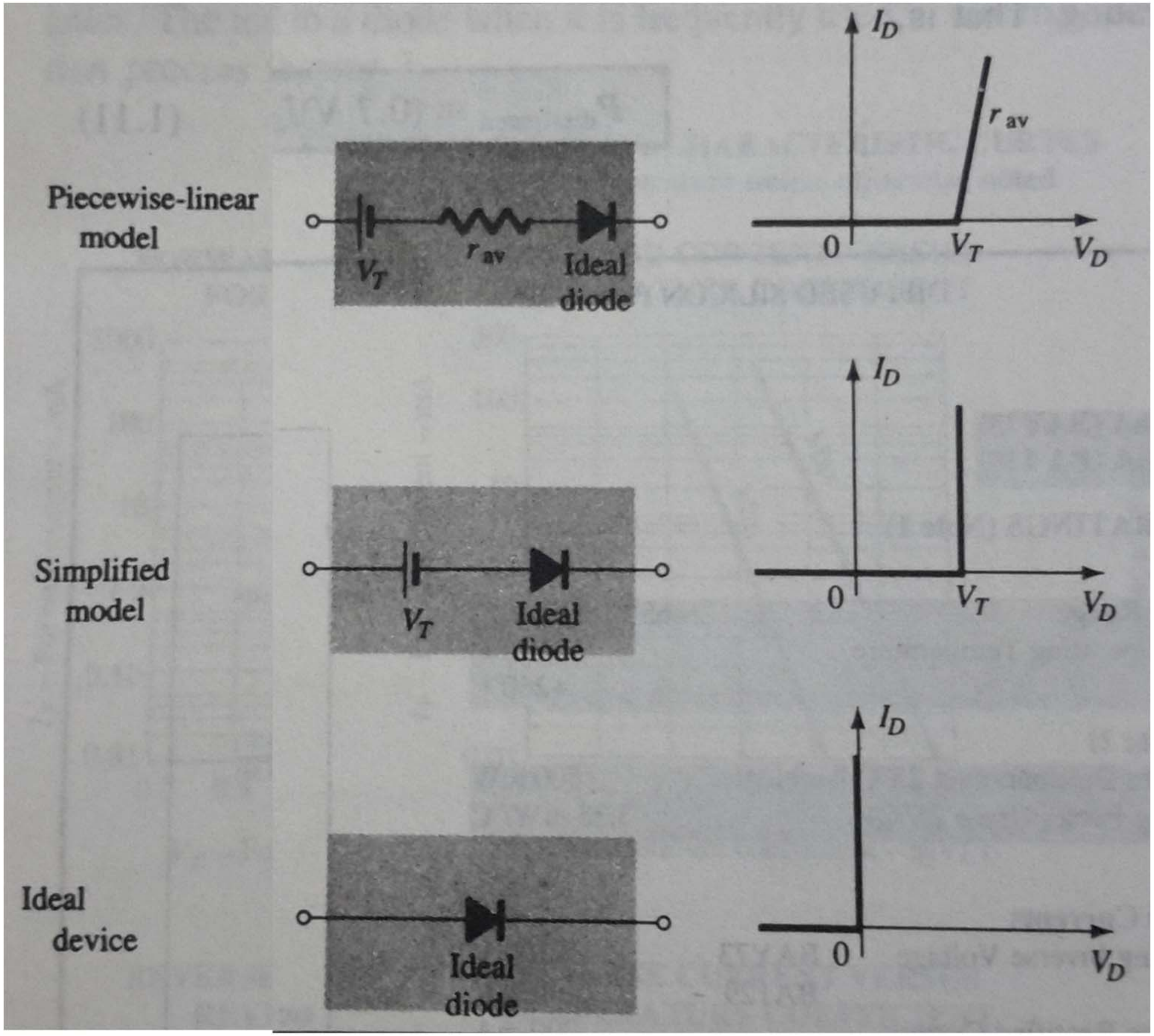
Diode circuits – AC equivalent

Diode equivalents & approximations:

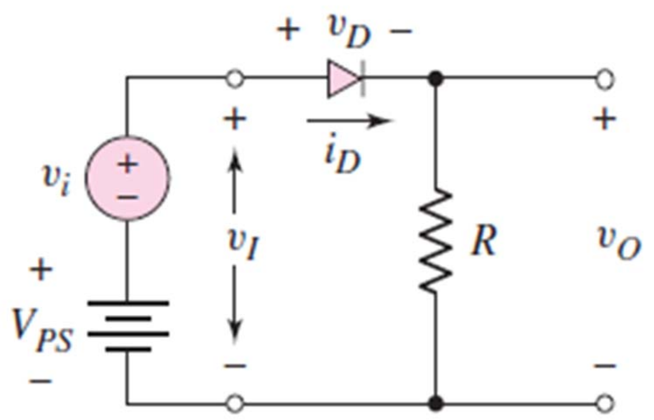


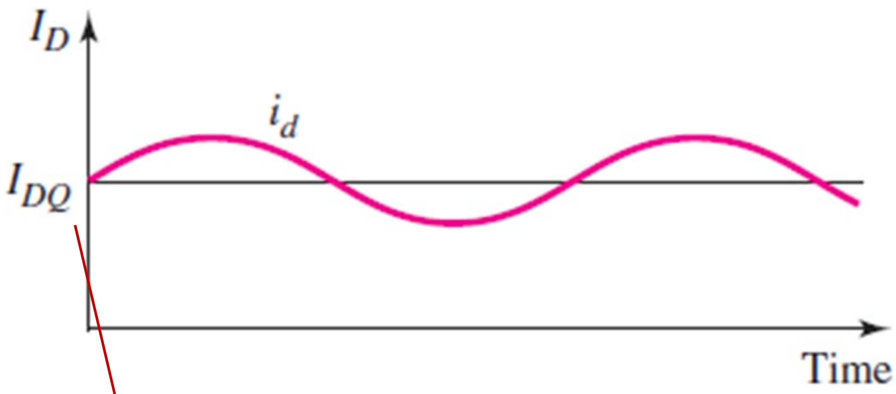
GOAL:

Develop an equivalent circuit for a diode that is used when a small, time-varying signal is applied to a diode circuit.

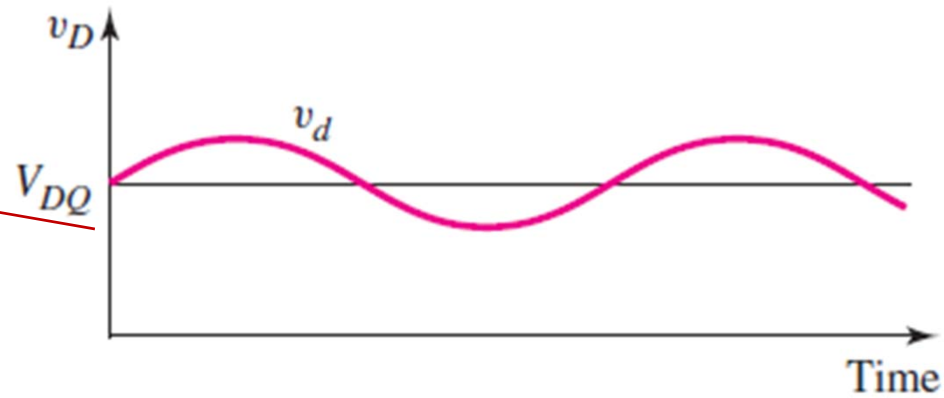
Why? - because sinusoidal signals may be superimposed on the dc currents and voltages

Sinusoidal Analysis





quiescent (Q)
diode current
& voltage



Input voltage contains a dc component with an ac signal superimposed

Diode current and diode voltage will also be so.

$$i_D \cong I_S e^{\left(\frac{v_D}{V_T}\right)} = I_S e^{\left(\frac{V_{DQ}+v_d}{V_T}\right)}$$

"-1 term neglected"

$$i_D = I_S \left[e^{\left(\frac{V_{DQ}}{V_T}\right)} \right] \cdot \left[e^{\left(\frac{v_d}{V_T}\right)} \right]$$

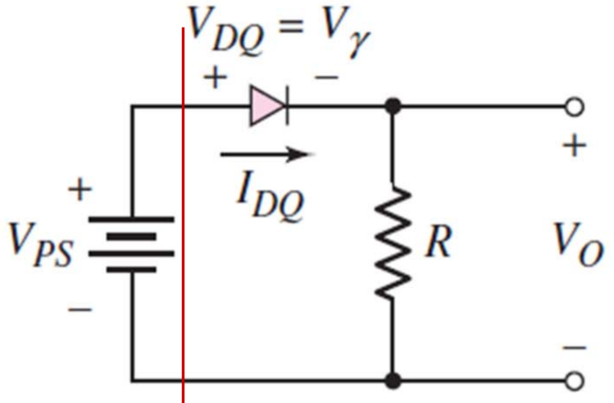
If the ac signal is "small," then $v_d << V_T$

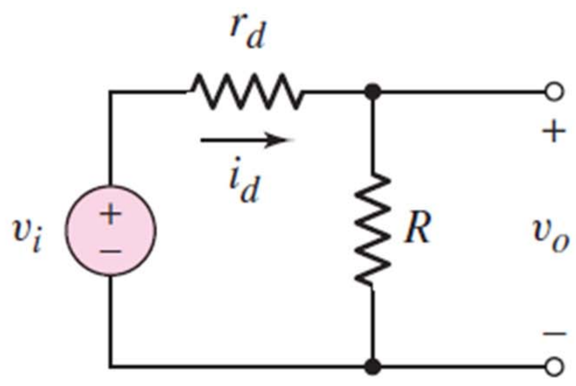
$$e^{\left(\frac{v_d}{V_T}\right)} \cong 1 + \frac{v_d}{V_T}$$

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

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

additive





Diode resistance very small

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

or

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

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

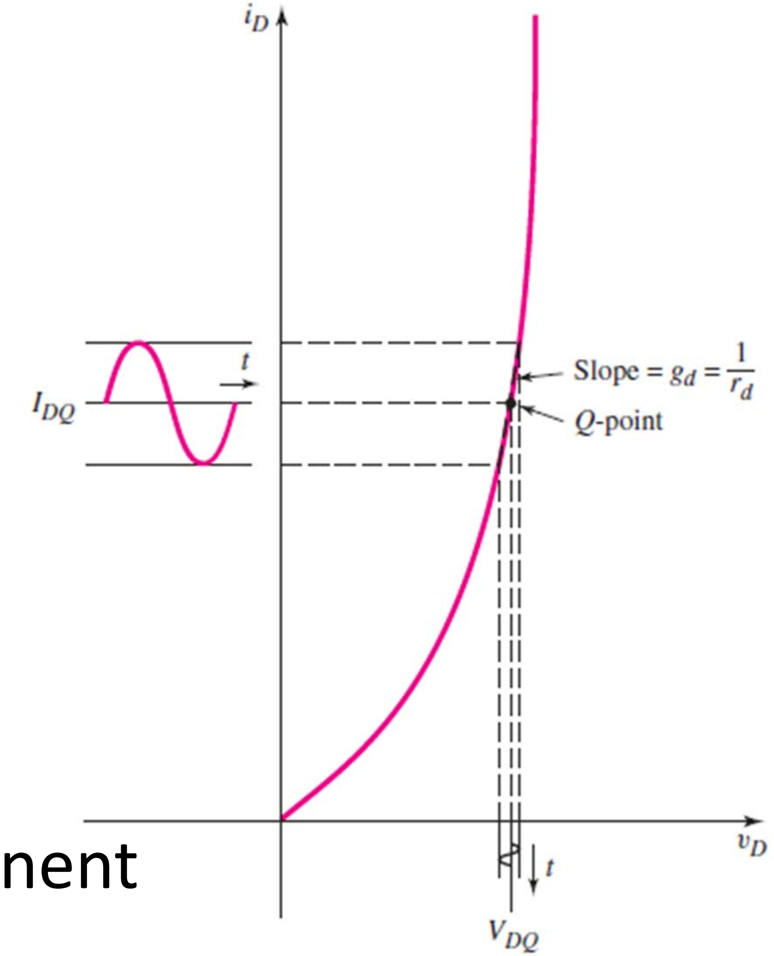
A dc analysis involving only the dc voltages and currents, and an ac analysis involving only the ac voltages and currents

Small-signal incremental conductance and resistance, also called the diffusion conductance and diffusion resistance

Incremental resistance is a function of the dc bias current I_{DQ} and is inversely proportional to the slope of the I–V characteristics curve

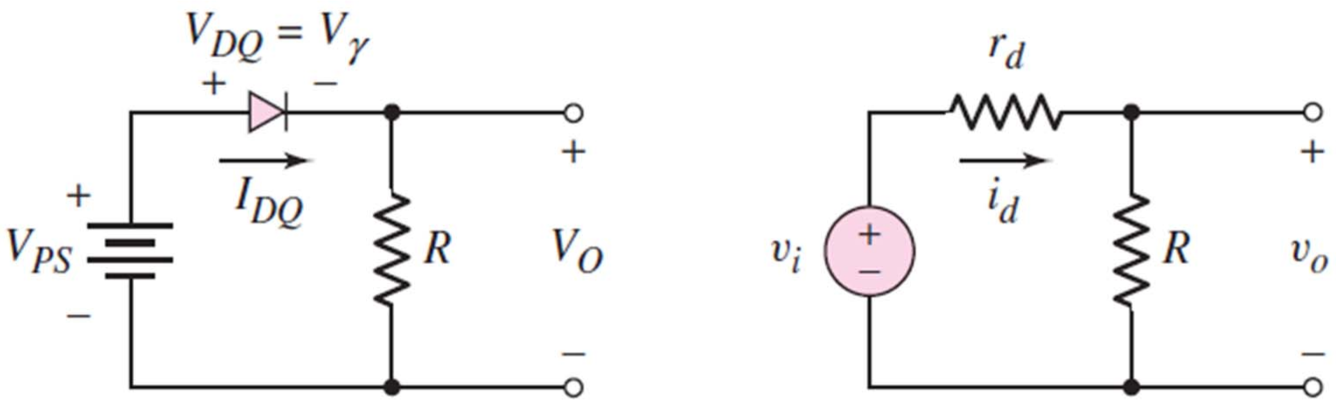
$$v_d = \left(\frac{V_T}{I_{DQ}}\right) \cdot i_d$$

Represents the changing voltage & current component



Circuit Analysis:

First perform a dc analysis and then an ac analysis



If the diode is forward biased, then the voltage across the diode is the piecewise linear turn-on voltage

The diode has been replaced by its equivalent resistance. All parameters are small-signal time-varying parameters

Assume circuit and diode parameters of V_{PS} = 5 V, R = 5 kΩ, V_{γ} = 0.6 V, and v_i = 0.1 sin(ωt) V.

DC analysis –

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

$$V_o = I_{DQ} R = (0.88)(5) = 4.4 \text{ V}$$

AC analysis –

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

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

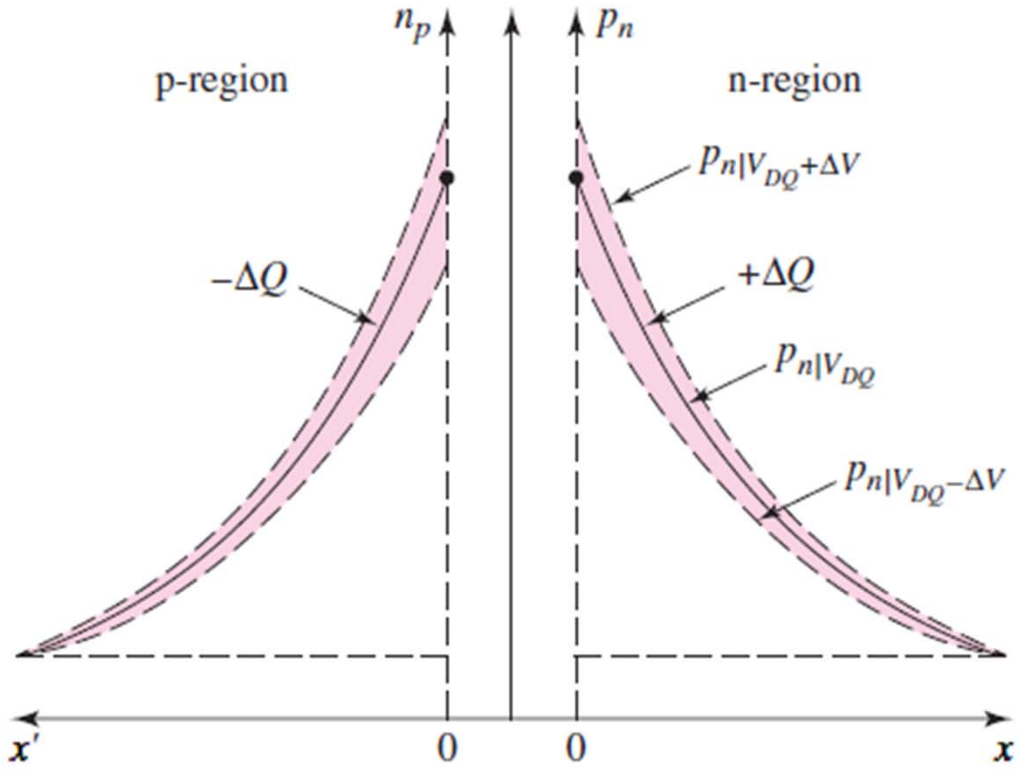
$$i_d = \frac{v_i}{r_d + R} = \frac{0.1 \sin \omega t}{0.0295 + 5} \Rightarrow 19.9 \sin \omega t \ (\mu A)$$

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

Frequency response:

- Frequency of the ac signal was small enough that capacitance effects in the circuit would be negligible.

- If the frequency of the ac input signal increases, the diffusion capacitance associated with a forward-biased pn junction becomes important



Fluctuations in diffused minority concentration

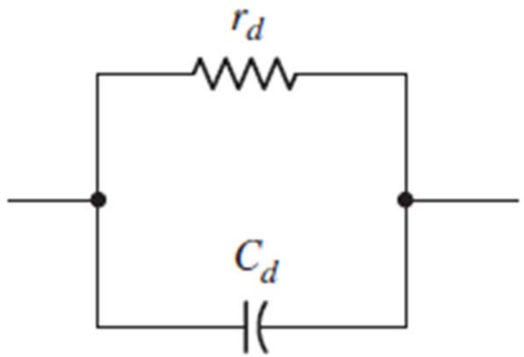
The $+\Delta Q$ charge is alternately being charged and discharged through the pn junction as the voltage across the junction changes.

$$C_d = \frac{dQ}{dV_D}$$

The diffusion capacitance is normally much larger than the junction capacitance.

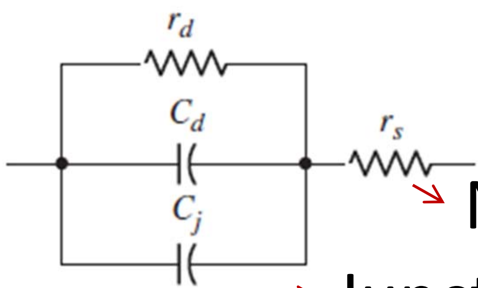
Small-Signal Equivalent Circuit:

$$g_d + j\omega C_d$$



Simplified

Complete



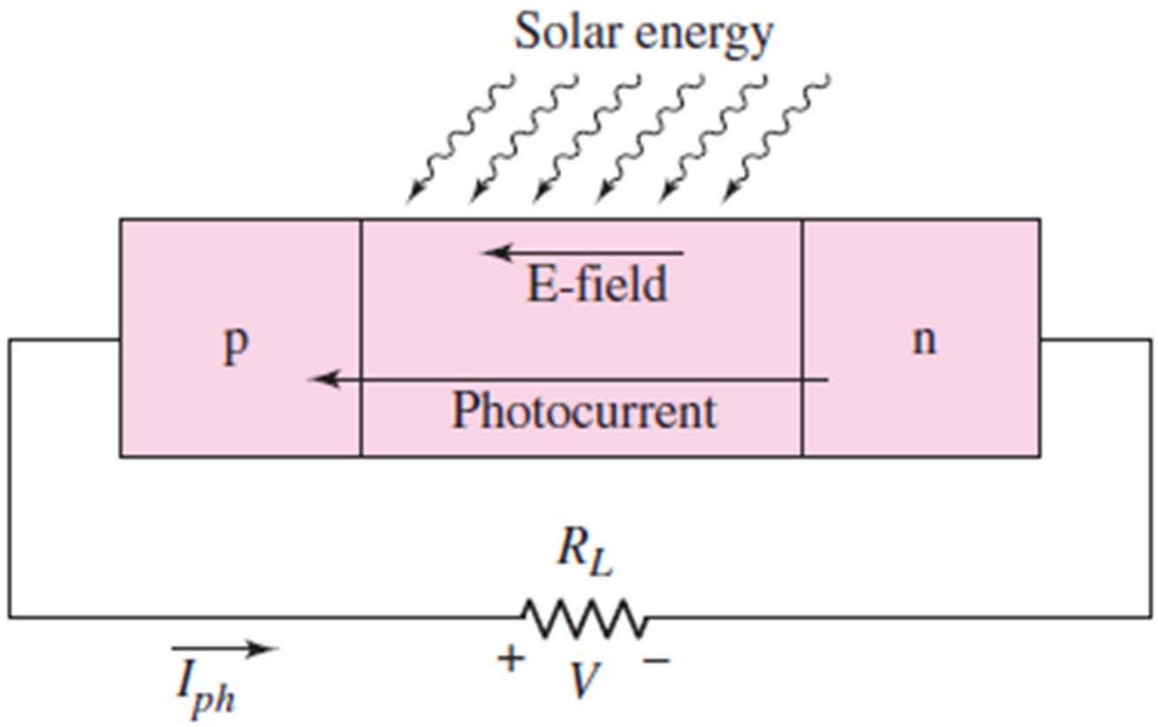
Neutral region resistance

Junction capacitance

Other Diodes!

Other Diode Types:

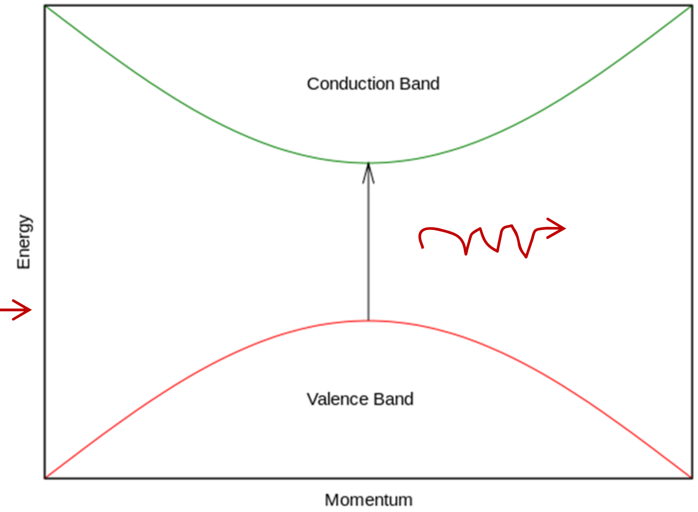
Solar Cell (photodiode)



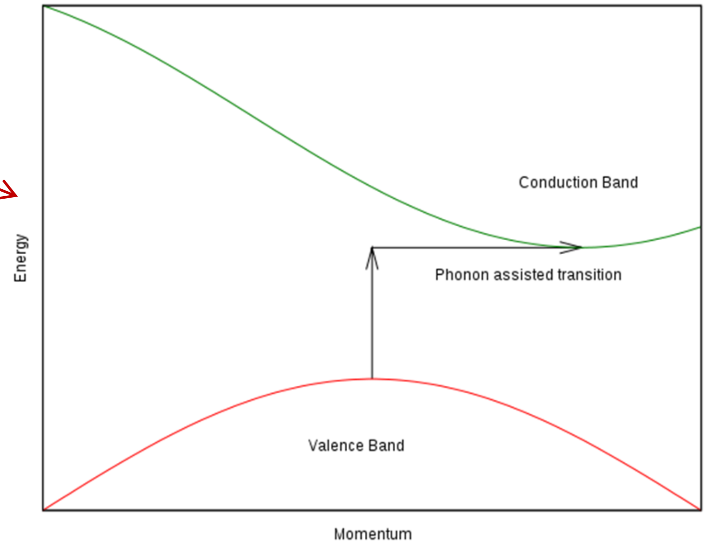
GaAs or Si

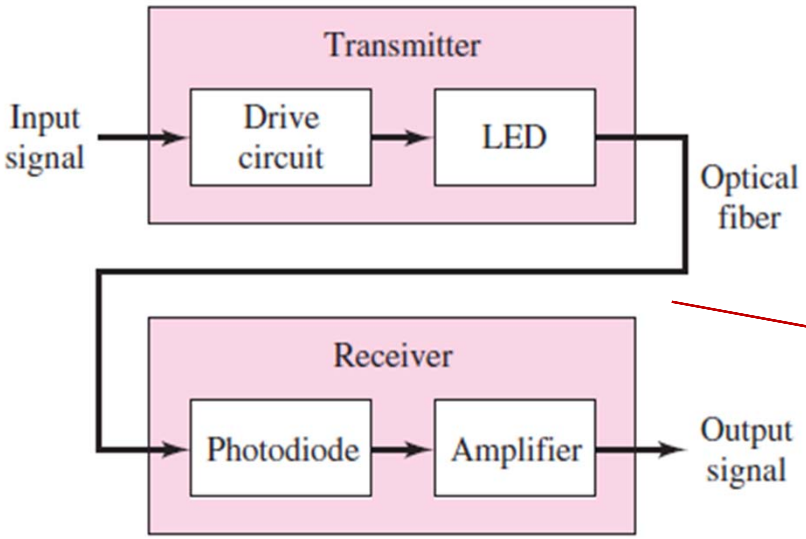
Light Emitting Diode (LED):

GaAs – direct band gap – Useful as LED



Si – indirect band gap – not useful





optical transmission system

Schottky diode:

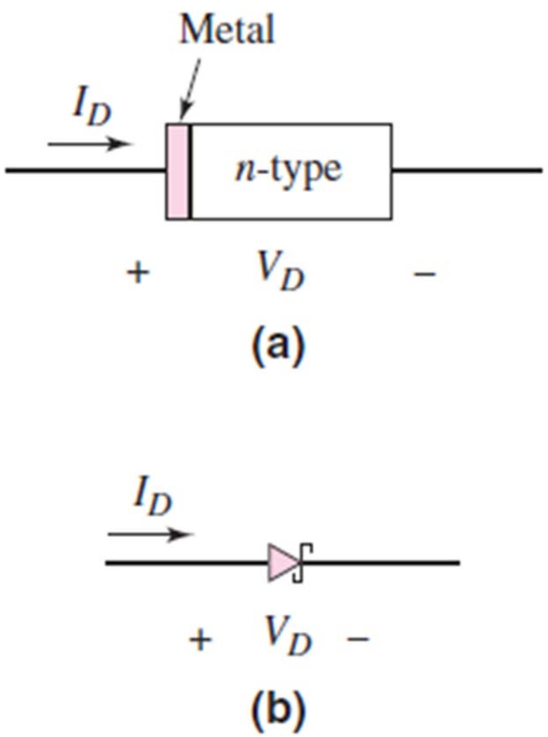
A metal (like Al) is brought into contact with a moderately doped n-type semiconductor

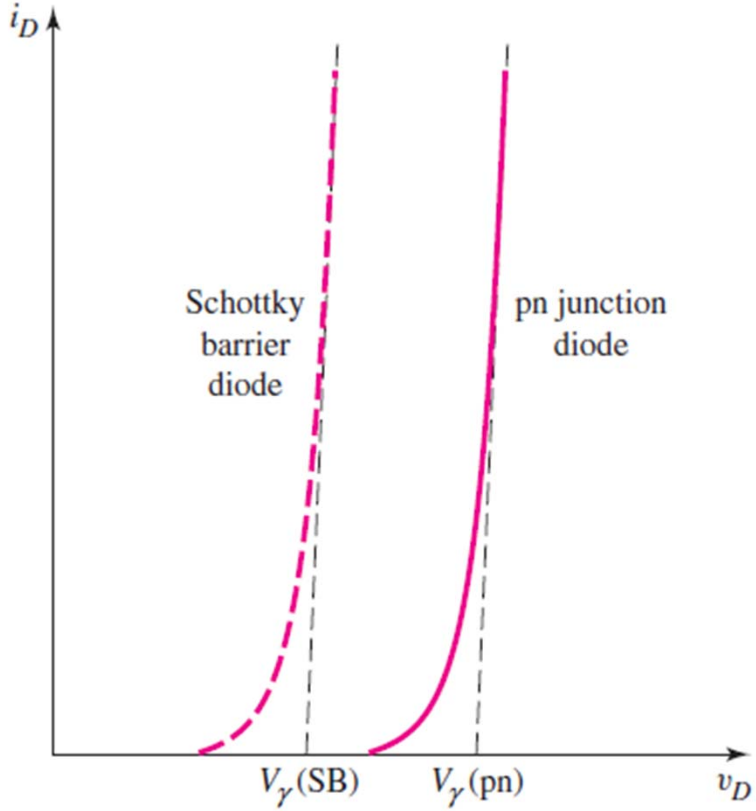
Current in a Schottky diode results from the flow of majority carriers over the potential barrier (+ive ion in n-type and excess electrons in metal). Electrons are majority both in n-type and metal.

Forward bias effects similar to pn-junction, but the barrier is much lesser. Reverse bias results in larger saturation current due to substantial amount of electrons in metal.

Adv:

Because there is no excess minority carrier accumulation, switching from on to off is much faster.



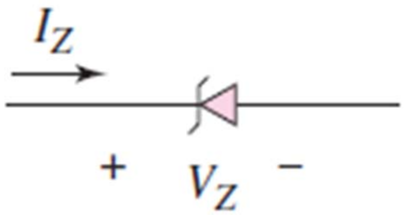


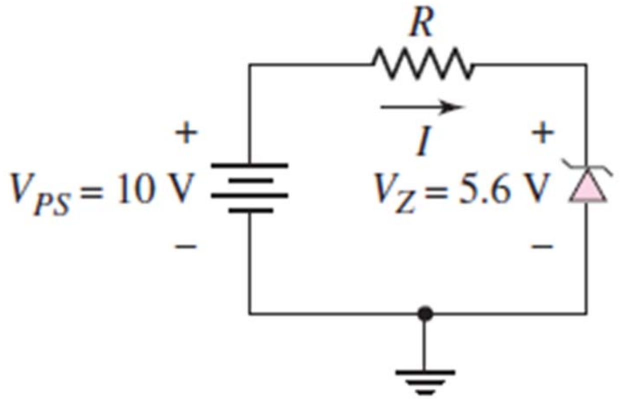
Zener diode:

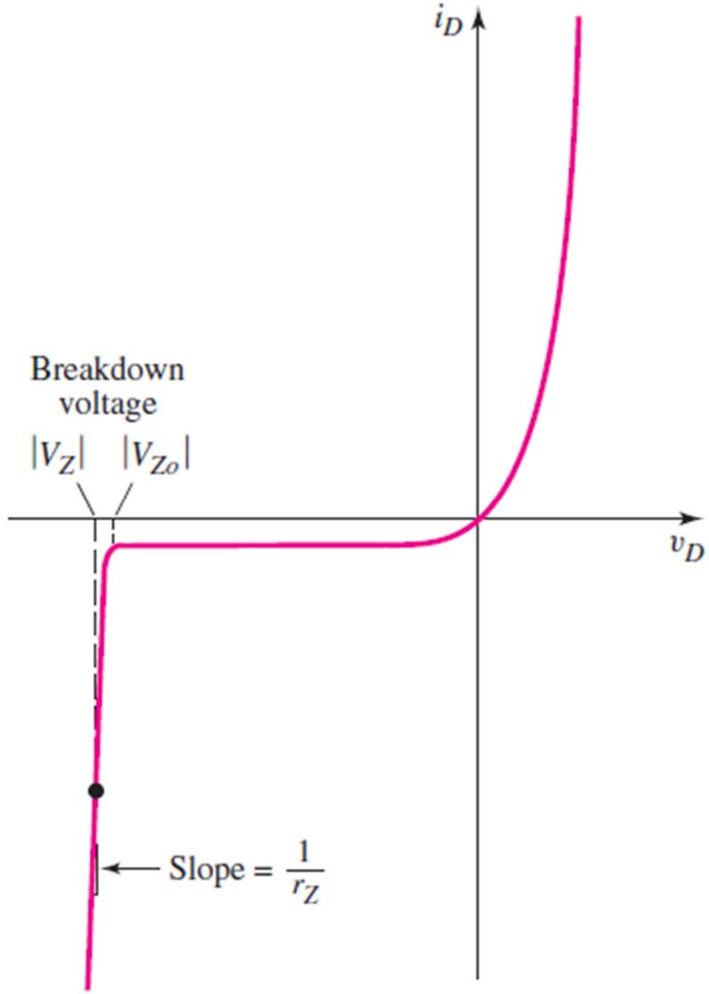
When reversed bias voltage is increased, at some point (breakdown voltage) breakdown occurs and the reverse bias current increases rapidly.

Zener diodes are fabricated to have a specified breakdown voltage V_{z0}, Zener potential / Zener breakdown voltage. The large current can be limited (otherwise catastrophic failure can occur).

Such a diode can be used as a constant-voltage reference in a circuit. The diode breakdown voltage is essentially constant over a wide range of currents and **temperatures**.





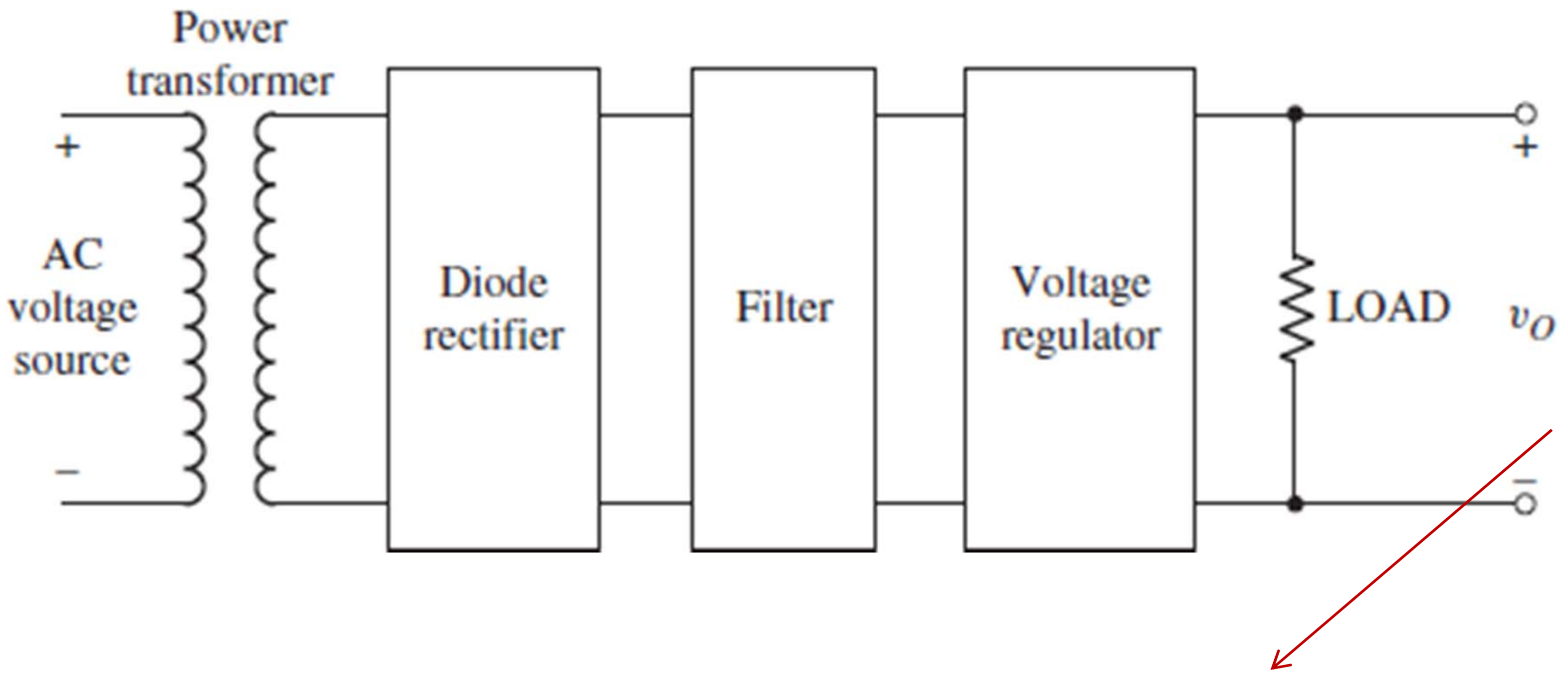


Current restriction to 3 mA

$$R = \frac{V_{PS} - V_Z}{I} = \frac{10 - 5.6}{3} = 1.47\,\mathrm{k}\Omega$$

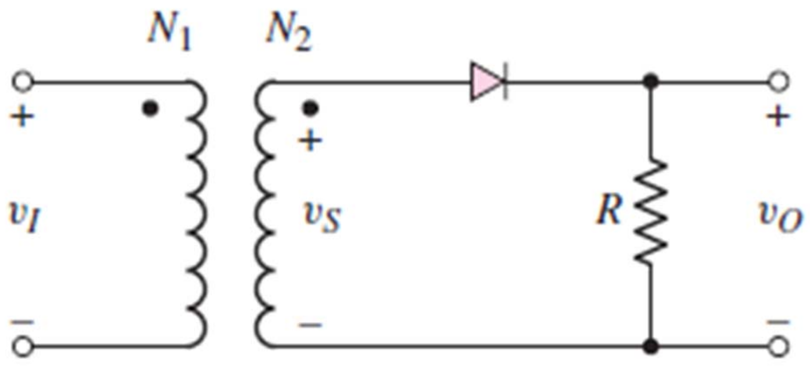
Diode circuits –
Rectifier circuits

A diode rectifier forms the first stage of a dc power supply, which is required in any kind of electronic device



Usually 3V to 24V

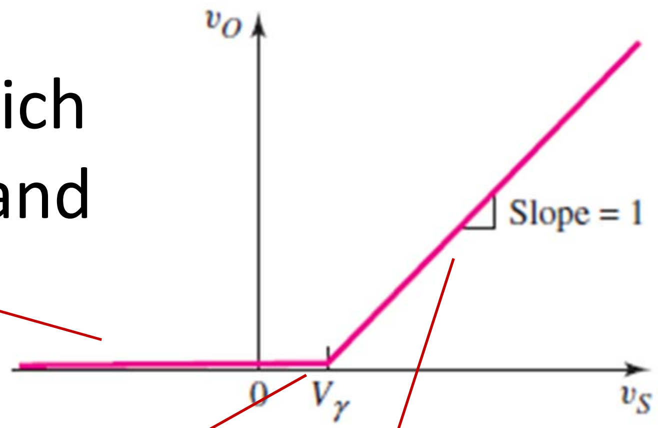
Half-Wave Rectification:



We use the piecewise linear approach in analyzing this circuit, assuming the diode forward resistance is 0.

RMS AC voltage $\leftarrow$ $$\frac{v_I}{v_S} = \frac{N_1}{N_2}$$ $\rightarrow$ transformer turns ratio

Desired relation between input and output of the rectifier circuit



The diode is reverse biased, which means that the current is zero and the output voltage is zero.

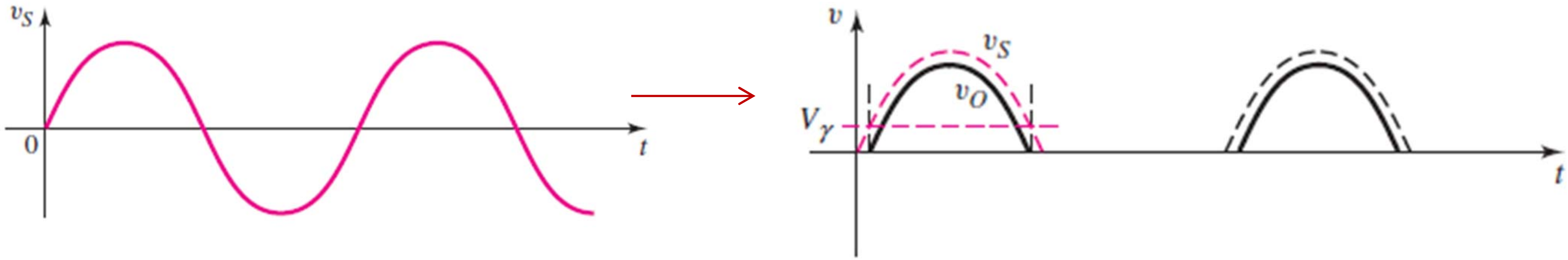
The diode will be non-conducting, so the output voltage will remain zero.

The diode is forward biased and a current is induced in the circuit.

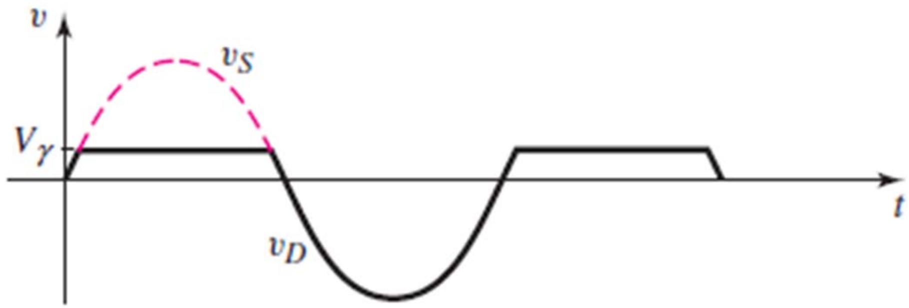
$$i_D = \frac{v_S - V_\gamma}{R} \qquad v_O = i_D R = v_S - V_\gamma$$

When v_s is sinusoidal, the output v_o is also the same. But it is zero when v_s is less than V_γ, otherwise it is

$$v_O = v_S - V_\gamma$$

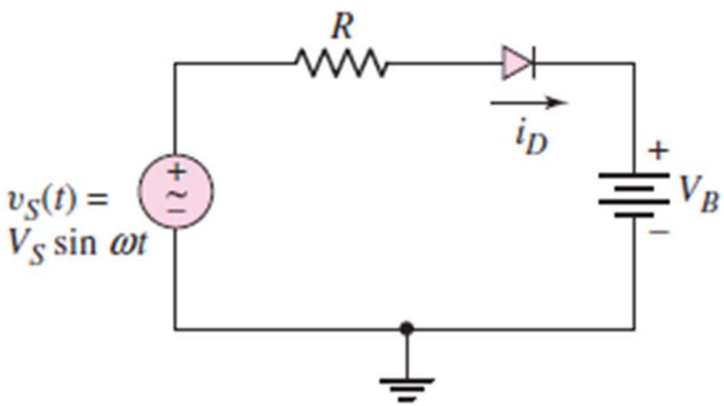


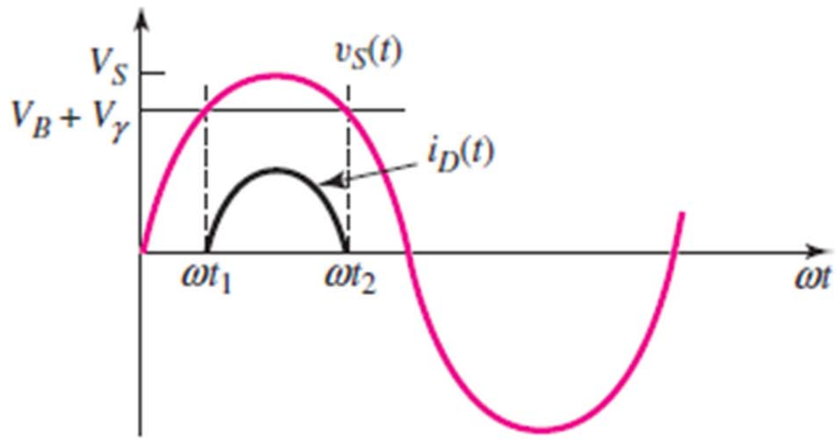
Since the output voltage appears only during the positive cycle of the input signal, the circuit is called a half-wave rectifier.



The diode must be capable of handling the peak current in the forward direction and sustaining the largest peak inverse voltage (PIV) without breakdown.

Half-wave rectifier circuit to charge a battery





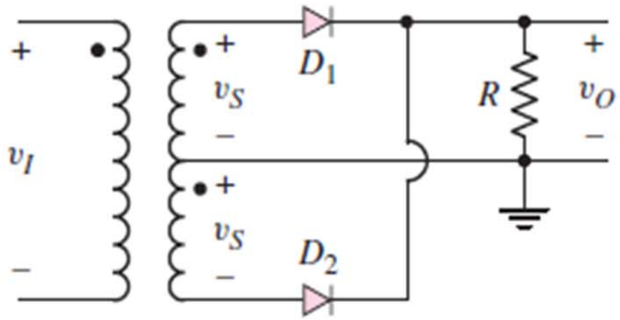
- Charging current exists whenever the instantaneous ac source voltage is greater than the battery voltage plus the diode cut-in voltage.

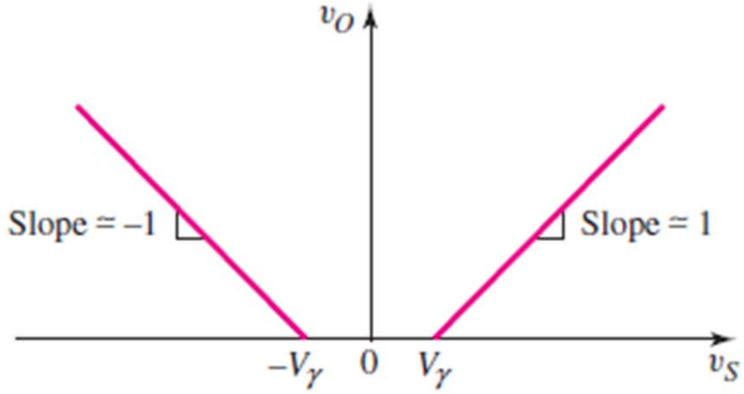
- The resistance R in the circuit is to limit the current.

- Thus current flows only in the direction to charge the battery as it is zero when the AC voltage is less than V_B.

Disadvantage of the half-wave rectifier is that we "waste" the negative half-cycles.

Full-Wave Rectification:

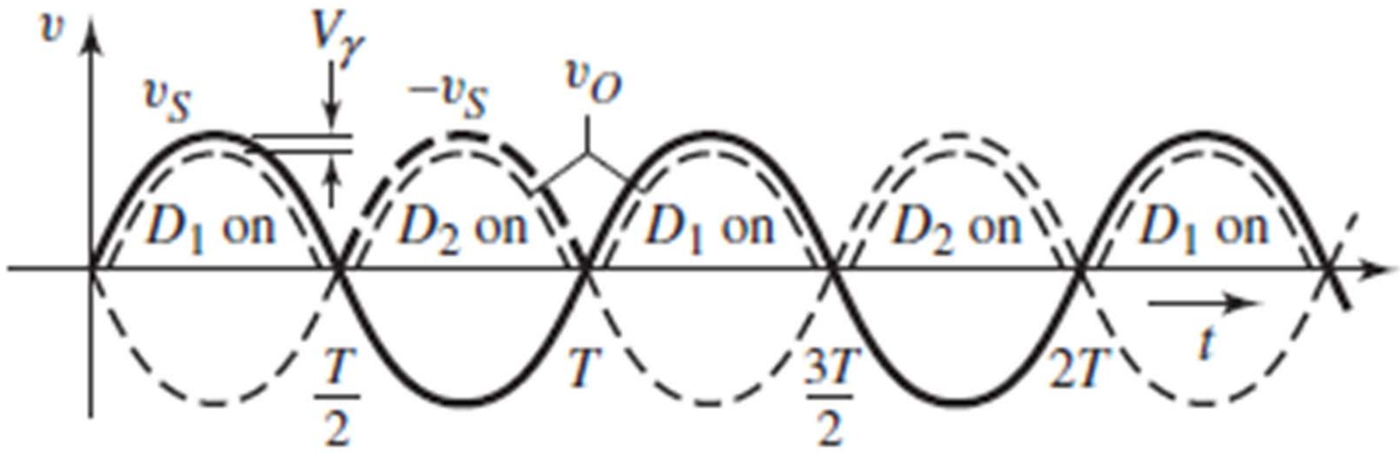




The output $v_o = v_s - V_\gamma$ when v_s is greater than V_γ with D1 open and D2 off.

The output $v_o = - v_s - V_\gamma$ when v_s is lesser than $-V_\gamma$ with D2 open and D1 off.

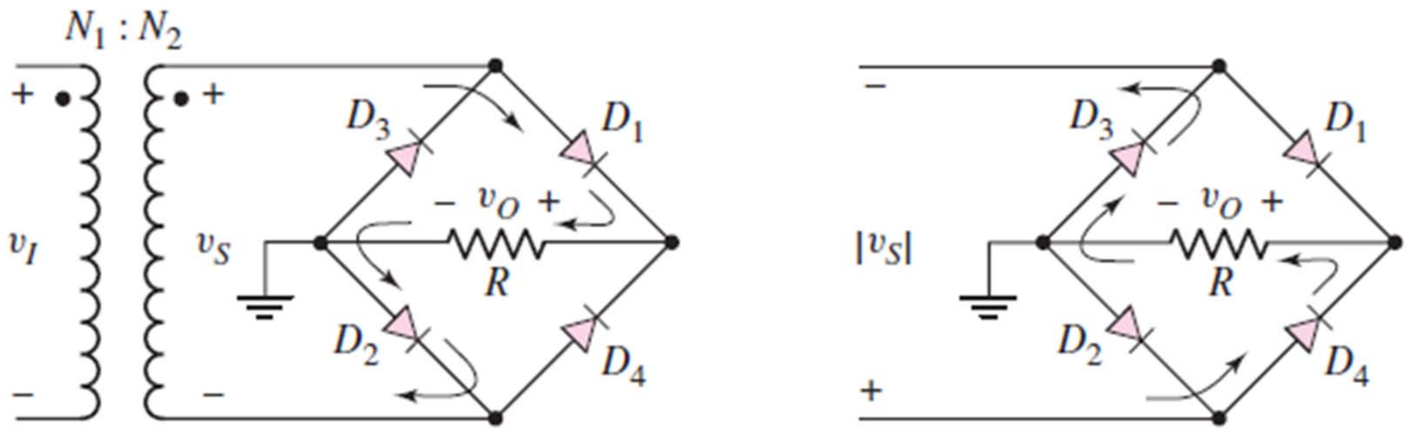
The output $v_o = 0$ when $-V_\gamma < v_s < V_\gamma$ with both D1 & D2 closed.



Since a rectified output voltage occurs during both the positive and negative cycles of the input signal, this circuit is called a full-wave rectifier.

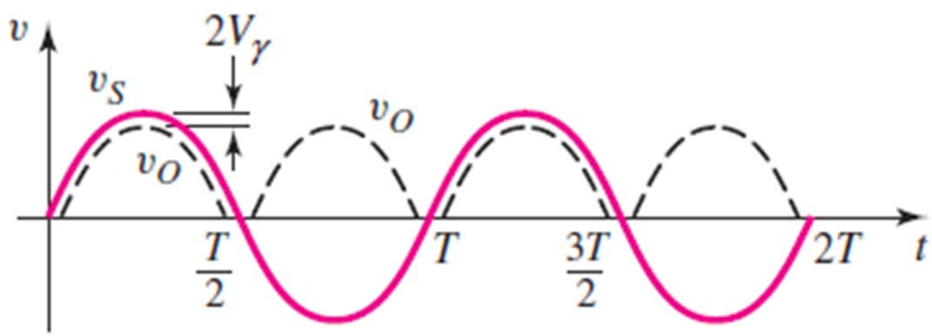
Bridge rectifier

2 more diodes but no center tapping!

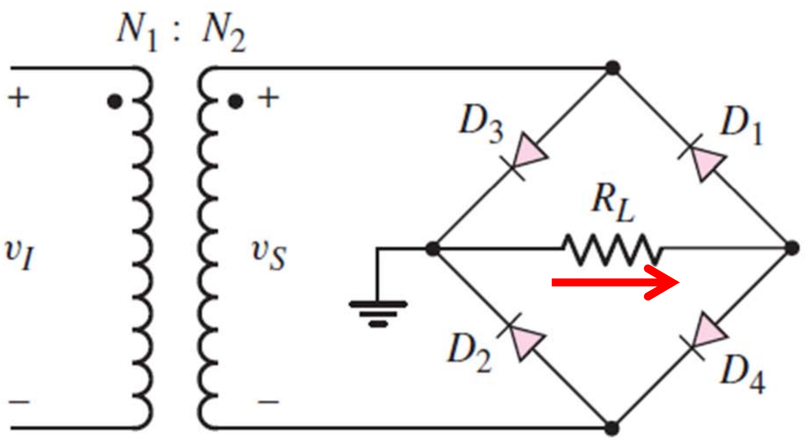


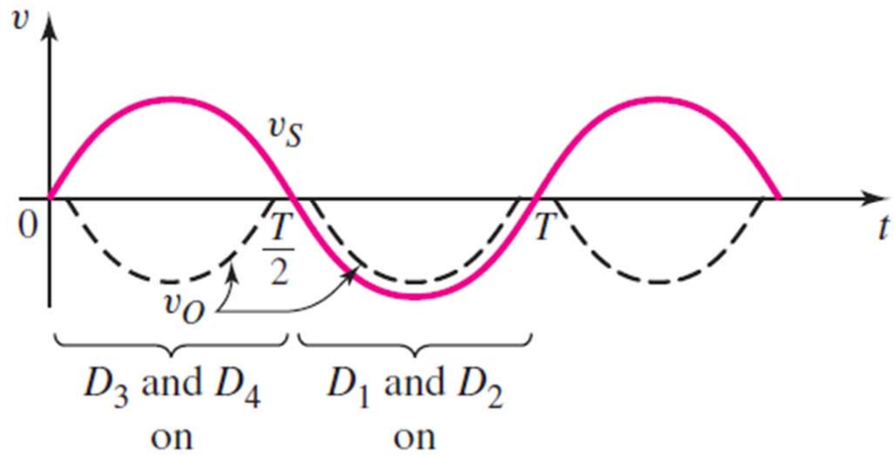
Secondary not grounded!

- During positive half of the cycle, only D1 and D2 are open and during the negative half of the cycle only D3 and D4 are open.
- The magnitude of v_O is two diode drops less than the magnitude of v_S



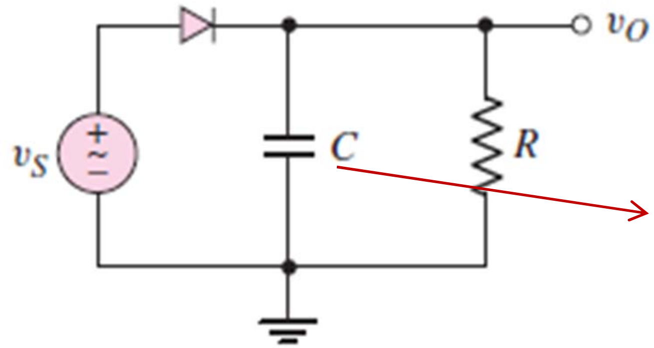
There are times when a negative dc voltage is also required. We can produce negative rectification by reversing the direction of the diodes in either circuit





- During positive half of the cycle, only D3 and D4 are open and during the negative half of the cycle only D1 and D2 are open.

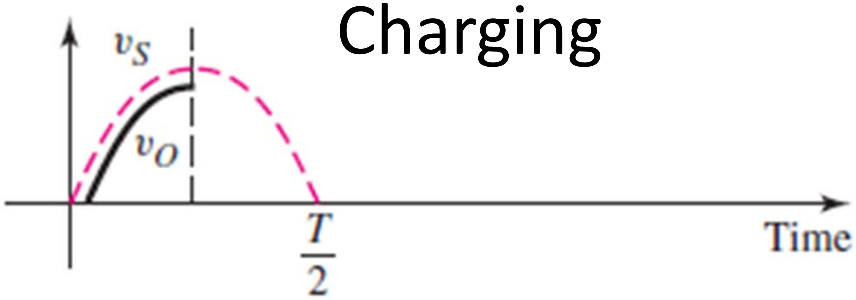
Filters, Ripple Voltage, and Diode Current

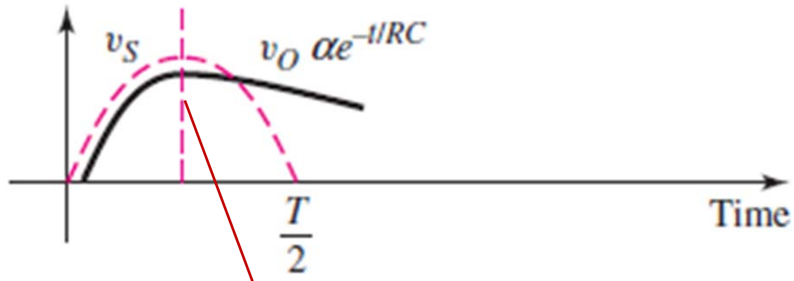


Filter capacitor

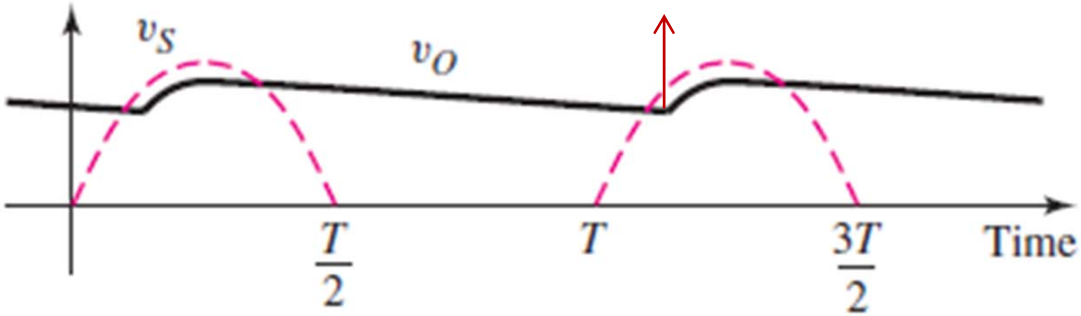
Discharging through R

Charging





Diode turns on

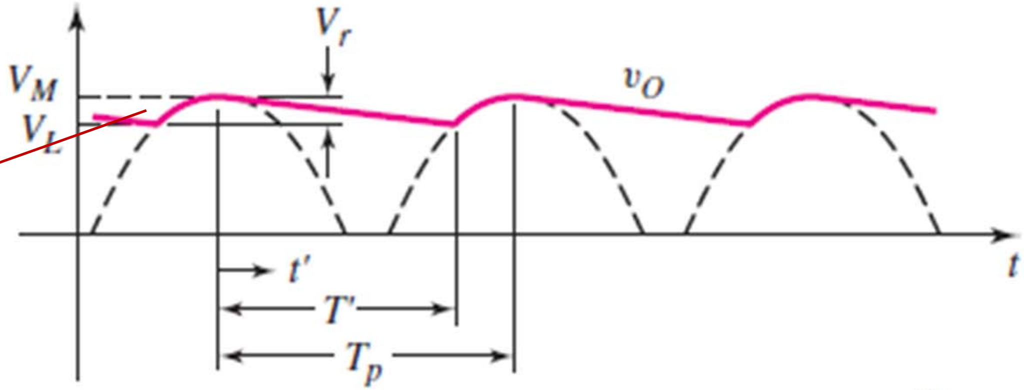


Diode turns off almost after peak, as difference between input voltage and capacitor discharge voltage is less the cut-in

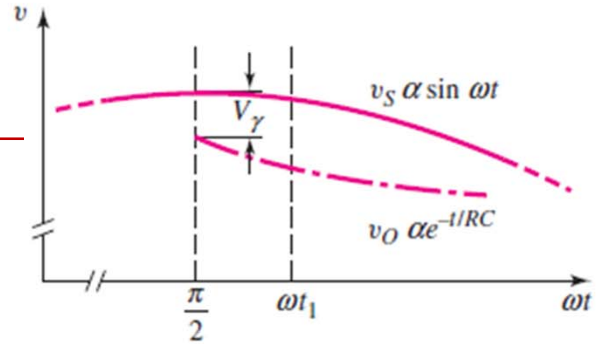
For half-wave rectifier

For full-wave rectifier

ripple voltage



Diode turns off a little while after peak



$$v_O(t) = V_M e^{-t'/\tau} = V_M e^{-t'/RC}$$

Smallest o/p voltage

$$V_L = V_M e^{-T'/RC}$$

Ripple voltage $V_r = V_M - V_L = V_M(1 - e^{-T'/RC})$

$$T' \ll RC \qquad e^{-T'/RC} \cong 1 - \frac{T'}{RC}$$

$$V_r \cong V_M \left(\frac{T'}{RC} \right)$$ → depends on RC!

If ripple effect is small -

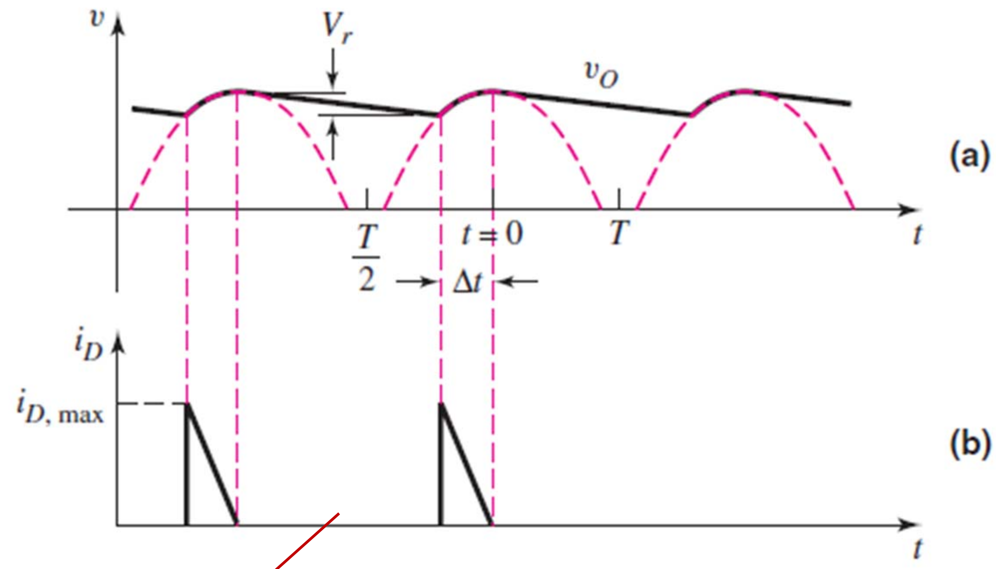
$$T' = T_p \qquad V_r \cong V_M \left(\frac{T_p}{RC} \right)$$

For full wave rectification $f = \frac{1}{2T_p}$ Half-wave $f = \frac{1}{T_p}$

$$V_r = \frac{V_M}{2fRC}$$

Full-wave rectifier has half the ripple voltage of the half-wave rectifier

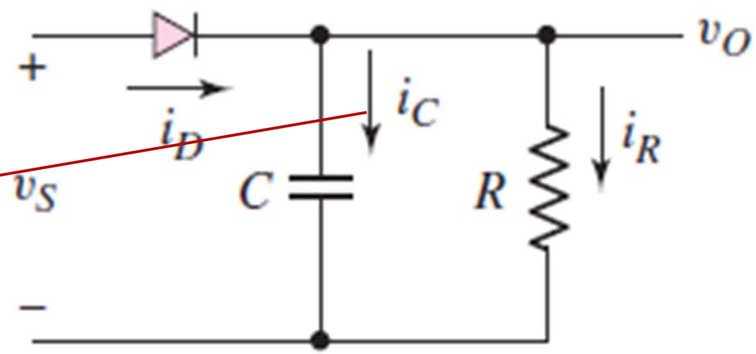
Consider ideal diode:



diode conduction time

diode current

Similar for capacitor current



$$i_D = i_C + i_R = C\frac{dv_O}{dt} + \frac{v_O}{R}$$

$$v_O = V_M \cos \omega t$$

$$v_O = V_M \cos \omega t \cong V_M \left[1 - \frac{1}{2}(\omega t)^2 \right]$$ → OK for smaller frequency

$$i_C = C \frac{dv_O}{dt} = C V_M \left[-\frac{1}{2}(2)(\omega t)(\omega) \right] = -\omega C V_M \omega t$$

$$i_{C,\text{peak}} = -\omega C V_M [\omega(-\Delta t)] = +\omega C V_M \omega \Delta t$$

$$V_L = V_M \cos[\omega(-\Delta t)] \cong V_M \left[1 - \frac{1}{2}(\omega \Delta t)^2 \right]$$

$$\omega \Delta t = \sqrt{\frac{2V_r}{V_M}} \qquad V_r = V_M - V_L$$

$$V_r = \frac{V_M}{2fRC} \qquad fC = \frac{V_M}{2RV_r} \qquad 2\pi f C = \omega C = \frac{\pi V_M}{RV_r}$$

$$i_{C,\text{peak}} = \left(\frac{\pi V_M}{R V_r}\right) V_M \left(\sqrt{\frac{2V_r}{V_M}}\right)$$

$$i_{C,\text{peak}} = \pi \frac{V_M}{R} \sqrt{\frac{2V_M}{V_r}}$$

$$i_{C,\text{avg}} = \frac{\pi}{2} \frac{V_M}{R} \sqrt{\frac{2V_M}{V_r}}$$

As charging current through capacitor is triangular

$$i_L \cong \frac{V_M}{R}$$ → Ignoring changing voltage, current through the load during charging time

$$i_{D,\text{peak}} \cong \frac{V_M}{R}\left(1 + \pi\sqrt{\frac{2V_M}{V_r}}\right)$$

$$i_{D,\text{avg}} \cong \frac{V_M}{R}\left(1 + \frac{\pi}{2}\sqrt{\frac{2V_M}{V_r}}\right)$$ → During conduction time

$$i_D(\text{avg}) = \frac{V_M}{R}\left(1 + \frac{\pi}{2}\sqrt{\frac{2V_M}{V}}\right)\frac{\Delta t}{T}$$ → During entire signal period

For full wave rectifier:

$$\omega \Delta t = \sqrt{\frac{2V_r}{V_M}} \longrightarrow \Delta t = \frac{1}{\omega}\sqrt{\frac{2V_r}{V_M}} = \frac{1}{2\pi f}\sqrt{\frac{2V_r}{V_M}}$$

$$\frac{\Delta t}{T} = \frac{1}{2\pi f}\sqrt{\frac{2V_r}{V_M}}2f = \frac{1}{\pi}\sqrt{\frac{2V_r}{V_M}}$$

$$i_D(\text{avg}) = \frac{1}{\pi}\sqrt{\frac{2V_r}{V_M}}\frac{V_M}{R}\left(1 + \frac{\pi}{2}\sqrt{\frac{2V_M}{V_r}}\right)$$