ELECTRONIC DEVICES AND CIRCUITS

UNIT I Diode

Diode:

Diode - Static and Dynamic resistances, Equivalent circuit, Diffusion and Transition Capacitances, V-I Characteristics, Diode as a switch- switching times.

1.1 Basics

Atom:

- The smallest particle of an element that can exist either alone or in combination.
- Atoms consist of a heavy central nucleus surrounded by a cloud of negatively charged particles called electrons.
- The nucleus contains positive particles (protons) and electrically neutral particles (neutrons).

Electronics:

- The branch of science that deals with the study of flow and control of electrons and the study of their behavior and effects in vacuums, gases, and semiconductors.

Passive Components:

- Those devices or components which do not required external source to their operation.
  Examples: Resistor, capacitor and inductor.

Active Components:

- Those devices or components which required external source to their operation.
  Examples: Diode, Transistors, SCR, Integrated Circuits, DIAC, TRIAC, LED etc.

DC (Direct Current):

- The electrons flow in one direction only. Current flow is from negative to positive.

AC (Alternating Current):

- The electrons flow in both directions in a cyclic manner.

Frequency:

- The rate of change of direction determines the frequency, measured in Hertz (cycles per second).

Valence Electrons:

- Valence electrons are the electrons present in the outermost orbit of an atom.

Free Electrons (or) Conduction Electrons:

- Free electrons are electrons that are not attached to an atom.

Energy band:

- The range of energies possessed by an electron in an atom.

Conduction band:

- The range of energies possessed by conduction electrons in an atom.

Valence Band:

- The range of energies possessed by valence electrons in an atom.

Energy band diagram:

- It is a diagram between interatomic spacing and energy

Forbidden Energy Gap:

- The separation between conduction band and valance band of the energy band diagram

1.1.1 Classification of Solid state materials

Insulators:

- Insulators are the materials which are not allowing flow of electric current through them.

  Examples – Glass, Wood, Rubber, Plastic and air.

Conductors:

- Conductors are the materials which are easily allowing flow of electric current through them.

  Examples – Copper, Aluminum, Iron and silver

Semiconductors:

- Semiconductors are the materials whose electrical conductivity lies in between insulators and conductors.

  Examples – silicon, Germanium and Gallium

1.2 Theory of P-N Junction

1.2.1 Types of Semiconductor

- Semiconductors can be classified into two types:
  - Intrinsic Semiconductors or Pure of Semiconductors
  - Extrinsic Semiconductors or Impure of Semiconductors

1.2.1.1 Intrinsic semiconductors:

- The normal silicon and Germanium are intrinsic semiconductors.
- The number of electrons present in the outermost orbit of intrinsic semiconductor is four
- So, intrinsic semiconductors are tetra valent in nature.

1.2.1.2 Doping:

- The process of adding impurities to an intrinsic semiconductor is known as doping.

1.2.1.3 Extrinsic Semiconductors:

- With respect to the type of impurity added, extrinsic semiconductors are classified into two types.
    - N- type semiconductors
    - P- type semiconductors

1.2.1.3.1 N- type semiconductors

- When a small amount of penta valent impurity (e.g. Antimony, Arsenic) is added to a pure semiconductor, we will get N - type semiconductor.
- The addition of penta valent gives a large number of free electrons in the semiconductors crystal.

Tetra valent	+	Penta valent	= N- type Semiconductor
(4 electrons)	+	(5 electrons)	= 9 electrons
			= 9 Negative charges
			= Excess of an electron

- The Majority Carriers in N - type are electrons (Negative charges) and Minority carriers are holes (positive charges).
- N – type semiconductors are known as Donor impurities because they donate free electrons to the semiconductor crystal.

1.2.1.3.2 P - type semiconductors

- When a small amount of trivalent material (e.g. Indium, Gallium) is added to a pure semiconductor, we will get P - type semiconductor.
- The addition of trivalent impurity gives a large number of holes in the semiconductor.
- The hole shows absence of an electron.

Tetra valent	+	Tri valent	= P – type Semiconductor
(4 electrons)	+	(3 electrons)	= 7 electrons
			= Shortage of an electron
			= One positive charge
			= Hole

- In a P - type semiconductor, Majority carriers are holes and Minority carriers are electrons.
- P - type semiconductors are called Acceptor Impurities because the holes created can accept the electrons.

1.3 P-N Junction as a Diode

- A junction is formed by joining P - type semiconductor with N – type semiconductor, the structure is called PN Junction or PN Diode.
- The structure of PN junction diode is shown in figure 1.1.

Fig.1.1 PN Junction diode

- Symbol of diode is given in figure 1.2.

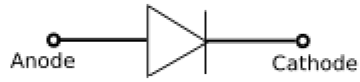


Fig. 1.2 Symbol of PN Junction diode

1.3.1 Parameters used in PN Junction diode

- Figure 1.3 shows the open circuited PN Junction.

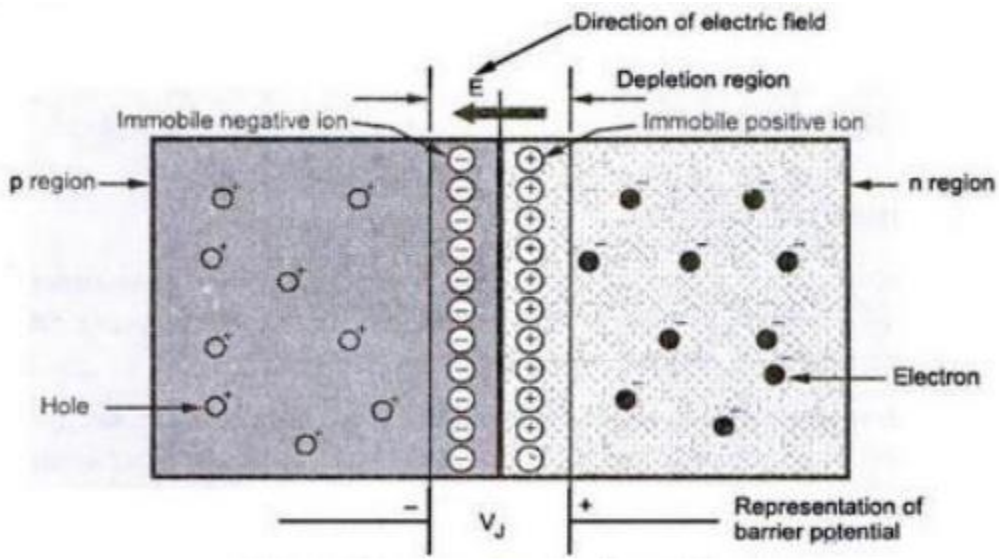


Fig. 1.3 Open circuited (No Biasing) PN Junction

- The free electrons from the n-region start diffusing into the p-region.
- The holes from p-side diffuse across the junction into the n-region.
- As more and more electrons recombine in p-region and holes in n-region, more charges get formed near the junction.
- Hence in equilibrium condition there exists a layer of negative charges in p-region and positive charges in n-region, near the junction.

1.3.1.1 Diffusion:

- Diffusion is the process by which electrons move from high concentration area towards low concentration area.

1.3.1.2 Depletion region:

- A region is formed with empty free charge carriers at both the sides of junctions are called as depletion region (or) depletion layer (or) space charge region.

1.3.1.3 Potential barrier:

- The barrier which does not allow charge flow across the junction is called as potential barrier.

Semiconductor material	Symbol	Barrier potential
Silicon	Si	0.6 V
Germanium	Ge	0.2 V

- The barrier potential depends on,
  - Type of semiconductor
  - The acceptor impurity added
  - The donor impurity added
  - The temperature
  - Intrinsic concentration

1.3.1.4 Biasing:

- Applying external D.C. voltage to any electronic device is called biasing.

1.4 Operation of PN Junction Diode

- Operation of a PN junction diode can be explained in two ways.
  - Forward Biasing
  - Reverse Biasing

1.4.1 Forward Biasing:

- If an external d.c voltage is connected in such a way that the p-region terminal is connected to the positive terminal of the d.c. voltage and the n-region is connected to the negative terminal of the d.c, voltage.

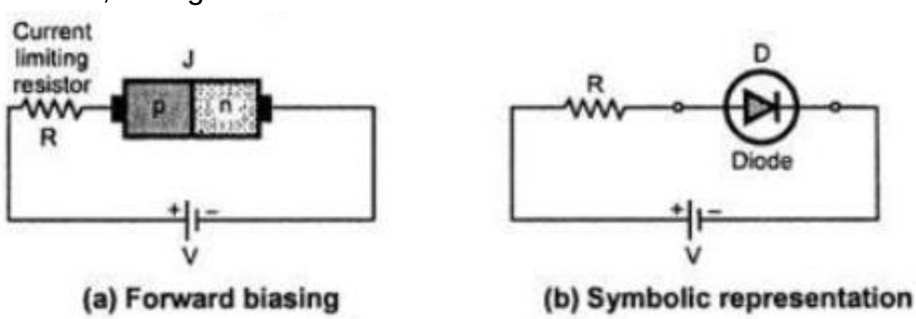


Fig. 1.4 Forward biasing of PN Junction Diode

1.4.1.1 Construction

- The Fig. 1.4 (a) shows the connection of forward biasing of a p-n junction.
- To limit the current, practically a current limiting resistor is connected in series with the p-n junction diode.
- The Fig. 1.4 (b) shows the symbolic representation of a forward biased diode.

1.4.1.2 Operation:

- As long as the applied voltage is less than the barrier potential, there cannot be any conduction.
- When the applied voltage becomes more than the barrier potential, the negative terminal of battery pushes the free electrons against barrier potential from n to p-region, and positive terminal pushes the holes from p to n-region.
- Thus holes get repelled by positive terminal & electrons get repelled by negative terminal and cross the junction against barrier potential.
- Thus the applied voltage overcomes the barrier potential, which reduces the width of depletion region.
- As forward voltage is increased, at a particular value the depletion region becomes very much narrow such that large number of majority charge carriers can cross the junction.
- Hence the overall forward current is due to the majority charge carriers.

1.4.1.3 Forward V-I Characteristics of PN Junction Diode

- The Fig. 1.5 shows the forward biased diode.

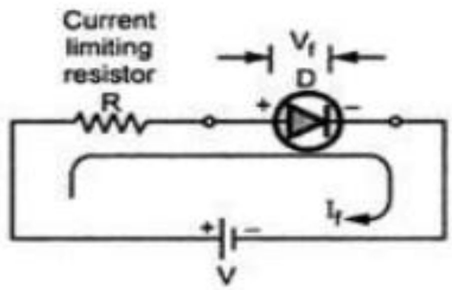


Fig. 1.5 Forward biased diode

- The applied voltage is V while the voltage across the diode is V_f and the current flowing in the circuit is the forward current I_f.
- The graph of forward current I_f against the forward voltage V_f across the diode is called forward characteristics of a diode and is shown in fig. 1.6.

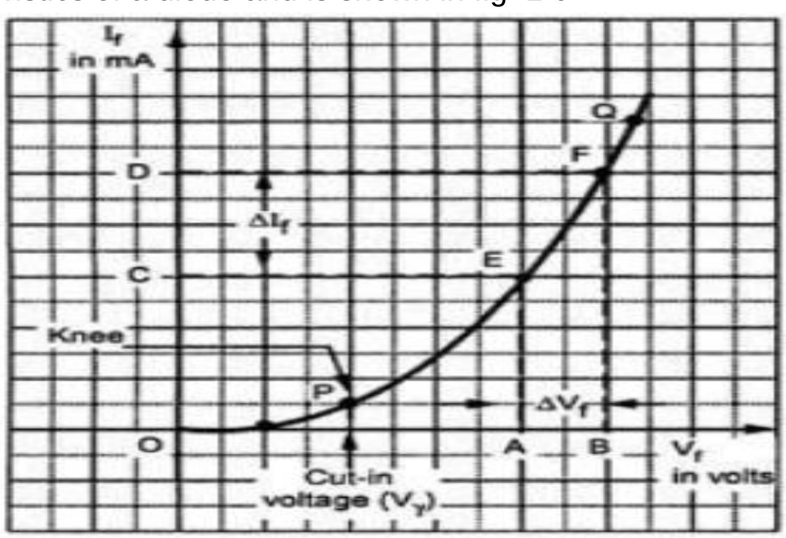


Fig. 1.6 Forward characteristics of a diode

Cut-in voltage:

- Minimum forward voltage required to conduct the diode.

Knee:

- The point P, after which the forward current starts increasing exponentially is called knee of the curve

1.4.1.4 Operation of forward characteristics

- **Region O to P (From Fig. 1.6):**
    - As long as V_f is less than cut in voltage (V_Y), the current flowing is very small.

- **Region P to Q and onwards (From Fig. 1.6):**
    - As V_f increases towards V_Y the width of depletion region goes on reducing.
    - When V_f exceeds V_Y i.e. cut-in voltage, the depletion region becomes very thin and current I_f Increases suddenly.
    - This increase in the current is exponential as shown in the Fig. 1.6 by the region P to Q.
    - The forward current is treated as positive and the forward voltage V_f is also treated positive.
    - Hence the forward characteristic is plotted in the first quadrant.

1.4.1.5 Forward Resistance of Diode

- The resistance offered by the p-n junction diode in forward biased condition is called forward resistance. The forward resistance is defined in two ways.

1.4.1.5.1 Static forward resistance:

- The resistance offered by the p-n junction under d.c, conditions is called static resistance and it is denoted as R_f
- It is calculated at any particular point on the forward characteristics.
- The static resistance R_f is defined as the ratio of the d.c, voltage applied across the p-n junction to the d.c. current flowing through the p-n junction.

$$R_f = \frac{\text{Forward d.c. voltage}}{\text{Forward d.c. current}} = \frac{OA}{OC} \text{ at point E}$$

1.4.1.5.2 Dynamic forward resistance:

- The resistance offered by the p-n junction under a.c, conditions is called as dynamic resistance and it is denoted as r_f.
- Consider the change in applied voltage from point A to B shown In the Fig. 1.6 and denoted as ΔV_f.
- The corresponding change in the forward current is from point C to D and denoted as ΔI_f.

$$r_f = \frac{\Delta V_f}{\Delta I_f} = \frac{1}{(\Delta I_f / \Delta V_f)} = \frac{1}{\text{Slope of forward characteristics}}$$

1.4.2 Reverse Biasing of P-N Junction Diode

- If an external d.c voltage is connected in such a way that the p-region terminal of a p-n junction is connected to the negative terminal of the battery and the n-region terminal of a p-n junction is connected to the positive terminal of the battery.

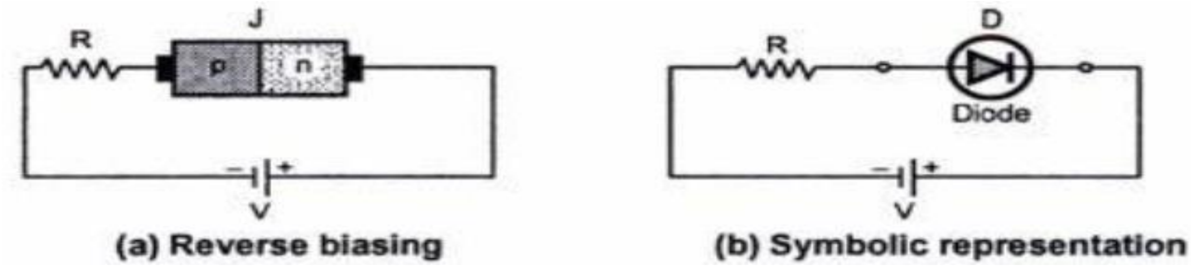


Fig. 1.7 Reverse biasing of PN Junction Diode

1.4.2.1 Construction

- The Fig. 1.7 (a) & 1.7 (b) shows the connection of a reverse biasing and symbolic representation of a p-n junction.

1.4.2.2 Operation:

- When the p-n junction is reverse biased, the negative terminal of battery attracts the holes in the p-region and it is away from the junction.
- The positive terminal of battery attracts the free electrons in the n-region and it is away from the junction.
- No charge carrier is able to cross the junction.
- As electrons and holes both move away from the junction, the depletion region widens.
- As depletion region widens, barrier potential across the junction also increases.
- The electrons on p side and holes on n side are minority charge carriers, which constitute the current in reverse biased condition.
- The current flow due to minority charge carriers alone is called as reverse saturation current (I_O) which are small in number.
- The generation of minority charge carriers depends on the temperature and not on the applied reverse bias voltage.

1.4.2.3 Reverse V-I Characteristics of PN Junction Diode

- The Fig. 1.8 shows the reverse biased diode.
- The reverse voltage across the diode is V_R while the current flowing is reverse current I_R due to minority charge carriers.
- The reverse voltage is taken as negative and reverse saturation current is also taken as negative.

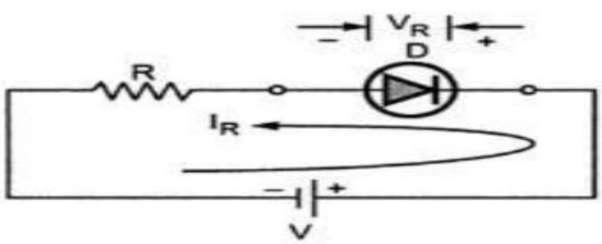


Fig. 1.8 Reverse biased diode

- The graph of I_R against V_R is called reverse characteristics of a diode and is shown in figure 1.9.

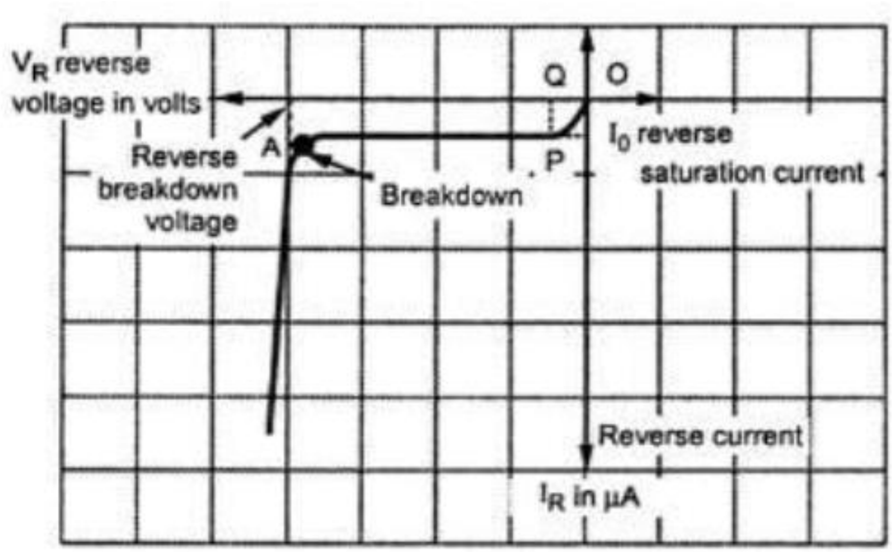


Fig. 1.9 Reverse characteristics of a diode

- As reverse voltage is increased, reverse current increases initially but after a certain voltage, the current remains constant equal to reverse saturation current I_O, though reverse voltage is increased.
- The point A where breakdown occurs and reverse current Increases rapidly is called knee of the reverse characteristics.

Reverse Breakdown Voltage

- The maximum voltage at which breakdown occurs is called as reverse breakdown voltage.

1.4.2.4 Reverse Resistance of Diode

- The p-n junction offers large resistance in the reverse biased condition and is as called reverse resistance.
- This is also defined in two ways.

1.4.2.4.1 Reverse static resistance:

- This is reverse resistance under d.c conditions and it is denoted as R_r.
- It is the ratio of applied reverse voltage to the reverse saturation current I_O.

$$R_r = \frac{OQ}{I_0} = \frac{\text{Applied reverse voltage}}{\text{Reverse saturation current}}$$

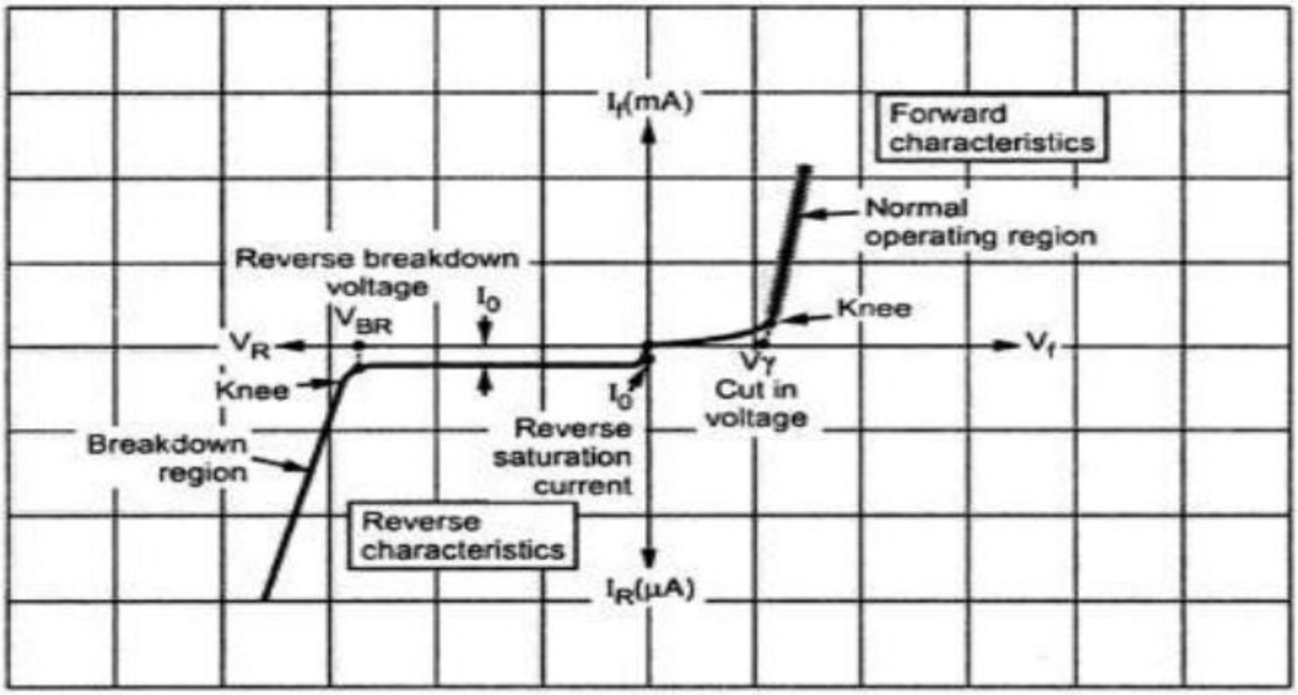
1.4.2.4.2 Reverse dynamic resistance:

- This is the reverse resistance under the a.c. conditions and it is denoted as r_r.
- It is the ratio of incremental change in the reverse voltage applied to the corresponding change in the reverse current.

$$r_r = \frac{\Delta V_R}{\Delta I_R} = \frac{\text{Change in reverse voltage}}{\text{Change in reverse current}}$$

1.4.3 Complete V-I Characteristics of a Diode

- Complete VI characteristics of PN Junction diode under the forward and Reverse bias is shown in single graph.



1.10 Complete V-I Characteristics of a Diode

1.5 Diode Equation

- The mathematical representation of V-I characteristics of diode is called V-I characteristics equation or diode current equation.
- It gives the mathematical relationship between applied voltage V and the diode current I and is given by,

$$I = I_0\left[e^{V/\eta V_T} - 1\right] \text{ A} \qquad \dots (1)$$

where

I_0 = Reverse saturation current in amperes

V = Applied voltage

η = 1 for germanium diode

= 2 for silicon diode

V_T = Voltage equivalent of temperature in volts.

- The factor η is called an emission coefficient or Ideality factor.
- This factor takes into account the effect of recombination taking place in the depletion region.
- The voltage equivalent of temperature indicates dependence of diode current on temperature.
- The voltage equivalent of temperature V_T for a given diode at temperature T is calculated as,

$$V_T = kT \text{ volts} \qquad \ldots (2)$$

where k = Boltzmann's constant = 8.62×10^{-5} eV/°K

T = temperature in °K.

At room temperature of 27 °C i.e. T = 27 + 273 = 300 °K and the value of V_T is 26 mV,

- The value of V_T also can be expressed as,

$$V_T = \frac{T}{\left(\frac{1}{k}\right)} = \frac{T}{\left(\frac{1}{8.62 \times 10^{-5}}\right)} = \frac{T}{11600} \qquad \ldots (3)$$

- The diode current equation is applicable for all the conditions of diode i.e, unbiased, forward biased and reverse biased.
- When unbiased V=0 tends to I=0
- For forward bias V=Positive value tends to I=Positive value
- For Reverse bias V=Negative value tends to I=Negative value

Example : *The voltage across a silicon diode at room temperature of 300°K is 0.71 V when 2.5 mA current flows through it. If the voltage increases to 0.8 V, calculate the new diode current.*

Solution : The current equation of a diode is

$$I = I_0 (e^{V/\eta V_T} - 1)$$

At 300 °K, $V_T = 26 \text{ mV} = 26 \times 10^{-3}$ V

$V = 0.71$ V for I = 2.5 mA

and η = 2 for silicon

$$\therefore \quad 2.5 \times 10^{-3} = I_0 [e^{(0.71/2 \times 26 \times 10^{-3})} - 1]$$

$$\therefore \quad I_0 = 2.93 \times 10^{-9} \text{ V}$$

Now V = 0.8 V, I_0 remains same.

$$\therefore \quad I = 2.93 \times 10^{-9} [e^{(0.8/2 \times 26 \times 10^{-3})} - 1] = 0.0141 \text{ A} = 14.11 \text{ mA}$$

1.6 Diode Equivalent Circuits

- The diode is required to be replaced by the equivalent circuit in many practical electronic circuits, for the analysis purpose. Such an equivalent circuit of a diode is called circuit model of a diode.
- There are three methods of replacing diode by its circuit model, which are,
  - Practical diode model
  - Ideal diode model
  - Piecewise linear model

- When the diode is forward biased, the total voltage drop across the diode is V_f which is equal to sum of the drop due to barrier potential (cut-in voltage V_γ) and the drop across the internal forward dynamic resistance r_f of the diode.
- When the diode is reverse biased, reverse saturation current is very small and practically neglected. Hence reverse biased diode is practically assumed to be open circuit.

1.6.1 Practical Diode Model

- In forward bias, the practical diode model consists of a battery equal to cut-in voltage and the forward resistance in series with an ideal diode which is shown in fig.1.11 (a).
- In reverse bias, it is open circuited and is shown in fig. 1.11 (b).
- While the Fig. 1.11 (c) shows the corresponding V-I characteristics.

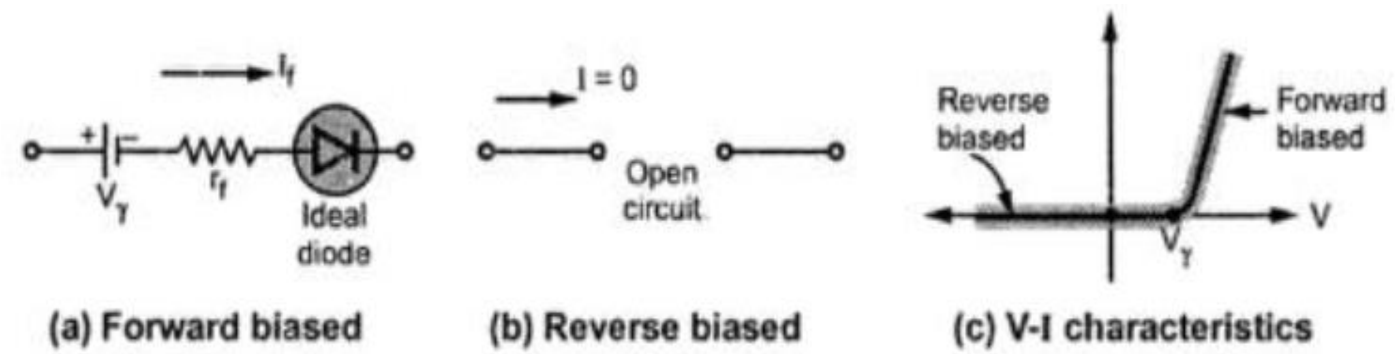


Fig. 1.11 Practical diode model

1.6.2 Ideal Diode Model

- In many cases, as the forward resistance of diode is small and cut-in voltage is also small, the diode is assumed to be an ideal diode.
- In case of ideal diode, it is assumed that it starts conducting instantaneously when applied voltage V_D is just greater than zero and the drop across the conducting diode is zero.
- So conducting diode can be ideally replaced by a short circuit, for the analysis of various diode circuits.
- The Fig. 1.12 shows the ideal diode characteristics.

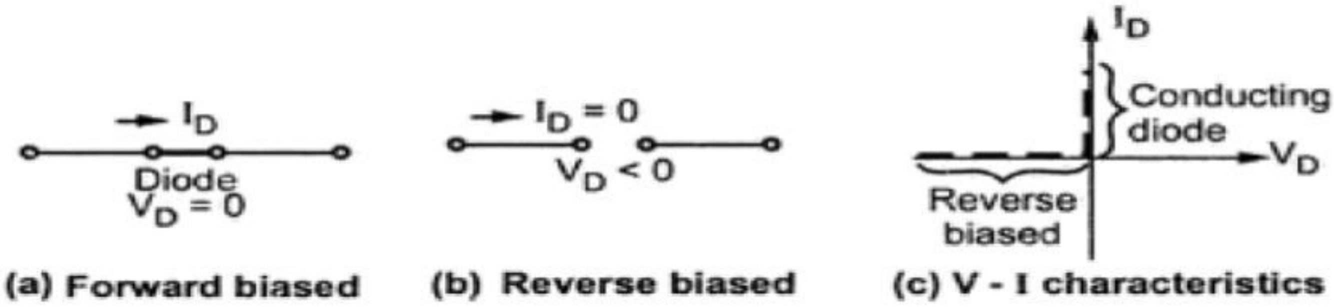


Fig. 1.12 Ideal diode model

1.6.3 Piecewise linear Model of Diode

- Another way to analyze the diode circuits is to approximate the V-I characteristics of a diode using only straight lines i.e. linear relationships.
- In such approximation, the diode forward resistance is neglected and the diode is assumed to conduct instantaneously when applied forward biased voltage V_D is equal to cut-in voltage V_γ and is shown in the fig. 1.13 (a).
- When the diode is in reverse biased condition i.e $V_D < 0$, the diode does not conduct at all and is shown in the Fig. 1.13 (b).
- As the diode conducts at $V_D = V_\gamma$, the V-I characteristics with straight lines is as shown in the Fig. 1.13 (c).

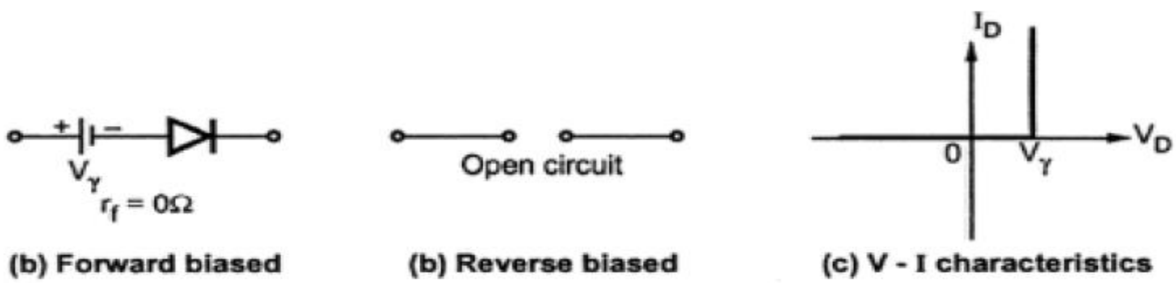


Fig. 1.13 Linear piecewise model of diode when $r_f = 0$

- If forward resistance is considered to be finite, then forward biased characteristic is a straight line with a slope equal to reciprocal of r_f and is shown in the fig. 1.14 (a).
- In reverse bias, the diode is still assumed to be open circuited and is shown in the fig. 1.14 (b).
- The linear piecewise model with finite forward resistance r_f is shown in the Fig. 1.14 (c).

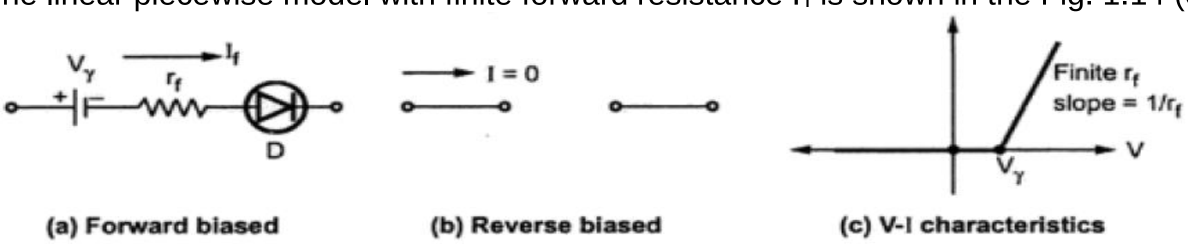


Fig. 1.14 Linear piecewise model of diode with finite r_f

1.7 Junction Capacitances

- Depending upon the biasing condition, two types of capacitive effects exist in the diodes. These are.
    - Transition capacitance (C_T) under reverse biased condition.
    - Diffusion capacitance (C_D) under forward biased condition.

1.7.1 Transition Capacitance (C_T or C_{pn})

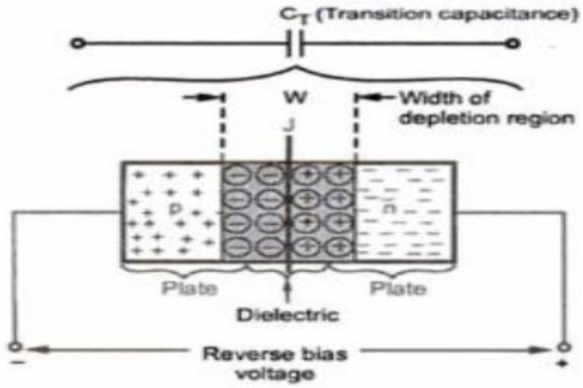


Fig. 1.15 Transition Capacitance

- When a diode is reverse biased, the width of the depletion region increases.
- So there are more positive and negative charges present in the depletion region.
- Due to this, the p-region and n-region act like the plates of capacitor while the depletion region acts like dielectric.
- Thus there exists a capacitance at the p-n junction called as transition capacitance.
- It is denoted as C_T and is shown in figure 1.15.
- Mathematically it is given by the expression,

$$\boxed{C_T = \frac{\varepsilon A}{W}}$$

where

ε = permittivity of semiconductor = $\varepsilon_0 \varepsilon_r$

$\varepsilon_0 = \frac{1}{36\pi \times 10^9} = 8.849 \times 10^{-12}$ F/m

ε_r = relative permittivity of semiconductor = 16 for Ge, 12 for Si

A = area of cross section

W = width of depletion region

- As the reverse bias applied to the diode increases, the width of the depletion region (W) increases. Thus the transition capacitance C_T decreases.
- In short, the capacitance can be controlled by the applied voltage. The variation of C_T with respect to the applied reverse bias voltage is shown in the Fig. 1.16.

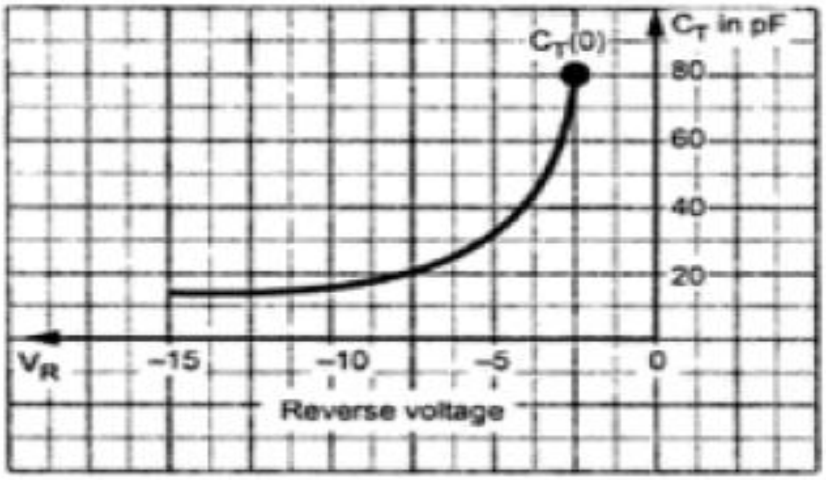


Fig. 1.16 Variation of C_T versus Reverse voltage

- As reverse voltage is negative, graph is shown in the second quadrant.
- The value of transition capacitance is of the order of pico farads.
- For a particular diode shown, C_T varies from 80 pF to less than 5 pF as V_R changes from 2 V to 15 V.

1.7.2 Diffusion Capacitance (C_D)

- During forward biased condition, another capacitance comes into existence called diffusion capacitance (or) storage capacitance and denoted as C_D.
- In forward biased condition, the width of the depletion region decreases and holes from p side get diffused in n side while electrons from n side move into the p-side.
- As the applied voltage increases, concentration of injected charged particles increases.
- This rate of change of the Injected charge with applied voltage is defined as a capacitance called diffusion capacitance.

$$\boxed{C_D = \frac{dQ}{dV}}$$

- The diffusion capacitance expression can also be given as

$$\boxed{C_D = \frac{\tau I}{\eta V_T}}$$

where

τ = mean life time for holes.

- So diffusion capacitance is proportional to the current.
- For forward biased condition, the value of diffusion capacitance is of the order of nano farads to micro farads while transition capacitance is of the order of pico farads.
- So $C_D >> C_T$.
- The graph of C_D against the applied forward voltage is shown in the Fig. 1.17.
- As the applied forward voltage increases, current I increases hence diffusion capacitance C_D increases.

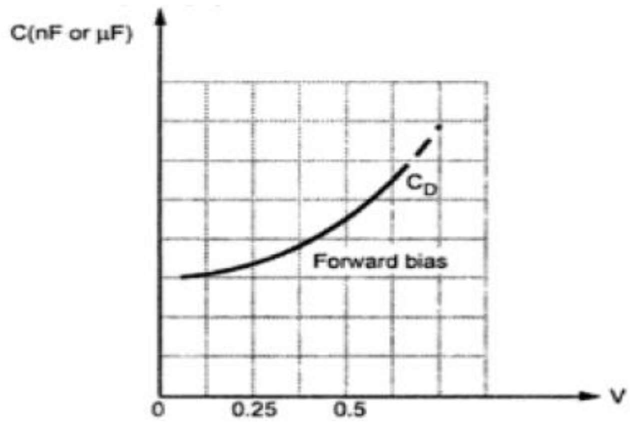


Fig. 1.17 Diffusion capacitance versus applied forward voltage

1.8 PN Junction Diode act as a switch

- The principle of working of a diode as a switch is nothing but the forward and reverse biasing of the diode.
- When a forward voltage is more than the cut-in voltage of the PN junction diode, the current flows through the junction. Thus, the diode junction becomes a short circuit.
- The diode comes in the reverse bias when the voltage at the diode's anode is more negative than the voltage at the cathode. In this condition, the diode junction is an open circuit.
- The figure 1.18 shows the Circuit diagram for diode act as a switch
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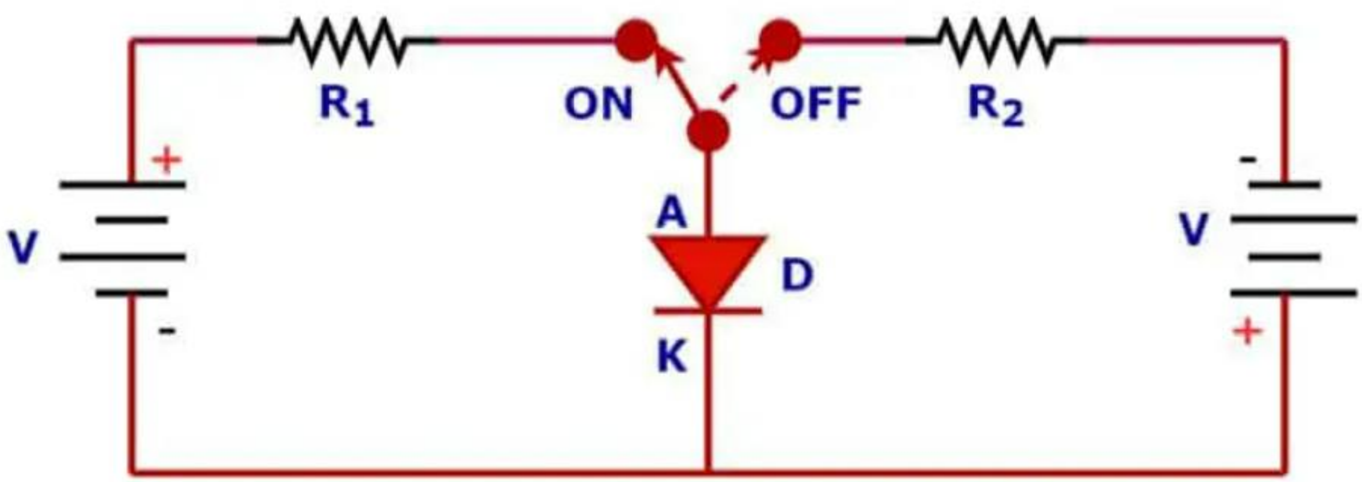

Fig. 1.18 Circuit diagram for diode act as a switch

- A diode has a PN junction.
- In a diode, P-region has lightly doped holes as the majority carriers and N- region has highly doped electrons as the majority carriers.
- When the switch is at the ON position, the anode of diode D gets a positive supply and the cathode of diode D gets a negative supply.
- In this condition, the diode gets forward biasing and it starts conducting.

- Now, when the switch position changes from ON to OFF state, the anode of the diode gets the negative voltage at the anode.
- Under this condition, the current that was flowing in the forward bias state drops to zero, and the diode becomes an open circuit.

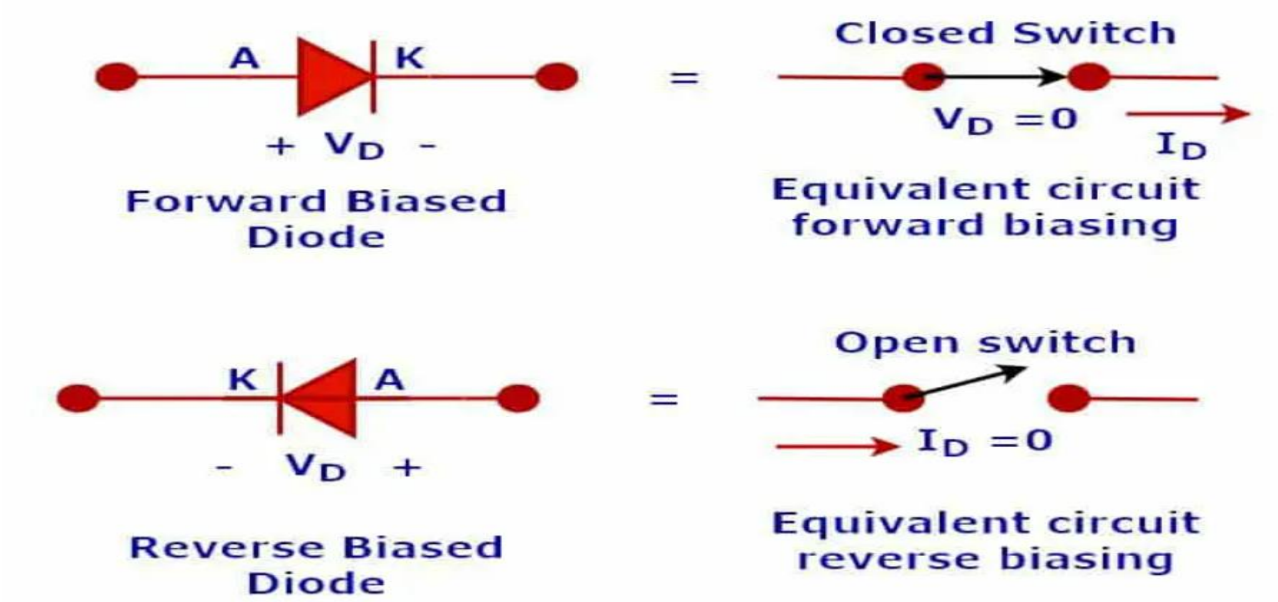

Fig. 1.19 Equivalent circuit for diode act as a switch

1.9 switching times of a PN Junction diode

- When the diode is switched from forward biased to reverse biased or vice versa, it takes finite time to reach the final steady state. The behaviour of diode during this time is called switching characteristics of diode.
- To study the switching characteristics of diode, consider simple diode circuit and an input waveform as shown in the Fig. 1.20.

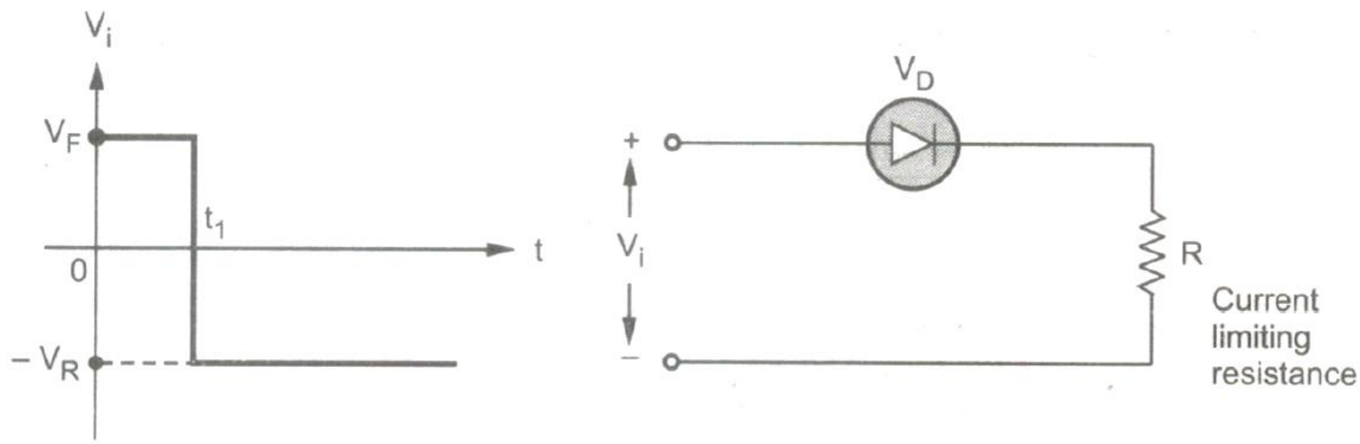

Fig. 1.20 Simple diode circuit

- The following events will take place due to the nature of the applied voltage.

- **Event 1:**
  - Till time t_1, the forward voltage applied is V_F and diode is forward biased.
  - The value of R is large enough such that drop across forward biased diode is very small compared to drop across R.
  - The forward current is then $I_F = V_F / R$, neglecting forward resistance of diode.
- **Event 2:**
  - At time t_1, the applied voltage is suddenly reversed and reverse voltage of $-V_R$ is applied to the circuit.
  - Ideally diode also must become OFF from ON state instantly. But this does not happen instantly.
  - The number of minority carriers take time to reduce from $P_n - P_{no}$ to zero at the junction as shown in the Fig. 1.21 (b).

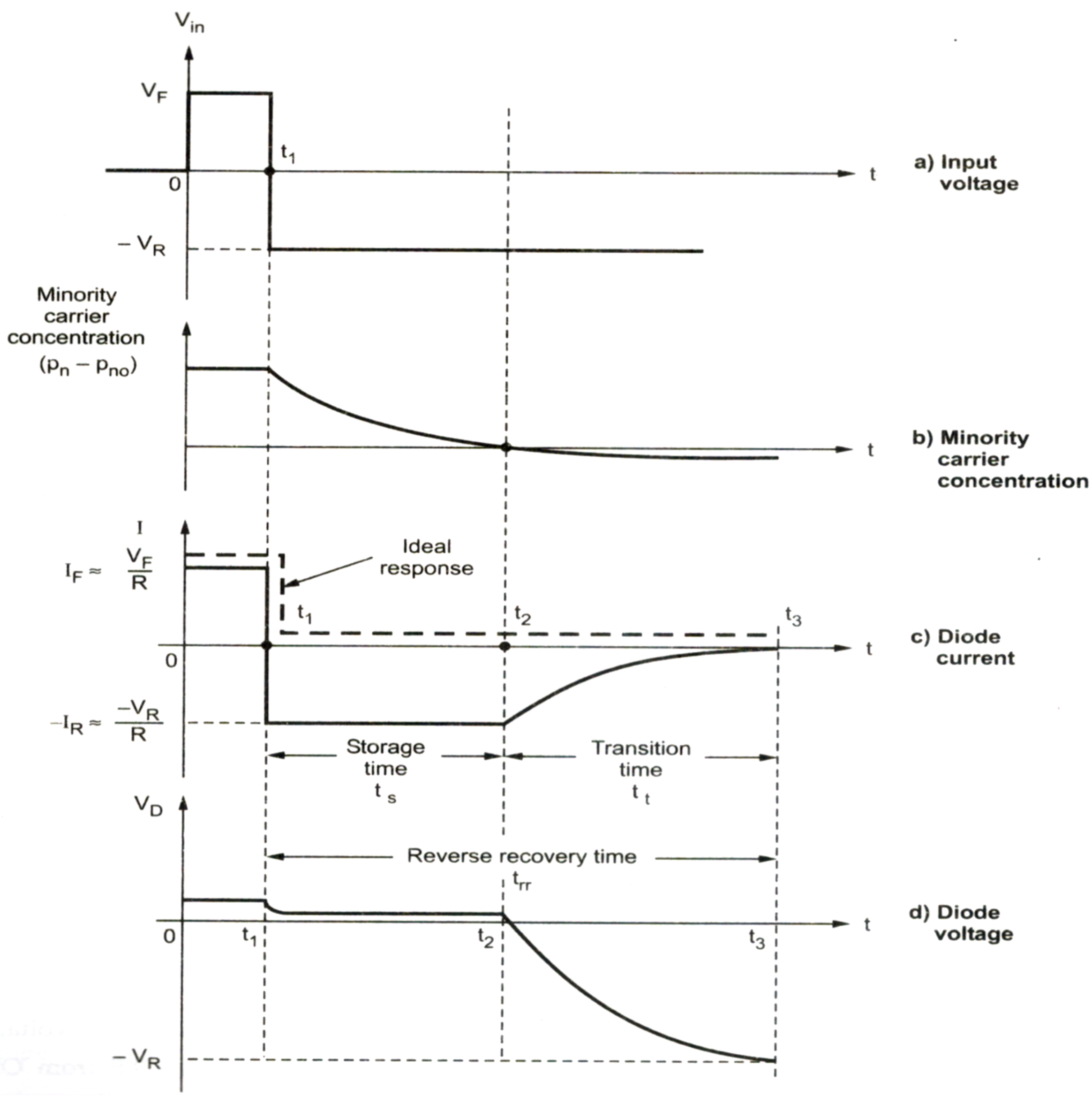

Fig. 1.21 Switching characteristics of diode

- Due to this, at t_1 current just reverses and remains at that reversed value —I_R till the minority carrier concentration reduces to zero.
- This current is given by $-I_R = -V_R/R$. This continues to flow till time t_2.
- **Storage time:**
  - During time t_1 to t_2, the minority charge carriers remain stored and decrease slowly to zero. Hence this time is called storage time denoted as t_s.

- **Event 3:**
  - From t_2 onwards, the diode voltage starts to reverse and the diode current starts decreasing as shown in the Fig. 1.21 (c).
  - At $t=t_3$, the diode state completely gets reversed and attains steady state in reverse biased condition.
  - **Transition time:**
    - The time from t_2 to t_3 i.e., time required by the diode current to reduce to its reverse saturation value is called the transition interval or transition time denoted as t_t.
  - **Reverse recovery time:**
    - The total time required by the diode which is the sum of storage time and transition time, to recover completely from the change of state is called reverse recovery time of the diode and denoted as t_{rr}. This is an important consideration in high speed switching applications.
  - For quick switching from ON to OFF state, the reverse recovery time should be as small as practicable.

$$t_{rr} = t_s + t_t$$

  - The reverse recovery time depends on the RC time constant where C is a transition capacitance of a diode.
  - To have fast switching from ON to OFF of a diode, the transition capacitance should be as small as possible.
- Thus, the transition capacitance plays an important role in the switching circuits using diodes.
- Most commercially available switching diodes have the reverse recovery time ranging from a few nanoseconds to one microsecond.
- However, diodes are specially manufactured having reverse recovery time as small as only a few picoseconds.
- The total switching time t_{rr} puts the limit on the maximum operating frequency of the diode. Hence t_{rr} is an important datasheet specification.
- To minimize the effect of the reverse current, the time period of the operating frequency must be atleast ten times t_{rr}.

$$T = 10\, t_{rr}$$

$$\boxed{f_{max} = \frac{1}{T} = \frac{1}{10\, t_{rr}}}$$

where fmax is the maximum operating frequency.