Handout 1 for EE-203

Chapter3: Diodes

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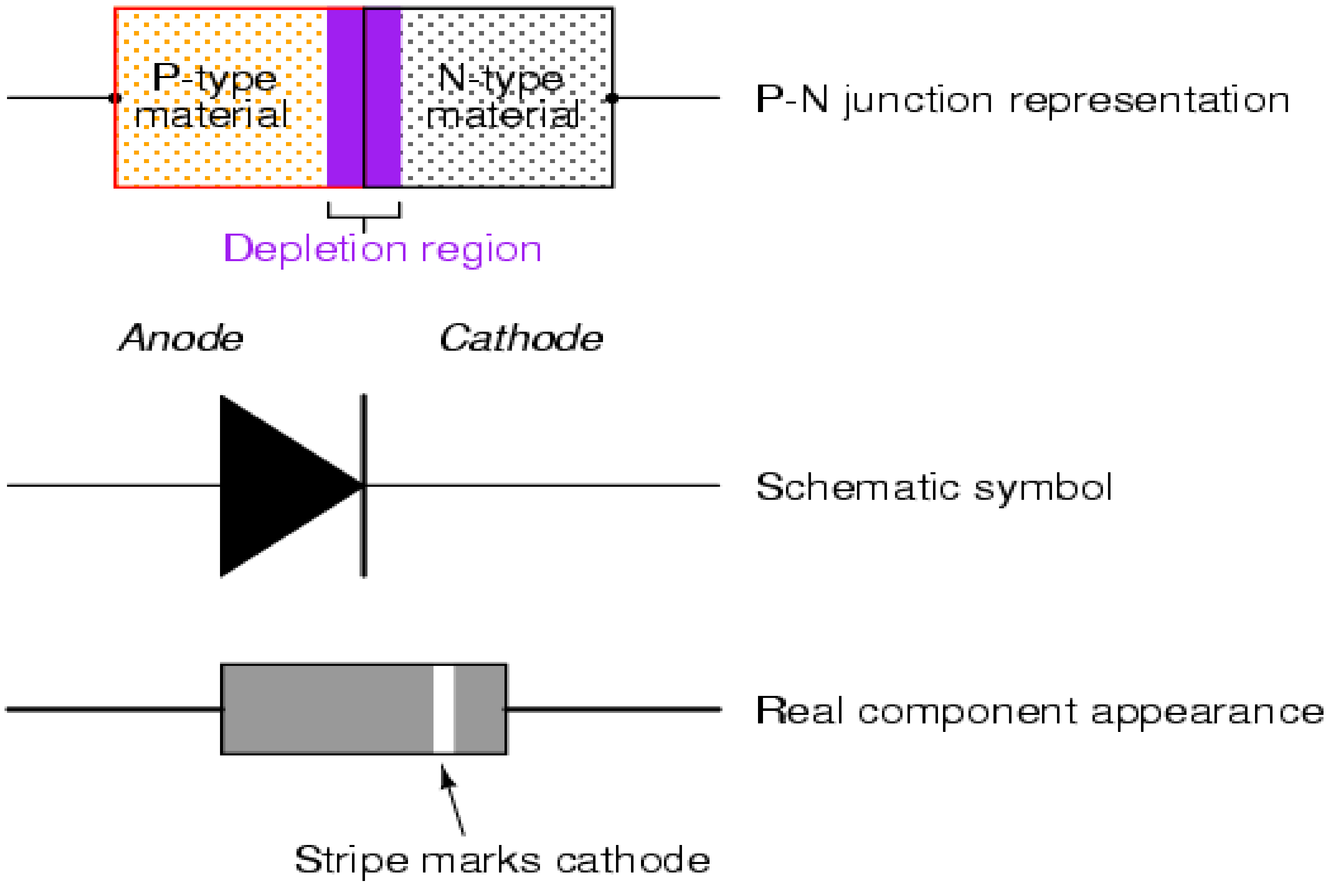
(Ref: Text book and
KFUPM Online course of EE-203)

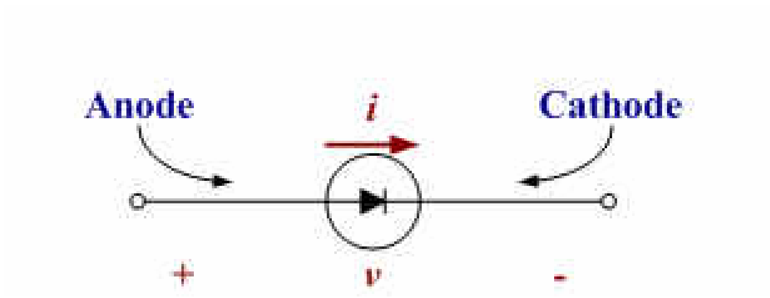
(Remember to solve all the related examples, exercises problems as given in the Syllabus)

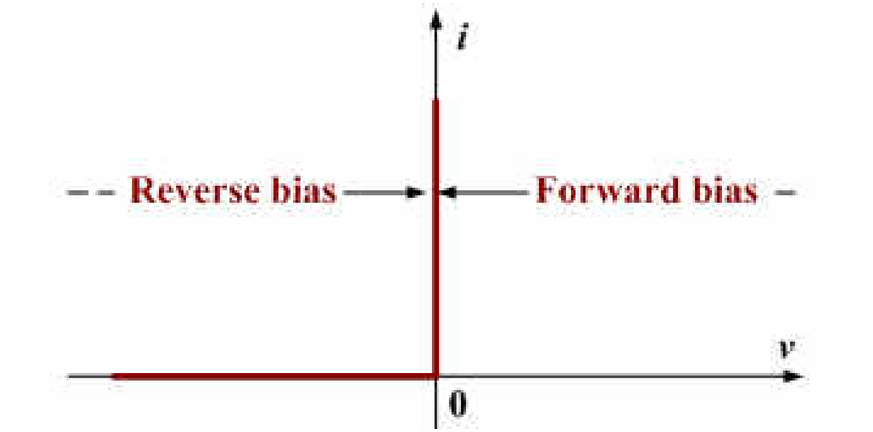
Introduction:

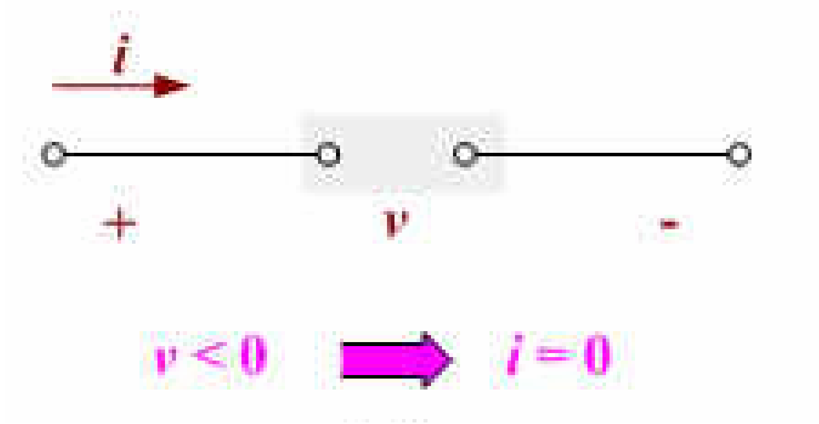
Ideal DIODE. Diode is two terminal device that controls current flow.

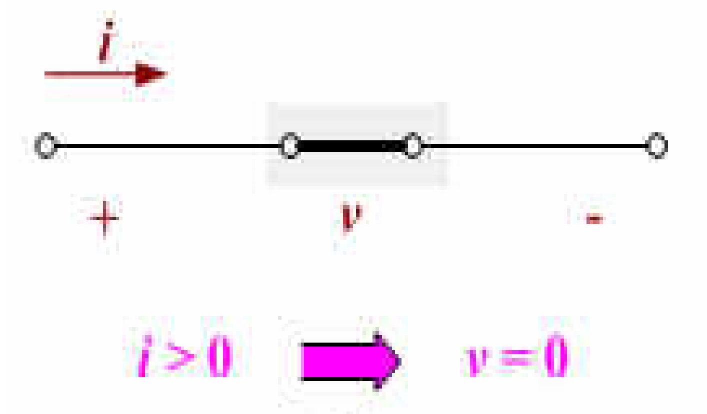


3.1: The Ideal Diode Characteristics:







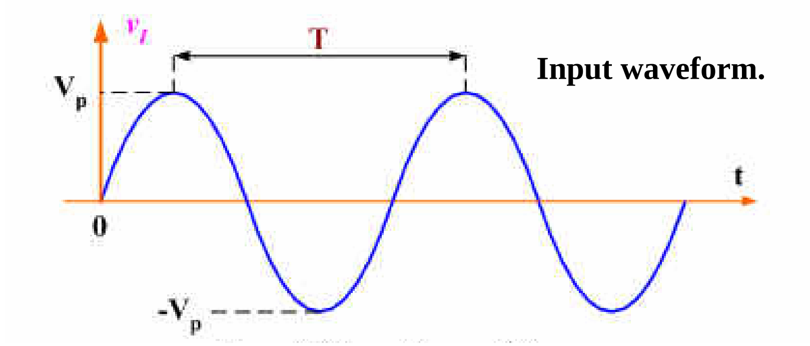


For an ideal diode, when Anode is connected with '-' terminal of the source, and Cathode is connected with '+' terminal of the source, the DIODE is Reverse Biased (R.B) and acts as a Open-circuited (S/C) device.

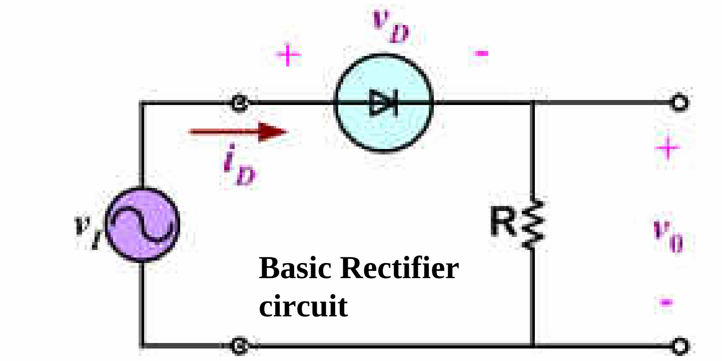
For an ideal diode, when Anode is connected with '+' terminal of the source, and Cathode is connected with '-' terminal of the source, the DIODE is Forward Biased (F.B) and acts as a short-circuited (S/C) device.

Figures are ***(a)*** *diode circuit symbol;* ***(b)*** *i-v characteristic;* ***(c)*** *equivalent circuit in the reverse direction;* ***(d)*** *equivalent circuit in the forward direction.*

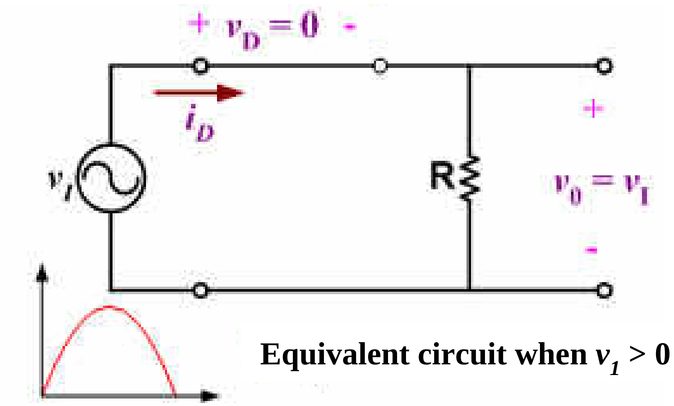
3.1: Rectifier using ideal-diode:



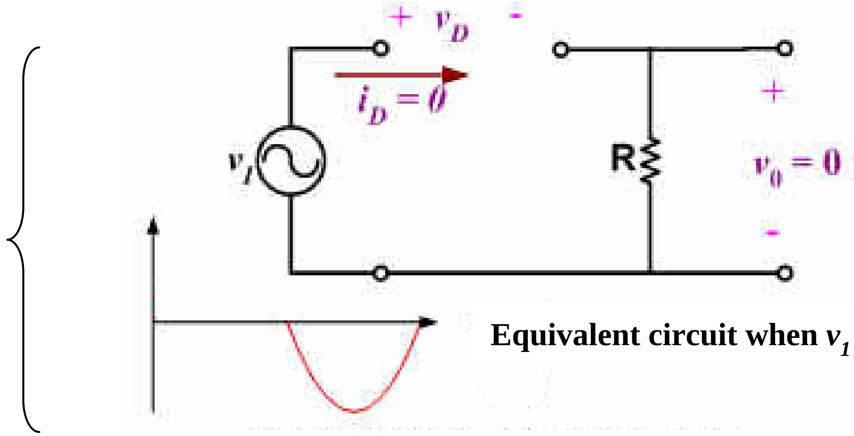
Input waveform.



Basic Rectifier circuit



Equivalent circuit when $v_I > 0$

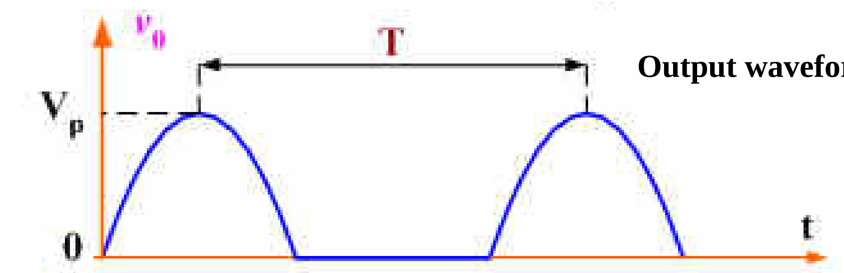


Equivalent circuit when $v_I \leq 0$

-For '+' half-cycle of the voltage, the diode is forward biased and acts as S/C as shown in figure

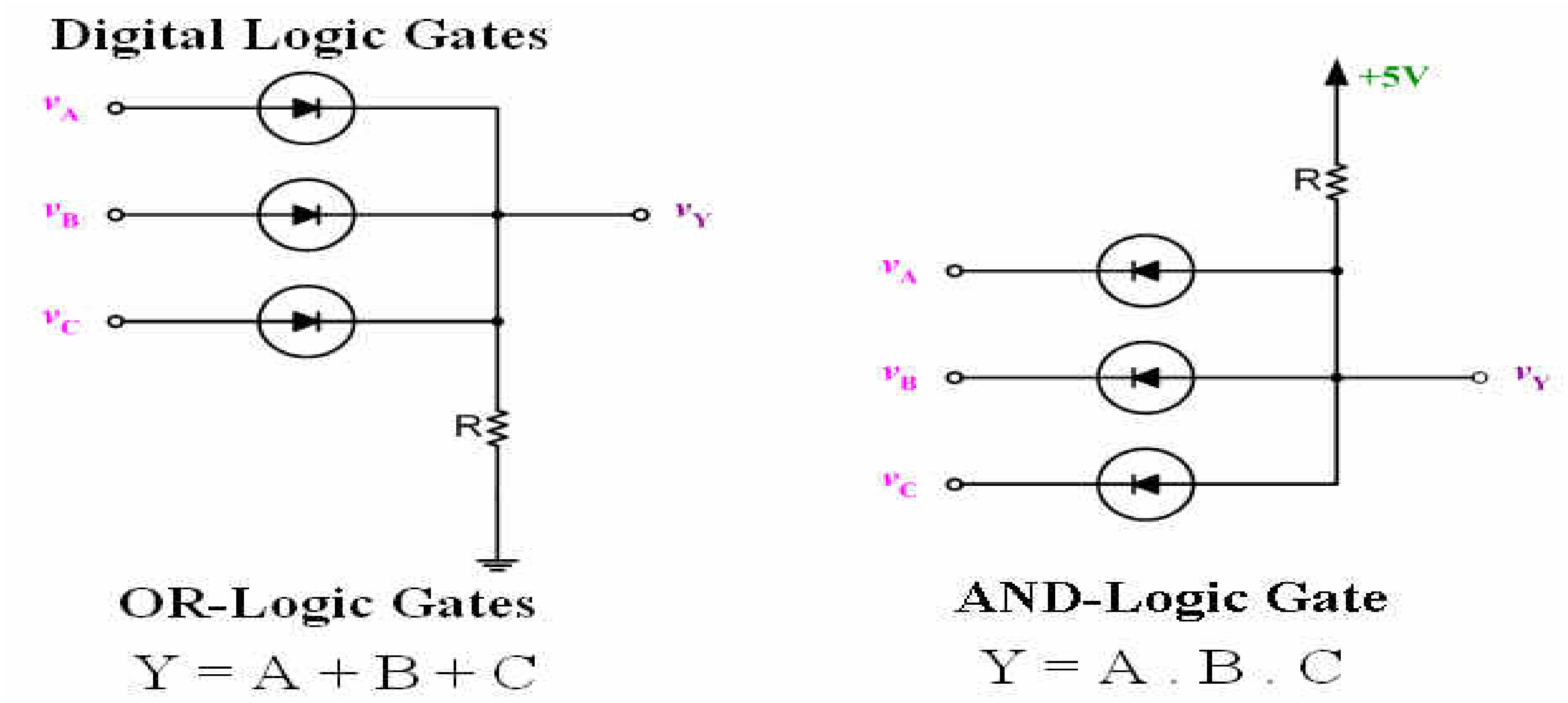
- For '-' half-cycle of the voltage, the diode is reverse biased and acts as S/C as shown in figure.

- Thus the Output waveform of the rectifier circuit (across the resistor 'R') is given by ➔

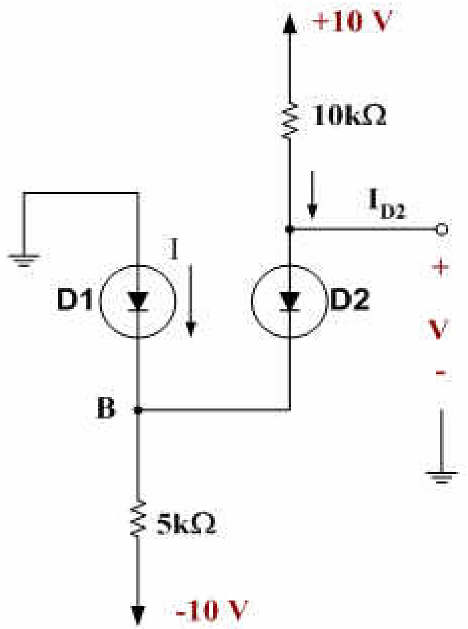


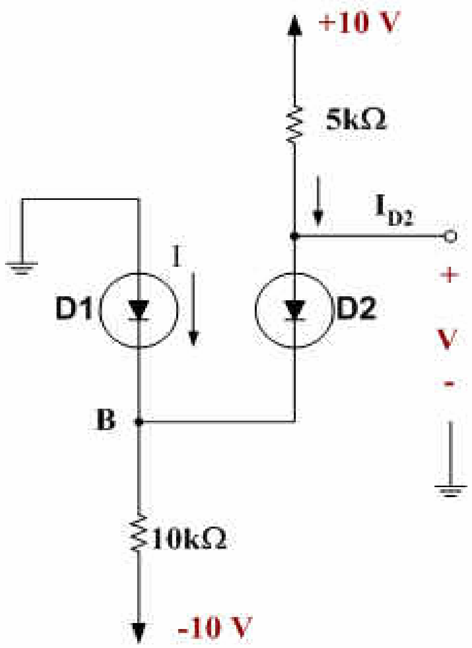
Output waveform.

- **Ideal diodes** used to implement logic circuits:



EXAMPLE 3.2 Assuming the diodes to be ideal, find the values of I and V in the circuits of Fig. 3.6.





In these circuits it might not be obvious at first sight whether none, one, or both diodes are conducting. In such a case, *we make a plausible assumption, proceed with the analysis, and then check whether we end up with a consistent solution*. For the circuit in Fig. 3.6(a), we shall assume that both diodes are conducting. It follows that $V_B = 0$ and $V = 0$. The current through D_2 can now be determined from

$$I_{D2} = \frac{10-0}{10} = 1 \text{ mA}$$

Writing a node equation at B,

$$I + 1 = \frac{0-(-10)}{5}$$

results in $I = 1$ mA. Thus D_1 is conducting as originally assumed, and the final result is $I = 1$ mA and $V = 0$ V.

For the circuit in Fig. 3.6(b), if we assume that both diodes are conducting, then $V_B = 0$ and $V = 0$. The current in D_2 is obtained from

$$I_{D2} = \frac{10-0}{5} = 2 \text{ mA}$$

The node equation at B is

$$I + 2 = \frac{0-(-10)}{10}$$

which yields $I = -1$ mA. Since this is not possible, our original assumption is not correct. We start again, assuming that D_1 is off and D_2 is on. The current I_{D2} is given by

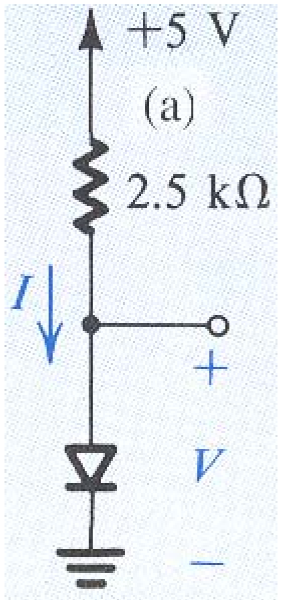
$$I_{D2} = \frac{10-(-10)}{15} = 1.33 \text{ mA}$$

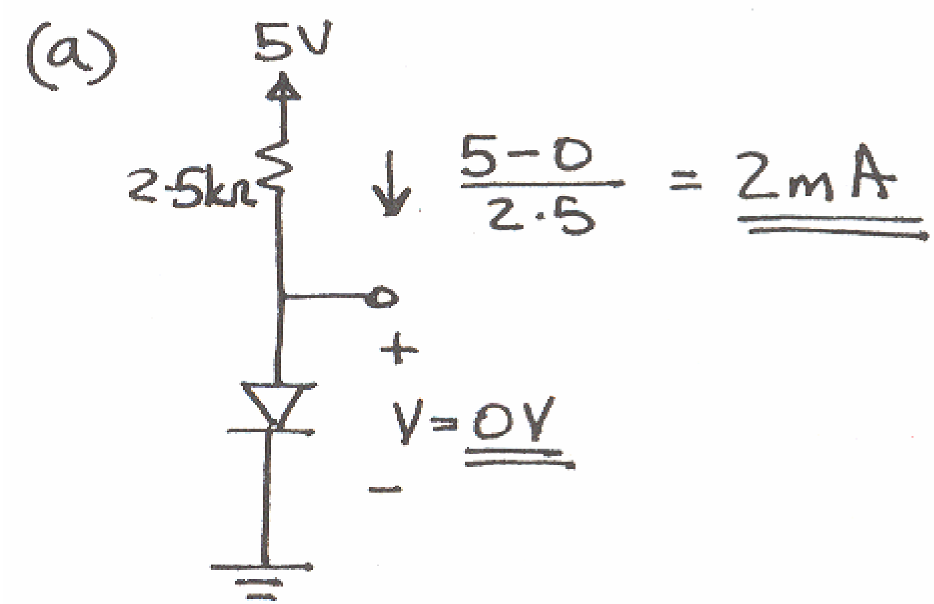
and the voltage at node B is

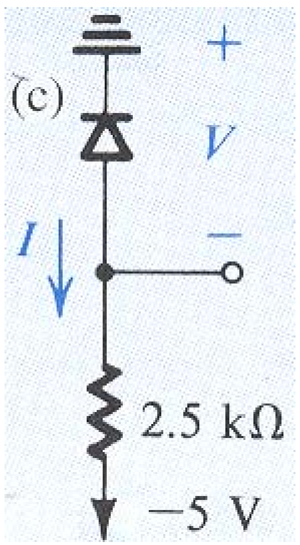
$$V_B = -10 + 10 \times 1.33 = +3.3 \text{ V}$$

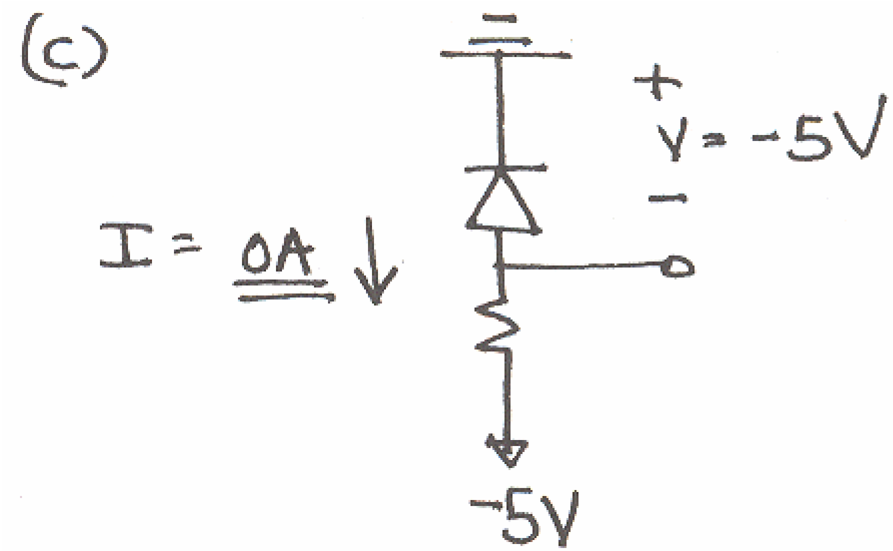
Thus D_1 is reverse biased as assumed, and the final result is $I = 0$ and $V = 3.3$ V.

EXERCISES **3.4** Find the values of I and V in the circuits shown in Fig. E3.4



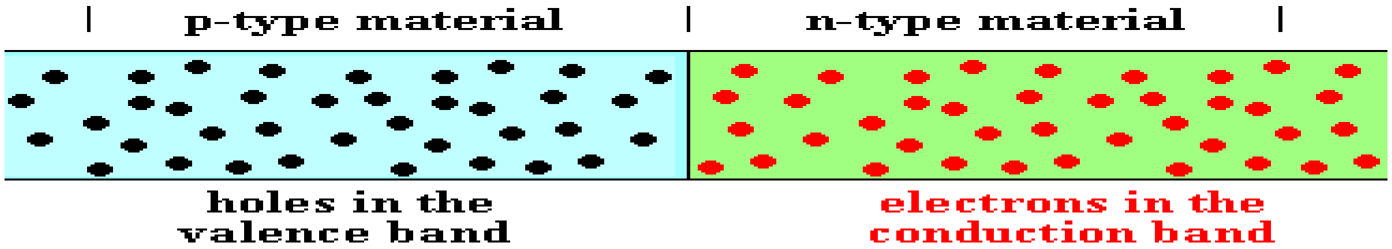




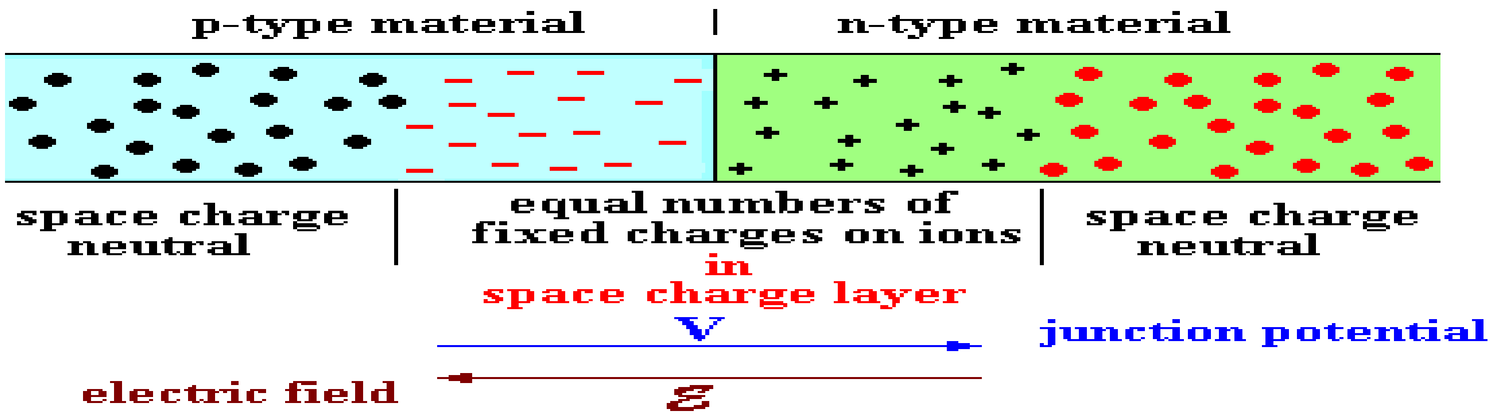


3.7: Physical Operation of Diode at the p-n Junction Interface:

On expanding a small section of the region around the junction, initially an excess of holes in the p-region and of electrons in the n-region would be expected.



However, it is all the one crystal around the junction and the excess of holes and electrons will naturally diffuse in their respective directions across the junction from regions of high concentration to low concentration. Now there will be a recombination of electrons and holes around the junction, as the electrons encounter holes where they may remain at a lower energy state.



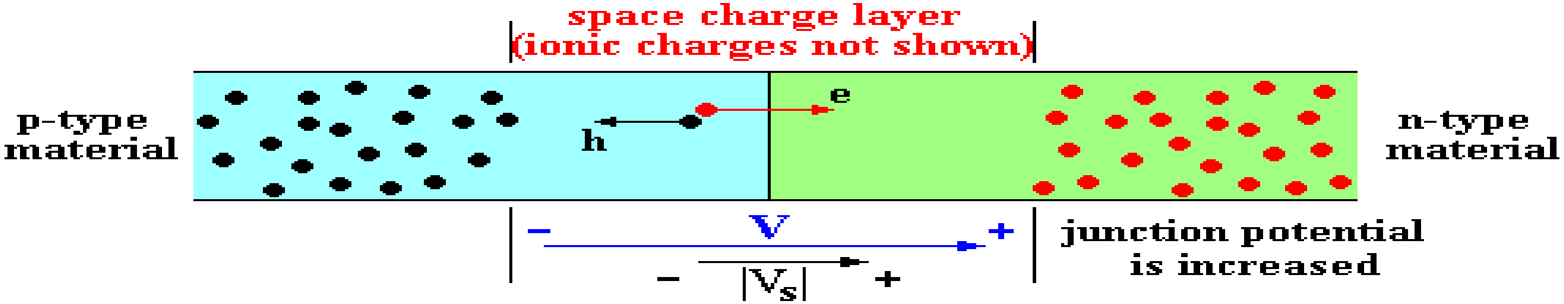
The potential difference across the space charge layer is reduced. Now, the diffusion effect dominates over the field effect on the electrons and holes and

i) electrons diffuse from the right to the left where they recombine with holes,
ii) holes diffuse from the left to the right where they recombine with electrons,
iii) with the charges being replenished from the external source, a current flows from left to right.

Case 3: The source voltage is negative.

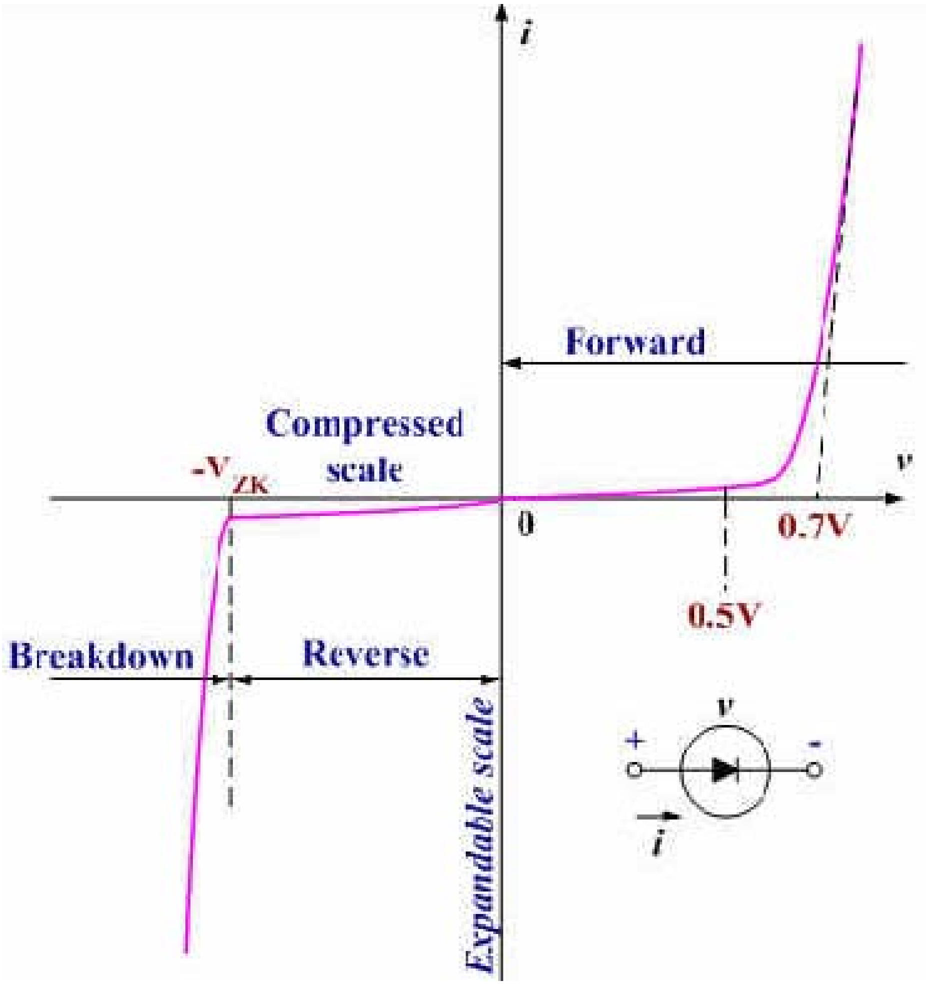
With the positive potential now being connected to the n-region, the potential difference across the space charge layer is increased and the electric field effects stop and diffusion of electrons or holes across the junction. There is no current flowing in the circuit.

Why does a small current actually flow in the reverse direction?



Thermal effects will continually generate electron-holes pairs throughout the crystal structure. Within the space charge layer, if an electron-hole pair is generated under reverse bias conditions, the electric field will cause the electron to move towards the positive potential and the hole towards the negative potential. Hence there will be a current flow from n-region to p-region, i.e. in the reverse direction under reverse bias.

3.2: Real Diode – *i-v* Characteristic:



$$i = I_S \cdot \left(e^{\frac{v}{n \cdot V_T}} - 1 \right)$$

$$V_T = \frac{k \cdot T}{q}$$

V_T = 25mV at room temp.
k = Boltzmann's constant
q = electronic charge

for i>> Is

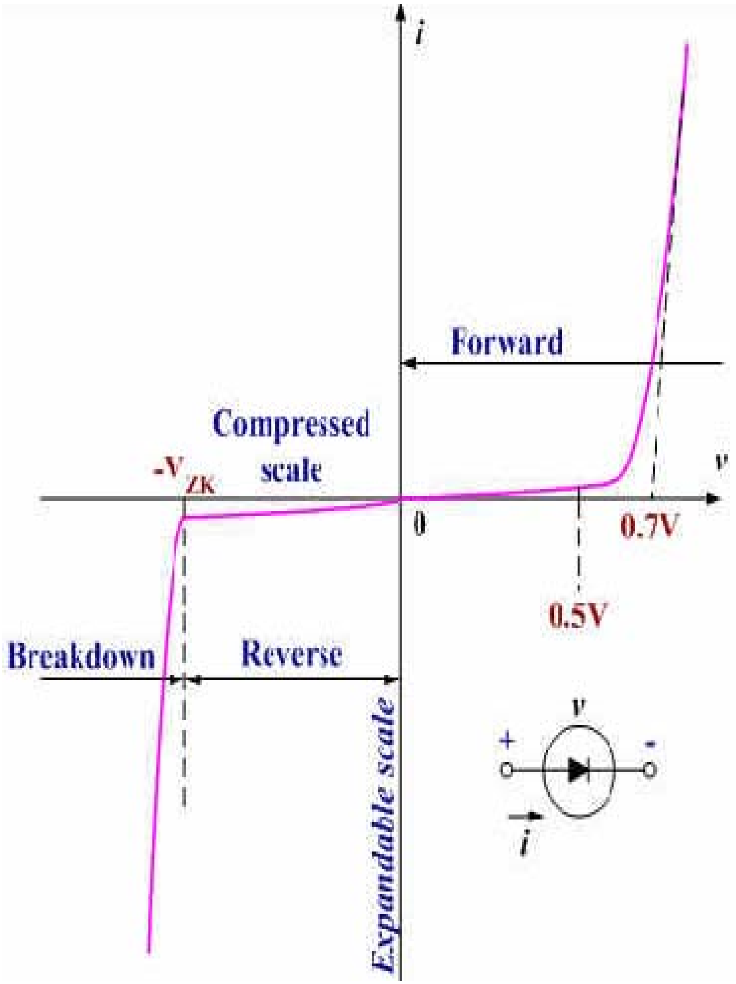
$$i = I_S \cdot \left(e^{\frac{v}{n \cdot V_T}} \right)$$

$$v = n \cdot V_T \cdot \ln\left(\frac{i}{I_S} \right)$$

Since, ln = 2.3 log → $V_2 - V_1 = 2.3 \cdot n \cdot V_T \cdot \log\left(\frac{I_2}{I_1} \right)$

The diode *i-v* relationship with some scales expanded and others compressed in order to reveal details

3.2: Real Diode – *i*-*v* Characteristic (cont'd):



The *i*-*v* characteristic of a silicon junction diode.

Thus:

$$I_D = I_S\,(e^{qV_D/NkT} - 1)$$

Note compared to previous page: n=N, v=V_D and i=I_D

Where,

I_D = diode current in amps

I_S = saturation current in amps (typically 1 x 10^{-15} amps)

e = Euler's constant (~ 2.718281828)

q = charge of electron (1.6 x 10^{-19} coulombs)

V_D = voltage applied across diode in volts

n = "Nonideality" or "emission" coefficient (typically between 1 and 2)

k = Boltzmann's constant (1.38 x 10^{-22})

T = Junction temperature in degrees Kelvin

<u>Remember</u>, typically thermal voltage $V_T \approx 25$ mV at room temperature of 20°C.

3.2: **Diode characteristics for a real diode:**

Question 1: If a current of 1A flows with a diode voltage of 0.65V, what is the value of the constant, I_s

Answer:

$$I = I_s\left\{e^{qV/kT} - 1\right\} \quad \text{gives} \quad 1 = I_s\left\{e^{0.65/0.026} - 1\right\}$$

Therefore $$1 = I_s\left\{7.2 \times 10^{10} - 1\right\}$$ — -1 insignificant

giving $$I_s = 1.4 \times 10^{-11}\ \text{A} \quad \text{i.e. } 14\ \text{pA}$$

Question 2: What is the voltage across this same diode if only 1mA is flowing?

Answer : The (–1) term in the diode current-voltage equation will again be ignored since I is much greater than I_s .Therefore, →

I_s

$$10^{-3} = 14 \times 10^{-12}\left\{e^{V/0.026}\right\}$$

$$e^{V/0.026} = 7.2 \times 10^{7}$$

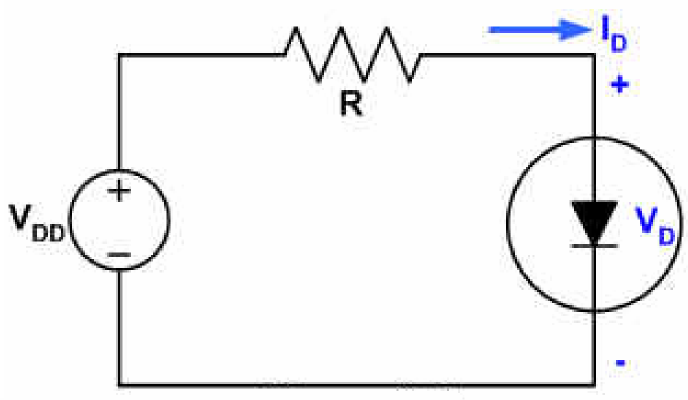
giving $$V = 0.026\ \ln\left(7.2 \times 10^{7}\right)$$

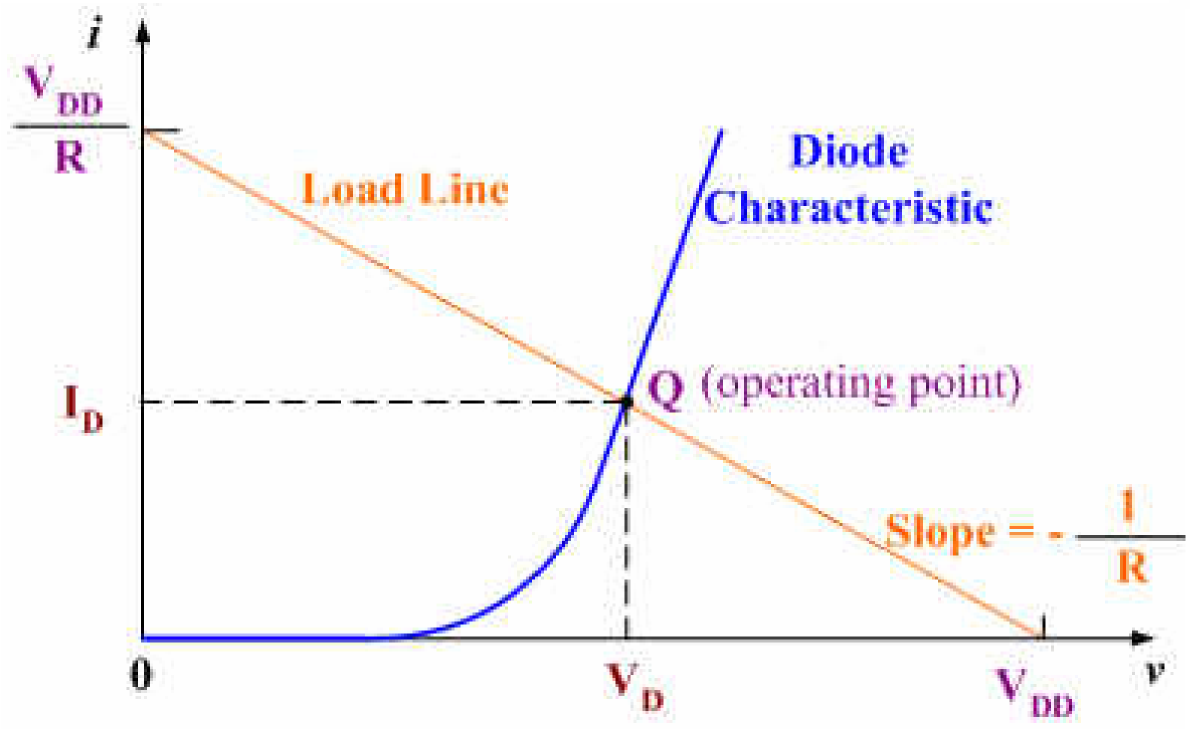
i.e. $$V = 0.47\ \text{volt.}$$

3.3: MODEING of diodes forward characteristics:

-The Exponential Model: $I_D = I_S\,(e^{qV_D/NkT} - 1)$

- The Graphical Analysis using exp. model





$$I_D = I_S e^{V_D/nV_T}$$

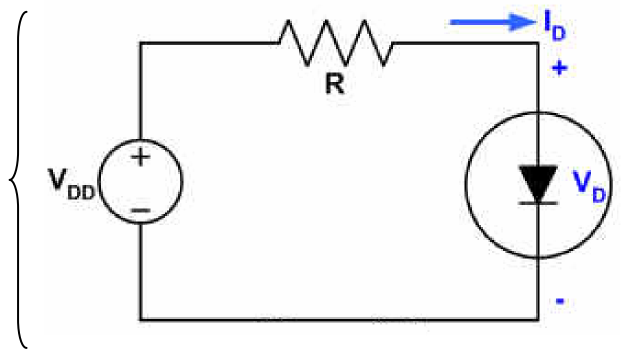
Assume I_S and n are known.

$$I_D = \frac{V_{DD} - V_D}{R}$$

Solve example 3.4

3.3: Iterative Analysis using the exp. Model: Example 3.4

Determine ID and VD for this circuit with VDD = 5 V and R1 = 1 K ohm.
Assume diode current 1 mA at voltage 0.7 V, and that its voltage drop changes by 0.1 V for every decade change in current.



$VDD := 5 \qquad R1 := 1000 \qquad VD := 0.7$

$$I_D = \frac{V_{DD} - V_D}{R_I} \qquad ID = 4.3 \times 10^{-3}$$

We then use the diode equation to obtain a better estimate for VD

$$V2 - V1 = 2.3 \cdot n \cdot V_T \cdot \log\left(\frac{I2}{I1}\right) \qquad V1 := 0.7 \ \ V \qquad I2 := 4.3 \ \ mA \qquad I1 := 1 \ \ mA$$

For our case 2.3.n.VT = 0.1 V (This results from the condition of 0.1 V change for every decade change in current

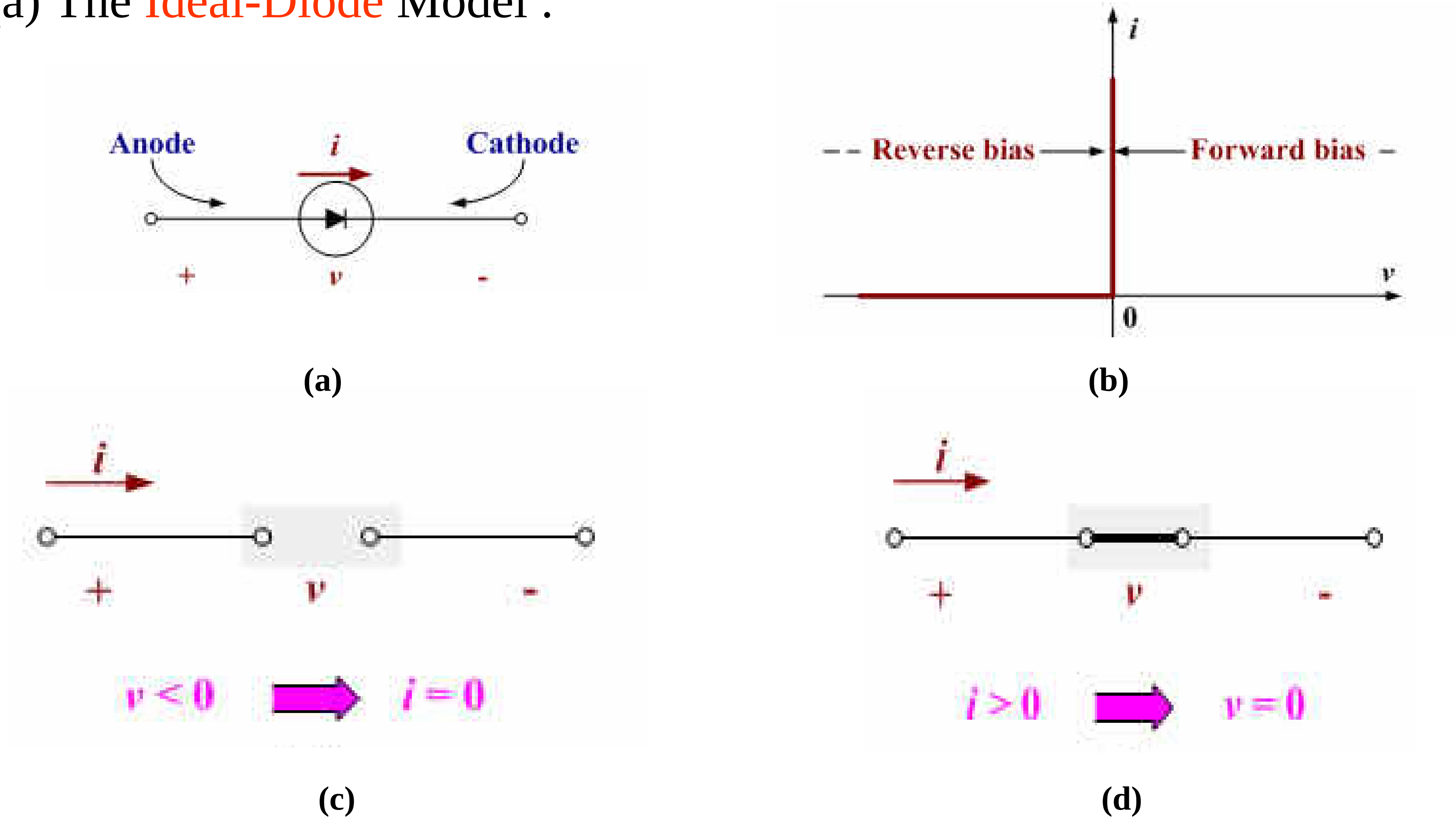
$$V2 := V1 + 0.1 \cdot \log\left(\frac{I2}{I1}\right) \qquad V2 = 0.763$$

$$ID2 := \frac{5 - 0.763}{1000} \qquad ID2 = 4.237 \times 10^{-3}$$

$$V2 := 0.763 + 0.1 \cdot \log\left(\frac{ID2}{ID}\right) \qquad V2 = 0.762$$

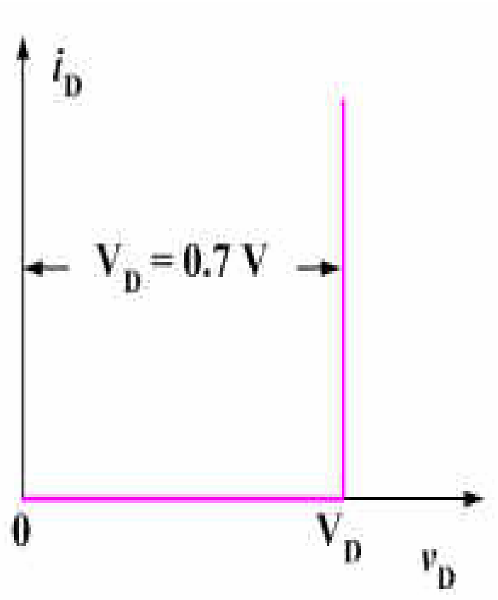
Review on MODEING of diodes forward characteristics:

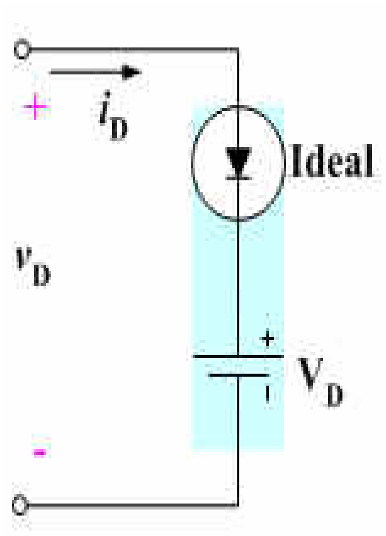
(a) The Ideal-Diode Model :

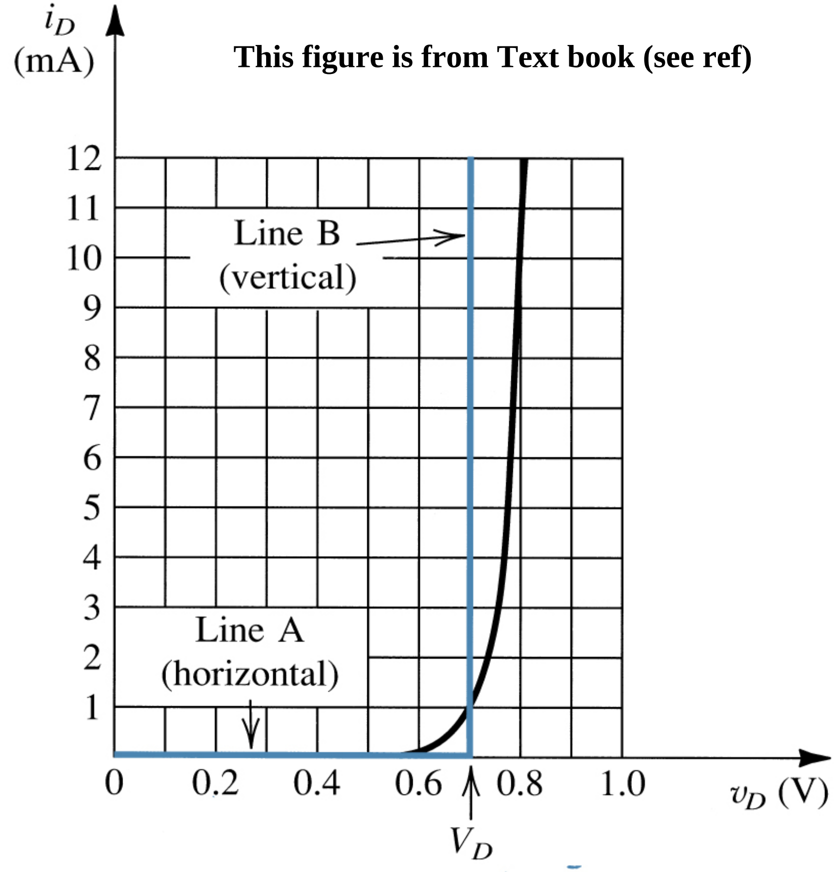


The ideal diode: **(a)** diode circuit symbol; **(b)** *i*-*v* characteristic; **(c)** equivalent circuit in the reverse direction; **(d)** equivalent circuit in the forward direction.

(b) The Constant-Voltage-Drop Model:

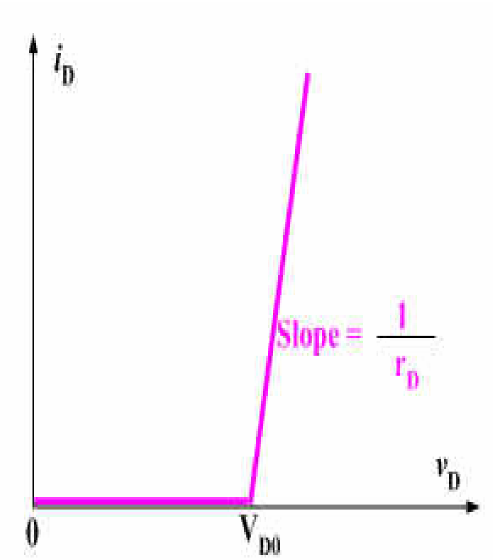


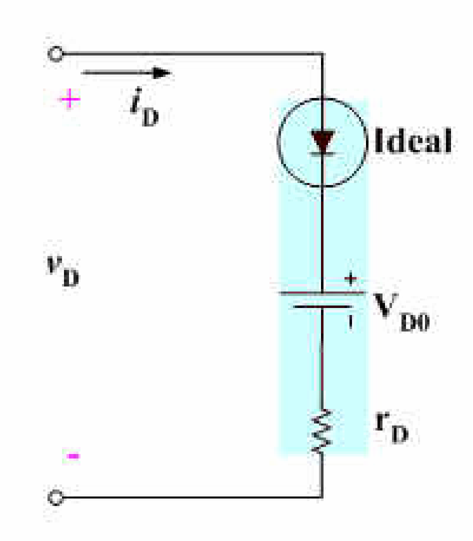


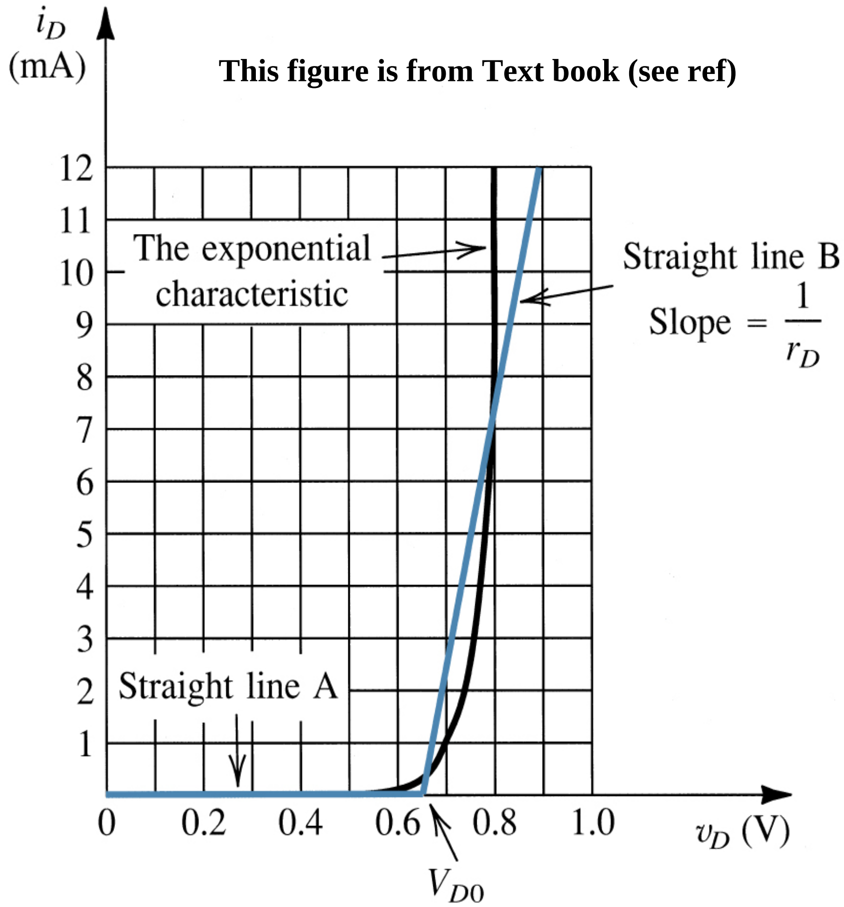


Development of the constant-voltage-drop model of the diode forward characteristics.

(c) Piecewise-linear Model of diode:





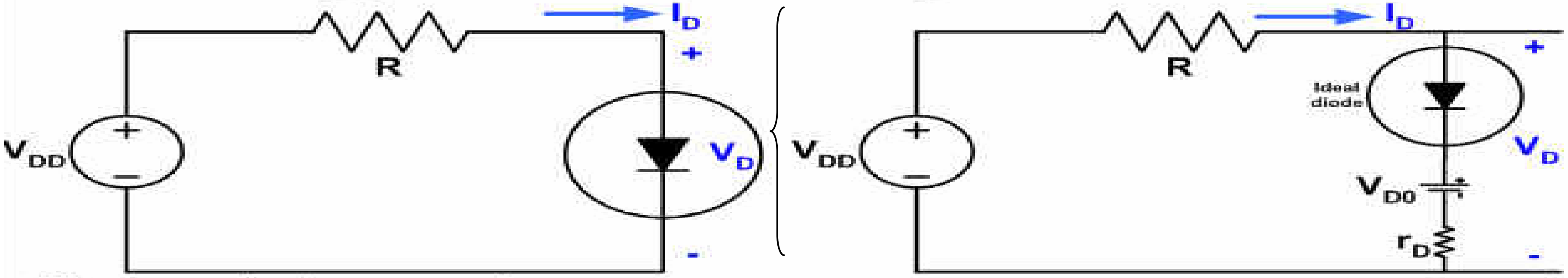


Approximating the diode **forward** characteristic with two straight lines.

Example on Diode Modeling:

Determine I_D and V_D for this circuit with V_{DD} = 5 V and R = 1 kΩ, using the piecewise-linear model whose parameters are:

V_{DO} = 0.65 V & r_D = 20 Ω



We can write the current I_D,

$$I_D = \frac{V_{DD} - V_{DO}}{R + r_D} = \frac{5 - 0.65}{1000 + 20} = 0.00426\ A$$

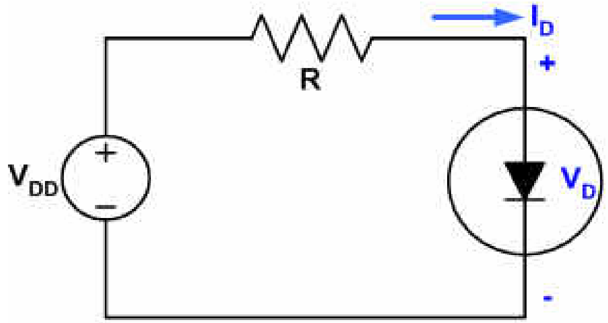
The diode voltage can now be computed,

$$V_D = V_{DO} + r_D \cdot I_D = 0.65 + 20 \times 0.00426 = 0.735\ V$$

Exercise on Diode Modeling:

For the circuit in Figure below find I_D & V_D for the case V_{DD} = 5V & R = 10 kW. Assume the diode has a voltage of 0.7 V at 1 mA current and that the voltage changes by 0.1 V/decade of current change. Use:

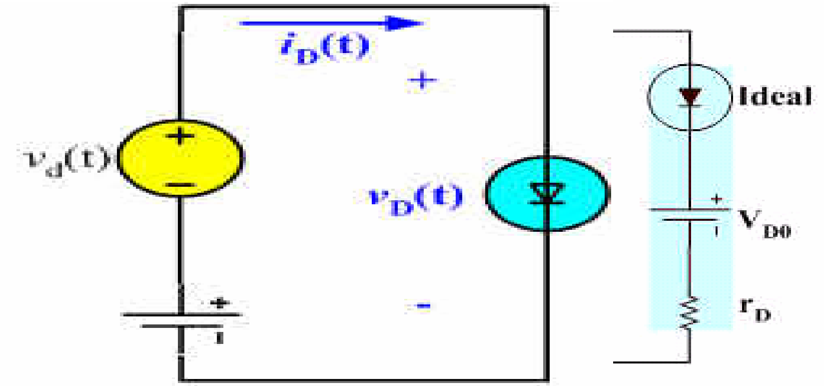
(a) iteration; (b) the piecewise linear model with V_{D0} = 0.65V & r_D = 20W ; and (c) the constant voltage drop.

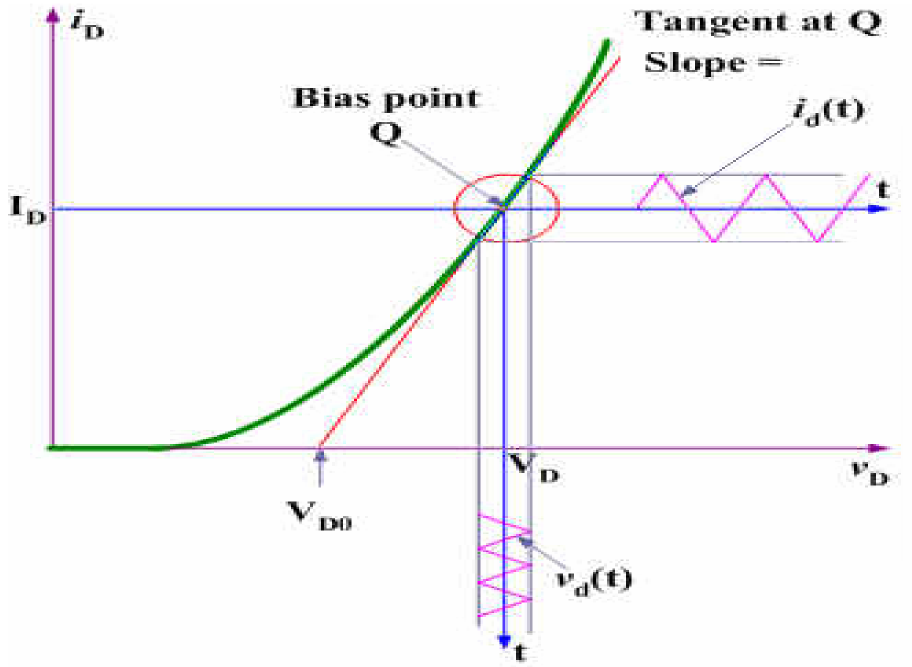


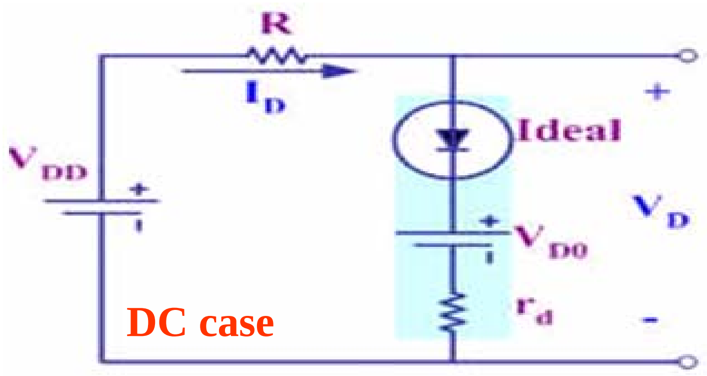
Ans. (a) 0.434 mA, 0.663 V
(b) 0.434 mA, 0.659 V
(c) 0.43 mA, 0.7 V

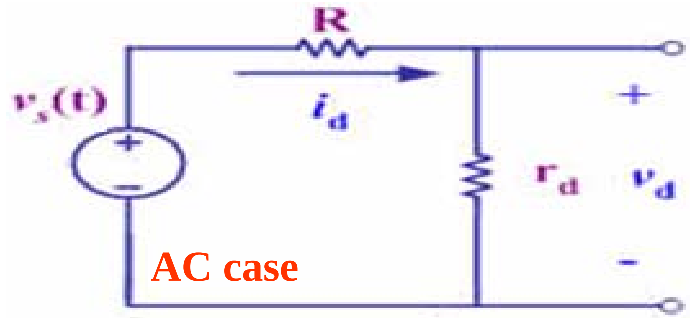
The Small-Signal Model of diode:

$$i_D(t) = I_D \cdot e^{\frac{v_d(t)}{n \cdot V_T}} = I_D + i_d(t)$$









Separating the dc and signal quantities on both sides, the dc equation is:

$$V_{DD} = R \cdot I_D + V_D$$

The signal equation is:

$$v_S = (R + r_d) \cdot i_d$$

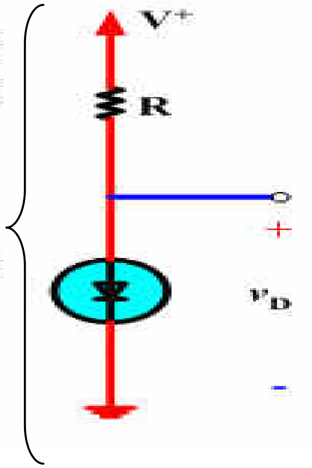
The signal analysis is performed by eliminating all dc sources and replacing the diode with its small-signal resistance r_d. The diode signal voltage can be simply found using voltage divider as:

$$v_d = v_s \frac{r_d}{R + r_d}$$

Example on Diode Modeling:

Consider the circuit shown in the figure for the case R = 10 kohm. The power supply, V^+ has a dc value of 10V in which is superimposed a 60 Hz sinusoid of 1-V peak amplitude. It is known as power supply ripple.

Calculate the dc voltage of the diode and the amplitude of the sine-wave signal appearing across it. Assume the diode to have a 0.7V drop at 1-mA current and n = 2.



Solution: (Note: all resistor values are in kohm)

Considering dc quantities only, we assume $V_D = 0.7V$ and calculate the dc current:

$$I_D = \frac{10-0.7}{10} = 0.93 \quad mA$$

Since this value is very close to 1-mA, the diode voltage will be very close to the assumed value of 0.7V. At this operation point, the diode incremental resistance r_d is:

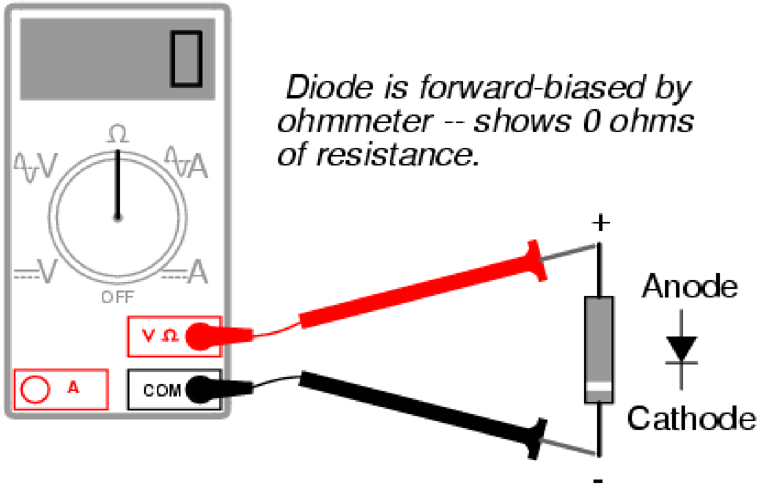
$$r_d = \frac{n \cdot V_T}{I_D} = \frac{2 \times 25}{0.93} = 0.0538 \qquad kohm$$

The peak-to-peak signal voltage across the diode can be found by using the voltage divider value as follows:

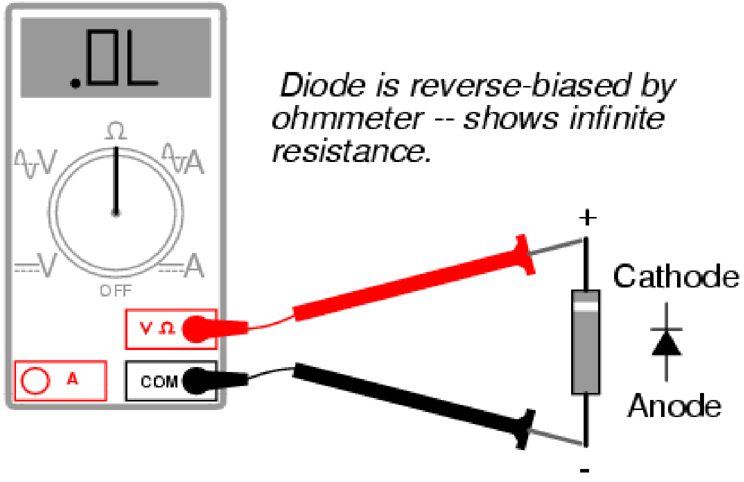
$$v_d(peak-to-peak) = 2 \cdot \frac{r_d}{r_d + R} = 2 \cdot \frac{0.0538}{10+0.0538} = 10.7 \quad mV$$

Thus the amplitude of the sinusoidal signal across the diode is 5.35 mV. Since this value is quite small, our use of the small-signal model of the diode is justified.

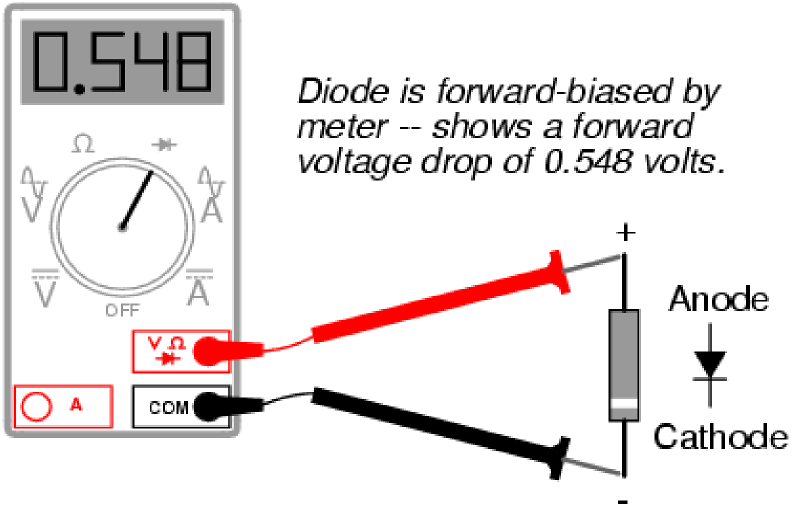
Diode – Measurements



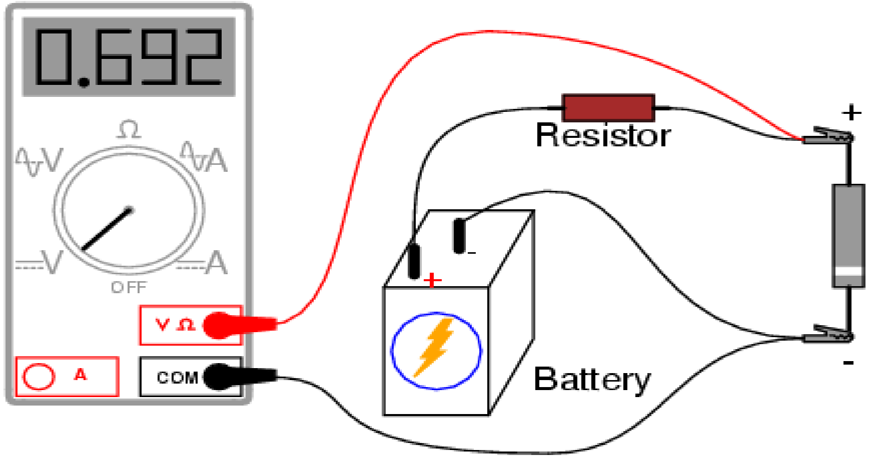
Diode is forward-biased by ohmmeter -- shows 0 ohms of resistance.



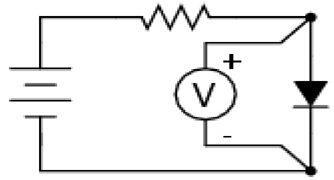
Diode is reverse-biased by ohmmeter -- shows infinite resistance.



Diode is forward-biased by meter -- shows a forward voltage drop of 0.548 volts.

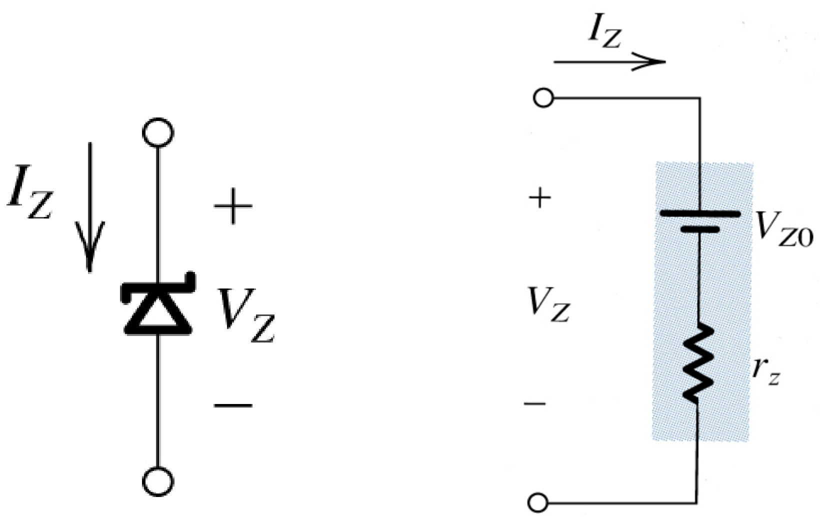


Schematic diagram



Resistor sized to obtain diode current of desired magnitude.

3.4: Zener Diode: used in break-down region to make voltage-regulators:

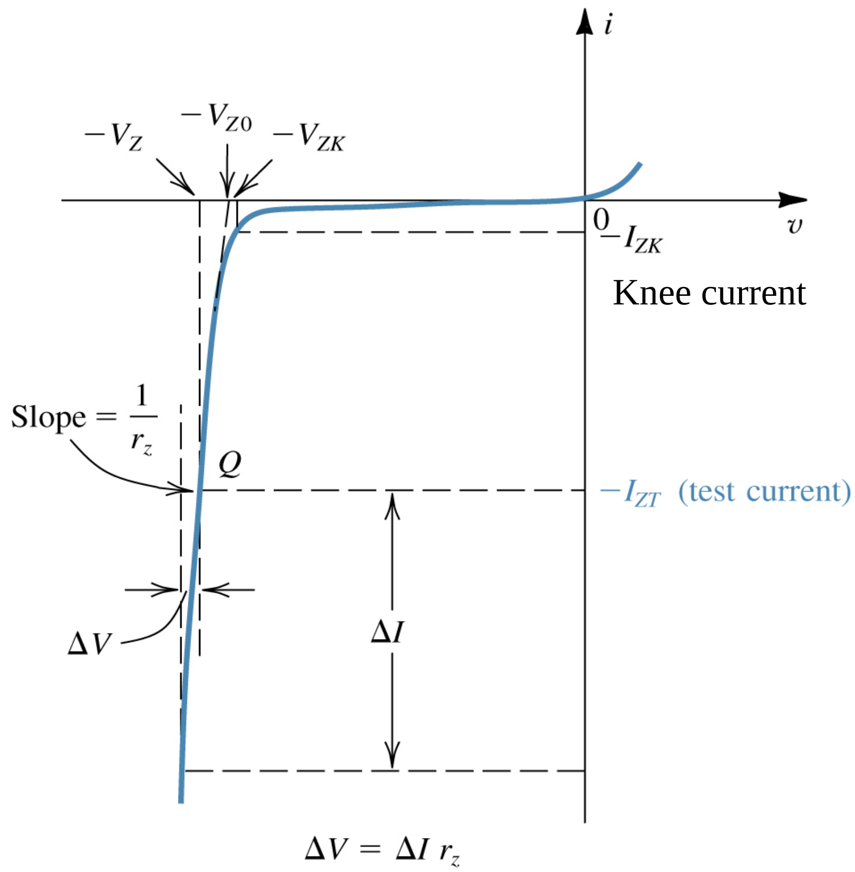


Symbol and Model for the Zener diode.

$$V_z = V_{z0} + r_z I_z$$

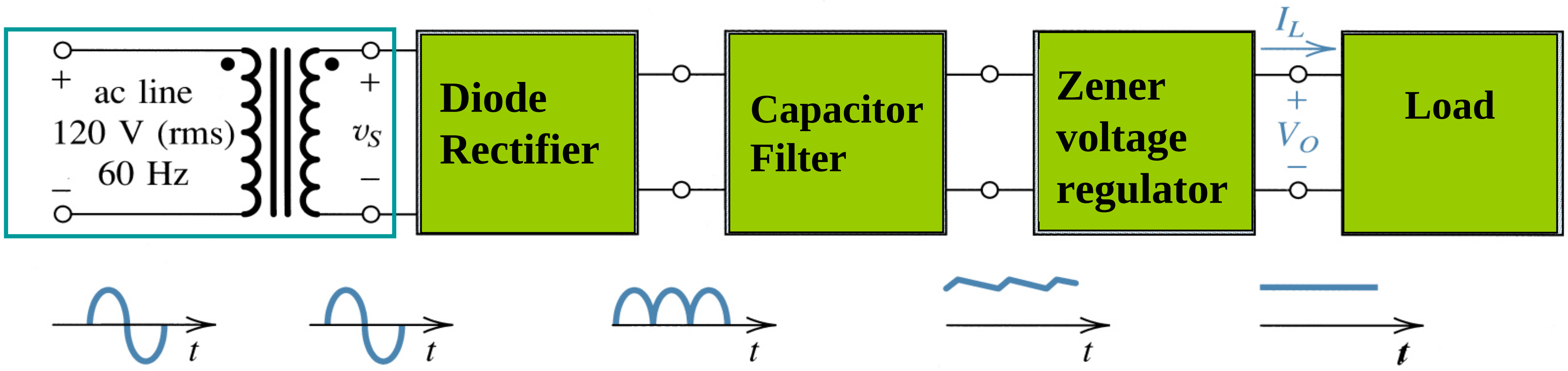
If $I_z > I_{zk}$ *and* $V_z > V_{zo}$

As an example, V_z=6.8V and I_{ZT}= 10mA



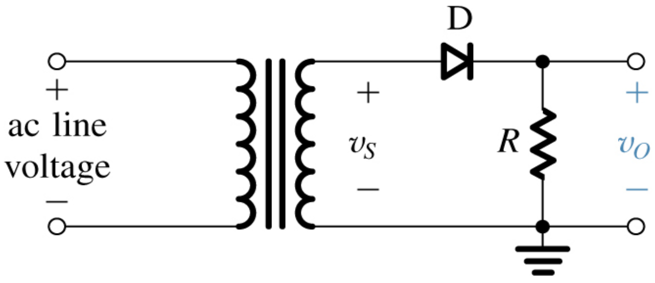
The diode *i*-*v* characteristic with the breakdown region shown in some detail.

3.5: Rectifier Circuits: Application of diodes,

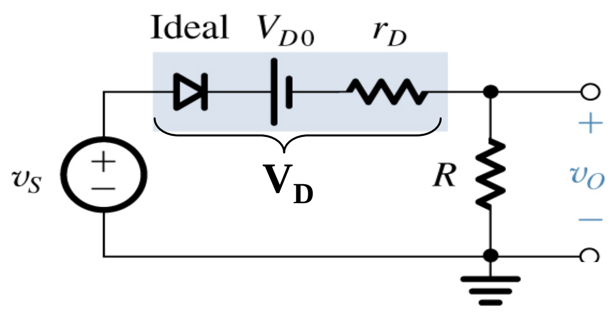


Block diagram of a dc power supply (ref text book).

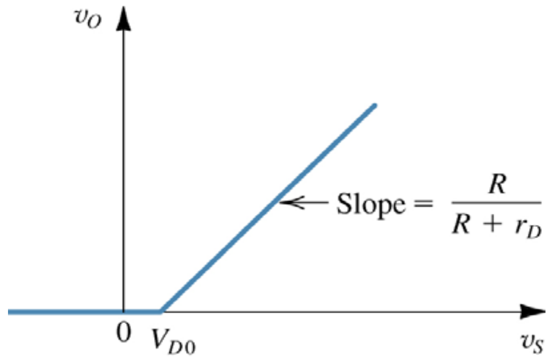
3.5: Halfwave Rectifier Circuits



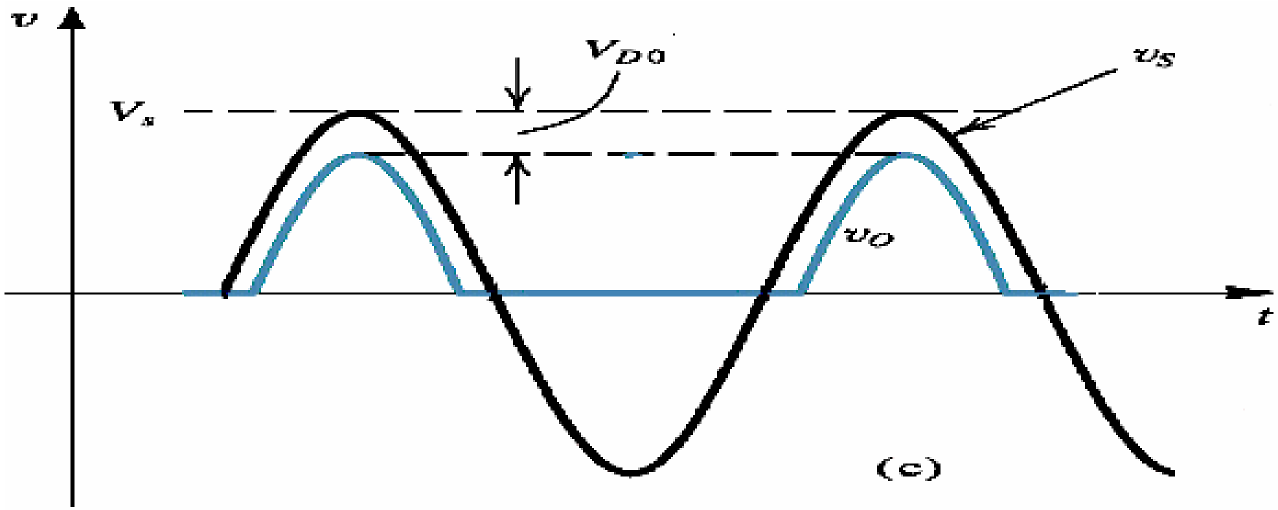
(a)



(b)



(c)



{ **assuming that** $r_D << R$.

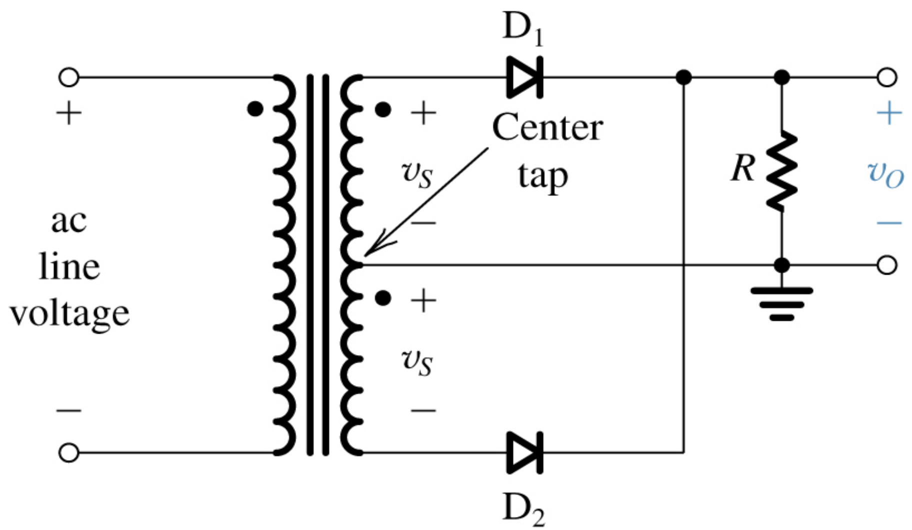
Note the expression for $(V_0)_{DC}$

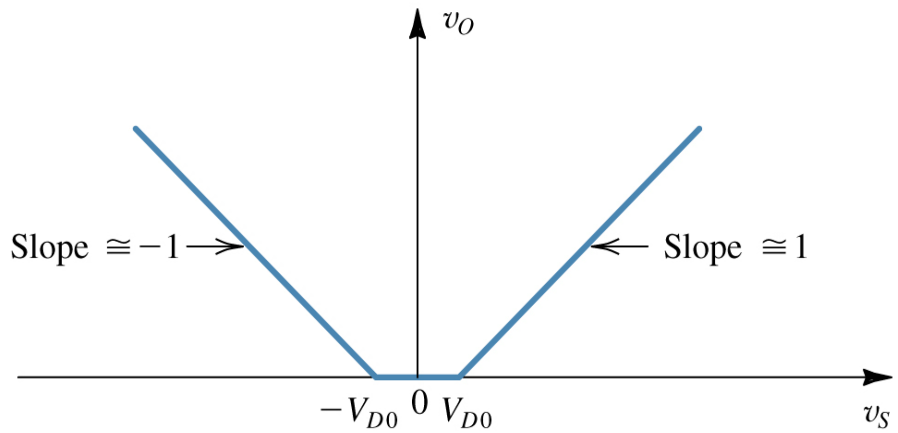
if $v_s < V_{D0}$ ➔ $v_0 = 0$,

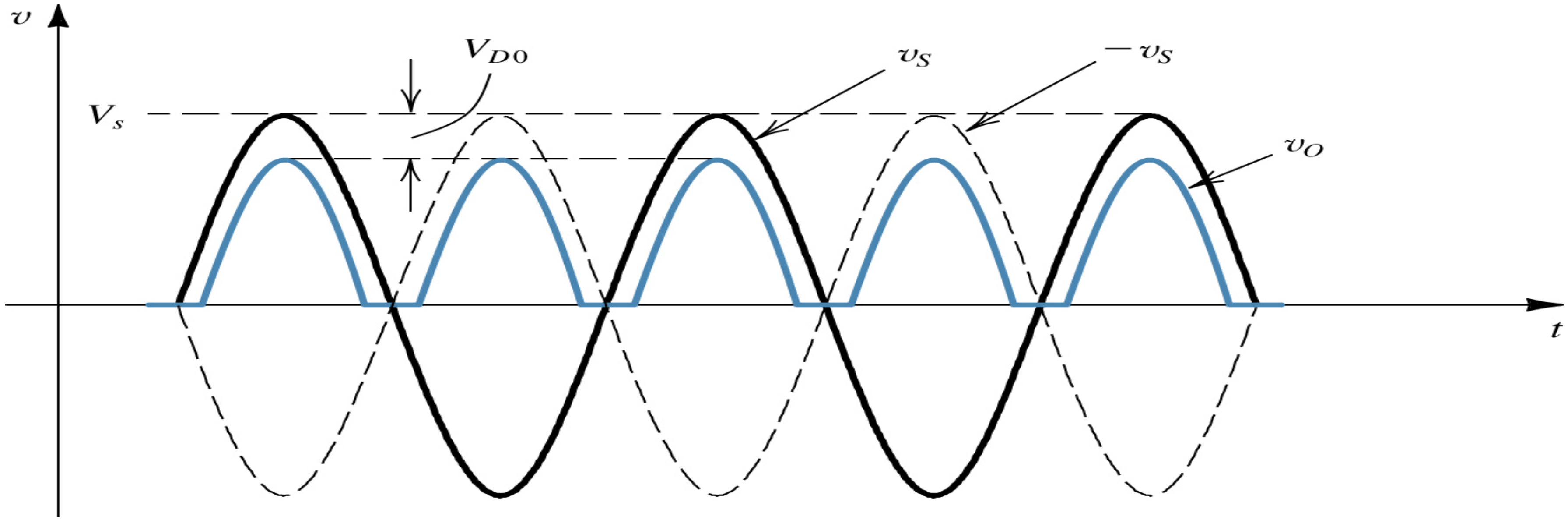
if $v_s \geq V_{D0}$ ➔ $v_0 = (R/(R+r_D).v_s - (R/(R+r_D).V_{D0}$ ➔ *for* $r_D << R$, $v_0 \approx v_s - V_{D0}$,

PIV = v_s ➔ Diode should withstand Peak-Inverse-Voltage without breakdown

3.5: Center Tip Rectifier Circuits





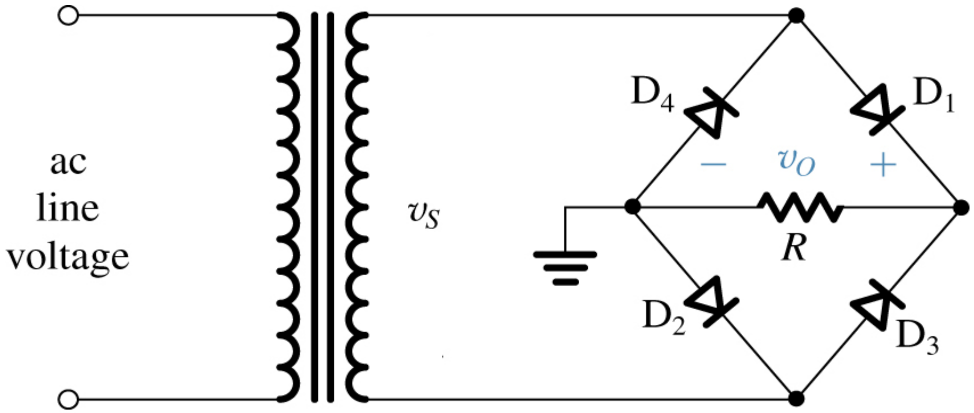


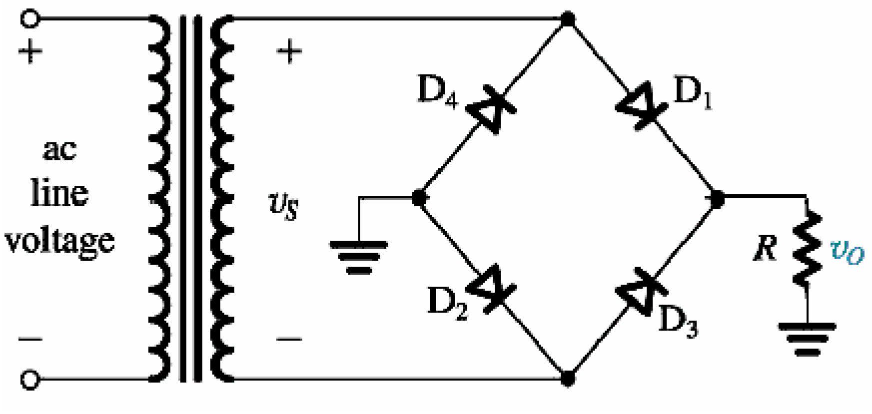
if $v_s < \boldsymbol{V_{D0}}$ ***and*** $\boldsymbol{v_s \geq V_{D0}}$ ➔ $(\boldsymbol{v_0})_p = (\boldsymbol{v_s})_p$ **-** $\boldsymbol{V_{D0}}$, *for* $\boldsymbol{r_D << R}$

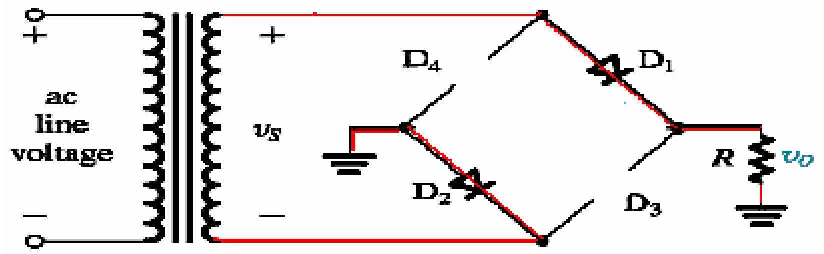
$PIV = 2 \cdot V_S - V_{DO}$

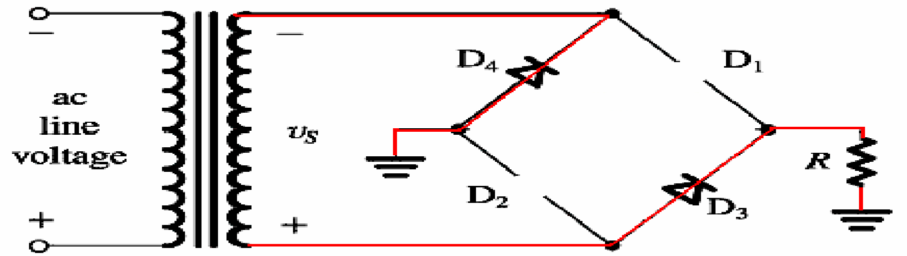
Note the expression for $(V_0)_{DC}$

3.5: Bridge Rectifier Circuits

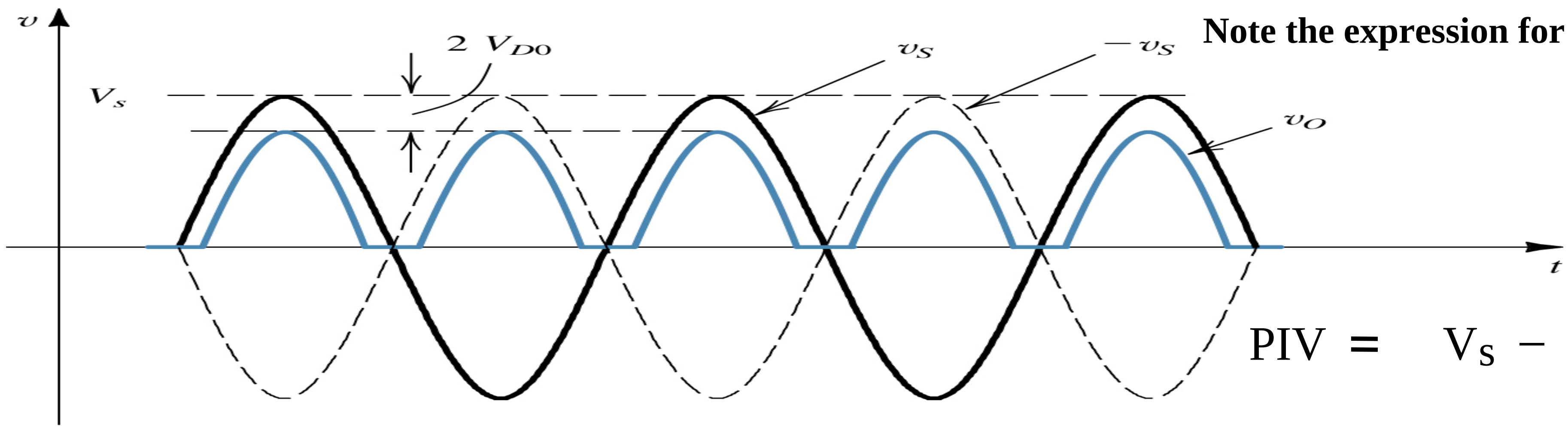






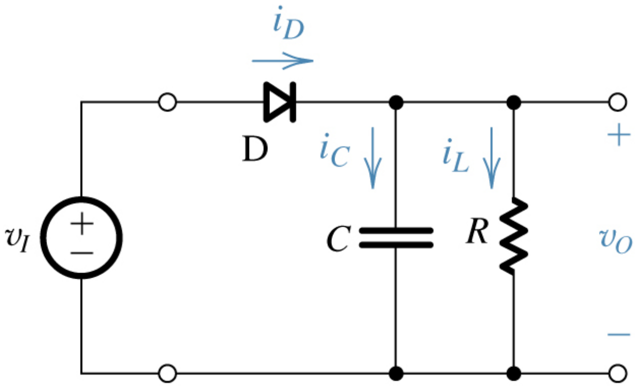


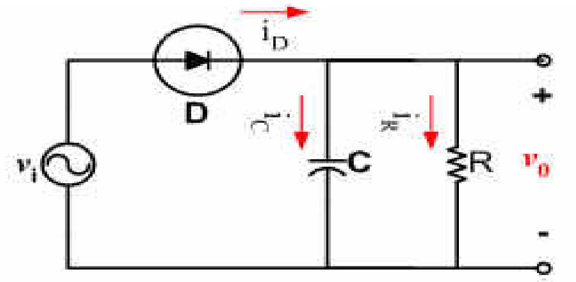
Note the expression for $(V_0)_{DC}$



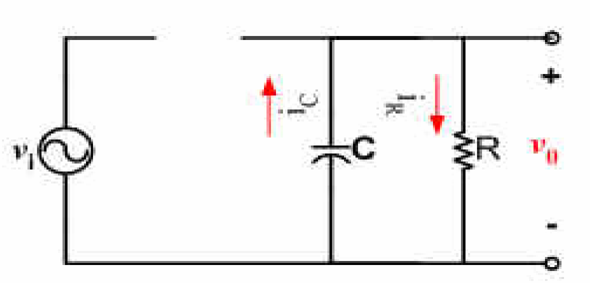
$$PIV = V_S - V_{DO}$$

3.5: Rectifier Circuits With A Filter Capacitor



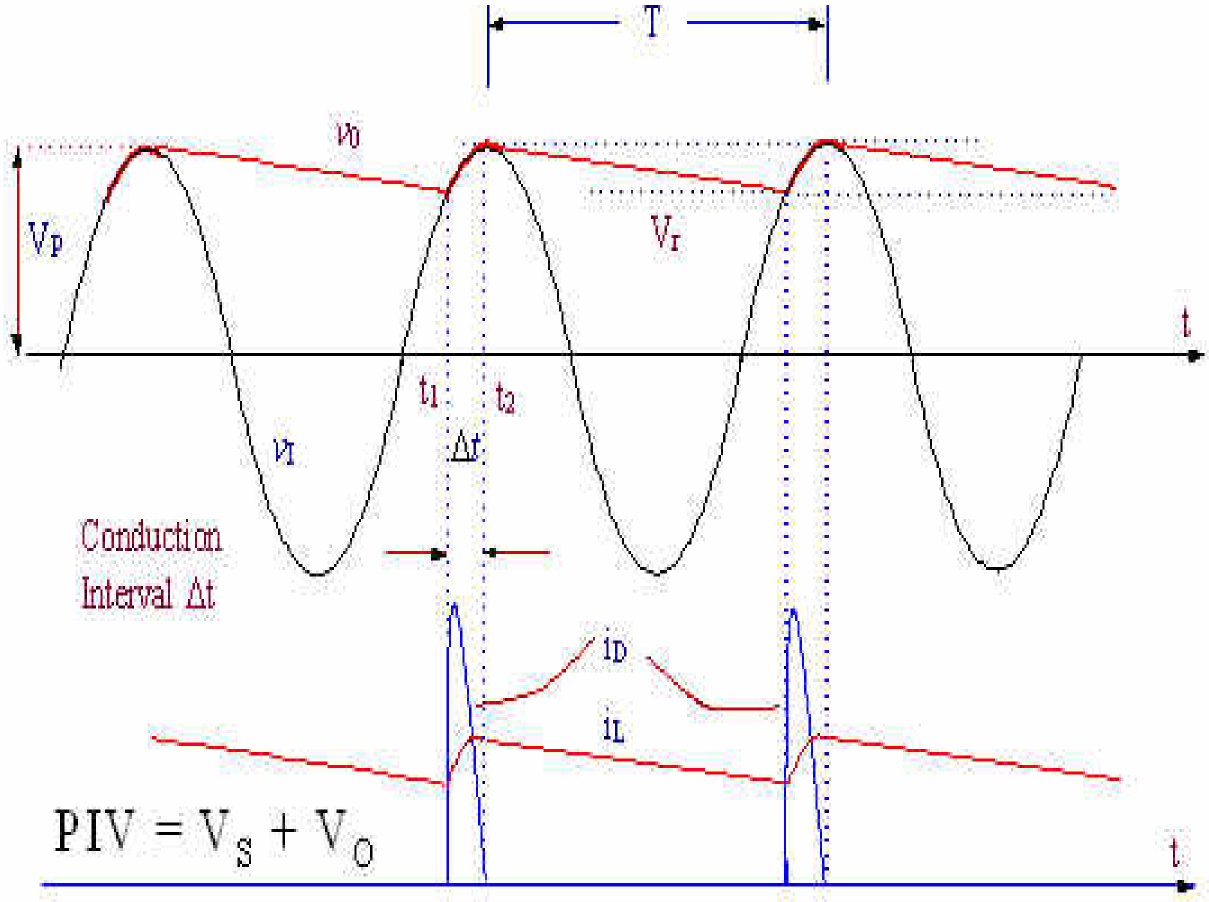


Charging capacitor



Discharging capacitor

Assuming RC>>T:



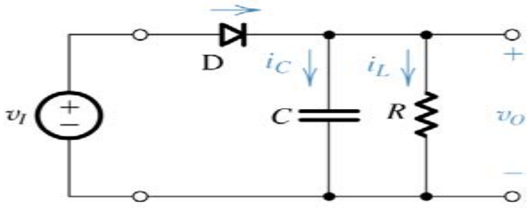
Note the different expression for $(V_0)_{DC}$

Voltage and current waveforms in the peak rectifier circuit with *CR* >> *T*. The diode is assumed ideal.

3.5: Rectifier Circuits

With A Filter Capacitor:

$$i_L = \frac{v_O}{R}$$



$$i_D = i_C + I_L = C\cdot\frac{d}{dt}v_I + i_L \qquad I_L = \frac{V_p}{R}$$

CR >> T $\qquad v_O = V_p\cdot e^{\frac{-t}{C\cdot R}}$

at the end of the discharge intervall

$$V_p - V_r = V_p\cdot e^{\frac{-T}{C\cdot R}}$$

SInce CR >> T and $\quad e^{\frac{-T}{CR}} = 1 - \frac{T}{CR}$

$$V_r = V_p\cdot\frac{T}{CR} \qquad V_r = \frac{V_p}{f\cdot C\cdot R} \qquad Vr << Vp$$

$$V_p\cdot\cos(\omega\Delta t) = V_p - V_r$$

for small angles ($\omega\Delta t$)

$$\cos(\omega\Delta t) = 1 - \frac{1}{2}\cdot(\omega\Delta t)^2$$

$$Vp\cdot\left[1 - \frac{1}{2}\cdot(\omega\Delta t)^2\right] = V_p - V_r$$

$$-V_p\cdot\frac{1}{2}\cdot(\omega\Delta t)^2 = -V_r \qquad \omega\Delta t = \sqrt{2\cdot\frac{Vr}{V_p}}$$

to determine the average diode current during conduction we equate the charge that the diode supplies the capacitor

$$Q_{supplied} = i_{Cav}\cdot\Delta t$$

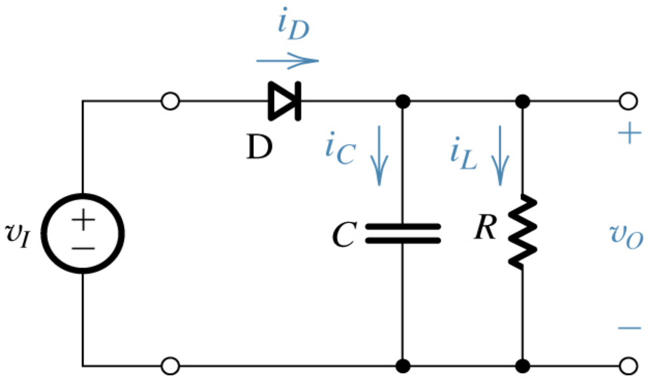
to the charge the capacitor losses during the discharge

$$Q_{lost} = C\cdot V_r$$

$$i_{Dav} = I_L\cdot\left(1 + \pi\cdot\sqrt{2\cdot\frac{V_p}{V_r}}\right)$$

$$i_{Dmax} = I_L\cdot\left(1 + 2\cdot\pi\cdot\sqrt{2\cdot\frac{V_p}{V_r}}\right)$$

Example 3.9:



(a)

If Vp = 100 V
R = 10 K

Calculate the value of the capacitance C that will result in a (a) peak-to-peak ripple V_r of 5 V, (b) the conduction angle and (c) the average and peak values of the diode current.

$V_p := 100$ $\quad R := 10000$ $\quad f := 60$

$V_r := 5$ $\quad I_L := \frac{V_p}{R}$ $\quad I_L = 0.01$ mA

$$C := \frac{V_p}{V_r \cdot f \cdot R} \qquad C = 3.333 \times 10^{-5}$$

Conduction angle

$$\omega\Delta t := \sqrt{2 \cdot \frac{V_r}{V_p}} \qquad \omega\Delta t = 0.316 \text{ rad}$$

Average diode current

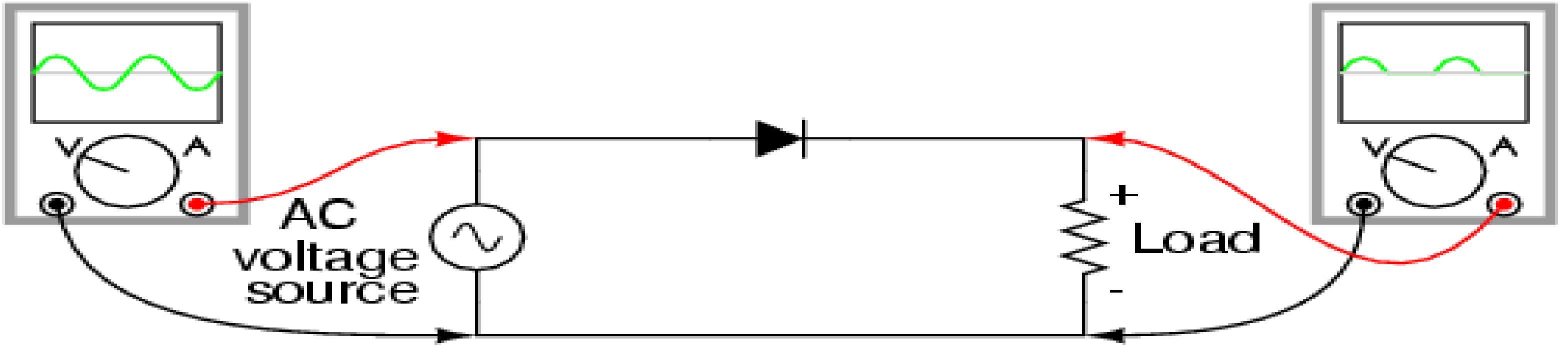
$$i_{Dav} := I_L \cdot \left(1 + \pi \cdot \sqrt{2 \cdot \frac{V_p}{V_r}}\right) \qquad i_{Dav} = 0.209$$

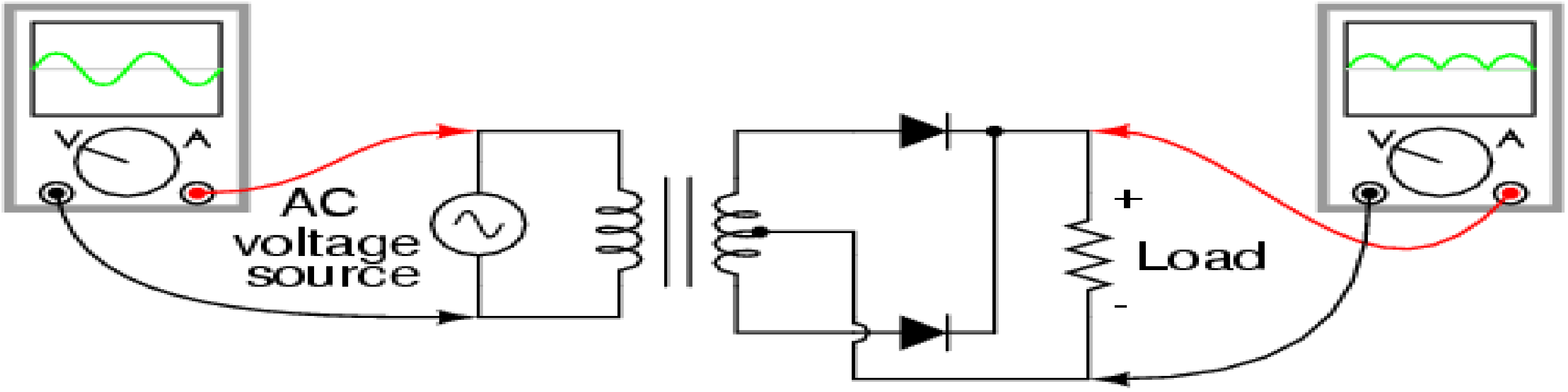
Peak diode current

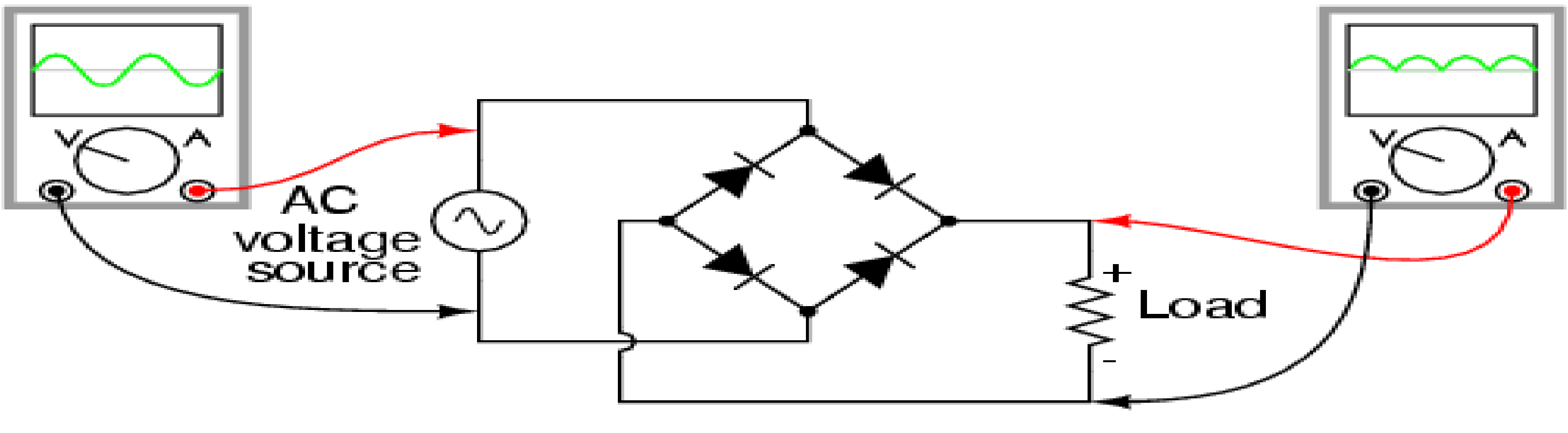
$$i_{Dmax} := I_L \cdot \left(1 + 2 \cdot \pi \cdot \sqrt{2 \cdot \frac{V_p}{V_r}}\right) \qquad i_{Dmax} = 0.407$$

Add a zener diode to regulate the output, v_0. ➔ fig 3.53

Diode – Applications



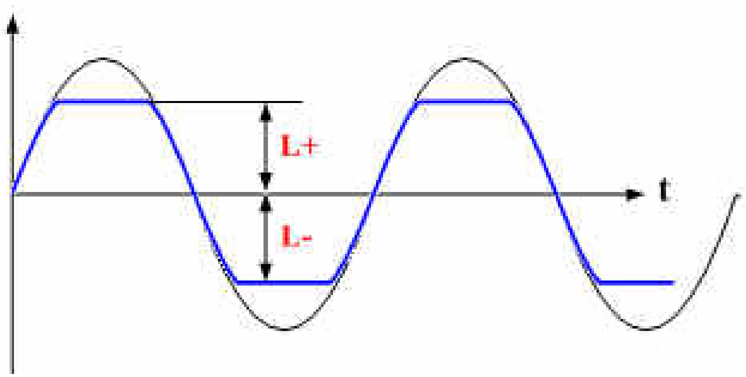




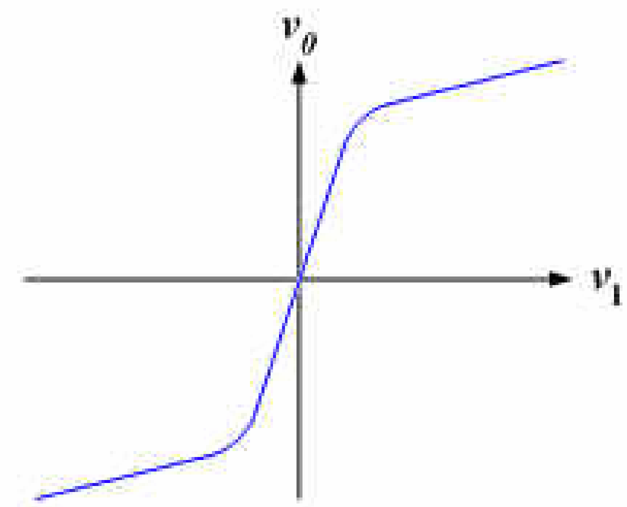
3.6.1: Limiting Circuits

- The objective of this lecture is to understand the functionality of other nonlinear circuit used in a variety of signal processing

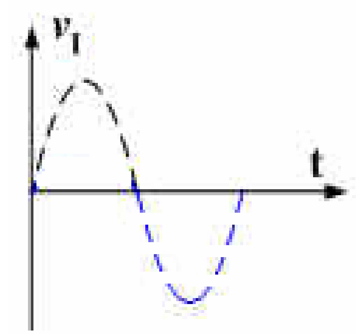
- If input waveform is sinusoid and is fed to a double limiter, the two peaks will be clipped off. Limiters therefore also referred to as clippers



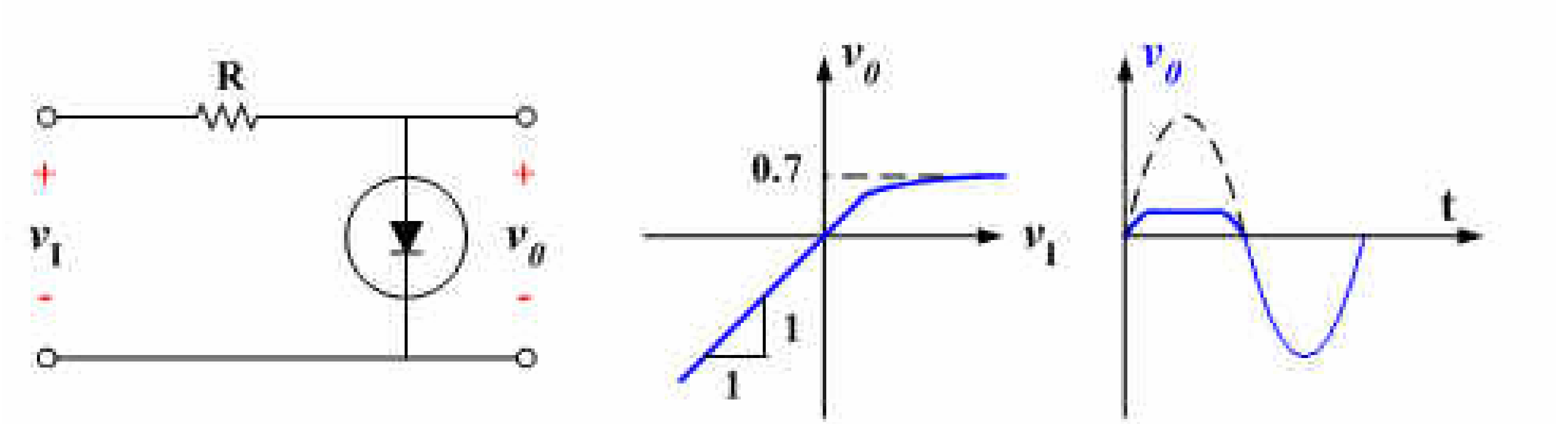
- Soft limiter is characterized by smoother transitions between the linear region and saturation regions & a slope greater than zero in the saturation region. Depending on the application, either hard or soft limiting may be preferred.



3.6.1: Examples of Limiting Circuits:

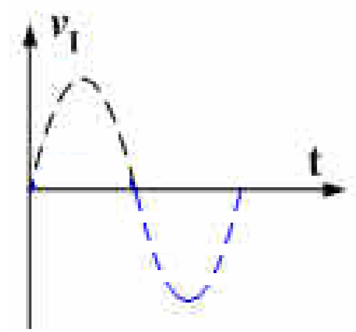


Input Waveform

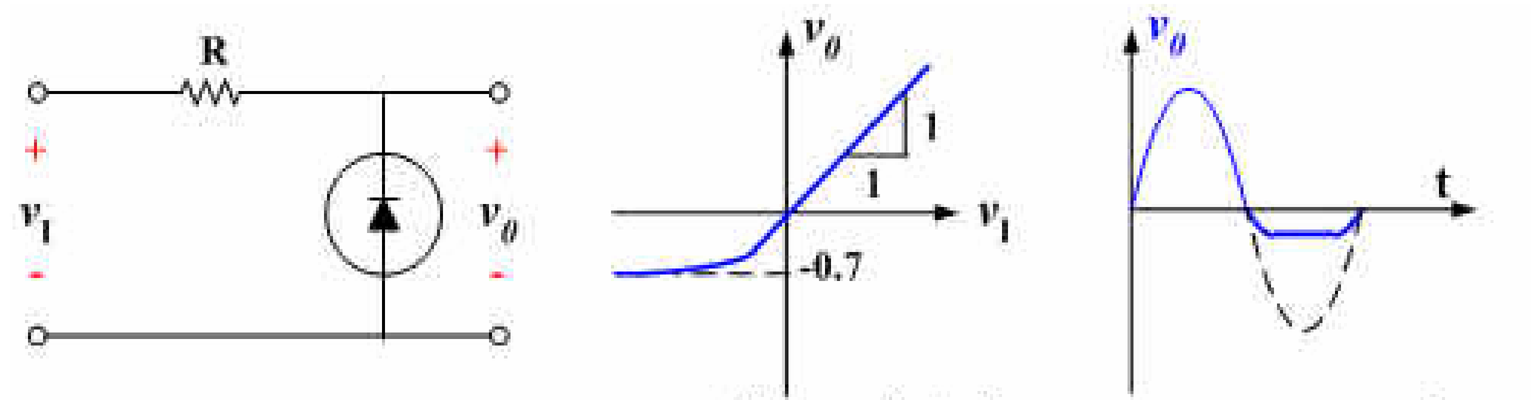


v_I-v_O Characteristic

Output Waveform



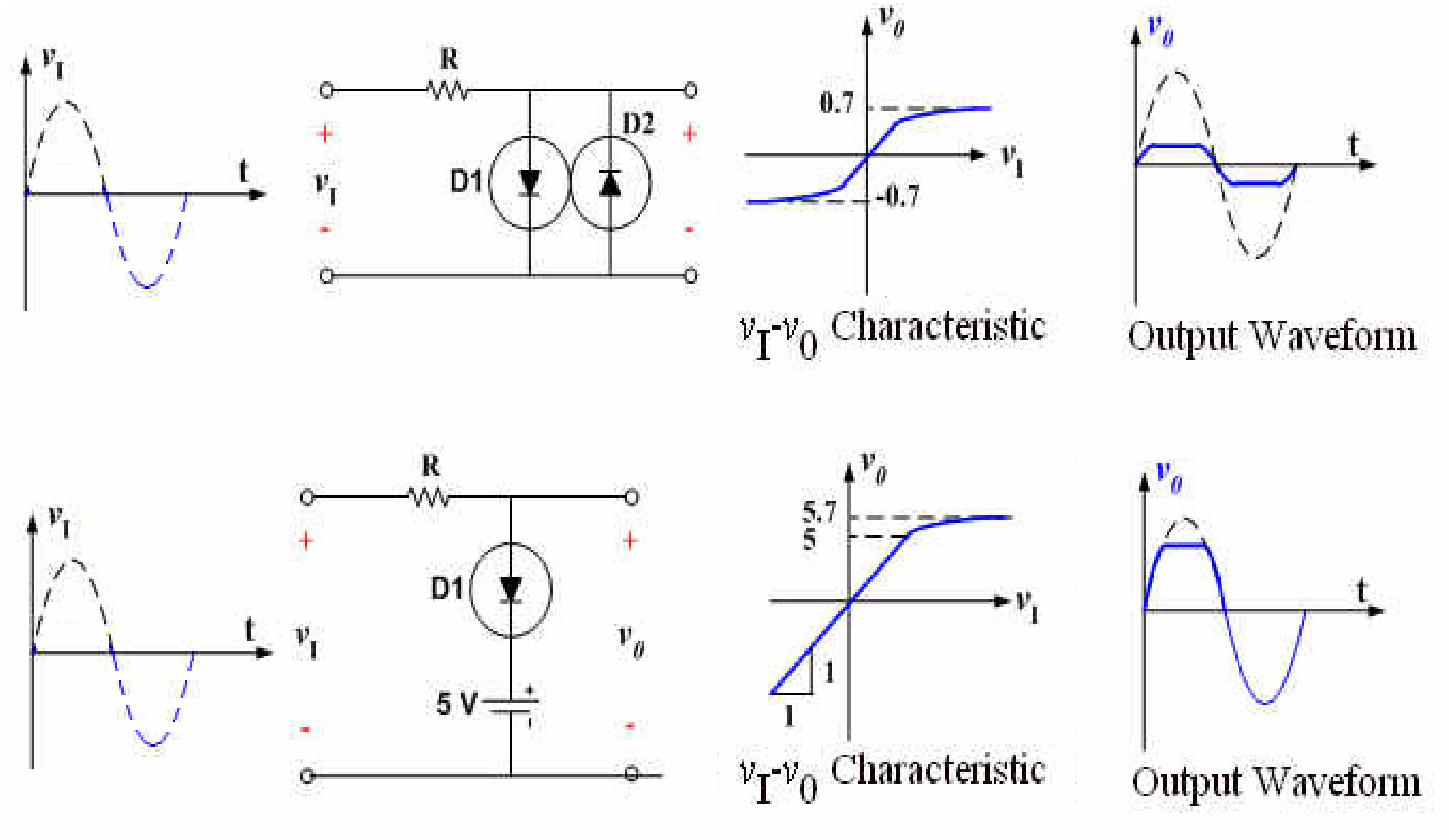
Input Waveform



v_I-v_O Characteristic

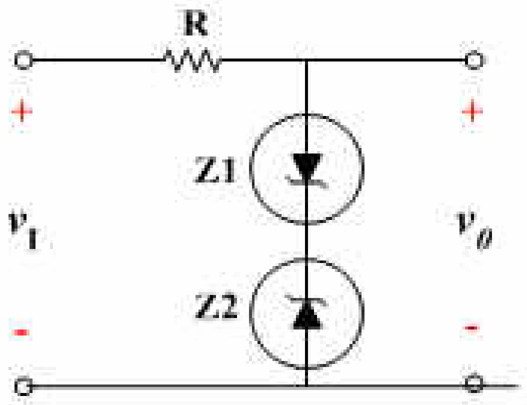
Output Waveform

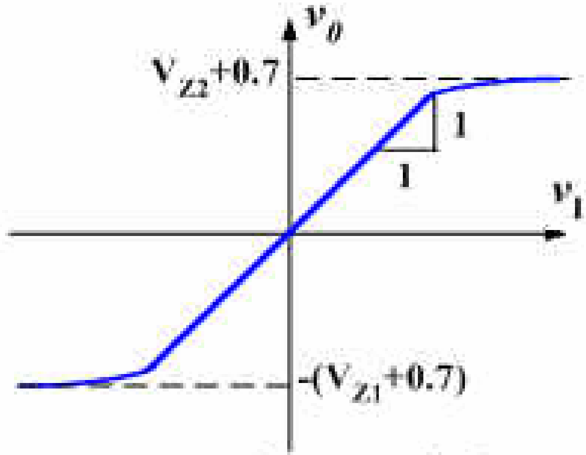
3.6.1: More Examples of Limiting Circuits:



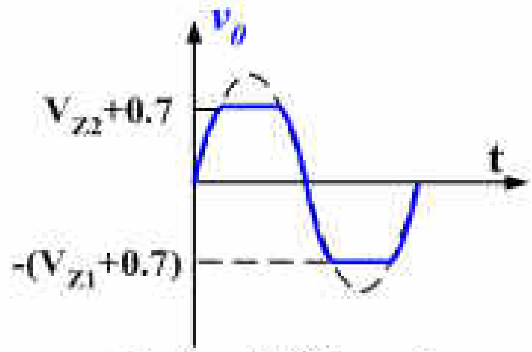
3.6.1: More Limiting Circuits:

LED's





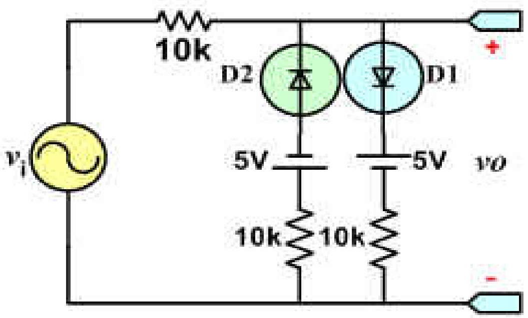
v_I-v_0 Characteristic

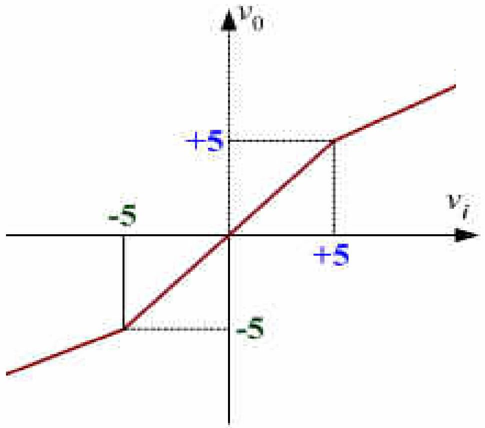


Output Waveform

Examples of Limiting Circuits:

Assuming the diodes to be ideal, describe the transfer characteristic of the following circuit.





$For\ -5 \le v_I \le +5$

$v_O = v_I$

$For\ v_I \ge 5V,\quad I = \dfrac{v_I - 5}{20k\Omega}$

$v_O = 5 + 10k\Omega \cdot I = 5 + \dfrac{1}{2}\cdot(v_I - 5)$

$v_O = \dfrac{1}{2} v_I + 2.5 \quad for\ v_I \ge 5V$

$For\ v_I \le -5V,\quad I = \dfrac{v_I + 5}{20k\Omega}$ $\quad v_O = -5 + 10k\Omega \cdot I = -5 + \dfrac{1}{2}\cdot(v_I + 5) = \dfrac{1}{2} v_I - 2.5 \quad for\ v_I \le -5V$