SAMPLE STUDY MATERIAL

Electrical Engineering

EE / EEE

Postal Correspondence Course

Power Electronics

GATE, IES & PSUs

ENGINEERS INSTITUTE OF INDIA
India's Best Institute for IES, GATE & PSUs
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CONTENT

CHAPTER-1

POWER SEMICONDUCTOR DEVICES

Power Electronics		
Power	Electronics	Control

Power: Power is the term related with the generation, transmission and distribution of electric power.

Electronics: It deals with the solid state devices and circuits to process the signal for meeting certain control objectives.

Control : It deals with the steady state and dynamic characteristics of a closed loop control System.

- Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches.
- Advent of silicon-controlled rectifiers, abbreviated as SCRs, led to the development of a new area of application called the power electronics. Prior to the introduction of SCRs, mercury-arc rectifiers were used for controlling electrical power, but such rectifier circuits were part of industrial electronics and the scope for applications of mercury-arc rectifiers was limited. Once the SCRs were available, the application area spread to many fields such as drives, power supplies, aviation electronics, high frequency inverters and power electronics originated.

Main task of power electronics:

Power electronics has applications that span the whole field of electrical power systems, with the power range of these applications extending from a few VA/Watts to several MVA / MW.

The main task of power electronics is to control and convert electrical power from one form to another.

The four main forms of conversion are:

- Rectification referring to conversion of ac voltage to dc voltage,
- DC-to-AC conversion,
- DC-to DC conversion and
- AC-to-AC conversion.

"***Electronic power converter***" is the term that is used to refer to a power electronic circuit that converts voltage and current from one form to another. These converters can be classified as:

- Rectifier converting an ac voltage to a dc voltage,
- Inverter converting a dc voltage to an ac voltage,
- Chopper or a switch-mode power supply that converts a dc voltage to another dc voltage, and
- Cycloconverter and cycloinverter converting an ac voltage to another ac voltage.

➢ *SCRs and other power semiconductor devices are used as static switches.*

Application Areas of Power Electronics:

- Heat control (induction heating).
- Motor control (DC and AC motors).
- Power supplies (for aircrafts), battery chargers.
- High voltage direct current (HVDC) system.
- Vehical propulsion systems
- Light dimmers, flashers.
- Conveyers, cranes and hoist control.
- Washing machines, dryers, blowers.
- Electric vehicles
- Furnaces, grinders.
- Locomotives, mass transit.
- Pump and compressor control.
- Air conditioning, refrigerators.
- VAR compensation.

- Servo systems.
- VLF transmitters.
- Machine tools.

Over View of Power Electronics

Definition: Power electronics involves the study of electronic circuits intended to control the flow of electrical energy. These circuits handle power flow at level much higher than the individual device ratings.

An power electronic system consists of an electrical source and load, a power electronic circuit containing switches and energy storage and control function. The power electronics circuit portion often had relatively few part and most of the components in a commercial system perform control functions.

On the basis of turn on and turn off characteristics and gate signal requirement, the power semiconductor device can be classified as:

(*a*) Diodes: These are uncontrolled power semiconductor devices. Their on and off states are not dependent on the control signals but controlled by power supply and load circuit conditions.

(*b*) Thyristors: These have controlled turn on by a gate signal. After thyristor are turned on they remain latched in on state due to internal regenerative action.

(*c*) Controllable switches: These devices are turned on and turned off by the application of control signals. The devices which behave as controllable switches as BJT, MOSFET, GTO, SITH, IGBT SIT and MCT.

→ SCR, GTO, SITH and MCT require pulse gate signal for turning on: once these devices are on, gate pulse is removed. But BJT, MOSFET, IGBT and SIT require continuous signal for keeping them in turn on state.

→ The device which can with stand uni-polar voltage are BJT, MOSFET, IGBT and MCT Thyristor and GTO^S are capable of supporting bipolar voltages.

→ Thyristor require extra force commutation circuit for their commutation (or turn off) if source is d.c. But power transistor and GTO do not require and extra commutation circuit for their turn off.

Advantages and Disadvantages:

The advantages possessed by power electronic system are as under:

(*i*) High efficiency due to low loss in power semiconductor devices.

(*ii*) High reliability of power electronic converter system.

(*iii*) Long life and less maintenance due to the absence of any moving part

(*iv*) Fast dynamic response of the power electronic system as compared to electromechanical converter system

System based on power electronics however, suffer from the following disadvantages

(*i*) Power electronic converter circuit have a tendency to generate harmonics in the supply system as well as in the load circuit.

(*ii*) AC to dc and ac to ac converter operate at low input power factor under certain operating conditions. In order to avoid a low p.f. some special measure have to be adopted.

Comparison between Silicon and Germanium

Generally or almost we used silicon in power electronics

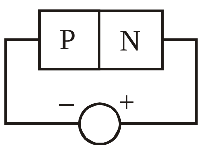
Silicon **Germanium**

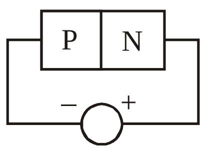
1. Higher thermal limit about 200° C Lower thermal limit 75° C $\rightarrow$ 100° C

So higher I^2R loss

2. Current carrying capacity very high Very low current carrying capacity

3. **PIV rating**



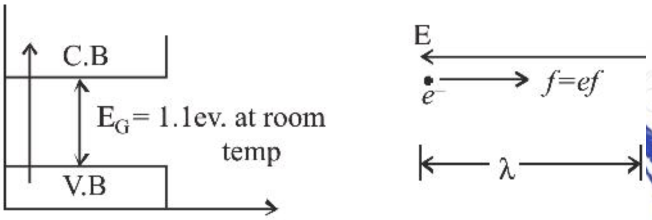


If we have identical Si bar higher Junction temperature	P-N junction have lower junction temperature
4. Reverse saturation current in ηA	Reverse saturation current in μA

Break down Mechanism

(*a*) Zener Breakdown Mechanism: If electric field is very high the force one in covalent bond is so large as e^- may break covalent bond and large no. of charge carrier are generating it is called "Zener Mechanism or direct rupturing of covalent bond.

(*b*) Avalanche Breakdown:



Work done in moving e^- at distance λ then kinetic energy $K.E = e\,E\,\lambda$

If $\quad K.E = e\,E\,\lambda > 1.1\,eV$

The electric field in not so high as e^- may break the covalent bond however very few charge carrier are always present in the depletion region when they move in the electric field they acquire kinetic energy.

The kinetic energy acquire by e^- after moving a distance λ is $K.E. = e\,E\,\lambda$. When these e^- collides with other e^- in covalent bond. These covalent bond will be broken if $e\,E\,\lambda > 1.1\,eV$.

The generating charge carrier further move and collide as result of the cumulative process of collision large no. of charge carrier are generated *i.e.*, Avalanche Mechanism.

POWER SEMICONDUCTOR DEVICES:

➢ **The power semiconductor devices can be divided into five types as shown in Figure-1.**

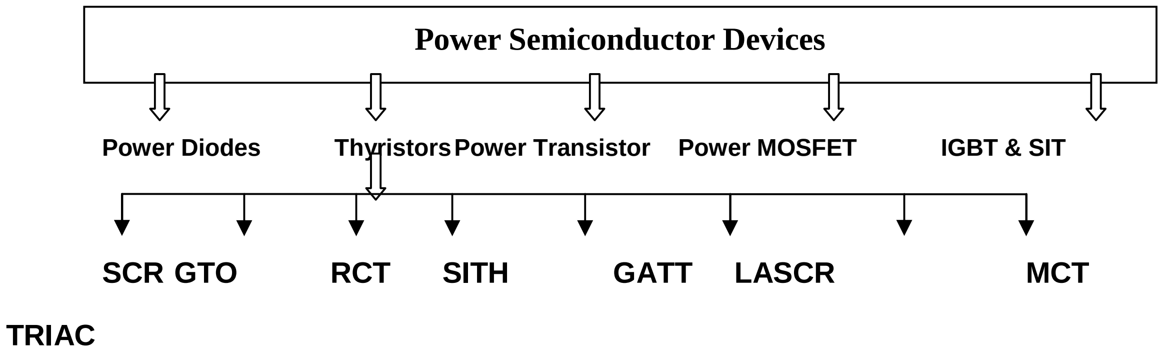


Figure 1: Classification of power semiconductor devices

General Requirements of Power Semiconductor Devices:

1. They should be capable of handling large current and power.
2. In the off state they should withstand very high voltage.
3. Low on state voltage.
4. Low on state resistance.
5. Very high off state resistance.
6. Capability to operate as a switch.
7. Capability to operate as a switch at very high frequency.

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.

- Power Diode (*power semiconductor diode*), has a much larger PN junction area compared to its smaller signal diode cousin, resulting in a high forward current capability of up to several hundred amps (KA) and a reverse blocking voltage of up to several thousand volts (KV). *Since the power diode has a large PN junction, it is not suitable for high frequency applications above 1MHz*, but special and expensive high frequency, high current diodes are available. For high frequency rectifier applications Schottky Diodes are generally used because of their short reverse recovery time and low voltage drop in their forward bias condition.

- Power diodes provide uncontrolled rectification of power and are used in applications such as battery charging and DC power supplies as well as AC rectifiers and inverters. Due to their high current and voltage characteristics they can also be used as freewheeling diodes and snubber networks. Power diodes are designed to have a forward "ON" resistance of fractions of an Ohm while their reverse blocking resistance is in the mega-Ohms range.
- If an alternating voltage is applied across a power diode, during the positive half cycle the diode will conduct passing current and during the negative half cycle the diode will not conduct blocking the flow of current. Then conduction through the power diode only occurs during the positive half cycle and is therefore unidirectional.
- The power semiconductor diodes are used to perform various operations like rectification, freewheeling, energy feedback etc. in power electronic applications.
- The switching speed of the power diodes is low as compared to that of the low power diodes.

Advantages of Power Diodes :

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

Type of Power Diodes:

Depending on the recovery characteristics and manufacturing techniques, they classified as :

1. **General purpose p-n junction diodes.**

- These are used for the low frequency applications (generally below 1 kHz) like rectification, due to their high reverse recovery time.

- At low operating frequencies these diodes are capable of handling currents from very low value i less than 1 amp) to very high values (thousands of amperes). The voltage ratings are from 50 V to 5 kV

2. **Fast recovery diodes.**

- These diodes have low recovery time as compared to the general purpose diodes.
- Therefore they are turned off more quickly and hence can be used in the high frequency applications such as dc-dc converters and dc-ac converters.

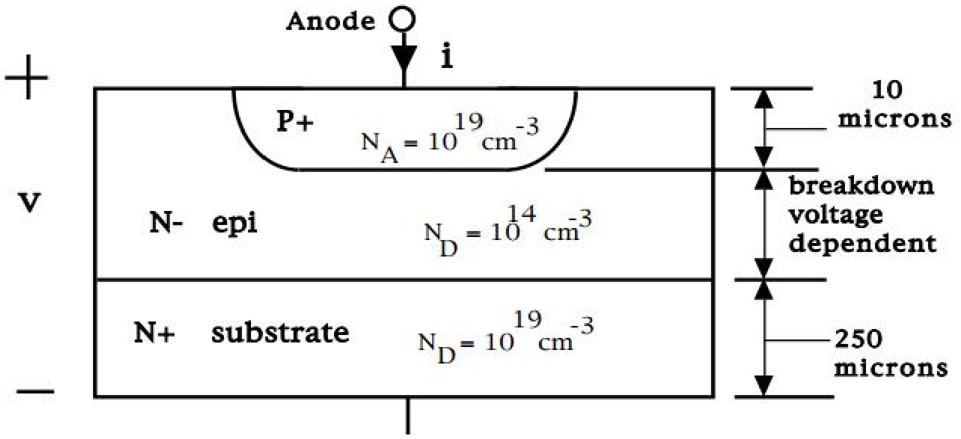
3. **Schottky diodes.**

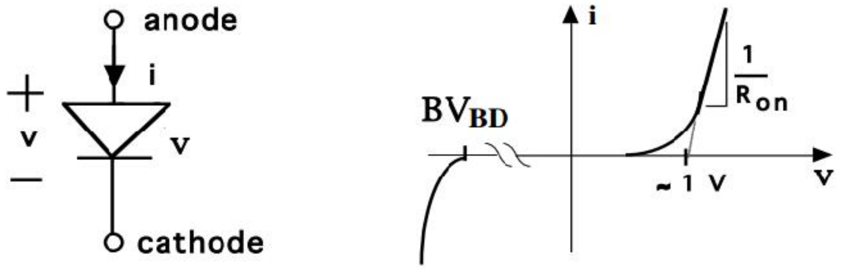
- The schottky diode has the rectifying I-V characteristics very similar to that of the pn junction diode. But the on state voltage drop across it is very low (0.3 to 0.4 volts only) as compared to the other diodes.
- In the reverse biased condition, the schottky diodes have a large reverse leakage current and therefore a lower breakdown voltage (50 to 100 volts only) as compared to other types.
- Therefore the schottky diodes are ideal for high current, low voltage applications like dc power supplies.

Comparison between different types of Diodes

General Purpose Diodes	Fast Recovery Diodes	Schottky Diodes
Upto 5000V & 3500A	Upto 3000V and 1000A	Upto 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 $5\mu s$	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 $0.6V$

Basic Structure of Power Diodes:

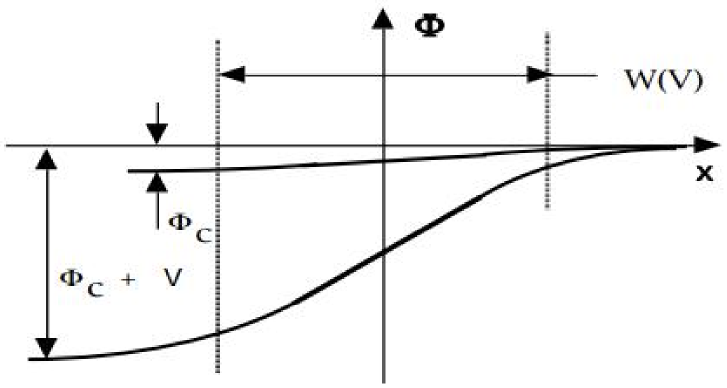




Breakdown Voltage Estimate - Step Junction

- **Non- punch- through diode. Drift region length Wd > W(BV_{BD}) = length**

of space charge region at breakdown.



- $W(V) = W_0\sqrt{1+V/\Phi_c}$
- $W_0 = W_0\sqrt{\dfrac{2£\Phi_c(N_a+N_d)}{qN_aN_d}}$
- $E_{max} = \dfrac{2F_c}{W_0}\sqrt{1+V/F_c}$
- **Power diode at reverse breakdown:** $N_a >> N_d$; $E = E_{BD}$; $V = BV_{BD} >> F_c$
- $W^2(BV_{BD}) = \dfrac{W_0^{\,2}BV_{BD}}{F_c}$; $W_0^{\,2} = \dfrac{2£F_c}{qN_d}$
- $(E_{max})^2 = (E_{BD})^2 = \dfrac{4\Phi_c BV_{BD}}{W_0^{\,2}}$
- Solve for $W(BV_{BD})$ and BV_{BD} to obtain (put in Si values)

$$BV_{BD} = \frac{£E_{BD}^{\,2}}{2qN_d} = \frac{1.3\times10^{17}}{N_d};[V]$$
$$W(BV_{BD}) = \frac{2BV_{BD}}{E_{BD}} = 10^{-5}BV_{BD}\;;[«m]$$

Conclusion:

1. **Large** $BV_{BD}(10^3V)$ requires $N_d < 10^{15}cm^{-3}$.
2. **Large** $BV_{BD}(10^3V)$ requires $N^-\ drift\ region > 100«m$.
3. **The width of the drift layer depends on the desired value of the breakdown voltage. The breakdown voltage of the power diode increases with increase in the width of the drift layer.**

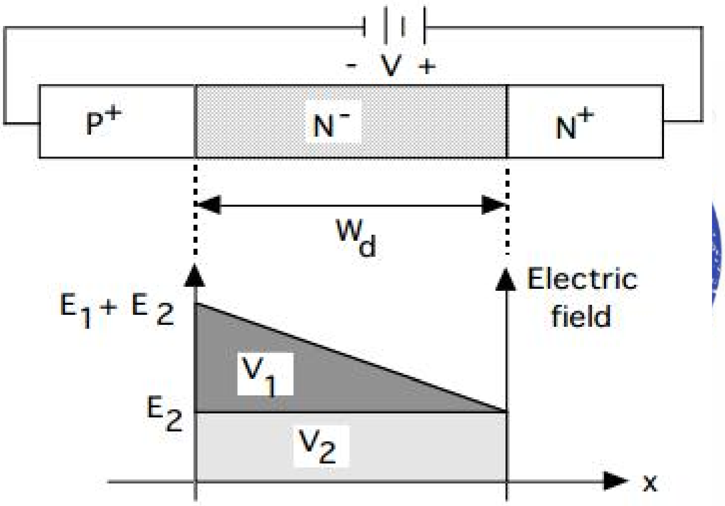
4. **The resistivity of the drift layer is high due to the low level of doping.**

Effects of drift layer:

1. **Increase in the reverse blocking capacity i.e. increase in the reverse breakdown voltage.**
2. **Increase in the on state voltage drop and hence the on state power losses.**

Breakdown Voltage - Punch-Through Step Junction

Punch-through step junction - $W(BV_{BD}) > W_d$



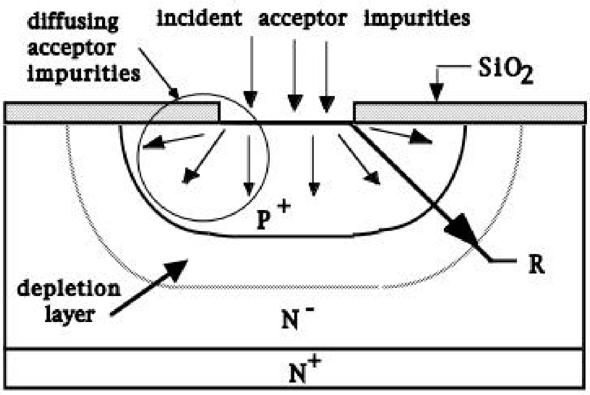
- $E_1 = \frac{qN_dW_d}{£}$; $V_1 = \frac{qN_dW_d^2}{2£}$
- $V_2 = E_2W_d$

At Break Down

- $V_1 + V_2 = BV_{BD}$
- $E_1 + E_2 = E_{BD}$
- $BV_{BD} = E_{BD}W_d - \frac{qN_dW_d^2}{2£}$
- If $N_d << \frac{£(E_{BD})^2}{2q(BV_{BD})}$ (required value of N_d for non-punch thru diode), then

- $BV_{BD} \approx E_{BD}W_d$
- $W_d\,(Punch-thru) \approx 0.5W_d\,(non-punch-thru)$

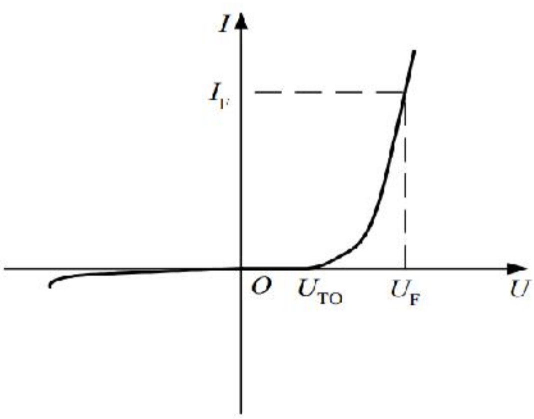
Effect of Space Charge Layer Curvature



- Impurities diffuse as fast laterally as vertically
- Curvature develops in junction boundary and in depletion layer.
- If radius of curvature is comparable to depletion layer thickness, electric field becomes spatially non-uniform.
- Spatially non-uniform electric field reduces breakdown voltage.
- R > 6 W(BV_{BD}) in order to limit breakdown voltage reduction to 10% or less.
- Not feasible to keep R large if BV_{BD} is to be large (> 1000 V).

I-V Characteristic of Power Diode (Static Characteristics):

- The forward current appears to rise linearly with increase in the forward bias voltage rather than increasing exponentially.



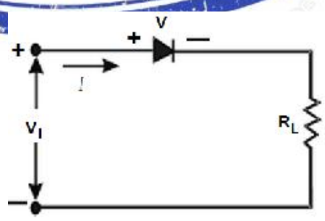
The I-V characteristic of power diode

The conclusions drawn from I-V characteristics are:

- The on state voltage across a power diode is higher than 1 volt which is higher than the on state voltage across a low power diode. This is mainly due to the presence of the (n^-) drift layer.
- When power diode reverse biased, a very small leakage current flows through it. The leakage current is independent of the applied reverse voltage. The leakage current flows due to the Oiermally generated charge carriers (minority carriers).
- If the reverse voltage reaches the reverse breakdown voltage BV_{BD}, avalanche breakdown takes place. The reverse voltage across the device remains constant whereas the reverse current increases drastically.
- The on state resistance of the diode (R_{on}) is the reciprocal of the slope of the characteristic.

Dynamic Characteristics of a Power Switching Diode:

At low frequency and low current, the diode may be assumed to act as a perfect switch. 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.



- A power diode or any power device cannot switch instantaneously from off state to on state; it requires finite time for switching from one state to the other.

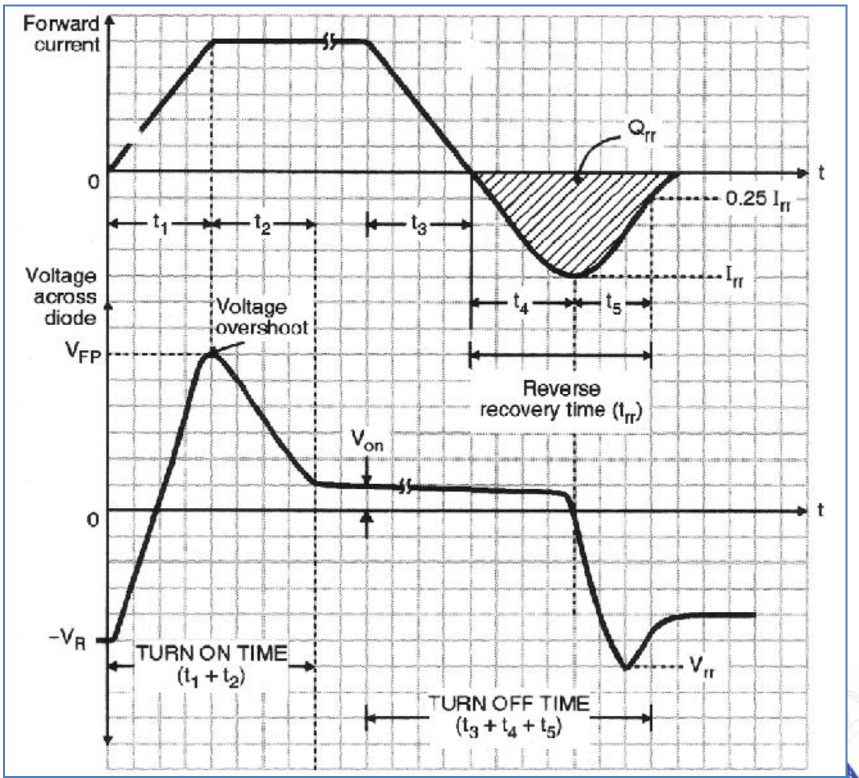


Figure 4: V-I waveforms for a power diode when it is being turned on and off

Turn ON Process: The time taken by a power diode to turn on is the sum of time periods (t_1) and (t_2). During the turn on interval two physical processes take place.

Key Point: Operation while turning on

1. As the forward current starts increasing, the space charge stored in depletion region is removed or discharged.
2. Forward current↑ **:** Voltage drop across the drift region↑ .
3. The voltage across the diode starts decreasing due to (a) Injection of excess carriers into the drift region (b) The forward current is constant.
4. To reduce the total turn on time (t_1 + t_2) it is necessary to have large (di_F / dt) and shorter carrier lifetime in the drift layer.
5. Resistance of the drift region↑ **:** ON state voltage across the diode↑ **.**

Notation : ↑ : Increase ↓ : Decrease

Key Point: Operation while Turn off

1. **The total turn off time = (t_3)+ (t_4) +** (t_5)

2. During turn off process, the excess carriers stored in the (n^-) drift region are removed by the combined action of recombination and carrier sweepout by a negative diode current.
3. During t_3 the forward current reduces at a rate of (di_R/dt).
4. During the interval t_3 the voltage across the diode remains almost constant and positive.

Reverse recovery characteristic: The minority carriers take some time to recombine with opposite charges and to be neutralized. This time is called the *reverse recovery time.*

$$t_{rr} = t_4 + t_5$$

It is the time measured from the zero crossing point of the diode current to 25% of the maximum (peak) reverse current I_{rr}. (see Figure 4).

- 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).
- t_4 : due to charge storage in the depletion region of the junction.
- t_5 : due to charge storage in the bulk semiconductor material.
- Softness factor - SF= t_5/t_4

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 from the area enclosed by the path of the reverse recovery current.

$$Q_{rr} \cong \left(\frac{1}{2} I_{rr} t_4 + \frac{1}{2} I_{rr} t_5 \right) = \frac{1}{2} I_{rr} t_{rr} \qquad \text{....(1)}$$

$$\therefore \qquad I_{rr} = \frac{2Q_{rr}}{t_{rr}} \qquad \text{....(2)}$$

The peak reverse current $I_{rr} = t_4 di_R / dt$ ....(3)

If $t_5 <<< t_4$, then $t_{rr} \approx t_4$ therefore equation (3) can be written as

$$t_{rr}^2 = \frac{2Q_{rr}}{di_R / dt} \qquad \Rightarrow \qquad t_{rr} = \sqrt{\frac{2Q_{rr}}{di_R / dt}}$$

$$\text{and } I_{rr} = \sqrt{2Q_{rr} di_R / dt}$$

Point to Remember:

1. **The reverse recovery time (t_{rr}) and peak reverse recovery current (I_{rr}.) depend on the storage charge Q_{rr} and the reverse or reapplied di_R/dt.**
2. **The storage charge (Q_{rr}) is dependent on the forward diode current I_F.**

Significance of reverse recovery time:

- **To use a power diode in high frequency applications, it is necessary to reduce the reverse recovery time.**
- **Lower the value of "t_{rr}" is higher will be the value of maximum frequency of operation.**

POWER TRANSISTORS

- Power transistors are widely used as static switches in power electronics convertors and available in **npn** and the **pnp** format.
- For operating them as switches, we should operate them in cutoff and saturation regions of operation.
- The power transistors can operate at much higher switching speeds as compared to those of thyristors.
- Power transistors are preferred for the low and medium power applications.