Power Diodes Characteristics

A Power diode and thyristor devices are most important in different power electronic converter topologies. However, the main differences between them is that the latter is a controlled device when it is turned on. Power diode controlled by the input source, while thyristors required to conditions to be controlled; the input source and gate control signal.

Power Diode

Power diodes are made of silicon p-n junction with two terminals, anode and cathode. 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).

Fig.1 shows V-I Characteristics of diode.

<u>**Forward Voltage Drop:**</u>

- Is the forward-conducting junction level
- The forward voltage drop is due to the forward resistance of the junction.
- forward volt drop is across the junction

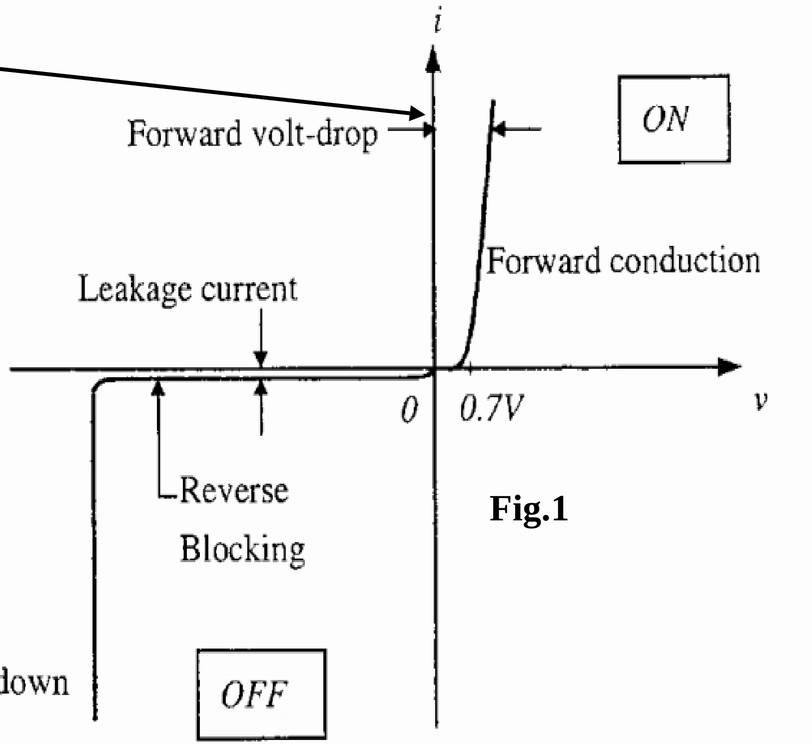


Fig.1

<u>**Reverse Leakage Current**</u>

<u>Thermal agitation does break some of the bonds in the crystal, resulting in minority carriers, which permit a small reverse current flow</u>, i.e. **leakage current**.

NOTE: The less abundant charge carriers are called **minority carriers**;

Reverse Recovery Characteristics

When a diode is in forward conduction mode, a sudden reversal of the polarity of the applied voltage would not stop the diode current at once. But the diode continues to conduct in the opposite direction due to minority carriers that remain stored in pn-junction and the bulk semiconductor material. Fig.2 shows the effect of minority carriers on the turn off characteristics of the power diode.

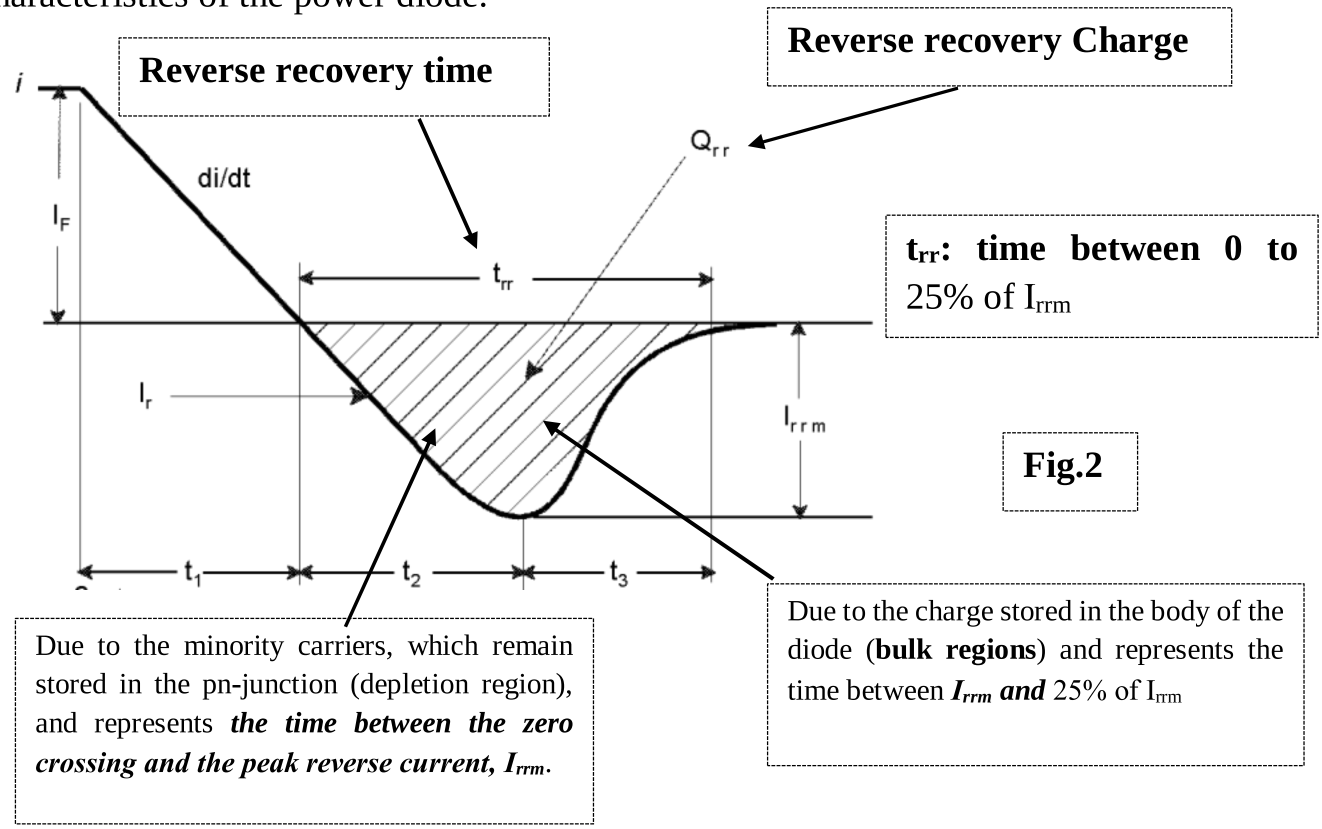


Fig.2

The charge carriers (holes & electrons) require a certain time to recombine with opposite charges and to be neutralized; this time is called the **reverse recovery time t_{rr} o**f the diode.

From Fig.2, one can found the following relationships:

$$t_{rr} = t_2 + t_3 \quad I_{rr} = t_2 \frac{di}{dt} \quad \text{then} \quad Q_{rr} = \frac{1}{2} I_{rrm} t_2 + \frac{1}{2} I_{rrm} t_3 = \frac{1}{2} I_{rrm} t_{rr}$$

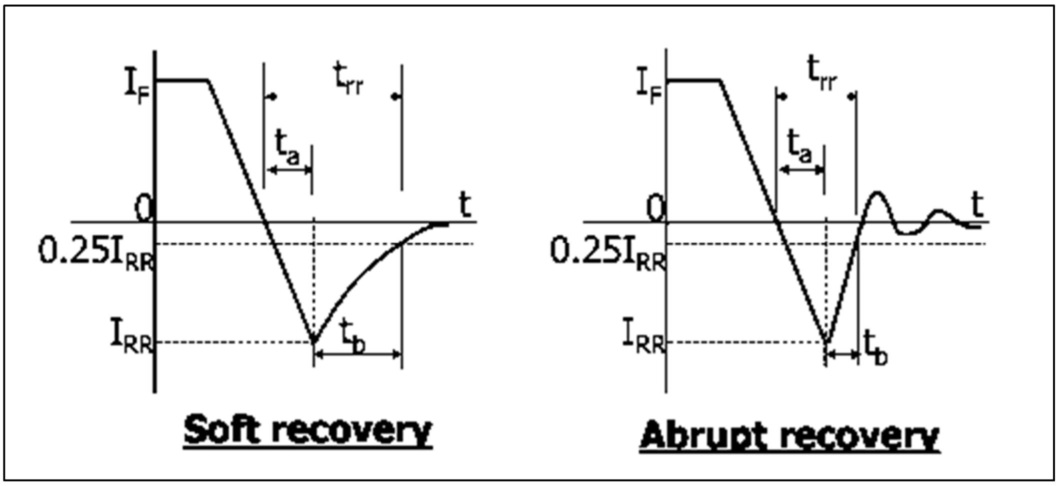
$$I_{rrm} \cong \frac{2Q_{rr}}{t_{rr}} = t_2 \frac{di}{dt}$$

For Fast recovery $t_3 \ll t_2 \rightarrow t_2 = t_{rr} \rightarrow t_{rr} = \sqrt{\frac{2Q_{rr}}{\frac{di}{dt}}}$

Hence, $I_{rrm} = \sqrt{2Q_{rr} \frac{di}{dt}}$

The fast decay of negative current creates an inductive drop that adds with the reverse blocking voltage V_R as illustrate in Fig.3.

There are two types of reverse recovery characteristics of junction diodes: **Soft recovery and Fast recovery** where, the **<u>softness factor, SF</u>** is the ratio of t_2/t_3.



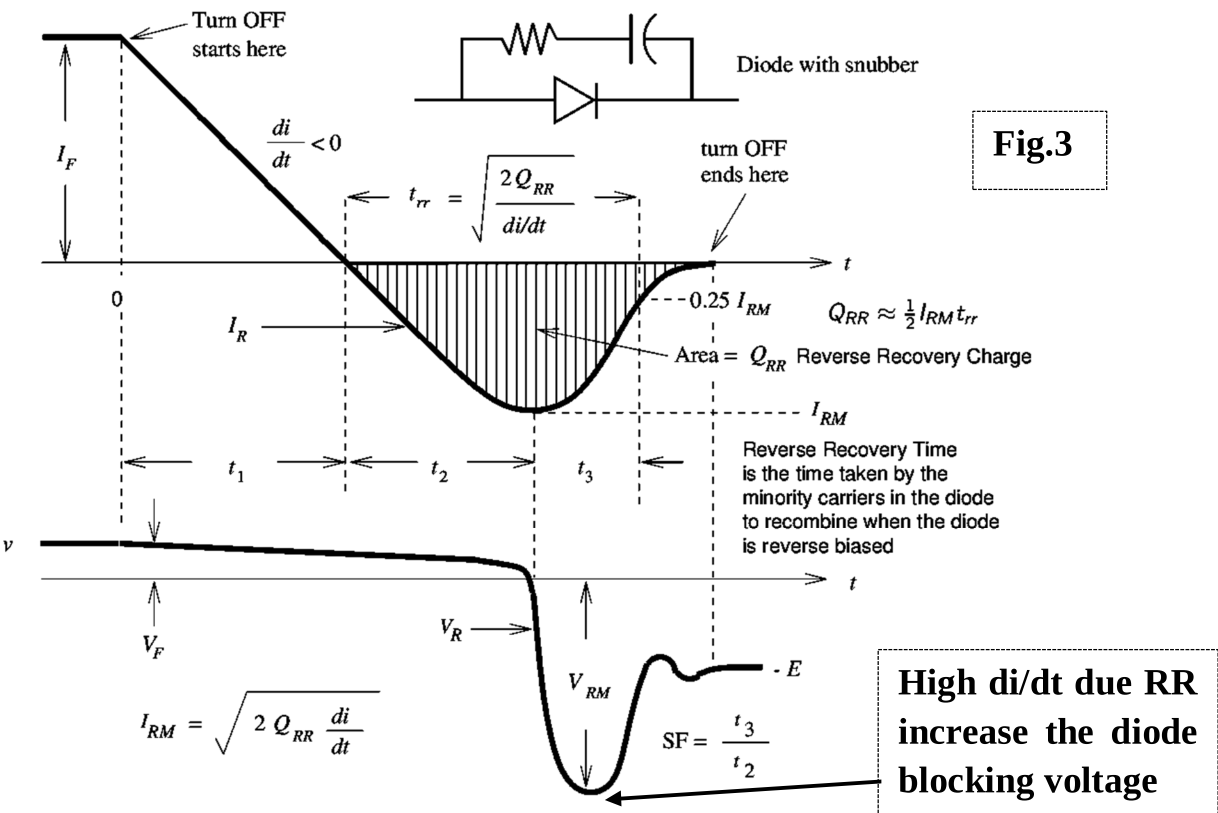


Fig.3

Hence, the blocking voltage across the diode increases to:

$V_{rrm} = V_{rr} + V_R$ where, V_{rr} is reverse recovery voltage due to the fast decay in the negative current and equal to: $V_{rr} = L\frac{di}{dt}$

Example 1: A power diode has the following specifications: forward current 50A, reverse blocking voltage = 100V, the reverse recovery time of a diode is t_{rr} = 3µs and the rate of fall of the diode current is di/dt= 30A/ µs. determine

- ❖ The storage charge
- ❖ The peak reverse current
- ❖ The maximum reverse voltage due to reverse recovery if internal stray inductance is 10µH.

Solution;

$$t_{rr} = \sqrt{\frac{2Q_{rr}}{\frac{di}{dt}}} \rightarrow Q_{rr} = \frac{1}{2}\frac{di}{dt}t_{rr}^2$$

$$Q_{rr} = \frac{1}{2} \times 30 \times 10^6 \times (3 \times 10^{-6})^2 = 135\mu C$$

$$I_{rrm} = \sqrt{2Q_{rr}\frac{di}{dt}} = \sqrt{2 \times (135 \times 10^{-6}) \times 30 \times 10^6} = 90A$$

It can be seen that due to reverse recover charge, the rated of the diode current is exceeded. Maximum reverse voltage equal to:

$$V_{rrm} = V_{rr} + V_R$$

$$V_{rr} = L\frac{di}{dt} = 10 \times 10^{-6} \times 30 \times 10^6 = 300V$$

$$V_{rrm} = 300 + 100 = 400V$$

Hence, due to reverse recover charge the reverse blocking voltage exceeding the rated of the diode.

This voltage may be destructive and can be softened by a resistance-capacitance snubber, which will be discussed later.

Important Notes:

- ► For practical purposes, one need be concerned with the total recovery time, t_{rr}, and the peak value of the peak reverse current, I_{RR}.

- ► The recovery current causes additional loss (switching loss) in the diode; this can be known by multiplying diode current times the diode voltage shown in Fig.3.

- ► For high frequency applications rectifier power diode can not be used, this is due to the long reverse recovery time of theses diodes. Increasing switching frequency (i.e. high sudden changing of polarity across the diode when working at high frequency) result in increasing the di/dt that will lead to high over shoot voltage across the diode. This will also lead that the charge carriers (holes & electrons) require a longer time to recombine with opposite charges and to be neutralized.

- ► As shown in example 1, longer t_{rr} results in increase the recovery charge stored that result in exceeding the rated current and voltage of the diode.

- The larger the active junction area, the larger the charge difference. Therefore, devices in the same family with larger die sizes, *represented by higher current ratings*, will have a larger reverse recovery charge.

- The maximum current reverse recovery current increases greatly with temperature and di/dt.

- When compared in real world applications, it is critical that the diodes have a fast recovery time along with having the least amount of ringing, measured by a SF value closest to 1. ***This means that, it is not only important to have a fast recovery, but one that is also a soft recovery.***

Based on the diode reverse recovery characteristics power diode are classified into:

- Standard Recovery (General) Diodes
- Fast Recovery Diodes
- Schottky Diodes
- Silicon Carbide Diodes.

For high frequency rectifier applications, Fast recovery and Schottky Diodes are generally used because of their short reverse recovery time and low voltage drop in their forward bias condition

General Purpose Diodes

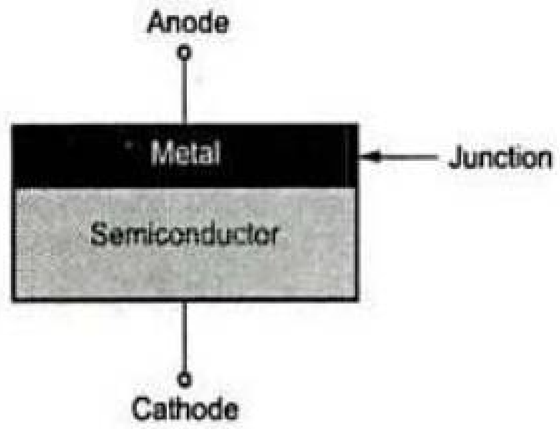
The diodes have high reverse recovery time of about 25 microsecs (µsec). They are used in low speed (frequency) applications. e.g., line commutated converters, diode rectifiers and converters for a low input frequency upto 1 KHz. Diode ratings cover a very wide range with current ratings less than 1 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.

Fast Recovery Diodes

The diodes have low recovery time, generally less than 5µs. 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 freewheeling in SCR circuits because of low recovery loss, lower junction temperature and reduced di/dt. For high voltage ratings greater than 400V 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.

Schottky Diodes

A Schottky diode has metal (aluminium) 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. Figure shows the Schottky diode.



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.

Silicon Carbide SiC Schottky Barrier Diode (SBD)

SiC (Silicon Carbide) is a compound semiconductor comprised of silicon (Si) and carbon (C). Compared to Si, SiC has

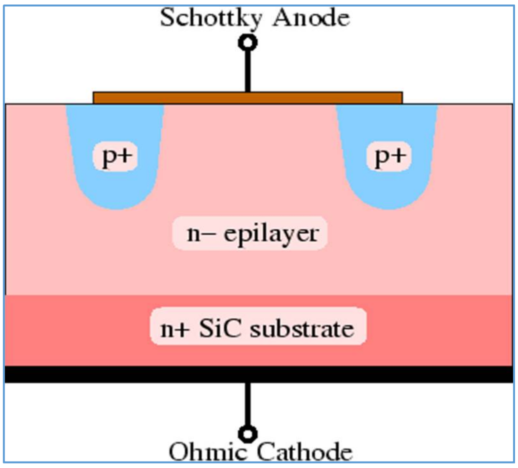
- Ten times the dielectric breakdown field strength.
- Three times the bandgap.
- Three times the thermal conductivity.

Both p-type and n-type regions, which are necessary to fashion device structures in a semiconductor materials, can be formed in SiC. These properties make SiC an attractive material from which to manufacture power devices that can far exceed the performance of their Si counterparts. SiC devices can withstand ***higher breakdown voltage, have lower resistivity, and can operate at higher temperature***.

SiC SBDs (Schottky barrier diodes) with breakdown voltage from 600V (which far exceeds the upper limit for silicon SBDs) and up are readily available. Compared to silicon FRDs (fast recovery diodes),

- SiC SBDs have much lower reverse recovery current and recovery time, hence dramatically lower recovery loss and noise emission.

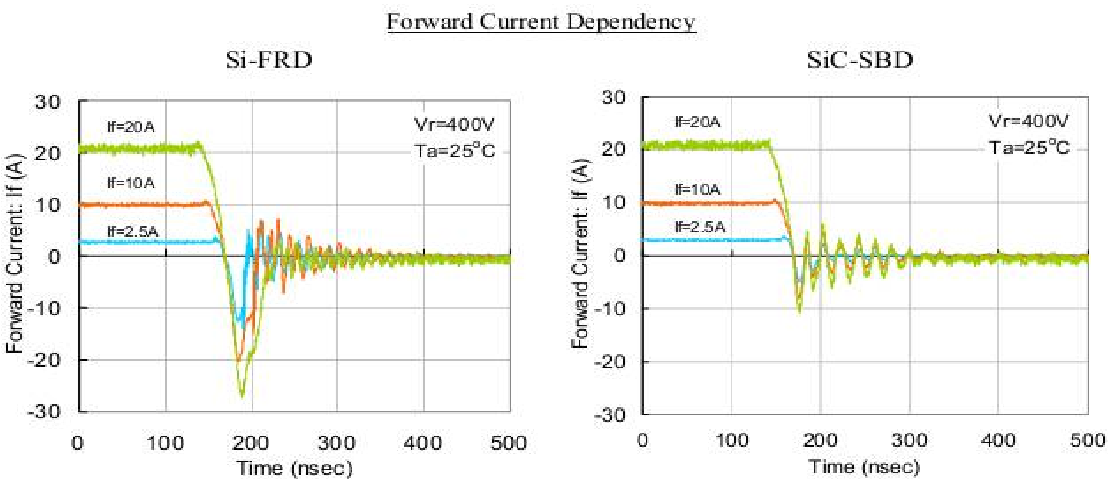
- Furthermore, unlike silicon FRDs, these characteristics do not change significantly over current and operating temperature ranges.
- SiC SBDs allow system designers to improve efficiency, lower cost and size of heat sink, increasing switching frequency to reduce size of magnetics and its cost, etc.
- SiC-SBDs have similar threshold voltage as Si-FRDs, i.e., a little less than 1V.



Reverse recovery characteristics of SiC-SBD

Si fast P-N junction diodes (e.g. FRDs: fast recovery diodes) have high transient current at the moment the junction voltage switches from the forward to the reverse direction, resulting in significant switching loss. This is due to minority carriers stored in the drift layer during conduction phase when forward voltage is applied. The higher the forward current (or temperature), the longer the recovery time and the larger the recovery current.

In contrast, since SiC-SBDs are majority carrier (unipolar) devices that use no minority carriers for electrical conduction, they do not store minority carrier s. The reverse recovery current in SiC SBDs is only to discharge junction capacitance. Thus the switching loss is substantially lower compared to that in Si-FRDs. The transient current is nearly independent of temperatures and forward currents, and thereby achieves stable fast recovery in any environment. This also means SiC-SBDs generate less noise from the recovery current.



A typical comparison between different types of diodes is shown in the table below:

Standard Recovery Diodes	Fast Recovery Diodes	Schottky Diodes	Silicon Carbide Diodes.
Upto 5000V & 3500A	**Upto 3000V and 1000A**	**Upto 100V and 300A**	**Upto 600V and 200A**
Reverse recovery time –High trr ~=25µs.	**Reverse recovery time – Low trr ≤5µs.**	**Reverse recovery time – Extremely low. trr is typically around few ns**	**have extremely fast switching behaviour with ultra-low trr**
Typically used in rectifiers at power frequencies i.e., at 50Hz or 60 Hz.	**Typically operating at higher frequencies as freewheeling diodes.**	**Typically operating at higher frequencies as freewheeling diodes.**	**Typically operating at higher frequencies as freewheeling diodes.**
V_F = 0.7V to 1.2V	**V_F = 0.8V to 1.5V**	**V_F = 0.4V to 0.6V**	**V_F <0.5V**

Self-assessments;

1. What is the difference between leakage current and reverse recovery current in the power diode?
2. Why the reverse recovery characteristics does not considered in signal diode?
3. What is the effect of diode revere recovery on the operation of the diode?
4. What are the differences between General propose diode and Fast-recovery and Schottky diodes?