Chapter 1: Diode circuits

- Objective
- To understand the diode operation and its equivalent circuits
- To understand various parameters of diodes
- Load line analysis
- Diode applications in rectifiers; HWR,FWR
- Diode testing
- Zener diode
- Diode data sheets and specifications
- Diode applications in clipper circuits
- Numerical

Semiconductor diode

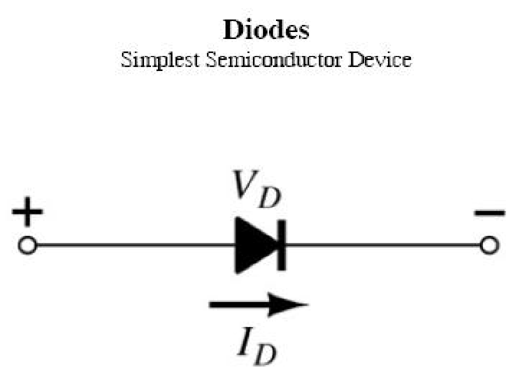


Fig – a semiconductor diode symbol

Basic operation

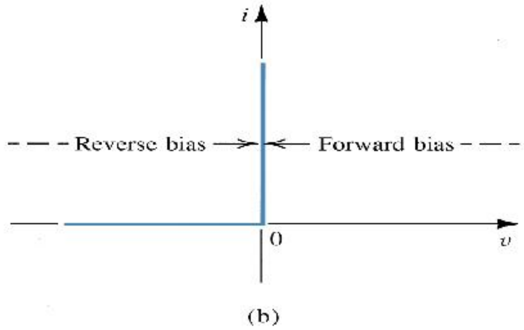


Fig – b Vi characteristics of a diode

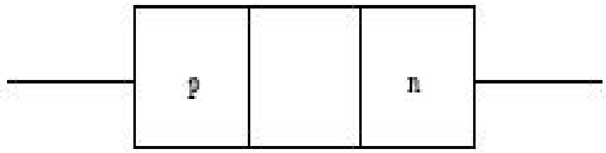
n-type versus p-type

- **n-type** materials make the Silicon (or Germanium) atoms more negative.
- **p-type** materials make the Silicon (or Germanium) atoms more positive.
- Join n-type and p-type doped Silicon (or Germanium) to form a **p-n junction**.

p-n junction

- When the materials are joined, the negatively charged atoms of the n-type doped side are attracted to the positively charged atoms of the p-type doped side.
- The electrons in the n-type material migrate across the junction to the p-type material (electron flow).

- the 'holes' in the p-type material migrate across the junction to the n-type material (conventional current flow).
- The result is the formation of a **depletion layer** around the junction.



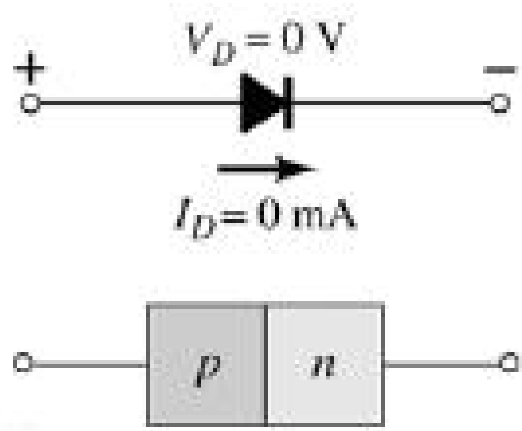
Depletion region

Operating conditions

- No Bias
- Forward Bias
- Reverse Bias

No bias condition

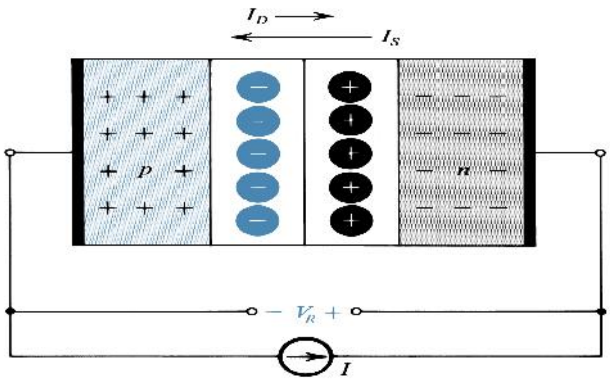
- No external voltage is applied: VD = 0V and no current is flowing ID = 0A.



Only a modest depletion layer exists

Reverse bias condition

External voltage is applied across the p-n junction in the opposite polarity of the p- and n-type materials.



- This causes the depletion layer to widen.
- The electrons in the n-type material are attracted towards the positive terminal and the ‘holes’ in the p-type material are attracted towards the negative terminal.

Avalanche breakdown

Avalanche breakdown occurs when a high reverse voltage is applied to a diode and large electric field is created across the depletion region. The effect is dependant on the doping levels in the region of the depletion layer. Minority carriers in the depletion region associated with small leakage currents are accelerated by the field to high enough energies so that they ionise silicon atoms when they collide with them. A new hole-electron pair are created which accelerate in opposite directions causing further collisions and ionisation and avalanche breakdown

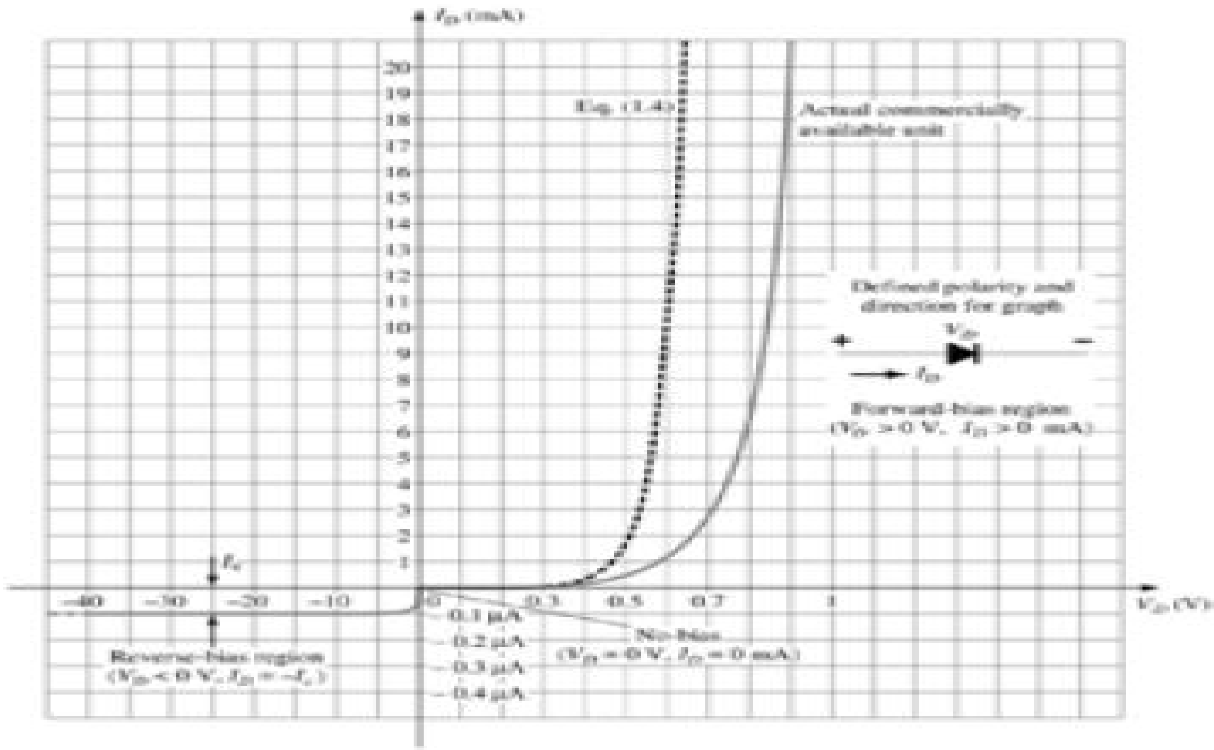
Zener breakdown

Breakdown occurs with heavily doped junction regions (ie. highly doped regions are better conductors). If a reverse voltage is applied and the depletion region is too narrow for avalanche breakdown (minority carriers cannot reach high enough energies over the distance traveled) the electric field will grow. However, electrons are pulled directly from the valence band on the P side to the conduction band on the N side. This type of breakdown is not destructive if the reverse current is limited.

Forward Bias Condition

- External voltage is applied across the p-n junction in the same polarity of the p- and n-type materials.
- The depletion layer is narrow.
- The electrons from the n-type material and ‘holes’ from the p-type material have sufficient energy to cross the junction.

- Actual v-i characteristics is as shown in fig below



Diode current expression:

ID = Is(eVD / VT-1)

- Is : Reverse saturation current
- q : Charge of an electron
- k : Boltzman constant 11600/η
- T : Environment temperature in °K

[°K = °C + 273]

- η =2 for silicon , η=1 for Germanium

Majority and Minority Carriers in Diode

A diode, as any semiconductor device is not perfect!

There are two sets of currents:

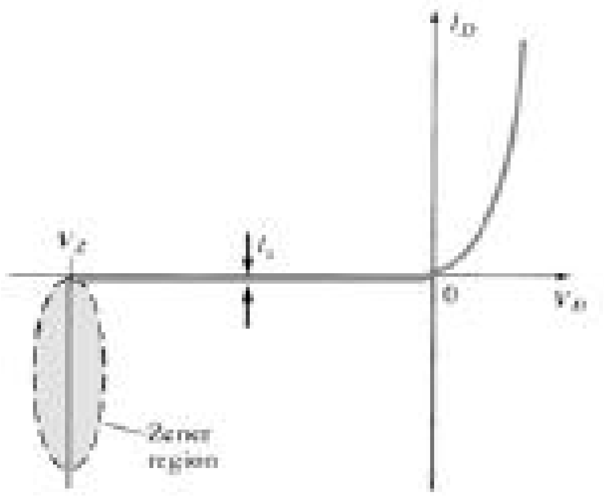
• ***Majority Carriers***

The electrons in the n-type and ‘holes’ in the p-type material are the source of the majority of the current flow in a diode.

- ***Minority Carriers***

Electrons in the p-type and ‘holes’ in the n-type material are rebel currents. They produce a small amount of opposing current.

Zener Region



Zener region

Zener diode operation:

- The diode is in the reverse bias condition.
- At some point the reverse bias voltage is so large the diode breaks down.
- The reverse current increases dramatically.
- This maximum voltage is called ***avalanche breakdown voltage*** and the current is called ***avalanche current.***

Forward Bias Voltage

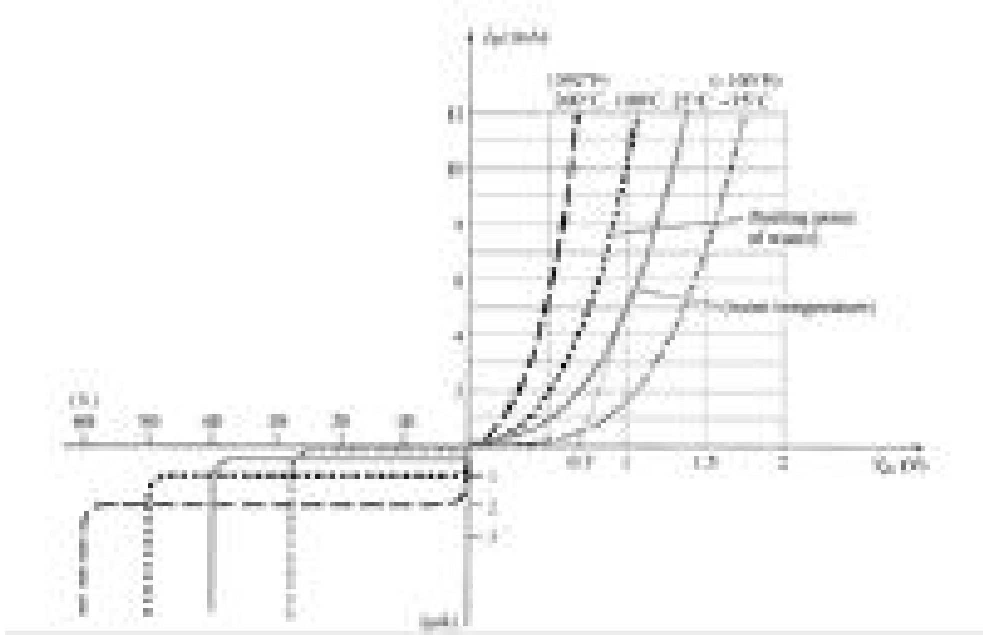
- No Bias condition to Forward Bias condition happens when the electron and ‘holes’ are given sufficient energy to cross the p-n junction.
- This energy comes from the external voltage applied across the diode.

  The Forward bias voltage required for a

  • Silicon diode VT ≅ 0.7V

  • Germanium diode VT ≅ 0.3V

Temperature Effects on performance of diode



- As temperature increases it adds energy to the diode.
- It reduces the required Forward bias voltage in Forward Bias condition
- It increases the amount of Reverse current in Reverse Bias condition
- It increases maximum Reverse Bias Avalanche Voltage
- Germanium diodes are more sensitive to temperature variations than Silicon Diodes.

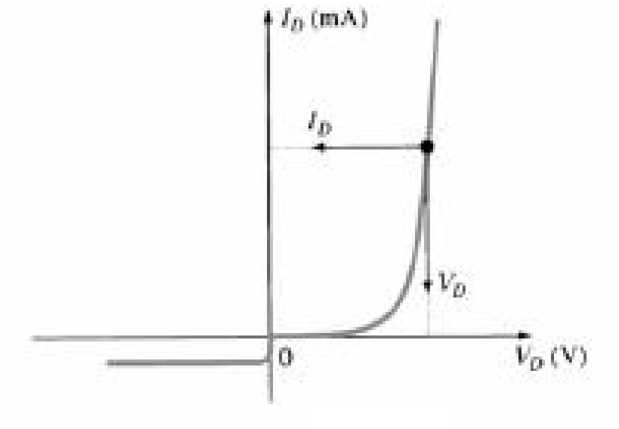
Resistance Levels

- Semiconductors act differently to DC and AC currents.

There are 3 types of resistances.

- DC or Static Resistance
- AC or Dynamic Resistance
- Average AC Resistance

DC or Static Resistance



RD=VD / ID

DC or static resistance

- For a specific applied DC voltage VD,   the diode will have a specific current ID, and a specific resistance RD.
- The amount of resistance RD, depends on the applied DC voltage.

AC or Dynamic Resistance

Forward Bias region:

• The resistance depends on the amount of current (ID) in the diode.

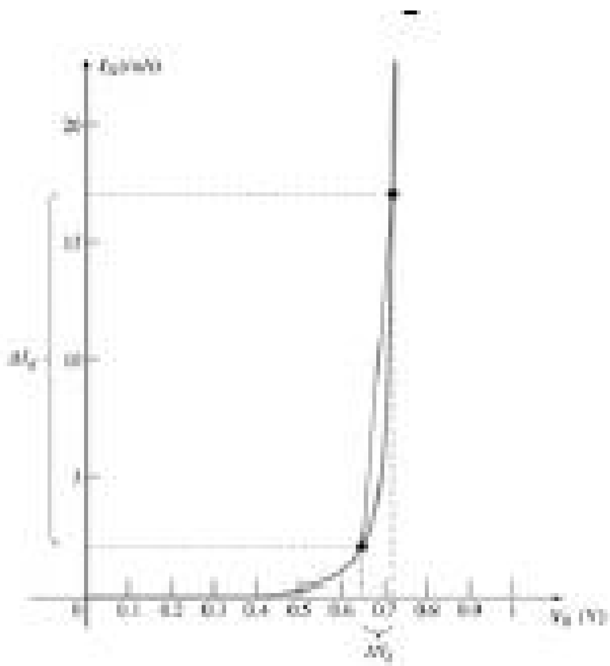
Rd=Δvd/ ΔId

- The resistance depends on the amount of current (ID) in the diode.
- The voltage across the diode is fairly constant (VT = 26mV for 25°C).
- Reverse Bias region:

  Rd=∞

The resistance is essentially infinite. The diode acts like an open.

Average AC Resistance

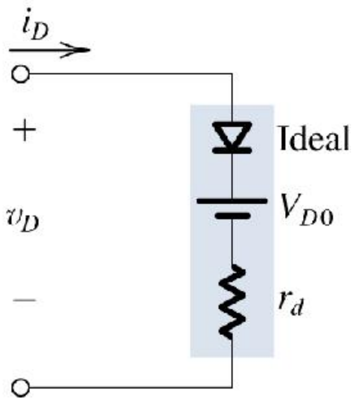


Rac=ΔVd/ΔId Point to point

Diode equivalent circuits

- An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device, system or such a particular operating region.
- Then device symbol can be replaced with the equivalent circuit which makes the analysis of the circuit easy and straight forward.

Piece wise linear equivalent circuit



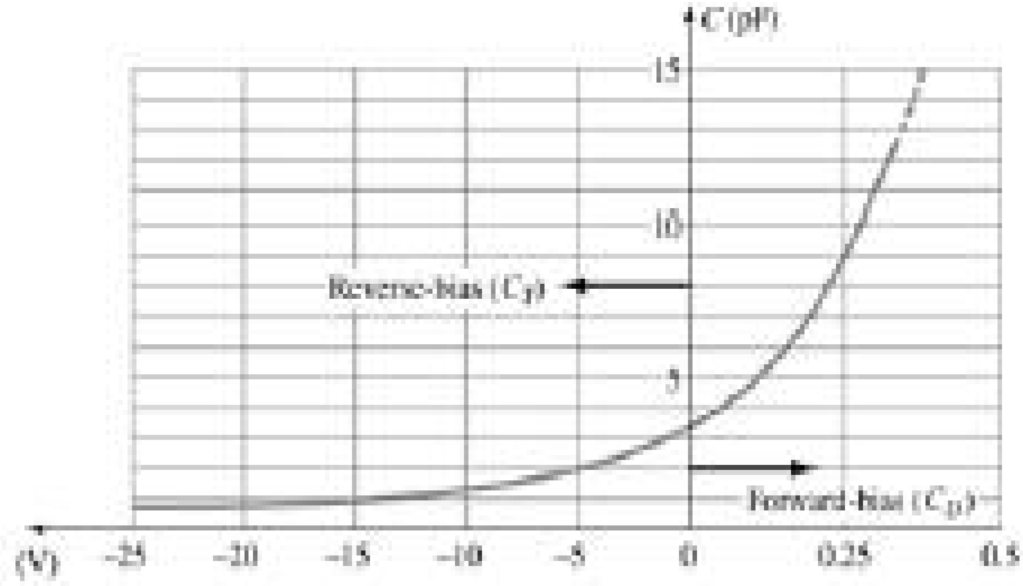
One technique for obtaining equivalent circuit is to approximate the characteristics of the device by straight line segments

- Rd defines the resistance level of the device when it is in the ON state.
- Ideal diode is included to establish that there is only one direction of conduction through the device.
- Since silicon semiconductor diode does not conduct until VD of 0.7V is reached, a battery opposing the conduction direction is included.

Simplified equivalent circuit

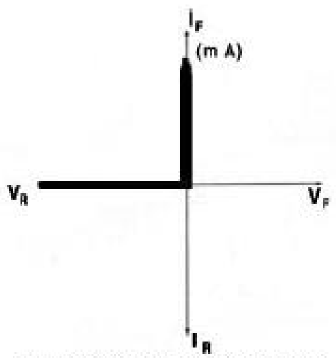
- In most of the applications, resistance r_{av} is very small in comparison to the other elements of the network.
- Removal of this r_{av} from the network makes a simplified equivalent circuit.
- And an ideal diode will start conduction for zero applied voltage.

Transition and diffusion capacitance

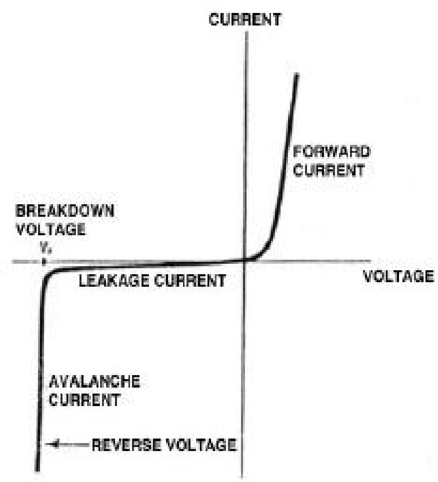


- The figure shows the capacitance v/s applied voltage across the diode.
- Shunt capacitive effects that can be ignored at very lower frequencies since $X_c = 1/2\pi fc$ is very large (open circuit)
- However this can not be neglected in very high frequencies since it introduces a low reactance (shorting) path.
- Two types of capacitive effects to be considered in FB and RB condition.
- In RB region transition or depletion region capacitance CT in FB diffusion capacitance CD or storage capacitance.
- W.k.t $C=\varepsilon A/d$.
- ε is the permittivity of dielectric between tow plates of area A separated by distance d.
- In RB, depletion region which is free of carriers that behaves essentially like an insulator between the layers of opposite charges. This depletion region width increase with increase in RB potential.
- Since d is increasing, capacitance effect is more in FB.

Diode characteristics



V-I characteristics of an ideal diode



V-I characteristics of a real diode

Diode characteristics

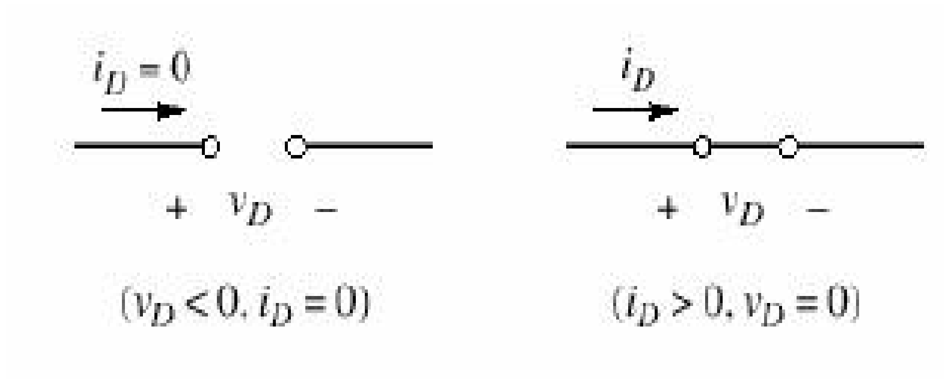
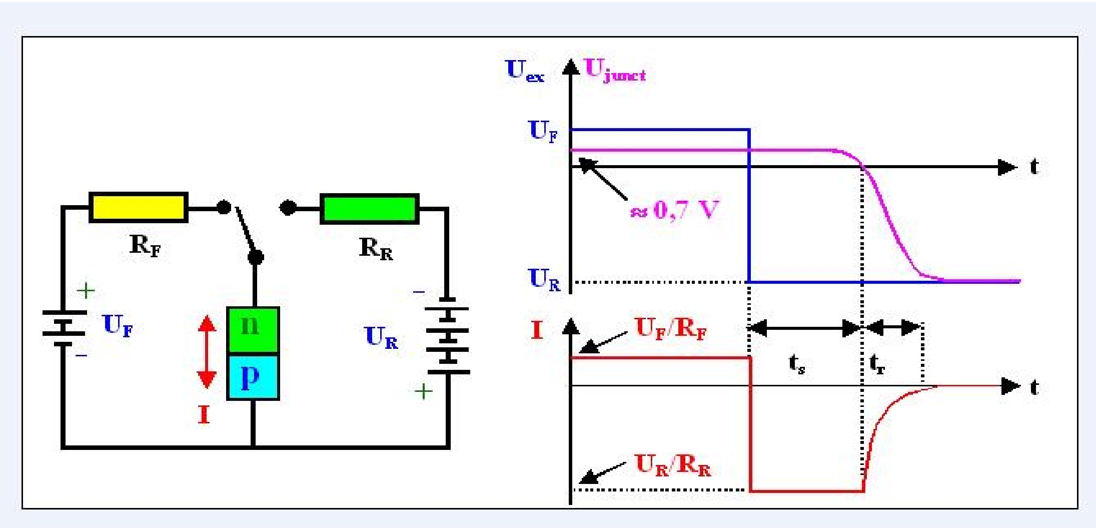


Figure 1-3 Equivalent Circuit of Diode

Reverse recovery time

- Denoted by trr.
- In FB condition, large number of electrons from n-type progressing through p-type and large number of holes in p-type is a requirement for conduction. The electrons in p-type and holes progressing through n-type establish a large number of minority carriers in each material.
- Now if the diode is changed from FB to RB

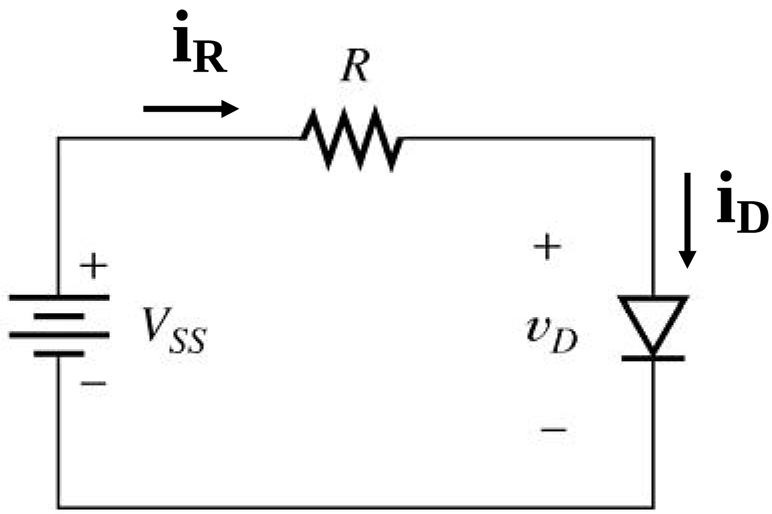
- The diode will not instantaneously react to this sudden change. Because of the large number of minority carriers in each material, the current sustains in diode for a time ts storage time which is required for minority carriers to return to their majority carrier state in the opposite material.
- Eventually current will reduce to non conduction levels.
- This time is tt transition interval
- Hence trr= ts + tt
- This is very important consideration in high frequency operation.
- Commercially available diodes have reverse recovery time of few nano seconds to 1micro second.



Load line Analysis

- The applied load will normally have an important impact on region of operation of device.
- If analysis is done in graphical approach, a line can be drawn on the characteristics of the device that represents applied load.
- The intersection of load line with the characteristics will determine the point of operation.
- Such an analysis is called as load-line analysis.
- The intersection point is called ‘Q’ point or operating point.

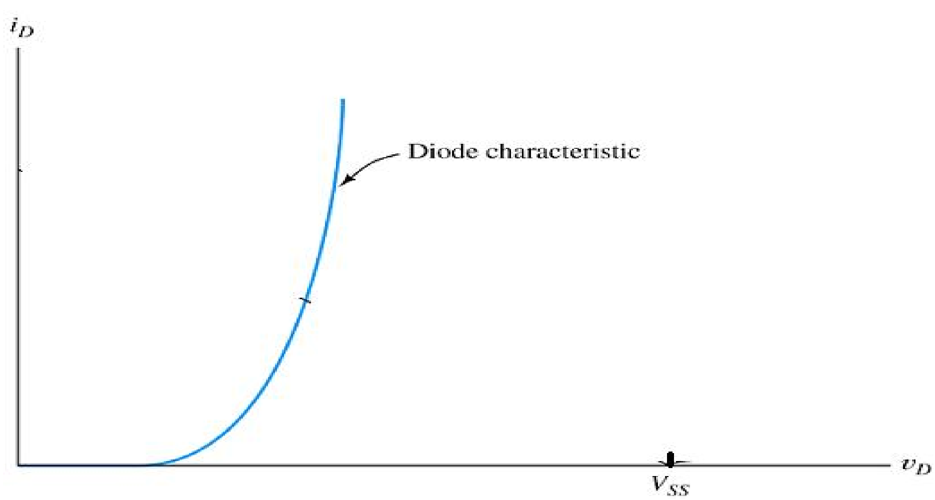
- Its very simple as compared to the non-linear analysis of diode which involves heavy maths……



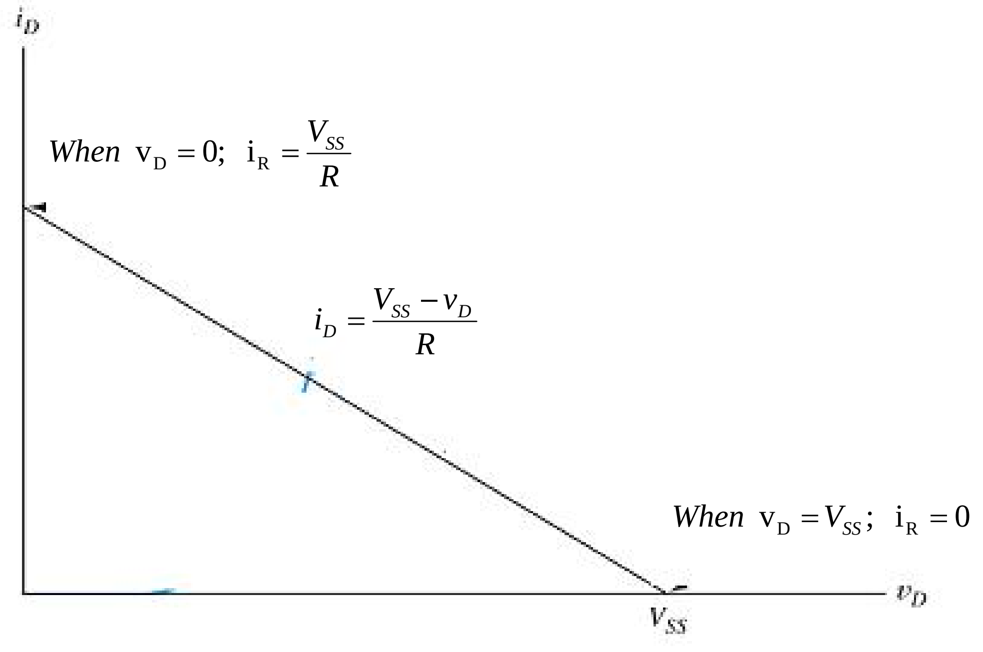
$$\textbf{By KVL}: V_{SS} = Ri_D + v_D$$
$$\textbf{By KCL}: i_R = i_D$$

Both KVL and KCL must be satisfied at all times

i-v curves plotted for diode (energised by Vss)

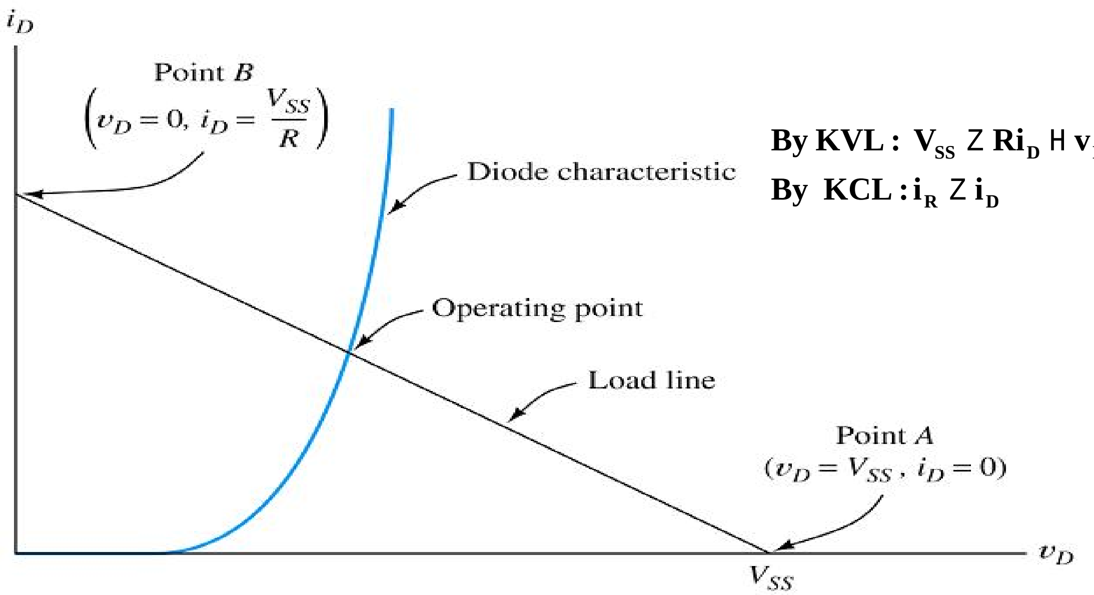


i-v curves plotted for resistor



We can combine these curves on one plot to do a load line analysis

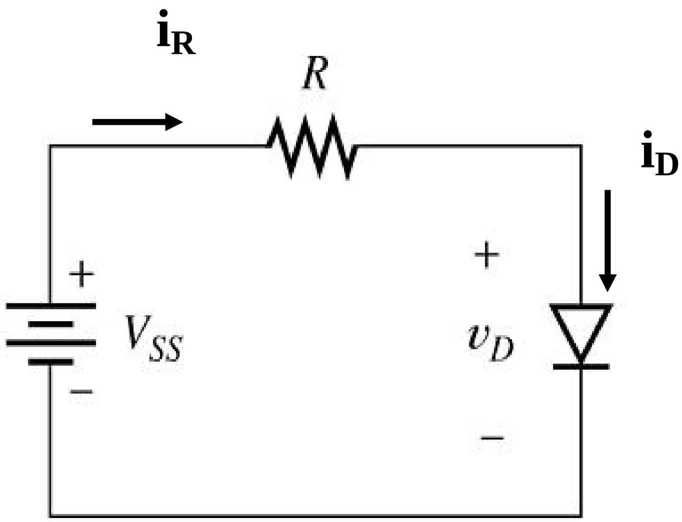
Load line analysis



By KVL : $\mathbf{V_{SS} = Ri_D + v_D}$

By KCL : $\mathbf{i_R = i_D}$

Example on load line analysis



$Assume: \mathrm{V_{SS}} = 3V$

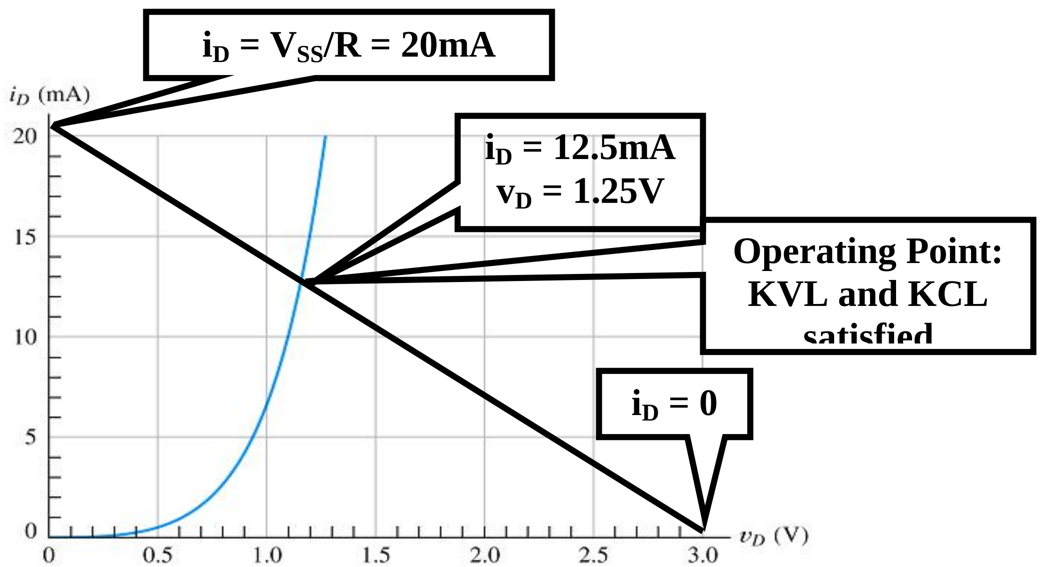
and $\mathrm{R} = 150\Omega.$

When $\mathrm{v_D} = 0:$

$$\mathrm{i_R} = i_D = \frac{V_{SS}}{R} = 20mA$$

$When\ \mathrm{v_D} = V_{SS}:$

$$\mathrm{i_R} = i_D = 0$$



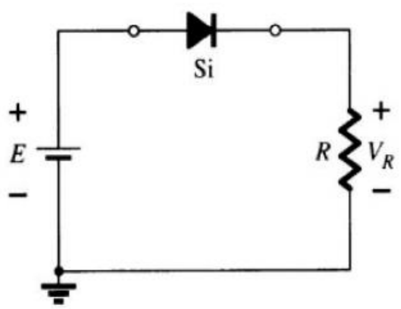
Diode approximations

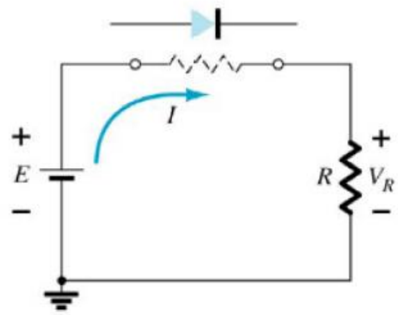
- In the approximate model of diode, the r_{av} is not used since the value of this r_{av} is much less than other series elements of the network.
- This model results in less expenditure of time and effort to obtain results.
- Unless otherwise mentioned this approximate model is used hereforth…

Series diode configuration with DC inputs

- When connected to voltage sources in series, the diode is on if the applied voltage is in the direction of forward-bias and it is greater than the V*T* of the diode
- When a diode is on, we can use the approximate model for the on state

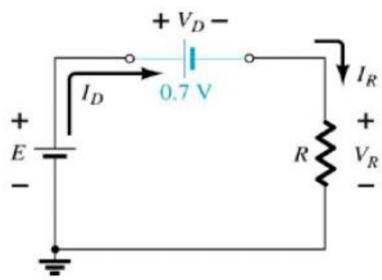
Series diode configuration

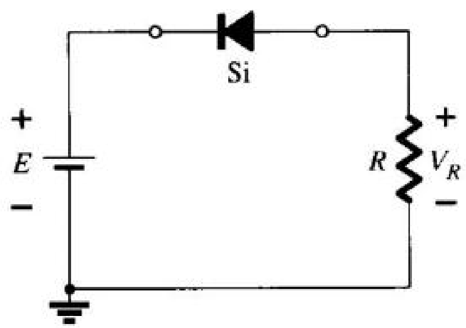


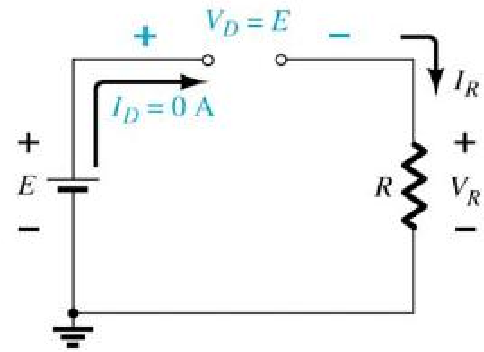


Here, VD = VT, VR = E - VT

ID = IR = VR / R





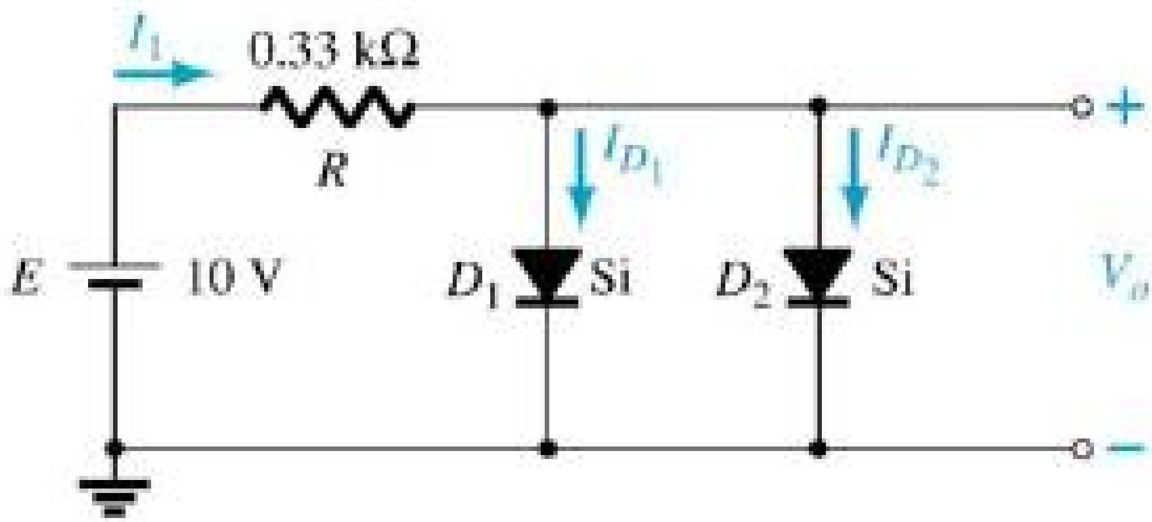


Here, VD = E, VR = 0, ID = 0

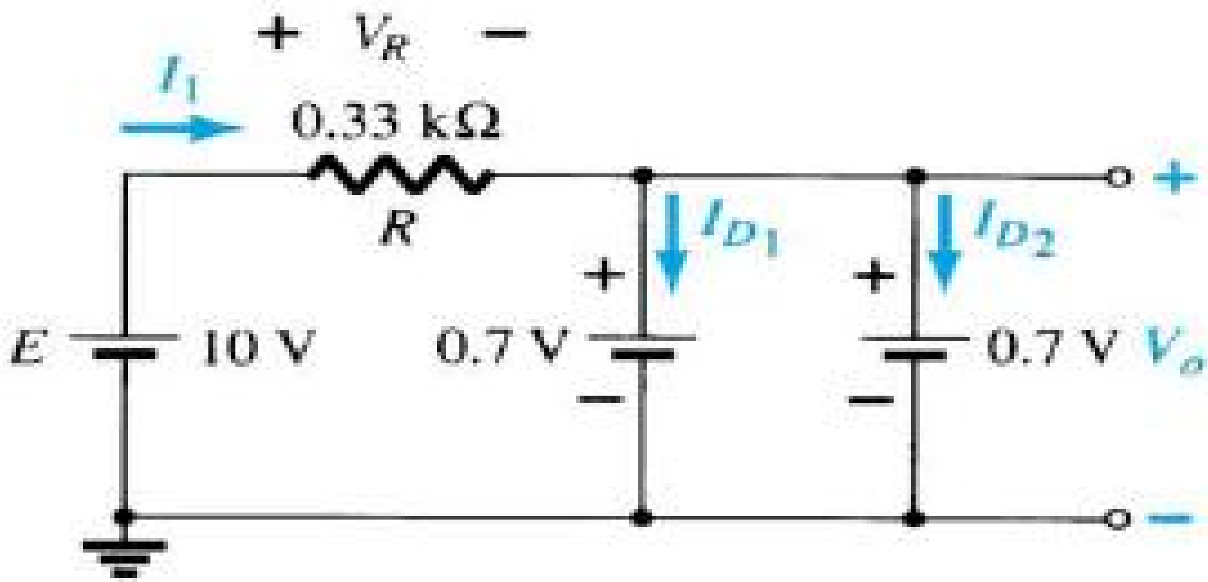
Keep in mind that KVL has to be satisfied under all conditions

Parallel diode configuration

Determine I1 , VD1 , VD2 and V0 for the parallel diode circuit in below figure

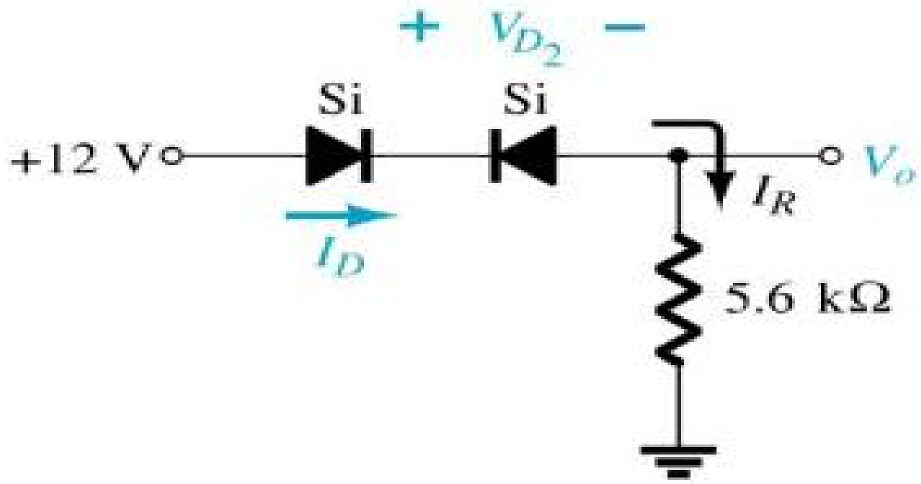


Solution



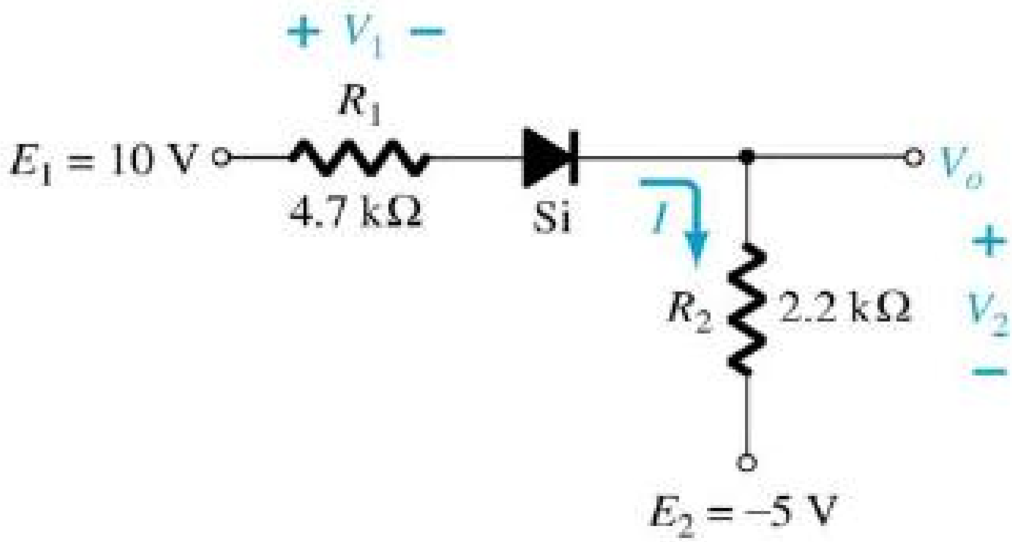
Examples

1. Find diode current and output voltage

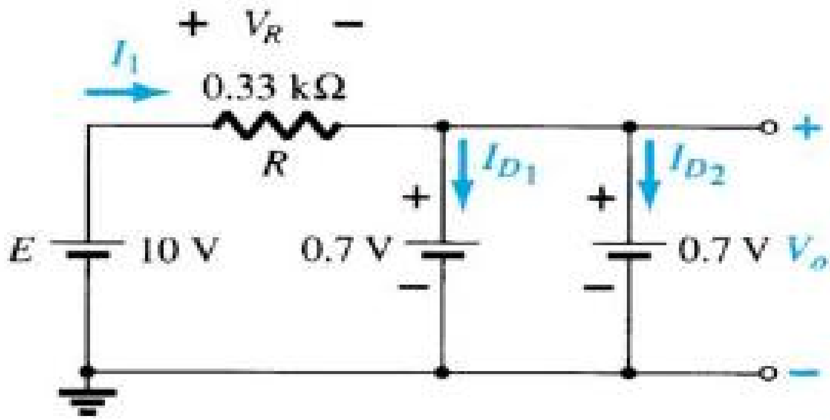


Solution:

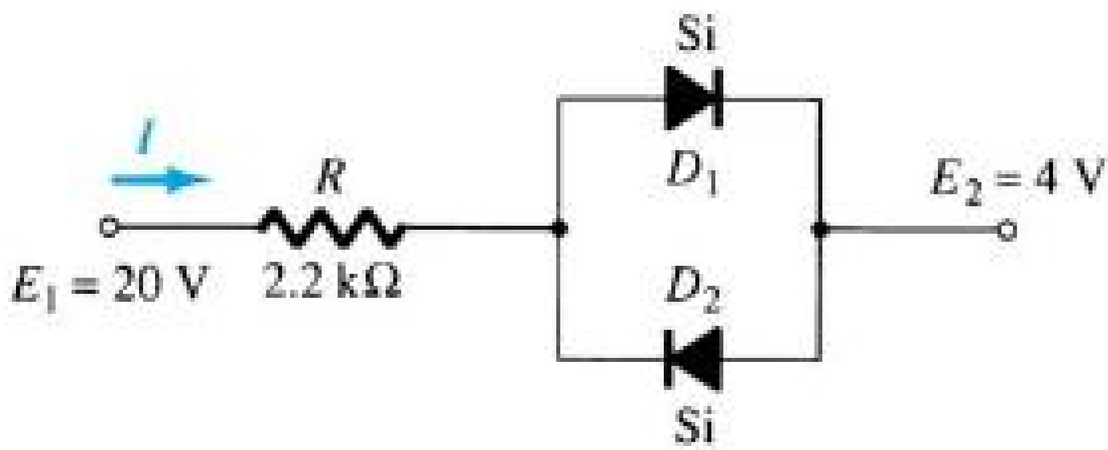
2. Solve for I , v1,v2 and vo



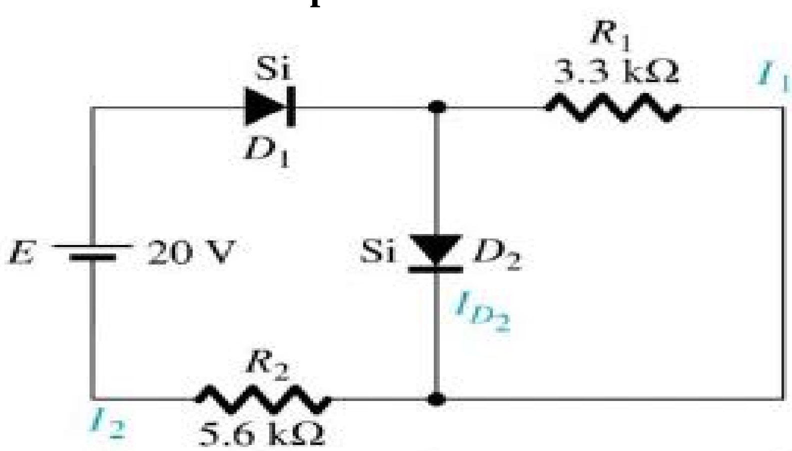
3.Determine unknown parameters



4.Determine unknown parameters

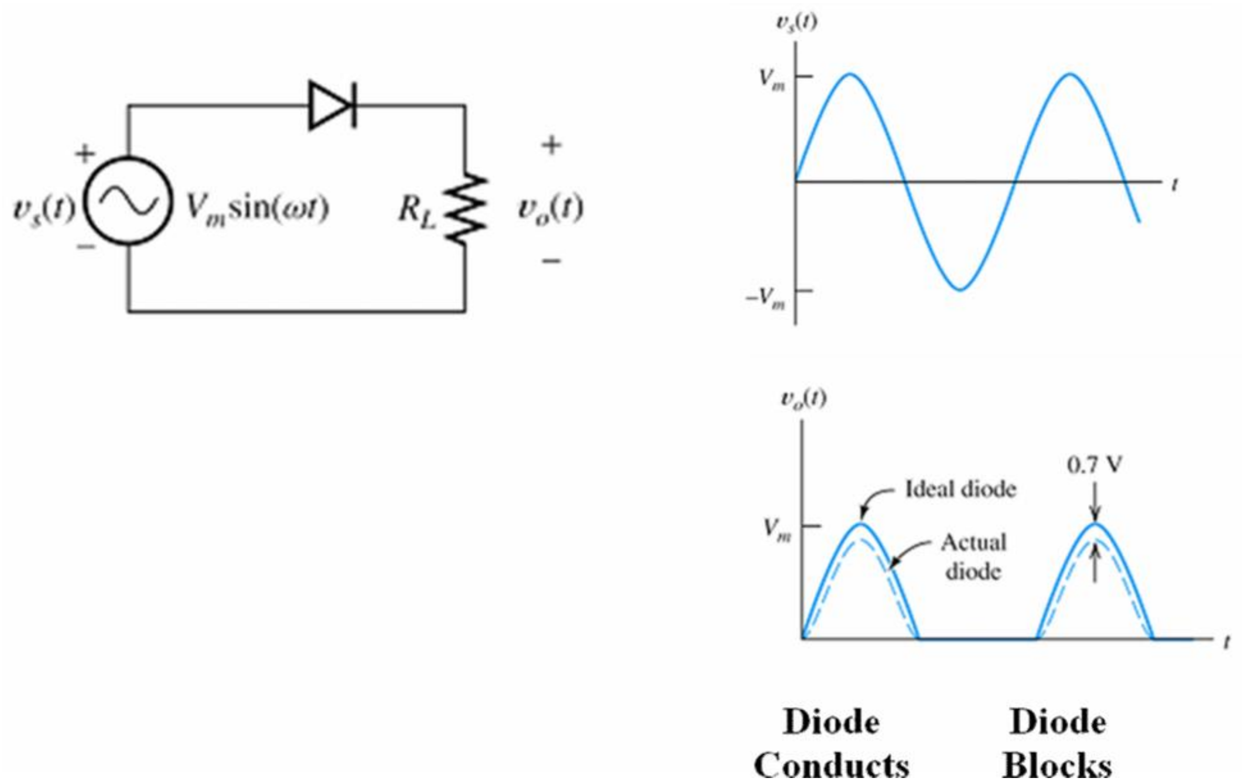


5.Determine unknown parameters



Rectifiers :

Half wave rectification



For the half-wave rectified signal:

Vdc = 0.318 Vm

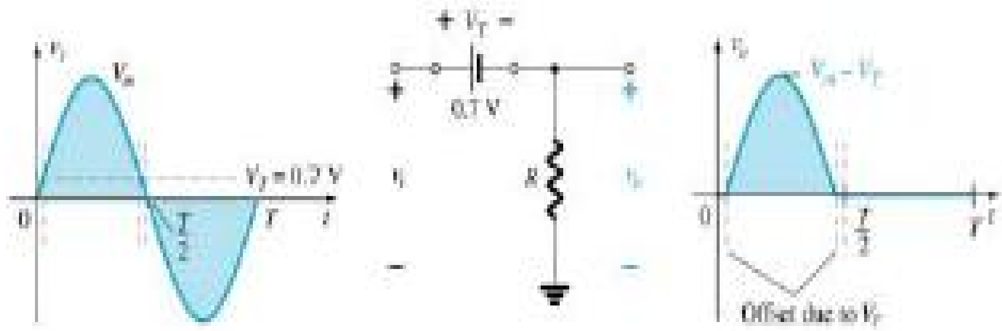
If the effect of V*T* is also

considered, the output of the

system will as below

Vdc = 0.318 (Vm- V*T*)

Effect of V*T* on half-wave rectified signal



PIV rating of Half-wave Rectifiers

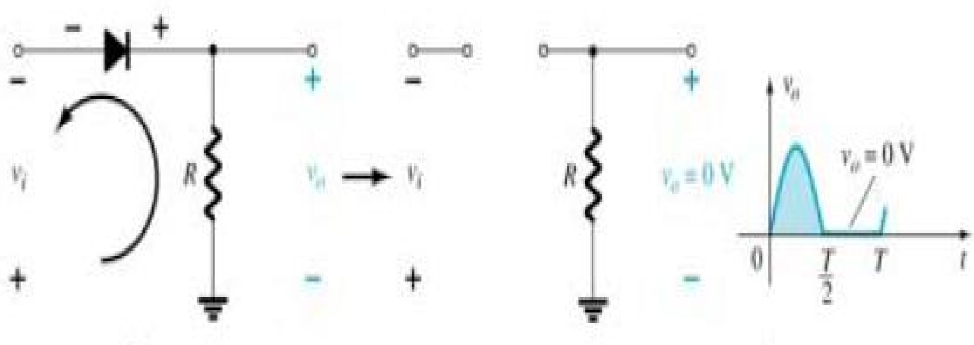
PIV rating is very important consideration for rectifier circuits

For the half-wave rectifier must be equal or must not exceed the peak value of the applied voltage

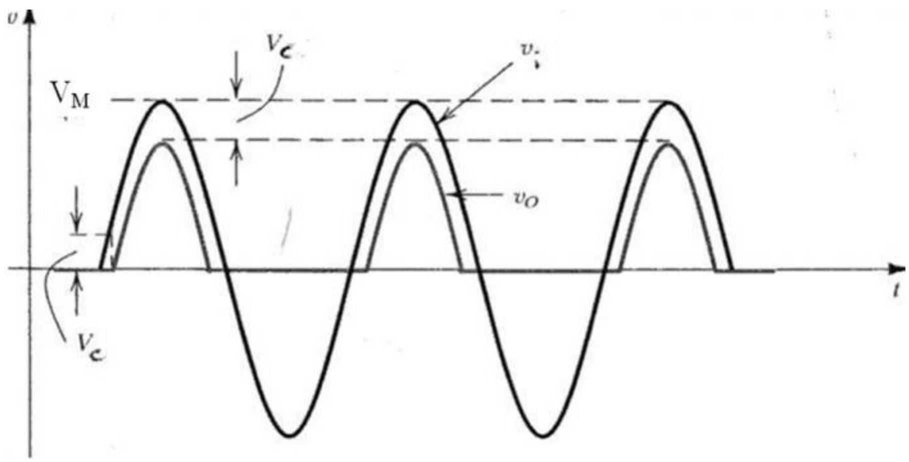
- PIV ≥ Vm

This is the voltage rating that must not be exceeded in the reverse bias region

When vin is negative.

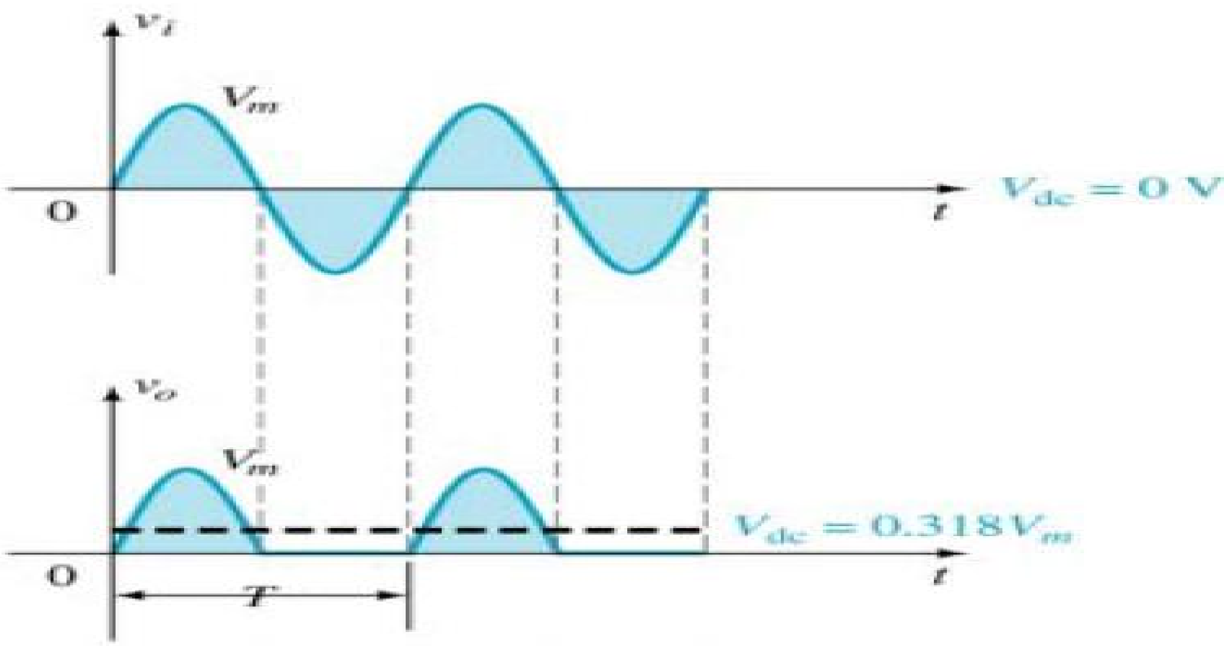


Non Ideal Waveform



Half-wave Rectifier

- The total effect of diode on the output signal is given in below



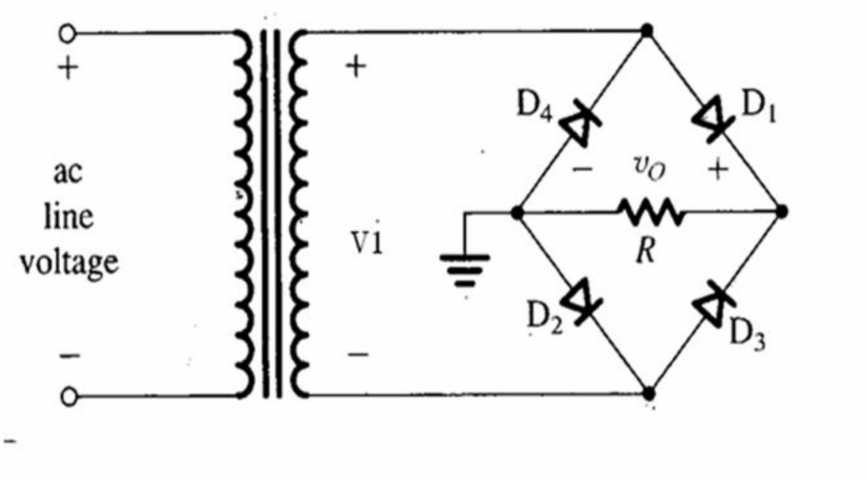
Average voltage $\mathbf{V_{AV}}$

- **The average d.c. value of this half-wave-rectified sine wave is**

$$V_{AV} = \frac{1}{2\pi}\left[\int_0^{\pi} V_M \sin\theta \, d\theta + 0\right]$$

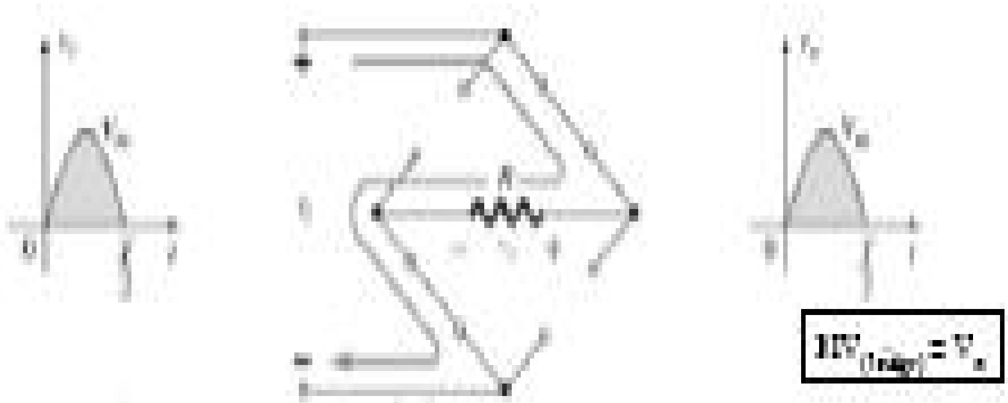
$$= -\frac{V_M}{2\pi}\left[\cos\pi - \cos 0\right] = \frac{V_M}{\pi}$$

Full-wave Rectifiers Bridge



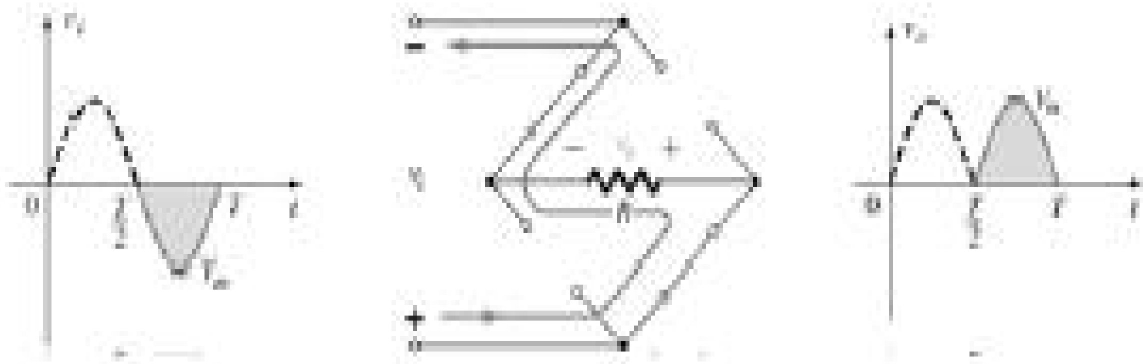
Working :

- For the positive half of the AC cycle:
- Diode D1 and D2 gets forward biased and conducts.



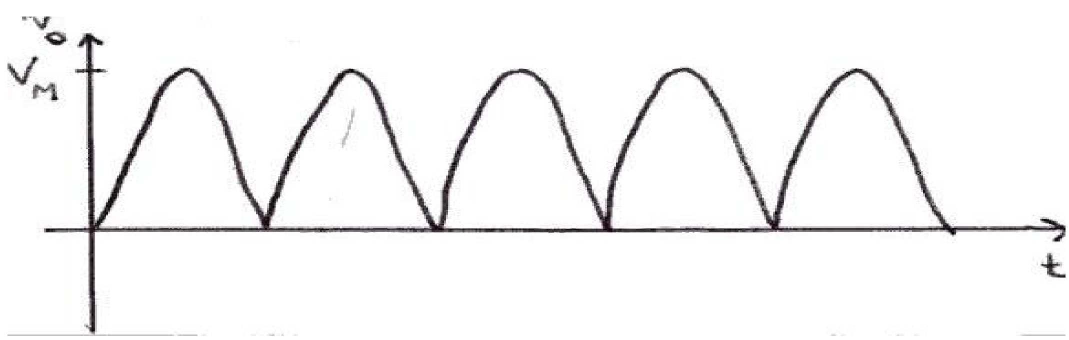
Working :

- For the negative half of the AC cycle
- Diode D3 and D4 gets forward biased and conducts during this half cycle.



Details of working of FWR

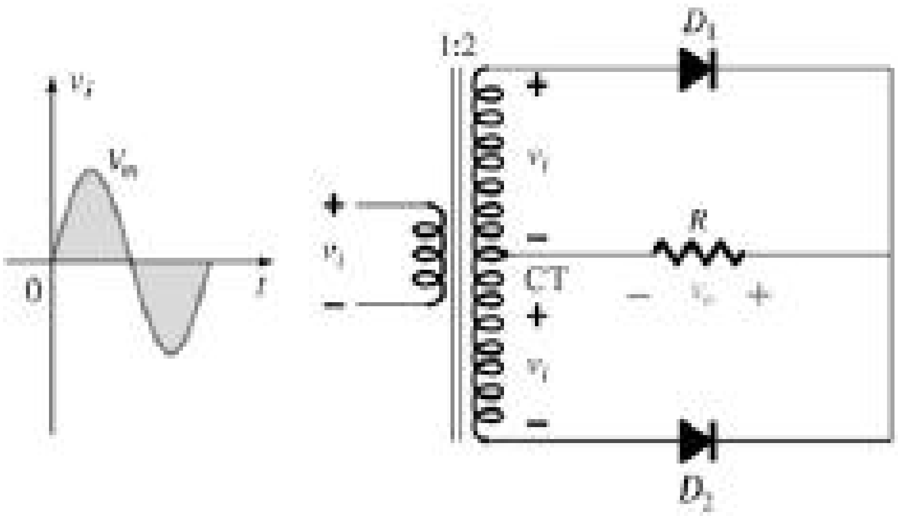
- We initially consider the diodes to be ideal, such that V_C =0 and R_f =0
- The four-diode bridge can be bought as a package During positive half cycles v_i is positive.
- Current is conducted through diodes D1, resistor R and diode D2
- Meanwhile diodes D3 and D4 are reverse biased
- During negative half cycles v_i is negative.
- Current is conducted through diodes D3, resistor R and diode D4
- Meanwhile diodes D1 and D2 are reverse biased.
- Current always flows the same way through the load R.



- the average d.c. value of this full-wave-rectified sine wave is $V_{AV} = 2V_M/\pi$ (i.e. twice the half-wave value)
- Two diodes are in the conduction path.
- Thus in the case of non-ideal diodes v_o will be lower than v_i by $2V_C$.
- As for the half-wave rectifier a reservoir capacitor can be used. In the full wave case the discharge time is T/2 and

$$\Delta V \approx \frac{V_M T}{2RC}$$

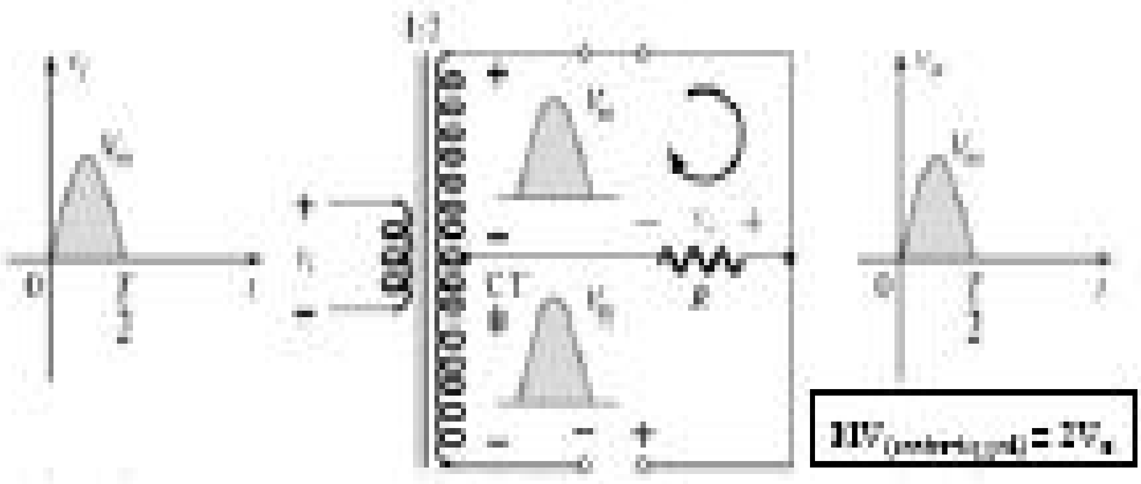
Centre - tap FWR



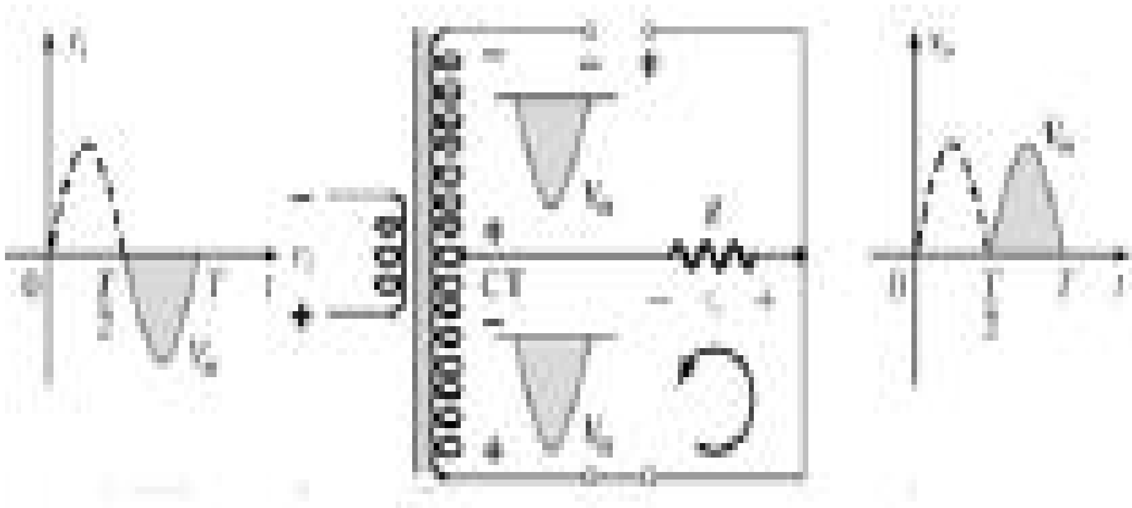
- Two diodes and a center-tapped transformer are required.
- VDC = 0.636(Vm)
- Note that Vm here is the transformer secondary voltage to the tap.

Operation

For the positive half of the AC cycle:



For the negative half of the AC cycle:



Summary

Type of rectifier	Ideal V_{DC}	Realistic V_{DC}
Half wave rectifier	$V_{DC} = 0.318\ V_m$	$V_{DC} = 0.318\ V_m - 0.7V$
Full wave rectifier	$V_{DC} = 0.636\ V_m$	$V_{DC} = 0.636\ V_m - 2(0.7V)$
Full wave centre tap transformer rectifier	$V_{DC} = 0.636\ V_m$	$V_{DC} = 0.636\ V_m - 0.7V$

Note: Vm = peak of the AC voltage.

Application of diode as Clippers

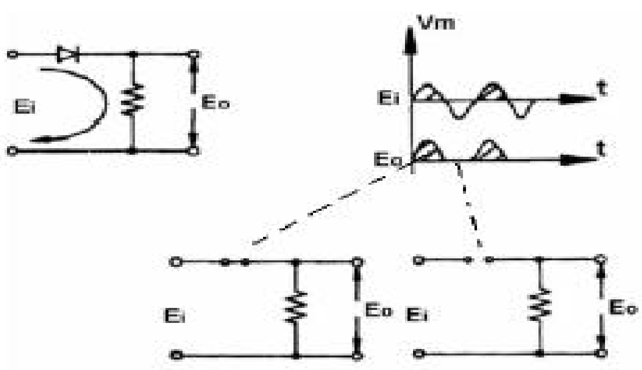
- Clippers have ability to "clip/remove" off a portion of the input signal without distorting the remaining part of the alternating waveform.
- HWR is simplest form of clippers. The orientation of diode is going to decide the part of sinusoidal waveform to be clipped off.

Clipper configuration

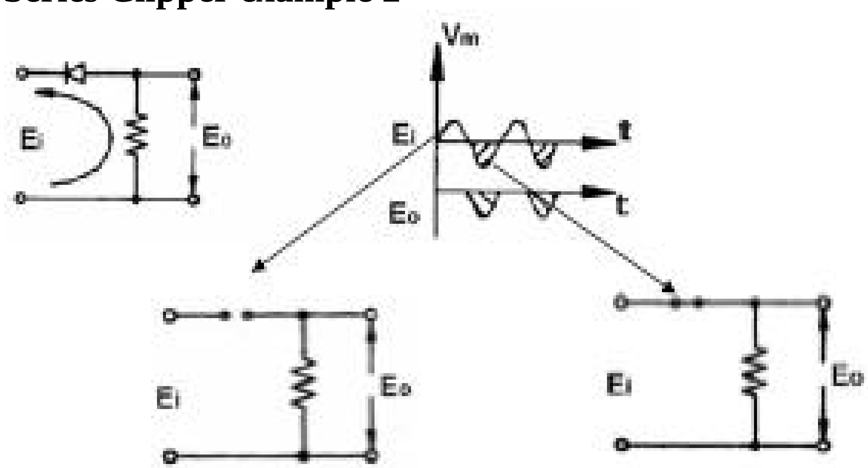
Depending on the way in which the diodes are connected with the input, the clipper are classified in to two major categories, viz.,

- Series configuration
- Parallel configuration

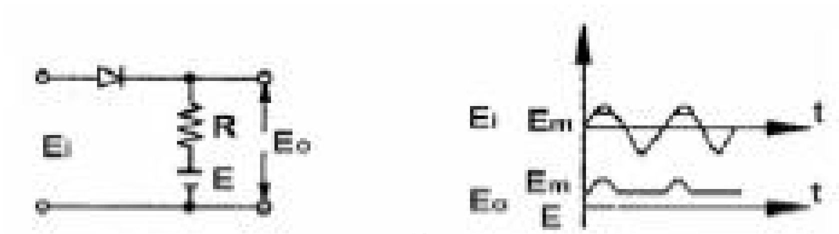
1. **Series clipper example 1**



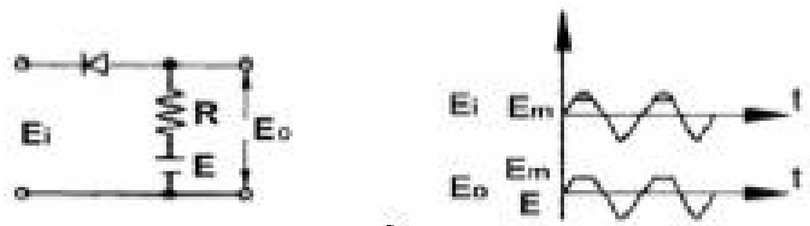
2. **Series Clipper example 2**



3. Series clipper ex – 3 & 4

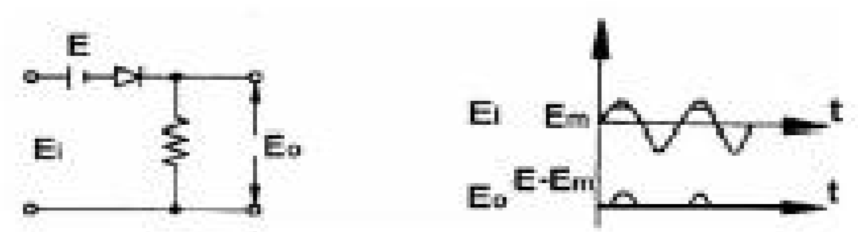


a

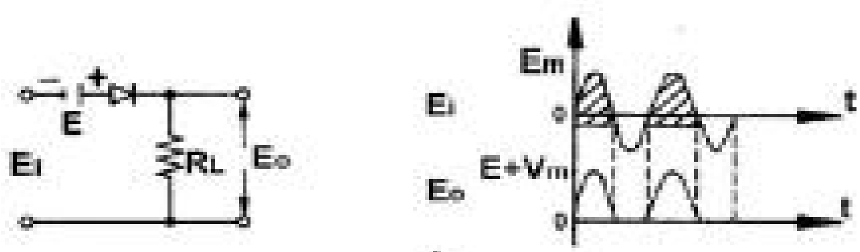


b

4. Series clipper Ex - 5 & 6

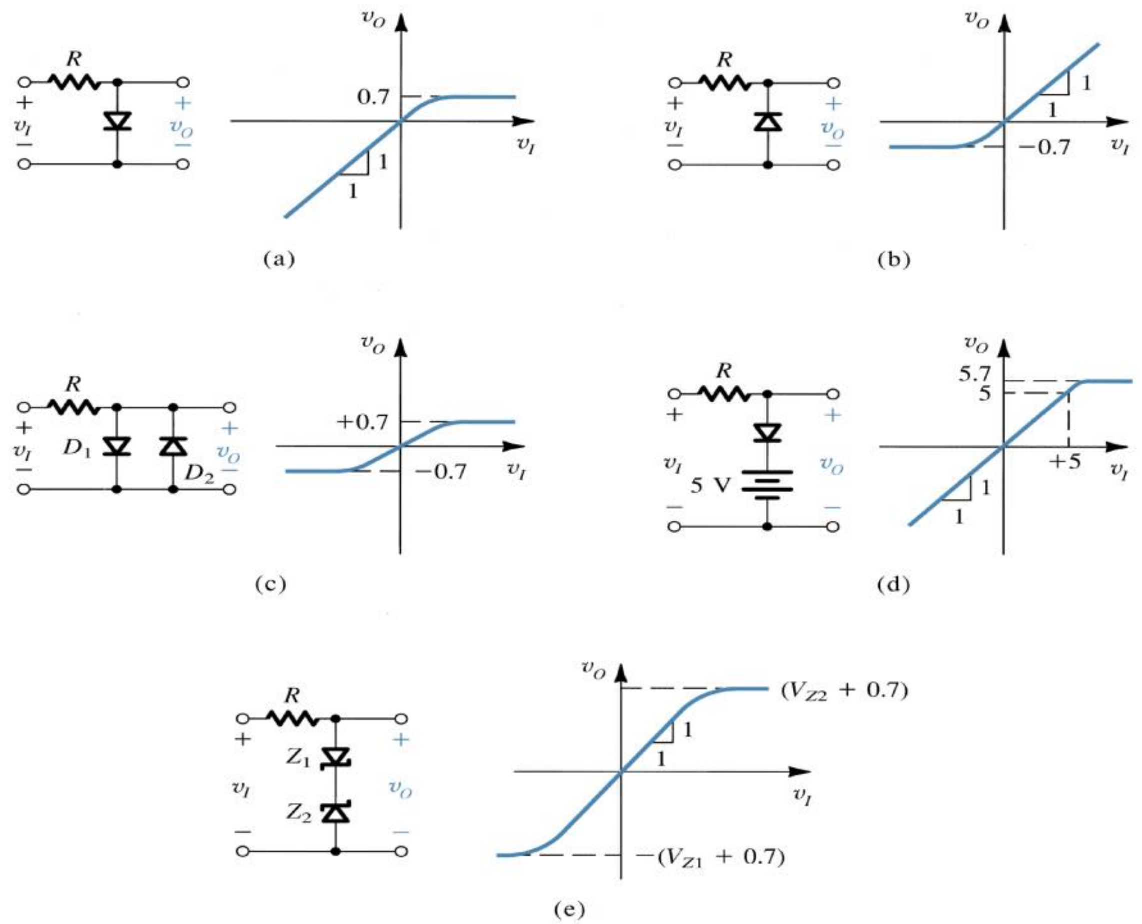


a



b

Various clipepr examples along with transfer characteristics



Biased parallel clippers

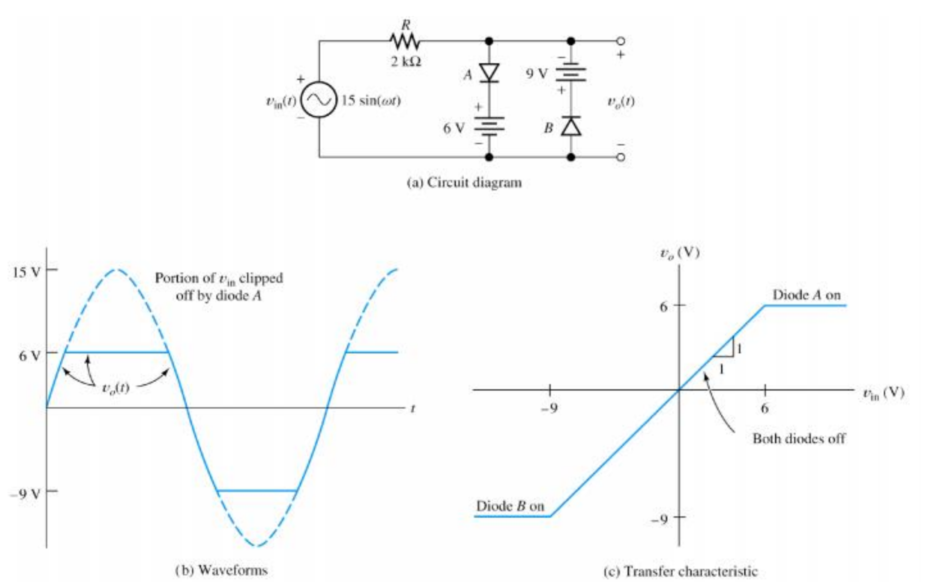
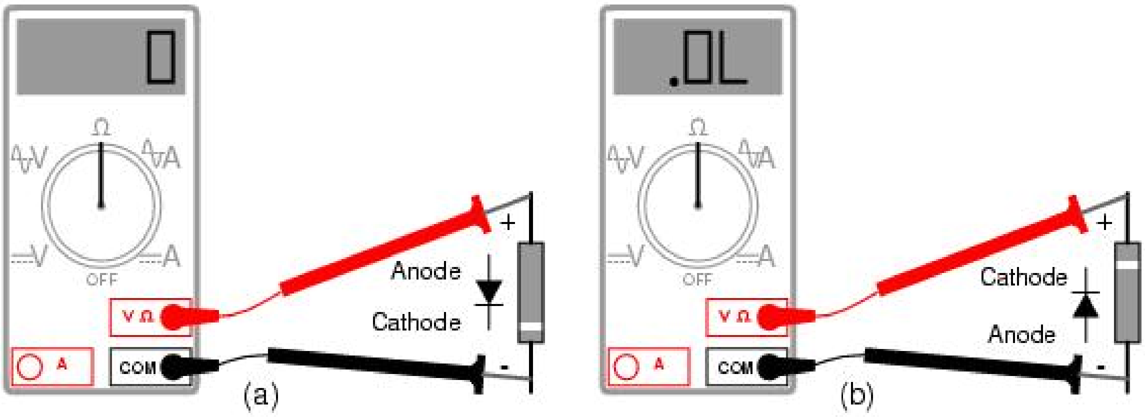


Figure 10.29 Clipper circuit.

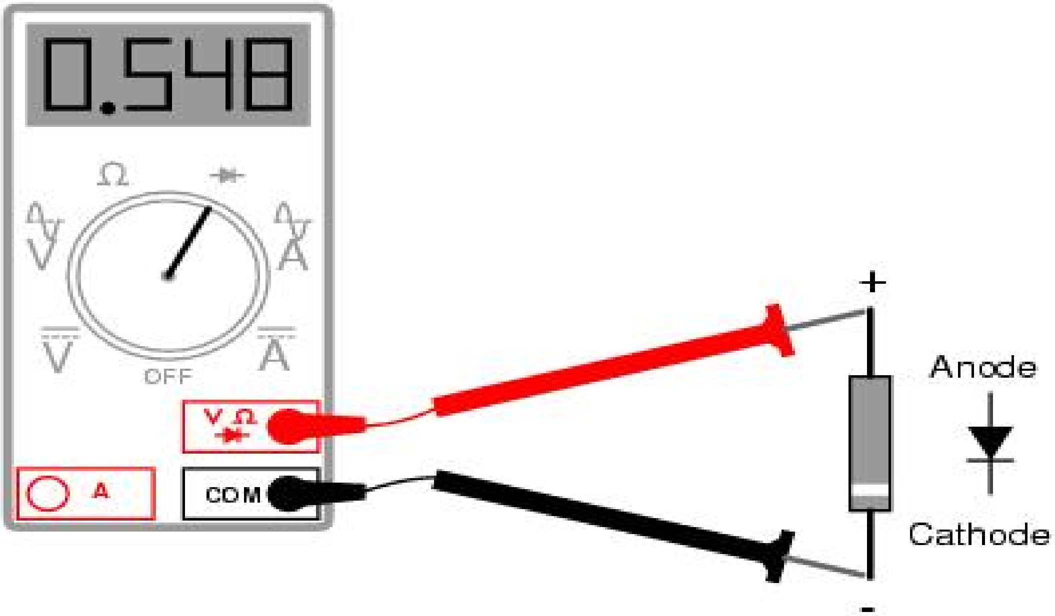
Diode testing :

1. Diode testing using multi-meter



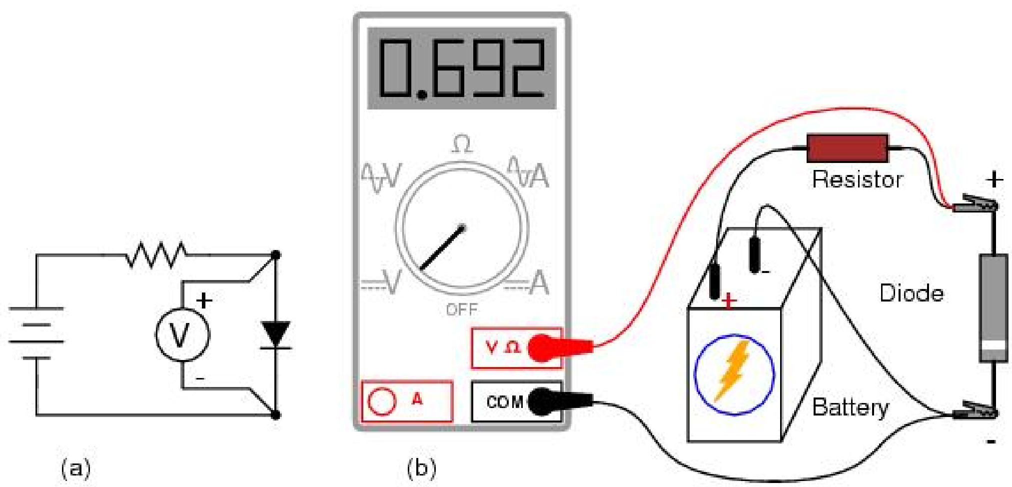
One problem with using an ohmmeter to check a diode is that the readings obtained only have qualitative value, not quantitative. In other words, an ohmmeter only tells you which way the diode conducts; the low-value resistance indication obtained while conducting is useless. If an ohmmeter shows a value of "1.73 ohms" while forward-biasing a diode, that figure of 1.73 Ω doesn't represent any real-world quantity useful to us as technicians or circuit designers.

It neither represents the forward voltage drop nor any "bulk" resistance in the semiconductor material of the diode itself, but rather is a figure dependent upon both quantities and will vary substantially with the particular ohmmeter used to take the reading. For this reason, some digital multimeter manufacturers equip their meters with a special "diode check" function which displays the actual forward voltage drop of the diode in volts, rather than a "resistance" figure in ohms. These meters work by forcing a small current through the diode and measuring the voltage dropped between the two test leads. (Figure below)



Meter with a "Diode check" function displays the forward voltage drop of 0.548 volts instead of a low resistance.

The forward voltage reading obtained with such a meter will typically be less than the "normal" drop of 0.7 volts for silicon and 0.3 volts for germanium, because the current provided by the meter is of trivial proportions. If a multimeter with diode-check function isn't available, or you would like to measure a diode's forward voltage drop at some non-trivial current, the circuit of Figure below may be constructed using a battery, resistor, and voltmeter



Measuring forward voltage of a diode without"diode check" meter function:
(a) Schematic diagram. (b) Pictorial diagram

2. Curve tracers

- A curve tracer can display the characteristics of a host device.
- Device could be diode or transistor or other semiconductor device.
- Curve tracer by tektronix and other companies available
- Easy to use and testing with less effort and time.

Diode specifications

- Data sheets provide data on specific semiconductor device.
- Manufacturers provide these information
- Usually given in easy readable formats like graphs, artwork, tables and so on.,
- These specifications are required for proper utilization of devices for specific applications

Important data to be considered are

- The forward voltage V_F (at specific T)
- Maximum forward current I_F
- Maximum reverse saturation current I_R
- The reverse voltage rating (PIV)
- Maximum power dissipation
- Capacitance levels
- Reverse recovery time t_{rr}
- Operating temperature range

Depending on type of diode being used, additional data such as

- Frequency
- Noise level
- Switching time
- Thermal resistance

Peak repetitive values are also provided

For IN4001 and 4007

ELECTRICAL CHARACTERISTICS†

Rating	Symbol	Typ	Max	Unit
Maximum Instantaneous Forward Voltage Drop, (i_F = 1.0 Amp, T_J = 25°C)	v_F	0.93	1.1	V
Maximum Full-Cycle Average Forward Voltage Drop, (I_O = 1.0 Amp, T_L = 75°C, 1 inch leads)	$V_{F(AV)}$	-	0.8	V
Maximum Reverse Current (rated DC voltage) (T_J = 25°C) (T_J = 100°C)	I_R	 0.05 1.0	 10 50	μA
Maximum Full-Cycle Average Reverse Current, (I_O = 1.0 Amp, T_L = 75°C, 1 inch leads)	$I_{R(AV)}$	-	30	μA

MAXIMUM RATINGS

Rating	Symbol	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	Unit
†Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	50	100	200	400	600	800	1000	V
†Non-Repetitive Peak Reverse Voltage (halfwave, single phase, 60 Hz)	V_{RSM}	60	120	240	480	720	1000	1200	V
†RMS Reverse Voltage	$V_{R(RMS)}$	35	70	140	280	420	560	700	V
†Average Rectified Forward Current (single phase, resistive load, 60 Hz, T_A = 75°C)	I_O	1.0							A
†Non-Repetitive Peak Surge Current (surge applied at rated load conditions)	I_{FSM}	30 (for 1 cycle)							A
Operating and Storage Junction Temperature Range	T_J T_{stg}	−65 to +175							°C

Maximum ratings are those values beyond which device damage can occur.

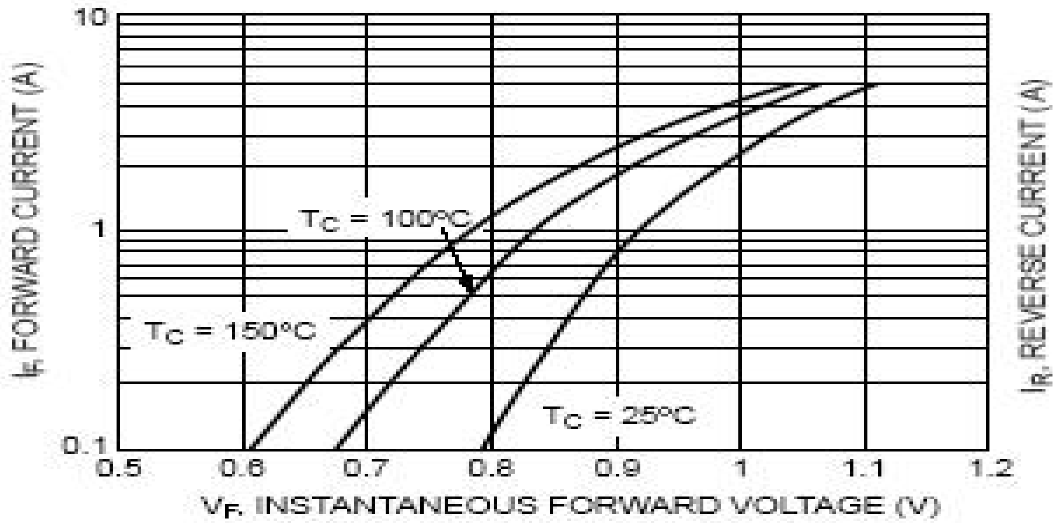


Figure 1. Typical Forward Voltage

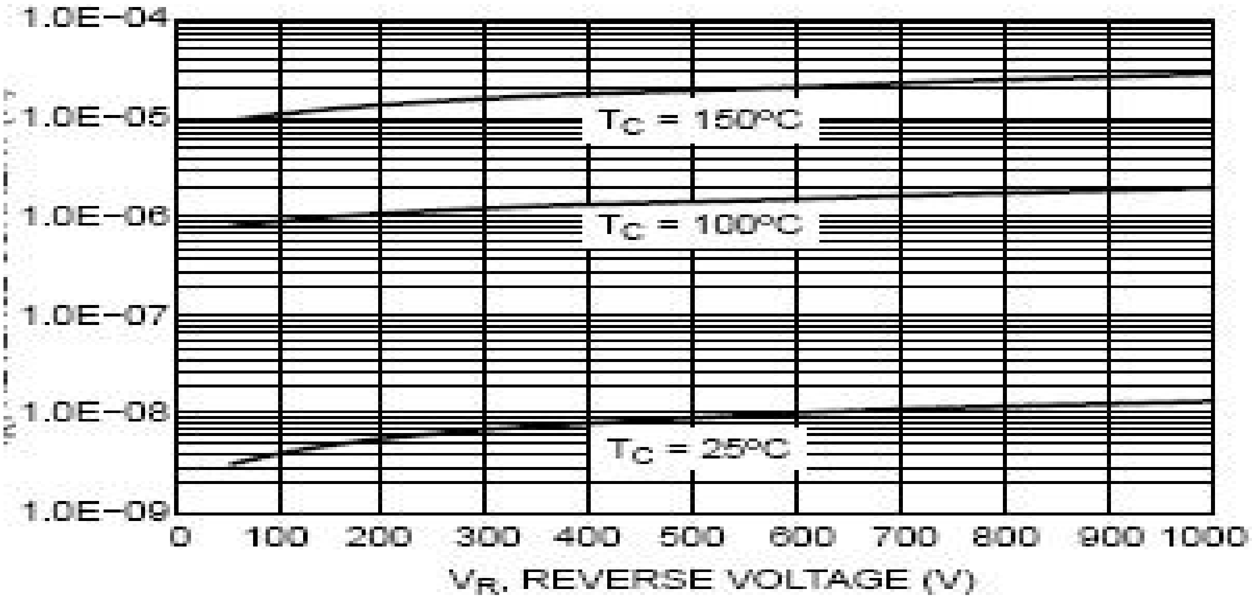


Figure 2. Typical Reverse Current

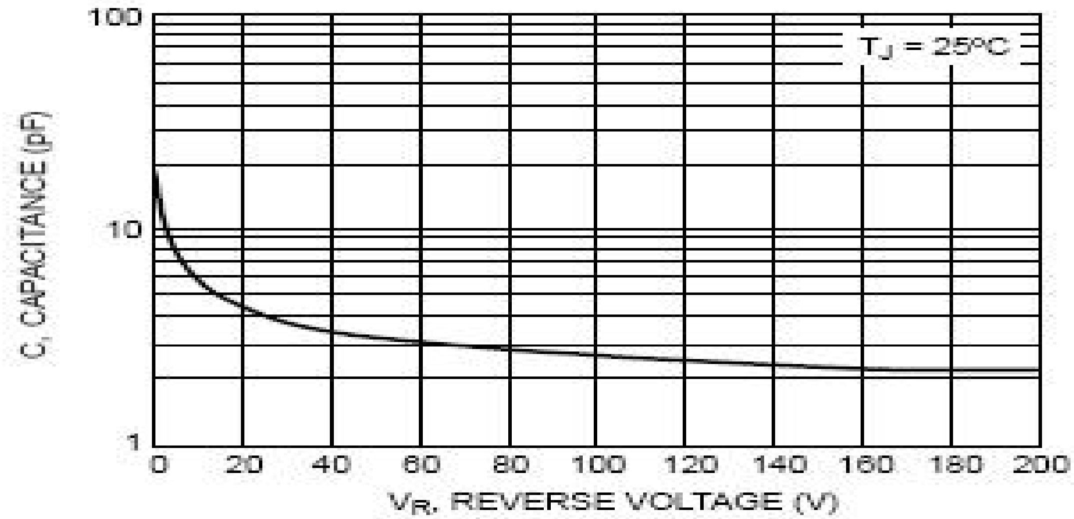
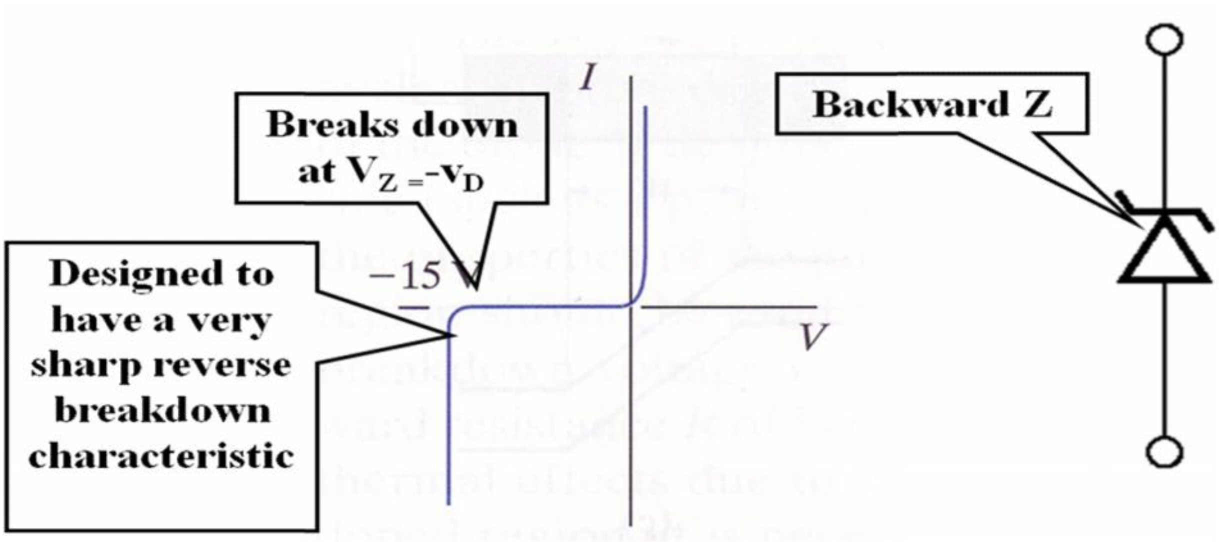


Figure 3. Typical Capacitance

Zener diodes

- By proper doping of the silicon, the “Zener Breakdown” can be made to have a very “sharp breakdown”.
- The breakdown voltage is commonly labeled as VZ.

Characteristics of Zener diode



- Equivalent circuit consist of a constant voltage supply of V_Z in series with a zener resistor r_Z.

- The approximate model is obtained just by neglecting the effect of r_Z in the equivalent model. Only a constant voltage source is used in this model.
- The temperature coefficients reflects the percentage change in V_Z with temperature and it is defined by the relation
- $T_c=\{\Delta V_Z/ V_Z(T_1\text{-}T_0) \} \times 100\%$
- $\Delta V_Z \rightarrow$ change in zener potential due to temperature variation
- $(T_1\text{-}T_0)$ change in temperature

Examples

1. Det. Nominal voltage for 1N961 fairchild zener diode at temp of 100^0c.

Solution:

$\Delta V_Z=T_c\, V_Z(T_1\text{-}T_0)/100$

$=\{0.072 \times 10V/100\}(100^0\text{-}25^0)$

$= 0.54V$

Therefore change in Zener voltage is 10.54V when temperature is raised from 25^0c to 100^0c.

---

2. Find Is and vL using zener characteristics for given data.

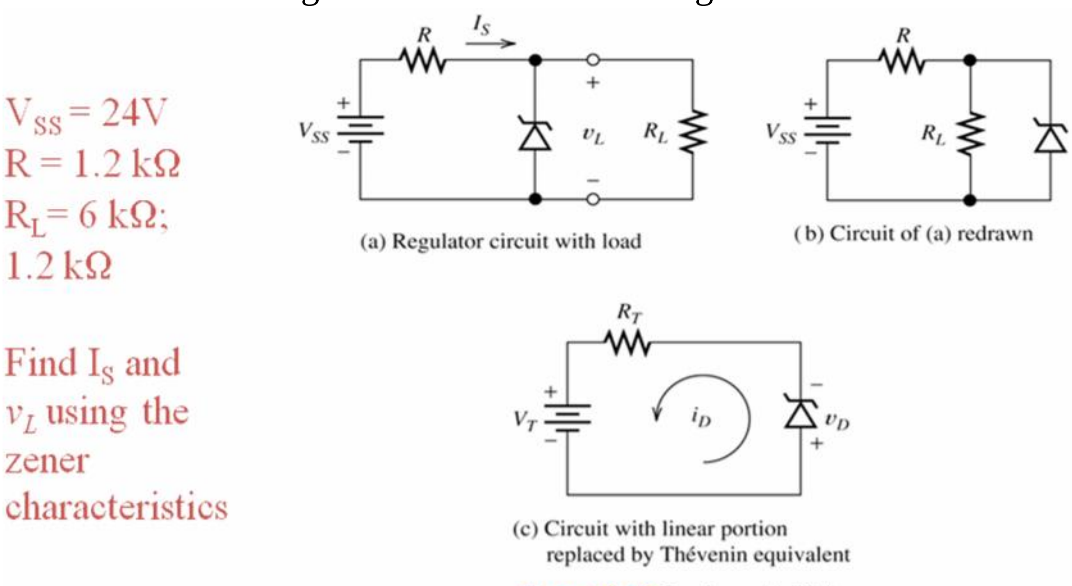


Figure 10.12 See Example 10.4.

---

3. Compute the Thevenin equivalent of the previous circuit with the zener diode as the load

Thevenin voltage

Thevenin resistance

We can then write VT +RT*iD*+*vD* = 0 and find out *vD*,, *iD* using the zener diode characteristics

$v_L = v_D$ and IS = v_L /RL + i_D

Solution

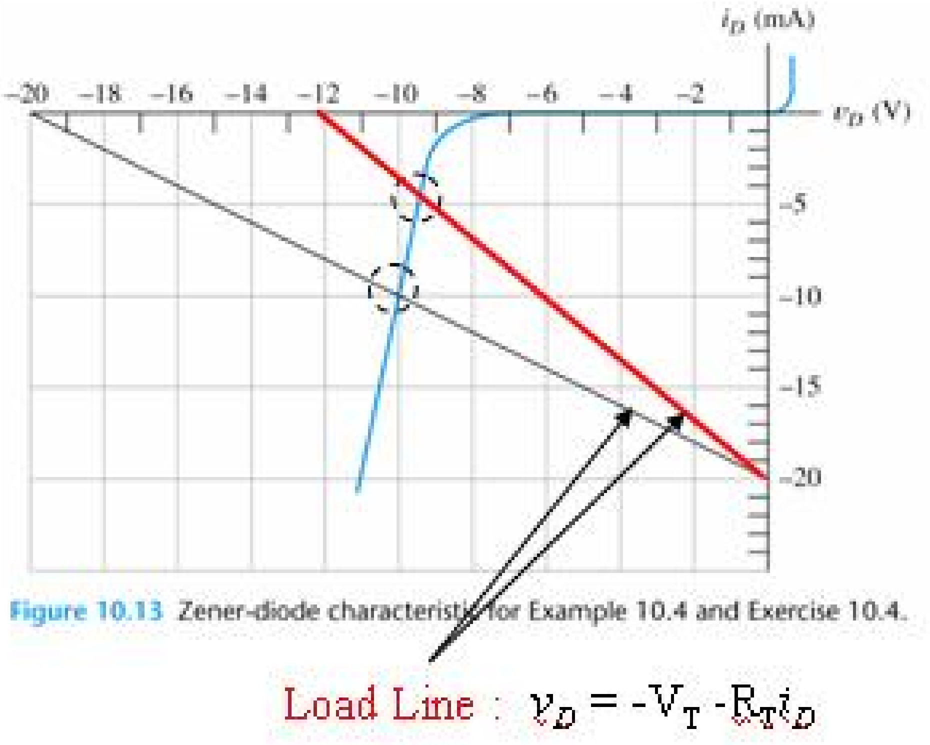


Figure 10.13 Zener-diode characteristic for Example 10.4 and Exercise 10.4.

Answers

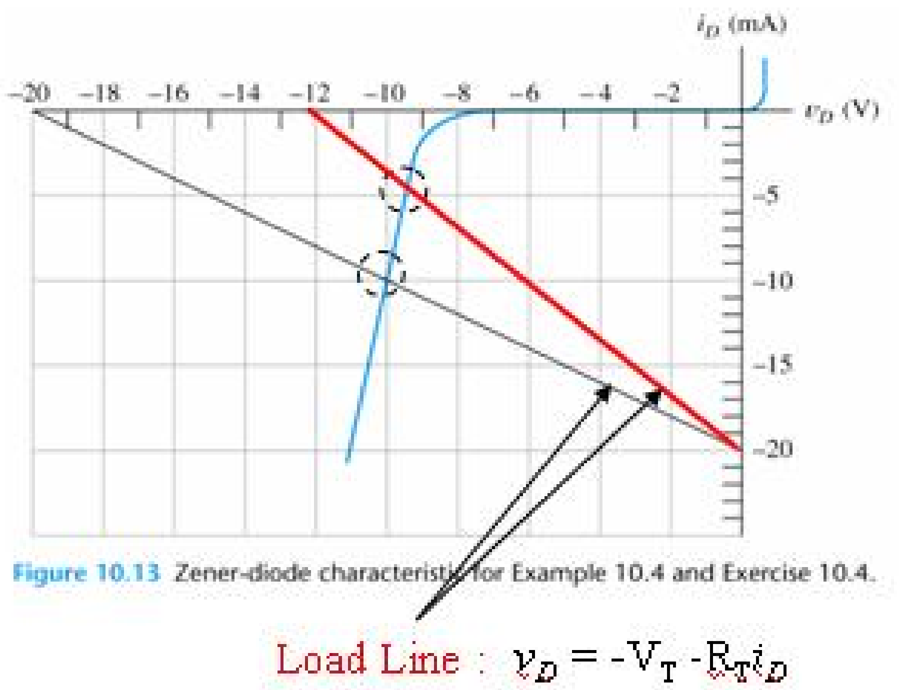
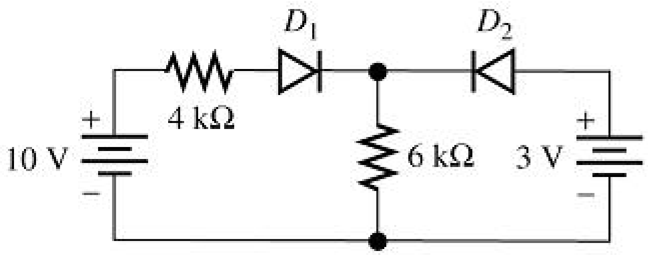


Figure 10.13 Zener-diode characteristic for Example 10.4 and Exercise 10.4.

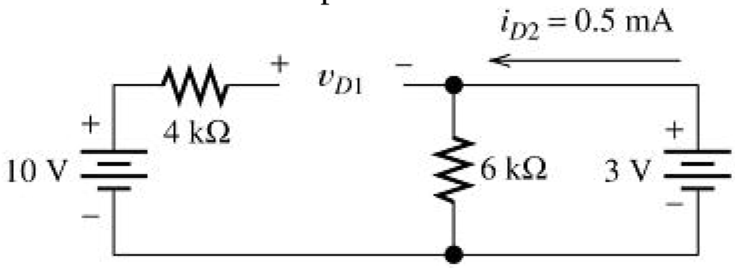
- v_L = 10V
- IS = v_L /RL + i_D = 10/6 +10 mA = 11.67mA
- v_L = 9.5 V
- IS = v_L /RL + i_D = 9.5/1.2 +5 mA = 12.92mA

4. Find currents through diode D1 and D2.



General Approach:

- Assume the state of each of the diodes: i.e., "<u>on</u>" or "<u>off</u>".
- Analyze the circuit and check to see if your assumptions were correct.
- If not correct try another set of assumptions.
- Assume D1 is "off": Replace with open
- Assume D2 is "on": Replace with short

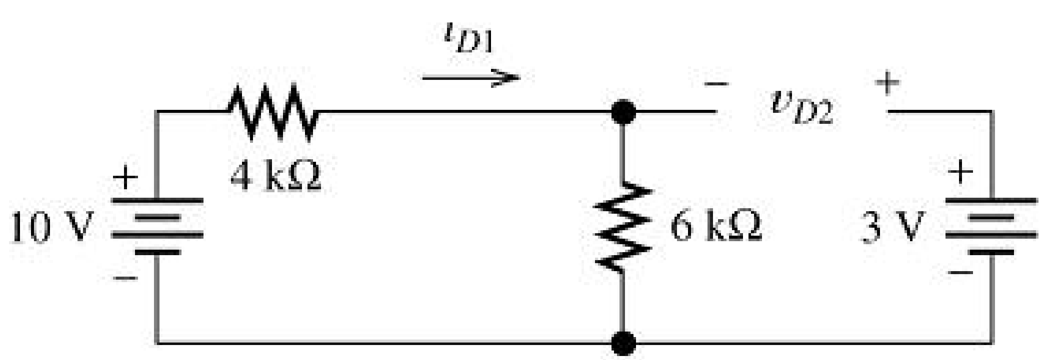


vD1 = 10V – 3V = 7V

But this is <u>not possible</u> since the D1 would be forward biased or "on" with vD1 = 0V.

We must try another set of assumptions

- **Assume D1 is "on" and D2 is "off"**

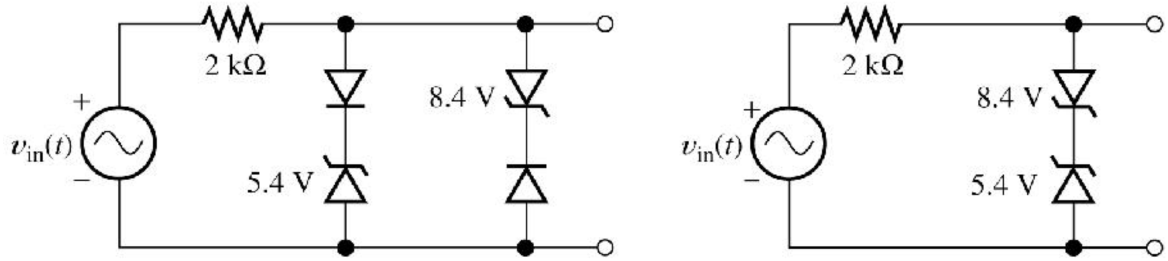


- i_{D1} = 10V/10kΩ = 1mA.
- v_{D2} = 3V – V_1 = 3V –6V = -3V
- We have a <u>valid solution</u>!

D_1 is forward biased - OK

D_1 is reverse biased - OK

Example 2



(a) Circuit of Figure 10.29 with batteries replaced by Zener diodes and allowance made for a 0.6-V forward diode drop

(b) Simpler circuit

Figure 10.30 Circuits with nearly the same performance as the circuit of Figure 10.29.
