Semiconductor diodes

Diode refers to a two electrode or two terminal device. It is a pn-junction with a connecting lead on each side.

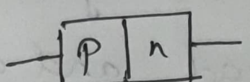


Fig 1 - pn junction

A diode is a one way device offering a low resistance when forward biased and behaving almost like an open switch when reverse biased.

A constant voltage drop occurs across a forward biased diode;, simplifying diode circuit analysis.

Some diodes are low current devices used in switching circuits. High current diodes are used in rectifiers. Zener diodes are operated in reverse breakdown because they have a stable breakdown voltage.

pn-junction diode

pn junction diode permits substantial current flow when forward biased and blocks current when reverse biased. Hence it can be used as a switch, on when forward biased and off when reverse biased.

A pn junction provided with copper wire connecting leads becomes an electronic device known as *diode*.

The circuit or graphic symbol for a diode is an arrowhead and a bar. The arrowhead indicates the conventional direction of current flow when the diode is forward biased. The p-side of the diode is the positive terminal and referred to as anode while the n-side of the diode is the negative terminal referred to as cathode.

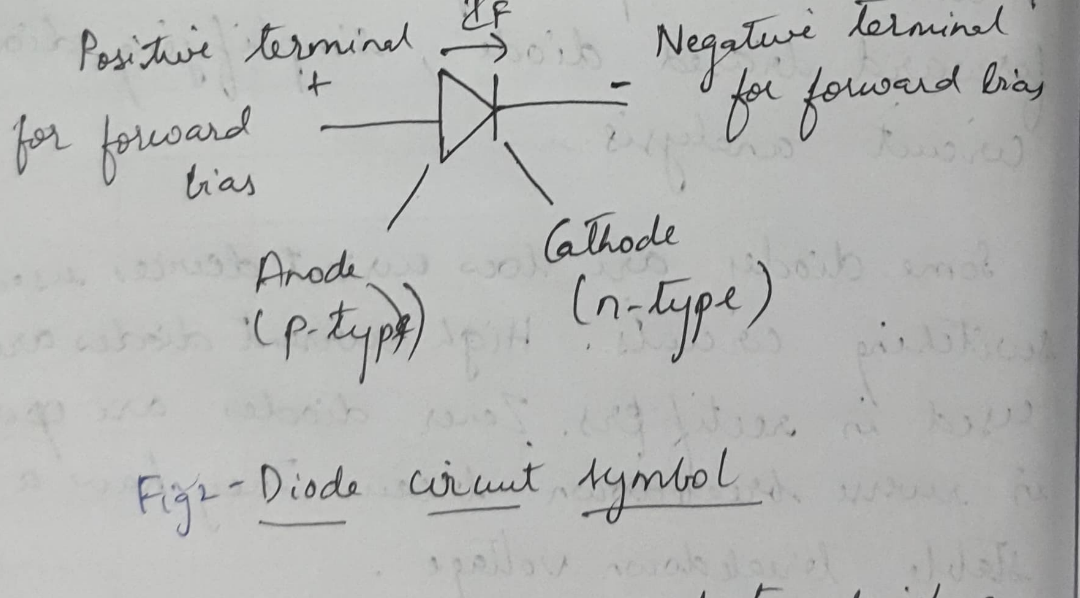


Fig 2 - Diode circuit symbol

A pn junction diode can be destroyed if a high level of forward current overheats the device or if a large reverse voltage causes the junction to breakdown.

Low current diode – Capable of passing max. forward current of approx. 100mA. Reverse voltage of 75V without breakdown. Reverse current < 1 μA at 25°C.

Medium current diode

Forward current – 400mA

Reverse bias voltage – 200V

High current diodes (or power diodes)

They generate lo of heat, hence are mechanically connected to a metal heat sink. Power diodes can pass forward currents of many amperes and several hundred volts of reverse bias.

Characteristics and parameters

Forward and reverse characteristics.

A graph of the forward current (I_F) plotted against forward voltage (V_F), is known as forward characteristics of the junction, while the plot of reverse current v/s reverse voltage is known as reverse ~~voltage~~ characteristics.

For a silicon diode, it is observed that the forward current (I_F) remains very low (less than 100 μA) until the diode forward bias voltage (V_F) exceeds approximately 0.7V. At V_F levels greater than 0.7V, I_F increases almost linearly.

In the reverse bias case, it is observed that the reverse current is much smaller than the forward current, hence plotted with expanded current scales. The reverse current (I_R) is largely a minority charge carrier reverse saturation current. For silicon diode, I_R is normally less than 100nA and is completly independent of the reverse bias voltage. Increasing the reverse bias voltage causes a small increase in the I_R due to the minority charge carriers leaking along the junction surface.

The reverse current is usually 1/10000 of the lowest normal forward current level. Hence I_R is quite negligible compared to I_F and a reverse biased diode can be treated as an open switch.

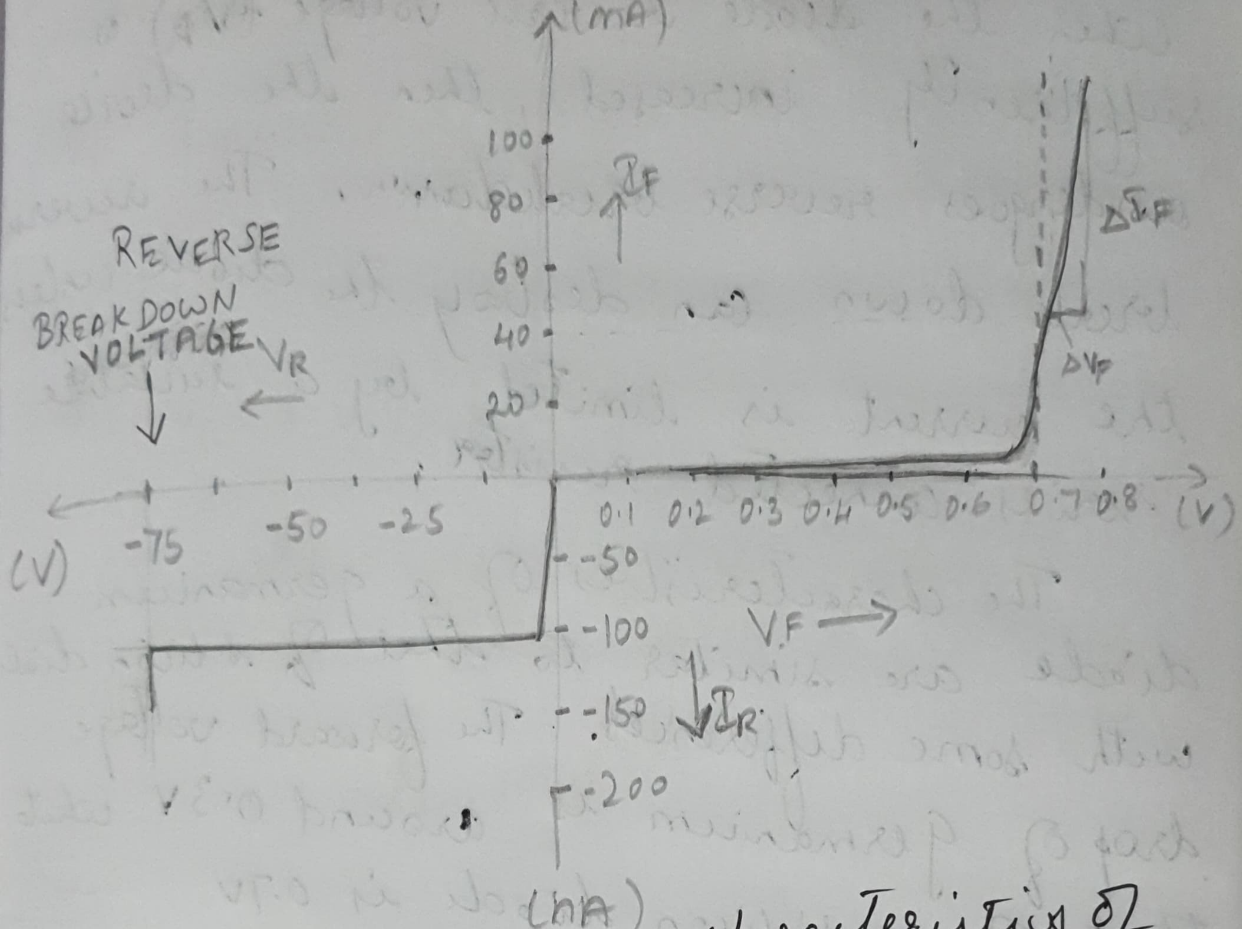


Fig3- Forward and reverse characteristics of silicon diode

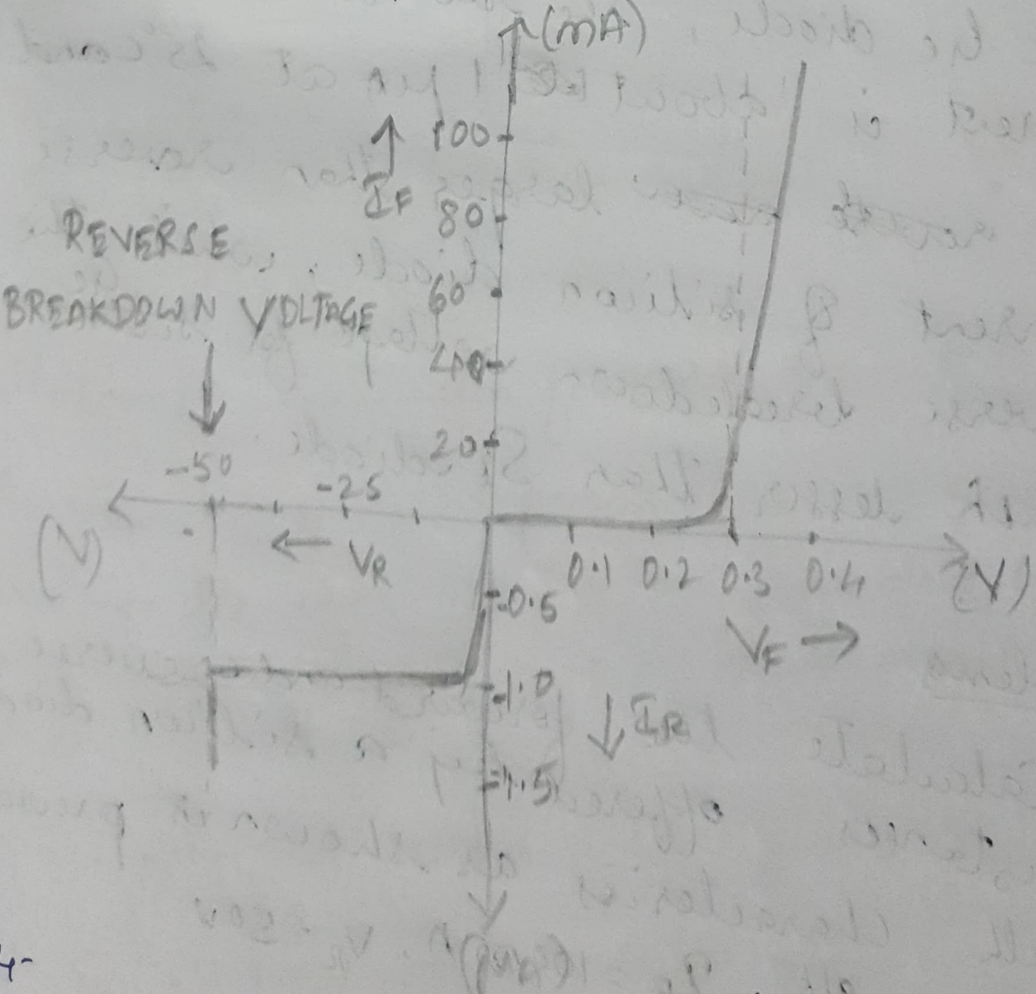


Fig4-

When the diode reverse voltage (V_R) is sufficiently increased, then the device undergoes reverse breakdown. The reverse breakdown can destroy the diode unless the current is limited by a suitable series connected resistor.

The characteristics of a germanium diode are similar to that of silicon diode with some differences. The forward voltage drop of germanium is around 0.3V while that of a silicon diode is 0.7V.

For Ge diode, the reverse saturation current is about ~~1~~ 1 μA at 25°C and is ~~The reverse~~ larger than reverse current of silicon diode, while the reverse breakdown voltage for ~~silicon~~ Ge is much lesser than Si diode.

Problems

1) Calculate the forward and reverse resistances offered by a silicon diode with characteristics as shown in previous page w.r.t. $I_F = 100mA$, $V_R = 50V$

At $I_F = 100mA$, $V_F \approx 0.75V$

Forward resistance $(R_F) = \frac{V_F}{I_F} = \frac{0.755}{100mA}$

$\therefore R_F = \underline{\underline{7.5\Omega}}$

At $V_R = 50V$, $I_F \approx 100nA$

$R_R = \frac{V_R}{I_R} = \frac{50V}{100nA} = 500M\Omega$

$\therefore R_R = \underline{\underline{100 M\Omega}}$

Diode parameters

V_F - Forward voltage drop

I_R = Reverse saturation current

r_d - dynamic resistance

$I_{F(max)}$ - maximum forward current.

The values of these parameters are generally listed on the diode data sheet provided by the manufacturer. I_F can also be determined by the diode characteristics.

The forward resistance (R_F) given by

$R_F = \frac{V_F}{I_F}$ is a static quantity and is also known as dc resistance

It is a constant resistance of the diode at a particular constant constant forward current.

The <u>dynamic resistance</u> (r_d) of the diode is the resistance offered to changing levels of forward voltage. The dynamic resistance of the diode is the resistance also known as incremental resistance or ac resistance. It is the reciprocal of the slope of the forward current characteristics beyond the knee.

$$\boxed{r_d = \frac{\Delta V_F}{\Delta I_F}} \rightarrow (1)$$

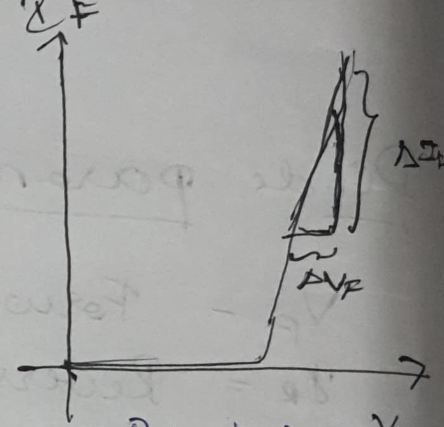


Fig 5: Dynamic resistance

$$r_d = \frac{\Delta V_F}{\Delta I_F}$$

It can also be calculated by equation,

$$r_d' = \frac{26\,mV}{I_F} \rightarrow (2)$$, where I_F = forward current

The above equation gives the value of the ac resistance only for the junction. It does not include the resistance of the semiconductor material.

Problem

Determine the dynamic resistance at a forward current of 70mA for diode characteristics in fig ① (VI characteristics of diode). Using ② estimate the diode dynamic resistance.

At $I_F = 70mA$

$\Delta I_F = 60mA$ & $\Delta V_F \approx 0.025V$

$$r_d = \frac{\Delta V_F}{\Delta I_F} = \frac{0.025}{60m} = 0.42\Omega$$

$$r_d = \frac{26mV}{I_F} = \frac{26 \times 10^{-3}}{70 \times 10^{-3}} = 0.37\Omega$$

Diode Approximations

A diode is a one way device, offering a low resistance when forward biased and a high resistance when reverse biased.

An ideal diode would have zero forward resistance and zero forward voltage drop. It also has infinitely high reverse resistance, which results in zero reverse current.

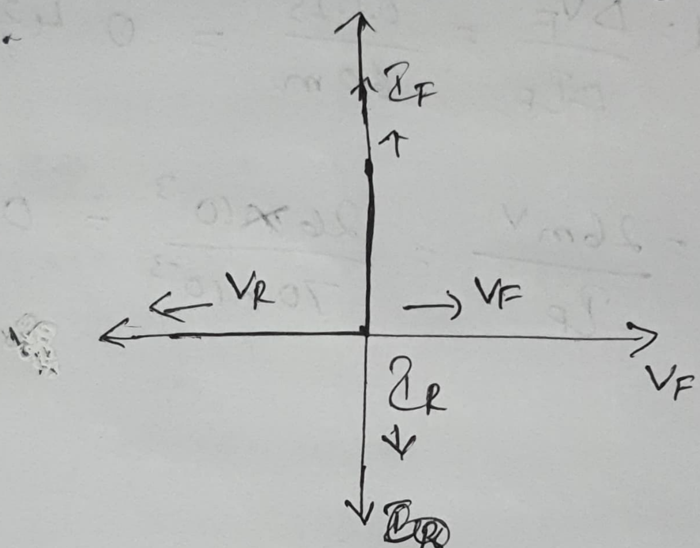


Fig 6 - Ideal diode characteristics

Ideal diodes do not exist. However, applications where diodes can be close to near ideal diode devices exist.

Eg: Circuits with supply voltages much larger than the diode forward voltage drop, can be assumed to be constant. The reverse current is normally much smaller than forward current and ~~it~~ can be ignored. These assumptions lead to near ideal or approximate characteristics for silicon & germanium diodes as shown in the figure below.

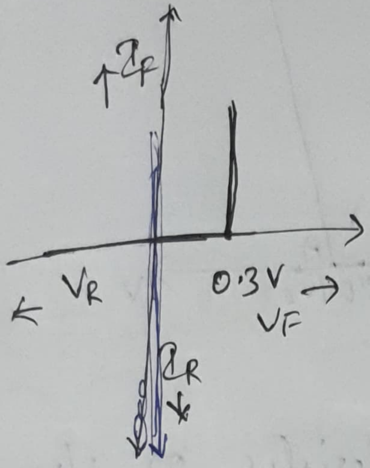


Fig 7(a)
Approximate characteristics of germanium diode.

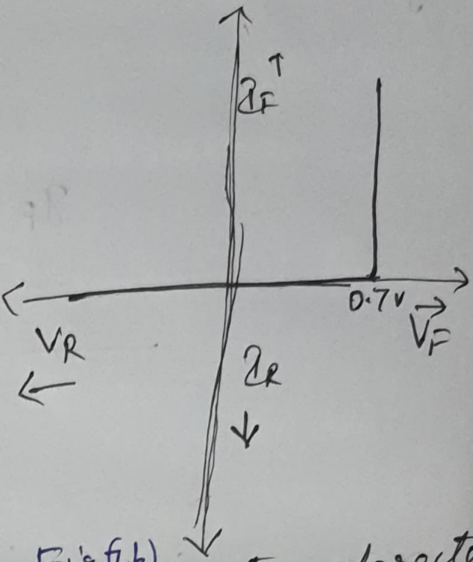


Fig 7(b)
Approximate characteristics of silicon diode

NOTE
Ideal diode has $V_F = 0$ and $I_R = 0$
Practical diodes can be considered as near ideal diode if forward voltage drop is taken into account.

Piecewise linear characteristic

A straight line approximation of the diode characteristics can be obtained if the forward characteristics of the diode is not available. This is known as piecewise linear characteristic.

To construct piecewise linear characteris

-tic, V_F is first marked on the horizontal axis. A straight line is then drawn from V_F with a slope equal to the diode dynamic resistance.

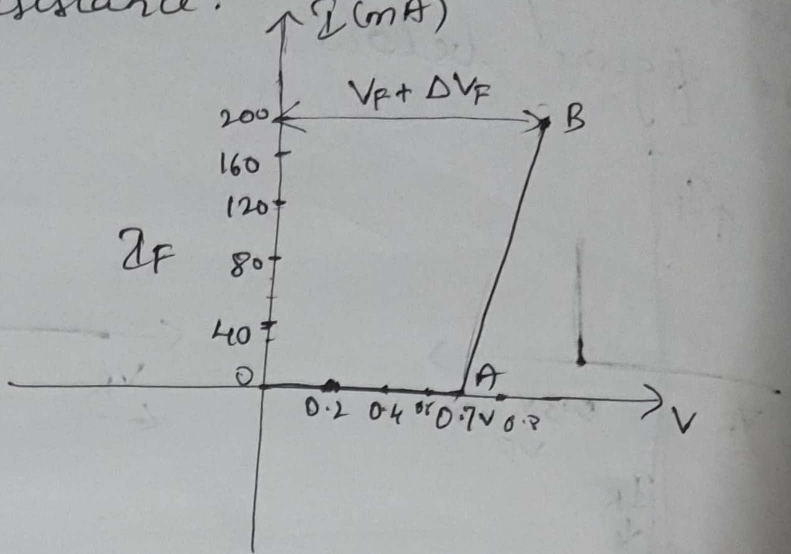


Fig 8: Diode piecewise linear characteristic or straight line approximation of diode forward characteristic

Problem

Construct the piecewise linear characteristic for a silicon diode which has 0.25Ω dynamic resistance and 200mA maximum forward current.

$V_F = 0.7V$

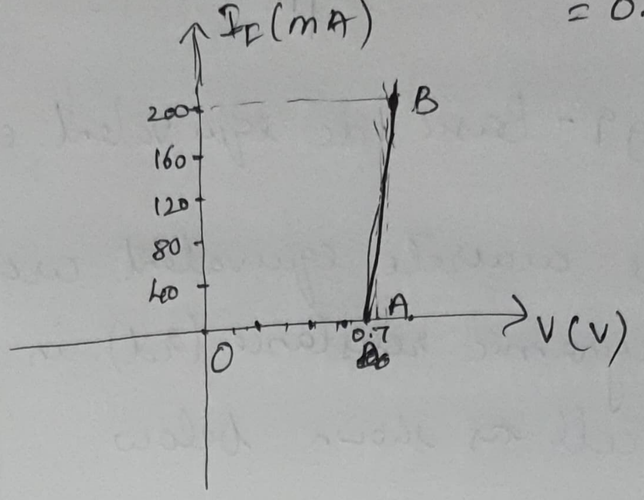
$r_d = 0.25$

$\Delta I_F = 200mA$

$\Delta V_F = \Delta I_F \times r_d = 200 \times 10^{-3} \times 0.25 = 0.05V$

Plot point A on horizontal axis at $V_F = 0.7V$.

Plot point B at $I_F = 200\,mA$ & $V_F = 0.7 + 0.05$
$= 0.75\,V$



DC Equivalent Circuits

An equivalent circuit for a device is a circuit that represent the device behaviour. Equivalent circuits is made up of number of components such as resistors and voltage cells.

A diode equivalent circuit can be substituted for the device when investigating a circuit with diode. It can also be used as device models for computer analysis.

A forward biased diode is assumed to have a constant forward voltage drop (V_F) and negligible series resistance. In this case the diode equivalent circuit is assumed to be a voltage cell with voltage V_F. This simple equivalent circuit is suitable for many diode applications.

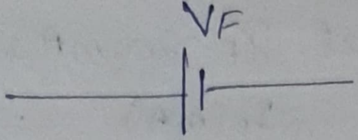


Fig 9 - Basic dc equivalent circuit

A more accurate equivalent circuit includes diode dynamic resistance (rd) in series with voltage cell as shown below.

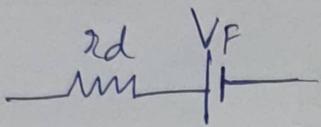


Fig 10 - Complete dc equivalent circuit.

This takes into account the small variation in V_F that occur with change in forward current.

The equivalent circuit without rd assumes the diode has approximate characteristics as in fig 7(a) & Fig 7(b).

With rd included, the equivalent circuit represents a diode with the piece wise characteristic in Fig 8. Hence the circuit is Fig 10 is known as piecewise linear equivalent circuit.

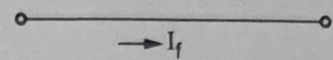
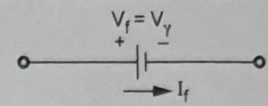
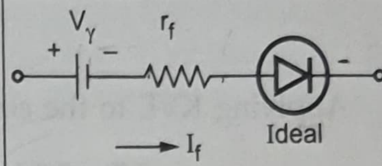
	Diode approximation	Behaviour	D.C. Equivalent circuit
1.	Ideal diode	$R_f = 0\ \Omega$ $R_r = \infty\ \Omega$ Short in forward bias.	
2.	Diode with constant forward voltage drop	The forward voltage drop is constant and it behaves as d.c. battery of voltage $V_f = V_\gamma$	
3.	Complete d.c. equivalent circuit	This assumes finite forward resistance which is its dynamic forward resistance r_f in series with battery of voltage V_γ.	 Total diode drop is, $V_f = V_\gamma + I_f r_f$

Table 2.2 D.C. Equivalent circuits of diode

Sectional Solved Examples

Example 2.4 : *Calculate the forward current through a diode having cut-in voltage of 0.7 V, connected in the circuit shown in the Fig. 2.25 if,*

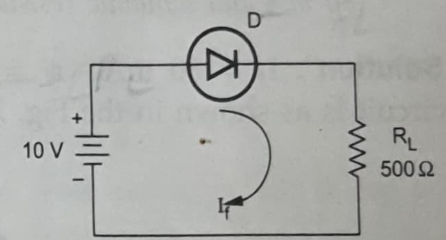


Fig. 2.25

i) r_f is neglected ii) with $r_f = 3.2\ \Omega$

Solution : i) When r_f is neglected, the diode behaves as battery of constant voltage $V_f = V_\gamma = 0.7$ V as shown in the Fig. 2.25 (a).

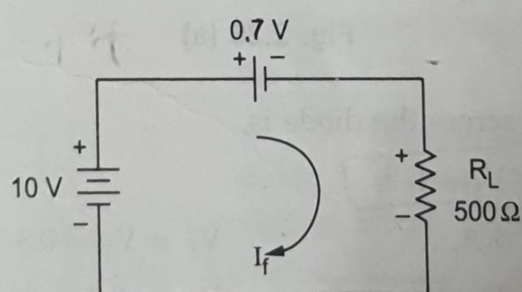


Fig. 2.25 (a)

Applying KVL to the circuit,

$$-0.7 - I_f \times R_L + 10 = 0$$

$$\therefore \quad I_f = \frac{10 - 0.7}{500} = \mathbf{18.6\ mA}$$

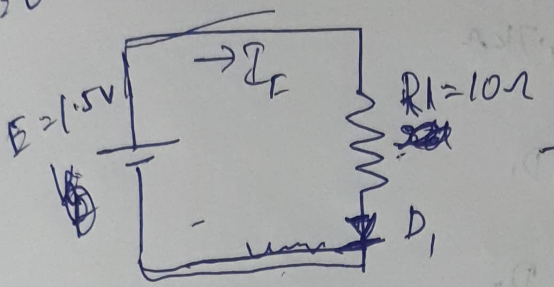
ii) When $r_f = 3.2\ \Omega$, the diode is to be replaced by complete d.c. equivalent circuit as shown in the Fig. 2.25 (b).

Problems

Calculate I_F for the diode circuit shown below assuming diode has $V_F = 0.7V$ and

i) $r_d = 0$

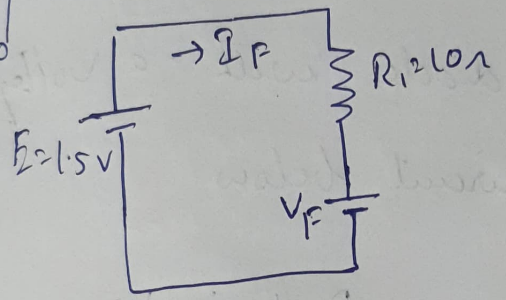
ii) $r_d = 0.25\Omega$.



– Diode circuit

Replacing diode with eq. circuit

i) $r_d = 0$

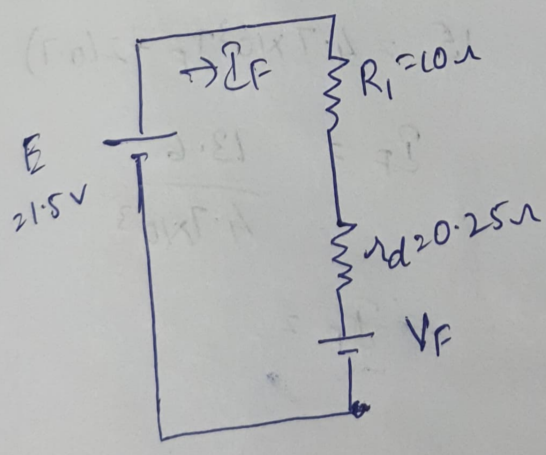


$$E = I_F R_1 + V_F$$

$$I_F = \frac{E - V_F}{R_1} = \frac{1.5 - 0.7}{10}$$

$$\therefore I_F = 80\,mA$$

ii) $r_d = 0.25\Omega$



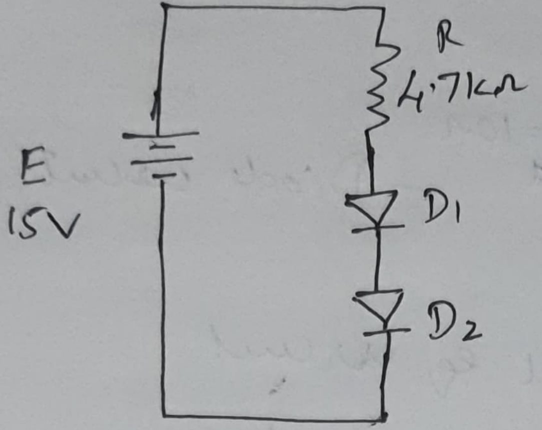
$$E = I_F(R_1 + r_d) + V_F$$

$$I_F = \frac{E - V_F}{R_1 + r_d}$$

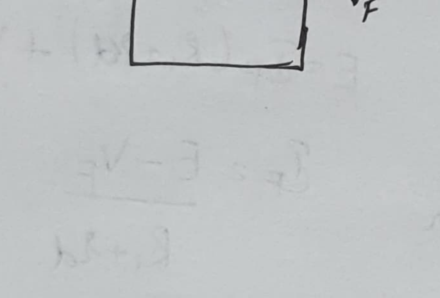
$$I_F = \frac{1.5 - 0.7}{10 + 0.025}$$

$$\therefore I_F = 78\,mA$$

2) Calculate the diode current in the circuit with two series connected diodes



Replacing the diode with a voltage all results in the circuit below.



Applying KVL,

$$E = (4.7 \times 10^3) I_F + 2V_F$$

$$15 = 4.7 \times 10^3 I_F + 2(0.7)$$

$$I_F = \frac{13.6}{4.7 \times 10^3}$$

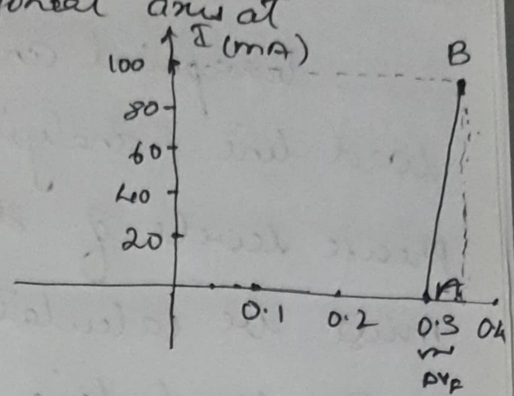
$\therefore I_F =$ 2

2) A germanium diode has a maximum forward current of 100mA and a 0.5Ω dynamic resistance. Construct piece wise linear characteristic for

the diode.

Plot point A on the horizontal axis at

$V_F = 0.3V$



$\Delta V_F = \Delta I_F \times r_d$

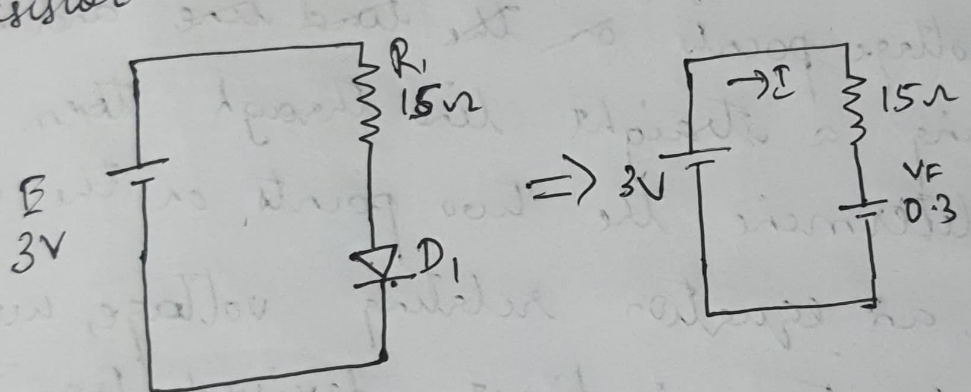
$= 100 \times 10^{-3} \times 0.5$

$= 0.05\,V$

Plot B at $I_F = 100\,mA$, $V_F = 0.3 + 0.05$

$= 0.35\,V$

3) Calculate the circuit current when the diode is forward biased in series with a 15Ω resistor and a 3V battery



Eqn: $3 = I(15) + 0.3$

$15I = 2.7$

$\therefore I = \frac{2.7}{15} = 0.18$

1.8×10

180×10^{-3}

$I = 0.18\,A$

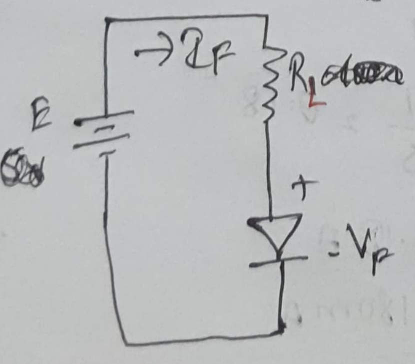
$I = 180\,mA$

DC load line analysis

Graphical analysis also known as dc load line analysis and is used when precise levels of diode current and voltage must be calculated.

DC load line is a straight line drawn on the forward characteristics which illustrates all the dc conditions that could exist within the circuit.

Since it is a straight line it can be constructed by plotting corresponding current and voltage points on the load line and then drawing a straight line through them. To determine the two points on the load line, an equation relating voltage, current and resistance is first derived from the circuit.



$$E = I_F R_L + V_F \rightarrow (1)$$

At $I_F = 0$

$E = V_F$.

Plot point A on the horizontal axis at (5, 0).

At $V_F = 0$, $E = I_F R_1 \Rightarrow I_F = E/R_1$

Plot B on the vertical axis (I_F) at $(0, E/R_1)$.

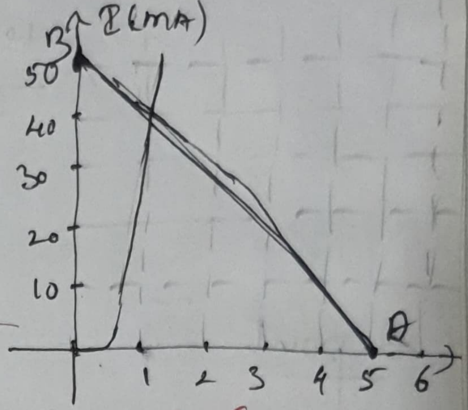
Join the two points to get the load line.

$E = I_F R_L + V_F$

÷ by R_L on both sides

* Any two convinient levels of I_F can be substituted to calculate corresponding V_F levels ~~and~~ or vice versa.

It is convinient to ~~calculate~~ determine the points by calculating I_F when $V_F = 0$ and calculating V_F when $I_F = 0$.

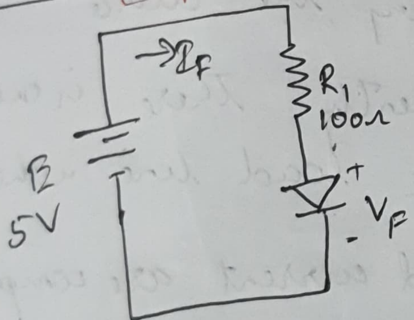


At a point current required to drive the load = current supplied by the device.

* $\frac{E}{R_L} = I_F + \frac{V_F}{R_L} \Rightarrow I_F = \frac{-V_F}{R_L} + \frac{E}{R_L}$

Comparing with eqn. of straight line, $y = mx + c$ ($y = I_F$, $x = V_F$) we get $m = -1/R_L$ which is the slope of the dc load line. It is so called since its slope ($= E/R_L$) is the reciprocal of the load resistance.

Problems



$E = I_F R_1 + V_F \rightarrow (1)$

Put $I_F = 0$ (to get point on x-axis)

$E = V_F = 5V$

Given characteristics

Plot point A on the diode characteristics at $I_F = 0$ and $V_F = 5V$

Put $V_F = 0$ (to get point in y axis)

$E = I_F R_1 + V_F$

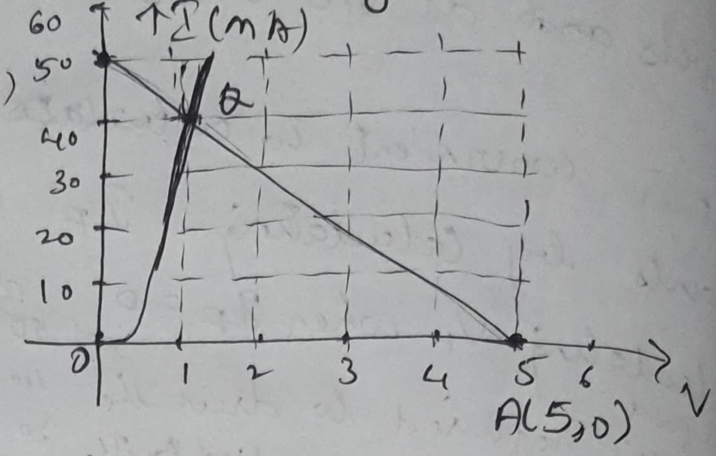
$5 = I_F R_1 + 0$

$\therefore I_F = \frac{5}{100} = 0.05 = 50mA$

Plot point B on the diode characteristic at

$I_F = 50 mA, V_F = 0 V$

Draw the DC load line through points A & B



Q point

The relationship between the diode forward voltage and current in the circuit is defined by the device characteristic. Consequently there is only one point on the dc load line where the diode voltage and current are compatible with the circuit conditions. This point is referred as the quiescent point or dc bias point ~~refer~~ labelled as Q point, where the load line intersects the characteristics.

It may be checked by substituting values of I_F & V_F at the Q point in the circuit equation.

At the Q point it is observed that,

$I_F = 40mA$ and $V_F = 1V$.

Substituting this in the circuit equation,

$$E = I_F R_1 + V_F \rightarrow (1)$$, we get

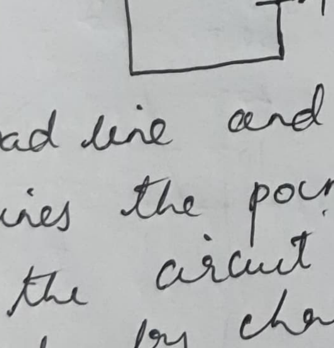
$$E = (40\times10^{-3})(100)+(1)$$

$$E = 5V$$

Thus, with $E = 5V$, $R_1 = 100\Omega$, The only values of V_F and I_F that can satisfy the eqn (1) is $I_F = 40mA$ and $V_F = 1V$.

Q point of quiescent point is the specific point in the diode where it operates at its most stable condition

Calculating load resistance and supply voltage



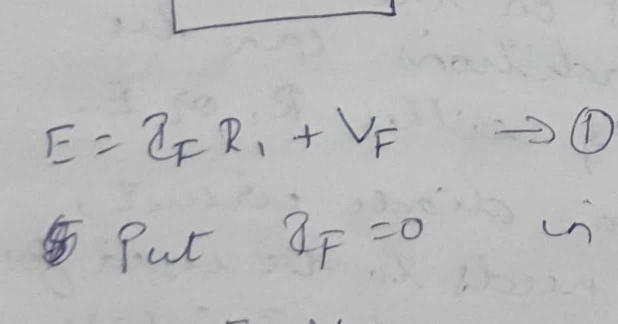
In a diode series circuit shown in the figure, the resistor R_1 dictates the slope of the dc load line and the supply voltage E determines the point A on the load line. Hence the circuit conditions can be altered by changing either R_1 or E.

(ii) When designing a diode circuit, a supply voltage needs to be used for a given forward current. In this case, a specific points A and Q are first plotted and the load line is drawn. Resistor R_1 is calculated from the slope of the load line.

(ii) Another use of dc load line is to determine the supply voltage, given R_1 and the required I_F. In this case the Q point is obtained by drawing a load line with slope $1/R_1$. The supply voltage is then obtained from point A.

Problems

1) Using the device characteristics given in the figure below, determine the required load resistance in the circuit for $I_F = 30mA$.



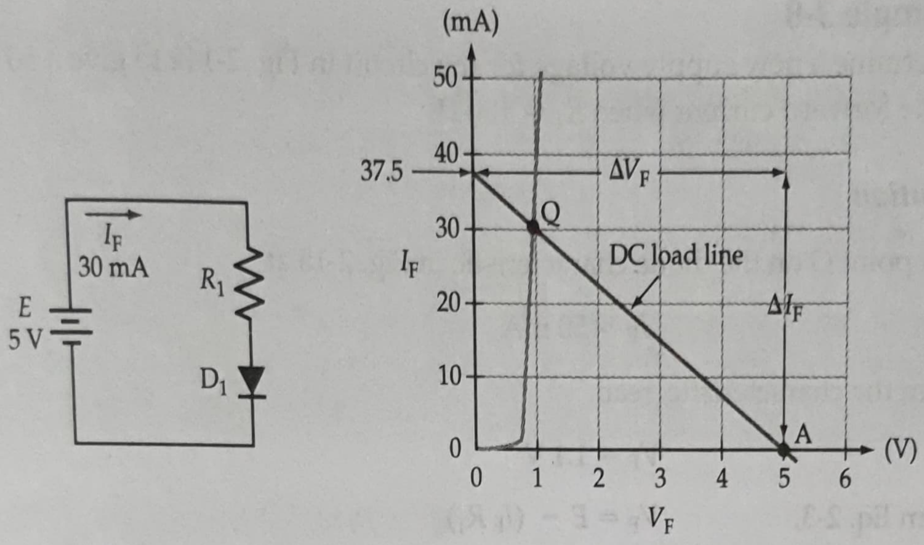
$E = I_F R_1 + V_F \rightarrow (1)$

Put $I_F = 0$ in (1)

$E = V_F$

$\therefore V_F = 5V$

Plot A at $I_F = 0$, $V_F = 5$ on the characteristic



(a) Diode-resistor circuit

(b) Resistor determination

Figure 2-14 Determination of the required circuit series resistance R_1 from the slope of the dc load line.

determined. This problem is solved by plotting point Q and drawing the load line with slope $1/R_1$. The supply voltage is then read at point A.

Example 2-7

Using the device characteristics in Fig. 2-14b, determine the required load resistance for the circuit in Fig. 2-14a to give $I_F = 30$ mA.

Solution

From Eq. 2-3, $$V_F = E - (I_F R_1)$$

Substituting $I_F = 0$, $$V_F = E - 0 = 5\text{ V}$$

Plot point A on the diode characteristic in Fig. 2-14b at

$$I_F = 0 \text{ and } V_F = 5\text{ V}$$

Now plot point Q in Fig. 2-14b at

$$I_F = 30\text{ mA}$$

Draw the dc load line through points A and Q. From the load line,

$$R_1 = \frac{\Delta V_F}{\Delta I_F} = \frac{5\text{ V}}{37.5\text{ mA}}$$

$$= 133\ \Omega$$

Example 2-8

Determine a new supply voltage for the circuit in Fig. 2-14a to give a 50 mA diode forward current when $R_1 = 100\ \Omega$.

Solution

Plot point Q on the diode characteristic in Fig. 2-15 at

$$I_F = 50\text{ mA}$$

From the characteristic, read

$$V_F = 1.1\text{ V}$$

From Eq. 2-3, $\quad V_F = E - (I_F R_1)$

When I_F changes from 50 mA to 0,

$$\Delta I_F = 50\text{ mA} \qquad \text{(see Fig. 2-15)}$$

and

$$\Delta V_F = I_F R_1 = 50\text{ mA} \times 100\ \Omega \qquad \text{(see Fig. 2-15)}$$
$$= 5\text{ V}$$

The new supply voltage is

$$E = V_F + \Delta V_F = 1.1\text{ V} + 5\text{ V}$$
$$= 6.1\text{ V}$$

Point A may now be plotted (on Fig. 2-15) at $I_F = 0$ and $E = 6.1$ V, and the new dc load line may be drawn through points A and Q.

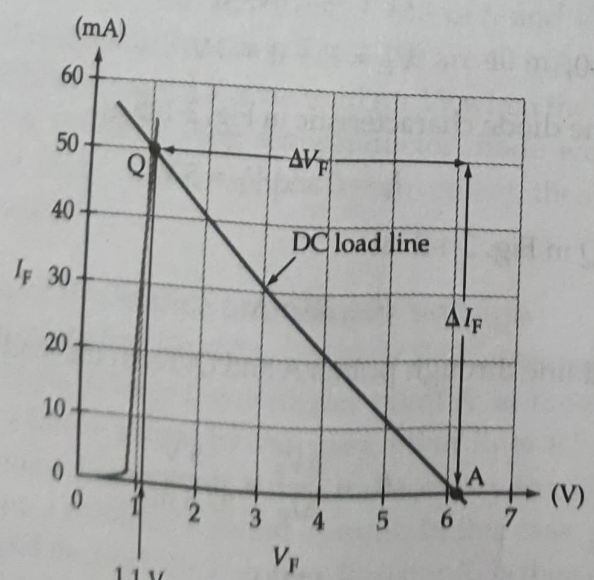
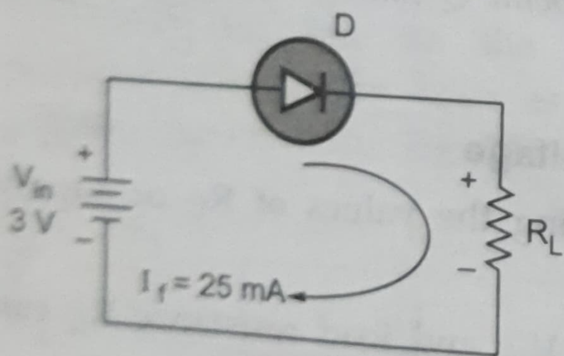
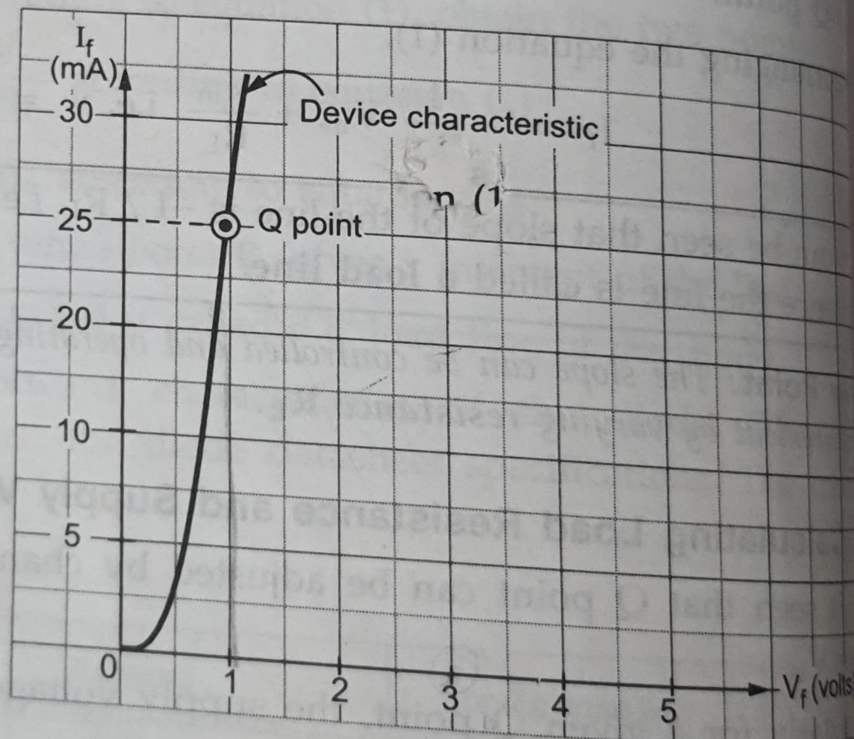


Figure 2-15 Determination of the required supply voltage for a diode-resistor circuit with a given resistor and a specified load current.

Example 2.6 : *The Fig. 2.29 (a) shows the diode circuit while the Fig. 2.29 (b) the forward characteristics of the diode D. Find the load resistance R_L for the conditions.*



(a) Circuit



(b) Device characteristics

Fig. 2.29

Solution : The equation of d.c. load line is,

$$V_f = V_{in} - I_f R_L$$

Now for Q point $I_f = 25$ mA given i.e. $I_Q = 25$ mA

While for $I_f = 0$, $V_f = V_{in} = 3$ V is point B

So draw the d.c. load line through Q point and point B. Obtain the slope of d.c. load line.

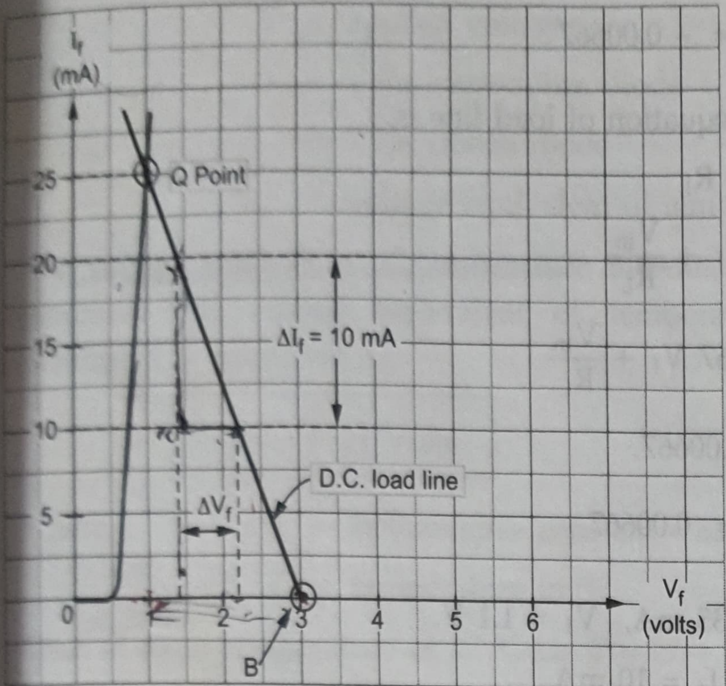


Fig. 2.29 (c)

$$\text{Slope} = \frac{\Delta I_f}{\Delta V_f}$$

For ΔI_f = 10 mA, from the graph ΔV_f = 0.9 V.

$$\therefore \text{Slope} = \frac{10 \times 10^{-3}}{0.9}$$

$$= 0.0111$$

$\therefore R_L$ = Load resistance

$$= \frac{1}{\text{slope}} = \frac{1}{0.0111}$$

$\therefore R_L = 90\ \Omega$

... Required load resistance.

Example 2.7 : *If now in the cicuit above, R_L is changed to 150 Ω, find the new supply voltage with I_f = 35 mA.*

Solution : R_L = 150 Ω , Q point is with I_f = 35 mA = I_Q.

Draw the new d.c. load line with slope as $-1/R_L$.

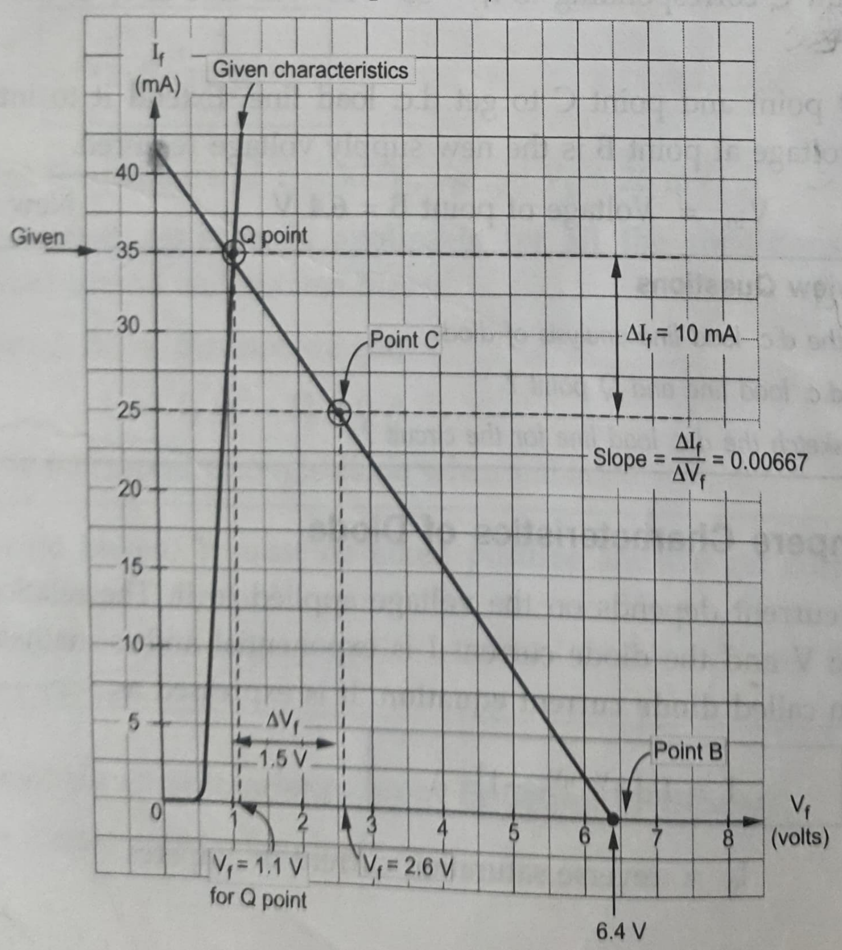


Fig. 2.30

$$\therefore \quad \text{slope} = -\frac{1}{150} = -0.00667$$

It passes through Q point, so equation of load line is,

$$V_f = V_{in} - I_f R_L$$

i.e.
$$I_f = -\frac{1}{R_L} V_f + \frac{V_{in}}{R_L}$$

i.e.
$$I_f = -0.00667 V_f + \frac{V_{in}}{R_L}$$

To sketch the line of slope – 0.00667,

$$|\text{slope}| = \frac{\Delta I_f}{\Delta V_f} = 0.00667$$

Now from the graph, for $I_f = 35$ mA, $V_f = 1.1$ V.

Let I_f changes by 10 mA i.e. $\Delta I_f = 10$ mA.

$$\therefore \quad 0.00667 = \frac{10 \text{ mA}}{\Delta V_f}$$

$$\therefore \quad \Delta V_f = \frac{10 \times 10^{-3}}{0.00667} = 1.5 \text{ V}$$

So from $V_f = 1.1$ V, obtain new V_f with $\Delta V_f = 1.5$ V.

This is point C corresponding to $I_f = 35 - 10 = 25$ mA as I_f is changed by 10 m and $V_f = 2.6$ V.

Join the Q point and point C to get d.c. load line. Extend it to intersect x-axis a point B. The voltage at point B is the new supply voltage required.

$$\therefore \quad V_{in} = \text{Voltage of point B} = \mathbf{6.4\ V}$$

... New supply voltage

Sectional Review Questions

1. *Explain the d.c. load line analysis of diode.*
2. *What is d.c. load line and Q point ?*
3. *How to sketch the d.c. load line for the circuit ?*

2.10 Volt-Ampere Characteristics of Diode

The diode current depends on the voltage applied to it. The relationship between applied voltage V and the diode current I is exponential and is mathematically given by the equation called **diode current equation.** It is expressed as,

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

Diode applications

One of the important applications of diode is rectification which is the process of converting a sinusoidal ac waveform to a dc waveform (a single polarity half cycle).

~~The are two type~~

A dc power supply converts a sinusoidal ac supply to dc by rectification and filtering.

Filtering process involves the use of large reservoir capacitor, which charges to the peak input voltage to produce the dc output.

- The capacitor partially ~~disposes~~ discharges between the peaks of the rectified waveform.
- Hence the o/p contains ripples and appear at the output.

a ripple voltage.

- The ripples can be reduced further by using RC (π filter) or LC filters.
- There are two types of rectifiers:
  i) Half wave rectifier (ii) Full wave rectifier.

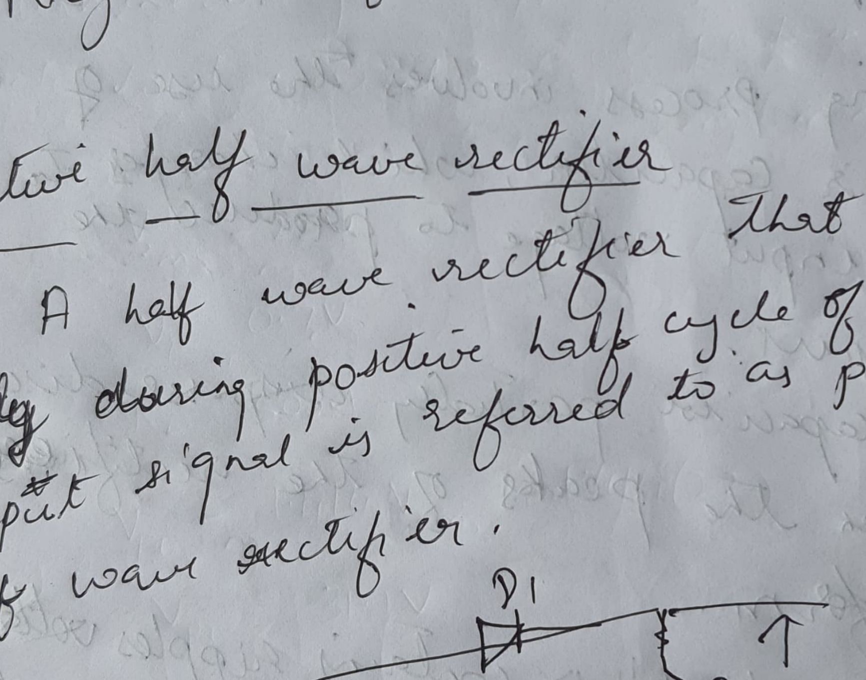
Half wave rectifier

A rectifier circuit that conducts during only for one half of the input cycle is referred to as half wave rectifier. There are two types of half wave rectifier:

i) Positive half wave rectifier
ii) Negative half wave rectifier

Positive half wave rectifier

A half wave rectifier that conducts only during positive half cycle of the input signal is referred to as positive half wave rectifier.



- An alternating i/p voltage is applied to a single diode via ~~series with~~ a transformer (T1).
- A transformer is normally ~~necessary~~ used to dc isolate the rectifier circuit from the ac supply.
- The diode is forward biased during the positive half cycles and reverse biased during the negative half cycles.
- Hence during positive half cycles of the input substantial current flows through R_L.
- For the negative half cycles the diode behaves almost as a open switch.
- The o/p voltage developed across R_L is thus a series of positive half cycles of alternating voltage with intervening very small negative voltages produced by diode reverse saturation current.

$V_{po} = V_{pi} - V_F$ — When diode is FB, the voltage drop across the diode is V_F and o/p voltage ~~($V_{rms} = \frac{V_m}{\sqrt{2}}$)~~ is given by,

$V_{pi} = 1.414 V_i$

where V_i = rms i/p voltage

$$I_p = \frac{V_{po}}{R_L},$$

I_p - Diode peak forward current, R_L - Load resistance

- During -ve half cycle, diode is reverse biased, very small current flows as the diode offers very high resistance and the o/p voltage is given by,

$V_o = -I_R R_L$

- When diode is reverse biased, the peak voltage of the negative half cycle of the i/p is applied to the i/p terminals. This is referred to as the peak inverse voltage and is given by

$V_R = PIV = V_{pi}$

The average and rms values of the o/p voltage are given by,

$$V_{o(ave)} = \frac{V_{po}}{\pi} = 0.318 V_{po}$$

$$V_{o(rms)} = 0.5 V_{po} \quad \left(\frac{V_{po}}{2}\right)$$

A reservoir capacitor is generally used at the o/p terminals to smooth the rectified voltage to direct voltage.

1) A diode with $V_F = 0.7V$ is connected to a half wave rectifier. The load resistance is 500Ω and rms i/p is 22V.

Determine the peak o/p voltage, the peak load current & diode peak inverse voltage.

$V_{rms} = 22V$

$V_F = 0.7V$

$R_L = 500\Omega$.

$V_{pi} = 1.414 V_{rms} = 1.414(22)$

$V_{pi} = 31.1V$

$V_{po} = V_{pi} - V_F = 31.1 - 0.7$

$= 30.4$

$I_p = \frac{V_{po}}{R_L} = \frac{30.4}{500}$

$= 60.8mA$

$PIV = V_{pi} = 31.1V$.

3.1.1) A HW rectifier has 15V ac i/p, 330Ω R_L. Calculate the peak o/p ~~voltage~~ voltage, peak load current and diode maximum reverse voltage.

$V_i = 15V$

$R_L = 330\Omega$

$V_{po} = ?$

$I_p = ?$

$PIV = ?$

$$I_p = \frac{V_{po}}{R_L} = \frac{13.6}{330} =$$

$$PIV = V_R = V_{pi} =$$

$$V_{pi} = V_i - V_F$$
$$= 15 - 0.7 = 14.3V$$

$$V_{po} = V_{pi} - V_F = 14.3 - 0.7 = 13.6V$$

3.1.2) A HW rectifier ~~that~~ produces 40mA peak load current through 1.2kΩ resistor. If diode is silicon, calculate the rms i/p voltage and diode PIV.

$I_p = 40mA$

$R_L = 1.2k\Omega$

$V_F = 0.7V$

$V_i = ?$

$PIV = ?$

$$I_p = \frac{V_{po}}{R_L}$$

$$\therefore V_{po} =$$

$V_{po} = V_{pi} - V_F$

V_{pi}

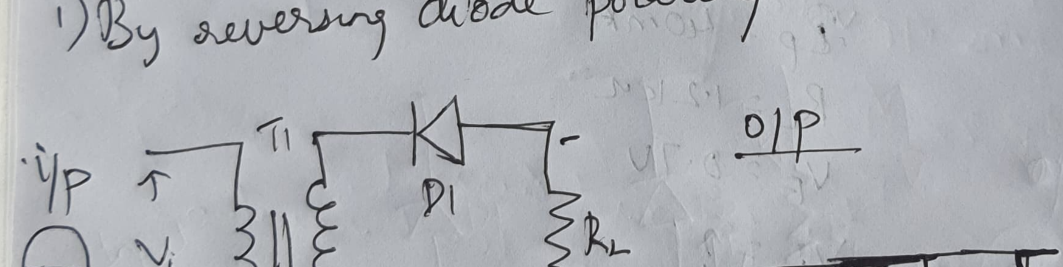
$V_{pi} = 1.414 V_i$

Negative half wave rectifier

- It is a half wave rectifier in which negative half cycle of the ac input signal is passed to the load resistance.
- There are two ways by which negative half wave rectifier can be implemented.

i) By reversing diode polarity
ii) By grounding the positive o/p terminals

i) By reversing diode polarity



- The diode D1 conducts only during negative half cycles of the i/p signals while it is reverse biased during the positive half cycles.

Full wave rectification

Full wave rectification is the process of converting ac to dc by using a full wave rectifier.

- A full wave rectifier is a rectifier circuit that conducts during both the half cycles of the input signal.
- There are two types of full wave rectifiers based on the number of diodes used in the circuit.
  i) Two diode full wave rectifier
  ii) Bridge rectifier.

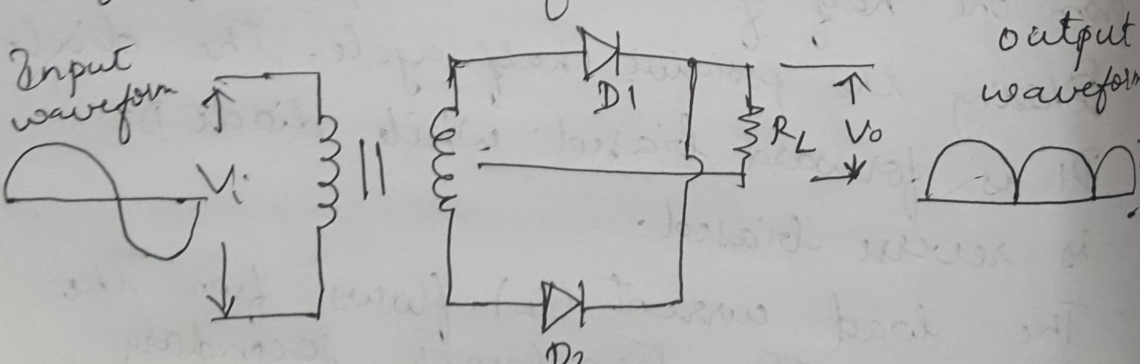
Two diode full wave rectifier

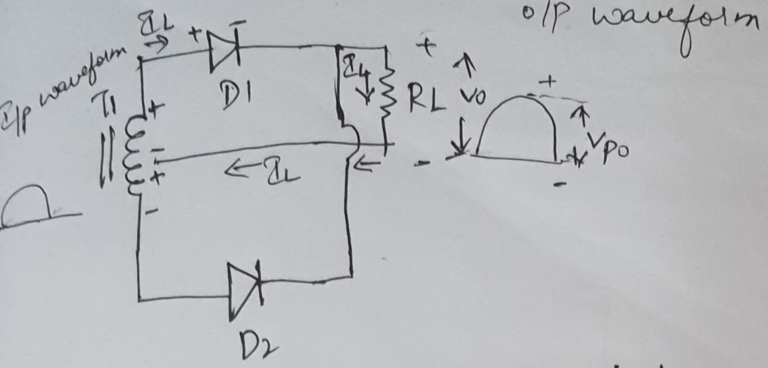
- It is a full wave rectifier that uses two diodes.
- The input is applied from a transformer with centre tapped secondary winding.
- The circuit is a combination of two half wave rectifier circuits with each supplied from one half of the secondary transformer.
- During the positive half cycle, the diode D1 is forward biased while diode D2 is reverse biased.
- The load current (I_L) flows from the top of the transformer secondary

through D1, through R_L from top to bottom and then back to the transformer centre tap.

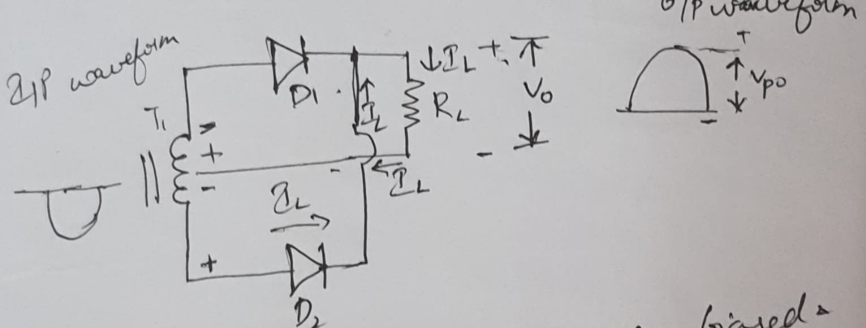
- During negative half cycle of the transformer output, the polarity of the transformer secondary voltage causes D_1 to be reverse biased and D2 to be forward biased.
- The load current i_L flows from the bottom terminal of the transformer secondary through diode D2. The direction of the diode-current is as shown in the figure
- The output waveform is thus a combination of two half cycles ie a continuous series of positive half cycles of the sinusoidal waveform.

Hence it is referred to as positive full wave rectification



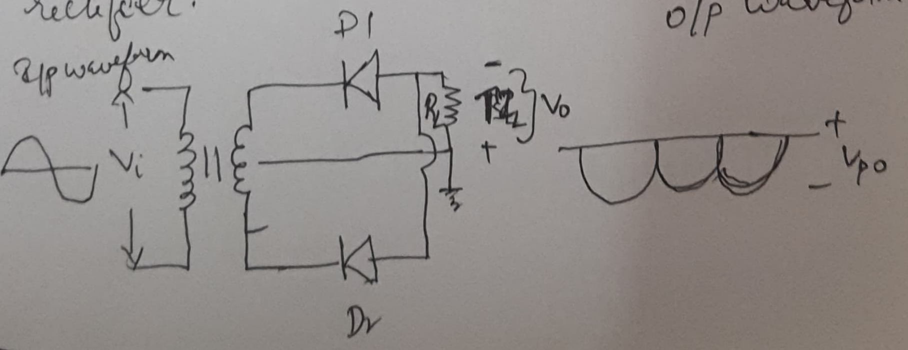


During +ve half cycle, D1 is forward biased
D2 is reverse biased

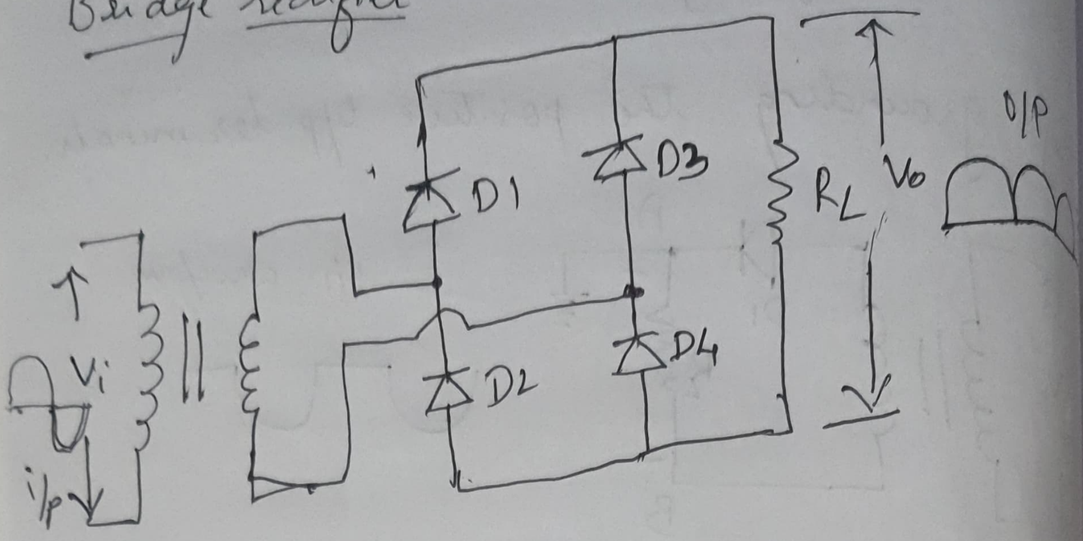


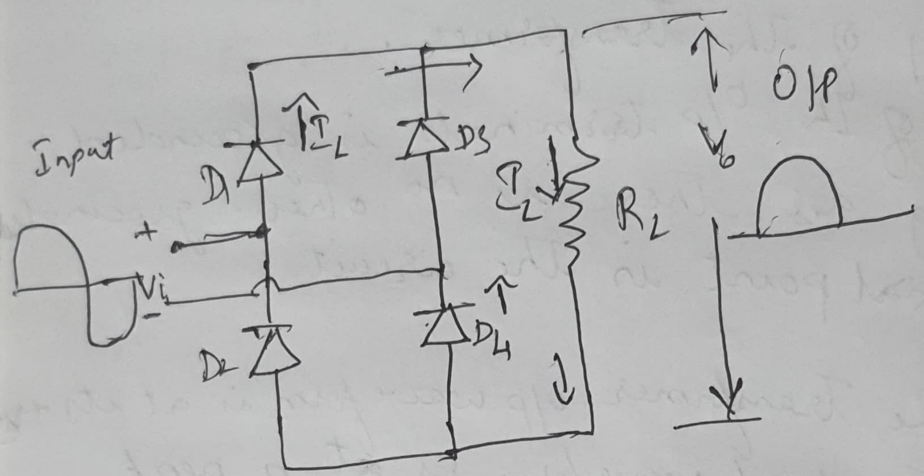
During negative half cycle, D1 reverse biased.
D2 forward biased.

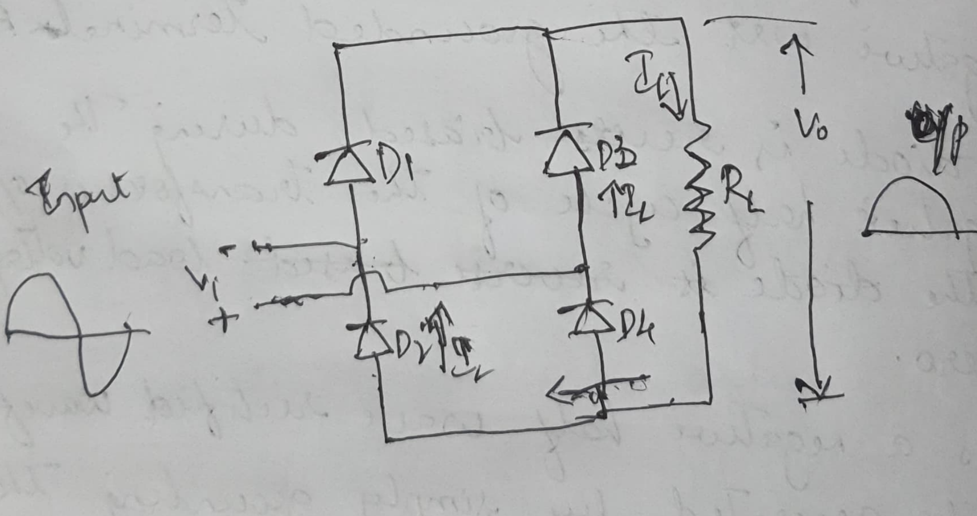
If the polarity of the diodes are reversed, then the output waveform is a series of sinusoidal negative half cycles. This is known as negative ~~half~~ full wave rectifier.



Bridge rectifier







$V_{po} = V_{pi} - 2V_F$

$V_o(ave) = 0.637\, V_{po}$

$V_o(rms) = 0.707\, V_{po}$

1) Determine the peak o/p voltage & current for the bridge rectifier circuit with $V_i = 30V$, $R_L = 300\Omega$ and diodes with $V_F = 0.7V$

$V_{pi} = 1.414\, V_i$

$= 42.42V$

$V_{po} = V_{pi} - 2V_F$

$= 41V$

$I_p = \frac{V_{po}}{R_L} = 137mA$

2) Determine the peak load voltage, peak current & power dissipation in a 470Ω resistor load connected to a bridge rectifier that has 24V ac i/p. Diodes are Germanium

$R_L = 470\,\Omega$

$V_i = 24\,V$

$V_F = 0.3\,V$

$V_{po} = ?$

$I_p = ?$

$P_L = ?$

$V_{pi} = 1.414\, V_i$

$= 1.414(24)$

$=$

$V_{po} = V_{pi} - V_F$

$=$

$$I_p = \frac{V_{po}}{R_L}$$

$\therefore I_p =$

Power dissipated in load $= I_p V_{po}$

Zener diode

Junction breakdown

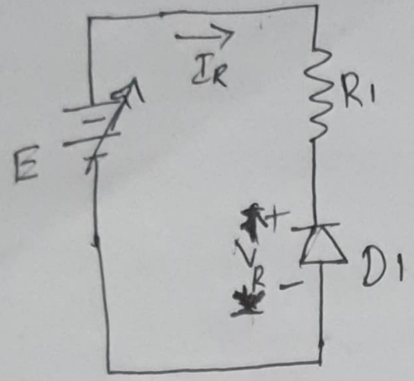
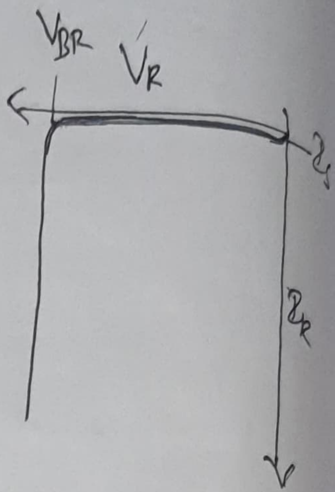


Fig ①.

Diode resistor circuit



Diode reverse characteristics

When a junction diode is reverse biased, there is a very small reverse saturation current, I_s.

- If the reverse voltage is sufficiently increased, the junction breaksdown and a large reverse current flows.

- If the reverse current is limited by a suitable series connected resistor, R1 as shown in fig ①, the power dissipation in the diode can be kept to a level that will not destroy the device.

- The diode can be operated continuously in the reverse breakdown voltage in this case.

- Diodes that are designed for operation in the reverse breakdown have breakdown voltage that remains extremely stable over a wide range of current levels. Such diodes are known as breakdown diodes

- Breakdown diodes are widely used as voltage reference source.

- There are two mechanisms that cause breakdown in reverse biased pn junction.

- (i) A pn junction with narrow depletion (obtained by high doping) results in a very high electric field when a reverse bias voltage is applied.

- The high intensity electric field causes the electrons to breakaway from their atoms, thus converting the depletion region from an insulating material to a conductor.

- This corresponds to ionization by electric field and is also referred to as Zener breakdown.

- The zener breakdown in this case usually occurs when the reverse bias voltage is less than 5V.

- Break down can also occur when sufficient energy is applied to the electrons

- This can be done when depletion region is too wide for junction breakdown.

- When the electrons are given sufficient energy the electrons strike other atoms in the depletion region, then their electrons break free. This is referred to as ionization by collision.

- The electrons released in this way collide with other atoms to produce more free electrons in an avalanche effect. This is known as avalanche breakdown.

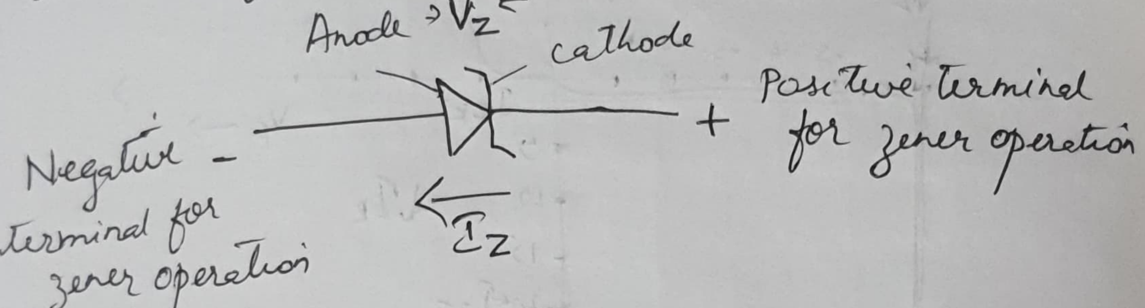
- Avalanche breakdown is generally produced by reverse voltage levels above 5V.

- Although there are two different types of breakdown, zener and avalance breakdown, the name zener diodes is generally used for all breakdown diodes.

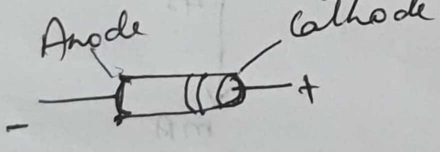
Circuit symbol for zener diode.

The circuit symbol for zener diode is the same as that for an ordinary diode but with the cathode bar approx. in the shape of letter 'Z'.

The arrowhead on the symbol points in the conventional direction of forward current when the diode is forward biased.



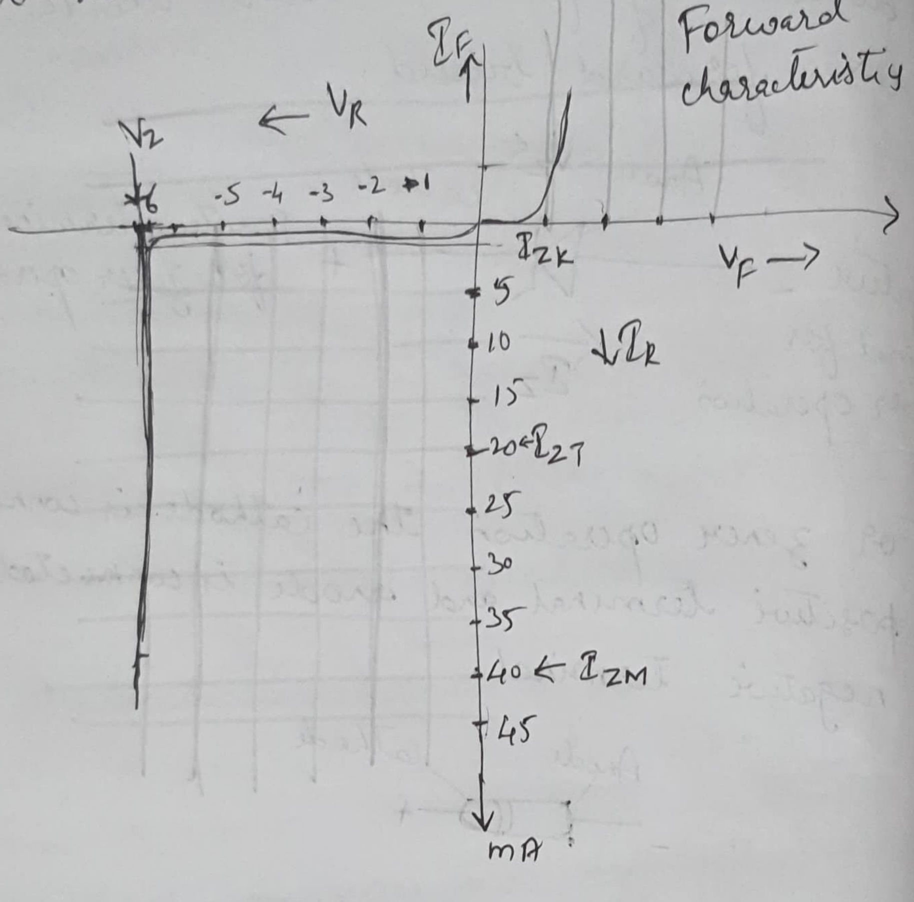
- For zener operation the cathode is connected to positive terminal and anode is connected to negative terminal.



Low power zener diodes

Characteristics & parameters

The typical characteristics of a zener diode is as shown in the figure below. The forward characteristics is similar to that of an ordinary diode that is forward biased.



Typical characteristics of zener diode

V_Z - Zener break down voltage

I_{ZT} - Test current for measuring V_Z

I_{ZK} - Reverse current near the knee of the characteristic, the minimum reverse current to sustain breakdown.

I_{ZM} - Maximum Zener current, limited by maximum power dissipation.

Z_Z - dynamic impedance

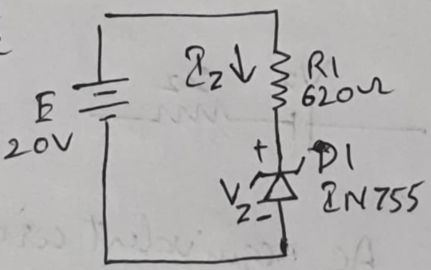
$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

$$P_D = V_Z I_{ZM}$$

Problems

1) For the zener diode 1N755 in the circuit, E=20V, R1=620Ω. Calculate the diode current and power dissipation.

From the data sheet, $V_Z = 7.5V$



$$V_{R1} = E - V_Z$$
$$= 20 - 7.5$$
$$= 12.5V$$

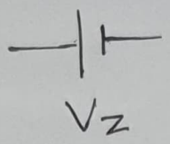
$$I_Z = I_{R1} = \frac{V_{R1}}{R1} = \frac{12.5}{620}$$

$$I_Z = 20.16mA$$

$$P_D = V_Z I_Z$$
$$= 7.5 \times 20.16 \times 10^{-3}$$
$$P_D = 151mW$$

Equivalent circuit

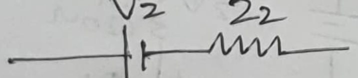
The dc equivalent circuit for a zener diode is a voltage cell with voltage V_Z.



dc equivalent circuit

This is the equivalent circuit for dc calculations.

For ac equivalent circuit, dynamic resistance is included in series with the voltage source. AC equivalent circuit is used when the zener current is varied in small amounts.



AC equivalent circuit

These equivalent circuits ~~must~~ is applicable when the Zener diode is ~~varied~~ maintained in reverse breakdown.

If the diode is forward biased then the equivalent circuit for forward biased diode must be used.

Problems

A zener diode with $V_Z = 4.3V$ has Z_Z equal to 22Ω when $I_Z = 20mA$. Calculate the upper and lower limits of V_Z when I_Z changes by $\pm 5mA$

$V_Z = 4.3V$

$Z_Z = 22\Omega$

$I_Z = 20mA$

$\Delta I_Z = \pm 5mA$

$\Delta V_Z = \pm(\Delta I_Z \times Z_Z)$

$= \pm 5mA \times 22\Omega$

$\Delta V_Z = \pm 110\ mV$

$V_{Z(max)} = V_Z + \Delta V_Z$

$= 4.3 + 110mV$

$= 4.41V$

$V_{Z(min)} = V_Z - \Delta V_Z$

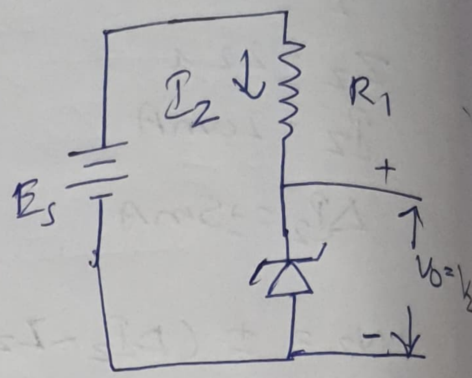
$= 4.3 - 110mV$

$= 4.19V$

Zener diode voltage regulator

Regulator circuit with no load

The most important application of Zener diode is in voltage regulation.



The circuit shown is the figure is used as a voltage reference source that supplies a very low current to the output.

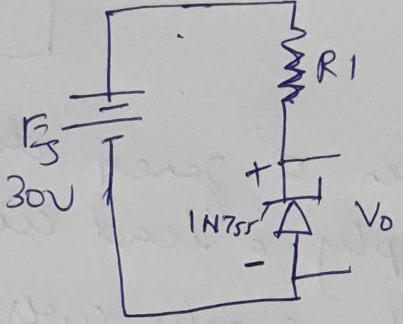
Resistor R1 limits the Zener diode current to the desired level. The zener current is given by,

$$I_Z = \frac{E_S - V_Z}{R_1}$$

The zener current is generally greater than the diode knee current

Problems

A 9V reference source is used to a series connected zener diode and resistor connected to a 30V supply. Determine the circuit components and the power dissipated. (Calculate the circuit current when the supply voltage drops to 27V.)



From data sheet,

$V_Z = 9.1V$

$I_{ZT} = 20mA$

When $E_S = 30V$,

$E = I_Z R_1 + V_Z$

$$R_1 = \frac{E - V_Z}{I_Z} = \frac{30 - 9.1}{20 \times 10^{-3}}$$

$R_1 = 1.05 k\Omega$

* use standard value of $R = 1k\Omega$

$$P_{R_1} = I_Z^2 R_1 = (20 \times 10^{-3})^2 \times 1 \times 10^3$$

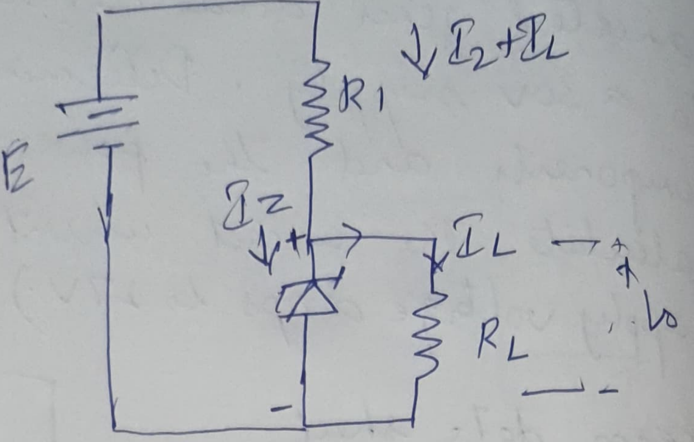
$= 0.4W$

When $E_S = 27V$,

$$I_Z = \frac{E - V_Z}{R_1} = \frac{30 - 9.1}{1 \times 10^3}$$

$= 17.9mA$

Loaded Regulator



When a zener diode regulator has to supply a load current (I_L), the total supply current flowing through ~~R1~~ resistor R1 is the sum of I_Z & I_L.

The minimum zener current must be large enough to keep the diode in reverse breakdown.

Typical values of $I_{Z(min)} = 5mA$
$I_{ZT} = 20mA$.

The circuit current equation is

$$\therefore \boxed{I_Z + I_L = \frac{E - V_Z}{R_1}}$$

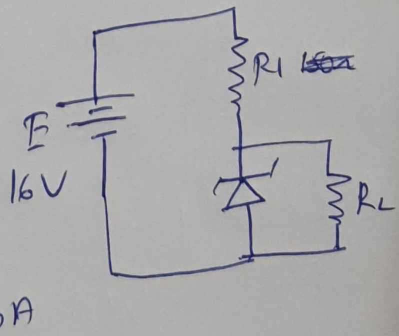
Since the voltage drop across R_1 remains constant, the supply current remains constant.

ie $I_{R_1} = I_Z + I_L$

All this current flows through the zener diode if the load is not connected.

The circuit design must ensure that the total current does not exceed the maximum Zener diode current.

Design a 6V DC reference source to operate from a 16V supply. Calculate the maximum load current that can be taken from the circuit.



From data sheet,

$V_Z = 6.2V$, $P_D = 400mW$

$$I_{ZM} = \frac{P_D}{V_Z} = \frac{400 \times 10^{-3}}{6.2} = 64.5mA$$

$$I_Z(max) + I_L(min) = I_{ZM} = 64.5mA$$

$$R1 = \frac{E_S - V_Z}{I_{ZM}} = \frac{16 - 6.2}{64.5mA} \approx 152\Omega$$

$$P_{R1} = I_1^2 R_1 = (64.5 \times 10^{-3})^2 \times 150 = 0.62W$$