POWER SEMICONDUCTOR DEVICES

2.1 INTRODUCTION

The Various power semiconductor devices are

- Power Diodes.
- Power Transistors (BJT's).
- Power MOSFETS.
- IGBT's.
- Thyristors

  Thyristors are a family of p-n-p-n structured power semiconductor switching devices

- SCR's (Silicon Controlled Rectifier)

  The silicon controlled rectifier is the most commonly and widely used member of the thyristor family. The family of thyristor devices includes SCR's, Diacs, Triacs, SCS, SUS, LASCR's and so on.

2.2 POWER SEMICONDUCTOR DEVICES USED IN POWER ELECTRONICS

The first thyristor or the SCR was developed in 1957. The conventional Thyristors (SCR's) were exclusively used for power control in industrial applications until 1970. After 1970, various types of power semiconductor devices were developed and became commercially available. The power semiconductor devices can be divided broadly into five types

- Power Diodes.
- Thyristors.
- Power BJT's.
- Power MOSFET's.
- Insulated Gate Bipolar Transistors (IGBT's).
- Static Induction Transistors (SIT's).

The Thyristors can be subdivided into different types

- Forced-commutated Thyristors (Inverter grade Thyristors)
- Line-commutated Thyristors (converter-grade Thyristors)
- Gate-turn off Thyristors (GTO).
- Reverse conducting Thyristors (RCT's).
- Static Induction Thyristors (SITH).
- Gate assisted turn-off Thyristors (GATT).
- Light activated silicon controlled rectifier (LASCR) or Photo SCR's.
- MOS-Controlled Thyristors (MCT's).

2.3 POWER DIODES

Power diodes are made of silicon p-n junction with two terminals, anode and cathode. P-N junction is formed by alloying, diffusion and epitaxial growth. Modern techniques in diffusion and epitaxial processes permit desired device characteristics.

The diodes have the following advantages

- High mechanical and thermal reliability
- High peak inverse voltage
- Low reverse current
- Low forward voltage drop
- High efficiency
- Compactness.

Diode is forward biased when anode is made positive with respect to the cathode. Diode conducts fully when the diode voltage is more than the cut-in voltage (0.7 V for Si). Conducting diode will have a small voltage drop across it. Diode is reverse biased when cathode is made positive with respect to anode. When reverse biased, a small reverse current known as leakage current flows. This leakage current increases with increase in magnitude of reverse voltage until avalanche voltage is reached (breakdown voltage) as shown in fig 1.

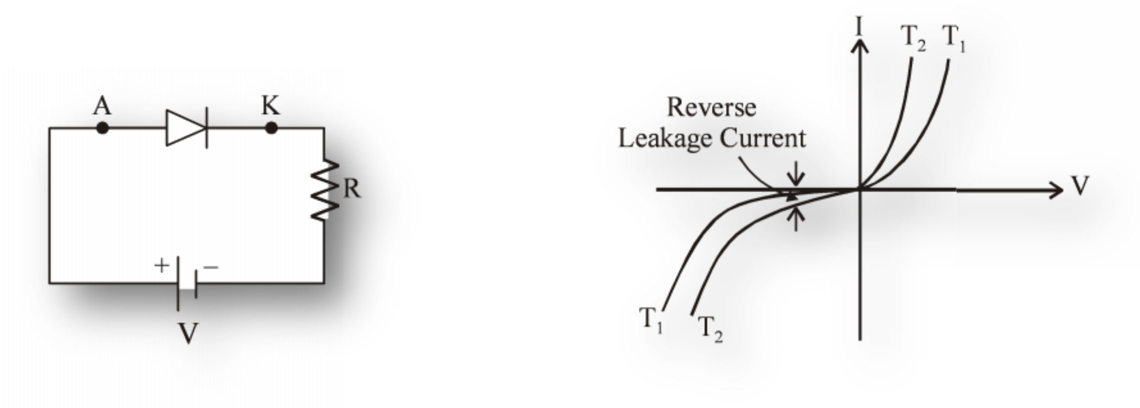


Fig 1 Diode Characteristics

2.3.1 DYNAMIC CHARACTERISTICS OF POWER SWITCHING DIODES

At low frequency and low current, the diode may be assumed to act as a perfect switch and the dynamic characteristics (turn on & turn off characteristics) are not very important. But at high frequency and high current, the dynamic characteristics plays an important role because it increases power loss and gives rise to large voltage spikes which may damage the device if proper protection is not given to the device as shown in figure 2.

2.3.2 REVERSE RECOVERY CHARACTERISTIC

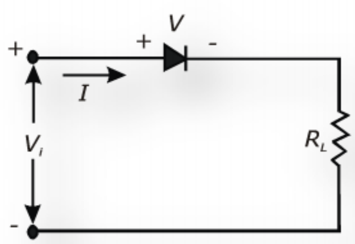
Reverse recovery characteristic is much more important than forward recovery characteristics because it adds recovery losses to the forward loss. Current when diode is forward biased is due to net effect of majority and minority carriers. When diode is in forward conduction mode and then its forward current is reduced to zero (by applying reverse voltage) the diode continues to conduct due to minority carriers which remains stored in the p-n junction and in the bulk of semi-conductor material. The minority carriers take some time to recombine with opposite charges and to be neutralized. This time is called the ***reverse recovery time.*** The reverse recovery time (t_{rr}) is measured from the initial zero crossing of the diode current to 25% of maximum reverse current I_{rr}. t_{rr} has 2 components, t_1 and t_2. t_1 is as a result of charge storage in the depletion region of the junction i.e., it is the time between the zero crossing and the peak reverse current I_{rr}. t_2 is as a result of charge storage in the bulk semi-conductor material.

$$t_{rr} = t_1 + t_2$$

$$I_{RR} = t_1 \left({}^{di}\!/_{dt} \right)$$

The reverse recovery time depends on the junction temperature, rate of fall of forward current and the magnitude of forward current prior to commutation (turning off).

When diode is in reverse biased condition the flow of leakage current is due to minority carriers. Then application of forward voltage would force the diode to carry current in the forward direction. But a certain time known as forward recovery time (turn-ON time) is required before all the majority carriers over the whole junction can contribute to current flow. Normally forward recovery time is less than the reverse recovery time. The forward recovery time limits the rate of rise of forward current and the switching speed. Figure 3 shows the reverse recovery characteristics.



The waveform in
(a) Simple diode circuit.
(b)Input waveform applied to the diode circuit in (a);
(c) The excess-carrier density at the junction;
(d) The diode current;
(e) The diode voltage.

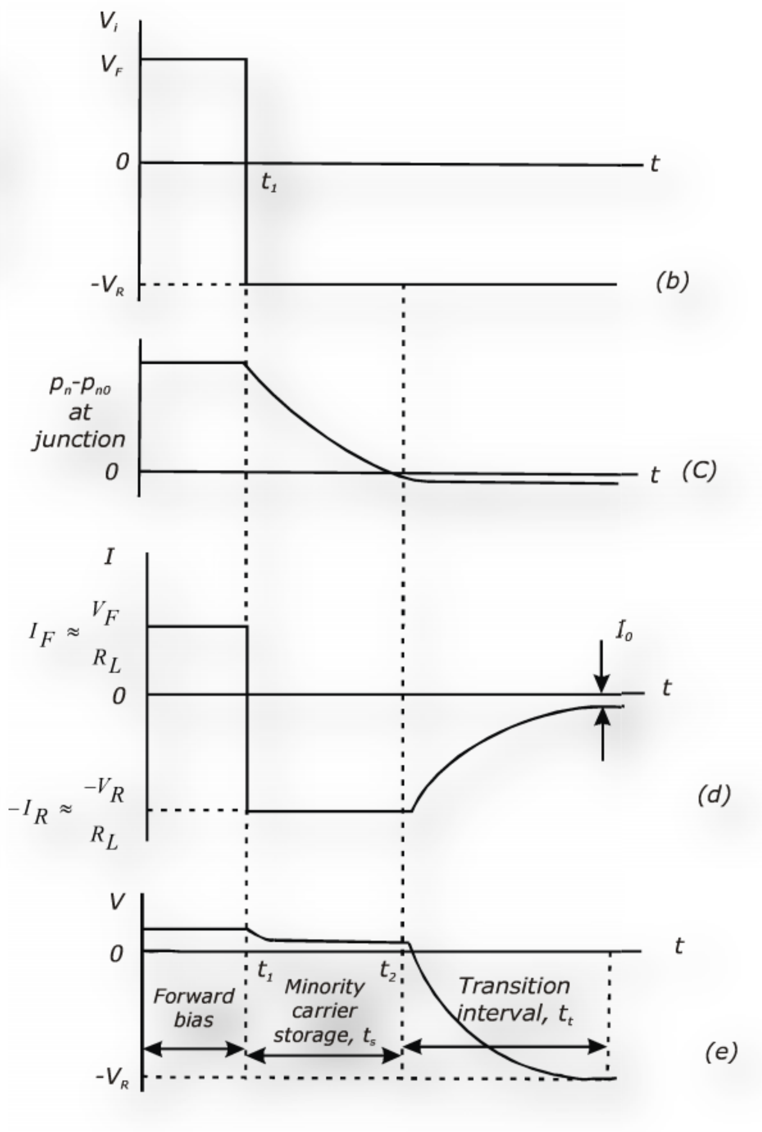


Fig 2: Storage & Transition Times during the Diode Switching

Reverse recovery charge Q_{RR}, is the amount of charge carriers that flow across the diode in the reverse direction due to the change of state from forward conduction to reverse blocking condition. The value of reverse recovery charge Q_{RR} is determined form the area enclosed by the path of the reverse recovery current.

$$Q_{RR} \cong \left(\frac{1}{2} I_{RR} t_1 + \frac{1}{2} I_{RR} t_2 \right) = \frac{1}{2} I_{RR} t_{RR} \qquad \therefore Q_{RR} = \frac{1}{2} I_{RR} t_{RR}$$

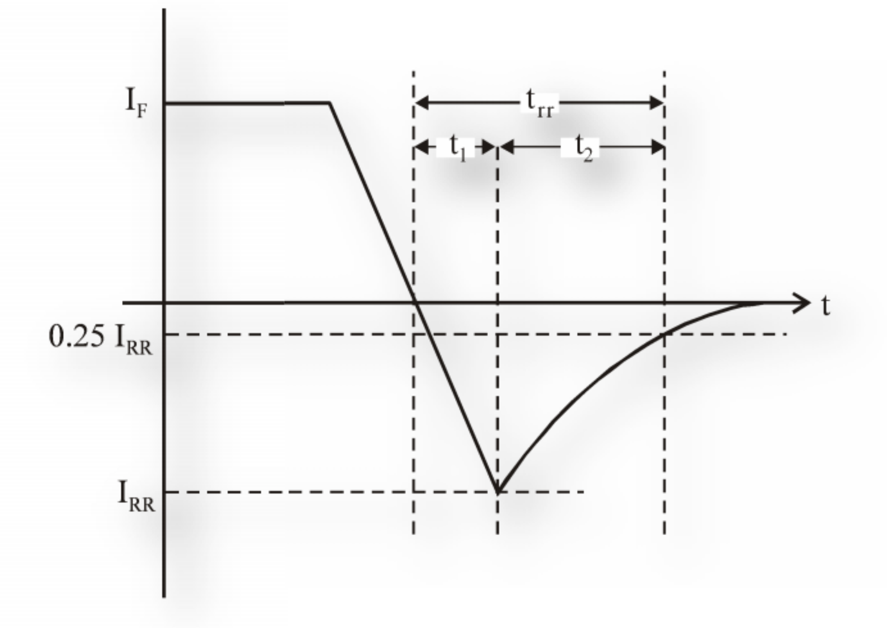


Fig 3 Reverse Recovery Characteristics

2.4 POWER DIODES TYPES

Power diodes can be classified as

- General purpose diodes.
- High speed (fast recovery) diodes.
- Schottky diode.

2.4.1 GENERAL PURPOSE DIODES

The diodes have high reverse recovery time of about 25 microsecs (μsec). They are used in low speed (frequency) applications. e.g., line commutated converters, diode rectifiers and converters for a low input frequency up to 1 KHz. Diode ratings cover a very wide range with current ratings less than 1 A to several thousand amps (2000 A) and with voltage ratings from 50 V to 5

KV. These diodes are generally manufactured by diffusion process. Alloyed type rectifier diodes are used in welding power supplies. They are most cost effective and rugged and their ratings can go up to 300A and 1KV.

2.4.2 FAST RECOVERY DIODES

The diodes have low recovery time, generally less than 5 μs. The major field of applications is in electrical power conversion i.e., in free-wheeling ac-dc and dc-ac converter circuits. Their current ratings is from less than 1 A to hundreds of amperes with voltage ratings from 50 V to about 3 KV. Use of fast recovery diodes are preferable for free-wheeling in SCR circuits because of low recovery loss, lower junction temperature and reduced di/dt. For high voltage ratings greater than 400 V they are manufactured by diffusion process and the recovery time is controlled by platinum or gold diffusion. For less than 400 V rating epitaxial diodes provide faster switching speeds than diffused diodes. Epitaxial diodes have a very narrow base width resulting in a fast recovery time of about 50 ns.

2.4.3 SCHOTTKY DIODES

A Schottky diode has metal (aluminum) and semi-conductor junction. A layer of metal is deposited on a thin epitaxial layer of the n-type silicon. In Schottky diode there is a larger barrier for electron flow from metal to semi-conductor.

When Schottky diode is forward biased free electrons on n-side gain enough energy to flow into the metal causing forward current. Since the metal does not have any holes there is no charge storage, decreasing the recovery time. Therefore a Schottky diode can switch-off faster than an ordinary p-n junction diode. A Schottky diode has a relatively low forward voltage drop and reverse recovery losses. The leakage current is higher than a p-n junction diode. The maximum allowable voltage is about 100 V. Current ratings vary from about 1 to 300 A. They are mostly used in low voltage and high current dc power supplies. The operating frequency may be as high 100-300 kHz as the device is suitable for high frequency application. Schottky diode is also known as hot carrier diode.

General Purpose Diodes are available up to 5000V, 3500A. The rating of fast-recovery diodes can go up to 3000V, 1000A. The reverse recovery time varies between 0.1 and 5μsec. The fast recovery diodes are essential for high frequency switching of power converters. Schottky diodes have low-on-state voltage drop and very small recovery time, typically a few nanoseconds.

Hence turn-off time is very low for schottky diodes. The leakage current increases with the voltage rating and their ratings are limited to 100V, 300A. The diode turns on and begins to conduct when it is forward biased. When the anode voltage is greater than the cathode voltage diode conducts.

The forward voltage drop of a power diode is low typically 0.5V to 1.2V. If the cathode voltage is higher than its anode voltage then the diode is said to be reverse biased.

Power diodes of high current rating are available in

- Stud or stud-mounted type.
- Disk or press pack or Hockey-pack type.

In a stud mounted type, either the anode or the cathode could be the stud.

2.4.4 COMPARISON BETWEEN DIFFERENT TYPES OF DIODES

General Purpose Diodes	**Fast Recovery Diodes**	**Schottky Diodes**
Up to 5000V & 3500A	Up to 3000V and 1000A	Up to 100V and 300A
Reverse recovery time – High	Reverse recovery time – Low	Reverse recovery time – Extremely low.
$t_{rr} \approx 25\mu s$	$t_{rr} = 0.1\mu$s to 5μs	t_{rr} = a few nanoseconds
Turn off time - High	Turn off time - Low	Turn off time – Extremely low
Switching frequency – Low	Switching frequency – High	Switching frequency – Very high.
V_F = 0.7V to 1.2V	V_F = 0.8V to 1.5V	$V_F \approx$ 0.4V to 0.6V

Natural or AC line commutated Thyristors are available with ratings upto 6000V, 3500A.

The turn-off time of high speed reverse blocking Thyristors have been improved substantially and now devices are available with t_{OFF} = 10 to 20µsec for a 1200V, 2000A Thyristors.

RCT's (reverse conducting Thyristors) and GATT's (gate assisted turn-off Thyristors) are widely used for high speed switching especially in traction applications. An RCT can be considered as a thyristor with an inverse parallel diode. RCT's are available up to 2500V, 1000A (& 400A in reverse conduction) with a switching time of 40μsec. GATT's are available upto 1200V, 400A with a switching speed of 8μsec. LASCR's which are available upto 6000V, 1500A with a switching speed of 200μsec to 400μsec are suitable for high voltage power systems especially in HVDC.

For low power AC applications, triac's are widely used in all types of simple heat controls, light controls, AC motor controls, and AC switches. The characteristics of triac's are similar to two SCR's connected in inverse parallel and having only one gate terminal. The current flow through a triac can be controlled in either direction.

GTO's & SITH's are self turn-off Thyristors. GTO's & SITH's are turned ON by applying and short positive pulse to the gate and are turned off by applying short negative pulse to the gates. They do not require any commutation circuits.

GTO's are very attractive for forced commutation of converters and are available up to 4000V, 3000A.

SITH's with rating as high as 1200V and 300A are expected to be used in medium power converters with a frequency of several hundred KHz and beyond the frequency range of GTO.

An MCT (MOS controlled thyristor) can be turned ON by a small negative voltage pulse on the MOS gate (with respect to its anode) and turned OFF by a small positive voltage pulse. It is like a GTO, except that the turn off gain is very high. MCT's are available up to 1000V and 100A.

High power bipolar transistors (high power BJT's) are commonly used in power converters at a frequency below 10KHz and are effectively used in circuits with power ratings up to 1200V, 400A.

A high power BJT is normally operated as a switch in the common emitter configuration.

The forward voltage drop of a conducting transistor (in the ON state) is in the range of 0.5V to 1.5V across collector and emitter. That is $V_{CE} = 0.5V$ to 1.5V in the ON state.