narrow and holes from P-side diffuse into the N-side and the electrons from the N-side diffuse into the P side as shown in figure 2.22. The current carried by these diffused electrons, which become minority carriers once they enter into the P-side, is denoted by I_{np} where n stands for electrons and p for the P-side.

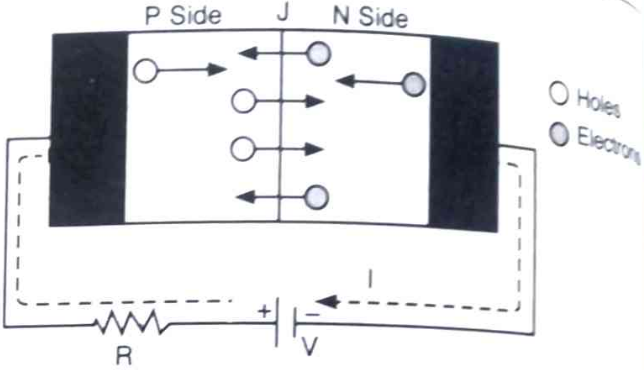


Fig. 2.22. A forward biased P-N junction

This current is the diffusion current on P-side and it decreases exponentially with increase in distance (x) from the junction. Similarly the current carried by the diffused holes which become minority carriers once they enter into the N-side is denoted by I_{pn} where p stands for holes and n for the N-side. This current is the diffusion current due to minority carriers on the N-side and it decreases exponentially with increase in distance (x) from the junction.

Thus, the two diffusion currents as a function of distance x from the junction can be defined as

$I_{np}(x)$ = Diffusion current due to electrons on the P-side as a function of x.

and $I_{pn}(x)$ = Diffusion current due to holes on the N-side as a function of x.

(i) Currents at the junction (x = 0): The diffusion currents due to electrons and holes at the junction, i.e., for x = 0 will be in the same direction, i.e., $I_{np}(0)$ and $I_{pn}(0)$ both will constitute a current in the same direction.

The current at the junction, i.e., the total current I shown in figure 2.23 will be the sum of these two diffusion currents $I_{np}(0)$ and $I_{pn}(0)$.

Hence,
$$I = I_{np}(0) + I_{pn}(0) \quad \ldots (2.5)$$

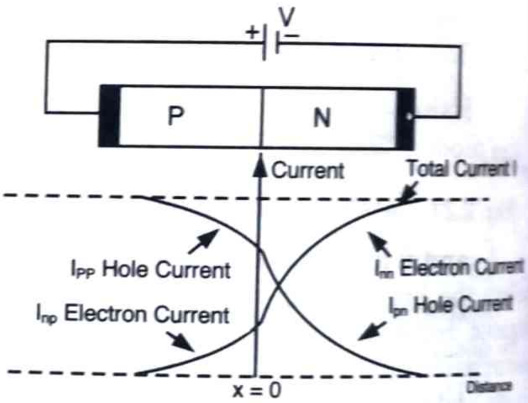


Fig. 2.23 Various current components

(ii) But, the total current should remain constant: These diffusion currents $I_{np}(x)$ and $I_{pn}(x)$ decrease exponentially with increase in x.

This means that on both the sides, there must be some other components of current present which can actually maintain the current I constant.

(iii) On P-side: Along with the minority diffusion current $I_{np}(x)$ there must be a majority current due to holes denoted by $I_{pp}(x)$ such that the sum of these two components will be equal to I.

On
$$\text{P-side}: I_{np}(x) + I_{pp}(x) = I \quad \ldots (2.6)$$

(iv) On the N-side: Similarly, on the N-side along with the minority diffusion current due to holes i.e., $I_{pn}(x)$, there is a majority current component due to electrons denoted by $I_{nn}(x)$ such that the sum of these two components will be equal to I.

On
$$\text{N-side}: I_{pn}(x) + I_{nn}(x) = I \quad \ldots (2.7)$$

All these current components have been plotted as a function of distance (x) from the junction in figure 2.23.

2.12. DIODE CURRENT EQUATION

With the help of solid state physics, the diode current equation, relating the voltage V and current I for the forward and reverse-bias regions, can be given by

$$I = I_0\left[e^{V/\eta V_T} - 1\right] \quad ...(2.8)$$

Here, I = diode current

I_0 = diode reverse saturation current at room temperature

V = external voltage applied to the diode

η = a constant

It is 1 for germanium and 2 for silicon

and $$V_T = \frac{kT}{q} = \frac{T}{11,600} = \text{Volt equivalent of temperature.} \quad ...(2.9)$$

where k = Boltzmann's constant = 1.38066×10^{-23} J/Kelvin

q = Electronic Charge = 1.6×10^{-19} Coulomb

T = Diode junction temperature in (°K)

Now, at room temperature, (T = 300°K), V_T = 26 mV

Putting these two values in current equation, we get

$$I = I_0\left[e^{40V/\eta} - 1\right] \quad ...(2.10)$$

For germanium diode, $\eta = 1$

Therefore, $$I = I_0\left[e^{40V} - 1\right] \quad ...(2.11)$$

and for silicon diode, $\eta = 2$

Therefore, $$I = I_0\left[e^{20V} - 1\right] \quad ...(2.12)$$

If the value of applied voltage is greater than unity then the diode current equation for germanium will be

$$I = I_0\left[e^{40V}\right]$$

and for silicon, $$I = I_0\left[e^{20V}\right] \quad ...(2.13)$$

If the diode is reverse biased, the current equation can be obtained by reversing the sign of the applied voltage V.

Hence, diode current with reverse bias is

$$I = I_0\left[e^{(-V/\eta V_T)} - 1\right] \quad ...(2.14)$$

Now, if $V >> V_T$

Then the term $e^{(-V/\eta V_T)} << 1$

Therefore, $$I \cong -I_0 \quad ...(2.15)$$

This equation is valid as long as the external voltage is below the breakdown value.

PIONEER IN ELECTRONICS

The unit of measure for capacitance, the farad (F), was named for Michael Faraday (1791-1867), an English chemist and physicist who discovered the principle of induction (1 F is the unit of capacitance that stores 1 coulomb (C) of charge when 1 volt (V) is applied).

EXAMPLE 2.2 The reverse saturation current at room temperature is 0.3 μA when a reverse bias is applied to a germanium diode. Find the value of current flowing in the diode when 0.15 V forward bias is applied at room temperature.

Solution: Given that $I_o = 0.3\ \mu A = 0.3 \times 10^{-6}$ A

and forward voltage, $V_F = 0.15$ Volt. The current flowing through the diode under forward bias is given by

$$I = I_o\left(e^{40V_F} - 1\right)$$

or $$I = 0.3 \times 10^{-6}\left(e^{40 \times 0.15} - 1\right)$$

or $$I = 120.73\ \mu A \qquad \text{Ans.}$$

2.13. COMPLETE V-I CHARACTERISTICS OF SILICON AND GERMANIUM DIODES

The complete V-I characteristics is the combination of forward and reverse characteristics. The typical V-I characteristics of Silicon and Germanium diodes are as shown in figure 2.24.

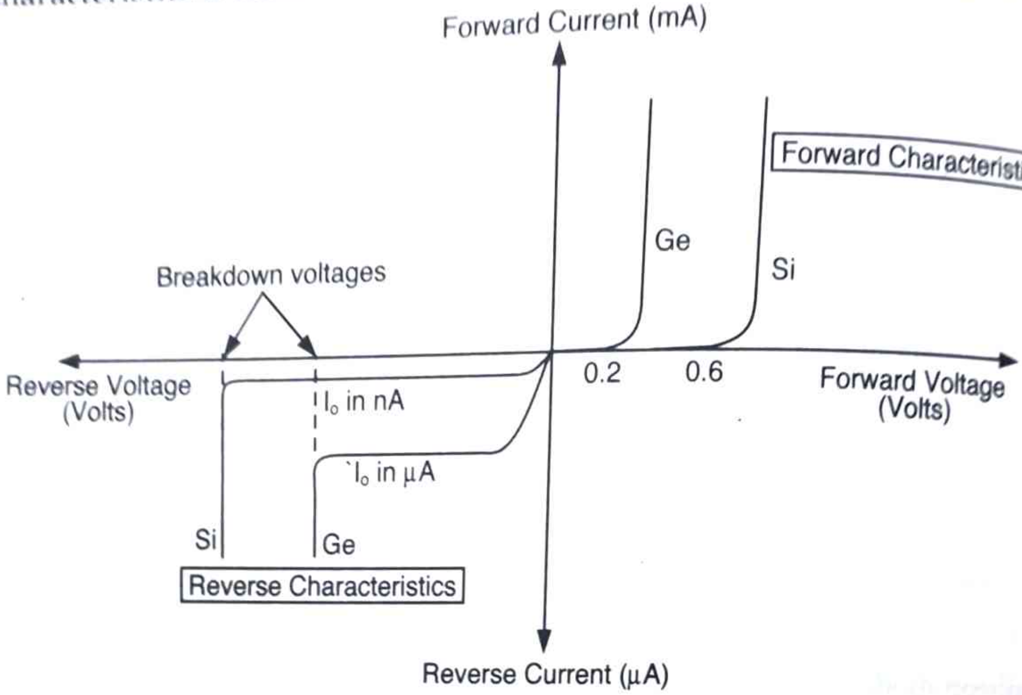


Fig. 2.24. V-I Characteristics of Silicon and Germanium diodes

Conclusions

We can draw following conclusions from V-I characteristics of figure 2.24:

(i) Cut-in voltages for Silicon and Germanium diodes are 0.6 and 0.2 V respectively.

(ii) Breakdown voltage of Silicon diode is higher than that of the Germanium diode. Therefore Silicon diodes can withstand to a higher reverse voltage.

(iii) The reverse saturation current I_0 for a Germanium diode is few µA whereas that for a Silicon diode, it is in nA at room temperature.

2.14. COMPARISON OF SILICON AND GERMANIUM DIODES

Table 2.2. Comparison of Silicon and Germanium Diodes

S.No.	Parameter of comparison	Silicon Diode	Ge Diode
1.	Material used	Silicon	Germanium
2.	Cut-in voltage	0.6 V	0.2 V
3.	Reverse saturation current	In nanoamp	In microamp
4.	Effect of temperature	Less	More
5.	Breakdown voltage	Higher	Lower
6.	Applications	Rectifiers, clippers clampers, etc.	Low voltage Low temperature applications

2.15. EFFECT OF TEMPERATURE ON THE V-I CHARACTERISTICS

(AKTU, Sem. Exam. 2012-13) (05 marks)

We know that the expression for diode current is given by

$$I_D = I_0\left[e^{V/\eta V_T} - 1\right]$$

where, I_0 = Reverse saturation current

$$V_T = \frac{T}{11600}$$

η = 1 for Ge diode = 2 for Si diode

V = diode voltage

The diode characteristics is mathematically expressed by the equation of I_D. Two parameters I_0 and V_T are temperature dependent. Hence, the characteristics is dependent on the temperature. The effect of change in temperature on the V-I characteristics are as shown in figure 2.25.

DO YOU KNOW?

For any diode, the forward voltage, V_F, decreases as the temperature of the diode increases. As a rough approximation, V_F decreases by 2 mV for each degree Celsius rise in temperature.

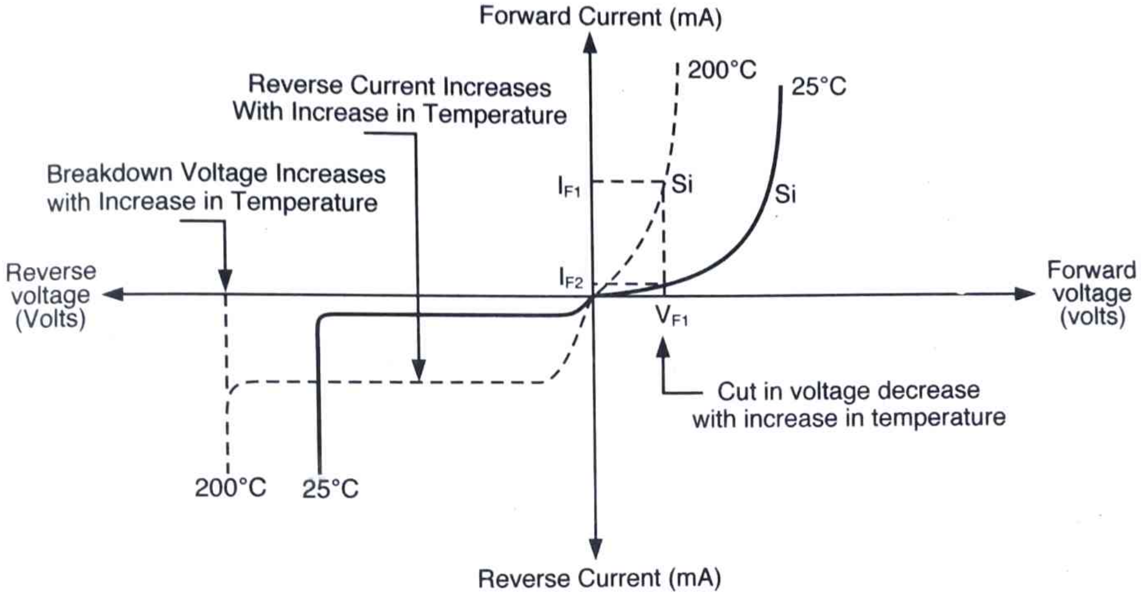


Fig. 2.25. Effects of temperature on V-I characteristics of a silicon diode

Conclusions

As Observed from figure 2.25, the effects of temperature may be listed as under :

(i) Reduction in the cut-in voltage takes place with increase in temperature. Therefore, at the same forward voltage V_{F1}, a larger current I_{F1} flows through the diode at increased temperature.

(ii) The breakdown voltage increases with increase in temperature.

(iii) Reverse saturation current increases with increase in temperature.

Key Point: In the expression for diode current, there are two factors which depend on the temperature. They are I_0 and V_T. Hence, the diode characteristics becomes the function of temperature.

2.15.1. Germanium Diodes and Effect of Temperature

As a matter of fact, junction diodes fabricated from germanium are also available. The principle of operation is same as that of the silicon diodes and the expression for volt-ampere characteristic is also same as that of the silicon diodes. The value of η = 1 for germanium (Ge). The reverse saturation current of the Ge diodes is three to four times higher than the silicon diodes of same dimensions and doping densities. The cut-in voltage V_γ = 0.2 V for the Ge diodes.

2.15.2. Ge Diodes Produce Higher Reverse Saturation Current

We know that the four valence electrons of Ge are in the fourth shell whereas those of a Si atom are in the third shell. Hence, the force of attraction between the nucleus and valence electrons is weak in the generation atoms than that in the silicon atoms. The forbidden energy gap is smaller in Ge than Si atoms. Therefore, at the same temperature, more valence electrons will jump to the conduction band to produce higher reverse saturation current in case of Ge diode.

2.15.3. Si Diode is More Popular than Ge Diode

Following are the reasons for the popularity of silicon (Si) diode:

(i) The reverse saturation current for a Silicon diode is much lower than that of a Ge diode. Therefore, even with the two fold increase in I_0 after every 10°C rise in temperature, the reverse saturation current through Silicon diodes will still remain very low. But, at increased temperature, the reverse saturation current through a Ge diode is very high. In fact, it is of the order of 100 μA or so. However, in practice, this level of reverse saturation current is unacceptable. Therefore, the Si diodes are more popular than the Ge diodes.

(ii) Ideally the diode characteristics should not change due to change in temperature and practically the change in characteristics should be minimum.

(iii) The characteristics of Ge diode are more dependant on temperature than that of a silicon diode.

2.15.4. Dependence of I_0 on Temperature

The dependence of I_0 on temperature is expressed by

$$I_0 = KT^m \, e^{-V_{GO}/\eta V_T} \qquad \text{... (2.16)}$$

where, K = Constant which is independent of temperature.

m = Constant which is equal to 2 for Germanium and 1.5 for Silicon

V_{GO} = Forbidden energy gap = 0.785 V for Germanium

= 1.21 V for Silicon

Practically we need not always use the expression for I_0 to calculate the reverse saturation current at a new temperature. As we know that there is a 7% rise in I_0 for every 1°C rise in temperature, we can write this as under:

$$I_{01} = (1.07)^{\Delta T} I_{02} \qquad \text{... (2.17)}$$

where, I_{01} = Reverse saturation current at temperature T_1

I_{02} = Reverse saturation current at temperature T_2

and $\Delta T = |T_2 - T_1|$

2.15.5. Conclusions

Some important conclusions related to the reverse saturation current may be listed as under:

(i) The reverse saturation current increases at a rate of 7% for every 1°C rise in temperature. In other words, I_0 doubles its value for every 10°C rise in temperature.

(ii) Reverse saturation current for silicon diode is lower than that for a germanium diode.

EXAMPLE 2.3 The forward current through a Silicon diode is 10 mA at room temperature (27°C). The corresponding forward voltage is 0.75 volts. Calculate the reverse saturation current I_0.

Solution: Given that

I_F = 10 mA, V_F = 0.75 Volt, T = 27°C = 300°K, η = 2 for a Silicon diode

We know that

$$V_T = \frac{T}{11,600} = \frac{300}{11,600} \quad \text{or} \quad V_T = 26 \text{ mV} \qquad \text{... (i)}$$

The forward current through a diode is given by

$$I_F = I_0 [e^{V_F/\eta V_T} - 1] \quad ...(ii)$$

Substituting all the values, we get

$$10 \times 10^{-3} = I_0 [e^{0.75/2 \times 26 \times 10^{-3}} - 1] \quad \text{or} \quad I_0 = 5.446 \text{ nA.} \quad \textbf{Ans.}$$

The reverse saturation current for silicon diode = 5.446 nA.

EXAMPLE 2.4 A diode operating at 300°K has V (forward) of 0.4 V across it when the current through it is 10 mA and 0.42 V when the current is twice as large. What values of I_0 and η allow the diode to be modelled by the diode equation ?

Solution: Given that $T = 300°K$, $V_1 = 0.4$ V, $V_2 = 0.42$ V, $I_1 = 10$ mA, $I_2 = 20$ mA

At T = 300°K, we have

$$V_T = \frac{T}{11,600} = \frac{300}{11,600} = 26 \text{ mV} \quad ...(i)$$

First, let us calculate the value of η.

From the given data we can write two equations of current for different values of V as under :

$$I_1 = I_0 \left[e^{V_1/\eta V_T} - 1\right] \quad \text{and} \quad I_2 = I_0 \left[e^{V_2/\eta V_T} - 1\right]$$

Substituting the given values, we get

$$10 \text{ mA} = I_0 \left[e^{0.4/\eta \times 26 \times 10^{-3}} - 1\right] \quad ...(ii)$$

$$20 \text{ mA} = I_0 \left[e^{0.42/\eta \times 26 \times 10^{-3}} - 1\right] \quad ...(iii)$$

Taking the ratio of equations (iii) and (ii), we obtain

$$\frac{20}{10} = \frac{I_0\left[e^{0.42/\eta \times 26 \times 10^{-3}} - 1\right]}{I_0\left[e^{0.4/\eta \times 26 \times 10^{-3}} - 1\right]}$$

Neglecting – 1 term, we have

$$2 = \frac{\left[e^{0.42/\eta \times 26 \times 10^{-3}}\right]}{\left[e^{0.4/\eta \times 26 \times 10^{-3}}\right]}$$

Taking log on both the sides, we obtain

$$0.693 = \frac{16.15}{\eta} - \frac{15.38}{\eta}$$

or $$0.693\,\eta = 0.77 \quad \text{or} \quad \eta = 1.11$$

Now, substituting this value of η into equation (ii), we get

$$10 \times 10^{-3} = I_0 \left[e^{0.4/1.11 \times 26 \times 10^{-3}} - 1\right]$$

Solving the equation, we get

$$I_0 = 9.69 \times 10^{-9} \text{ Amp} \quad \text{or} \quad 9.69 \text{ nA.} \quad \textbf{Ans.}$$

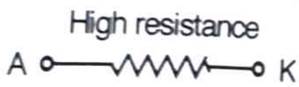
2.16. FEW IMPORTANT TERMS USED FOR P-N JUNCTION

In this subsection, let us discuss few important terms which are generally used for P-N junction. They are as under:

1. **Breakdown Voltage:** Under normal reverse bias voltage, a very little amount of reverse current flows through a P-N junction. However, on increasing the reverse voltage, a point may reach at which the junction breaks down with sudden rise in reverse current. Breakdown

2.18. COMPARISON OF IDEAL DIODE AND PRACTICAL DIODE

Table 2.4.

S.No.	Parameter of comparison	Ideal Diode	Practical Diode
1.	Forward resistance	0 Ω	Few Ω
2.	Reverse resistance	∞	Few hundred kΩ
3.	Cut in voltage	0 V	0.6 V for Si and 0.2 V for Ge diode
4.	Reverse saturation current	Zero	Few nA for Si diode Few μA for Ge diode
5.	Equivalent circuit in the forward biased state		
6.	Equivalent circuit in the reverse biased state		

2.19. DIODE RESISTANCE

The resistance of a diode is non-zero and finite, as diode is not a perfect conductor nor it is a perfect insulator. The resistance of a diode will change depending on the region of charactersitics it is operating in. The resistance of a diode is also defined depending on whether it is operating in DC or AC condition as:

(i) Static resistance

(ii) Dynamic resistance

2.19.1 DC or Static Resistance

When a DC voltage is applied to a diode, a DC current will flow through it and the operating point on the characteristic curve of the diode will not change its position with time. The resistance of a diode at the operating point can be obtained by taking the ratio of V_F and I_F. This resistance offered by the diode to the DC operating conditions is called as **DC or static resistance** and it is denoted by R_F. This has been shown in figure 2.35.

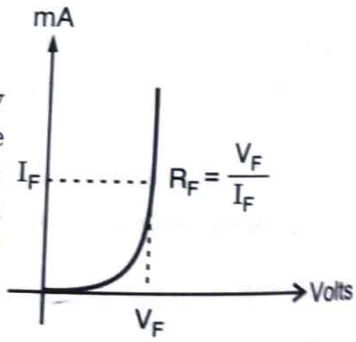


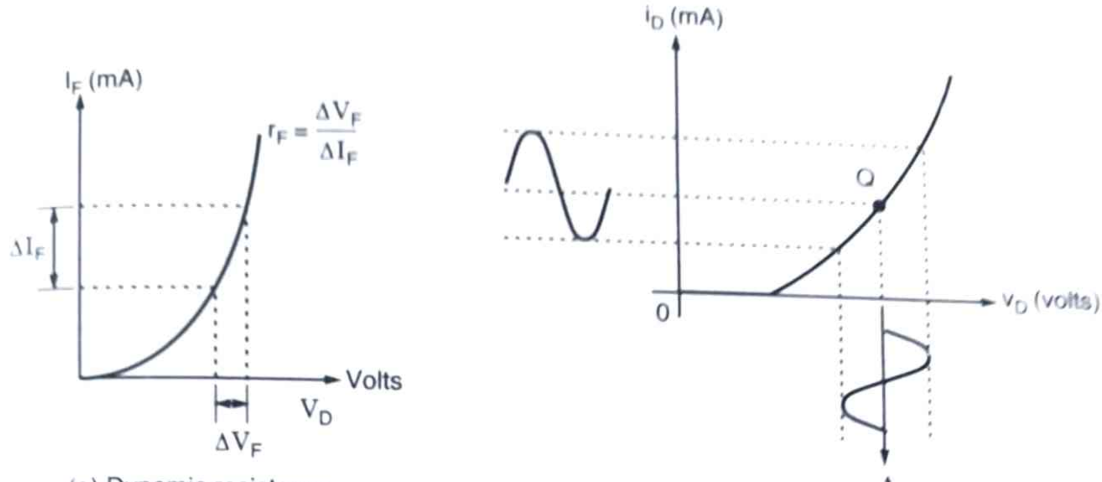
Fig. 2.35 DC or static resistance

$$\text{Static resistance } R_F = \frac{V_F}{I_F} \qquad ...(2.20)$$

Similarly, we can define the static resistance of a diode in the reverse biased condition as R_r. It is the ratio of reverse voltage to reverse current at a particular operating point. The typical value of forward static resistances R_F is between 10 Ω to 50 Ω and that of R_r is a few hundred kΩ. The forward and reverse static resistances appear in the large signal model of the diode.

2.19.2 AC or Dynamic Resistance (r_F)

When an AC voltage rather than a DC voltage is applied to a diode, the situation is altogether different. The operating point of the diode does not remain fixed. Its position will keep changing continuously, due to change in the input voltage as shown in figure 2.36.



(a) Dynamic resistance

(b) Variation in diode current due to ac voltage

Fig. 2.36

The resistance offered by a diode to the AC operating conditions is known as the **Dynamic Resistance** or **Incremental Resistance** or **AC Resistance** or a diode. It is denoted by r_F and defined as under:

$$\text{Dynamic resistance, } r_F = \frac{\Delta V_F}{\Delta I_F} \qquad ...(2.21)$$

Dynamic resistance is actually the reciprocal of the slope of the forward characteristics as shown in figure 2.36(a). Therefore, dynamic resistance, $r_F = \dfrac{1}{\text{Slope of the characteristics}}$

A reverse dynamic resistance can also be defined as the reciprocal of slope of the reverse characteristics. As the current flowing in the reverse biased condition is very small, the reverse dynamic resistance will be very large. The reverse dynamic resistance is denoted by r_r.

Dynamic resistances r_F and r_r are used in the small signal equivalent circuit of a diode. The variation of diode current due to variation in the anode to cathode voltage has been shown in figure 2.36(b).

2.19.3 Expression for the Dynamic Resistance of a Diode

The dynamic resistance has already been defined as under:

$$r = \frac{1}{\text{Slope of V-I characteristics}} = \frac{1}{[dI/dV]} \qquad ...(2.22)$$

Now, we have

$$I = I_o\left[e^{V/\eta V_T} - 1\right] \qquad ...(2.23)$$

Taking the derivative with respect to V, we get,

$$\frac{dI}{dV} = I_o\left[\frac{1}{\eta V_T} e^{V/\eta V_T}\right] = \frac{I_o e^{V/\eta V_T}}{\eta V_T} \qquad ...(2.24)$$

Substituting this into equation (2.22), we get,

$$r = \frac{1}{[dI/dV]} = \frac{\eta V_T}{I_o e^{V/\eta V_T}} \qquad ...(2.25)$$

But, from equation (2.23), we get,

$$I = I_o e^{V/\eta V_T} - I_o \qquad ...(2.26)$$

or
$$I_o e^{V/\eta V_T} = I + I_o \quad ...(2.27)$$

Substituting this into equation (2.25), we get,
$$r = \frac{\eta V_T}{I + I_o} \quad ...(2.28)$$

This is the required expression for the dynamic resistance of diode.

Key Point: It is possible to obtain the forward dynamic resistance r_F as well as the reverse dynamic resistance r_r. In order to do so, we have to use the generalised expression in equation (2.25) by substituting V to be positive for forward resistance and negative for reverse resistance.

EXAMPLE 2.5. The reverse saturation current for a Ge diode is 1μA at a reverse voltage of – 0.52 Volts. Calculate the values of the forward and reverse dynamic resistance. Assume the forward voltage to be + 0.52 V at room temperature.

Solution: Given that

$I_o = 1\ \mu A$, $V_F = 0.52$ volt for the forward biased condition.

$V_R = -0.52$ volt for the reverse biased condition.

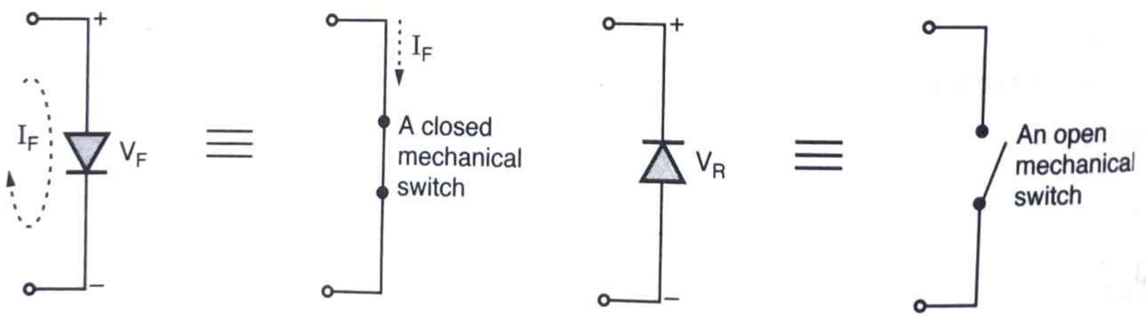
$\eta = 1$ for Germanium diode and $V_T = \dfrac{T}{11{,}600}$

Therefore, at room temperature i.e. at T = 300°K, we have
$$V_T = \frac{300}{11{,}600} = 25.86\ \text{mV}$$
or
$$V_T \cong 26\ \text{mV}$$

(i) Dynamic resistance in forward biased condition

Considering equation (2.25), we can write
$$r_F = \frac{\eta V_T}{I_o\, e^{V_F/\eta V_T}}$$

Substituting the values, we get,
$$r_F = \frac{26 \times 10^{-3}}{1 \times 10^{-6} \times e^{0.52/26 \times 10^{-3}}} = 0.0536 \times 10^{-3}\ \Omega \quad \textbf{Ans.}$$



(a) A forward biased diode is equivalent to a closed mechanical switch

(b) A reverse biased diode is equivalent to an open mechanical switch

Fig. 2.37

(ii) Dynamic resistance in the reverse biased condition

We have
$$r_r = \frac{26 \times 10^{-3}}{1 \times 10^{-6} \times e^{-0.52/26 \times 10^{-3}}} = 1.26 \times 10^{13}\ \Omega \quad \textbf{Ans.}$$

Key Point: A forward biased diode is equivalent to a closed mechanical switch due to its low forward resistance whereas a reverse biased diode is equivalent to an open mechanical switch as shown in figure 2.37.

EXAMPLE 2.6 A p-n junction diode has a temperature of 125°C and a reverse saturation current of 30μ A. At a temperature of 125°C, find the dynamic resistance for 0.2 volt bias in the forward and reverse direction.

Solution: Given that

$$I_{o(125)} = 30\ \mu A,$$
$$T = 125°\ C = 398°K,$$
$$V = \pm\ 0.2\ Volt$$

We have
$$V_T = \frac{398}{11{,}600} = 34.3\ mV$$

(i) Dynamic resistance in the forward biased condition.

We have
$$r_F = \frac{\eta V_T}{I_o \times e^{V/\eta V_T}}$$

Assuming $\eta = 1$ and substituting other values, we get,

$$r_F = \frac{1 \times 34.3 \times 10^{-3}}{30 \times 10^{-6} \times e^{0.2/34.3 \times 10^{-3}}} = 3.36\ \Omega \quad \text{...Ans.}$$

(ii) Dynamic resistance in the reverse biased condition.

We have
$$r_r = \frac{\eta V_T}{I_o \times e^{-V/\eta V_T}} = \frac{34.3 \times 10^{-3}}{30 \times 10^{-6} \times e^{-0.2/34.3 \times 10^{-3}}} = 389.5\ k\Omega \quad \text{...Ans.}$$

EXAMPLE 2.7 Find ac resistance for a semiconductor diode having a forward bias of 200 mV and reverse saturation current of 1 μA at room temperature.

Solution: At room temperature (i.e., 300°K)

$$V_T = 26\ mV = 0.026\ V$$

Applied forward voltage $V_F = 200\ mV = 0.2\ V$

Reverse saturation current $I_0 = 1\ \mu A = 1 \times 10^{-6}\ A$

We know that the a.c. resistance for the diode is given as

$$r_F = \frac{\eta V_T}{I_0 e^{V_F/\eta V_T}}$$

Substituting all the values, we get

$$r_F = \frac{0.026}{1 \times 10^{-6} \times e^{0.2/0.026}}$$

On solving, we get $r_F = 11.86$ ohms **Ans.**

2.20. DIODE CAPACITANCE

Basically, diode offers two types of capacitance, one in forward bias and other in reverse bias. Thus, the two capacitances associated with a p-n junction diode are as under:

(i) Transition Capacitance, (ii) Diffusion Capacitance

2.20.1. Transition Capacitance

1. Basic Concepts

When a PN-junction is formed, there exists a depletion region at the junction. This depletion region or layer consists of positive and negative immobile ions. This depletion layer is non-conductive and hence acts as a dielectric medium between P-region and N-region. The P-region and N-region act as the two plates of a capacitor because they have a low resistance. These two plates are separated by a dielectric (depletion layer).

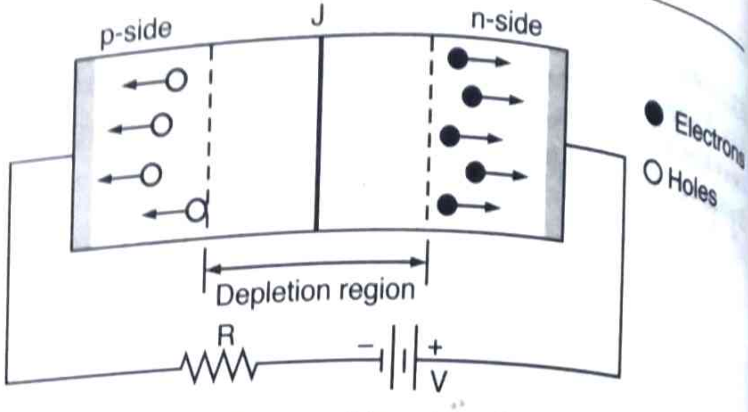


Fig. 2.38. Reverse biased p-n junction diode.

Let us consider figure 2.38, where, a p-n junction diode is being reverse diode. We know that with reverse voltage applied, the majority carriers move away from the junction. Thus, as shown in figure 2.38, the holes in the p-side and electrons in the n-side move away from the junction.

Due to the movement of majority carriers away from the junction, the width of depletion region will increase with increase in the reverse voltage. Due to the movement of charge carriers, there is a change in charge (dQ) with change in voltage (dV). This increase in charge caused by the change in reverse voltage is defined as the **transition capacitance**.

Therefore, $$C_T = \left|\frac{dQ}{dV}\right|$$

The transition capacitance C_T is also known as **space charge capacitance** or **barrier capacitance** or **depletion region capacitance**. This capacitance is not constant but it depends on the magnitude of reverse voltage.

2. Few Important Points about Transition Capacitance C_T

(i) We know that the basic expression relating the voltage on C, charge and capacitance C is given by

$$Q = CV, \quad \text{or} \quad Q = C_T V$$

Differentiating both the sides in above expression, we get

$$\frac{dQ}{dt} = C_T \times \frac{dV}{dt}, \quad \text{But,} \quad \frac{dQ}{dt} = i, \quad \text{or} \quad i = C_T \times \frac{dV}{dt}$$

(ii) The above expression shows that the reverse current i through the p-n junction diode is proportional to the transition capacitance C_T and the rate of change of reverse voltage V.

(iii) Therefore, if a reverse voltage of high $\frac{dV}{dt}$ appears across a diode (that means a reverse voltage at high frequency), then a large current will flow through it, and its reverse blocking capacity will be lost.

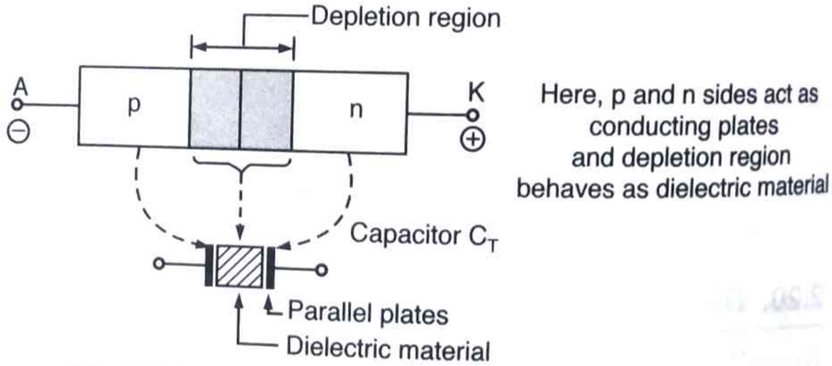


Fig. 2.39. Physical significance of transition capacitance

(iv) Therefore, the maximum frequency of operation of a diode is dependent on the value of C_T.

(v) Further, the two sides of a p-n junction act as the conducting plates and the depletion region behaves as the dielectric material between them to form the junction capacitance or transition capacitance C_T. This has been shown in figure 2.39.

3. Expression for Transition Capacitance C_T

Basically, the mathematical expression for transition capacitance C_T is given by

$$C_T = \frac{\in A}{W}$$

where, A = Area of the junction, W = Width of the depletion region, $\in$ = Dielectric constant

According to above expression, the value of C_T is inversely proportional to the width of depletion region W. As W increases, the transition capacitance decreases.

4. Relation between Transition Capacitance C_T and the Reverse Voltage V

(i) We know that the width W of the depletion region increases with increase in the reverse bias voltage V.

Therefore, the transition capacitance C_T decreases with increase in the reverse voltage.

(ii) Similarly, for an increased forward voltage (V positive), W decreases and transition capacitance C_T increases. Therefore, the barrier capacitance (C_T) is not constant but varies with the applied voltage. Figure 2.40 illustrates this variation in C_T.

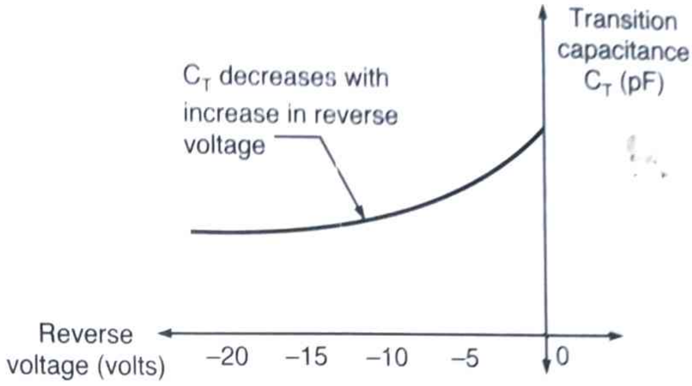


Fig. 2.40. Variation in C_T with reverse voltage

2.20.2. Diffusion Capacitance

(AKTU, Sem. Exam. 2006-07, 2007-08, 2008-09, 2013-14, 2014-15)

1. Basic Concepts: The capacitance which exists in a forward-biased junction is called a diffusion or storage capacitance. It is called diffusion capacitance to account for the time delay in moving charges across the junction by diffusion process.

If in a forward-biased junction the applied voltage is suddenly reversed, then forward current I_F ceases at once but a lot of majority charge carriers are left in the depletion region. This charge represents a stored charge in the reverse bias condition and should be removed from the space charge region. This removal of charge takes a finite time. This effect is similar to the discharge of a capacitor. Therefore, the amount of stored charge represents the magnitude of diffusion capacitance. It may be expressed as under:

$$C_D = \frac{\tau.I_F}{\eta.V_T} \quad ...(2.29)$$

where, C_D = Diffusion capacitance

η = Constant (η = 2 for Si, η = 1 for Ge)

V_T = Volt equivalent of temperature

τ = Mean life time of carriers

I_F = Forward current

Hence, the diffusion capacitance is directly proportional to the value of forward current I_F. The typical value of diffusion capacitance is about 0.02 μF. The effect of diffusion capacitance is negligible for a reverse-biased PN-junction.

2. Few Important Points about Diffusion Capacitance

(i) From the expression of diffusion capacitance, it is obvious that the diffusion capacitance is proportional to the current I_F. In the forward biased state, the value of C_D is much large than the transition capacitance C_T.

(ii) For a reverse bias, C_D must be neglected as compared to C_T.

(iii) In forward biased condition, C_D appears to be in parallel with the forward resistance. As this resistance is very small, the time constant r_d C_D will also be very small. Therefore, C_D will be ineffective for the normal signals, hence, it can be ignored. But, for the fast signals, C_D becomes effective and hence should be considered.

(iv) The variation in the diffusion capacitance with change in forward voltage has been shown in figure 2.41.

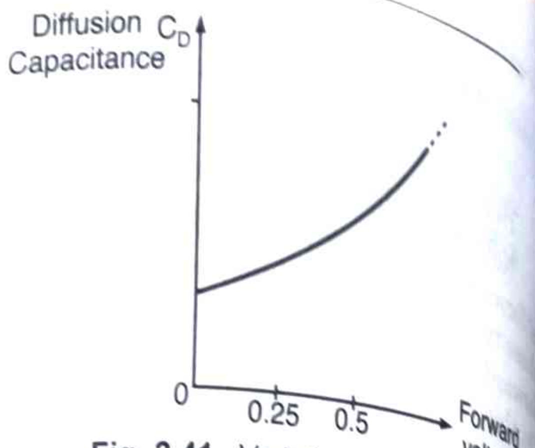
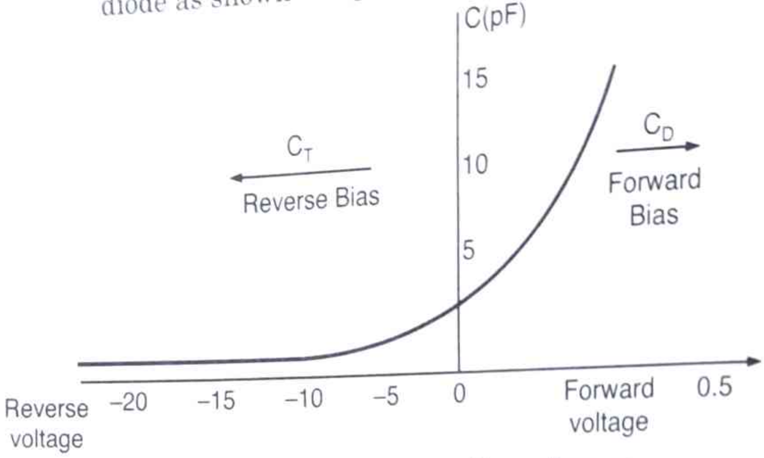


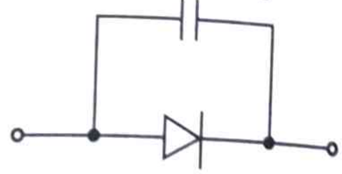
Fig. 2.41. Variation in C_D with forward voltage

(v) In forward biased state, with increase in the current level I_F, the diffusion capacitance C_D becomes more predominant. But, for the reverse biased condition, C_D is negligible and C_T will be dominant as shown in figure 2.42 (a).

(vi) The capacitive effects i.e., C_T and C_D are represented by a capacitor in parallel with an ideal diode as shown in figure 2.42 (b).



(a) Effect of forward and reverse bias voltage on transition and diffusion capacitance



(b) Including the effect of transition or diffusion capacitance

Fig. 2.42.

2.20.3. Comparison of Transition and Diffusion Capacitances

Table 2.5.

S.N.	Transition Capacitance	Diffusion Capacitance
1.	C_T is significant when the diode is reverse biased.	C_D is significant when the diode is forward biased.
2.	C_T decreases with increase in reverse voltage.	C_D increases with increase in forward voltage.
3.	$C_T = \frac{\in A}{W}$	$C_D = \frac{\tau I}{\eta V_T}$

2.21. DIODE AS A CIRCUIT ELEMENT AND LOAD LINE CONCEPT

Let us consider a simple diode circuit shown in figure 2.43 (a). The d.c. voltage V_{in} is applied such that diode is forward biased. The output is the voltage across the load resistance R_L.

The current I_f, which is forward current of diode, flows through the circuit. Now, V_f can be obtained by using any one diode approximation.

Important Point : But, if precise relationship between V_f and I_f is required then graphical analysis is necessary. This analysis is called d.c load line analysis of the diode.

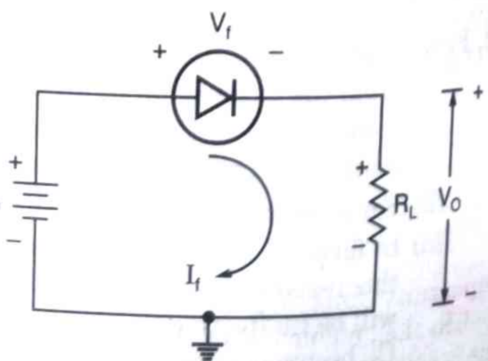


Fig. 2.43 (a). A simple diode circuit

Applying Kirchhoff's voltage law to the circuit, we have

$$-V_f - I_f R_f + V_{in} = 0$$

Hence $$V_f = V_{in} - I_f R_F \quad ...(2.30)$$

Now, we have two unknowns V_f and I_f and only one equation. The second equation is the equation of forward characteristics of the diode which is an exponential equation. But, analytically, solving these two equations is difficult, hence, graphical analysis is used. For graphical analysis, the diode forward characteristics as given in the datasheet specifications, is considered. This is known to use. On this characteristics, equation (2.30) is drawn. The equation (2.30) is a straight line equation, which gives linear equation (2.30) between V_f and I_f. This equation is called **equation of d.c. load line** for the diode.

Important Point : The load line is always straight line.

Sketching d.c. load line : According to equation (2.30), we obtain the two points as under:

Point A. $V_f = 0$, hence, $I_f = \frac{V_{in}}{R_L}$ according to equation (2.30).

Point B. $I_f = 0$, hence, $V_f = V_{in}$ according to equation (2.30).

The point A gives y intercept while point B gives x intercept of the line.

The line joining the points A and B is called **d.c. load line** of the diode.

We sketch this line on the forward characteristics of the diode. The forward characteristics already exists as per the diode datasheet specifications. The combined graph is shown in figure 2.43 (b).

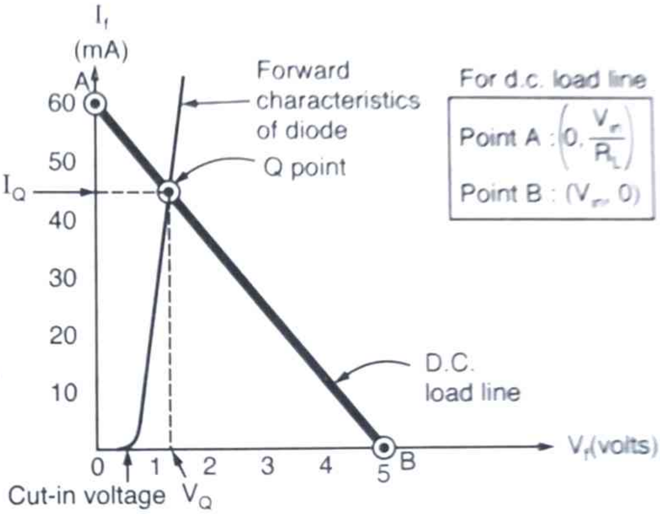


Fig. 2.43 (b). D.C. load line analysis of diode

2.21.1. Operating Point (Q Point)

The relation between V_f and I_f is **predefined** for the device interms of its **forward characteristics**, given in the datasheet of the diode. For the given circuit conditions, V_f and I_f relationship is given by the d.c. load line.

Important Point : Thus, there exists only the point on the d.c. load line as per the forward characteristics of the diode. It is the intersection of the forward characteristics and d.c. load line of the diode. This is called operating point, quiescent point or Q point of the device.

It is also called as d.c biasing point for the diode.

Remember that practically points A and B may not be achieved. The points A and B are theoretical points used to sketch the d.c. load line. **The Practical operating point is the Q point.** Rearranging the equation (2.30), we have

$$I_f = -\frac{1}{R_L} V_{in} + \frac{V_{in}}{R_L} \quad ...(2.31)$$

i.e., $$y = mx + C$$

Important Conclusion: It can be seen that slope of the line is $-1/R_L$, i.e., reciprocal of the load resistance R_L. Hence, the line is called a load line .

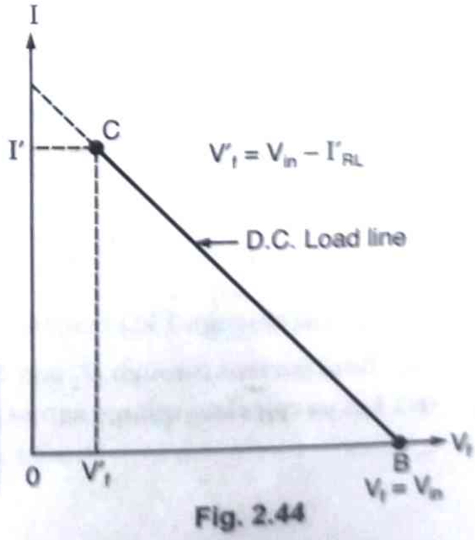


Fig. 2.44