EE105
Microelectronic Devices and Circuits:
Diode Circuits

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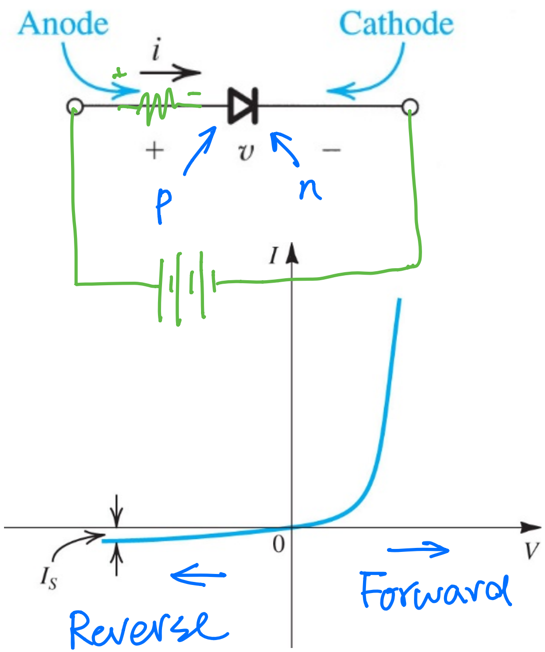
Summary of pn Junction



Built-in potential : $V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$

Under forward bias :

I-V curve : $I = I_S\left(e^{V/V_T} - 1\right)$

Diffusion capacitance : $C_d = \left(\frac{\tau_T}{V_T}\right) I$

Under revserse bias :

Negligible current, $I = -I_S$

Depletion capacitance : $C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}}$

Other important parameter :

Depletion Width: $W = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 - V)}$

GaN
GaAs Direct Bandgap
InP

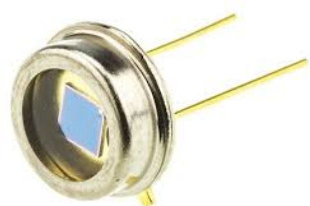
Many Applications of Diodes

LED (Light-Emitting Diode)

LED Lighting

Laser Diode

Solar Cells (PV)



Photodiode

OLED

How Many Diodes are in a Smart Phone?

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http://image-sensors-world.blogspot.com/2017/09/yole-on-iphone-x-3d-innovations.html

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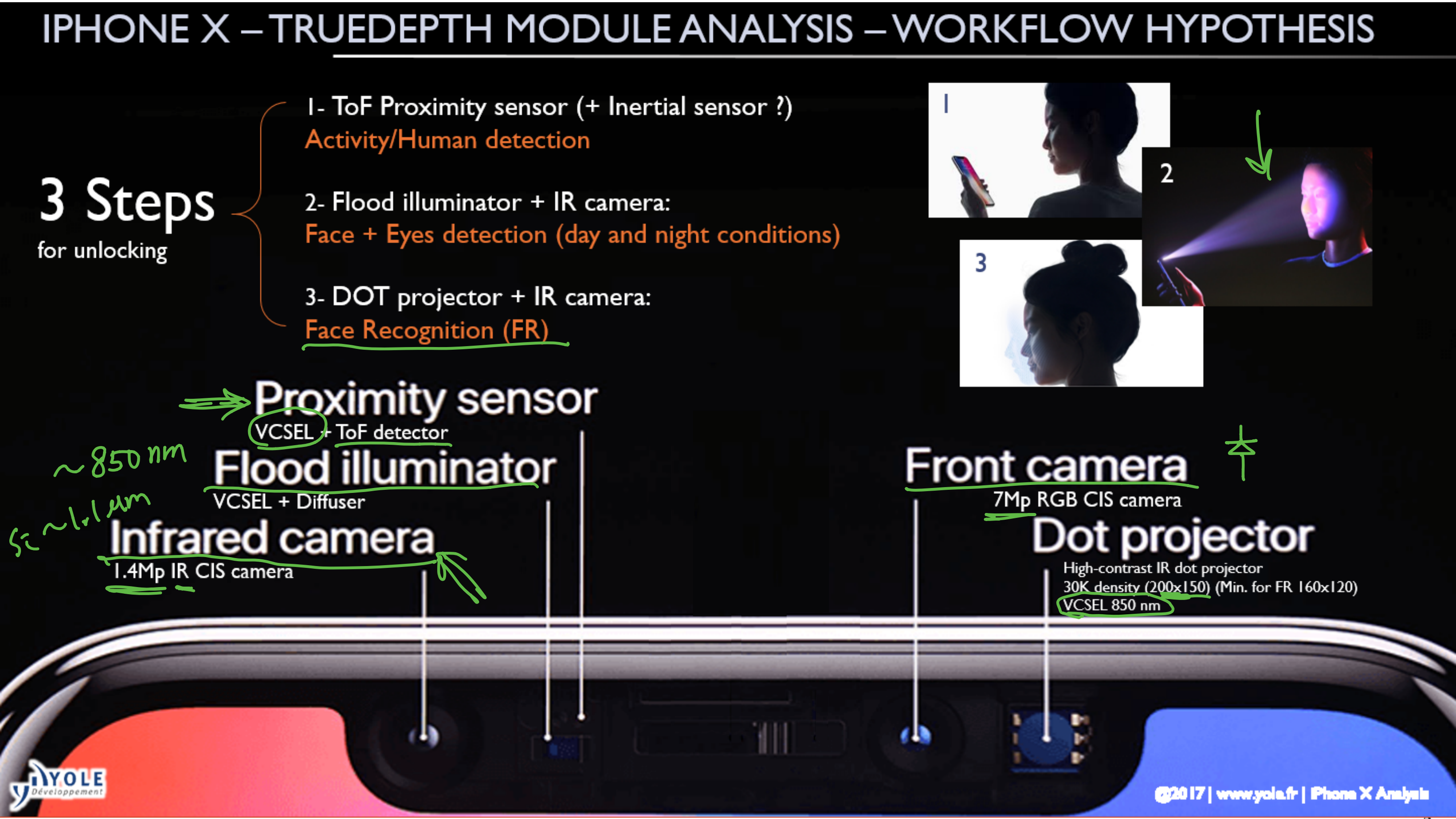

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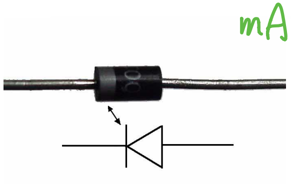
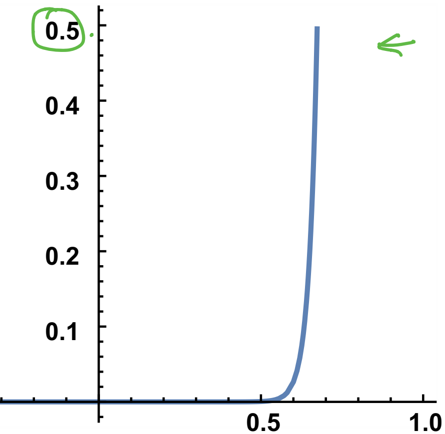
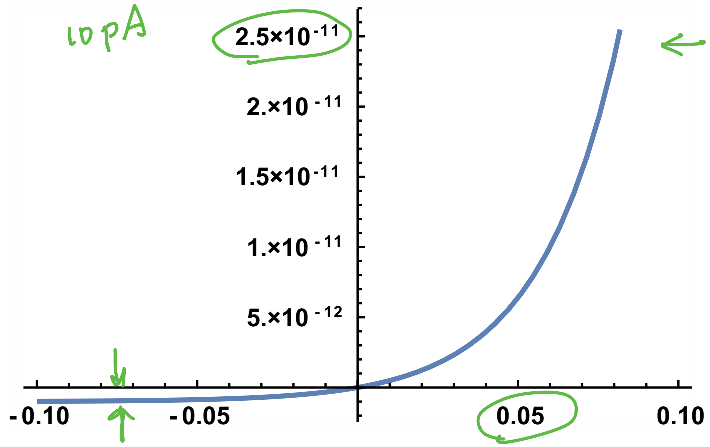
BSAC

Diode I-V Curve (Forward)



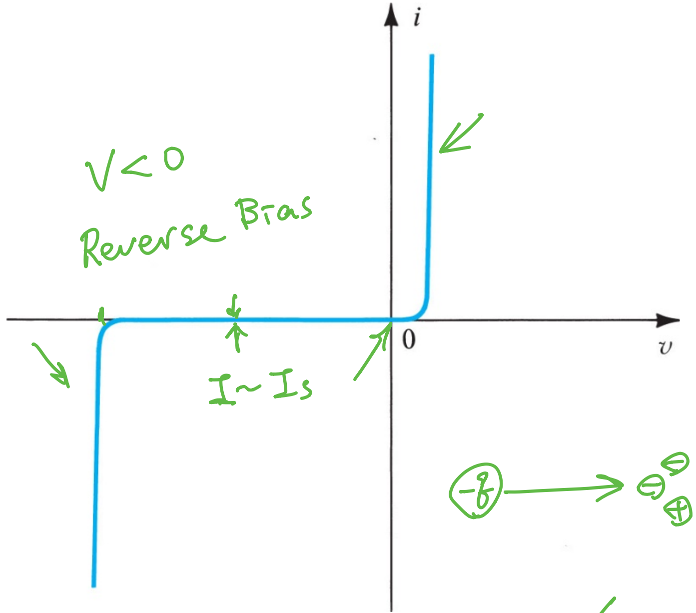


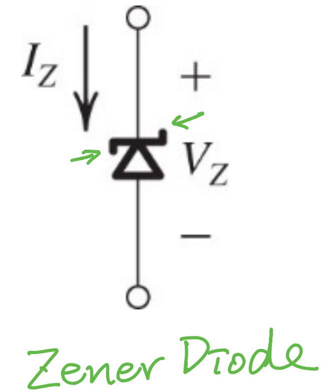


- I-V curve at high current
- *Approximate* "turn-on" voltage at 0.7V for Si
  - There is no exact turn-on voltage
  - Current keeps increasing exponentially

- I-V curve at low current
- Soft increase at forward bias
- Can see reverse saturation current, I_S

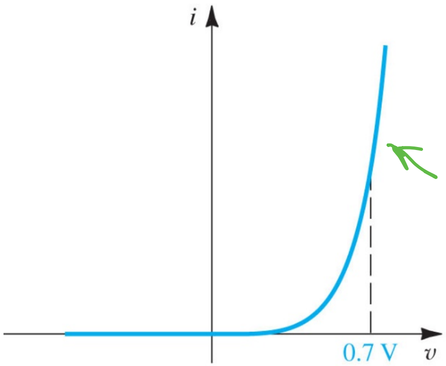
Reverse Breakdown





- **At sufficiently large reverse bias voltage, current starts to increase dramatically**
  - **Due to avalanche breakdown or quantum mechanical tunneling**
  - **Breakdown voltage can be designed**
  - **Sometimes used as a voltage limiter**

Ideal Diode Model



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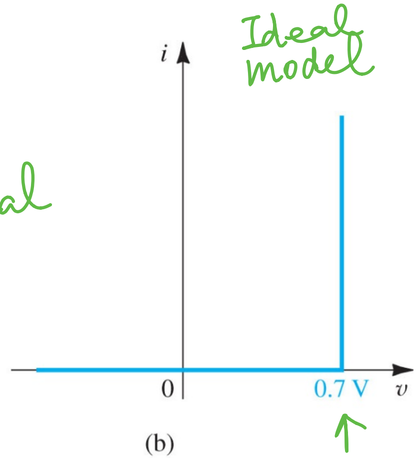

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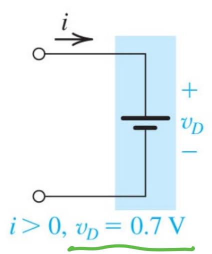
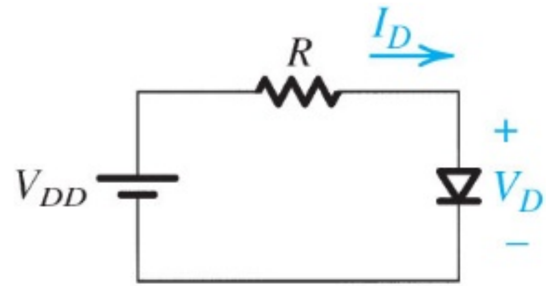


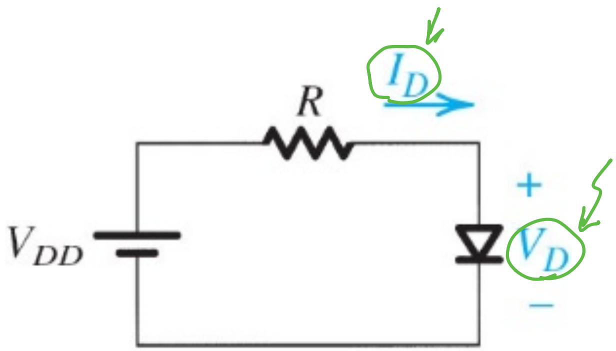
(c)

Example:

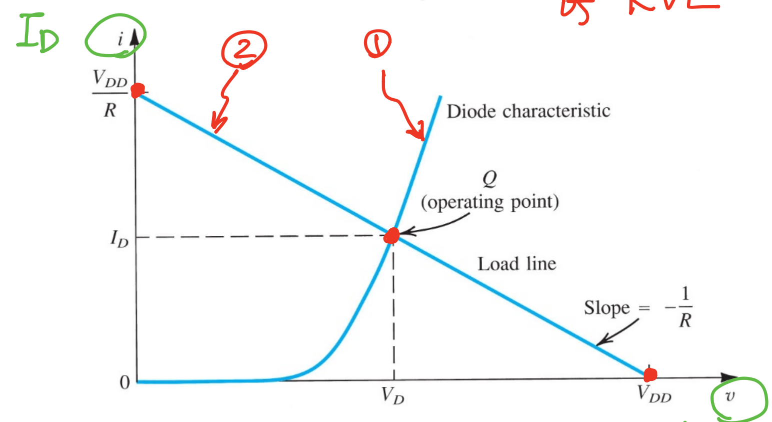


- **An ideal diode only allows current to flow in one direction**
  - **Short circuit for $V > V_{ON}$ (~ 0.7V for Si)**
  - **Open circuit for $V < V_{ON}$ (as well as reverse bias)**

Exact Solution with Real Diode I-V



Load Line ⇒ Graphic Representation of KVL



Simple model: $V_D = 0.7\,V$

$I_D = \frac{V_{DD} - 0.7}{R}$

Load line

$V_{DD} = I_D \cdot R + V_D$ ($I_D \to y$, $V_D \to x$)

$I_D = 0 \Rightarrow V_D = V_{DD}$

$V_D = 0 \Rightarrow I_D = V_{DD}/R$

Precise model

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

KVL: $V_{DD} = I_D \cdot R + V_D$ ②

Iterative:

① $V_D = 0.7\,V$, $\Rightarrow I_D = \frac{2 - 0.7}{1k\Omega} = 1.3\,mA$

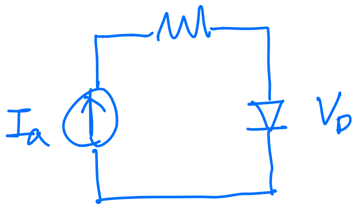
② Find V_D so $I_D = 1.3\,mA$

$V_D = V_T \cdot \ln\frac{1.3\,mA}{I_S} = 0.72\,V$

③ $I_D = \frac{2 - 0.72}{1k\Omega} = 1.28\,mA$

Example: $V_{DD} = 2V$, $I_S = 10^{-15}A$, $R = 1k\Omega$

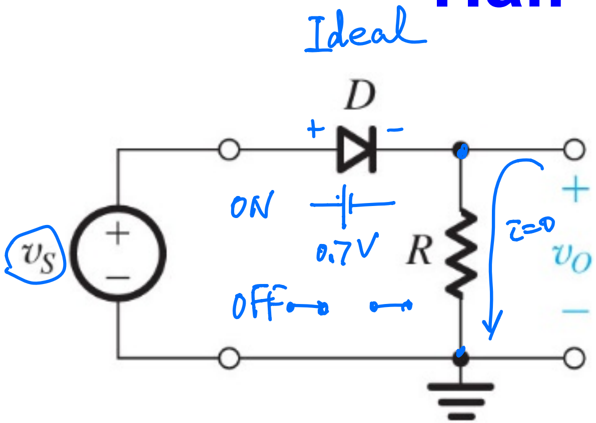
⇒ Find out I_D



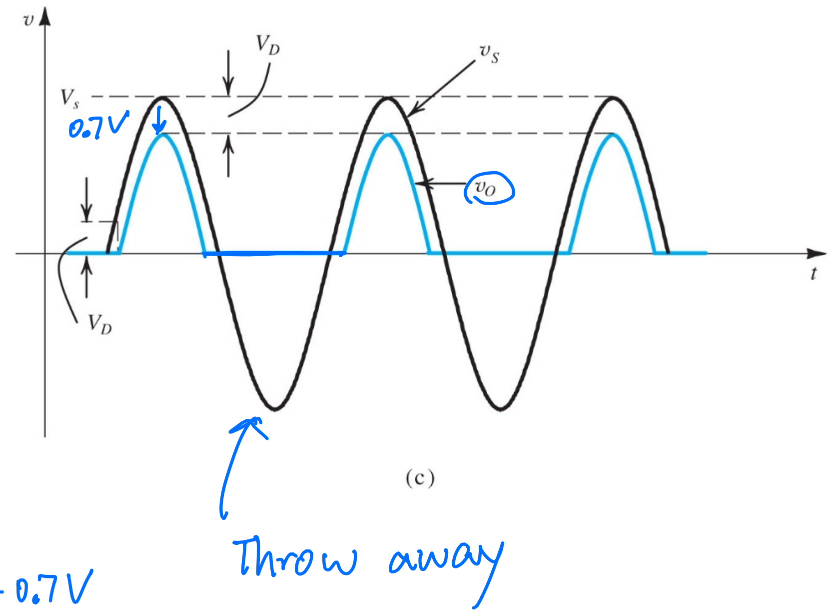
$$I_a = I_s \cdot e^{\frac{V_D}{V_T}}$$

$$\Rightarrow V_D = V_T \ln \frac{I_a}{I_s}$$

Half-Wave Rectifier



(a)



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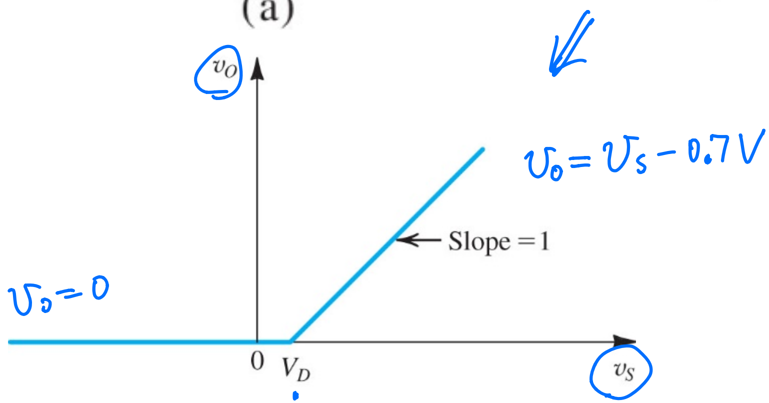
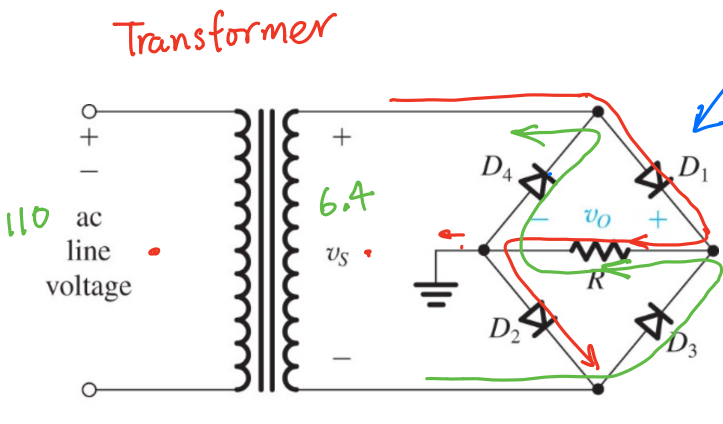
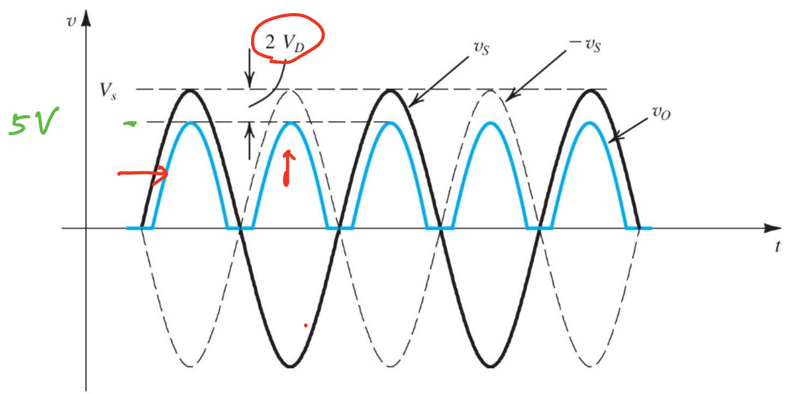


(b)

Full-Wave Bridge Rectifier

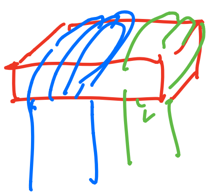


(a)



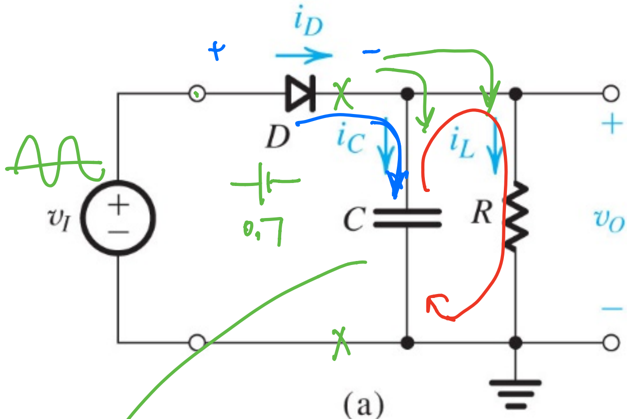
(b)

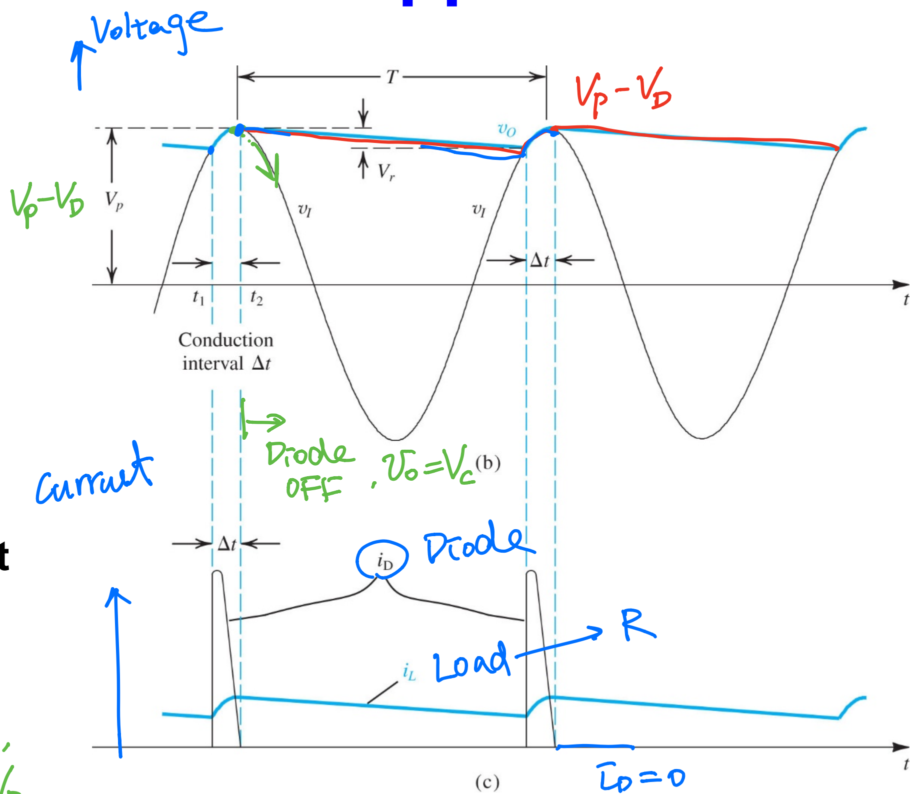
Positive cycle D_1, D_2 ON
Negative cycle D_3, D_4 ON



← select transformer with desired turn ratio

Filter to Remove Ripples





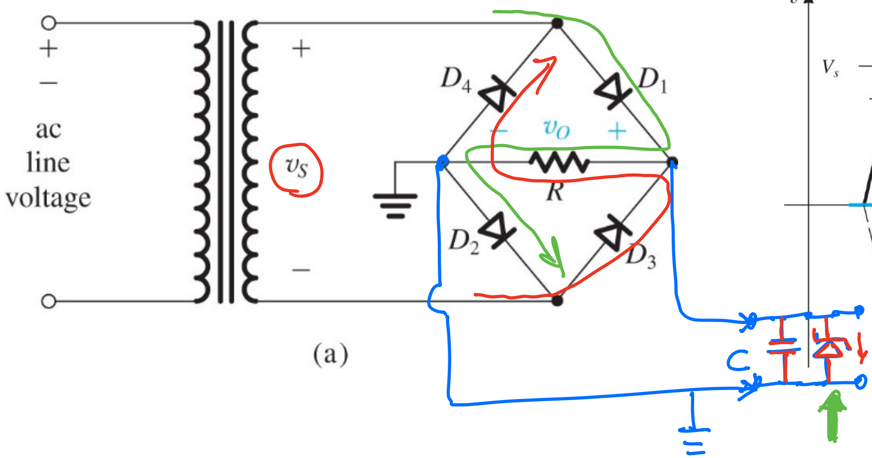
What is the RC time constant in forward bias?
What is RC in reverse bias?

In positive cycle, charged to $V_p - V_D$

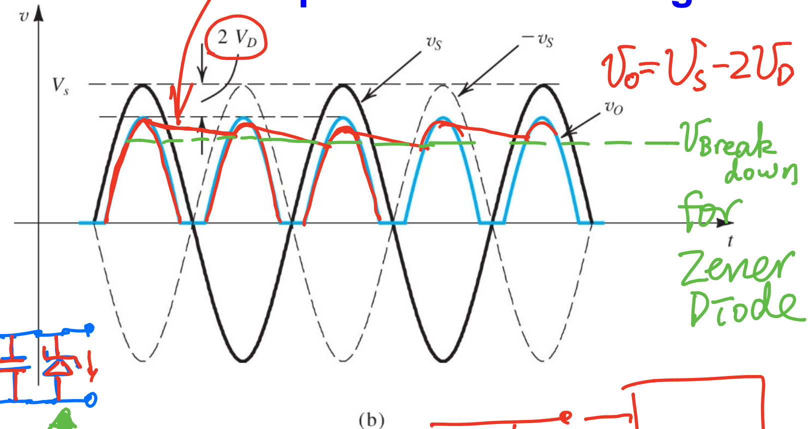
$V_C = \frac{Q}{C}$

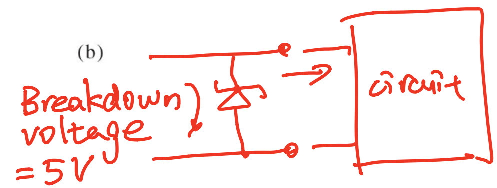
Full-Wave Bridge Rectifier with Smoothing Capacitor

Where do you add capacitor?

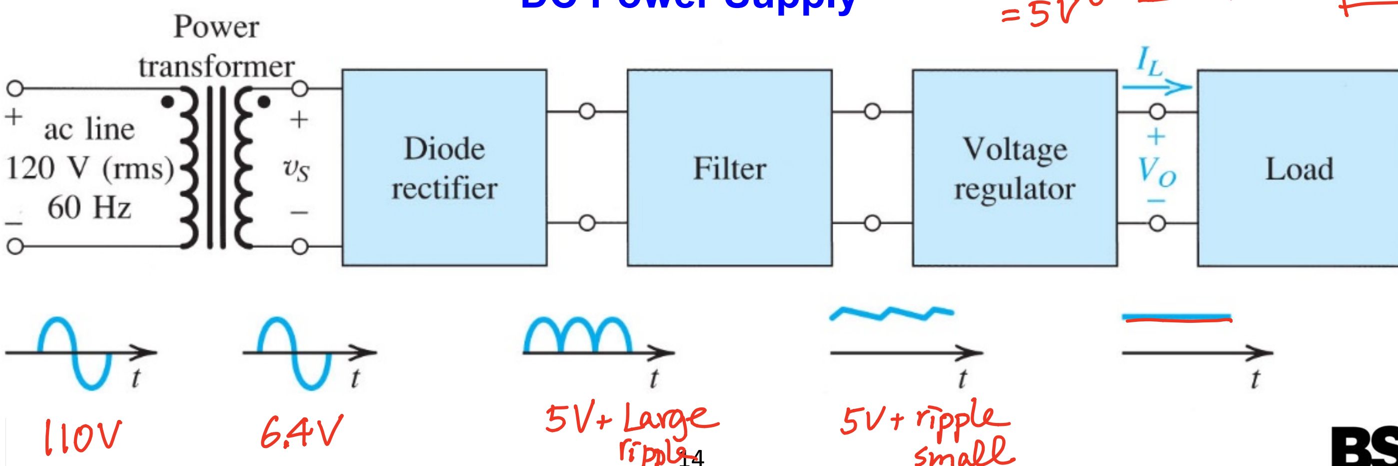


How does output waveform change?

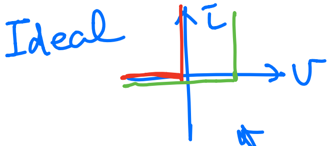


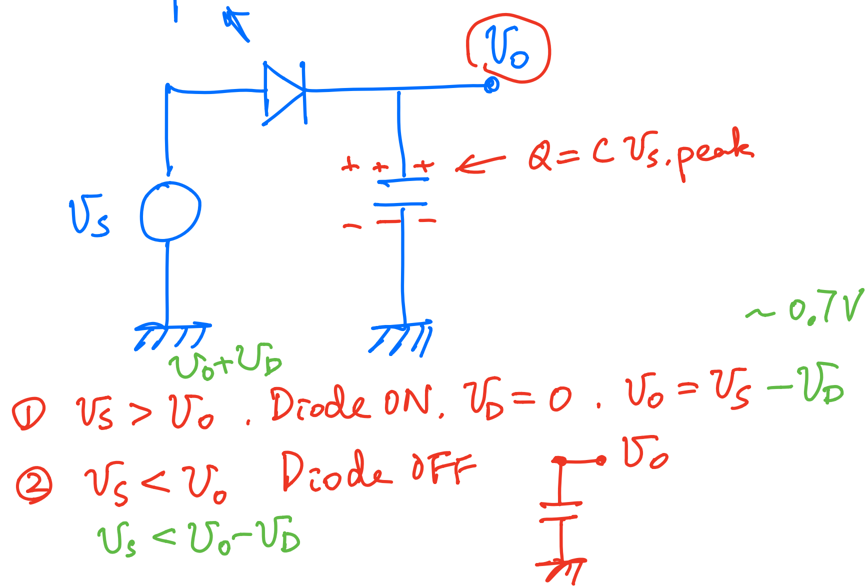


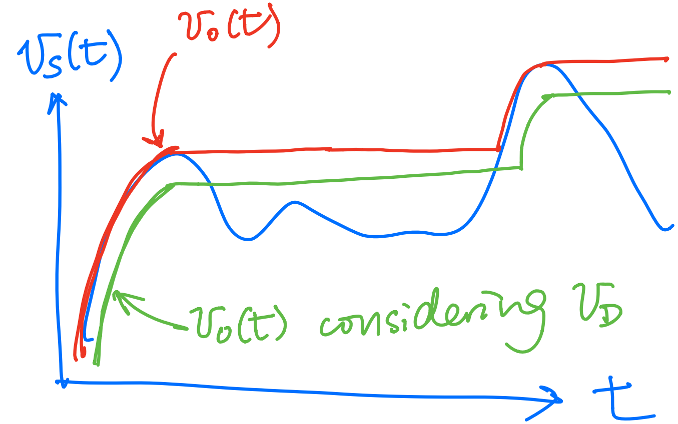
DC Power Supply



Peak Detector

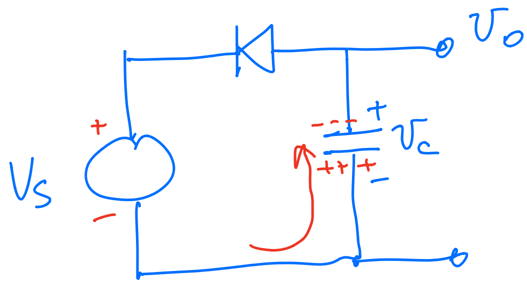


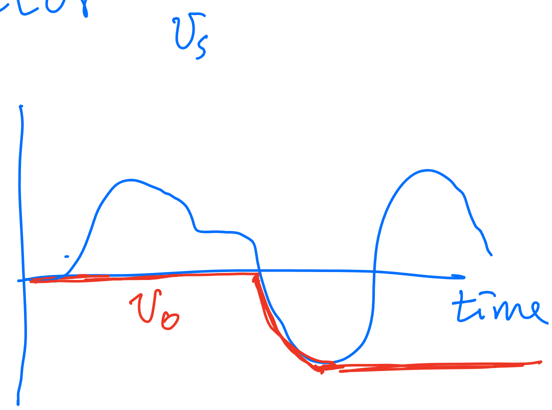




- **The capacitor is charged to the peak voltage and the output is held at the peak**
  - **When input > output, diode is ON, charge capacitor to new peak**
  - **When input < output, diode is OFF. Capacitor holds output at peak**
- **If you flip the direction of the diode, you get a negative peak detector.**

Negative Peak Detector



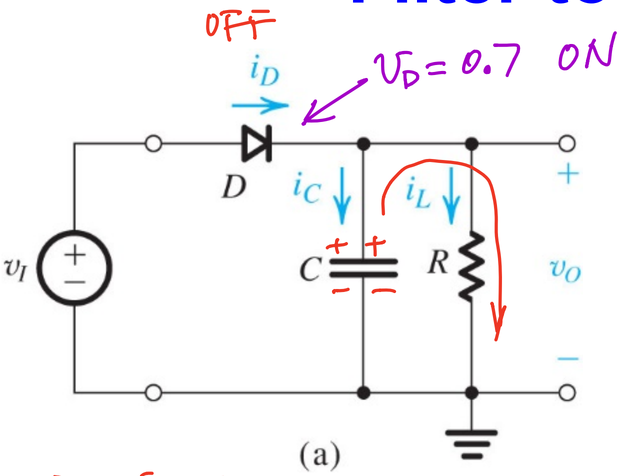


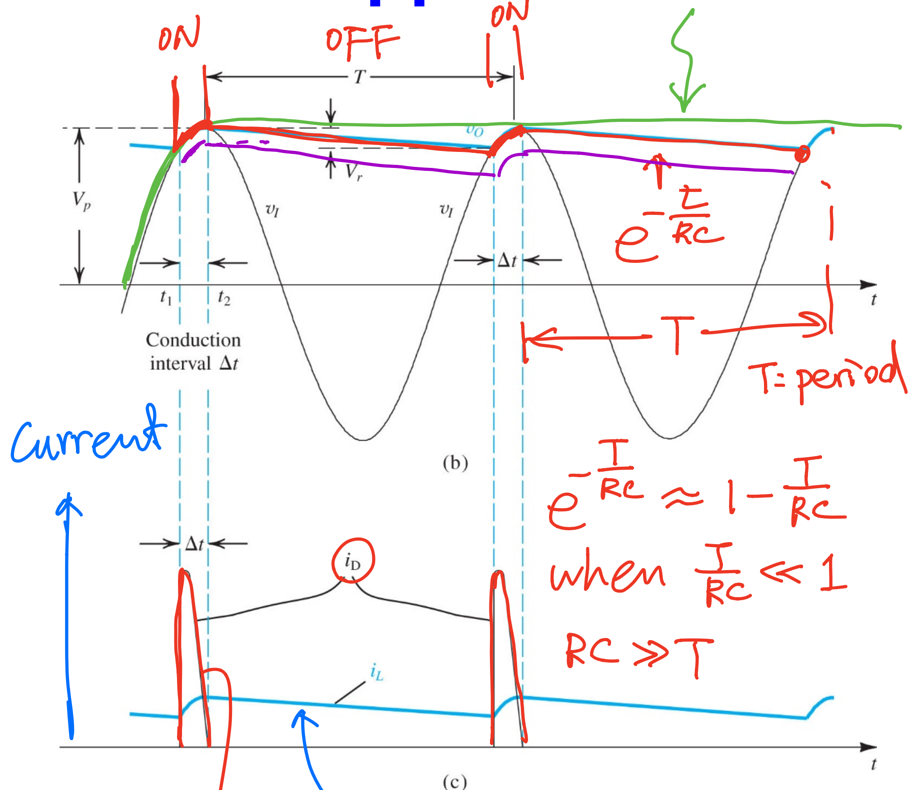
$v_s > v_o$, Diode OFF. $v_o = v_c$

$v_s < v_o$, Diode ON $v_c = v_s \rightarrow v_{s,peak,neg}$

$v_o = v_c$

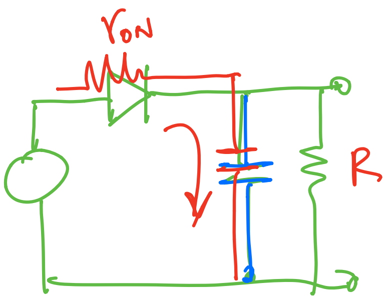
Filter to Remove Ripples

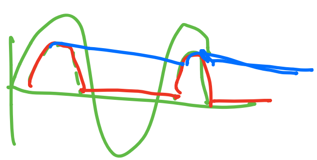




$V_S > V_0 - V_D$

What is the RC time constant in forward bias?
What is RC in reverse bias?





current through R

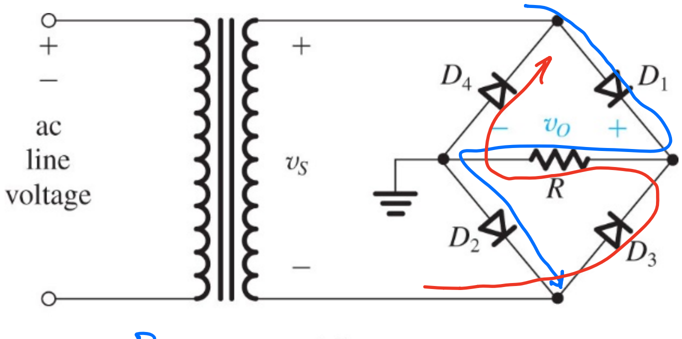
$i_L = \frac{V_o}{R}$

$\propto (1 - e^{-t/r_{ON}C})$

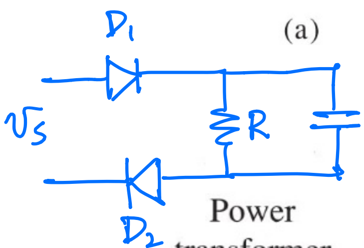
r_{ON} = ON resistance of diode

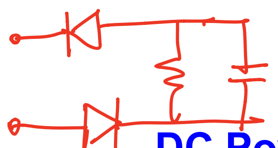
Full-Wave Bridge Rectifier with Smoothing Capacitor

Where do you add capacitor?

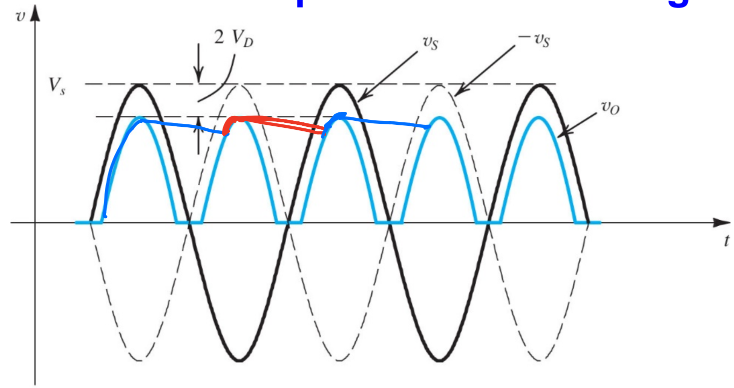


(a)



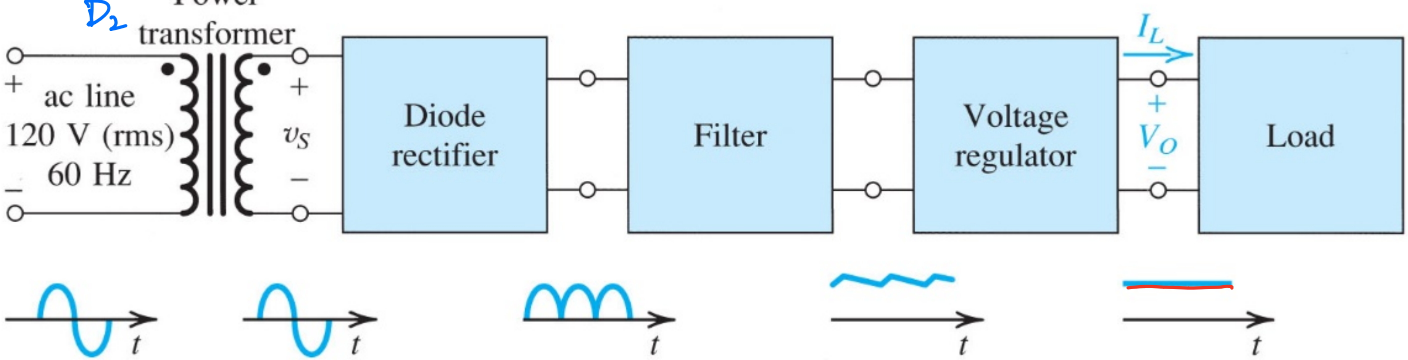


How does output waveform change?

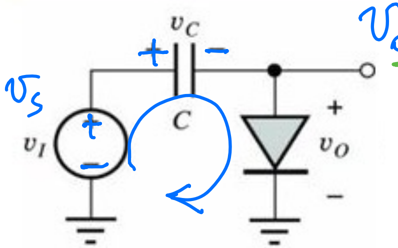


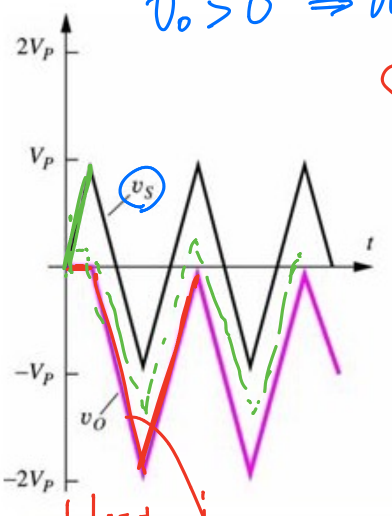
(b)

DC Power Supply



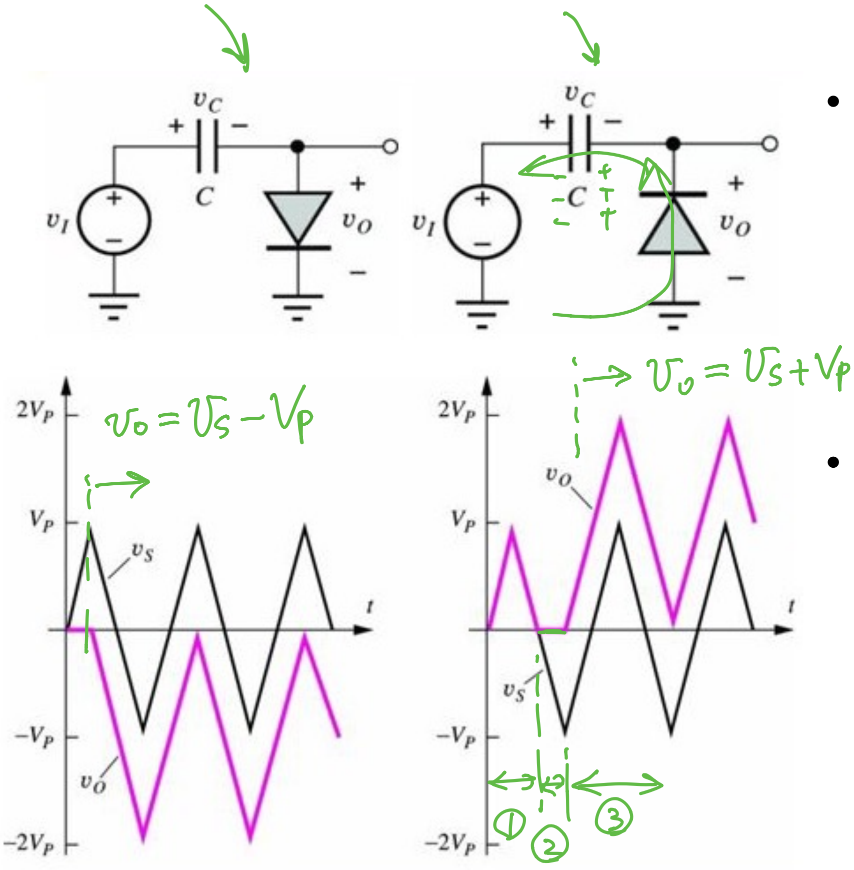
Level Restorers





- Diode turns on initially and charges the capacitor to the AC voltage.
  - Note that once the voltage starts to drop, the diode turns off
- The output voltage is therefore level shifted by the DC voltage held on the capacitor
- In this case the voltage excursions are now negative and never rise above zero!
  - If a load is connected, then the capacitor should be large enough to minimize droop

Level Restorers



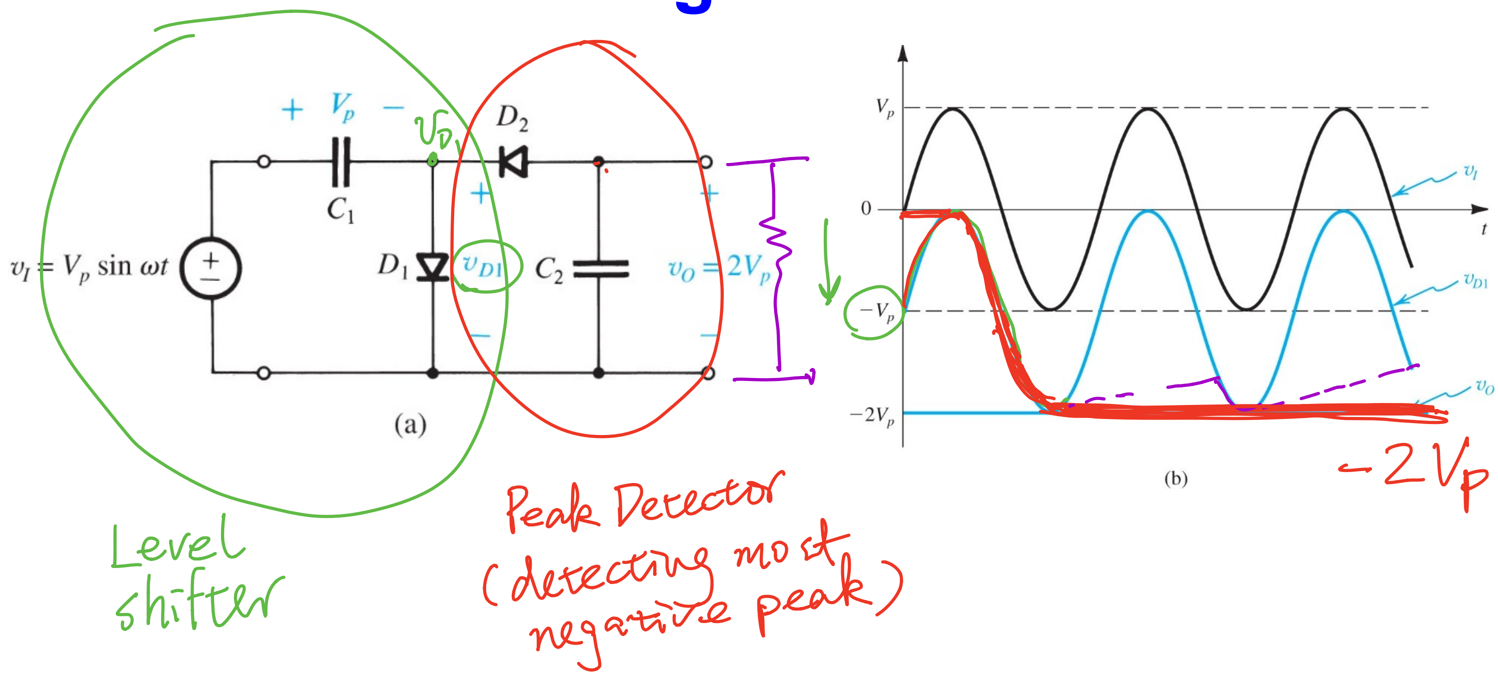
- **If we now flip the direction of the diode, the current will only flow during the negative half cycle, charging the capacitor now in the opposite direction.**
- **Then output is now lifted by the DC voltage stored on the capacitor. The voltage will now always remain positive and never go below zero!**

① Diode OFF. $v_o = v_s - v_c = v_s$
Cap C not charged yet. $v_c = 0$

② Diode ON, $v_c = v_s$. $v_o = v_s - v_c = 0$

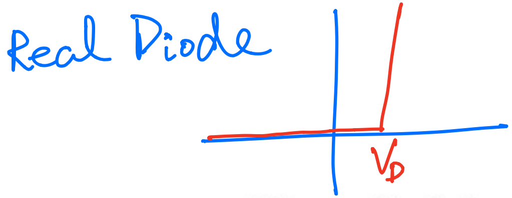
③ Diode OFF. $v_c = -V_p$
$v_o = v_s - v_c = v_s + V_p$

Voltage Doubler

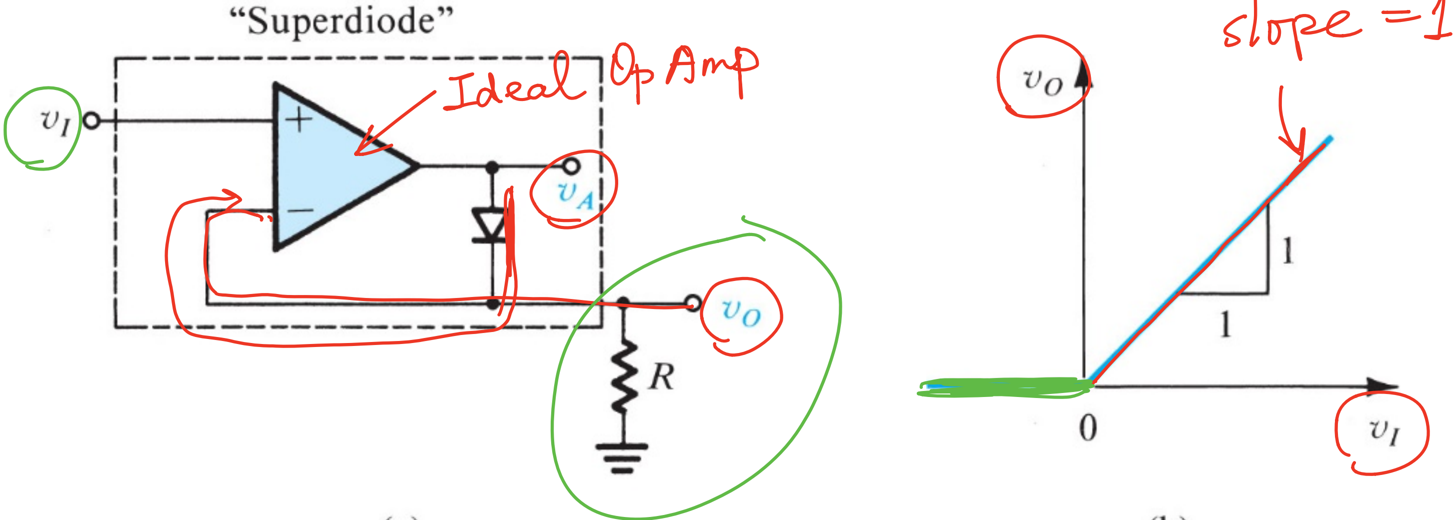


(a) (b)

- **If we rectify the above voltages, we can generate positive or negative DC voltages of twice the magnitude. This is a voltage doubler!**



"Superdiode"



(a) (b)

Use an op-amp to make circuit precise

$V_I > 0$, $V_A = A_{open} \cdot (V_+ - V_-) \rightarrow$ large Positive voltage

Diode ON, $\Rightarrow V_- = V_I$ by feedback

$V_O = V_- = V_I$, $V_A = V_O + V_D$

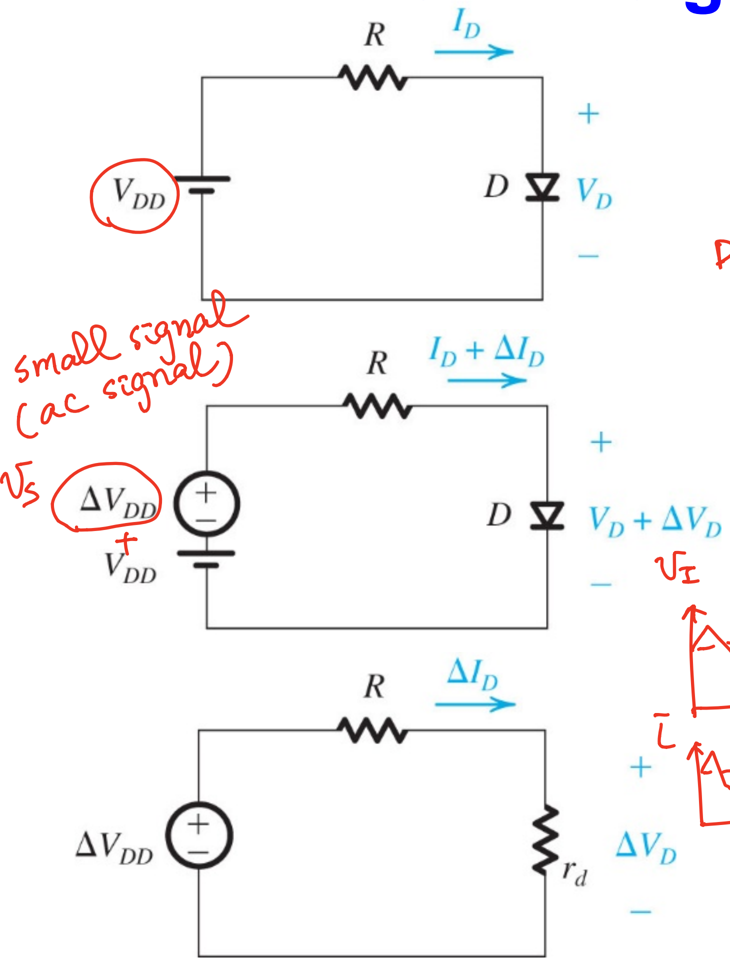
$V_I < 0$, $V_A = A_{open} (V_+ - V_-) \rightarrow$ large negative voltage

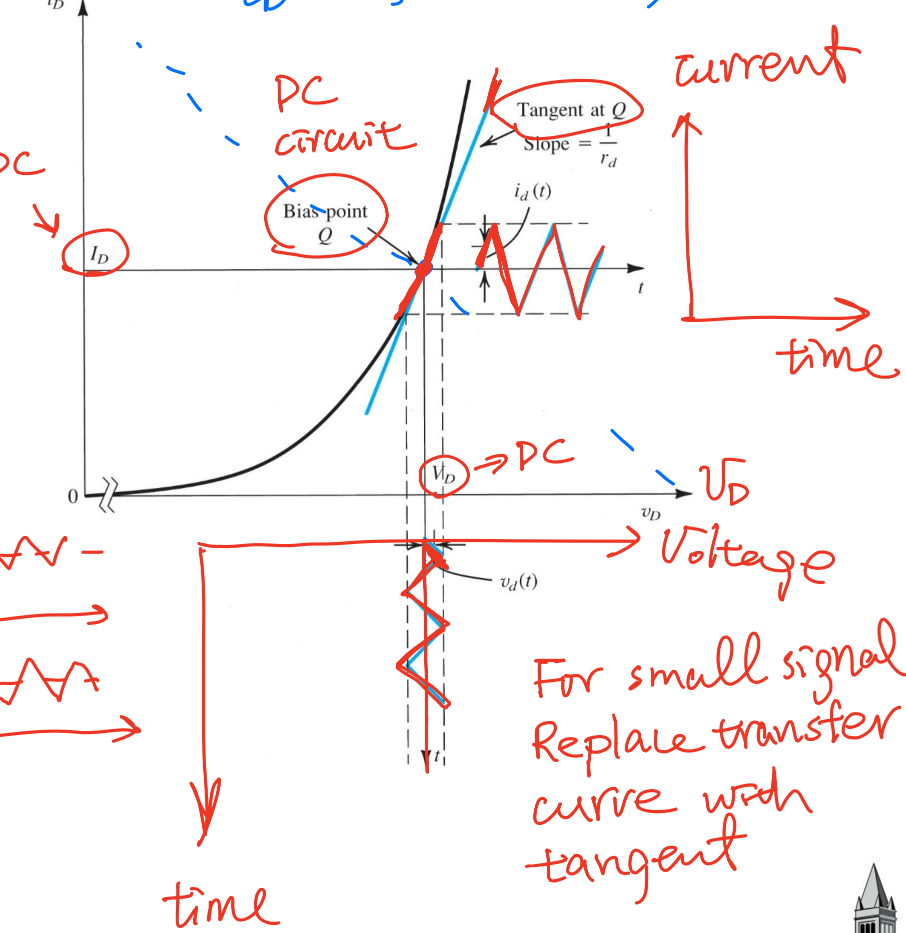
Diode OFF. no feedbak 

$V_O = 0$

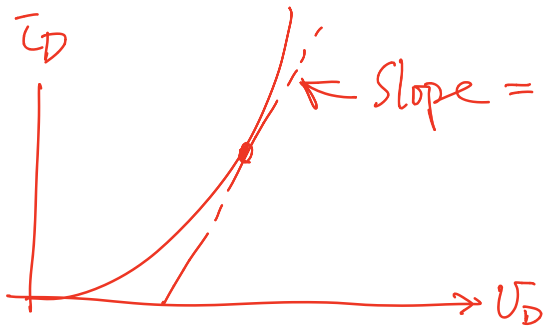
Small Signal Resistance

$$i_D = I_s\left(e^{v_D/V_T} - 1\right) \approx I_s e^{\frac{v_D}{V_T}}$$





For small signal
Replace transfer curve with tangent



$$\text{Slope} = \frac{\Delta i_D}{\Delta v_D} = \frac{1}{r_d}$$

$$r_d = \frac{\Delta v_D}{\Delta i_D} = \frac{1}{\left(\frac{d i_D}{d v_D}\right)} = \frac{1}{\left(\frac{I_D}{V_T}\right)} = \frac{V_T}{I_D}.$$

$V_T = 26\,mV$ at room temp

$$i_D = I_S e^{\frac{v_D}{V_T}}$$

$$\frac{d i_D}{d v_D} = I_S \cdot \frac{1}{V_T} e^{\frac{v_D}{V_T}} = \frac{1}{V_T}\left(I_S e^{\frac{v_D}{V_T}}\right) = \frac{I_D}{V_T}$$

Symbol convention

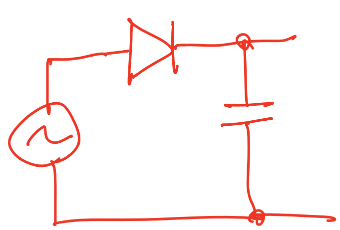
I_D = DC current

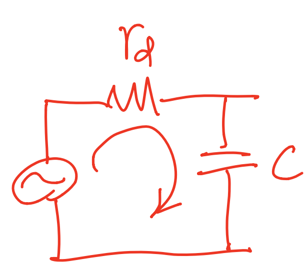
i_D = AC current

If diode is biased at $I_D = 1\,mA$

$$r_d = \frac{V_T}{I_D} = 26\,\Omega$$

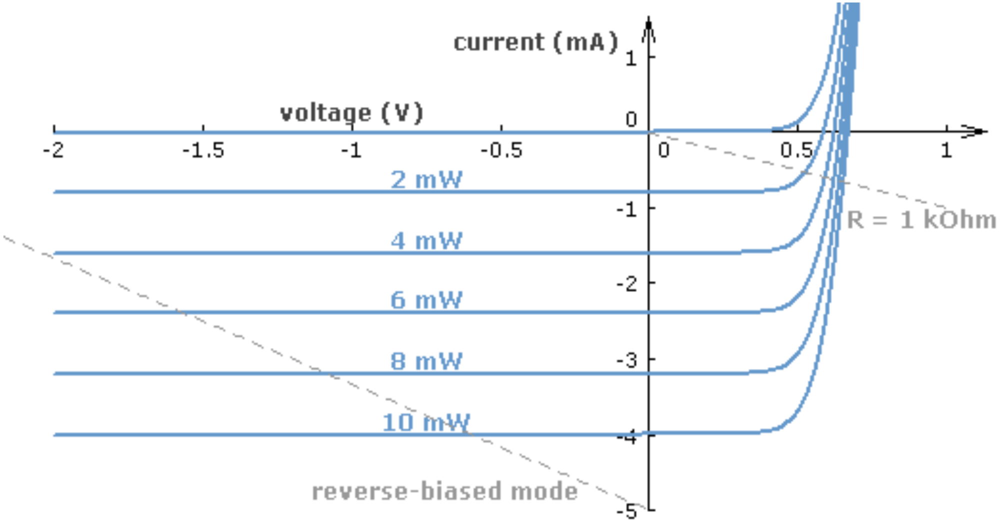
$RC = r_d \cdot C$



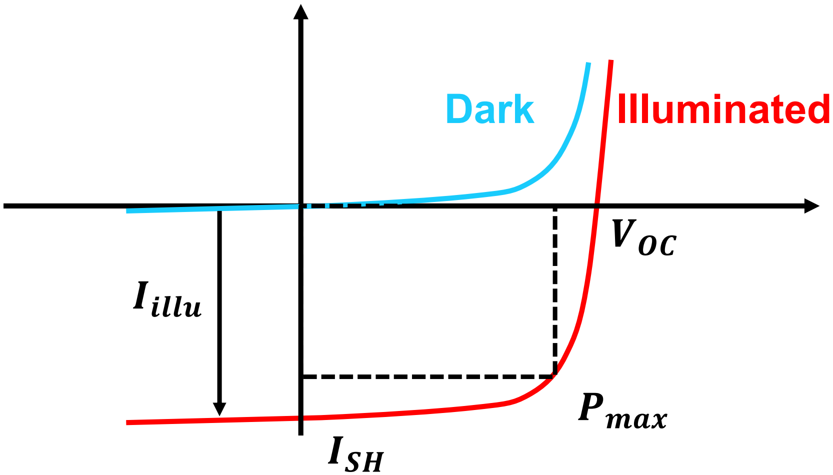


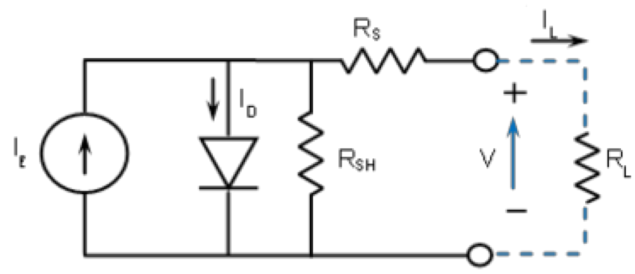
Thu: Video.
No Class

Photodiodes



Solar (Photovoltaic, or PV) Cells





- **Operating in the 4th quadrant of the I-V curve**
  → It generates power !

- **Key parameters:**
  - **Open circuit voltage, V_{OC}**
  - **Short-circuit current, I_{sh}**
  - **Fill factor**