Electrical Engineering

Power Electronics

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

MADE EASY Publications

MADE EASY Publications Pvt. Ltd.

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016
E-mail: infomep@madeeasy.in
Contact: 011-45124660, 8860378007
Visit us at: www.madeeasypublications.org

Power Electronics

First Edition : 2015
Second Edition : 2016
Third Edition : 2017
Fourth Edition : 2018
Fifth Edition : 2019
Sixth Edition : 2020
Seventh Edition : 2021

Eighth Edition : 2022

Contents

Power Electronics

CHAPTER 1

Introduction

The task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads.

1.1 Block Diagram of Power Electronic Systems

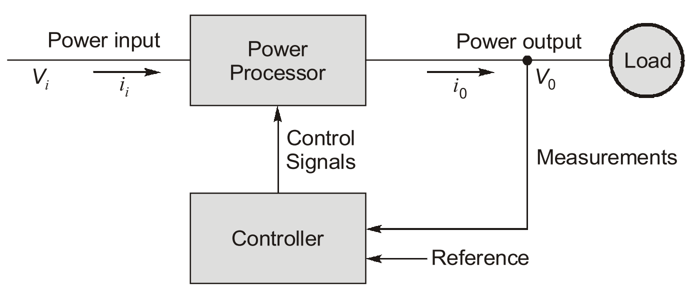


***Figure*-1.1**

Power electronics may be defined as the application of solid state electronics for the control and conversion of electric power.

History of Power Electronics

The history of power electronics began with the introduction of the mercury arc rectifier in 1900. The first electronics revolution began in 1948 with the invention of the silicon transistor at Bell Telephone Laboratories by Bardeen, Brattain and Shockley. The next break through, in 1956, was also from Bell Laboratories: the invention of the PNPN triggering transistor, which was defined as a thyristor or silicon controlled rectifier (SCR). The second electronics revolution began in 1958 with the development of the commercial thyristor by the General Electric Company. That was the beginning of a new era of power electronics. The micro electronics revolution gave us the ability to process a huge amount of information at incredible speed. The power electronics revolution is giving us the ability to shape and control large amounts of power with ever increasing efficiency.

Scope and Applications

1. Switch Mode (DC) Power Supplies and Uninterruptible Power Supplies

Advances in micro electronics fabrication technology have led to the development of computers, communication equipment and consumer electronics, all of which require regulated dc power supplies and often uninterruptible power supplies.

2. Energy Conservation

Increasing energy costs and the concern for the environment have combined to make energy conservation a priority. Adjustable speed motor drives, load proportional, capacity modulated heat pumps and air conditioners are examples of applying power electronics to achieve energy conservation.

3. Process Control and Factory Automation

There is a growing demand for the enhanced performance offered by adjustable speed driven pumps and compressors in process control. Robots in automated factories are powered by electric servo (adjustable speed and position) drives. It should be noted that the availability of process computers is a significant factor in making process control and factory automation feasible.

4. Transportation

In many countries, electric trains have been in widespread use for a long time. Now, there is also a possibility of using electric vehicles in large metropolitan areas to reduce smog and pollution. Electric vehicles would also require battery chargers that utilize power electronics.

5. Electro Technical Applications

These include equipment for welding, electroplating, and induction heating.

6. Utility Related Applications

One such application is in transmission of power over high voltage dc (HVDC) lines. Power electronics is also beginning to play a significant role as electric utilities attempt to utilize the existing transmission network to a higher capacity. Potentially, a large application is in the interconnection of photo voltaic and wind electric systems to the utility grid.

Power Electronic Applications

1. Residential

Refrigeration and freezers, Space heating, Air conditioning, Cooking, Lighting, Electronics (personal computers, other entertainment equipment).

2. Commercial

Heating, Ventilating, and Air conditioning, Central refrigeration, Lighting, Computers and Office equipment, Uninterruptible Power Supplies (UPSs), Elevators.

3. Industrial

Pumps, Compressors, Blowers and Fans, Machine tools (Robots), Arc furnaces, Induction furnaces, Lighting, Industrial lasers, Induction heating, Welding.

4. Transportation

Traction control of electric vehicles, Battery chargers for electric vehicles, Electric locomotives, Street cars, Trolley buses, Subways, Automotive electronics including engine controls.

5. Utility Systems

High voltage dc transmission (HVDC), Static var compensation (SVC), Supplemental energy sources (wind, photovoltaic), Fuel cells, Energy storage systems, Induced draft fans and Boiler feedwater pumps.

6. Aerospace

Space shuttle power supply systems, Satellite power systems, Aircraft power systems.

7. Telecommunications

Battery chargers, Power supplies (DC and UPS).

Interdisciplinary Nature of Power Electronics

The study of power electronics encompasses many fields with in electrical engineering. Combining the knowledge of these diverse fields makes the study of the subject challenging as well as interesting. There are many potential advances in all these fields that will improve the prospects for applying power electronics to new applications.

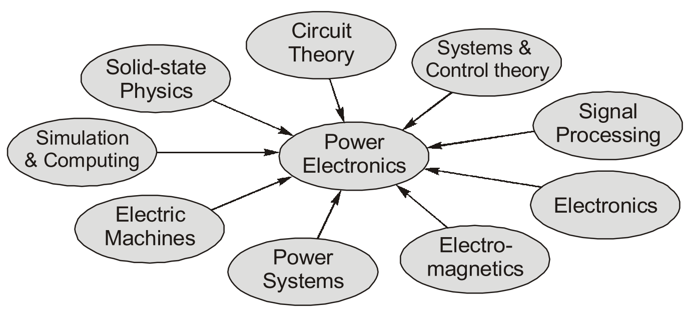


***Figure*-1.2 :** *Interdisciplinary nature of power electronics*

Types of Power Electronic Circuits

1. Diode Rectifiers

A diode rectifier circuit converts ac input voltage into a fixed dc voltage. The input voltage may be single-phase or three-phase. Diode rectifiers find wide use in electric traction, battery charging, electroplating, electrochemical processing, power supplies, welding and uninterruptible power supply (UPS) systems.

2. AC to DC Converters (Phase-controlled rectifiers)

These convert constant ac voltage to variable dc output voltage. These rectifiers use line voltage for their commutation, as such these are also called line-commutated or naturally-commutated ac to dc converters. Phase-controlled converters may be fed from single-phase or three-phase source. These are used in dc drives, metallurgical and chemical industries, excitation systems for synchronous machines etc.

3. DC to DC Converters (DC Choppers)

A dc chopper converts fixed dc input voltage to a controllable dc output voltage. The chopper circuits require forced, or load, commutation to turn-off the thyristors. For lower power circuits, thyristors are replaced by power transistors. Classification of chopper circuits is dependent upon the type of commutation and also on the direction of power flow. Choppers find wide applications in dc drives, subway cars, trolley trucks, battery-driven vehicles etc.

4. DC to AC Converters (Inverters)

An inverter converts fixed dc voltage to a variable ac voltage. The output may be a variable voltage and variable frequency. These converters use line, load or forced commutation for turning-off the thyristors. Inverters find wide use in induction motor and synchronous motor drives, induction heating, UPS, HVDC transmission etc. At present, conventional thyristors are also being replaced by GTOs in high power applications and by power transistors in low power applications.

5. AC to AC Converters

These convert fixed ac input voltage into variable ac output voltage. These are of two types as under:

AC voltage controllers (AC voltage regulators): These converter circuits convert fixed ac voltage directly to a variable ac voltage at the same frequency. AC voltage controllers employ two thyristors in antiparallel or a triac. Turn-off of both the devices is obtained by line commutation. Output voltage is controlled by varying the firing angle delay. AC voltage controllers are widely used for lighting control, speed control of fans, pumps etc.

Cycloconverters: These circuits convert input power at one frequency to output power at a different frequency through one-stage conversion. Line commutation is more common in these converters, though forced and load commutated cycloconverters are also employed. These are primarily used for slow-speed large ac drives.

6. Static Switches

The power semiconductor devices can operate as static switches or contactors. Static switches possess many advantages over mechanical and electromechanical circuit breakers. Depending upon the input supply, the static switches are called ac static switches or dc static switches.

- Power electronics is based primarily on the switching of the power semiconductor devices.
- Modern power electronics equipment uses,
  1. Power semiconductors that can be regarded as the muscle, and
  2. Microelectronics that have the power and intelligence of a brain.

1.2 Classification of The Power Semiconductors

The power semiconductor switching devices can be classified on the basis of

- Uncontrolled turn-on and turn-off (e.g., diode)
- Controlled turn-on and uncontrolled turn-off (e.g. SCR)
- Controlled turn-on and turn-off characteristics (e.g., BJT, MOSFET, GTO, SITH, IGBT, SIT, MCT)
- Continuous gate signal requirement (BJT, MOSFET, IGBT, SIT)
- Pulse gate requirement (e.g., SCR, GTO, MCT)
- Bipolar voltage withstanding capability (SCR, GTO)
- Unipolar voltage withstanding capability (BJT, MOSFET, IGBT, MCT)
- Bidirectional current capability (TRIAC, RCT)
- Unidirectional current capability (SCR, GTO, BJT, MOSFET, MCT, IGBT, SITH, SIT, Diode).

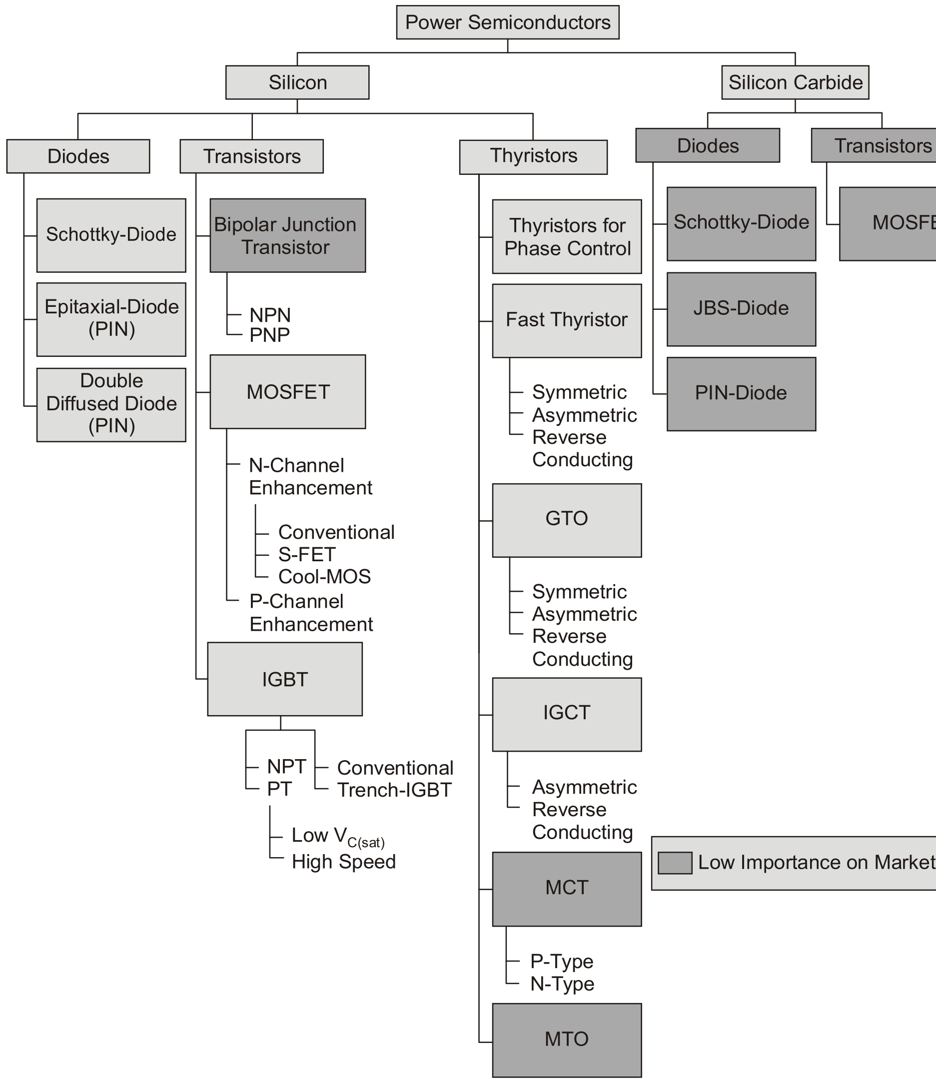


***Figure*-1.3 :** *Classification of the power semiconductors*

Characteristics and Specifications of Switches

There are many types of power switching devices. Each device, however, has its advantages and disadvantages and is suitable to specific applications. The motivation behind the development of any new device is to achieve the characteristics of a "***Super device***". The characteristics of any real device can be compared and evaluated with reference to the ideal characteristics of a super device.

Ideal Characteristics

The characteristics of an ideal switch are as follows:

- In the on-state when the switch is on, it must have (a) the ability to carry a high forward current I_F, tending to infinity; (b) a low on-state forward voltage drop V_{ON}, tending to zero; and (c) a low on-state resistance R_{ON}, tending to zero. Low R_{ON} causes low on-state power loss P_{ON}. These symbols are normally referred to under dc steady state conditions.

- In the off-state when the switch is off, it must have (a) the ability to withstand a high forward or reverse voltage V_{BR}, tending to infinity; (b) a low off-state leakage current I_{OFF}, tending to zero, and (c) a high off-state resistance R_{OFF}, tending to infinity. High R_{OFF} cause low off-state power loss P_{OFF}. These symbols are normally referred to under dc steady-state conditions.
- During the turn-on and turn-off process, it must be completely turned on and off instantaneously so that the device can be operated at high frequencies. Thus it must have (a) a low delay time t_d, tending to zero; (b) a low rise time t_r, tending to zero; (c) a low storage time t_s, tending to zero; and (d) a low fall time t_f, tending to zero.
- For turn-on and turn-off, it must require (a) a low gate-drive power P_G, tending to zero; (b) a low gate-drive voltage V_G, tending to zero; and (c) a low gate-drive current I_G, tending to zero.
- Both turn-on and turn-off must be controllable. Thus, it must turn-on with a gate signal (e.g., positive) and must turn-off with another gate signal (e.g., zero or negative).
- For turning on and off, it should require a pulse signal only, that is a small pulse with a very small width t_W, tending to zero.
- It must have a high *dv*/*dt*, tending to infinity. That is, the switch must be capable of handling rapid changes of the voltage across it.
- It must have a high *di*/*dt*, tending to infinity. That is, the switch must be capable of handling a rapid rise of the current through it.
- It requires very low thermal impedance from the internal junction to the ambient R_{JA}, tending to zero so that it can transmit heat to the ambient easily.
- The ability to sustain any fault current for a long time is needed; that is, it must have a high value of i^2t, tending to infinity.
- Negative temperature coefficient on the conducted current is required to result in an equal current sharing when the devices are operated in parallel.
- Low price is a very important consideration for reduced cost of the power electronics equipment.

Switch Specifications

There are many parameters that are important to the devices. The most important among these are:

- **Voltage ratings:** Forward and reverse repetitive peak voltages, and an on-state forward voltage drop.
- **Current ratings:** Average, root-mean-square (rms), repetitive peak, non-repetitive peak, and off-state leakage currents.
- **Switching speed or Frequency:** Transition from a fully non-conducting to a fully conducting state (turn-on) and from a fully conducting to a fully non-conducting state (turn-off) are very important parameters. The switching period T_S and frequency f_S are given by

$$f_S = \frac{1}{T_S} = \frac{1}{t_d + t_r + t_{on} + t_s + t_f + t_{off}}$$

  where t_{off} is the off time during which the switch remains off.
- ***di*/*dt* Rating:** The device needs a minimum amount of time before its whole conducting surface comes into play in carrying the full current. If the current rises rapidly, the current flow may be concentrated to a certain area and the device may be damaged. The *di*/*dt* of the current through the device is normally limited by connecting a small inductor in series with the device, known as a series snubber.

- ***dv/dt* Rating:** A semiconductor device has an internal junction capacitance C_J. If the voltage across the switch changes rapidly during turn-on, turn-off and also while connecting the main supply the initial current, the current $C_J\, dv/dt$ flowing through C_J may be too high, thereby causing damage to the device. The dv/dt of the voltage across the device is limited by connecting an RC circuit across the device, known as a shunt snubber, or simply snubber.
- **Switching losses:** During turn-on the forward current rises before the forward voltage falls, and during turn-off the forward voltage rises before the current falls. Simultaneous existence of high voltage and current in the device represents power losses. Because of their repetitiveness, they represent a significant part of the losses, and often exceed the on-state conduction losses.
- **Gate drive requirements:** The gate-drive voltage and current are important parameters to turn-on and turn-off a device. The gate-driver power and the energy requirement are very important parts of the losses and total equipment cost. With large and long current pulse requirements for turn-on and turn-off, the gate drive losses can be significant in relation to the total losses and the cost of the driver circuit can be higher than the device itself.
- **Safe Operating Area (SOA):** The amount of heat generated in the device is proportional to the power loss, that is the voltage current product. For this product to be constant $P = vi$ and equal to the maximum allowable value, the current must be inverse proportional to the voltage. This yields the SOA limit on the allowable steady-state operating points in the voltage current coordinates.
- **I^2t for fusing:** This parameter is needed for fuse selection. The $I^2\,t$ of the device must be less than that of the fuse so that the device is protected under fault current conditions.
- **Temperatures:** Maximum allowable junction, case and storage temperatures, usually between 150°C and 200°C for junction and case, and between –50°C and 175°C for storage.
- **Thermal resistance:** Junction to case thermal resistance, Q_{JC}, case to sink thermal resistance, Q_{CS}, and sink ambient thermal resistance, Q_{SA}. Power dissipation must be rapidly removed from the internal wafer through the package and ultimately to the cooling medium. The size of semiconductor power switches is small, not exceeding 150 mm, and the thermal capacity of a bare device is too low to safely remove the heat generated by internal losses. Power devices are generally mounted on heat sinks. Thus, removing heat represents a high cost of equipment.

Summary

With 'n' number of variables the maximum possible minterm or maxterm is equal to '2^n'.
As the technology for the power semiconductor devices and integrated circuits develops, the potential for the applications of power electronics becomes wider. The power converters fall generally into six categories:

- Rectifiers
- AC-DC converters
- AC-AC converters
- DC-DC converters
- DC-AC converters and
- Static switches

The design of power electronics circuits requires designing the power and control circuits. The voltage and current harmonics that are generated by the power converters can be reduced (or minimized) with a proper choice of the control strategy.

■■■■

CHAPTER 2

Power Semi-conductor Diode and Transistor

2.1 Basic Semiconductor Physics Important Concepts are as follows:

- Current in a semiconductor is carried by both electrons and holes.
- Electron and holes move by both drift and diffusion.
- Intentional doping of the semiconductor with impurities will cause the density of holes and electrons to be vastly different.
- The density of minority carriers increases exponentially with temperature.
- A *pn* junction can be formed by doping one region *n*-type and the adjacent region *p*-type.
- A potential barrier is set up across a pn junction in thermal equilibrium that balances out the drift and diffusion of carriers across the junction so that no net current flows.
- In reverse bias a depletion region forms on both sides of the *pn* junction and only a small current can flow by drift.
- In forward bias large numbers of electrons and holes are injected across the *pn* junction and large currents flow by diffusion with small applied voltages.
- Large numbers of excess electron-hole pairs are created by impact ionization if the electric field in the semiconductor exceeds a critical value.
- Avalanche breakdown occurs when the reverse-bias voltage is large enough to generate the critical electric field E_{BD}.

2.2 Basic Structure and I-V Characteristics

The practical realization of diode for power application is shown below.

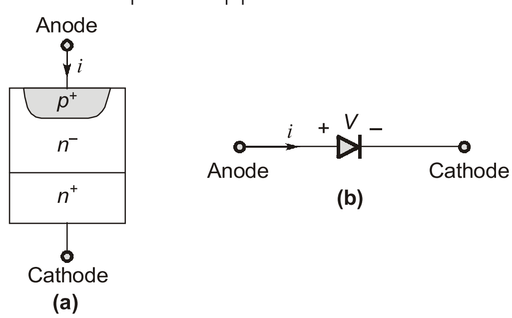


***Figure*-2.1**

It consists of a heavily doped *n*-type substrate on top which is grown a lightly doped 'n^-' epitaxial layer of specified thickness. Finally, the *p-n* junction is formed by diffusing in a heavily doped p-type region that forms the anode of the diode.

The n^- layer which is often termed the drift region, is the prime structural feature not formed in low power diodes. Its function is to absorb the depletion layer of the reverse biased p^+ n^- junction.

This relatively long lightly doped region would appear to add significant ohmic resistance to the diode when it is forward biased.

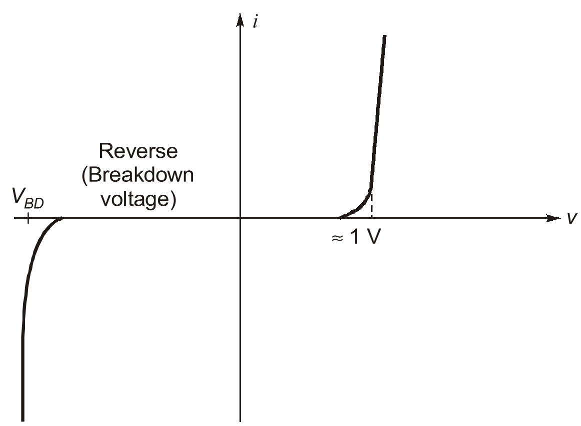


***Figure*-2.2**

The current grows linearly with the forward bias voltage rather than exponentially.

In reverse bias only a small leakage current, which is independent of the reverse voltage, flows until the reverse break down voltage V_{BD} is reached. When breakdown is reached the voltage appears to remain essentially constant while the current increases dramatically.

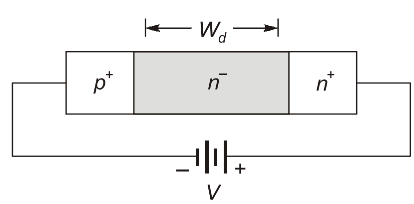


***Figure*-2.3**

If the length W_d of the lightly doped region is longer than the depletion layer width at breakdown, then the structure is termed a non punch through diode, that is, the depletion layer has not reached through (or punched through) the lightly doped drift region and reached the highly doped n^+ subtract.

Two basic facts; first, large breakdown voltages require lightly doped junctions, at least on one side. Second, the drift layer in the diode must be fairly long in high voltage devices to accommodate the long depletion layers.

Switching Characteristics

A power diode requires a finite time to switch from the blocking state (reverse bias) to the on state (forward bias) and vice versa.

The features of particular interest in these waveforms are the voltage overshoot during turn on and the sharpness of the fall of the reverse current during the turn off phase.

The overshoot of the voltage during turn on is not observed with signal level diodes.

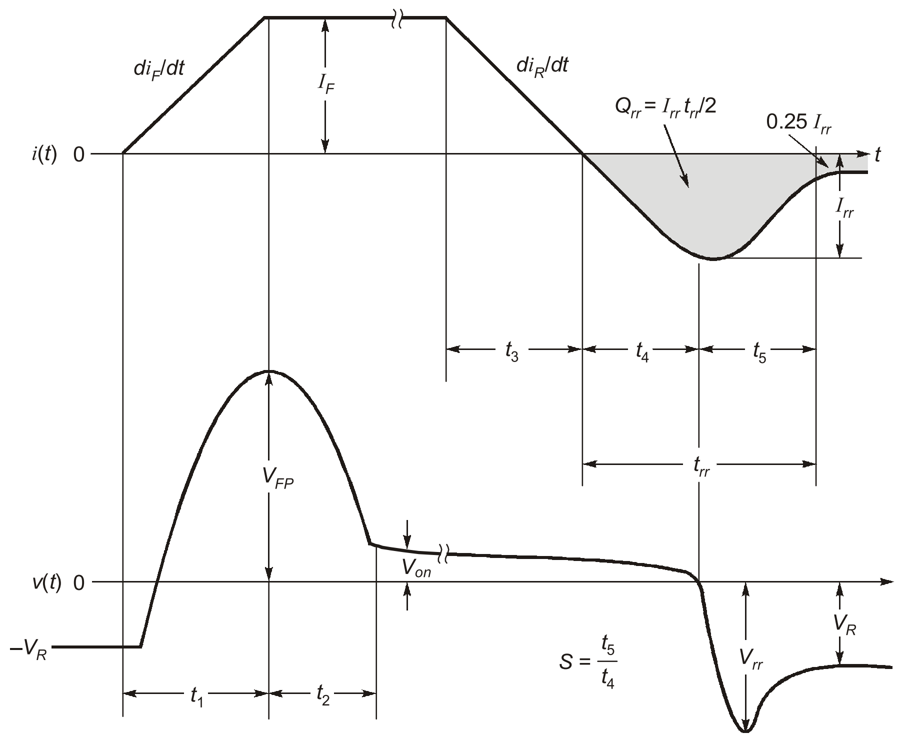


***Figure*-2.4**

Turn-on Transient

The turn on portion of the diode waveform is encompassed by the times labeled t_1 and t_2. During these intervals two physical process occur in sequence. First the space charge stored in the depletion region (located mainly in the drift region) because of the large reverse bias voltage is removed (discharged) by the growth of the forward current. When the depletion layer is discharged to its thermal equilibrium level, the metallurgical junction becomes forward biased and the injection of excess carriers across the junction into the drift region commences at time t_1, thus marking the start of the second phase and the end of the first. During the second phase, the excess-carrier distribution in the drift region grows towards the steadily state value that can be supported by the forward diode current I_f.

NOTE: Excess carries are injected into the drift region from both ends with holes being injected from the $p^+ n^-$ junction and electrons from the $n^+ n^-$ junction.

Turn-off Transient

The turn off portion of the switching waveform is encompassed by the times labeled t_3, t_4 and t_5 and is essentially the inverse of the turn on process. First the excess carriers stored in the drift region must be removed before the metallurgical junctions can become reverse biased.

Once the carriers are removed by the combined action of recombination and sweep out by negative diode currents, the depletion layer acquires a substantial amount of space charge from the reverse bias voltage and expands into the drift region from both ends (junctions).

As long as there are excess carriers at the ends of the drift region, the $p^+ n^-$ and $n^+ n^-$ junctions must be forward biased. Thus, the diode voltage will little change from its on state value except for a small decrease due to ohmic drops caused by the reverse current. But after the current goes negative and carrier sweep-out has proceeded for a sufficient time (t_4) to reduce the excess carriers density at both junctions to zero, the junctions become reverse biased. At this point the diode voltage goes negative and rapidly acquires substantial negative values as the depletion regions from the two junctions expand into the drift region towards each other.

The diode current ceases its growth in the negative direction and quickly falls, becoming zero after a time t_5.

The reverse current has its maximum reverse value, I_{rr}, at the end of the t_4 interval.

Reverse Recovery

The time interval $t_{rr} = t_4 + t_5$ shown in the graph is often termed the reverse recovery time. Its characteristics are important in almost all power electronic circuits where diode are used.

t_{rr} = reverse recovery time

Q_{rr} = reverse recovery charge

$\frac{di_R}{dt}$ = rate of change of reverse current

S = snappiness factor or softness factor

There quantities are inter related to each other.

We note that I_{rr} can be written as

$$I_{rr} = \frac{di_R}{dt} \times t_4$$

$$\because \quad \boxed{s = \frac{t_5}{t_4}}$$

$$t_4 = t_{rr} - t_5 = \frac{t_{rr}}{s+1}$$

$$\therefore \quad I_{rr} = \frac{di_R}{dt} \times \frac{t_{rr}}{s+1}$$

$$\boxed{Q_{rr} \cong \frac{1}{2} I_{rr} t_{rr}}$$

So that,
$$Q_{rr} = \frac{di_R}{dt} \frac{t_{rr}^2}{2(s+1)}$$

Reverse recovery time,
$$\boxed{t_{rr} = \sqrt{\frac{2Q_{rr}(1+s)}{\left(\frac{di_R}{dt}\right)}}} \; ; \quad \boxed{I_{rr} = \sqrt{\frac{2Q_{rr}\left(\frac{di_R}{dt}\right)}{(s+1)}}}$$

The charge Q_{rr} represents the portion of the total charge Q_F (the charge stored in the diode during forward bias), which is swept out by the reverse current and not lost to internal recombination. Most of Q_F is stored in the drift region.

***Example* - 2.1** A power diode is in the forward conduction mode and the forward current is now decreased. The reverse recovery time of the diode is tr and the rate of fall of the diode current is *di*/*dt*. What is the stored charge?

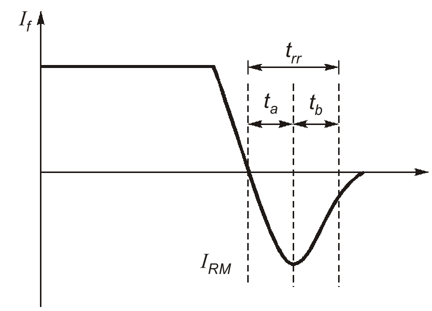
(a) $\left(\frac{di}{dt}\right) \cdot t_r$ (b) $\frac{1}{2}\left(\frac{di}{dt}\right) \cdot t_r^2$

(c) $\left(\frac{di}{dt}\right) \cdot t_r^2$ (d) $\frac{1}{2}\left(\frac{di}{dt}\right) \cdot t_r$

Solution : (b)

From figure,

$$I_{RM} = t_a \frac{di}{dt}$$



Reverse Recovery Characteristic

Assuming reverse recovery characteristics to be triangular, storage charge Q_R

$$Q_R = \frac{1}{2} I_{RM}\, t_{srr} = \frac{1}{2}\left(t_a \frac{di}{dt}\right) t_{rr}$$

if $\quad t_a \approx t_{rr}$

$$Q_R = \frac{1}{2}\left(\frac{di}{dt}\right) t_{rr}^2$$

Schottky Diodes: Structure and I-V Characteristics

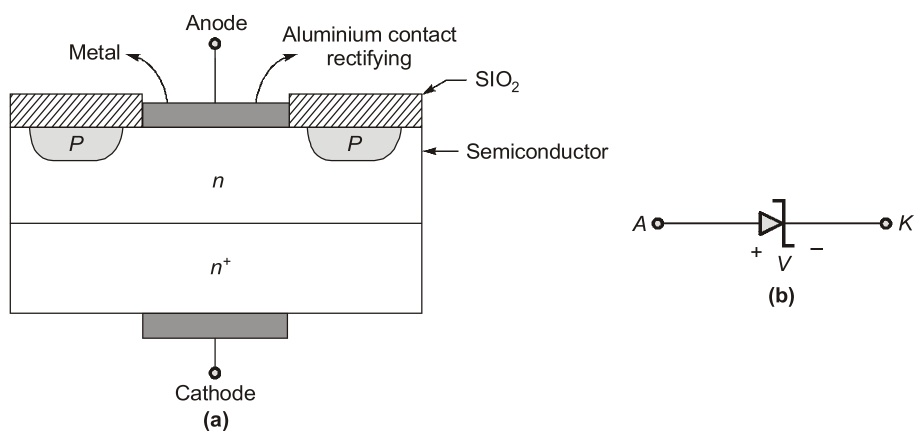


***Figure*-2.5**

A metal semiconductor junction is established. When the materials are joined, the electrons in the *n*-type silicon semiconductor material immediately flow into the adjoining metal, establishing a heavy flow of majority carriers. Since the injected carriers have a very high kinetic energy level compared to the electrons of the metal, they are commonly called **"hot carriers"**.

In the conventional p-n junction, there was the injection of minority carriers into the adjoining region. Here the electrons are injected into a region of the same electron polarity. Schottky diodes are therefore unique in that, conduction is entirely by majority carriers.

The heavy flow of electrons into the metal creates a region near the junction surface depleted of carriers in the silicon material much like the depletion region in the *p*-*n* junction diode. The additional carriers in the metal establish a **'negative wall'** in the metal at the boundary between the two materials. The net result is a 'surface barrier' between the two materials, preventing any further current.

The application of forward bias will reduce the strength of the negative barrier. The result is a return to the heavy flow of electrons across the boundary, the magnitude of which is controlled by the level of the applied bias potential.

The barrier at the junction for a schottky diode is less than that of the *p-n* junction device in both the forward and reverse bias regions. The result is therefore a higher current at the same applied bias in the forward and reverse bias regions. This is a desirable effect in the forward bias region but highly undesirable in the reverse bias region.

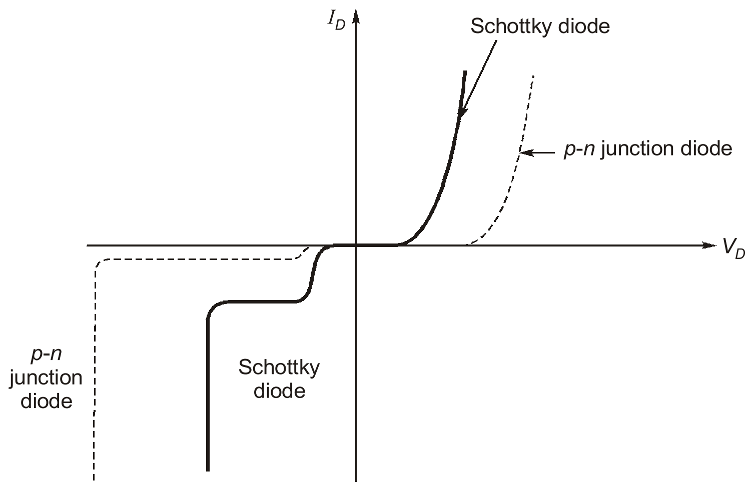


Figure-2.6 : *Comparison of characteristics of schottky diode and p-n junction diode*

The absence of minority carriers at any appreciable level in the schottky diode results in a reverse recovery time of significantly lower levels, this is the primary reason schottky diodes are so effective at frequencies approaching 20 GHz, where the device must switch states at a very high rate.

Points to Remember in Power Semiconductor Diodes

- Power diodes are constructed with a vertically oriented structure that includes a 'n^-' drift region to support large blocking voltages.
- The breakdown voltage is approximately inversely proportional to the doping density of the drift region, and the required minimum length of the drift region scales with the desired breakdown voltage.
- Achievement of large breakdown voltages requires special depletion layer boundary shaping techniques.
- Conductivity modulation of the drift region in the on state keeps the losses in the diode to manageable levels even for large on-state currents.
- Low on-state losses require long carrier lifetimes in the diode drift region.
- Minority-carrier devices have lower on-state losses than majority-carrier devices such as MOSFETs at high blocking voltage ratings.
- During the turn-on transient the forward voltage in a diode may have a substantial overshoot, on the order of tens of volts.
- Short turn-off times require short carrier lifetimes, so a trade-off between switching times and on-state losses must be made by the device designer.
- During turn-off, fast reverse recovery may lead to large voltage spikes because of stray inductance.