ECE321 Electronics I
Fall 2006

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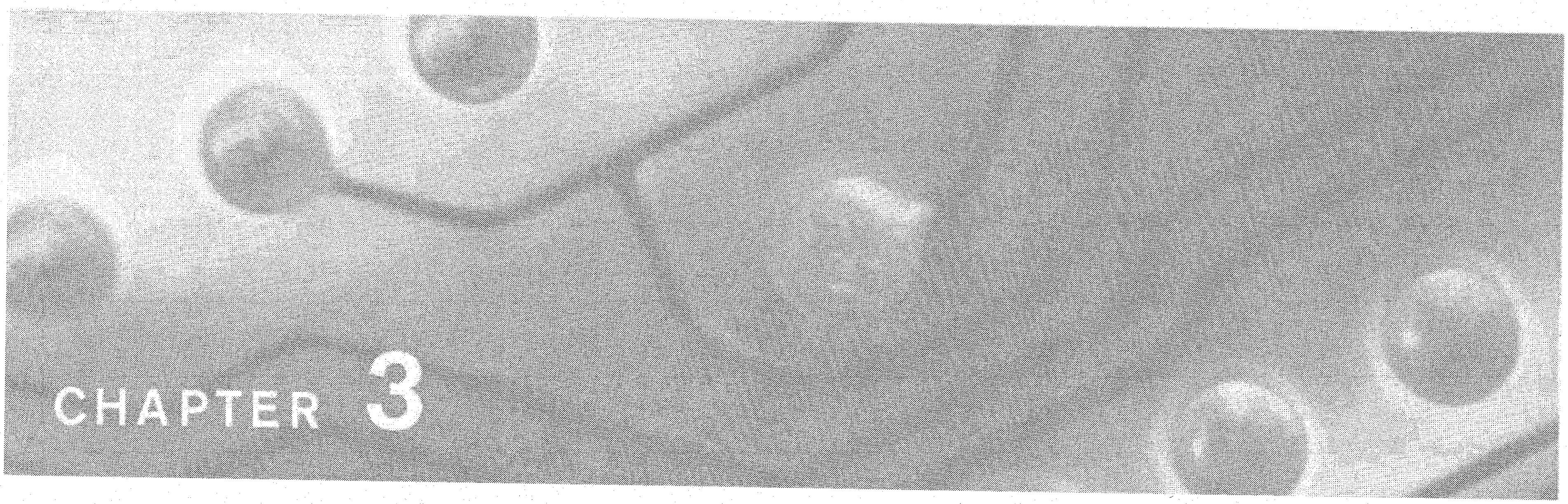
Lecture 6

12th October, 2006



Diodes

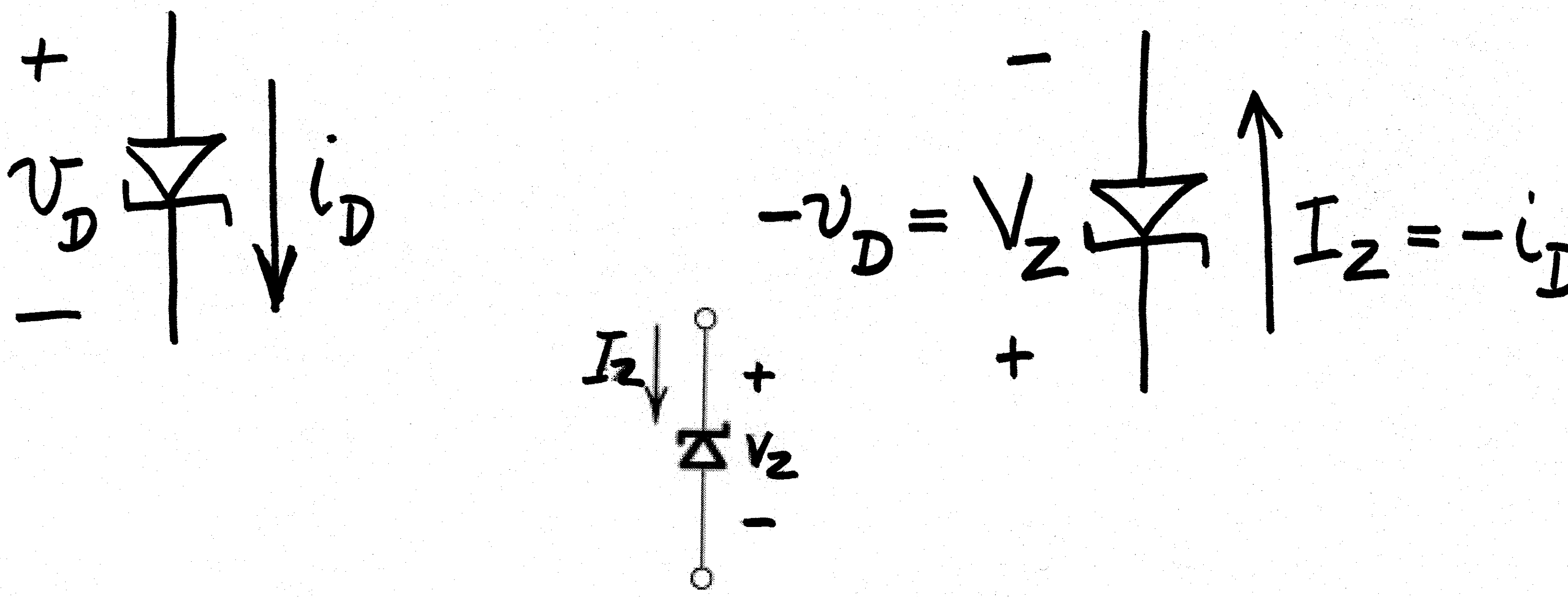
3.4 Zener Diodes — Reverse breakdown

3.5 Rectification — Revisit & develop

3.6 Clipping & Clamping ← Capacitor effects

Non-linear composites

Zener diode symbol

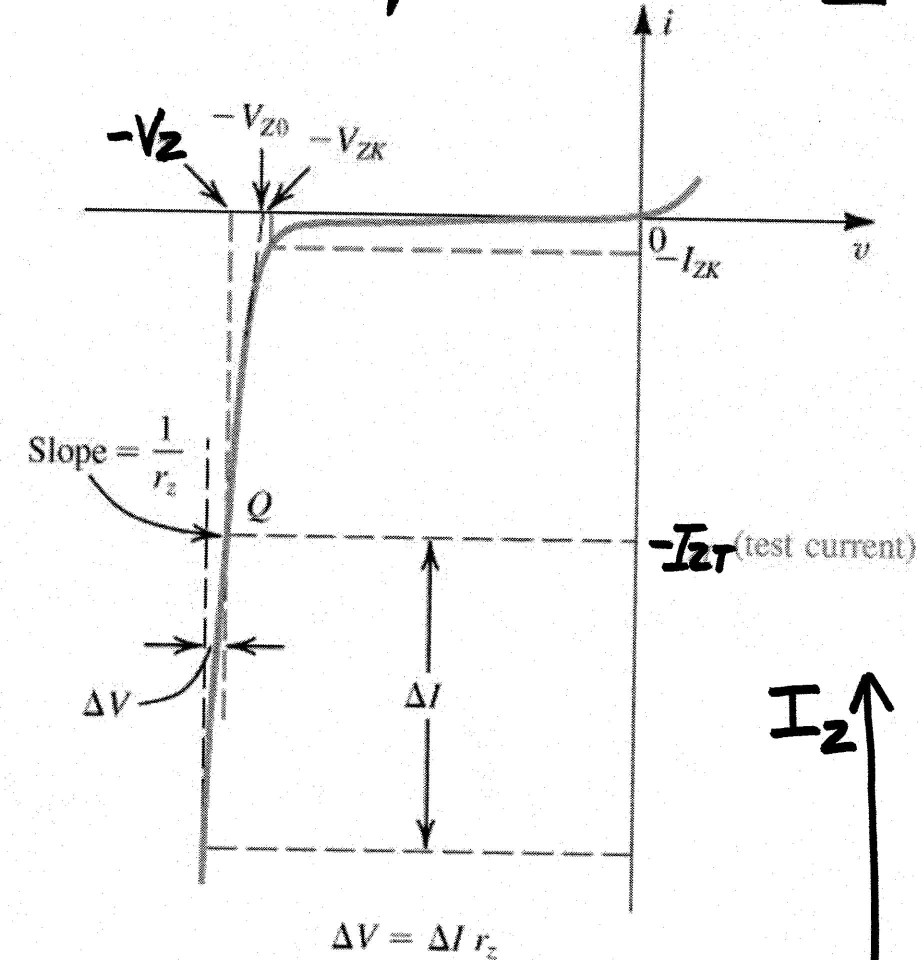


Breakdown diode
Avalanche diode
Reference diode

Figure 3.20 Circuit symbol for a zener diode.

Manufacturer specifies V_Z at test I_{ZT}

V_{ZK}, I_{ZK}
"Knee" voltage/current



$\Delta V = \Delta I . r_Z$

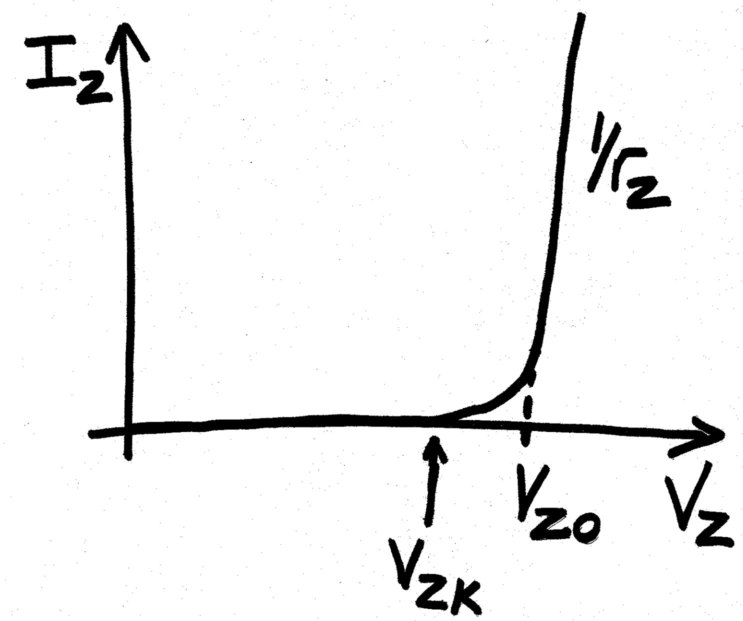
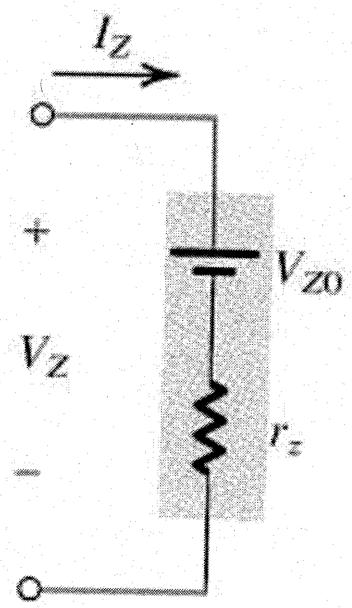


Figure 3.21 The diode *i–v* characteristic with the breakdown region shown in some detail.

Linear Zener Model



$$V_Z = V_{Z0} + I_Z r_Z$$

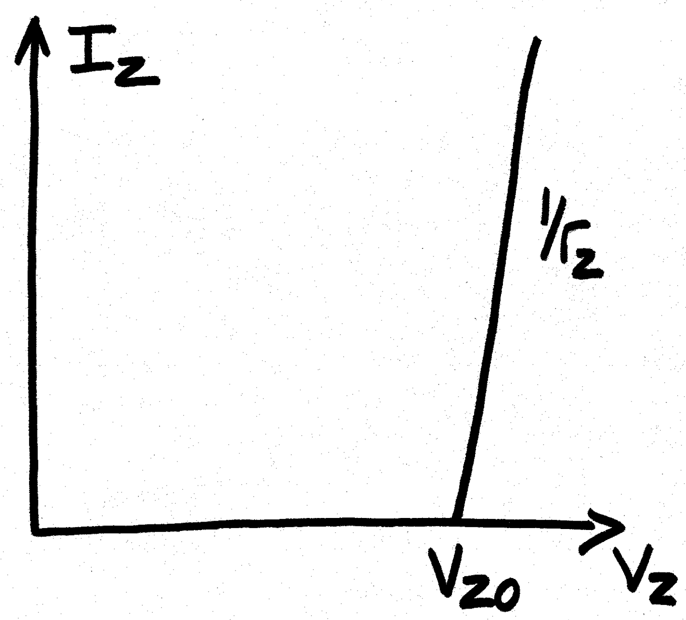


Figure 3.22 Model for the zener diode.

Example 3.8 Voltage regulation

Ex. 3.17

Ex. 3.18

Ex. 3.19

Thermal Effects

For $V_{z0} \lesssim 5v$ neg T.C. (Zener breakdown)

$V_{z0} \gtrsim 5v$ pos T.C. (Avalanche breakdown)

At $\sim 5v$, positive or negative temperature coefficient of V_{z0} can depend on bias point.

Use with series diode $V_{z0}' = V_{z0} + 0.7v$ (nominal)

Pos. TC ($\sim 2mV/^\circ C$) Neg. TC $2mV/^\circ C$

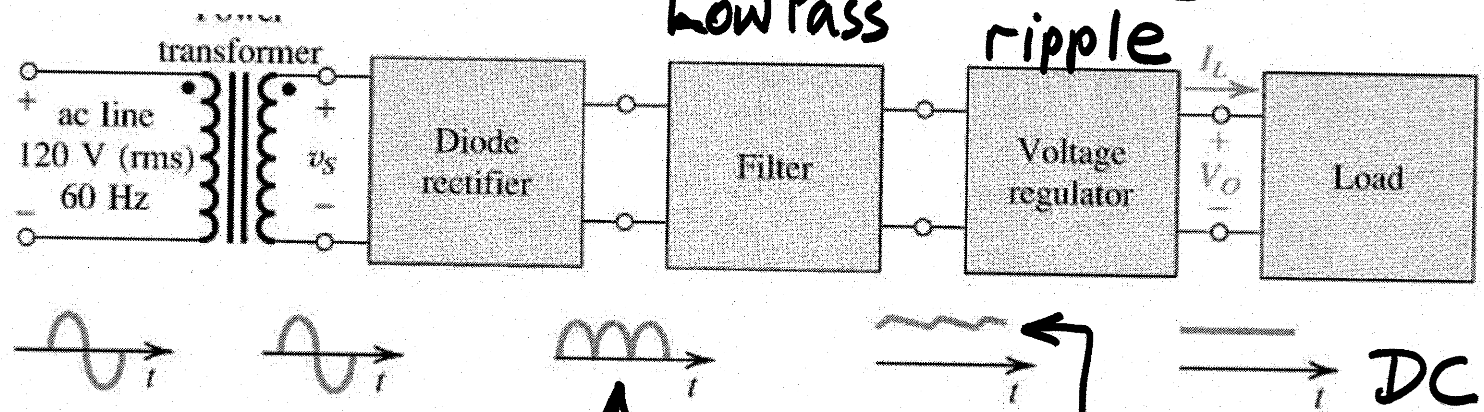
Rectification

AC → DC
power conversion

Isolation

LowPass

Reduce ripple



AC

DC

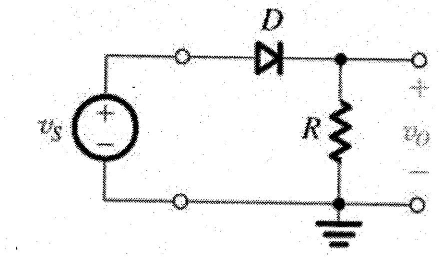
$$v_s = \frac{N_2}{N_1} \cdot 120\text{v}$$

Full-wave rectification

Ripple

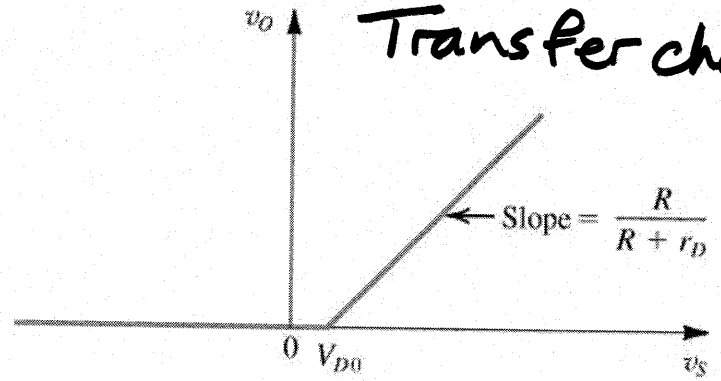
Figure 3.24 Block diagram of a dc power supply.

Half-Wave Rectifier



(a)

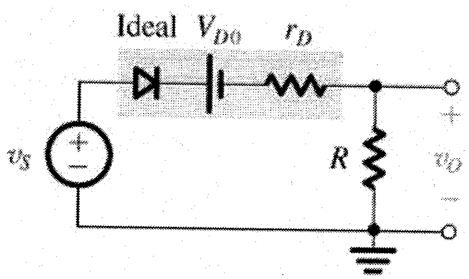
Transfer characteristic



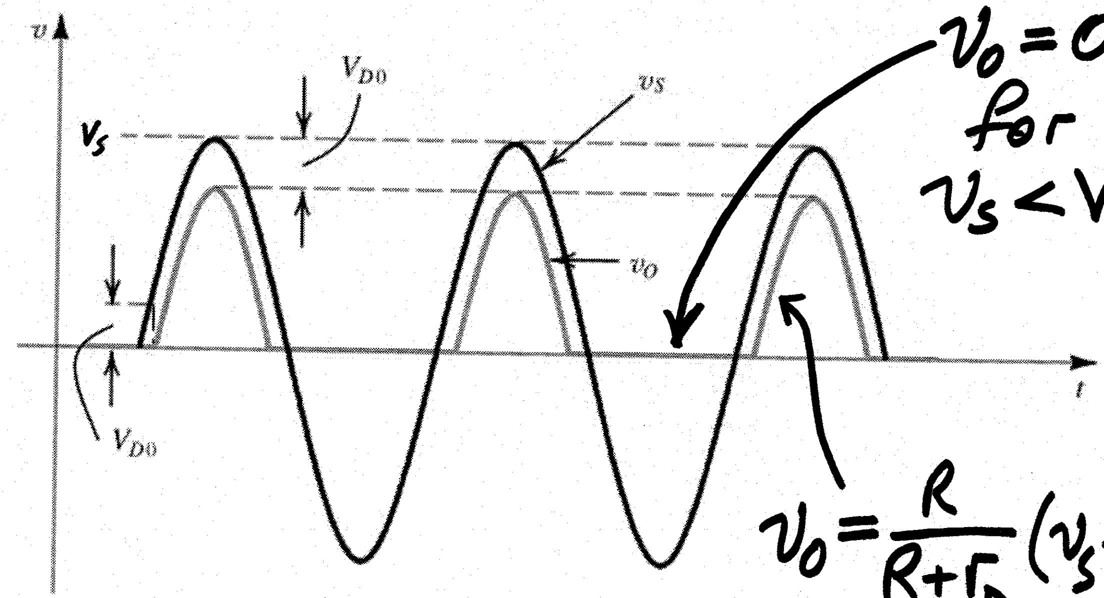
$\lesssim 1$

(c)

Equivalent circuit



(b)



$v_O = 0$ for $v_S < V_{DO}$

$$v_O = \frac{R}{R+r_D}(v_S - V_{DO})$$

for $v_S > V_{DO}$

(d)

Figure 3.25 **(a)** Half-wave rectifier. **(b)** Equivalent circuit of the half-wave rectifier with the diode replaced with its battery-plus-resistance model. **(c)** Transfer characteristic of the rectifier circuit. **(d)** Input and output waveforms, assuming that r_D ! R. $r_D \ll R$

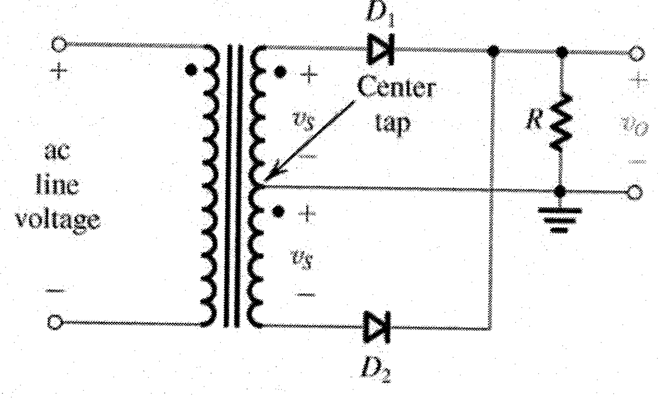
$\approx v_S - V_{DO}$

Notes:

(1) Maximum diode current

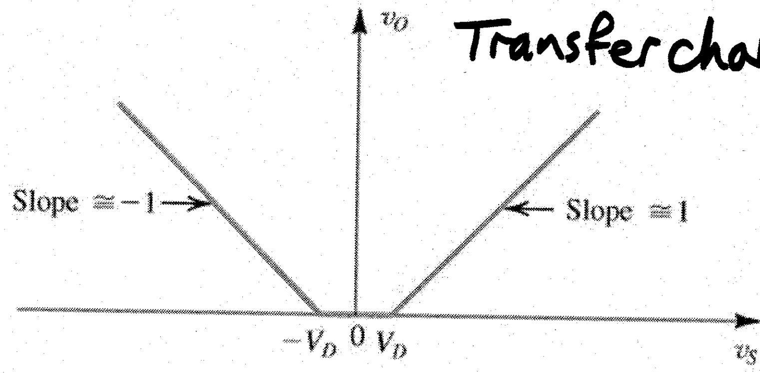
(2) Max PIV – peak inverse voltage across diode when reverse biased — here V_S

Full-wave Rectification

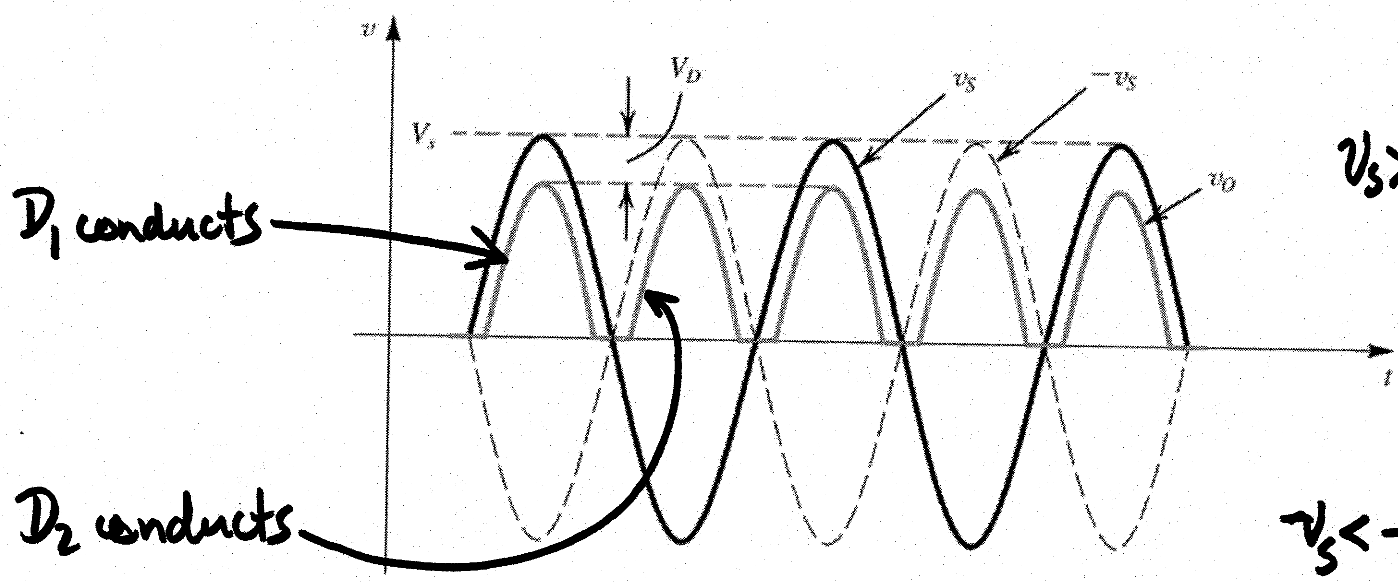


(a)

Transfer characteristic



(b)



(c)

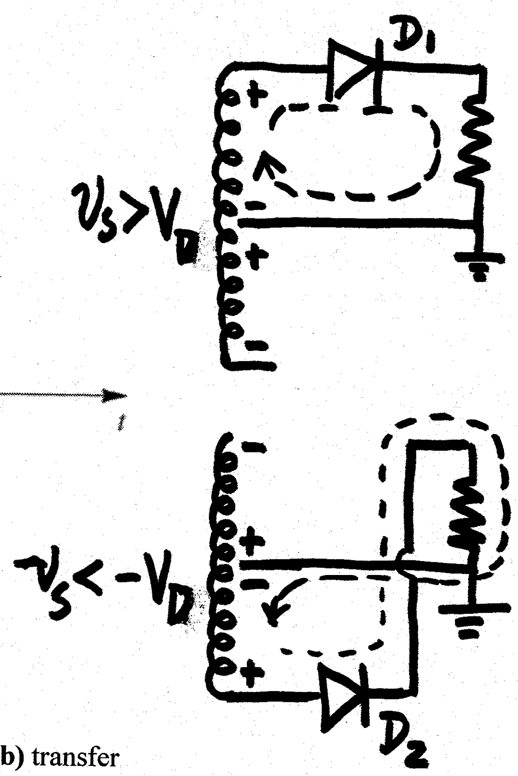
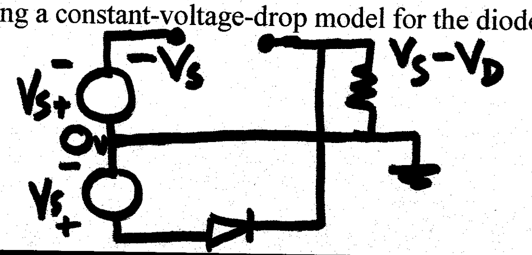


Figure 3.26 Full-wave rectifier utilizing a transformer with a center-tapped secondary winding: **(a)** circuit; **(b)** transfer characteristic assuming a constant-voltage-drop model for the diodes; **(c)** input and output waveforms.

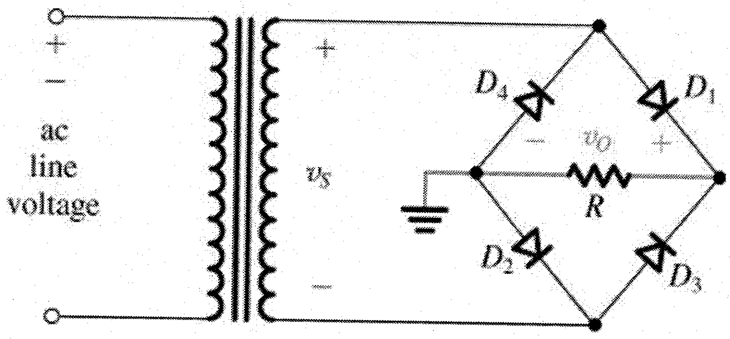
PIV



$$PIV = (V_s - V_D) - (-V_s)$$
$$= 2V_s - V_D \approx 2V_s$$

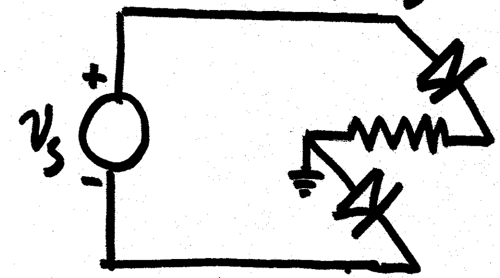
Expensive:
2 windings,
CT transformer

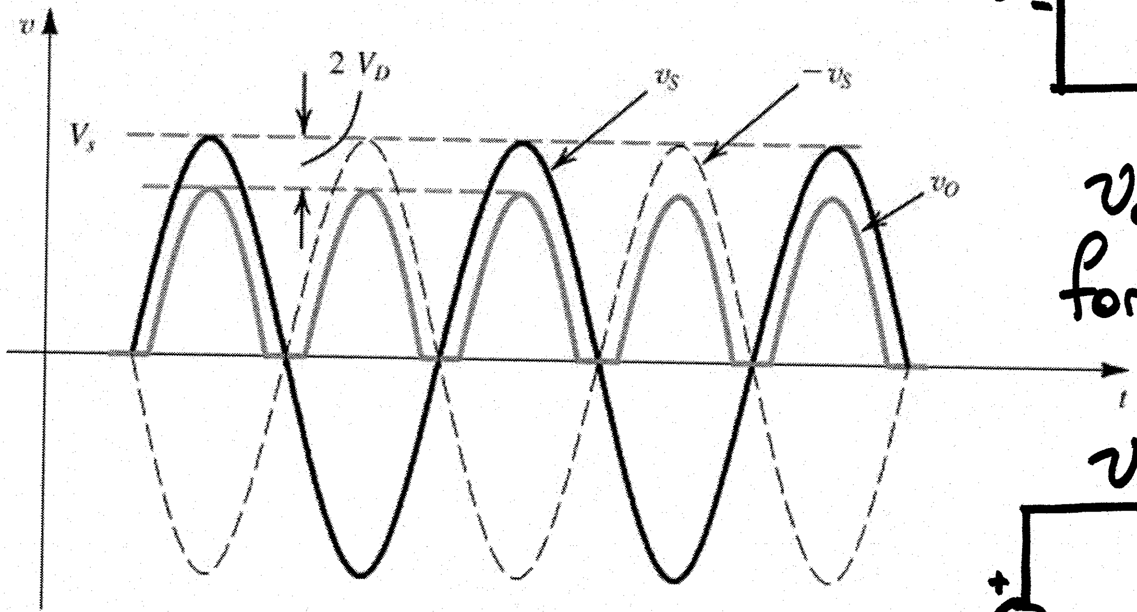
Bridge Rectifier



(a)

$v_S > 2V_D$





(b)

$v_o = |v_s| - 2V_D$
for $|v_s| > 2V_D$

$v_S < -2V_D$

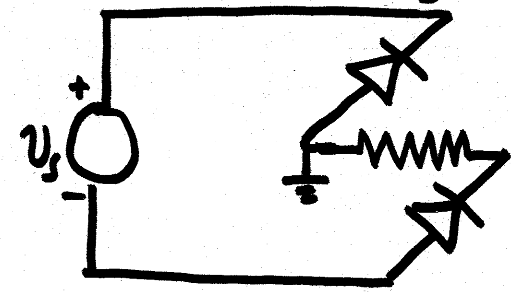
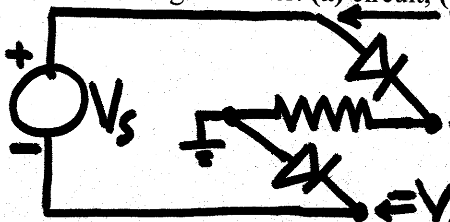


Figure 3.27 The bridge rectifier: **(a)** circuit; **(b)** input and output waveforms.

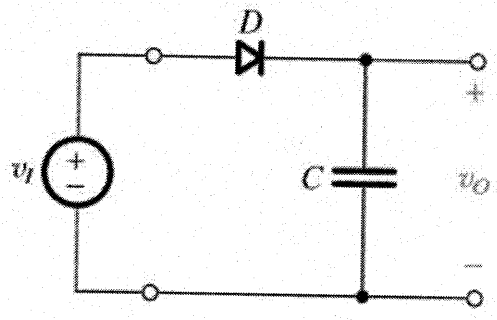
PIV



So across D_3
$PIV = (V_s - 2V_D) - (-V_D)$
$= V_s - V_D \propto V_s$

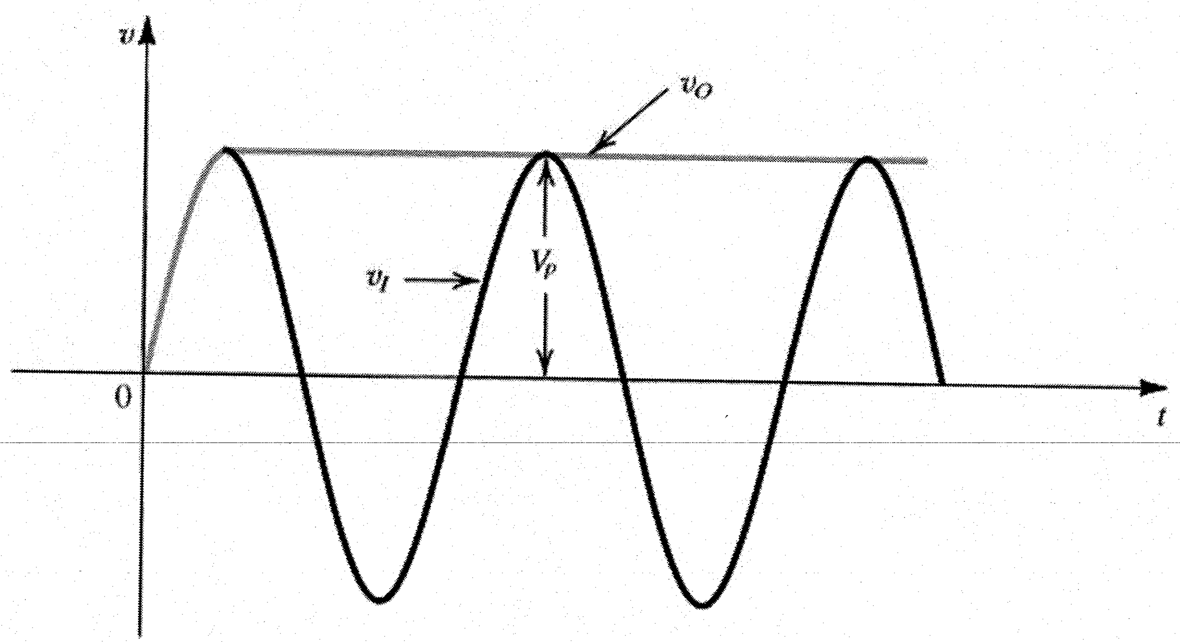
Extra diodes cheap.
Single package

Peak Rectifier



(a)

C charges to V_p & then $v_s \leq v_o$ forever!



(b)

Figure 3.28 (a) A simple circuit used to illustrate the effect of a filter capacitor. **(b)** Input and output waveforms assuming an ideal diode. Note that the circuit provides a dc voltage equal to the peak of the input sine wave. The circuit is therefore known as a peak rectifier or a peak detector.

Peak Rectifier with Load

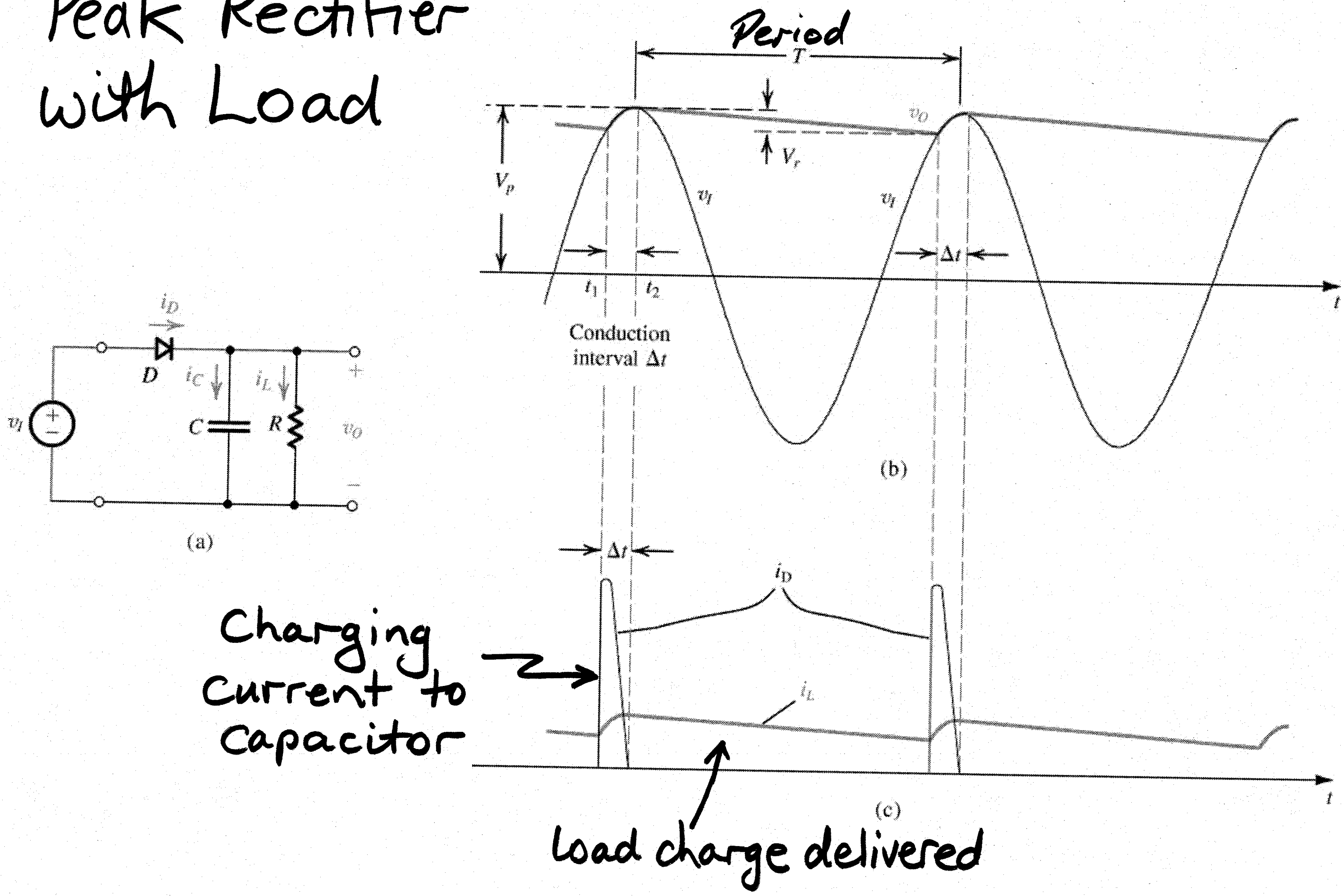
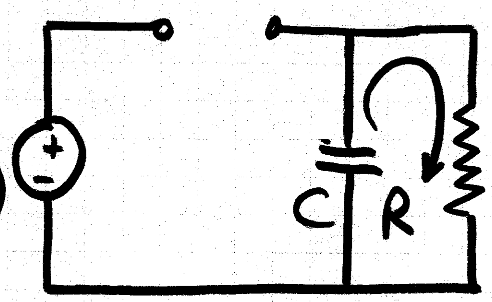


Figure 3.29 Voltage and current waveforms in the peak rectifier circuit with *CR* @ *T*. The diode is assumed ideal.

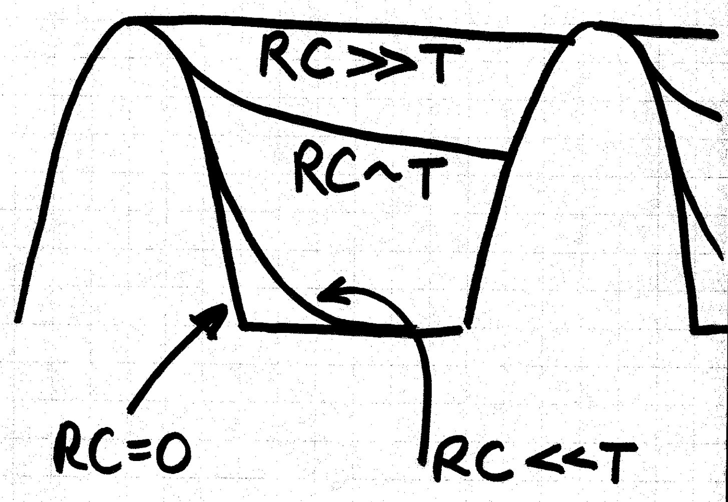
Actually:

v_s decreasing



Assume ½ wave

$v_o = V_p \exp -t/RC$

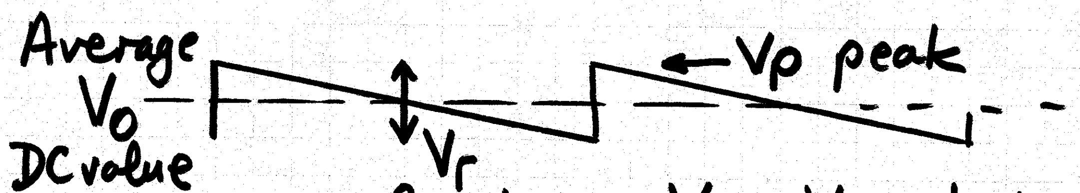


Large load current → R small

∴ Large C needed

For $RC \gg T$, approx linear sag.

For small ripple:



$V_o \approx V_p - \frac{1}{2} V_r$

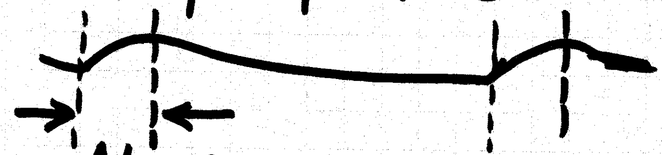
assumes linear approx.

Discharge current = Load current
(constant for linear approximation)

$$i_c = C\frac{dV_c}{dt} = C\frac{V_r}{T} = \underbrace{\frac{V_o}{R}}_{\text{average}} = \frac{V_p - 1/2\,V_r}{R} \approx \frac{V_p}{R}$$

$$\therefore \quad V_r = \frac{V_p}{RC/T + 1/2} \approx V_p\, T/RC$$

Notes: This has approximated $v_o = V_p \exp -t/RC$



Assumes $\Delta t \approx 0$

i.e. at the end of the cycle

$$V_p - V_r \approx V_p \exp -T/RC$$
$$\approx V_p\,(1 - T/RC)$$

gives $V_r \approx V_p\, T/RC$

For fullwave or bridge $T \rightarrow T/2$

Conduction angle: time Δt $\quad V_p \cos \omega \Delta t = V_p - V_r$

For $\omega \Delta t$ small $\quad \cos \omega \Delta t \approx 1 - \frac{1}{2}(\omega \Delta t)^2$

$\therefore 1 - V_r/V_p \approx 1 - \frac{1}{2}(\omega \Delta t)^2 \quad \therefore \omega \Delta t \approx \sqrt{2 V_r/V_p}$

Average diode current during conduction angle/pulse } Charge supplied to C $= i_c)_{Av} \cdot \Delta t$

Charge C supplies to R $= C V_r$

Also $i_c)_{Av} = i_D)_{Av} - i_L$

$$\therefore i_D)_{Av} = i_c)_{Av} + i_L = Q/\Delta t + i_L = \omega C V_r / \sqrt{2 V_r/V_p} + i_L = i_L\left(1 + 2\pi \sqrt{\frac{V_p}{2 V_r}}\right)$$

$\omega C V_r = 2\pi C V_r/T = 2\pi C\, V_p T / RCT = 2\pi V_p/R \approx 2\pi i_L$ $\quad = i_L\left(1 + \pi \sqrt{V_p/V_r}\right)$

Full Wave Peak Rectifier (or Bridge)

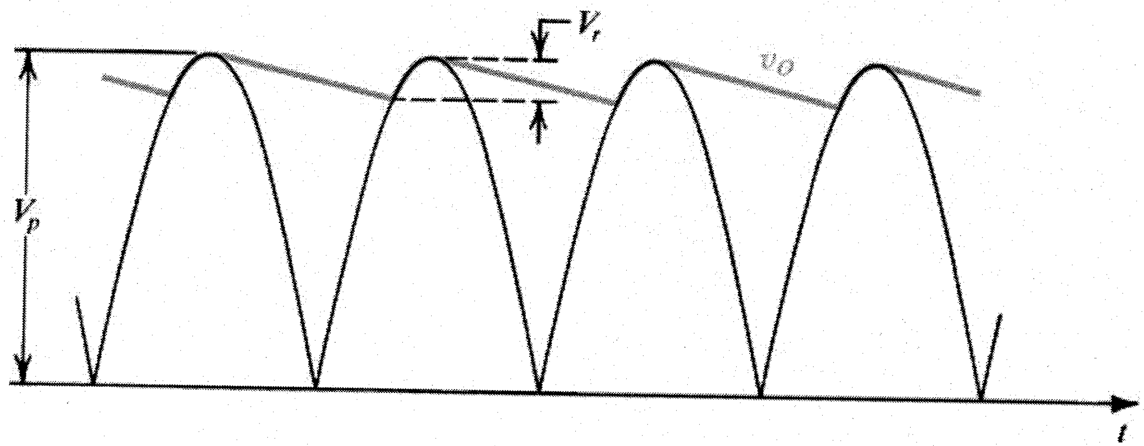


Figure 3.30 Waveforms in the full-wave peak rectifier.

Full wave: Replace T above with T/2

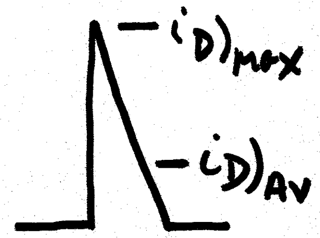
$$\therefore \; V_r = \frac{V_p T}{RC} \Longrightarrow \frac{V_p (T/2)}{RC} = \frac{V_p}{2fRC}$$

Conduction angle same (as function of V_r)

But charge delivered twice as often ∴ current pulse halved.

$$\therefore \; i_D)_{AV} = I_L\left(1 + \pi\sqrt{V_p/2V_r}\right)$$

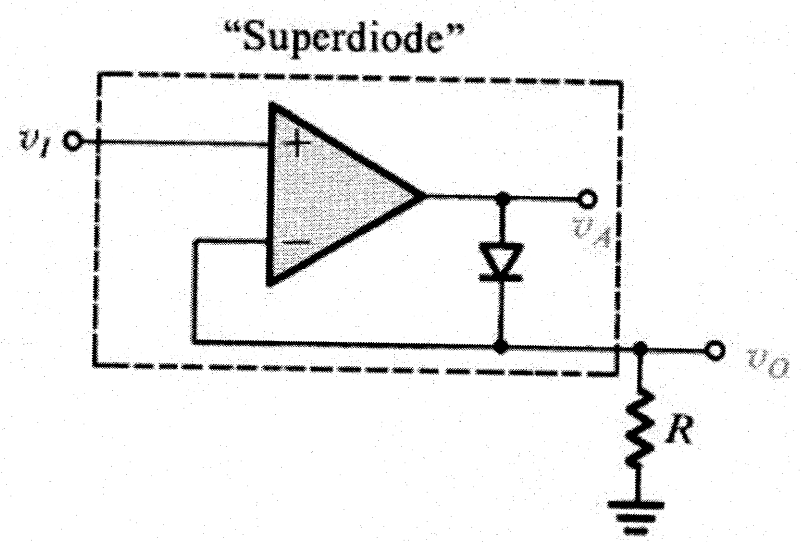
$$\& \quad i_D)_{max} = I_L\left(1 + 2\pi\sqrt{V_p/2V_r}\right)$$



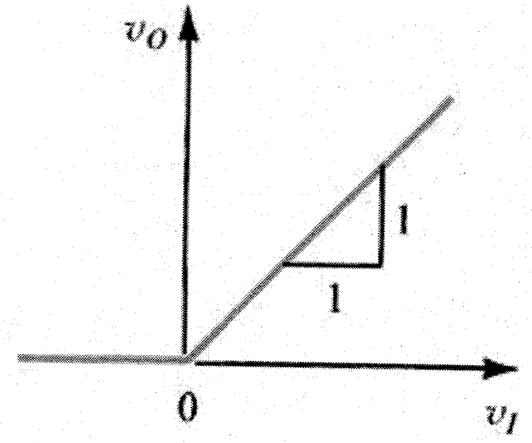
Problem D3.24

Bridge rectification with C smoothing filter

"Superdiode" or Precision Rectifier



(a)



(b)

$v_I > 0$ $\quad v_o \rightarrow$ positive

$\therefore$ D on $\therefore$ negative feedback

$\therefore v_o \approx v_i$

$v_I < 0$

$v_o \rightarrow$ negative

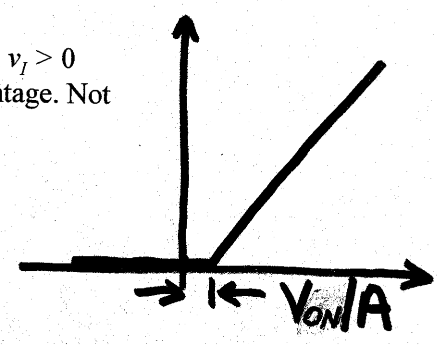
$\therefore$ D off

$\therefore v_o = 0$

Figure 3.31 The "superdiode" precision half-wave rectifier and its almost-ideal transfer characteristic. Note that when $v_I > 0$ and the diode conducts, the op amp supplies the load current, and the source is conveniently buffered, an added advantage. Not shown are the op-amp power supplies.

If op amp gain A finite

Turn-on voltage $= V_{ON}/A$

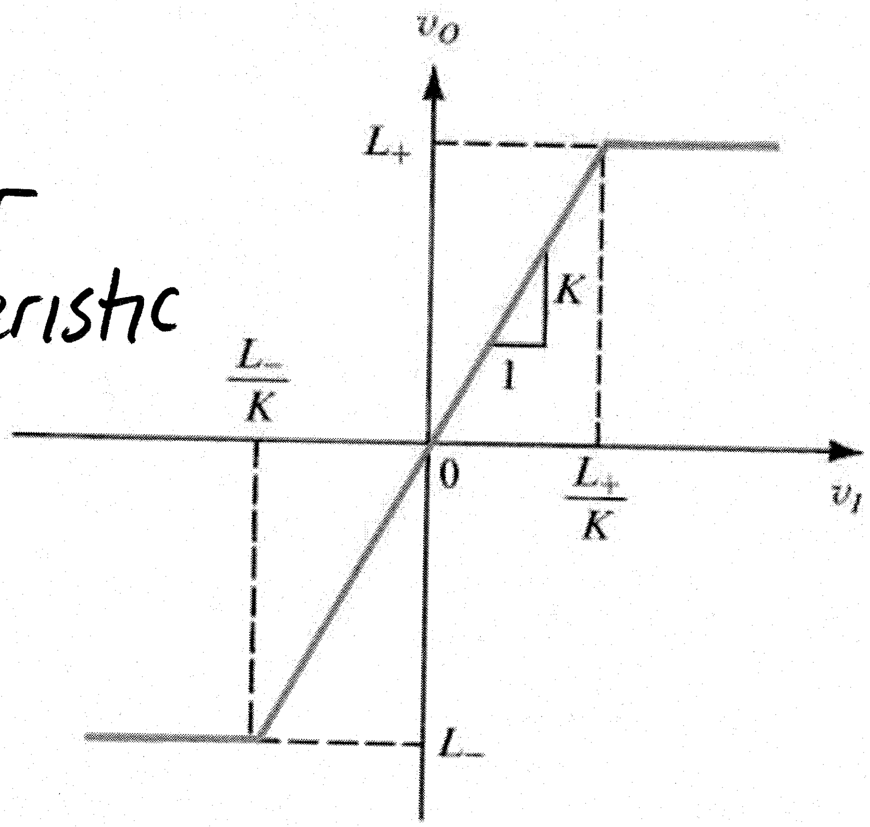


Ex 3.26

Superdiode

Limiting/Clipping Circuits

Transfer characteristic



Note: Similar to saturated output op-amp circuits

Figure 3.32 General transfer characteristic for a limiter circuit.

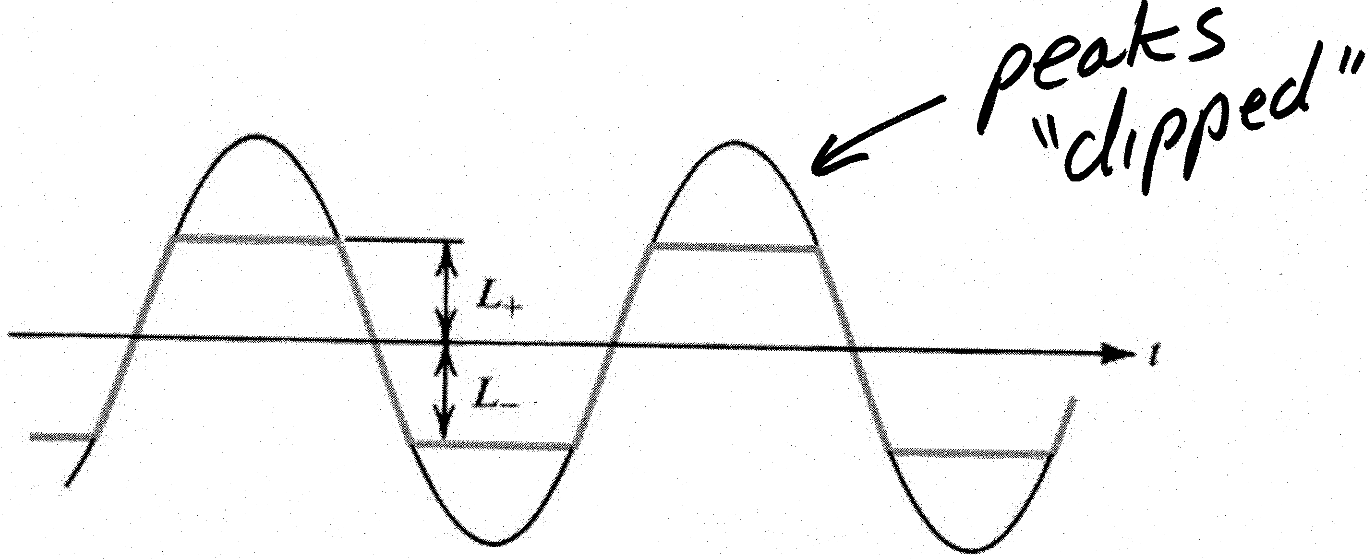


Figure 3.33 Applying a sine wave to a limiter can result in clipping off its two peaks.

"Soft" limiting

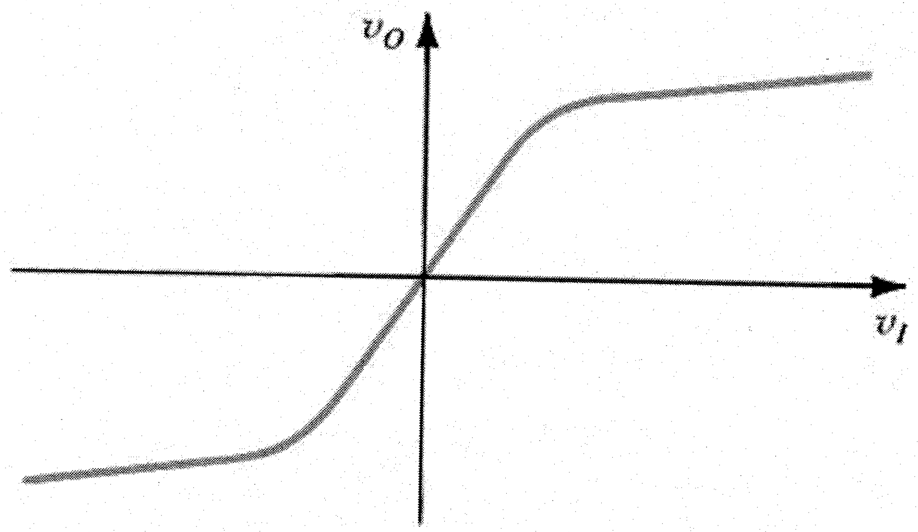


Figure 3.34 Soft limiting.

Diode Limiters

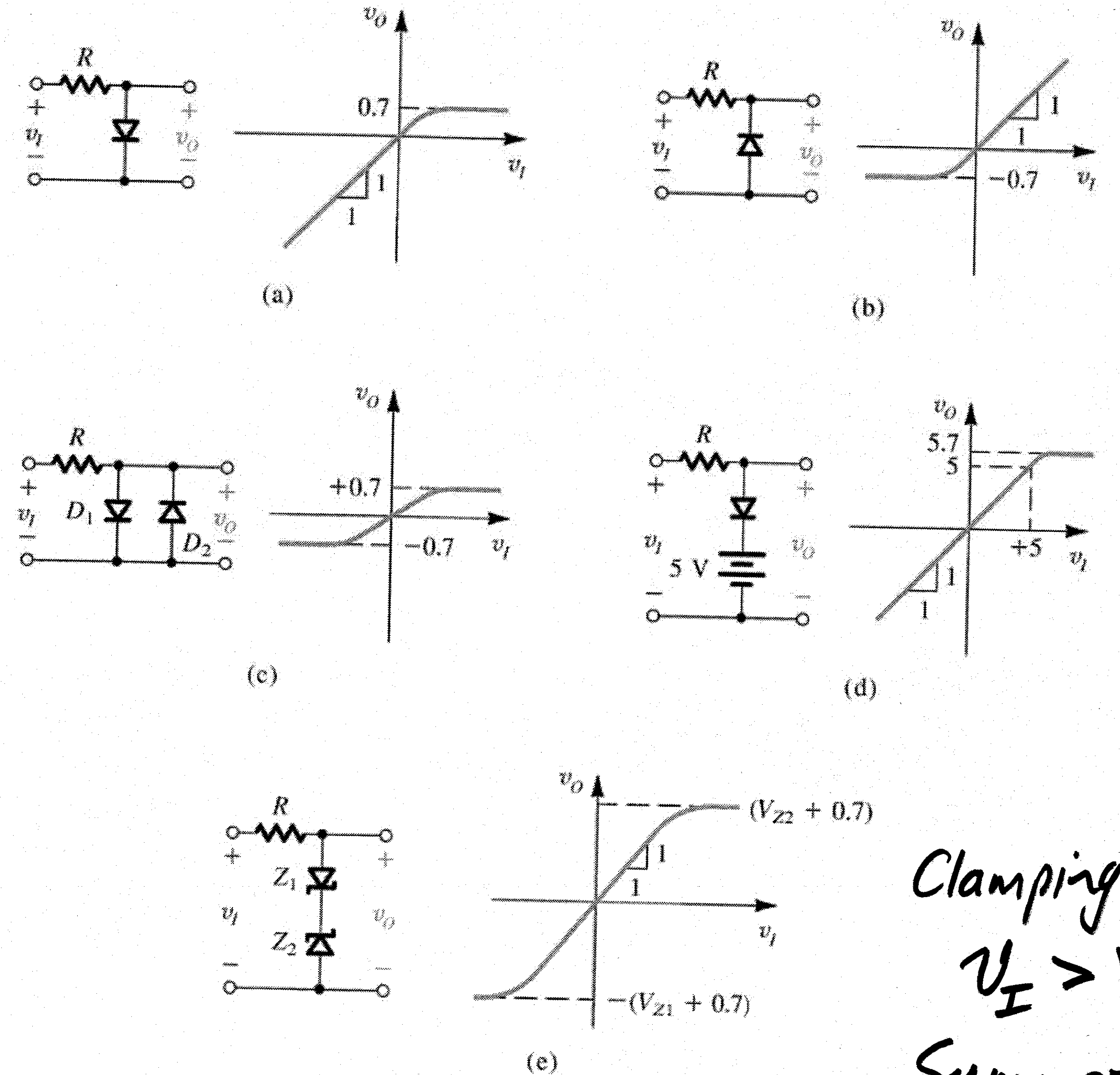


Figure 3.35 A variety of basic limiting circuits.

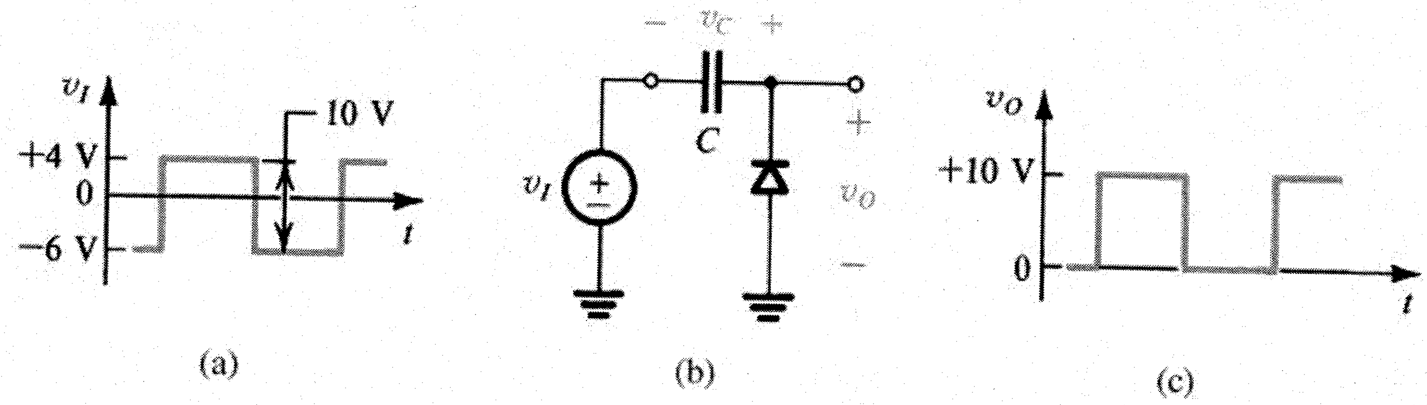
Clamping for
$v_I > V_Z + 0.7\text{V}$
Symmettrical

Ex. 3.27

Diode limiter

(diode clipping)

DC Restorer



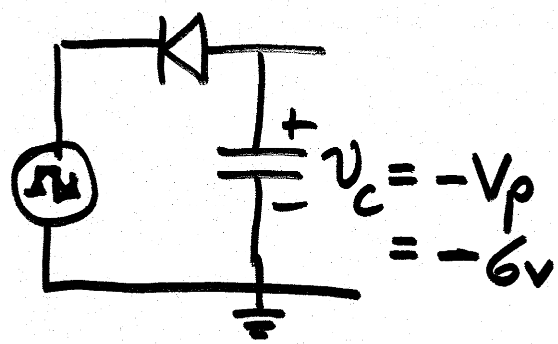
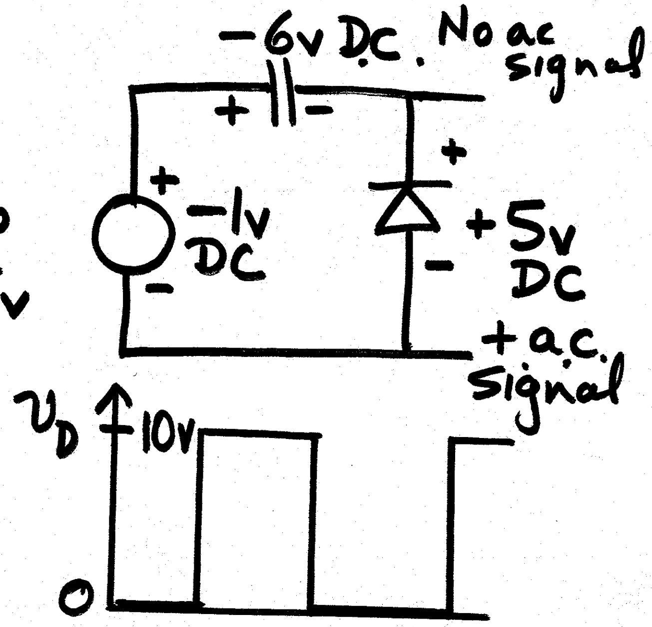
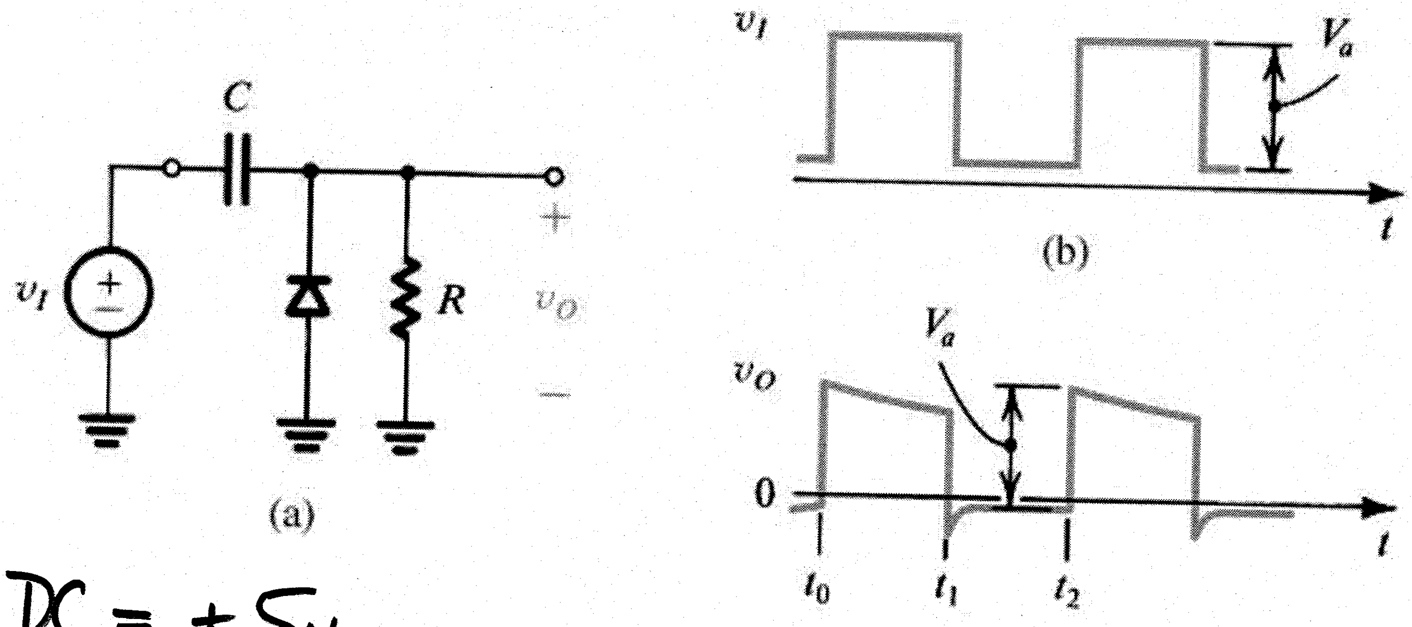


Figure 3.36 The clamped capacitor or dc restorer with a square-wave input and no load.

Diode clamps output to 0v



DC Restorer with Load



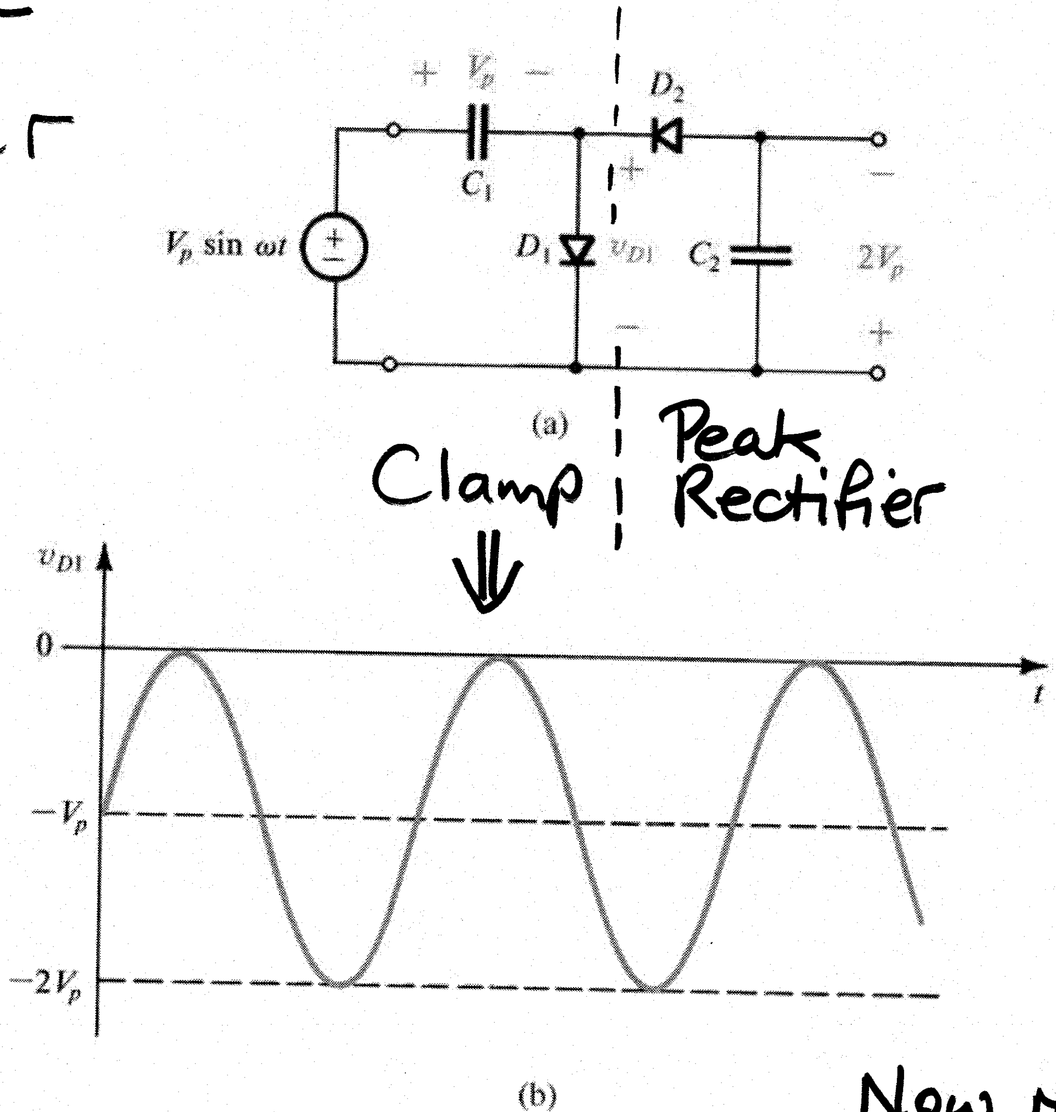
(c)

v_o DC = +5v
∴ I_R flows

Diode reverse biased, ∴ I_R from C (discharges slowly)
Then diode re-charges fast when input → neg
& turns diode on ($v_o < 0$)

Figure 3.37 The clamped capacitor with a load resistance R.

Voltage Doubler



Clamps to 0v

$v_{D1} < 0v$

Now rectifier

$\rightarrow v_0 = -2V_p$

Figure 3.38 Voltage doubler: **(a)** circuit; **(b)** waveform of the voltage across D_1.

Assignment #3

3.29

D3.43

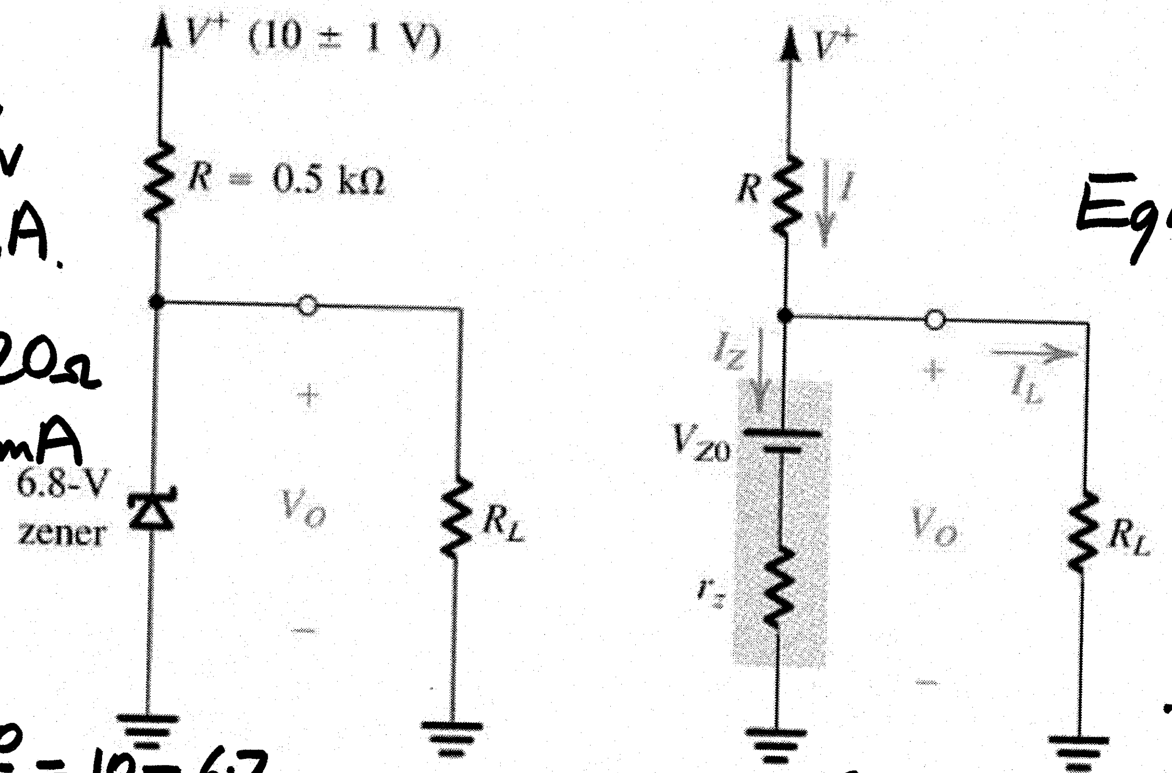
D3.68

3.85

3.102

Example 3.8 Voltage Regulation

Given:
$V_Z = 6.8_V$
at $I_Z = 5mA$.
And $r_z = 20\Omega$
$I_{ZK} = 0.2mA$



Equivalent circuit:

Need V_{Z0}

$V_Z = V_{Z0} + I_Z r_z$
$\therefore V_{Z0} = 6.8_V - 20_\Omega \times 5mA$
$= 6.7_V$

(a) For $R_L = \infty$
$I_Z = \dfrac{V^+ - V_{Z0}}{R + r_z} = \dfrac{10 - 6.7}{520} = 6.35mA \therefore V_o = 6.7 + 6.35 \times 10^{-3} \times 20 = 6.83_V$

(b) $\pm 1_V$ change in $V^+ \longrightarrow \pm 1_V \dfrac{r_z}{R + r_z}$ (for $R_L = \infty$) $= \dfrac{20}{520} = \pm 38.5mV$

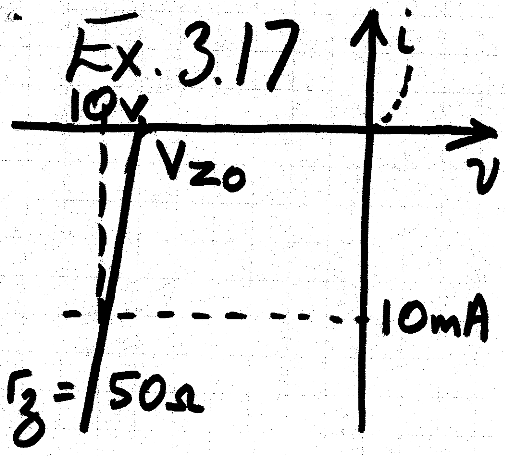
"Line regulation" $= (\Delta V_o / \Delta V^+) 100\% = 3.85\%$ or $38.5mV/V$

Figure 3.23 **(a)** Circuit for Example 3.8. **(b)** The circuit with the zener diode replaced with its equivalent circuit model.

(c) For $I_L = 1mA$, $I_Z \to 5.35mA$ But can find $\Delta V_o = r_z \Delta I = 20 \times (-1mA)$
$= -20mV$

"Load regulation" $= (\Delta V_o / \Delta I_L) = -20mV/mA$

Ex. 3.17



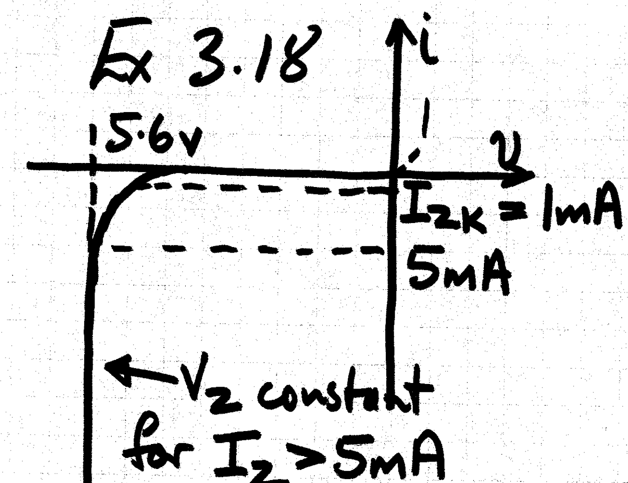
Zener 10mA @ 10v. $r_z = 50\Omega$

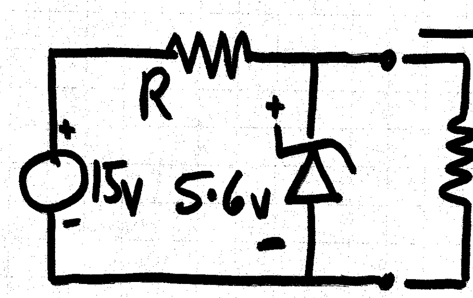
V_Z for 5mA? $= 10v - 5mA \times 50\Omega = 9.75v$

V_Z for 20mA? $= 10v + 10mA \times 50\Omega = 10.5v$

V_{Z0}? $= 10v - 10mA \times 50\Omega = 9.5v$

Ex 3.18





0-15mA

For $V_Z = 5.6v$, need $I_Z \geq 5mA$.

Max $I_L = 15mA$

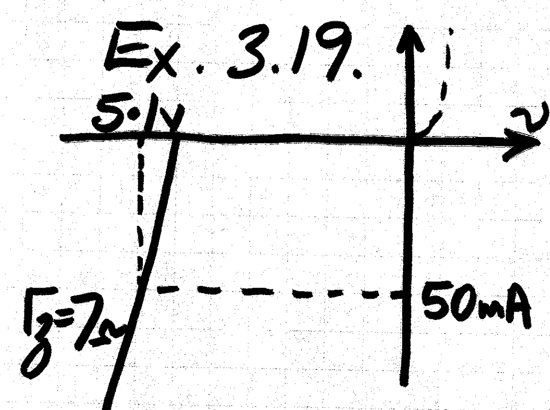
$\therefore$ need 20mA through R

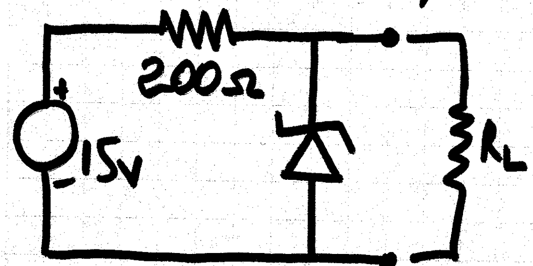
so $I_Z = \underset{\text{max } I_L}{5}$ to $\underset{I_L = 0}{20mA}$

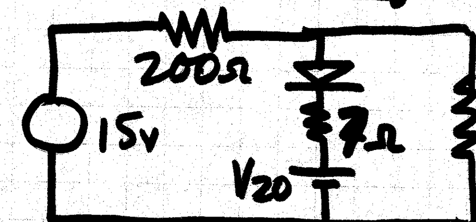
$\therefore R = \dfrac{15v - 5.6v}{20mA} = 470\Omega$

Max zener power $= V_Z I_Z)_{max} = 5.6v \times 20mA = 112mW$

Ex. 3.19.







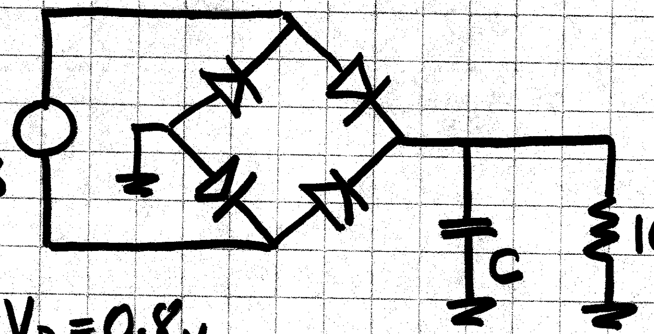
Assume $V_{Z0} = 5.1v - 50mA \times 7\Omega$
$= 4.75v$

No load: $V_Z = 4.75v + 7\Omega \dfrac{15 - 4.75v}{200\Omega}$
$= 4.75 + 0.359 = 5.11v$

Line regulation: $\dfrac{7}{7+200}$ V/V $= 33.8mV/V$

Load regulation: $\dfrac{\Delta V}{\Delta I_L} = -\dfrac{\Delta I_L r_z}{\Delta I_L} = -7mV/mA$

D3.24



$V_D = 0.8v$

Find C for $V_r < 1v$ pk-pk

Find dc voltage V_o

Find load current

Find diode PIV

Specify diode I_{pk} and PIV.

$12v)_{RMS} \longrightarrow 12\sqrt{2}$ pk $\therefore V_p \approx 17.0v$ & $V_r = \dfrac{V_p}{2fRC}$

So $C \geq \dfrac{V_p}{V_r}\dfrac{1}{2fR} = \dfrac{17.0}{1.2.60.100}$

$= 1{,}417\mu F$

Or more accurately: $V_p = 17 - 2V_D = 15.4v$

$\therefore C \geq \dfrac{15.4}{12\times10^3} = 1{,}283\mu F$

So say $C = 1.5\,mF$

$V_o = 15.4 - V_r/2 = 14.9v$

$I_L = 14.9v/100\Omega = 149mA$

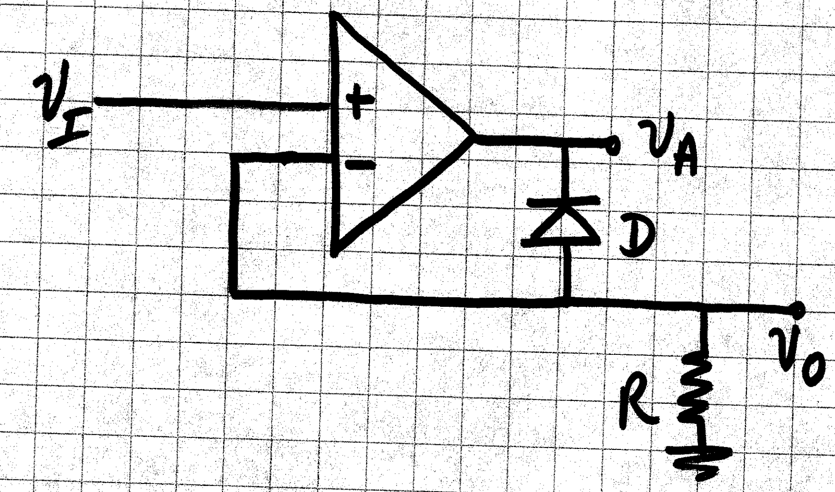
Diode PIV $= V_s - V_D = 17 - 0.8 = 16.2v$

Specify $I_{pk} \gtrsim 3A$

PIV $\gtrsim 20v$

$i_D)_{MAX} = I_L\left(1 + 2\pi\sqrt{(V_p - 2V_D)/2V_r}\right) = 149mA\left(1 + 2\pi(15.4/2)^{1/2}\right) = 2.75A$

Ex 3.26

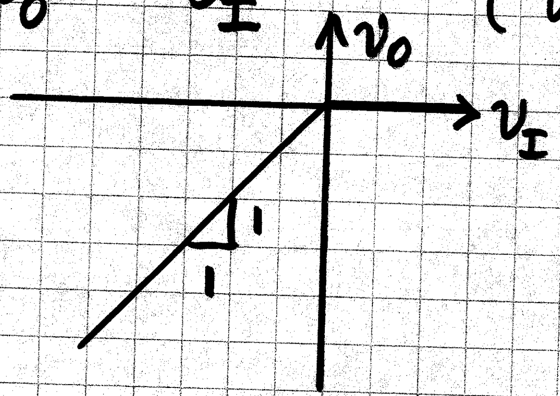


If $v_I > 0$ $\quad v_A \to$ high $\quad$ D reverse biased (OFF)

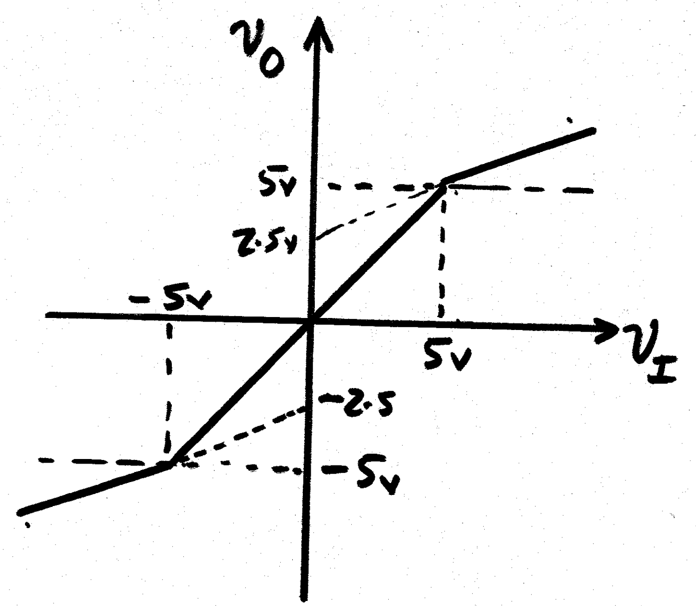
$\therefore v_O = 0$

If $v_I < 0$ $\quad v_A \to$ Low $\quad$ D forward biased (ON)
(negative feedback)

$\therefore v_O = v_I$ $\quad (v_A = v_I - V_D)$



Ex 3.27



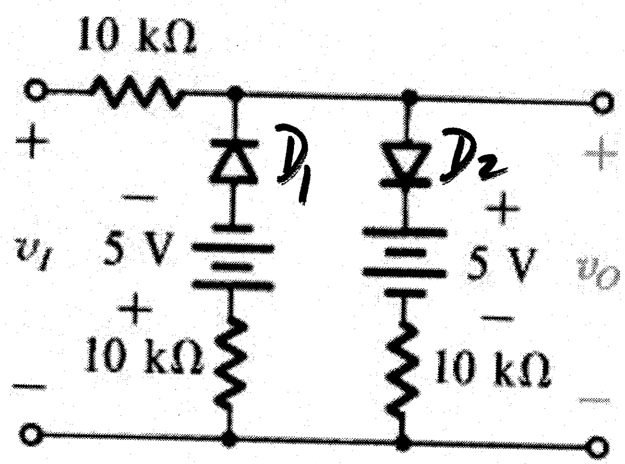


Figure E3.27

D_1 off unless $v_I < -5_v$, $v_O = -5_v + \frac{v_I - (-5_v)}{20K} 10K$

$= -5 + \frac{v_I}{2} + \frac{5}{2}$

$= v_I/2 - 2.5_v$

D_2 off unless $v_I > +5_v$

$v_O = +5 + \frac{1}{2}(v_I - 5_v)$

$= v_I/2 + 2.5_v$

$-5_v < v_I < 5_v$, D_1 & D_2 off, $v_O = v_I$