controlled if the device current is less than the maximum controllable current.

For small currents rating device, the width of the off pulse doesn’t matter. For high currents rating device, the width of the off pulse is critical and probably it should take the entire off time of the switch. The on-state resistance of an MCT is slightly higher than that of an equivalent thyristor.
1.5 OTHER SWITCHING DEVICES

There are several other power switching device available such as: Diac, Static Induction Transistors (SITs), COOLMOS Transistor, Static Induction Thyristors (SITHs) and Gate commutated thyristor (GCT).

1.5.1 Static Induction Transistors (SITs), and Static Induction Thyristors (SITHs)

The first invention of SIT was in the 1950s where the PIN diode was also invented. This new SIT technology may challenge SCRs, GTOs, MOSFETs, IGBTs, magnetrons and most other power semiconductors. SITs have extremely low forward voltage drop, very fast switching speeds and greater radiation tolerance than most semiconductors. They operate at thousands of volts, hundreds of amperes, frequency up to 10GHz and levels up to one megawatt. It is believed that this new technology will bring revolution in power electronics industry.

The static induction thyristor (SITH) acts like a diode, in the absence of gate signal, conducting current from anode (A) to cathode (K). Negative gate voltage turns the switch off and must be maintained to give reverse voltage blocking. The SITH is similar to the GTO in performance with higher switching speed but lower power rating.

1.5.2 Gate Commutated Thyristor (GCT Thyristor)

The GCT thyristor is designed to obtain a very low parasitic inductance and its package is integrated with a specially designed gate-drive circuit. The specially designed gate drive circuit allows the GCT to be operated without a snubber circuit and switch with higher anode di/dt, than a similar GTO. At blocking voltages of 4.5 kV and higher the GCT seems to provide better performance than a conventional GTO. The speed at which the cathode current is diverted to the gate (di/dt) is directly related to the peak snubberless turn-off capability of the GCT. The gate drive circuit can sink current for turn-off at di/dt values of 7000 A/ms. This hard gate drive results in a low charge storage time of ≈1 ms. Low storage time and fail-short mode make the GCT attractive for high-voltage series applications.

1.6 WIDE BAND GAP SEMICONDUCTOR DEVICES FOR POWER ELECTRONICS

Nowadays, a real breakthrough in the Power Electronics field may come from the development and use of Wide Band Gap (WBG) semiconductor devices. WBG semiconductors such as silicon carbide (SiC) and gallium nitrite (GaN) and diamond show superior material properties, which allow operation at high-switching speed, high-voltage and high-temperature. These unique performances provide a qualitative
change in their application to energy processing with increased the conversion efficiency.

Table 1.1 summarizes the main material parameters of WBG semiconductors devices to replace Si in the next generation of power switches. GaN and especially SiC process technologies are more mature and, therefore, more attractive especially for high power and high temperature electronics (HTE).

Although GaN can offer better high-frequency and high-voltage performances and presents a lower thermal conductivity than SiC, but at present, SiC is considered to have the best trade-off between properties and commercial maturity with considerable potential for both HTE and high power devices. However, the industrial interest for GaN power devices is increasing recently.

Table 1.1. Physical properties of WBG for power devices.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$(eV) at 33K</th>
<th>$\mu_n$ (cm$^2$/Vs)</th>
<th>$\mu_p$ (cm$^2$/Vs)</th>
<th>$V_{sat}$ (cm/s)</th>
<th>$E_c$ (cm/s)</th>
<th>$\lambda$ (W/cm.$^\circ$K)</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.2</td>
<td>1450</td>
<td>450</td>
<td>$10^7$</td>
<td>3x$10^5$</td>
<td>1.3</td>
<td>11.3</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>3.3</td>
<td>950</td>
<td>115</td>
<td>$2x10^7$</td>
<td>3x$10^6$</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>GaN</td>
<td>3.39</td>
<td>1000</td>
<td>350</td>
<td>$2x10^7$</td>
<td>5x$10^6$</td>
<td>1.3</td>
<td>8.9</td>
</tr>
<tr>
<td>Diamond</td>
<td>5.6</td>
<td>2200</td>
<td>1800</td>
<td>$3x10^7$</td>
<td>5x$10^7$</td>
<td>20</td>
<td>5.7</td>
</tr>
</tbody>
</table>

**Characteristics of Silicon Carbide Semiconductors**

Silicon carbide is naturally occurring in very small quantities because it is only found in meteorites or corundum deposits. It was first identified in its natural state by Dr. Ferdinand Henri Moissan in 1893 as a small component of the Canyon Diablo meteorite in Arizona-USA. Many of silicon carbide's advantages are due to its much larger band gap. SiC has a band gap of 3.3 eV as compared to silicon's band gap of 1.2 eV as given in Table 1.1. By having a band gap three times higher than silicon, SiC material properties are better suited for power semiconductor switches. One such parameter is the critical electric field; this parameter dictates how much electric field a junction can support before avalanche breakdown occurs. SiC's critical electric field is approximately 8 times higher than silicon. This results in much thinner devices for a given operating voltage eading to smaller resistive losses in SiC switches.

Silicon carbide also has a much lower intrinsic carrier concentration (~10-8 cm$^3$) than silicon (~1012 cm$^3$) at 300 K. The biggest implication this has on device performance is that it controls the maximum operating temperature. For silicon this results in a maximum temperature of
approximately 450 K (150°C). For SiC the resulting maximum operating temperature can be as high as 900 K. So, not only are SiC devices generally more efficient than their silicon counterparts but they also operate reliably at lower efficiencies. This simplifies many of design requirements on power electronics systems making these switches easier to implement into industry. There are many emerging markets that can benefit from the advantages presented by silicon carbide based power electronic systems. For example, green energy initiatives such as solar power generation and wind power generation can benefit from the higher efficiency offered by SiC based inverters that are used to tie these systems to the electric grid. Hybrid electric vehicles benefit greatly by the higher operating temperatures and power densities that silicon carbide offers for the dc-dc converters used to distribute energy to and from the motors.

The use of silicon carbide as a raw material for power semiconductor switches is a relatively new technology in terms of semiconductor research. It was not until the early 90’s that it became a viable alternative to silicon and significant investment into the technology started to occur. The silicon carbide is a compound of silicon and carbon with chemical formula SiC. It is a semiconductor, which can be doped n-type by nitrogen or phosphorus and p-type by beryllium, boron, aluminum, or gallium. Metallic conductivity has been achieved by heavy doping with boron, aluminum or nitrogen. SiC is used in semiconductor electronics devices that operate at high temperatures or high voltages, or both.

Compared to Si, the silicon carbide has a bandgap almost three times wider than Si, meaning that the electrons need higher activation energy to jump to the conduction band. As a result, SiC junctions can operate at higher temperature, without any unwanted conduction.

Another advantage is that its electric breakdown field is almost ten times higher than silicon’s, so either it can withstand much higher electric field, or we can make the transistor thinner. By making it thinner we achieve much better switching characteristics, as turn-on and turn-off times are smaller, thus having lower switching losses over the transistors. In power electronics, SiC based power electronic devices have significant advantages over silicon (Si) in capabilities. They operate at much higher frequencies and temperatures and convert electric power at higher efficiency or lower losses. Additionally, SiC-based devices manage the same level of power as Si devices at half the size, which will enable dramatic increases in power density and reliability.

The first devices available were Schottky diodes, and MOSFETs. MOSFET and SiC Schottky diodes can be superior to a traditional all-silicon system. SiC devices allow power circuits to operate at higher switching speeds, which reduce the cost of magnetic components as well as system size and weight. In addition, thermal management considerations such as heat sinking and cooling are less stringent, because these
systems are more thermally efficient. SiC MOSFETs in an n-channel configuration rated higher than 1200 V, is available now in the markets and for high-power switching, bipolar transistors and thyristors are currently developed.

SiC features can be summarised as:

i. Extremely low switching losses.
ii. Zero reverse recovery charge-improves system efficiency (High Power Density).
iii. Smaller footprint device reduces system size and weight. High thermal conductivity and high thermal stability.
iv. $2.5 \times$ more thermally conductive than silicon.
v. Reduced sink requirements results in lower cost and smaller size.
vi. High temperature operation.
vii. Increased power density and improved reliability.
viii. High breakdown electric field strength (about $\times 10$ of Si),
ix. Wide bandgap.

1.7 SWITCHING LOSSES IN A POWER SWITCH

When a power switch is switched on, voltage and current are switched instantaneously in the ideal switch as shown in Fig.1.25 (a). The ideal switch requires zero transition time, hence the voltage across it will fall to zero and the current through it will raise to its maximum value $I$ depending on the load.

In real switch, due to the non-idealities of power switches, the switching profile is as shown in Fig.1.25(b). The switching losses occur as a result of both the voltage and current changing simultaneously during the switching period.

Fig.1.25 Transition of voltage and current in a power switch during turn-on: (a) Ideal switching profile, (b) Real switching profile.
The product of device voltage and current gives instantaneous power dissipated in the device. The heat energy that developed over the switching period is the integration (summation) of instantaneous power over time as shown by the shaded area under the power curve (Fig. 1.25(b). The average power loss is the sum of the turn-on and turn-off energies multiplied by the switching frequency. When frequency increases, switching losses increases. This limits the usable range of power switches unless proper heat removal mechanism is employed.

1.8 SUMMARY OF POWER SEMICONDUCTOR DEVICE CAPABILITIES

Although there are a number of other devices that have been developed or are being developed, the workhorse power semiconductor devices today are SCRs, GTOs, MOSFETs, and IGBTs. Each of these devices dominates a specialized power arena. The MOSFET has excellent dynamic and static performance. It dominates low voltage applications below 600 V. The IGBT is slower than the MOSFET but has better forward voltage drop above 600 V. It dominates applications from 600 to 3000 V. At an even higher voltage level, the GTO becomes the dominant device with better current-carrying capability but much slower dynamic response. Without turn-off capability, the SCR has an even better current conduction capability, so it is suitable for even higher power a.c. applications where gate-controlled turn-off capability is not necessary. For a typical application, the switching frequency is an important index in determining system performance. Generally, the higher the switching frequency, the better the dynamic performance of the system, the smaller the size of the system due to reduced passive components and the lower the cost of the system due to savings on passive components. The practical switching frequency of an application system is a trade-off of many issues including maximum device switching frequency, maximum magnetic switching frequency, switching losses of the power switches, overall system efficiency, etc. In the low power field where the MOSFET plays the major role, the switching frequency is normally subject to system efficiency and/or magnetic considerations instead of device limitations. In the medium power field, where the IGBT plays the major role, the situation changes.

At the lower end, the limitation of the device does not dominate since the lower-rating IGBT is normally fast enough. However, when the power rating is higher, the IGBT switching speed decreases and the switching losses increase significantly. The practical switching frequency is thus subject to the limitation of the device. When the power level moves even higher, the GTO is the only available device. Since it has several tens of microseconds switching time, significant turn-off, and $dv/dt$ snubber loss, the GTO is traditionally the limitation of the switching frequency of
the system. Fig.1.26 gives a summary of power semiconductor device capabilities for clarity.

Fig.1.26 Summary of power semiconductor device capabilities.

**REVIEW QUESTIONS AND PROBLEMS**

1.1 Explain the terms latching current and holding current in a thyristor device.
1.2 What are the conditions that must be satisfied to make a thyristor be on?
1.3 Why does a thyristor have a \((di/dt)_{\text{max}}\) rating?
1.4 Explain the principle of turning off a thyristor in a d.c. circuit, why we need force commutation circuit to achieve turn off? How the forced turn-off of an SCR is different from natural turn-off.
1.5 Give the broad classification of power semiconductor devices.
1.6 What are the types of power diodes?
1.7 Why the current in power diodes varies linearly rather than exponentially with voltage.
1.8 Describe, with the aid of a sectional diagram, the construction of a triac. Draw an equivalent circuit of the device and explain why force commutation cannot be applied to triac?
1.9 Compare the relative advantages of triacs and thyristors and hence give two examples of application: one in which a triac is particularly suitable and the other where silicon controlled rectifier type of thyristor is preferable. Give the reasons for your selection.
1.10 What is GTO? How GTO can be turned on and turned off?
1.11 Give the merits and demerits of GTO, as compared to conventional SCR.
1.12 Sketch typical static characteristics of a gate turn-off device and explain briefly how can this device turned on and off from its gate.
1.13 What are the types of power transistors?
1.14 What are the advantages of MCT?
1.15 What is an IGBT? Sketch the symbol and characteristics of an IGBT. Discuss its advantages and disadvantages.
1.16 Compare IGBT with the power MOSFET and give the applications of IGBTs.
1.17 What are the advantages of power bipolar transistors over FETs and thyristors for use in inverter circuits for power applications? What are the factors limit their usage?

Are the following statements True or False?

1.18 Thyristors are used only for low voltage, low current applications.
1.19 MOSFETs are used for high frequency applications.
1.20 BJT is more efficient than IGBT in high power applications.
1.21 GTO requires very low current applied to its gate to be turn off.
1.22 IGBT is a voltage driven device.
1.23 Thyristors are preferred to be used in the output stage of 10W 1MHz transmitter.
1.24 MOSFETs are preferred to be used for 1000 kW motor control circuit.
1.25 TRIAC is used for lighting dimmer circuits.
1.26 IGBT used in high voltage d.c. rectifier circuits (above 5 kV level).
1.27 BJT is the fastest switching device in power applications.

Choose the correct answer for the following questions:

1.28 The conditions which must be satisfied to turn on the thyristor with its current is more than its latching current are:
(a) The anode is more positive than the cathode and a positive current pulse is applied to the gate.
(b) The anode is more negative than the cathode and a positive current pulse is applied to the gate.
(c) The cathode is more positive than the anode and a negative current pulse is applied to the gate.
(d) The cathode is more negative than the cathode and a negative current pulse is applied to the gate.

1.29 The latching and holding currents are terms applicable to:

(a) Thyristor (b) BJT (c) IGBT (d) MOSFET

1.30 For a certain application of power supply a power semiconductor switch is required to operate with 3000 V, 2000 A load and switching frequency of 30 kHz. The power switching device suitable for this task is:

(a) Thyristor (b) Diode (c) IGBT (d) MOSFET

1.31 A thyristor (SCR) has a latching current of 100 mA is connected between a d.c. source of 200 V and a purely inductive load of \( L = 0.2 \) H. The minimum width of the gate pulse current required to turn on this SCR is:

(a) 50 ms (b) 50 µs (c) 100 µs (d) 40ms (e) 60 µs

1.32 For certain application of power supply a power semiconductor switch is required to operate with 400 V, 200 A load and switching frequency of 100 kHz. The power switching device suitable for this task is:

(a) GTO (b) IGBT (c) MOSFET (d) BJT (e) Triac

[Ans: 1.18 F, 1.19 T, 1.20 F, 1.21 F, 1.22 T, 1.23 F, 1.24 F, 1.25 T, 1.26 F, 1.27 F, 1.28 (a), 1.29 (a), 1.30 (e), 1.31 (e), 1.32 (e)]