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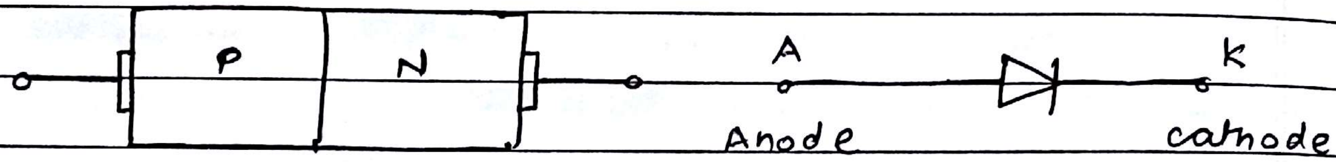
Unit 1.3 PN junction Diode characteristics - Small signal Model -

Introduction -

- A PN junction diode consists of PN junction formed either in germanium or silicon crystal.
- It has two terminals namely anode & cathode.
- The anode refers to the P-type region & cathode refers to N-type region.

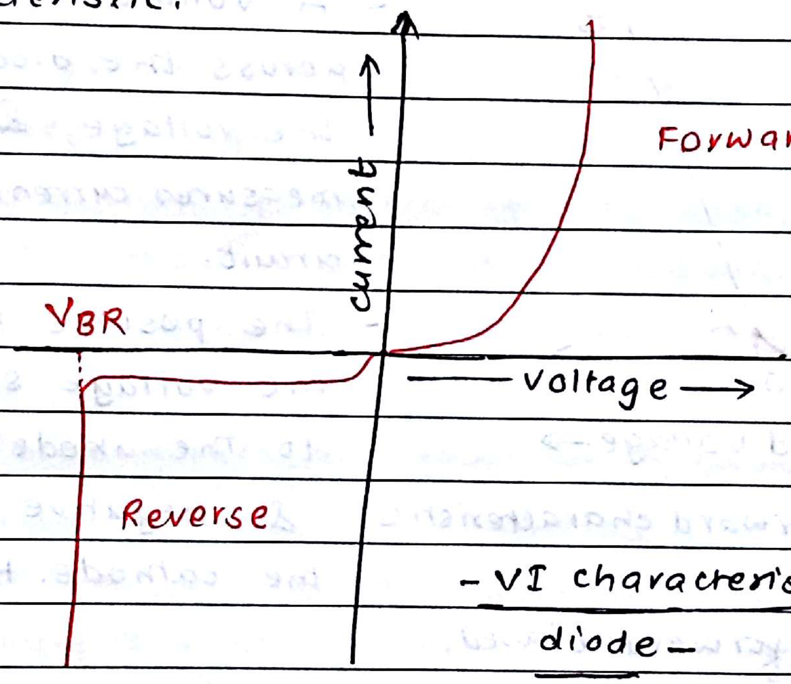


a) construction   b) symbol

- The arrowhead in the symbol points the direction of current flow, when it is forward biased. It is the same direction in which the movement of holes take place.
- The most common function of a diode is to allow an electric current to pass in one direction (called diode's forward direction) while blocking current in the opposite direction (called reverse direction).
- The standard notation consists of type numbers preceded by IN, such as IN240 & IN1250. Here 240, & 1250 correspond to colour bands.

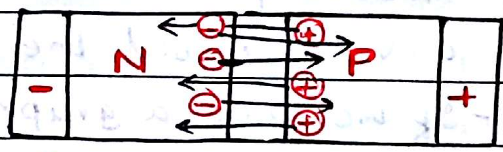
* V-I Characteristic of a PN junction Diode :-

- It is a graph between the voltage applied across the terminals of a device & the current that flows through it.
- Next figure shows the V-I characteristics of a typical PN junction diode w.r.t. breakdown voltage (V_{BR}).
- It may be noted that the complete graph can be divided into two parts forward characteristic & reverse characteristic.



- VI characteristic of a PN junction diode -

① Forward characteristic -



Forward Biased Diode

- fig@ shows the circuit arrangement for obtaining the forward characteristic of a diode.
- In this circuit, diode is connected to a d.c (V_{AA}) through a potentiometer (P) & a resistance (R).
- The potentiometer helps in varying the voltage applied across the diode.
- The resistance (R) is included in the circuit, so as to limit the current through diode.

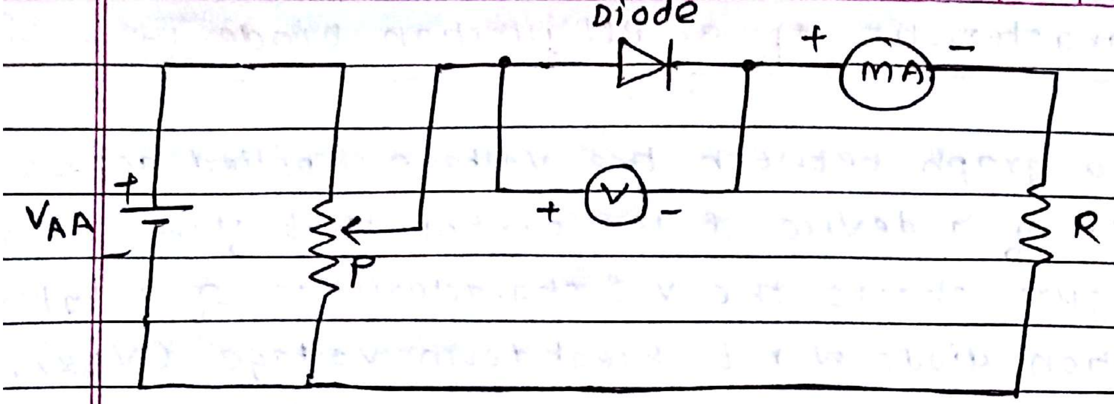


fig a) circuit arrangement

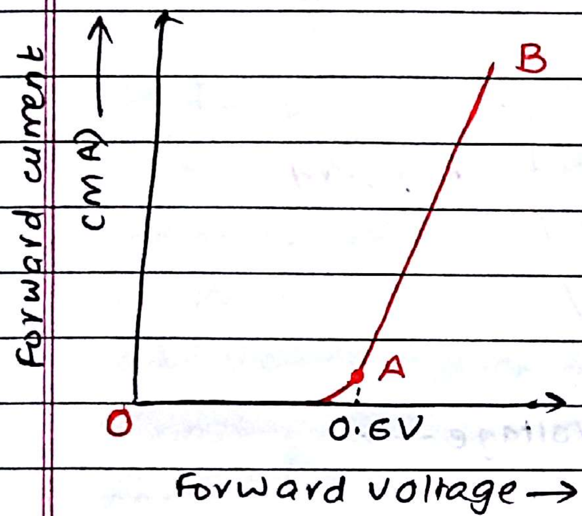
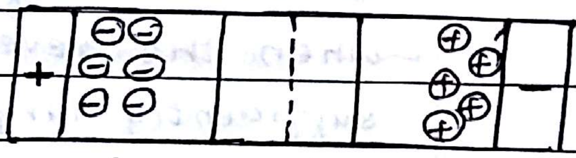


fig b) forward characteristic

- A voltmeter is connected across the diode to measure the voltage, & a milliameter measures current in the circuit.
- The positive terminal of the voltage source connected to the anode of a diode & negative terminal to the cathode. Hence the diode is forward biased.
- Gradually increase the voltage in small steps of about 0.1V, & record the corresponding values of diode current.
- If we plot a graph with voltage across the diode, along the horizontal axis & diode currents along the vertical axis, we shall obtain a curve OAB as shown in fig (b).
- The curve OAB is called the forward characteristic of silicon PN junction code.
- There is no diode current till point A is reached. It is because of the fact, that the external applied voltage is being opposed by the junction voltage, whose value is 0.7V for silicon & 0.3V for germanium.

- As the voltage is increased above that of point A, the diode current increases rapidly.
- A voltage of about 1volt produces a forward current of about 20 to 50mA.
- The applied voltage should not be increased beyond a certain safe limit, otherwise the diode is likely to burn out.
- The voltage at which the diode starts conducting is called knee voltage, cut in voltage or threshold voltage. V_K or V_g. It is equal to 0.6V for Si & 0.2V for Ge.
- The knee voltage may be obtained from the forward characteristic by extending the curve AB backwards, till it meets the horizontal axis. The value on the horizontal axis is equal to the knee voltage.

2.) Reverse characteristics



Reverse biased diode

The circuit arrangement for obtaining the reverse characteristics of a diode is as shown in fig@.

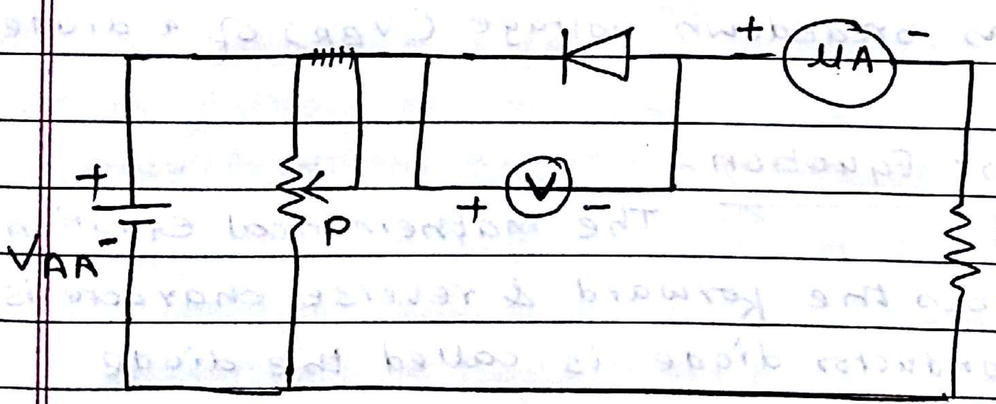
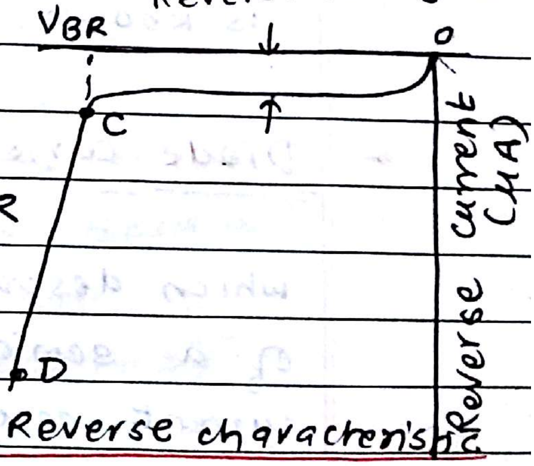


fig a) circuit arrangement



b) Reverse characteristic

- Negative terminal of the voltage source is connected to the anode of a diode & positive terminal to the cathode. Hence, the diode is reverse biased.

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- The applied reverse voltage is gradually increased above zero in suitable steps & the values of diode current are recorded at each step.
- If we plot a graph with reverse voltage along the horizontal axis & the diode current along the vertical axis, we shall obtain a curve marked OCD as shown in figure b).
- The curve OCD is called reverse characteristic of the diode.
- When the applied reverse voltage is below the breakdown voltage (V_{BR}) the diode current is small & remains constant. This value of current is called reverse saturation current (I_0). It is of order of nanoamperes ($1nA = 10^{-9}A$) for Si diode & microampere ($1\mu A = 10^{-6}A$) for Ge diode.
- When the reverse voltage is increased to a sufficiently large value, the diode reverse current, increases as rapidly as shown by the curve CD in the figure.
- The applied reverse voltage, at which this happens, is known as breakdown voltage (V_{BR}) of a diode.

* **Diode current Equation -**

The mathematical equation, which describes the forward & reverse characteristic of a semiconductor diode is called the diode current equation.

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Let I = Forward (or reverse) diode current

I_0 = Reverse saturation current

V = External voltage. It is positive for forward bias & negative for reverse bias.

η = A constant called ideality factor, quality factor or emission coefficient, whose value is equal to 1 for Ge diodes & 2 for Si diodes for relatively low value of diode current (i.e at or below the knee of the curve) & $\eta = 1$ for Ge & silicon for higher levels of diode current (i.e. in the rapidly increasing section of the curve.

V_T = volt equivalent of temperature. Its value is given by $= \frac{T}{11600}$, where T = absolute temp.

At Room temperature, i.e 300K $V_T = 26mV$

The current equation for a forward biased diode is given by
$$\boxed{I = I_0 \left(e^{V/\eta \cdot V_T} - 1\right)} \quad \text{①}$$

$V_T = 26mV$

Putting $V_T = 26mV$ to $0.026V$

$$I = I_0 \left(e^{40V/\eta} - 1\right)$$

Diode current at or below the knee of the curve for Ge,
$$= I_0 \left(e^{40V} - 1\right) \quad (\because \eta = 1)$$

for silicon, $= I_0 \left(e^{20V} - 1\right) \quad (\because \eta = 2)$

- If the value of applied voltage is greater than unity (i.e for the diode current in the rapidly increasing section of the curve), then the equation of diode current for germanium or silicon $I = I_0 \cdot e^{20V}$

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Data

- The current equation for a reverse biased diode may be obtained from eqn ① by changing the sign of the applied voltage (V).

Thus the diode current for reverse bias,

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

- If the value of $V >> V_T$ then term $e^{-V/\eta . V_T} << 1$

Therefore $I = I_o$.

- Thus the diode current under reverse bias is equal to the reverse saturation current as long as the external voltage is below its breakdown value.

EX1) The current flowing in a certain PN junction diode at room temperature is 2×10^{-7} A. When the large reverse voltage is applied: calculate the current flowing when 0.1V forward bias is applied at room temperature.

Soln_ given $I_o = 2 \times 10^{-7}$ A ; $V_F = 0.1$ V

we know that the current flowing through the diode under forward bias,

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

$$= 2 \times 10^{-7}(e^{40 \times 0.1} - 1)$$

$$= 2 \times 10^{-7}(e^{4} - 1)$$

$$= 1.07 \times 10^{-5} A$$

$$\boxed{I = 10.7 \mu A}$$

EX2) Determine the germanium PN junction diode current for the forward bias voltage of 0.22V at room temperature 25°C with reverse saturation current equal to 1mA.

Take $\eta = 1$

Soln_ Given- $V_F = 0.22$ V $T = 25°C = 298$ K

$I_o = 1 mA = 1 \times 10^{-3}$ A $\eta = 1$

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$$V_T = \frac{T}{11600} = \frac{298}{11600} = 25.7 mV = 25.7 \times 10^{-3} V$$

The diode current,

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

$$= (1 \times 10^{-3})(e^{0.22/(1 \times 25.7 \times 10^{-3})} - 1) \quad (\because \eta = 1 \text{ for Ge})$$

$$= (1 \times 10^{-3})(e^{8.56} - 1)$$

$$\boxed{I = 5.22 A}$$

EX3) The current voltage characteristic of a PN junction diode is given by the relation:

$$I = I_0 (e^{qV/\eta . k . T} - 1)$$

The diode current is 0.5mA & V=340mV & 15mA at V=440mV. Determine the value of η. assume $\frac{kT}{q} = 25 mV$

Sol^n- Given $I_1 = 0.5 mA = 0.5 \times 10^{-3} A$

$V_1 = 340 mV$

$I_2 = 15 mA = 15 \times 10^{-3} A$

$V_2 = 440 mV$ & $\frac{k.T}{q} = 25 mV$

Diode current (I_1)

$$0.5 \times 10^{-3} = I_0 \, e^{q . V_1 / \eta . k . T} - 1)$$

$$= I_0 e^{qV_1/\eta kT}$$

$$= I_0 e^{340/25\eta}$$

$$= I_0 e^{13.6/\eta} \quad —①$$

Diode current (I_2)

$$15 \times 10^{-3} = I_0 . e^{440/25\eta}$$

$$= I_0 e^{17.6/\eta} \quad —②$$

dividing eq^n ① & ②,

$$30 = e^{(17.6 - 13.6)/\eta} = e^{4/\eta}$$

Taking natural logarithms on both sides,

$$\log_e 30 = \log_e (e^{4/\eta}) = \frac{4}{\eta} . \log_e = \frac{4}{\eta}$$

$$3.4 = 4/\eta \quad \text{or} \quad \eta = 4/3.4 = \underline{1.18}$$

Ex 4) A germanium diode carries a current of 1mA at room temperature when a forward bias of 0.15V is applied. estimate the reverse saturation current at room temperature.

Sol^n –

$V_F = 0.15V \qquad I_F = 1mA = 1\times10^{-3}A$

$$V_T = \frac{T}{11600} = \frac{300}{11600} = 26mV = 26\times10^{-3}V$$

diode current, $I_F = I_0(e^{V_F/\eta V_T} - 1)$

$$(1\times10^{-3}) = I_0(e^{0.15/(1\times26\times10^{-3})} - 1)$$

$$= \frac{(1\times10^{-3})}{(e^{5.8}-1)} = 3.03\times10^{-6} \qquad (\eta = 1)$$

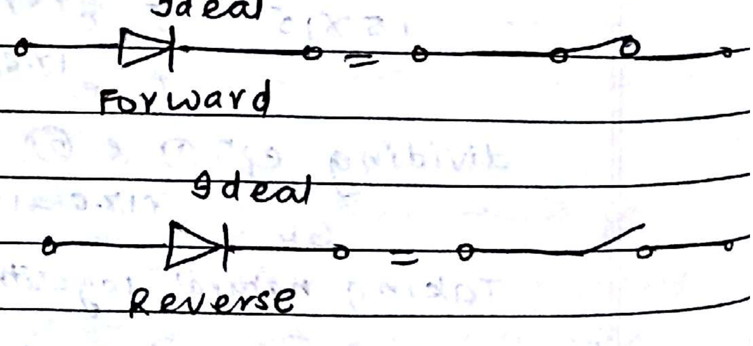
$$\boxed{I_0 = 3.03\mu A}$$

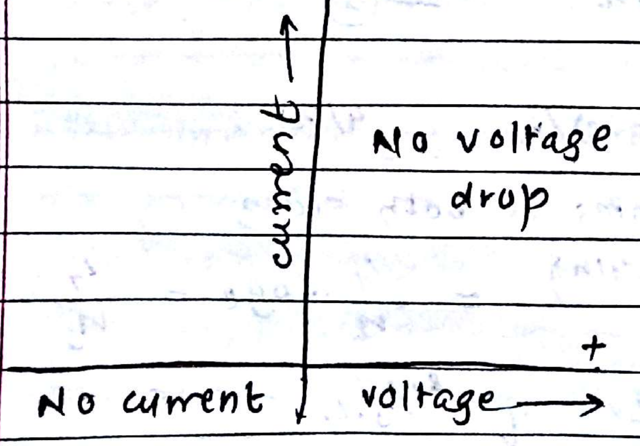
* **The Idea Diode** –

A PN junction diode conducts well, when it is forward biased & poorly conducts (practically no current) when reverse biased.

– It will behave as an idea, if the diode acts as a perfect conductor (with no voltage drop across it) when forward biased & as a perfect insulator (with no current through it) when reverse biased.

– The V–I characteristic of such an ideal diode is shown in figure.





Ideal diode

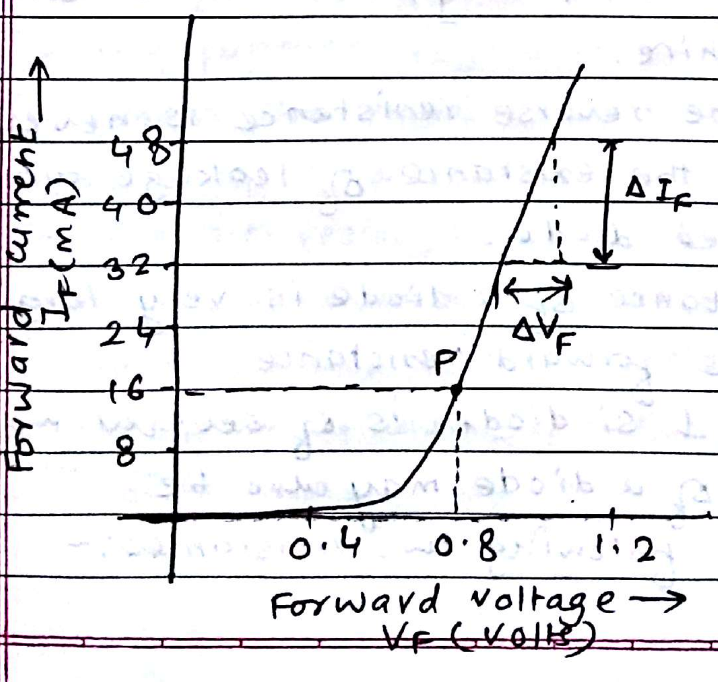
- An ideal diode is a device, which conducts with zero resistance when forward biased & appears as an infinite resistance when reverse biased.
- It cannot be manufactured in actual practice. It is only a theoretical approximation of a real diode.

* Static & Dynamic Resistance of a Diode :-

- Diode does not offer zero resistance when forward biased & an infinite resistance when reverse biased.
- It means that a diode has a definite value of resistance when forward biased. This resistance is known as d.c or static forward resistance of the diode.
- It is given by the ratio of the d.c voltage across the diode to the d.c current flowing through it.
- Mathematically the static forward resistance (in ohms)

$$\boxed{R_F = \frac{V_F}{I_F}}$$

- The static forward resistance may be obtained graphically from the diode forward characteristic as shown in fig ⓐ



- The value of R_F is quite low, as it should be.
- In practice we don't use the static forward resistance.
- Instead, we use the dynamic or a.c resistance.

static & dynamic forwared resistance of a diode from characteristic curve

- The resistance offered by the diode to an a.c. signal is called its dynamic or a.c resistance.
- The a.c resistance of a diode, at a perticular d.c voltage, is equal to the reciprocal of the slope of the characteristic at that point. i.e. the a.c. resistance,

$$r_{ac} = \frac{1}{\Delta I_F / \Delta V_F} = \frac{\Delta V_F}{\Delta I_F} = \frac{\text{change in voltage}}{\text{Resulting change in current}}$$

- Because of the non-linear shape of the forward characteristic, the value of a.c resistance of the diode is in range of 1 to 25 Ω.
- Usually it is smaller than the d.c resistance of a diode.
- In addition to the forward resistance, the diode also possesses another resistance when it is reverse biased. such a resistance is known as reverse resistance. It can be either d.c or a.c depending upon whether the reverse bias is direct or alternating voltage.
- It may be noted that, ideally, the reverse resistance of a diode is infinite.
- In actual practice, the reverse resistance is never finite. It is due to the existance of leakage current in a reverse biased diode.
- The reverse resistance of a diode is very large as compared to its forward resistance.
- Its value for Ge & Si diodes is of several megaohms.
- The a.c resistance of a diode may also be determined from the following two resistances:-

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(1) Bulk Resistance –

The resistance of the P & N-semiconductor materials of which the diode is made of, is known as bulk resistance or body resistance.

- It also includes the resistance introduced by the connection between the semiconductor material & the external metallic conductor also called contact resistance.
- It is generally designated by r_B.
- Mathematically, the bulk resistance

$$r_B = r_P + r_N$$

where r_P = Ohmic resistance of P-type semiconductor
r_N = Ohmic resistance of N-type semiconductor.

- The bulk resistance can range from typically 0.1 Ω for high power devices to 2 Ω for some low power general purpose diodes.

(2) Junction Resistance –

- Its value for a forward biased PN junction depends upon the value of forward d.c current. It is given by the relation,

$$r_j = \frac{26}{I_F}$$

where I_F = forward current in miliamperes.

- The junction resistance is a variable resistance.
- Higher the value of d.c current, lower will be the value of r_j & vice versa.
- The a.c resistance is equal to the sum of junction resistance & bulk resistance.

Mathematically, the a.c resistance,

$$\boxed{r_{ac} = r_j + r_B}$$

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Ex. 1) An ideal germanium diode at a temperature of 125°C has a reverse saturation current of 30 µA. At a temperature of 125°C, find the dynamic resistance for a 0.2V bias in a) the forward direction & b) the reverse direction.

Soln – given $T = 125°C = 398 K$, $I_0 = 30 \mu A = 30 \times 10^{-6} A$
$V = 0.2V$

(a) Dynamic resistance in forward direction –

$$V_T = \frac{T}{11600} = \frac{398}{11600} = 0.0343$$

∴ Diode current; $I = I_0 (e^{V/\eta . V_T} - 1)$

$$= I_0 . (e^{V/V_T} - 1) \quad (\because \eta = 1 \text{ for Ge})$$

Differentiating the above expression with respect to V,

$$\frac{dI}{dV} = \left(\frac{I_0}{V_T}\right) \times e^{V/V_T}$$

$$\frac{1}{r_{ac}} = \left(\frac{I_0}{V_T}\right) \times e^{V/V_T}$$

$$r_{ac} = \frac{V_T}{I_0} . e^{-V/V_T} \quad \text{—— (1)}$$

$$= \frac{0.0343}{30 \times 10^{-6}} \times e^{-0.2/0.0343} \quad 1143.3 \times e^{-5.83}$$

$$= 1143.3 \times (2.938 \times 10^{-3})$$

$$\boxed{r_{ac} = 3.36 \Omega}$$

(b) Dynamic resistance in reverse direction –

Put value in eqn (1) with $V = 0.2$, $V = -0.2$ (due to reverse direction)

$$= \frac{0.0343}{30 \times 10^{-6}} e^{(-0.2)/0.343}$$

$$= 1143.3 \times e^{5.83} = \boxed{0.389 M\Omega}$$

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* The Real Diode –

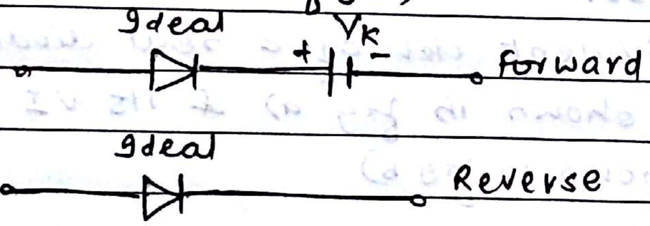
A diode can be approximated to an automatic switch, which is closed when a diode is forward biased & open switch when it is reverse biased.

But in actual practice, we have to consider two more factors, in addition to a simple switch for a diode operation as below :–

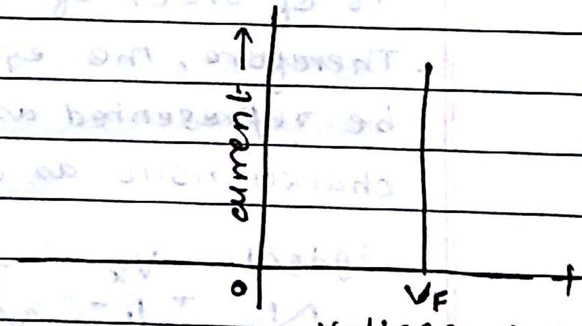
When a diode is forward biased, it does not pass any current until the applied voltage exceeds the knees voltage or the cut-in voltage.

Therefore, a diode may be represented by an automatic switch (or an ideal diode) in series with a battery of e.m.f. equal to the knee voltage.

- The knee voltage has no effect on the diode operation, when it is reverse biased.
- Therefore, the equivalent circuit of a real diode may be represented as shown in fig a) & its V-I characteristic as shown in fig b)



a) Equivalent ckt



b) VI characteristic

- In addition to a knee voltage (V_K), a diode possesses a.c or dynamic resistance, which is equal to the sum of bulk resistance & the junction resistance.
- Thus when a diode is forward biased, it does not conduct until the applied voltage exceeds the knee voltage.
- As the applied voltage exceeds further, the current through a diode increases & produces a voltage drop

across the a.c resistance. Since the a.c resistance is linear, therefore the voltage drop across a real diode is given by the relation,

$$V_F = V_K + I_F \cdot r_{ac}$$

where V_F = knee voltage whose value is 0.6 V for Si & 0.2 V for Ge,

I_F = forward current

r_{ac} = A.C resistance.

* Piecewise Linear Diode Model –

When a diode is reverse biased, it does not behave like an open switch.
– In other words, the reverse current is not zero, though it has a small value. It is known as reverse saturation current. This means that a reverse biased diode is equivalent to an ideal diode in series with a high resistance (r_r) which is of order of MΩ.

• Therefore, the equivalent ckt of a real diode may be represented as shown in fig a) & its VI characteristic as shown in fig b)

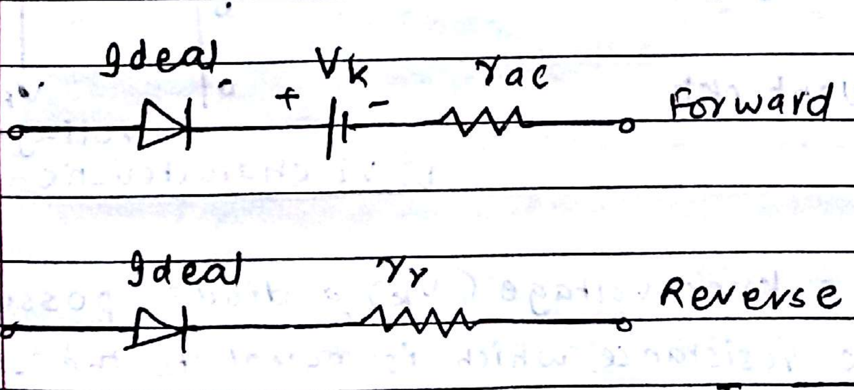


fig a) Equivalent ckt

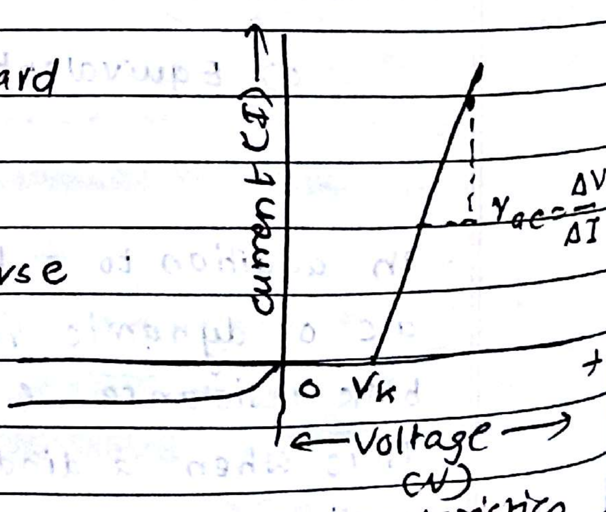


fig b) VI characteristics

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* Diode Applications -

1. as a rectifier or power diodes in d.c power supplies.
2. As signal diodes in communication circuits.
3. As zener diodes in voltage stabilizing ckts.
4. As a varactor diodes in radio & TV receivers.
5. As a switch in logic circuits used in computers.
6. As over-voltage protection device in integrated ckts & motor controllers.
7. As a ionizing radiation detector.
8. As a current steering device is uninterruptable power supplies & electronic musical keyboards.

* Diode Circuits : AC Equivalent Model/Circuit :-

Equivalent ckt for a diode when a small, time varying signal is applied.

- When semiconductor devices with pn junctions are used in linear amplifier ckt, the ac (or time varying) characteristics of the pn junction become important, because sinusoidal signals may be superimposed on the dc currents & voltages.

Sinusoidal Analysis :-

In the ckt shown in fig a), the voltage source v_i is assumed to be a sinusoidal, or time varying signal.

- The total i/p vtg V_I is composed of a dc component V_{PS} & an ac component v_i superimposed on the dc value.
- There are two types of analysis
  1. dc analysis :- involving only dc vtgs & currents
  2. Ac analysis :- involving only ac vtgs & currents.

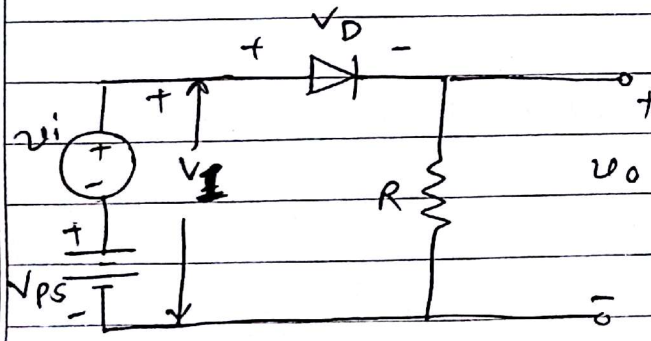

fig a) ckt with combined dc & AC i/p vtg

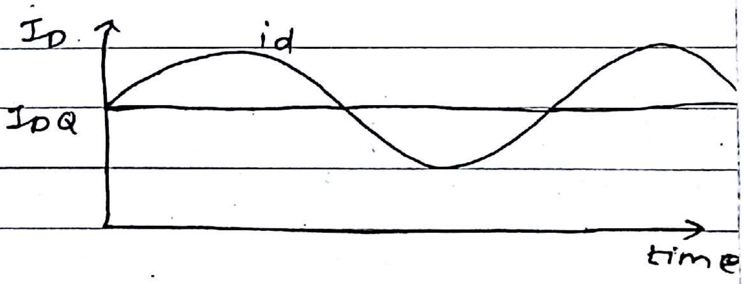

fig b) sinusoidal diode current superimposed on quiescent current

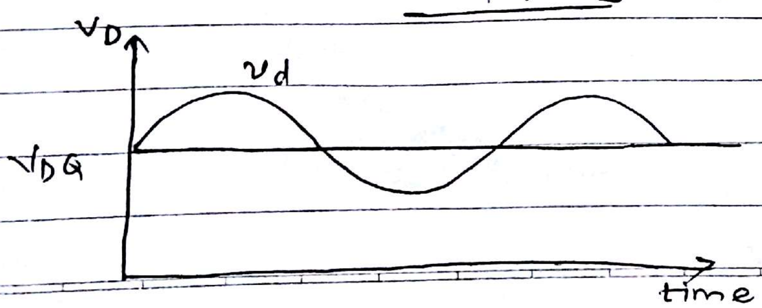

fig c) sinusoidal diode vtg superimposed on quiescent vtg

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current-voltage Relationships:-

- since I/p vtg contains a dc component with an ac signal superimposed, the diode current will also contain a dc component with ac signal superimposed as shown in fig b).
- Here I_{DQ} is the dc quiescent diode current.
- The diode vtg will contain a dc value with an ac signal superimposed as shown in fig c.)
- for this analysis, assume that ac signal is small compared to the dc component so that a linear ac model can be developed from the nonlinear diode.
- The relationship bet^n diode current & vtg can be written as

$$i_D \cong I_S e^{(V_D/V_T)} = I_S e^{\left(\frac{V_{DQ}+v_d}{V_T}\right)} \quad -①$$

where V_{DQ} = dc quiescent vtg (we are neglecting "-1" term in diode eq^n)
v_d = ac component

$$i_D = \underbrace{I_S\left[e^{\left(\frac{V_{DQ}}{V_T}\right)}\right]}_{I_{DQ}} \cdot \underbrace{\left[e^{\left(\frac{v_d}{V_T}\right)}\right]}_{1+v_d/V_T} \quad -②$$

- If ac signal is small, then $v_d \ll V_T$ & we can expand the exponential function into a linear series as follows:-

$$e^{\left(\frac{v_d}{V_T}\right)} \cong 1 + \frac{v_d}{V_T} \quad -③$$

we may also write I_{DQ} as

$$I_{DQ} = I_S e^{\left(\frac{V_{DQ}}{V_T}\right)} \quad -④$$

By putting values from eq^n ③ & ④ we can rewrite eq^n ② as

$$\cancel{i_D = I_{DQ} + \frac{I_{DQ}}{}}$$

$$i_D = I_{DQ}\left(1+\frac{v_d}{V_T}\right) = I_{DQ} + \frac{I_{DQ}}{V_T}\cdot v_d$$

$$i_D = I_{DQ} + i_d$$

where i_d is the ac component of diode current.

- The relationship between the ac components of the diode vtg & current is then,

$$i_d = \left(\frac{I_{DQ}}{V_T}\right) \cdot v_d \quad \text{OR} \quad v_d = \left(\frac{V_T}{I_{DQ}}\right) \cdot i_d$$

$$\boxed{i_d = g_d \cdot v_d} \quad (5) \qquad \boxed{v_d = r_d \cdot i_d} \quad (6)$$

where g_d = diode small signal incremental conductance / diffusion conductance

r_d = diode small signal incremental resistance / diffusion resistance.

comparing eqn (5) & (6),

$$\boxed{r_d = \frac{1}{g_d} = \frac{V_T}{I_{DQ}}}$$

- This equation tells us that the incremental resistance is a function of the dc bias current I_{DQ} & is inversely proportional to slope of IV characteristics curve as shown in fig d)

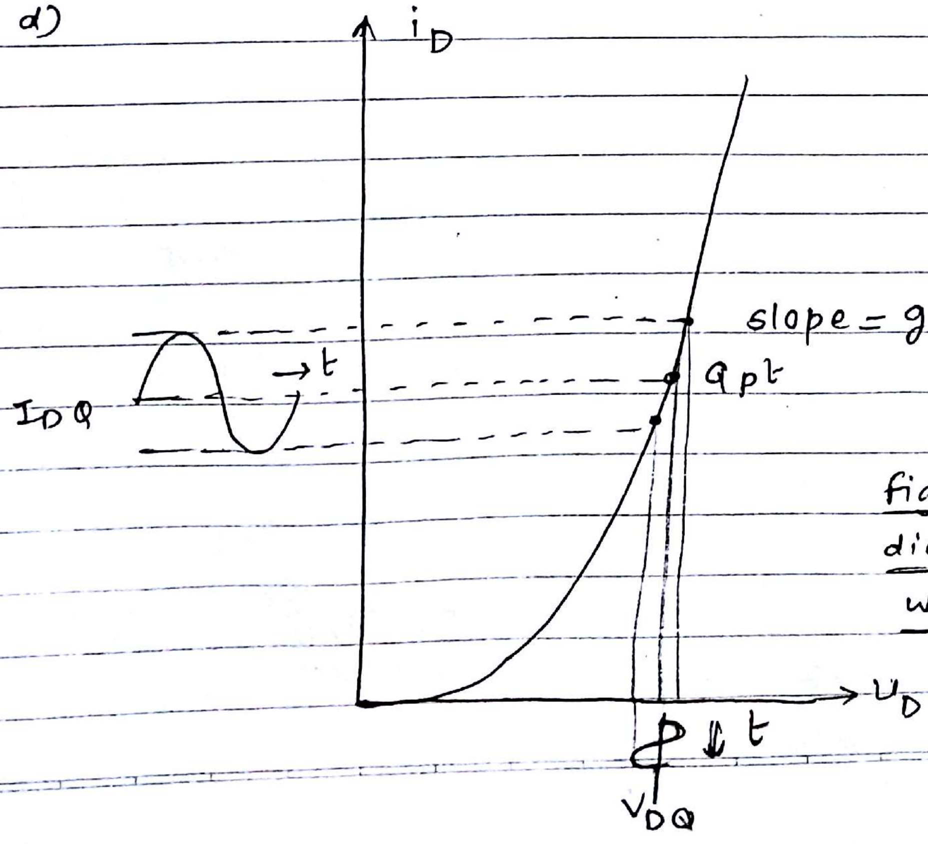


fig d) forward biased diode IV characteristics with a sinusoidal current & vtg superimposed on Q values circuit analysis :-

- To analyse the ckt shown in fig a), we first perform dc analysis & then an ac analysis.
- These two types of analyses will use two equivalent ckt.

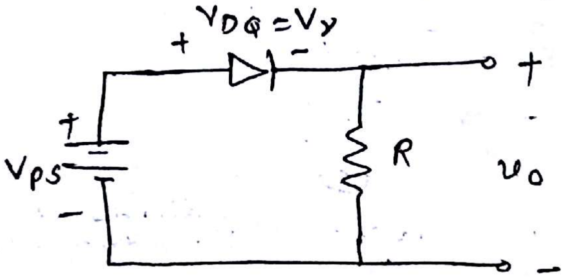


fig e) dc equivalent ckt

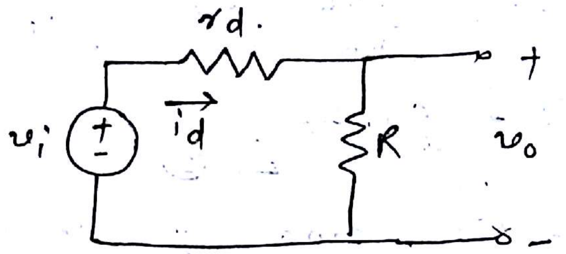


fig f) ac equivalent ckt

- fig e) is the dc equivalent ckt (that we have seen earlier) If Diode is forward biased, then V_D is the piecewise linear turn on vtg

Fig f) is ac equivalent ckt. The diode is replaced by its equivalent resistance r_d.

- All parameters are small signal time varying.

* Frequency Response :-

- In previous analysis, we have assumed that the frequency of the ac signal was small enough that capacitance effect in the ckt would be negligible.
- If the frequency of ac i/p signal increases, the diffusion capacitance associated with a forward biased pn junction becomes important.
- The diffusion capacitance is the change in the stored minority carrier charge that is caused by a change in the voltage or $\boxed{C_d = \frac{dQ}{dV_D}}$

– The diffusion capacitance Cd is normally much larger than the junction capacitance Cj, because of the magnitude of the charges involved.

Small Signal Equivalent Circuit :–

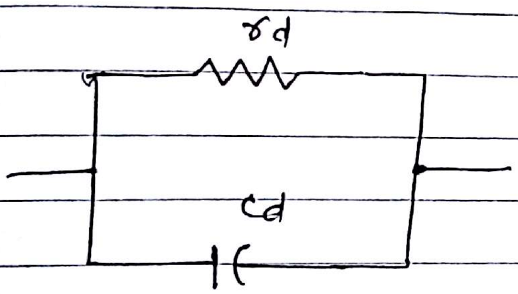
(a) For forward Bias :–

– The small signal equivalent ckt of the forward biased pn junction is shown in fig ①.

– It is developed partially from the equation for the admittance, which is given by

$$\boxed{Y = g_d + j\omega C_d}$$

where C_d = diffusion capacitance
g_d = diffusion conductance.



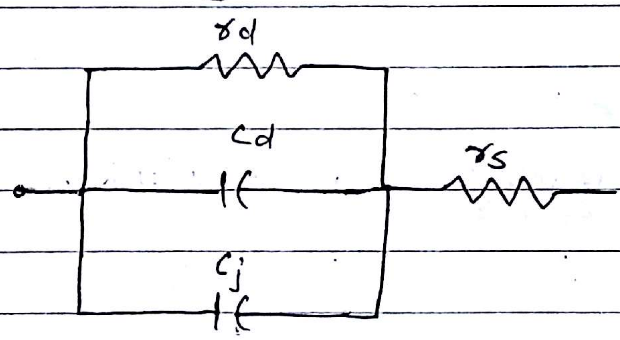


fig ① small signal equivalent ckt

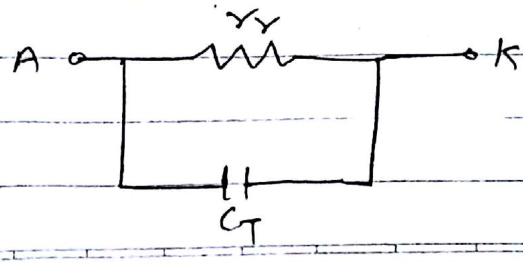
simplified version　　　　complete ckt

– We must also add the junction capacitances, which is in parallel with diffusion resistance & capacitance & a series resistance is required to indicate finite resistances in the neutral n & p regions.

(b) For Reverse Bias :–

– r_r is the incremental resistance when diode is in reverse bias.

& C_T = transition capacitance.

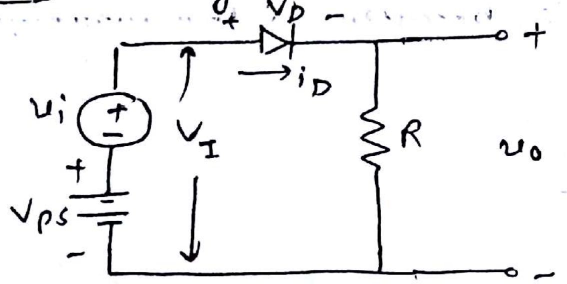


Ex 1) Analyze the circuit shown. assume circuit & diode parameters of $V_{PS} = 5V$

$R = 5k\Omega$

$V_\gamma = 0.6V$ &

$v_i = 0.1 \sin \omega t\,(V)$



Ans :- DC Analysis :-

i) we set $v_i = 0$ for DC analysis

ii) find Q pts.

$$I_{DQ} = \frac{V_{PS} - V_\gamma}{R} = \frac{5 - 0.6}{5} = 0.88\,mA$$

$$V_o = I_{DQ} \cdot R = 0.88 \times 5 = 4.4V$$

AC analysis :-

i) set $V_{PS} = 0$ Apply KVL,

$$v_i = i_d r_d + i_d R$$
$$= i_d (r_d + R)$$

r_d = small signal diode diffusion resistance

$$r_d = \frac{V_T}{I_{DQ}} = \frac{0.026}{0.88} = 0.0295\,k\Omega$$

$$i_d = \frac{v_i}{r_d + R} = \frac{0.1 \sin \omega t}{0.0295 + 5} = 19.9 \sin \omega t\,(\mu A)$$

ac component of o/p vtg is

$$v_o = i_d R = 0.0995 \sin \omega t\,(V)$$