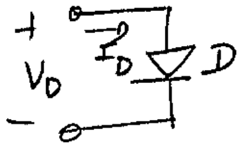
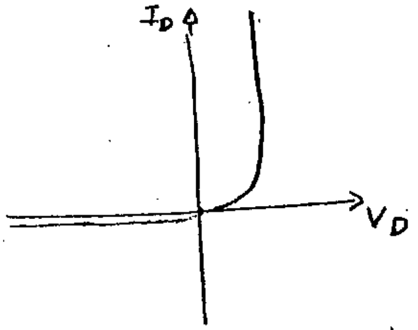
Diode



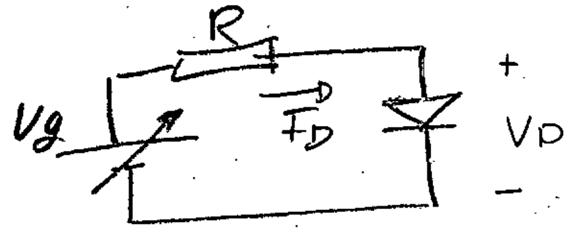
$$I_D = I_0\left(e^{\frac{V_D}{V_T}} - 1\right)$$

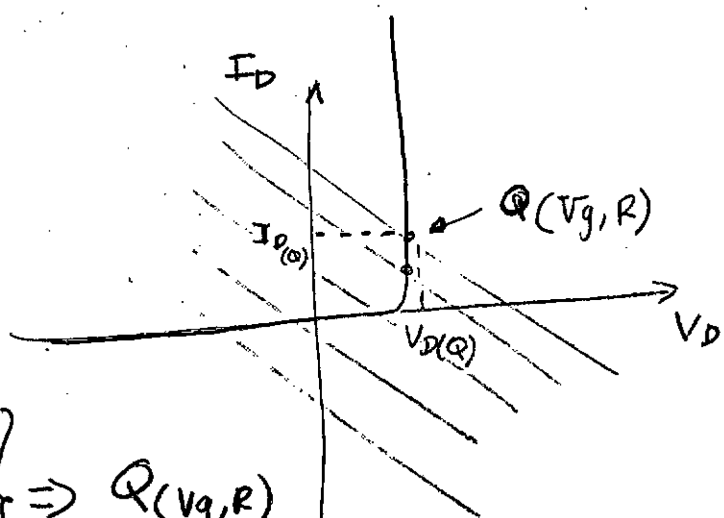
- I_0: Reverse saturation current (ORDER OF 10^{-12} to 10^{-15})
- V_T: Thermal Threshold Voltage $\simeq$ 25mV (300°K)



- We can see that: if $I_D \uparrow\uparrow \Rightarrow V_D \simeq$ constant and
  if $V_D \downarrow\downarrow \Rightarrow I_D \simeq 0$

- Diode in a circuit





$$\left.\begin{array}{l} ① \; V_g - I_D R - V_D = 0 \; (\text{Load}) \\ ② \; I_D = I_0\left(e^{\frac{V_D}{V_T}} - 1\right) \; (\text{Diode}) \end{array}\right\} \Rightarrow Q(V_g, R) \equiv (V_{DQ}, I_{DQ})$$

The equation is highly non linear.
It is interesting to model the diode in a piecewise linear model

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DIODE	

Typical diode

$$I_D = 6'9144 \cdot 10^{-13}\left(e^{\frac{V_D}{0'025}} - 1\right)$$

In Matlab:

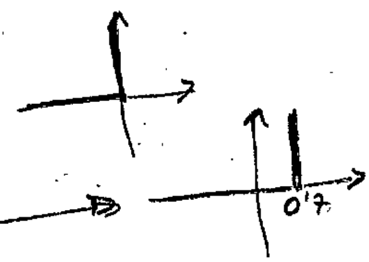
① $V = [-1 ; 0'005 : 2]$

② $I = I_0 \left(e^{\frac{V}{0'025}} - 1\right)$

③ plot(V, I)

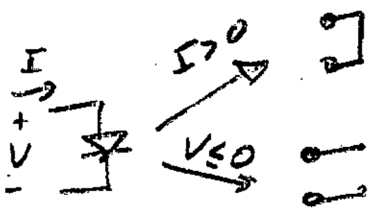
Several models can be obtained:

- Ideal diode →
- Ideal diode with offset →

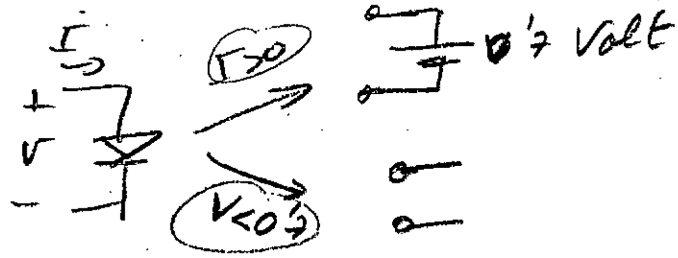


- Piecewise linear model
- Small signal model

- Ideal diode →



- Ideal with offset →



Analog Systems

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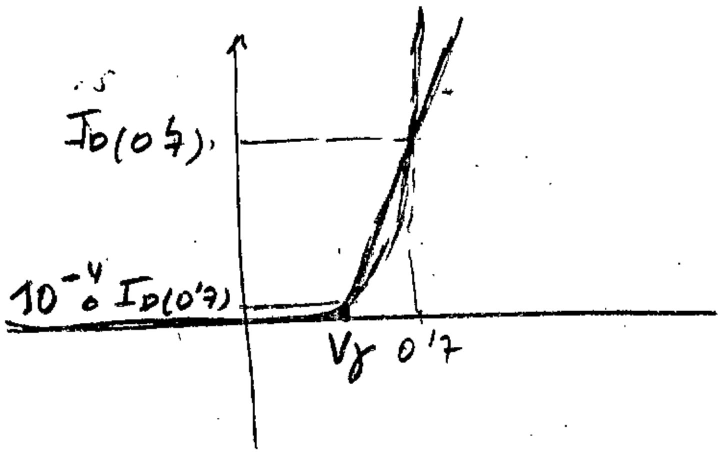
DIODE

· Piecewise linear model



It's assumed to model the diode, that:

① $I_D(V<V_\gamma) \stackrel{\Delta}{=} 0$

② $I_D(V>V_\gamma) \stackrel{\Delta}{=}$ Linear, slope $= \dfrac{I_D(0'7) - I_D(V_\gamma)}{0'7 - V_\gamma}$

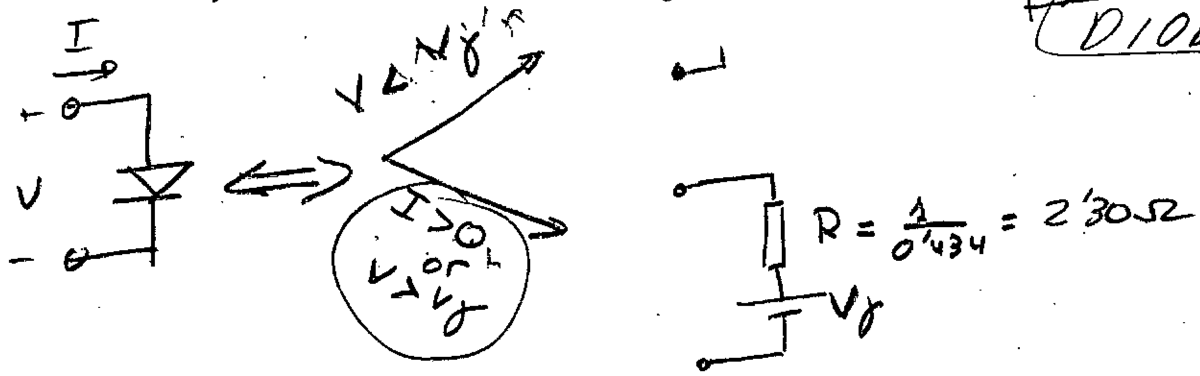
Let's find out V_γ and slope

$$I_0 \cdot \left(e^{\frac{V_\gamma}{0'025}} - 1\right) = 10^{-4} \cdot I_0 \cdot \left(e^{\frac{0'7}{0'025}} - 1\right) \Longrightarrow$$

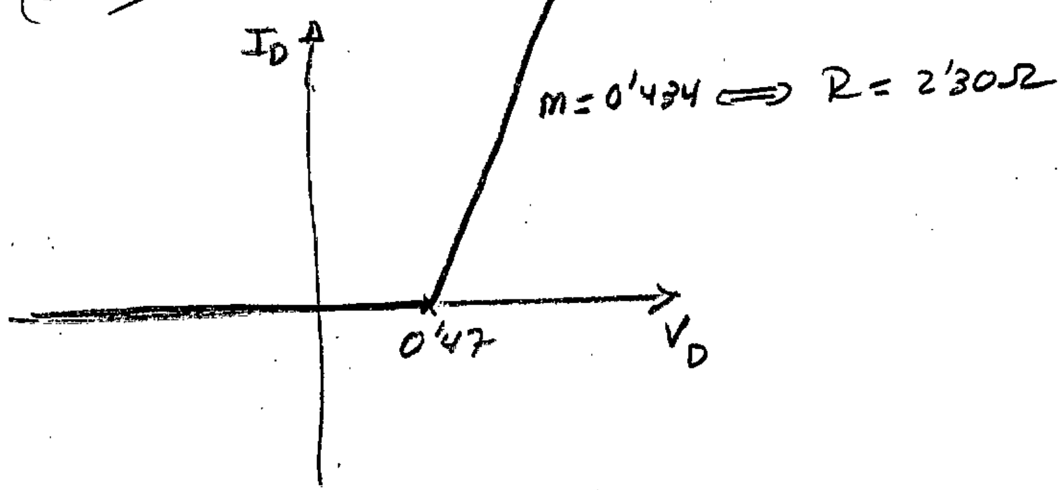
· $V_\gamma = 0'47$ Volt (Note that V_γ is independent of I_0)

· $\text{slope} = \dfrac{0'1 - 9'7077 \cdot 10^{-5}}{0'7 - 0'47} = 0'4344\ \Omega^{-1}$

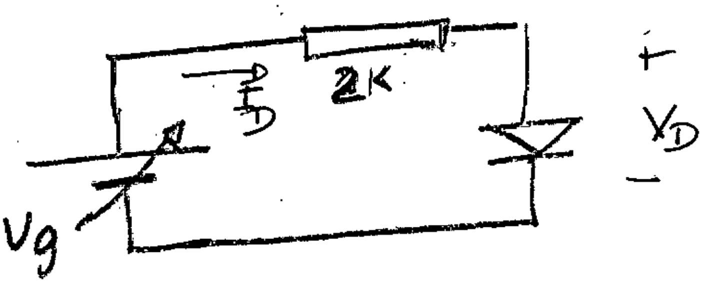
We can graph the model



And The (I-V) is



- The ideal, offset and piecewise models as well as the original equation will be used to solve a simple circuit.



$-1 < V_g < 100$ Volt

① Ideal model

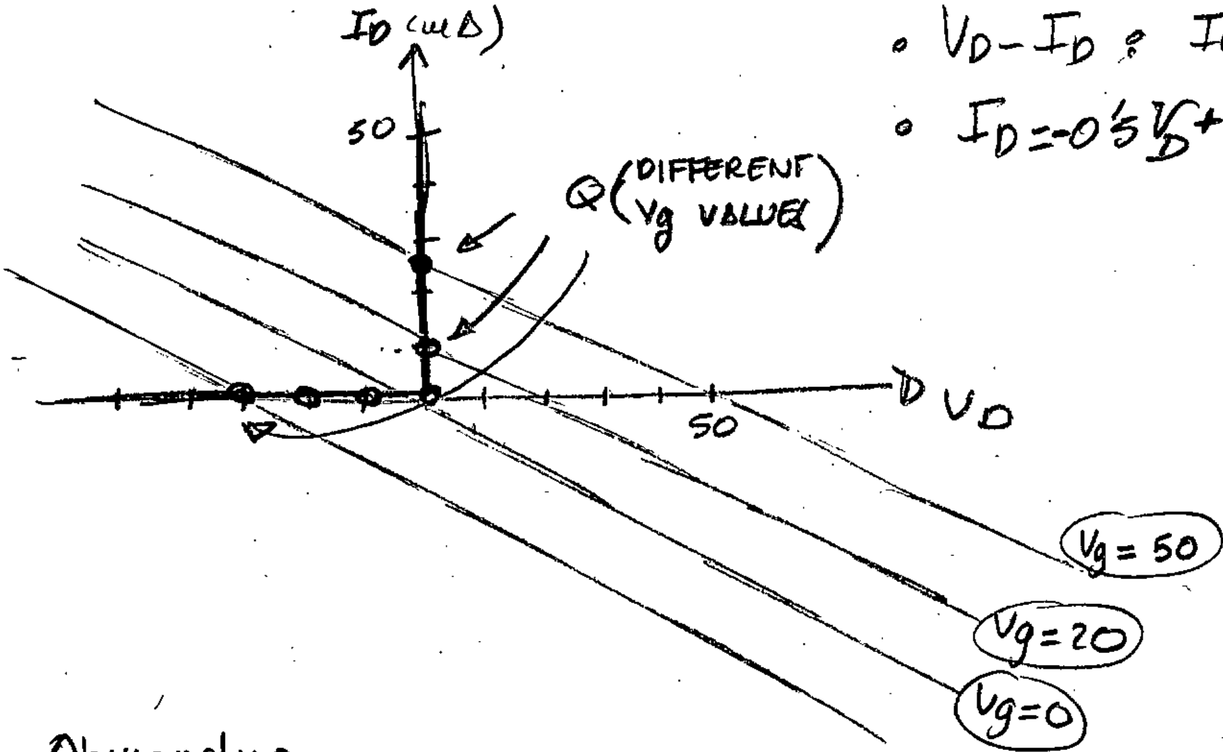
The system is defined by two equations:

① $I_D - V_D$ Diode characteristics

② Load line: $V_g - I_D \cdot 2 - V_D = 0$

If both equations are plotted in the same graph, the bias point Q can be obtained:

- $V_D - I_D$: Ideal
- $I_D = -0'5 V_D + 0'5 V_g$



Obviously:

- $V_D = 0$, $I_D = \dfrac{V_g}{2} = 0'5\, V_g$ IF $V_g > 0$
- $V_D = V_g$, $I_D = 0$ IF $V_g < 0$

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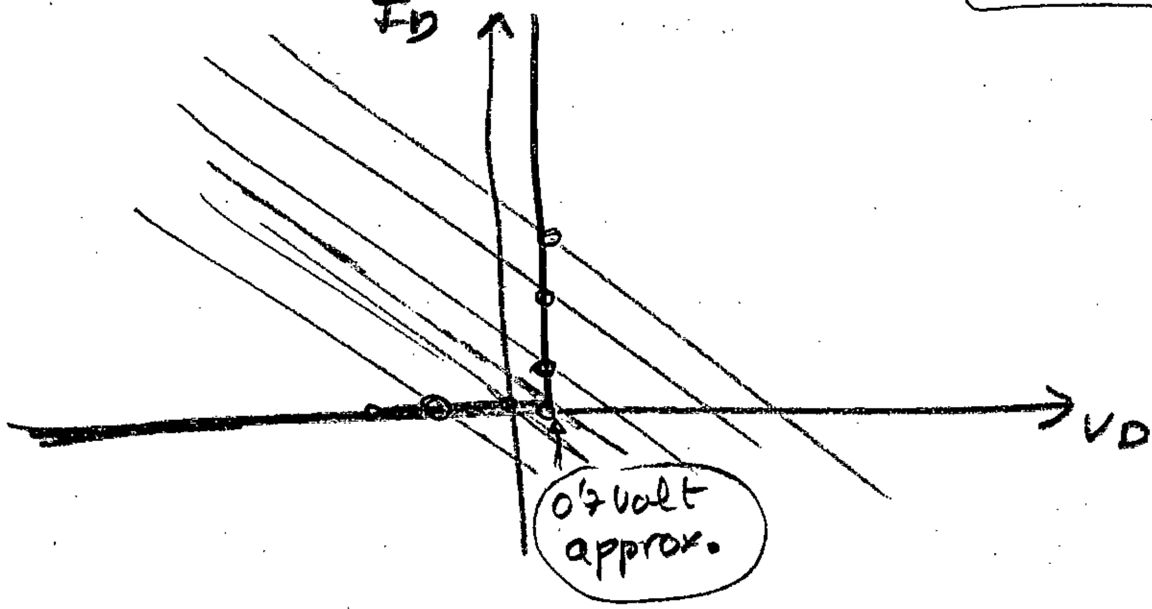
DIODE

② Ideal with offset

The same applies and:



It's obvious that:

IF $V_g > 0'7 \Longrightarrow$ $V_D = 0'7$, $I_D = \frac{V_g - 0'7}{2}$

IF $V_g < 0'7 \Longrightarrow \left\{ \begin{array}{l} V_D = V_g \\ I_D = 0 \end{array} \right.$

③ The exact model (at first instance)

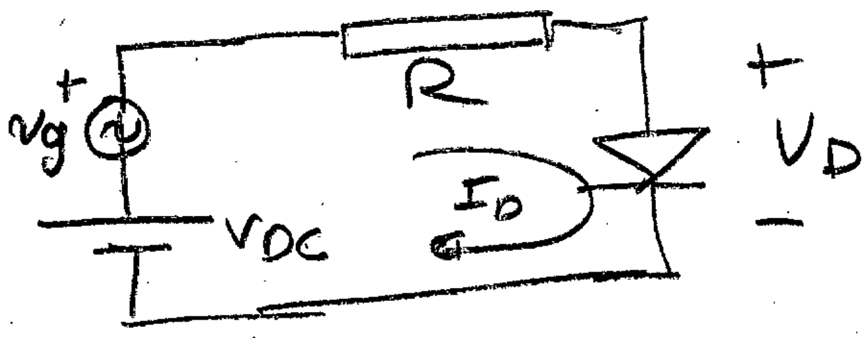
$$\left.\begin{array}{l} ① \; I_D = I_0 \left(e^{\frac{V_D}{V_T}} - 1\right) \\ ② \; V_g - 2 I_D - V_D = 0 \end{array}\right\} \longrightarrow \text{MATLAB SOLVER!!}$$

↓

you can work out with it!!

There's an important question to be worked out:

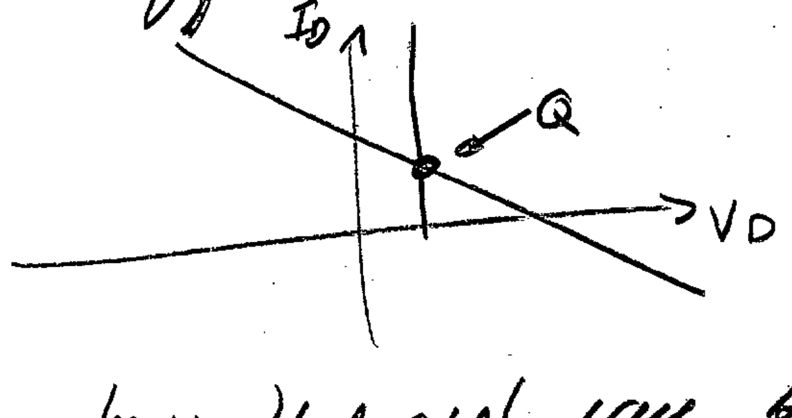
· If $V_g = V_{DC} + v_g$, that is



$I_D = I_D\big|_Q + i_d$ and
$V_D = V_D\big|_Q + v_d$

• Q subindex means BIAS POINT

① $V_D\big|_Q$ $I_D\big|_Q$ can be easily obtained using the ideal models (with a small inaccuracy) That is:



, but how $\{i_d, v_d\}$ can be obtained is v_g is known?

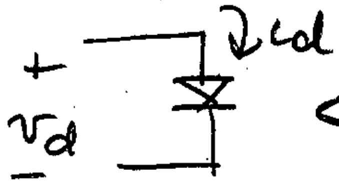
SMALL SIGNAL MODEL OF A DIODE

In fact what should be worked out, is how to obtain ΔI_D, when ΔV_D is applied.
Taylor's series solve this question

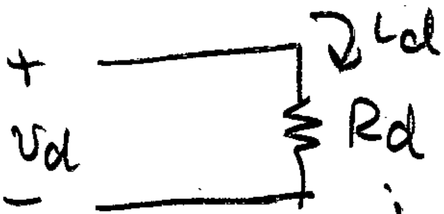
$$I_D\big|_Q + \Delta I_d = I_D\big|_Q + \frac{\partial I_D}{\partial V_D}\bigg|_Q \underbrace{(V_D - V_D|_Q)}_{\Delta V_D}$$

If $\Delta I_d \equiv i_d$ and $\Delta V_D = v_d$,

$$i_d = \frac{\partial I_D}{\partial V_D}\bigg|_Q \cdot v_D \iff$$



$\iff$



where $R_d = \dfrac{1}{\dfrac{\partial I_D}{\partial V_D}\Big|_Q}$

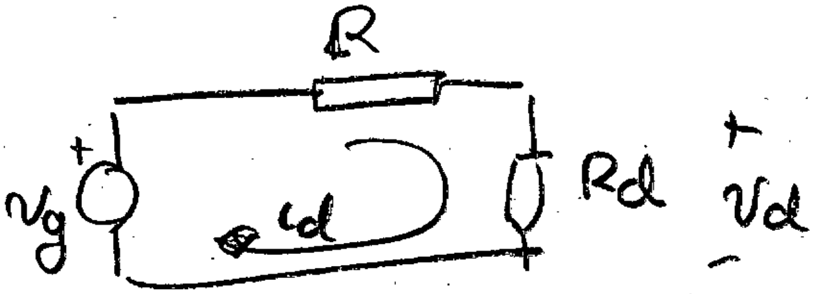
DYNAMIC RESISTANCE OF THE DIODE IN Q BIAS POINT

$$\left.\frac{\partial I_D}{\partial V_D}\right|_Q = I_0\, e^{\frac{V_D|_Q}{V_T}} \cdot \frac{1}{V_T} = (R_d)^{-1}$$

and, for instance, for a Si diode:

Si DIODE: $\left.\begin{array}{l} V_{DQ} \simeq 0'65 \\ I_0 \simeq 3 \cdot 10^{-14} \\ V_T = 0'025 \end{array}\right\} \Rightarrow R_d = 4'26\ \Omega$

Then



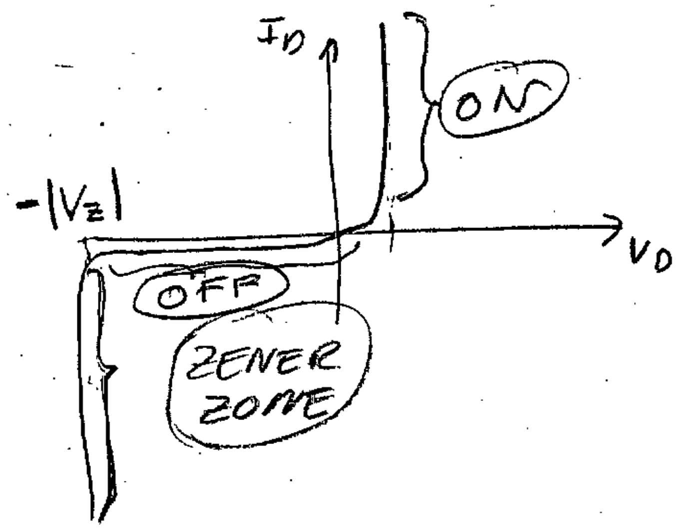
$$i_d = \frac{v_g}{R + R_d}$$

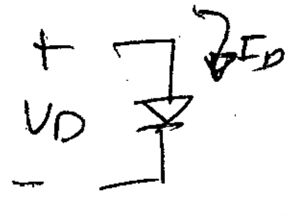
$$v_d = \frac{v_g}{R + R_d} \cdot R_d$$

Try to simulate, and verify the previous formulas

- The Breakdown voltage:
  zener diode

When a high enough inverse voltage is applied, the diode enters the 'zener zone'





Then $V_D = 0'7 \Rightarrow I_D > 0 \rightarrow \boxed{D_{ON}}$

$-V_Z < V_D < 0'7 \Rightarrow I_D \simeq 0 \rightarrow \boxed{D_{OFF}}$

$V_D = -V_Z \Rightarrow I_D < 0 \rightarrow \boxed{D_{ZENER}}$

- $I_{D_{min}}$ is required to assure $V_D = -|V_Z|$

The power supplied to de diode is about:

D_{ON}: $P = |I_D| \cdot 0'7$ ← $V_D|_{ON}$

D_{OFF}: $P \simeq 0$

D_{zener}: $P = |I_D| |V_Z|$

Obviously

$P_{ZENER} >> P_{ON}$

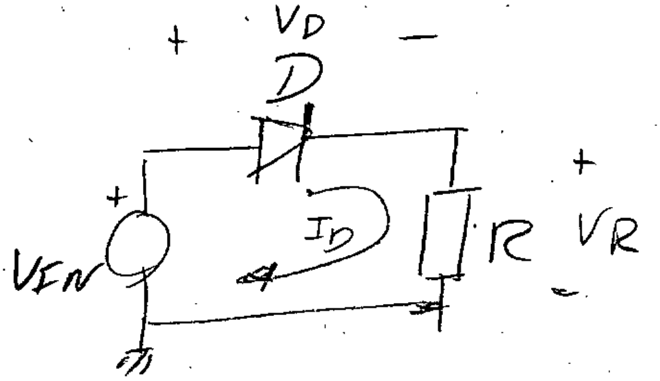
Zener diodes are designed to withstand the heating caused by P_{zener}.

- $P_{Z max}$ is defined in the specs.

APLICATION CIRCUITS

① HALF WAVE RECTIFIER

RESISTIVE LOAD



→ Large signal model is assumed

- $I_D > 0 \Rightarrow \begin{cases} V_R = V_{IN} - 0'7 \\ I_R = \dfrac{V_{IN} - 0'7}{R} \end{cases} \Rightarrow V_{IN} > 0'7$

- $I_D = 0 \Rightarrow \begin{cases} V_R = 0 \\ V_D = V_{IN} \end{cases} \Rightarrow V_{IN} < 0'7$

$$\boxed{\text{When } \begin{array}{l} V_{IN} > 0'7 \Rightarrow V_R = V_{IN} \\ V_I < 0'7 \Rightarrow V_R = 0 \end{array} \Bigg\} \text{ RECTIFYING PROCESS}}$$

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Diode

· Simulate when:

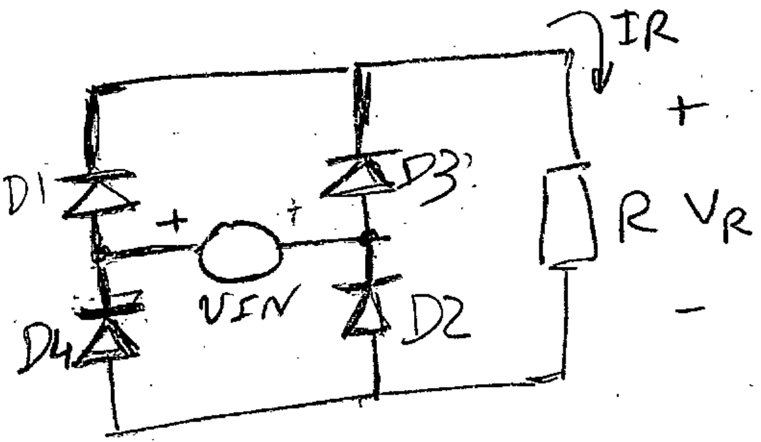
① $V_{i(t)} = A \sin(\omega t)$ and $A >> 0'7$

② $V_{i(t)} = A \sin(\omega t)$ and $A \cancel{>>} 0'7$

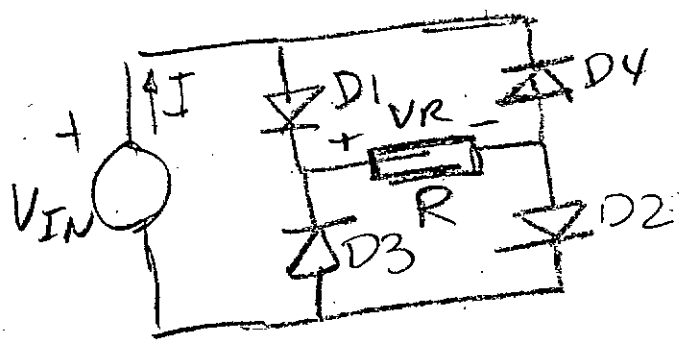
Plot $\{V_{IN}, i_D, V_R, V_d\}$ in each case

② FULL WAVE RECTIFIER

RESISTIVE LOAD



OR



- If $I>0$ $\Rightarrow$ D_1 ON, D_2 ON $\Rightarrow$ $\begin{cases} V_R = V_{IN} - 2 \cdot 0'7 \\ I_R = \frac{V_R}{R} \end{cases}$

$\Rightarrow$ $\boxed{V_{IN} > 1'4 \text{ Volt}}$

It can be seen that

$$\left.\begin{aligned} V_{D3} &= -(V_{IN} - 0'7) < 0'7 \\ V_{D4} &= -(V_{IN} - 0'7) < 0'7 \end{aligned}\right\} \Rightarrow \begin{aligned} &D_3 \text{ OFF} \\ &D_4 \text{ OFF} \end{aligned}$$

- If $I<0$, $\begin{Bmatrix} D_3 \text{ ON} \\ D_4 \text{ ON} \end{Bmatrix}$, $\begin{Bmatrix} D_1 \text{ OFF} \\ D_2 \text{ OFF} \end{Bmatrix}$, $V_R = -V_{IN} - 2 \cdot 0'7$
$I_R = \frac{V_R}{R}$

and $\boxed{V_{IN} < -1'4 \text{ Volt}}$

- If $\left.\begin{aligned} -1'4 < V_{IN} < 1'4 \\ I = 0 \end{aligned}\right\} \Rightarrow I_R = 0 \Rightarrow V_R = 0$

$\{D_1, D_2, D_3, D_4\}$ OFF

- Notice that R is floating (V_{IN} and R don't have common-ground connection

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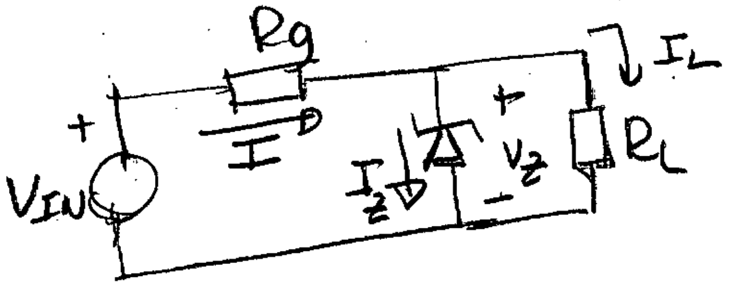
DIODE

③ Zener Voltage Regulator



If the diode is operating in its zener zone

that is $\left\{ \begin{array}{l} I_Z > I_{Zmin} \\ P_Z < P_{Zmax} \end{array} \right\}$, $\boxed{V_{R_L} = V_Z}$

in spite of V_{IN} may change.

- $I = \dfrac{V_{IN} - V_Z}{Rg} = I_Z + \dfrac{V_Z}{R_L} \Longrightarrow$

① $$\boxed{I_Z = \frac{V_{IN}}{Rg} - V_Z\left(\frac{1}{Rg} + \frac{1}{R_L}\right)}$$ and

② $$\boxed{P_Z = V_Z \cdot I_Z}$$. Also

ⓐ $I_Z > I_{Zmin}$ and ⓑ $P_Z < P_{Zmax}$

must be met

Usually, the specs of the regulator are:

① $V_{I_{min}} < V_I < V_{I_{max}}$

and

② $I_{L_{min}} < I_L < I_{L_{max}}$

③ V_L

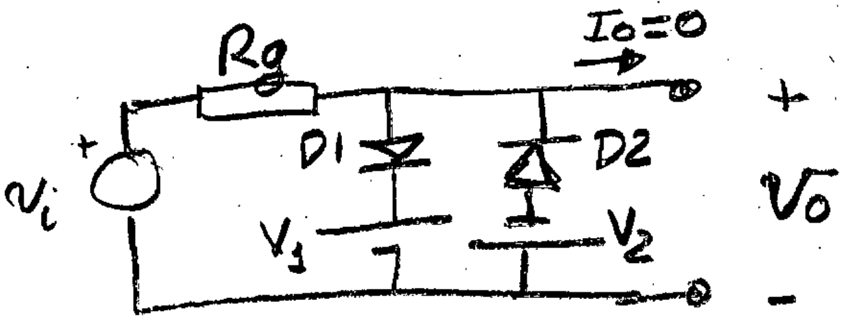
R_g and the diode have to be chosen

<u>Example</u>. Solve the following regulator:

$15 < V_I < 25$
$0 < I_L < 200\,mA$
$V_L = 18\,Volt$

$\rightarrow$ R_g?
ZENER?

Voltage Limiter

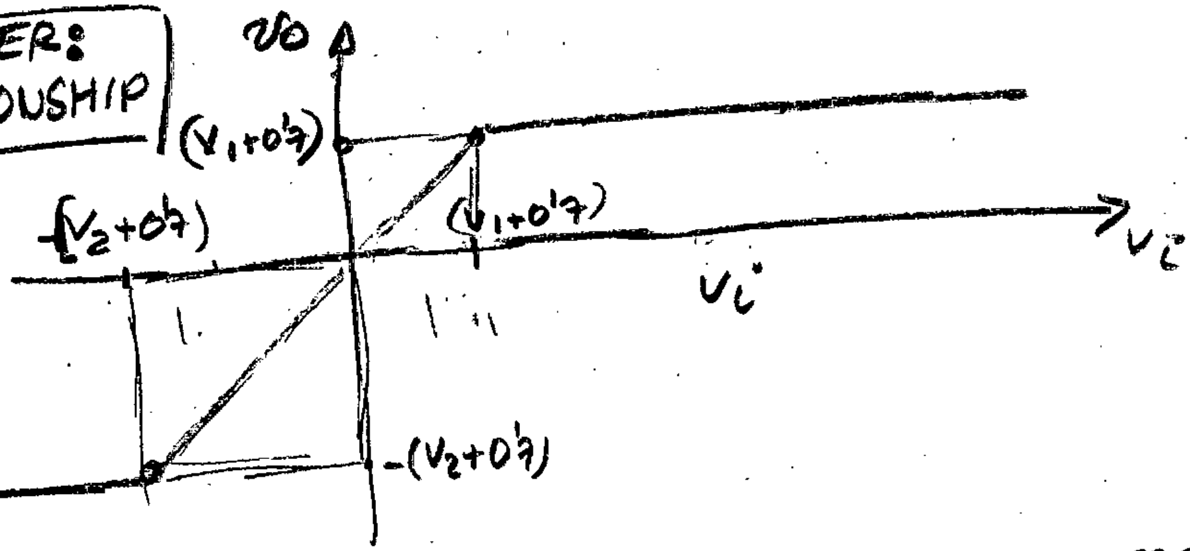


$v_i > V_1 + 0'7 \Rightarrow v_o = V_1 + 0'7$ (D1 ON || D2 OFF)

$v_i < -(V_2 + 0'7) \Rightarrow v_o = -(V_2 + 0'7)$ (D1 OFF || D2 ON)

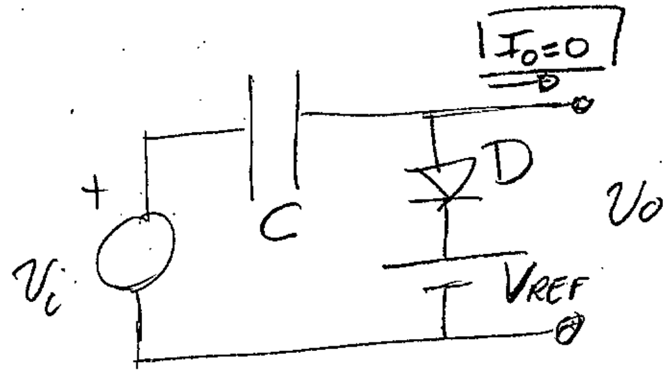
$-(V_2 + 0'7) < v_i < (V_1 + 0'7) \Rightarrow v_o = v_i$

TRANSFER RELATIONSHIP



- Notice that $I_o = 0$ has been assumed

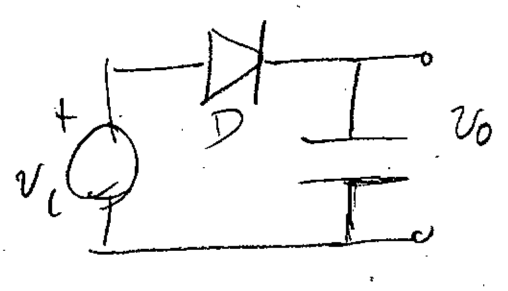
Peak limiter



This circuit adds a DC voltage to v_i so that the peak voltage of v_o is V_{REF}.

You can see the pspice models
peak limiter.sch and
peak limiter enhaced.sch

Peak follower

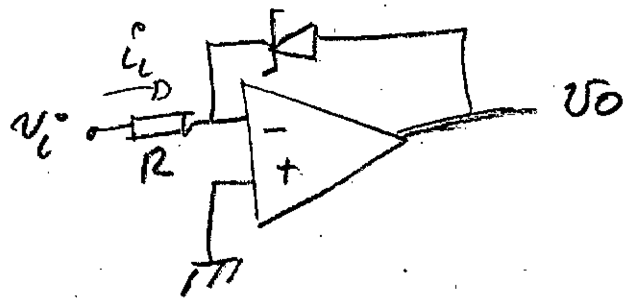


pspice model

$V_o(t)$ i. equals the maximum of $V_i(t)$.
In fact $V_o(t)$ follows the maximum of $V_i(t)$

Circuits with OPAMPS and Diodes

Limiter



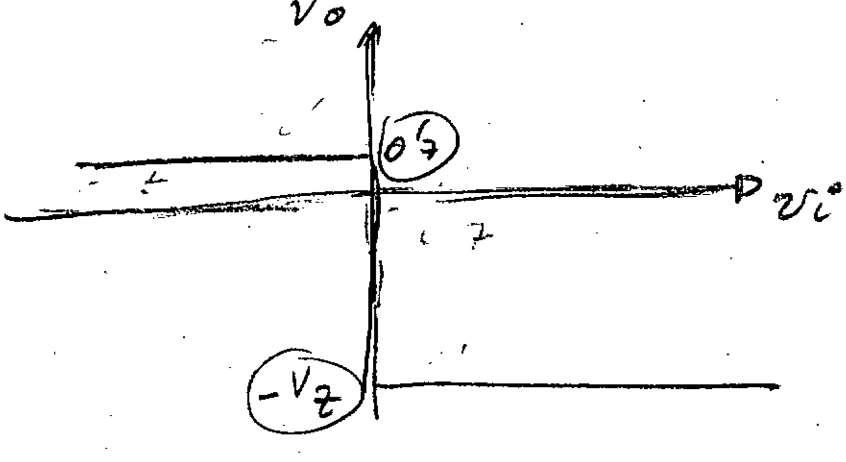
The OPAMP operates in negative feedback mode, because i_i flows through the diode.
So the diode state is DON or DZENER

Then

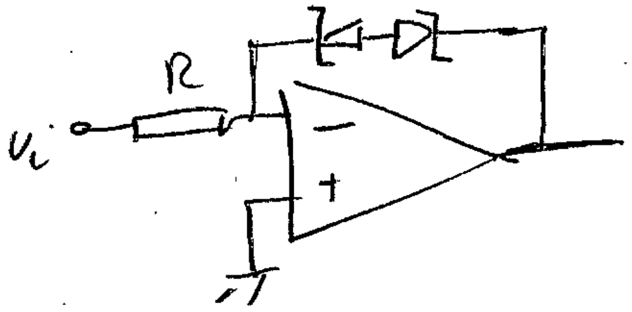
$v_i > 0 \Rightarrow i_i > 0 \Rightarrow V_o = -V_Z$

$v_i < 0 \Rightarrow i_i < 0 \Rightarrow V_o \cong 0.7$ volt

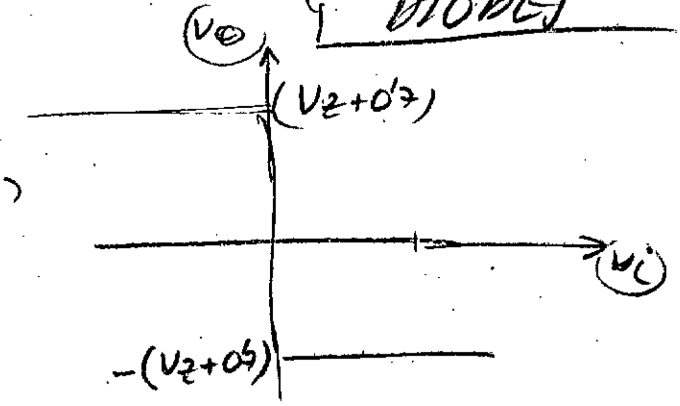
The transfer relationship:



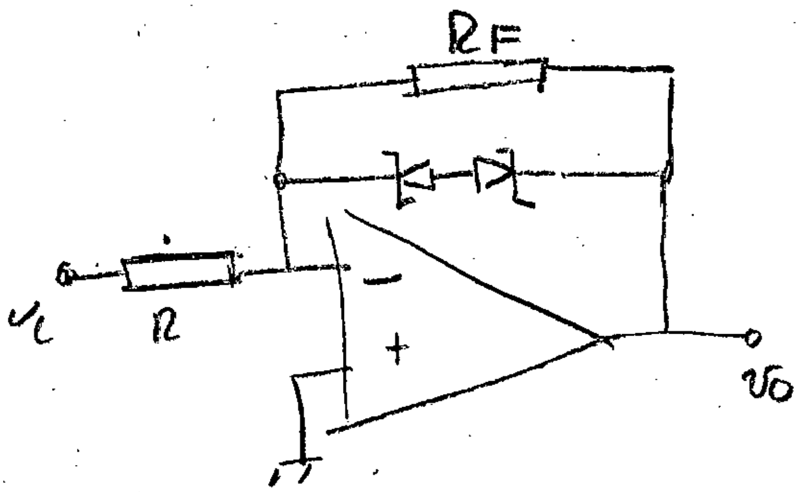
Simetrical limiter



$\Rightarrow$



OR



① If $\frac{|v_i|}{R} \cdot R_F < (V_Z + 0'7)$:

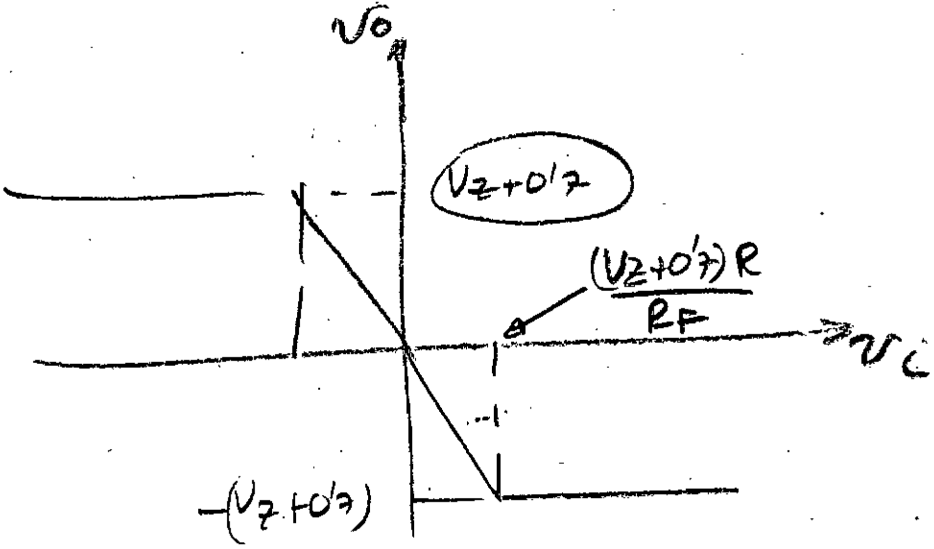
That is : $|v_i| < (V_Z+0'7)\,\frac{R}{R_F} \Rightarrow$

DIODES OFF

$v_o = -v_i \frac{R_F}{R}$

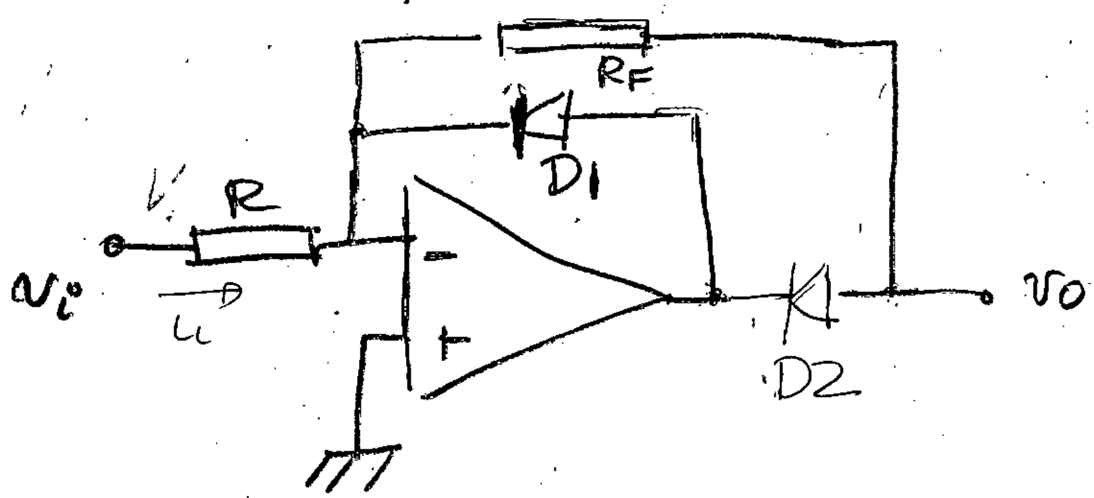
② ELSE : DIODES ON

$v_o = \pm(V_Z + 0'7)$



Precision rectifier (half wave)

In fact, if $v_{i(t)}$ is processed by a precision rectifier, $|v_i|$ is obtained.



$v_i > 0 \Rightarrow i_i > 0 \Rightarrow \begin{cases} D2 \text{ ON} \\ D1 \text{ OFF} \end{cases} \Rightarrow v_o = -v_i \frac{R_F}{R}$

$v_i < 0 \Rightarrow \begin{cases} D_1 \text{ ON} \\ D2 \text{ OFF} \end{cases} \Rightarrow v_o = 0$

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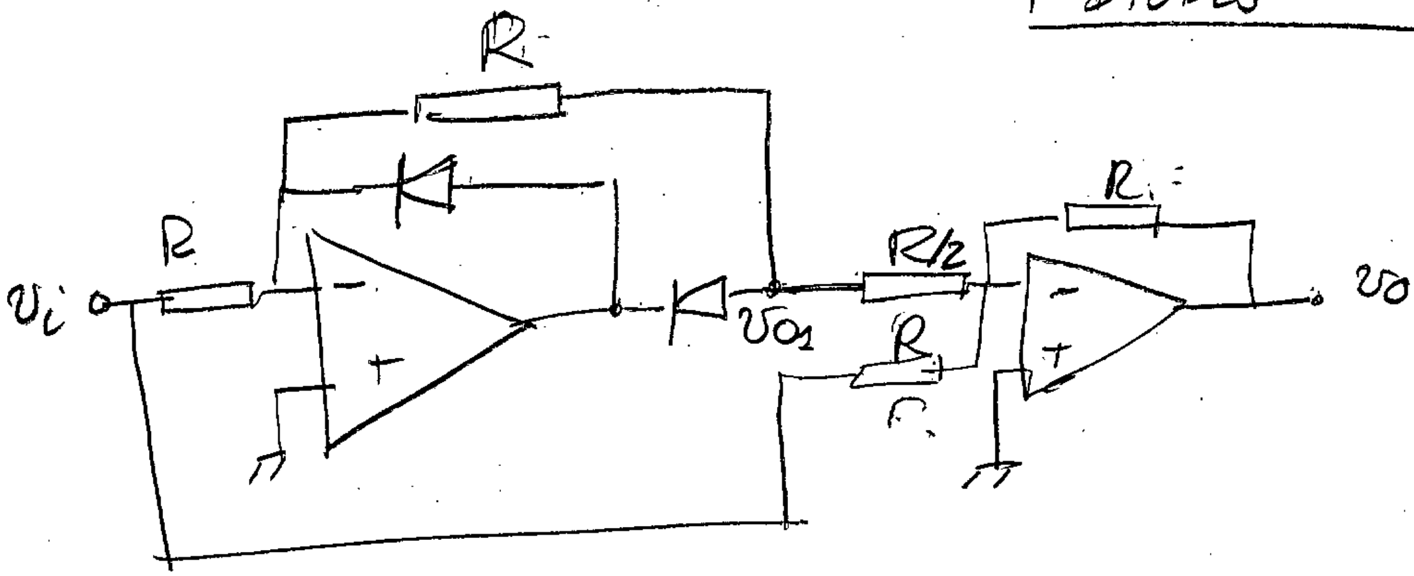
DIODES

Precision rectifier (full wave)



$$v_i > 0 \Rightarrow v_{o1} = -v_i \Rightarrow$$

$$v_o = v_{o1}\cdot\left(-\frac{R}{R/2}\right) + v_i\left(-\frac{R}{R}\right)$$

$$= +v_i \cdot 2 - v_i = v_i$$

$$v_i < 0 \Rightarrow v_o = -v_i$$

$$\Rightarrow$$

$$v_o = |v_i|$$