

EE105

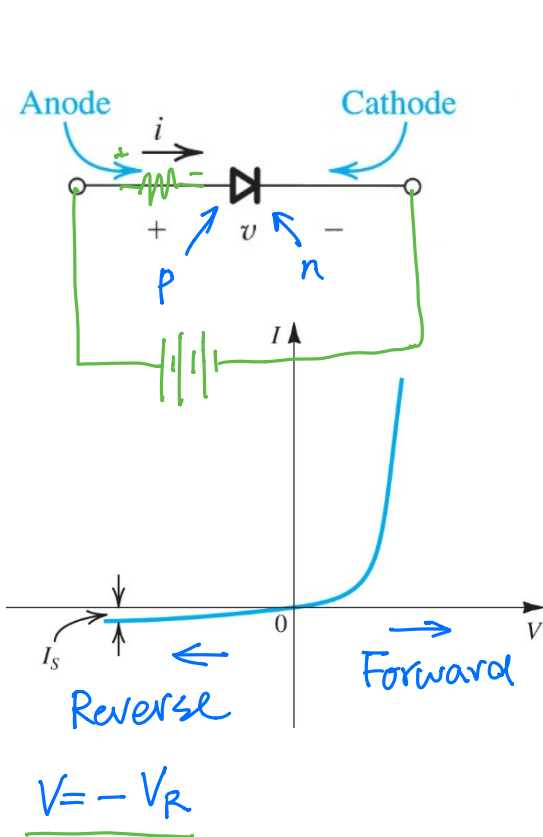
Microelectronic Devices and Circuits: Diode Circuits

Prof. Ming C. Wu

wu@eecs.berkeley.edu

511 Sutardja Dai Hall (SDH)

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 : $I = I_s (e^{v/V_T} - 1)$

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

$I_s = 10^{-15} \text{ A}$
 $V = 2.6 \text{ V}$
 $I = I_s \cdot e^{100}$
 $\approx I_s \cdot 10^{50}$

Under reverse bias :

Negligible current, $I = -I_s$

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

Forward
 $V > 0$
 Reverse
 $V < 0$

Other important parameter :

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

GaN
GaAs
InP
Direct
Bandgap

Many Applications of Diodes



LED (Light-Emitting Diode)



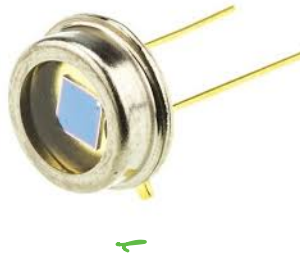
LED Lighting



Laser Diode



Solar Cells (PV)



Photodiode



OLED

How Many Diodes are in a Smart Phone?



How Many Diodes are in a Smart Phone?

UNLOCKING THE NEXT DECADE

2017



FRONT Side

Structured Light approach has been chosen as a starting point for the 3D imaging era. The front 3D module could evolve toward ToF technology in the future, showing more reliability in direct sunlight and lower computation need.

Beginning of the 3D imaging era



Yole's expectations

REAR Side

Dual camera
x2 AF-OIS

FRONT Side

3D Camera
+2D Camera



2027

@2017 | www.yole.fr | iPhone X Analysis

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

How Many Diodes are in a Smart Phone?

IPHONE X – TRUEDEPTH MODULE ANALYSIS – WORKFLOW HYPOTHESIS

3 Steps

for unlocking

- 1- ToF Proximity sensor (+ Inertial sensor ?)
Activity/Human detection
- 2- Flood illuminator + IR camera:
Face + Eyes detection (day and night conditions)
- 3- DOT projector + IR camera:
Face Recognition (FR)



Proximity sensor

VCSEL + ToF detector

Flood illuminator

VCSEL + Diffuser

Infrared camera

1.4Mp IR CIS camera

Front camera

7Mp RGB CIS camera

Dot projector

High-contrast IR dot projector
30K density (200x150) (Min. for FR 160x120)
VCSEL 850 nm



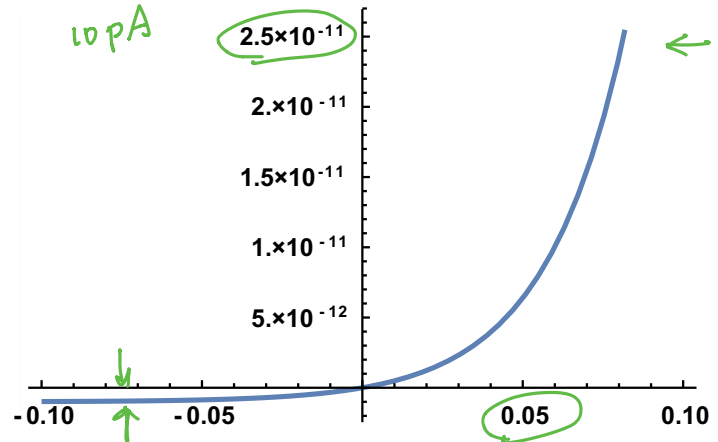
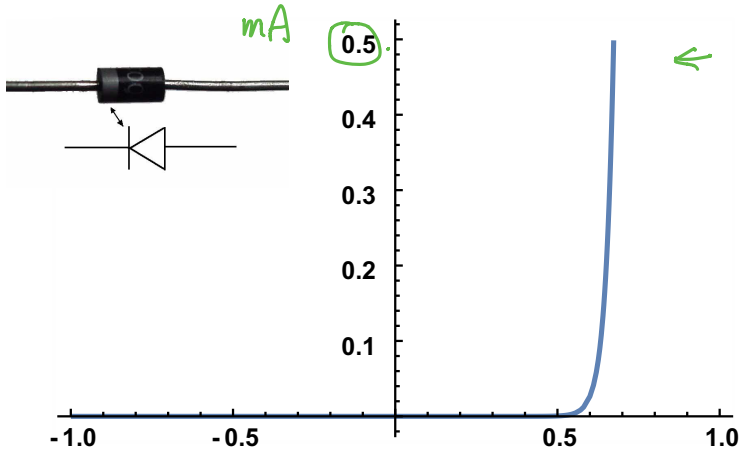
©2017 | www.yole.fr | iPhone X Analysis



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



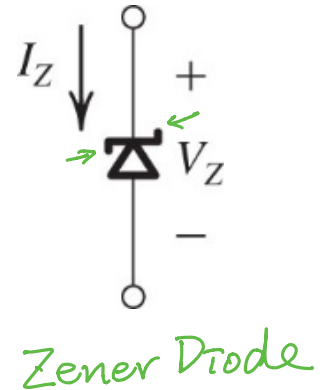
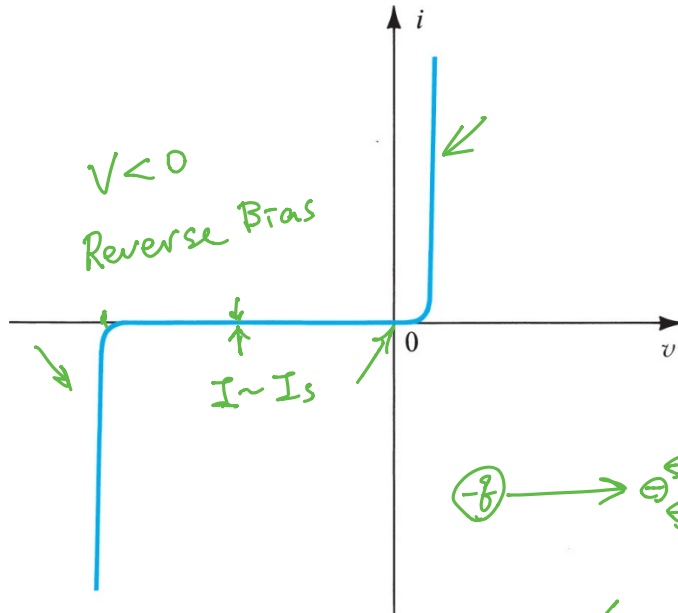
Diode I-V Curve (Forward)



- 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

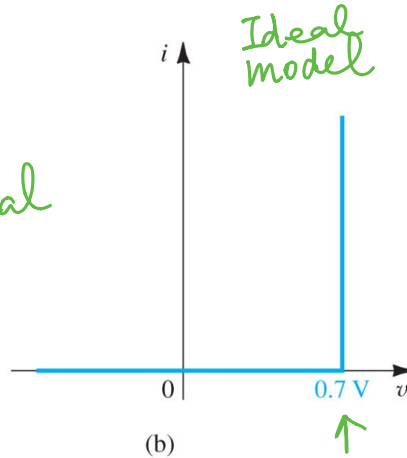
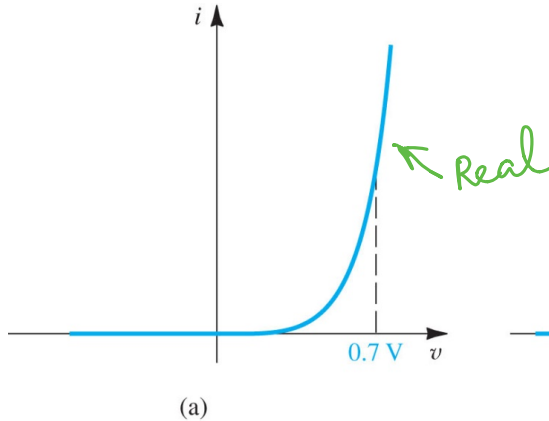
- I-V curve at low current
- Soft increase at forward bias
- Can see reverse saturation current, I_S

Reverse Breakdown

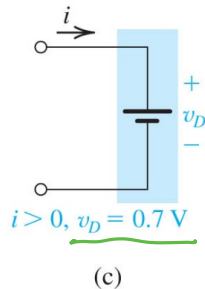
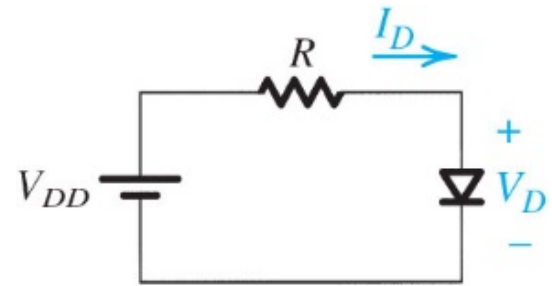


- At sufficiently large reverse bias voltage, current starts to increase dramatically
 - Due to avalanche breakdown or quantum mechanical tunneling
 - Breakdown voltage can be designed
 - Sometimes used as a voltage limiter

Ideal Diode Model

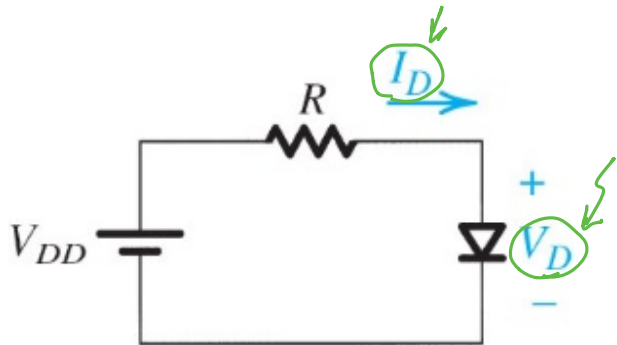


Example:



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

Exact Solution with Real Diode I-V



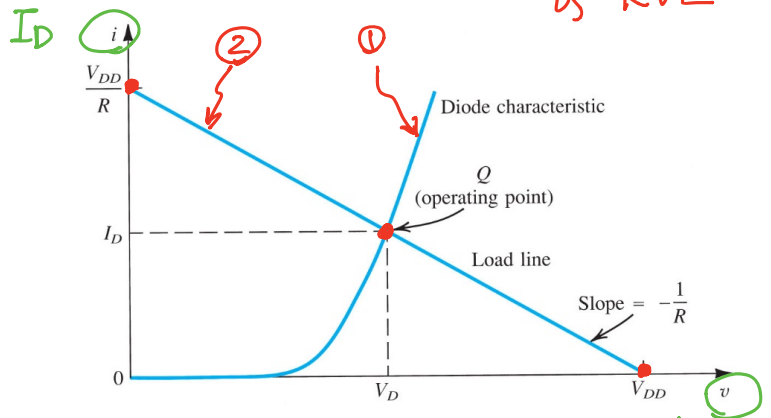
Simple model = $V_D = 0.7V$
 $I_D = \frac{V_{DD} - 0.7}{R}$

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: $V_{DD} = I_D R + V_D$ ②

Example: $V_{DD} = 2V$, $I_S = 10^{-15}A$, $R = 1k\Omega$ $V_D = V_T \cdot \ln \frac{1.3mA}{I_S} = 0.72V$
 \Rightarrow Find out I_D

Load Line \Rightarrow Graphic Represent of KVL



Load line

$$V_{DD} = \underbrace{I_D}_{y} R + \underbrace{V_D}_{x}$$

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

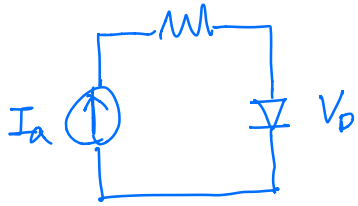
Iterative:

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

② Find V_D so $I_D = 1.3mA$

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

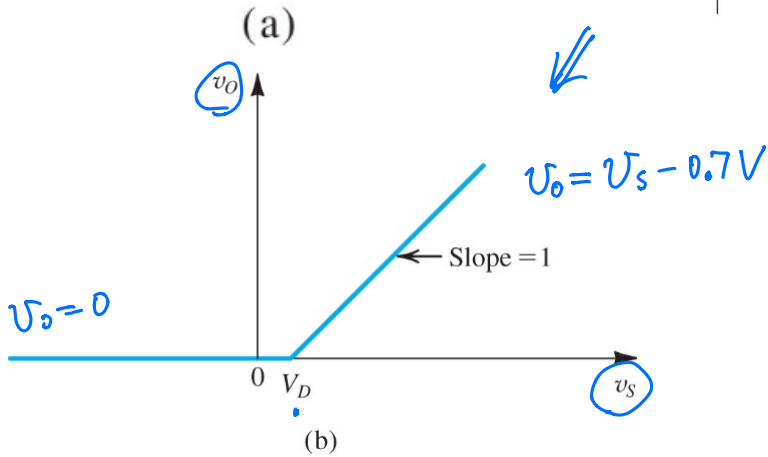
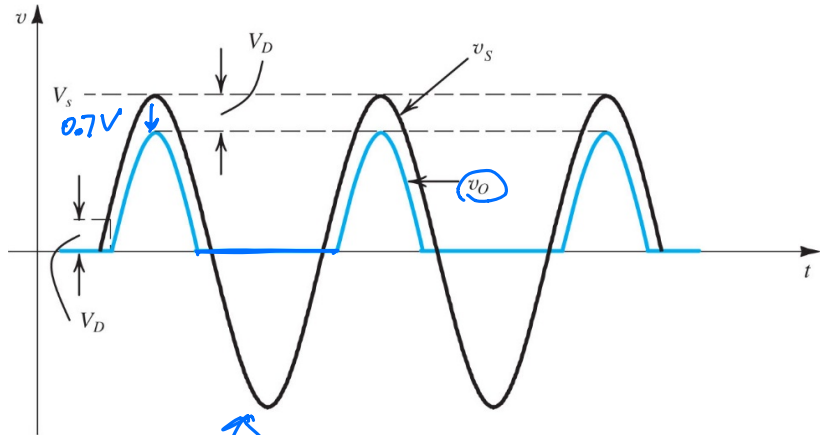
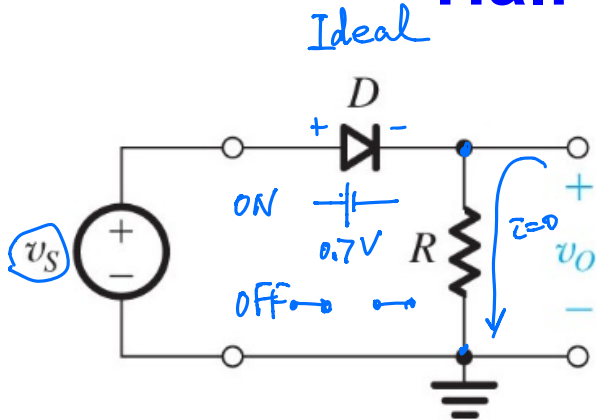
③ $I_D = \frac{2 - 0.72}{1k\Omega} = 1.28mA$



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

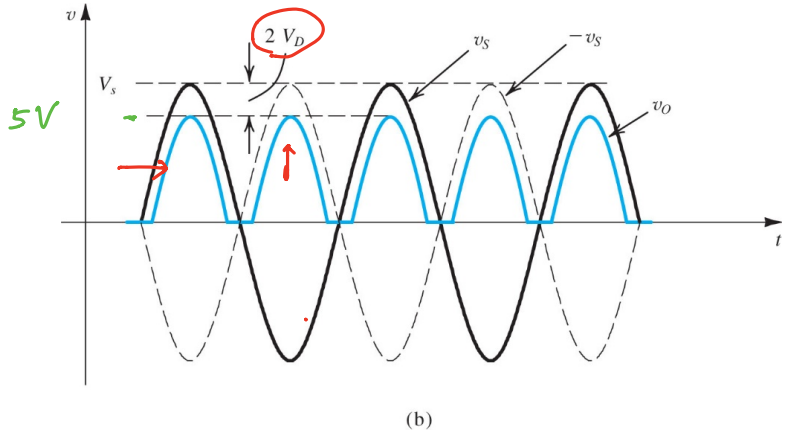
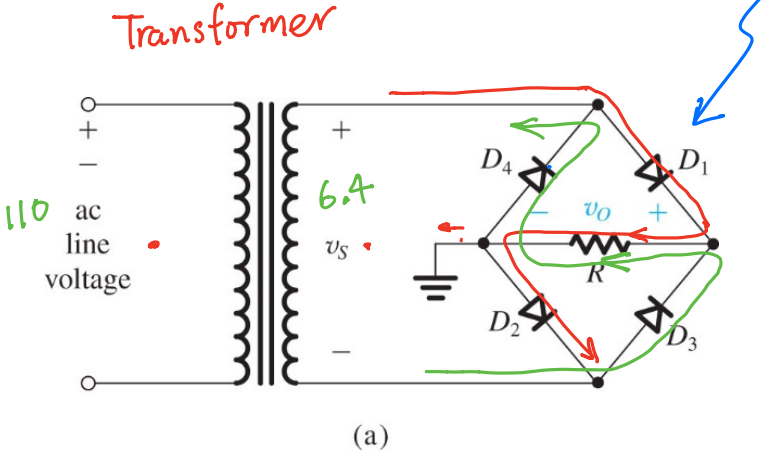
$$\Rightarrow V_D = V_T \ln \frac{I_a}{I_s}$$

Half-Wave Rectifier

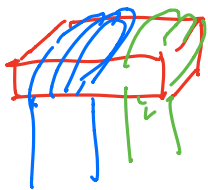


Throw away

Full-Wave Bridge Rectifier

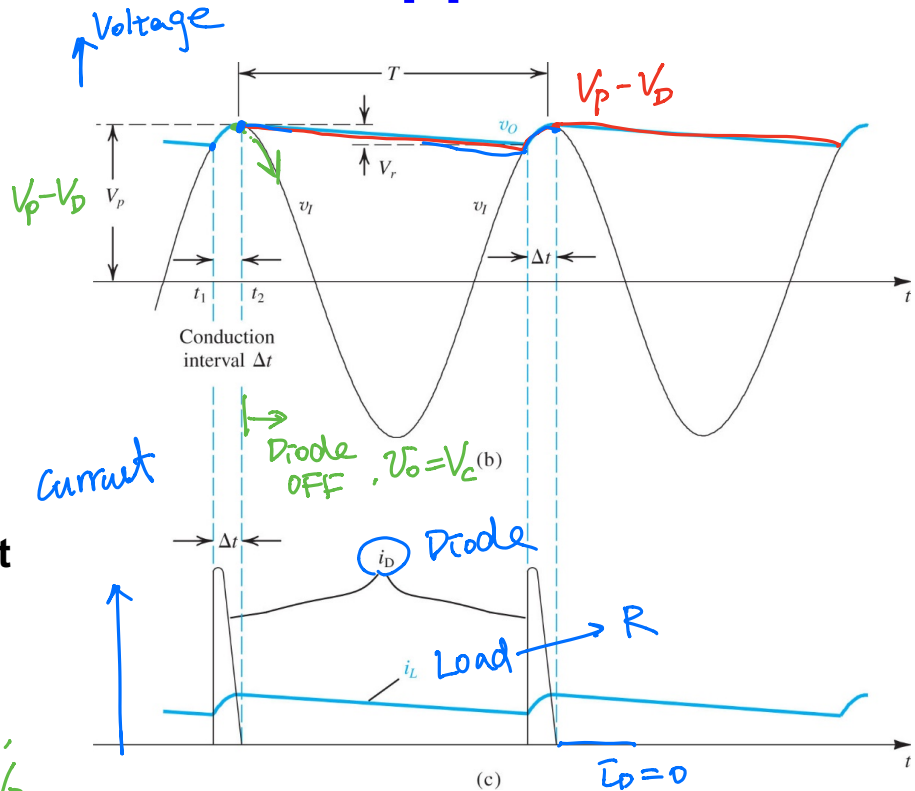
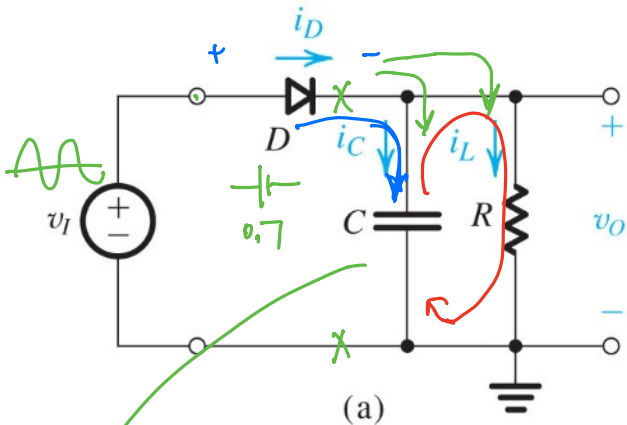


Positive cycle D_1, D_2 ON
 Negative cycle D_3, D_4 ON



← select transformer with desired turn ratio

Filter to Remove Ripples



What is the RC time constant in forward bias?

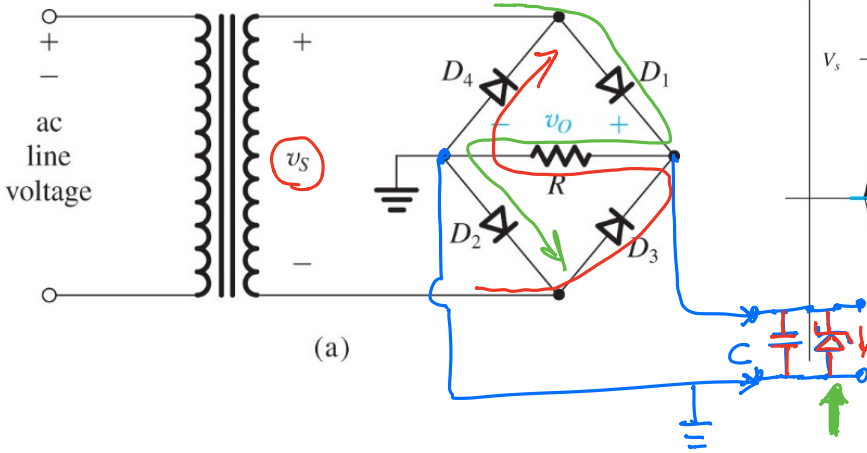
What is RC in reverse bias?

In positive cycle, charged to $V_p - V_b$
 $V_c = \frac{Q}{C}$

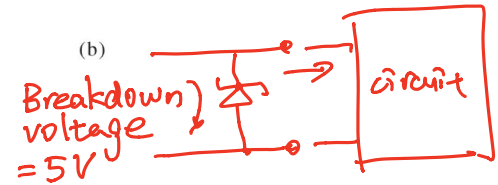
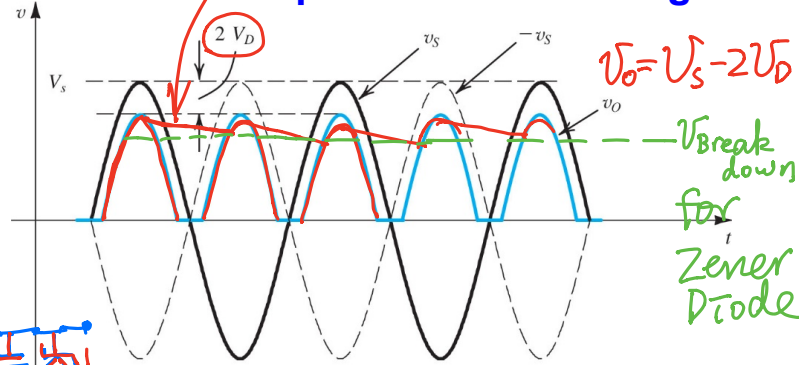
Full-Wave Bridge Rectifier with Smoothing Capacitor

RC discharging $e^{-t/RC}$

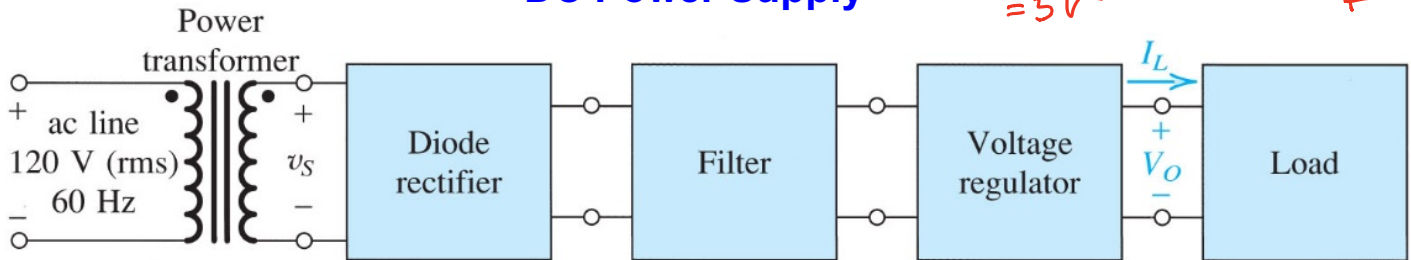
Where do you add capacitor?



How does output waveform change?



DC Power Supply



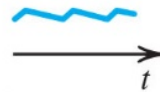
110V



6.4V

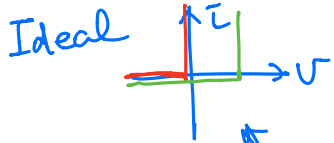


5V + Large ripple

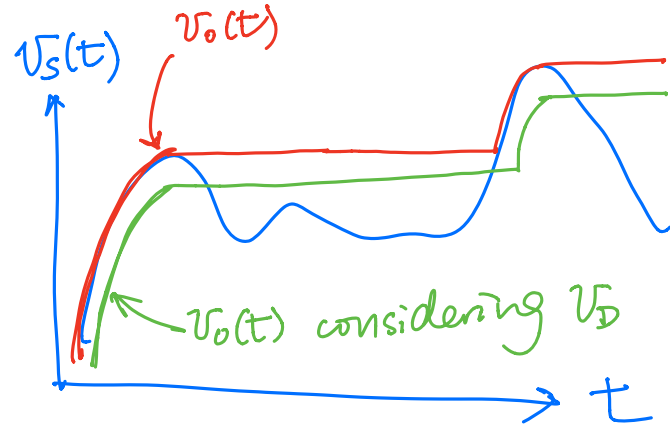
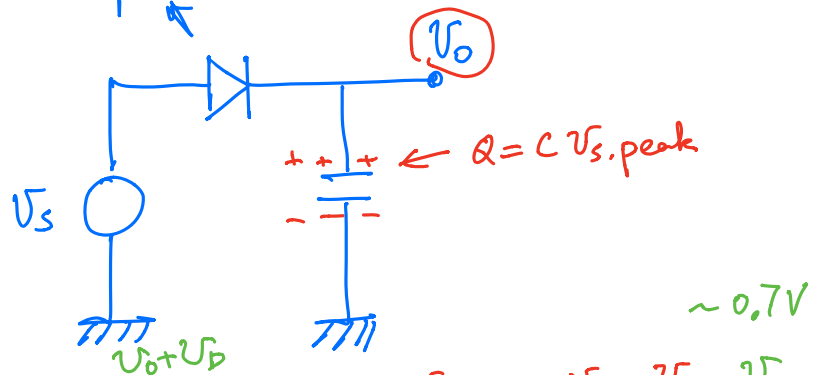


5V + ripple small





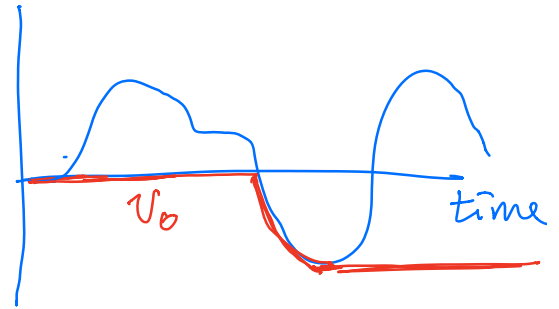
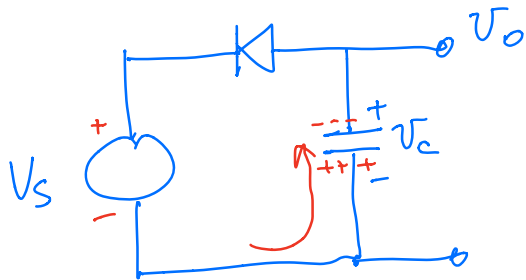
Peak Detector



- ① $v_s > v_o$. Diode ON, $v_D = 0$. $v_o = v_s - v_D$
- ② $v_s < v_o$ Diode OFF
 $v_s < v_o - v_D$

- 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



$v_s > v_o$, Diode OFF .

$v_s < v_o$, Diode ON

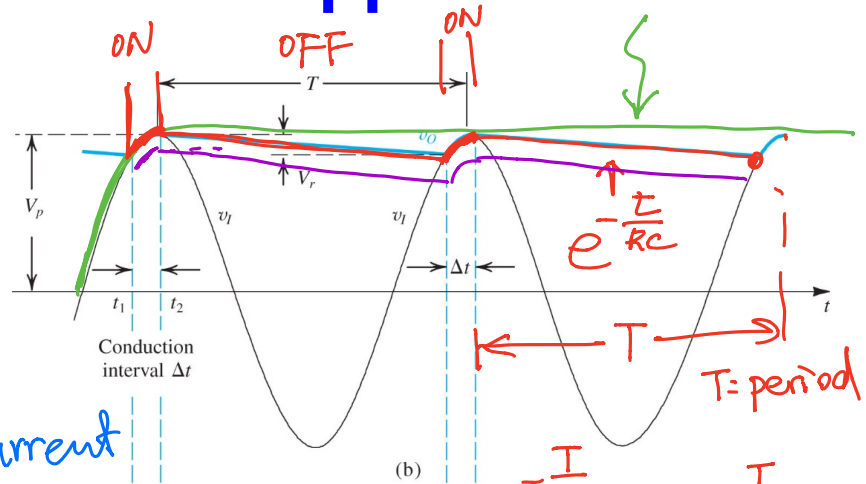
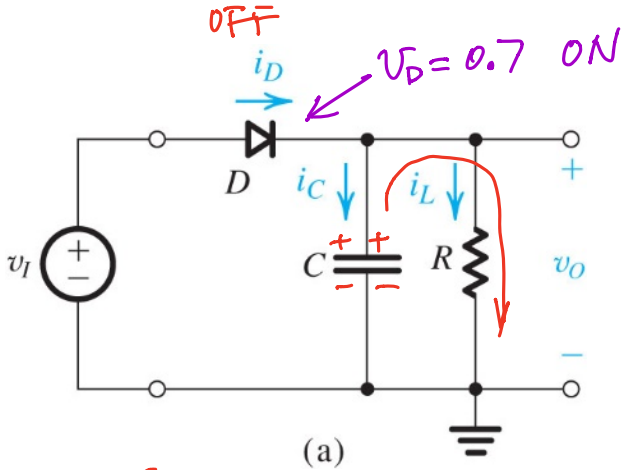
$$v_o = v_c$$

$$v_c = v_s \rightarrow v_{s, \text{peak, neg}}$$

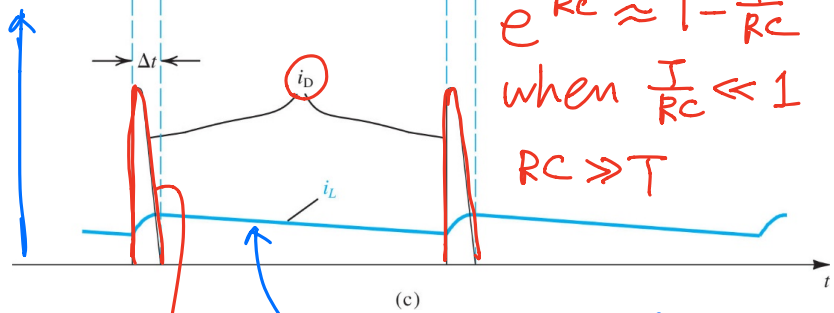
$$v_o = v_c$$

Filter to Remove Ripples

peak detector without R



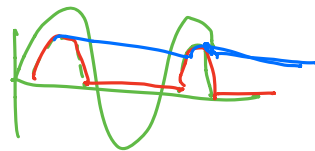
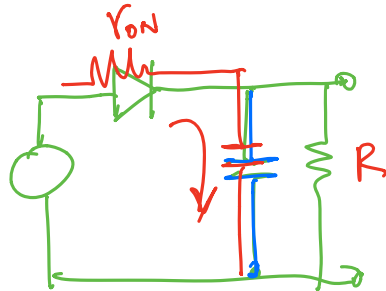
Current



$$V_s > V_o - V_D$$

What is the RC time constant in forward bias?

What is RC in reverse bias?



current through R

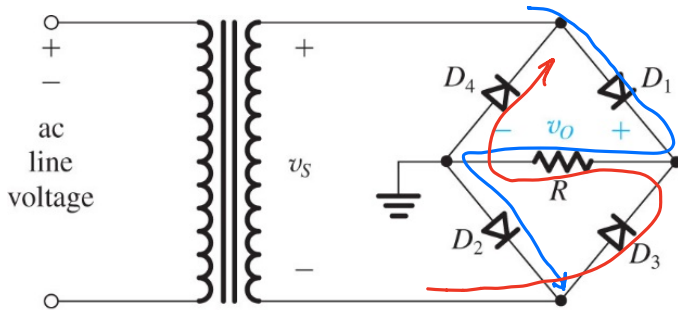
$$i_L = \frac{V_o}{R}$$

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

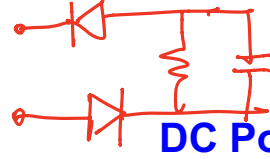
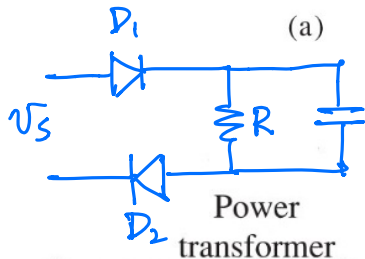
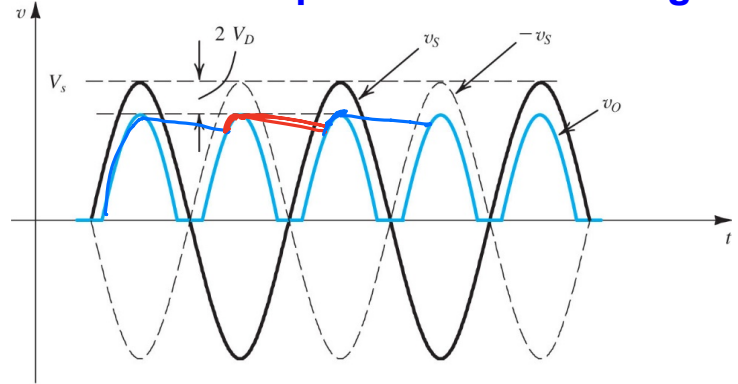
$r_{on} = ON$ resistance of diode

Full-Wave Bridge Rectifier with Smoothing Capacitor

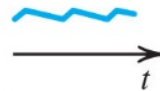
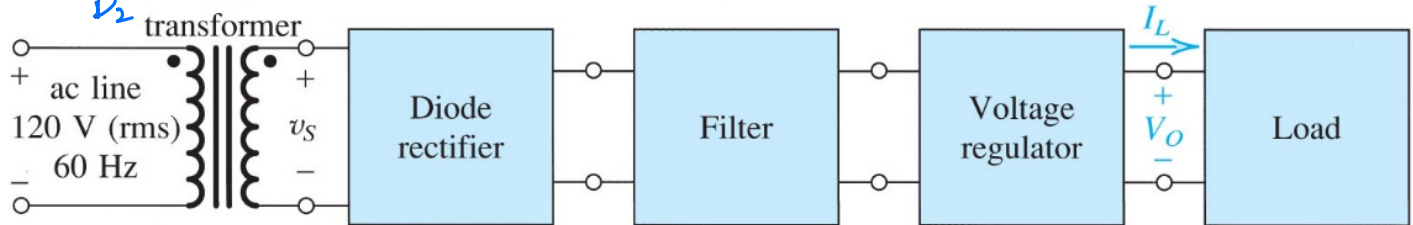
Where do you add capacitor?



How does output waveform change?



DC Power Supply



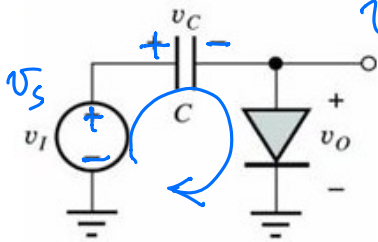
Ideal diode

Level Restorers

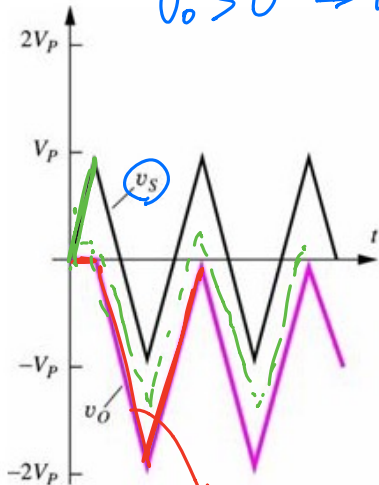
Level shifter

Diode ON, $V_c = V_s$.

$$v_o = V_s - v_c$$



$$v_o > 0 \Rightarrow \text{ON} \Rightarrow v_o = 0$$



$$\textcircled{1} \begin{aligned} v_o &= V_s - v_c \\ v_c &= V_s \text{ KVL} \\ v_o &= 0 \end{aligned}$$

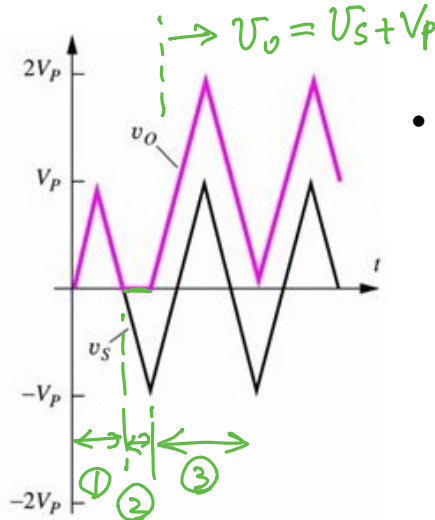
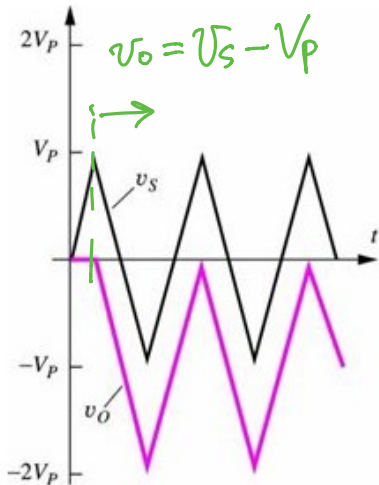
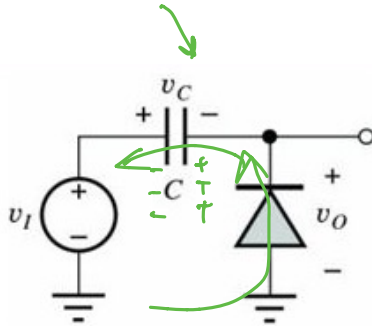
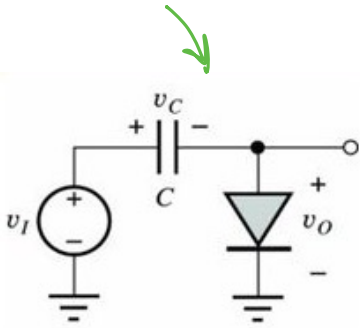
$$\textcircled{2} \begin{aligned} v_s &< V_p \\ v_c &= V_p (= C \cdot Q_p) \\ v_o &= V_s - v_c \\ &= V_s - V_p \end{aligned}$$

$$\textcircled{3} \begin{aligned} v_o &\leq 0, \text{ Diode OFF} \\ v_o &= V_s - v_c = V_s - V_p \end{aligned}$$

$$v_o = V_s - V_p$$

- 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

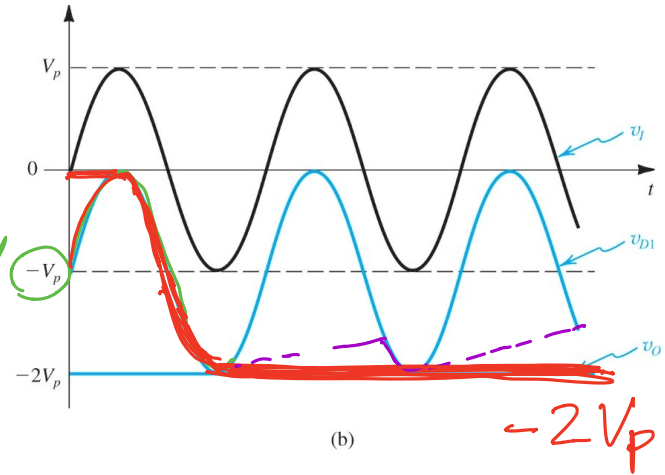
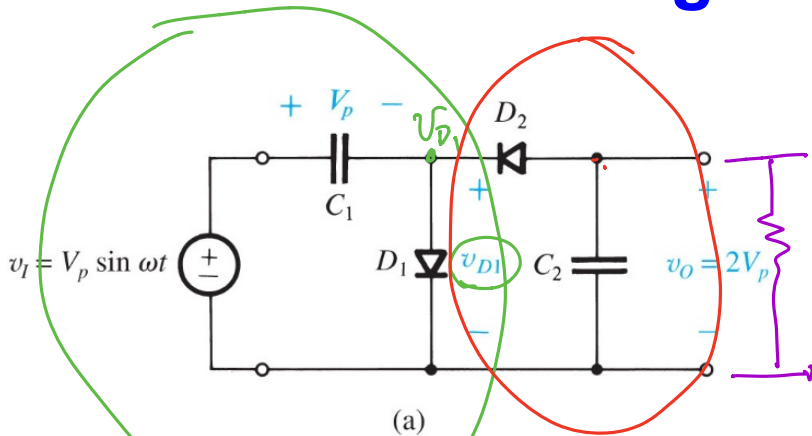


- If we now flip the direction of the diode, the current will only flow during the negative half cycle, charging the capacitor now in the opposite direction.

- 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

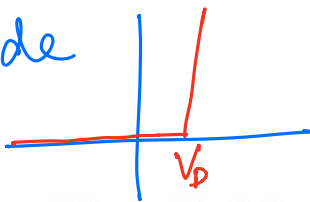


Level shifter

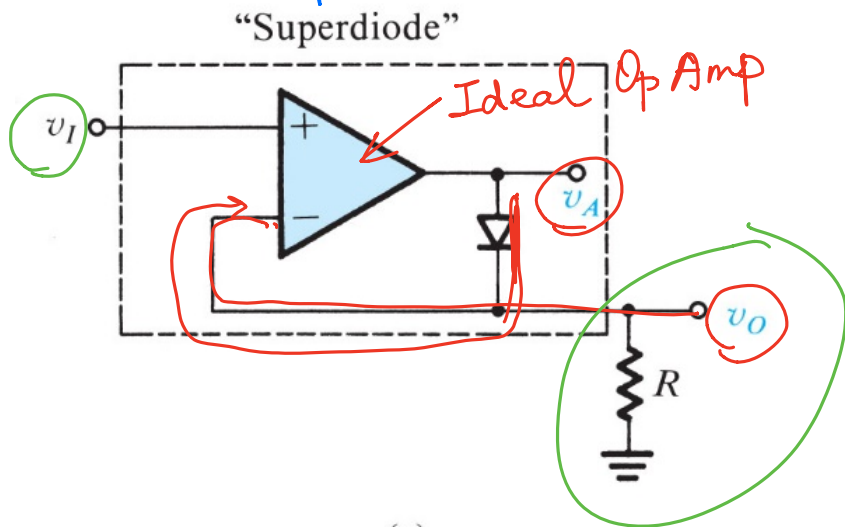
Peak Detector
(detecting most negative peak)

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

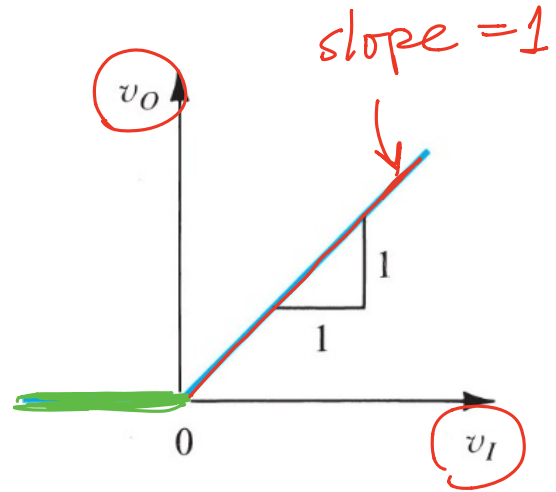
Real Diode



“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

$$v_O = v_- = v_I \quad , \quad v_A = v_O + v_D$$

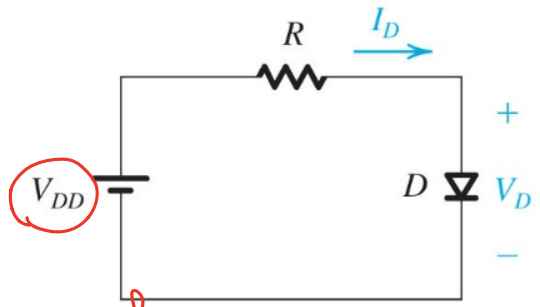
$v_I < 0$, $v_A = A_{open} \cdot (v_+ - v_-) \rightarrow$ large negative voltage

Diode OFF, no feedback

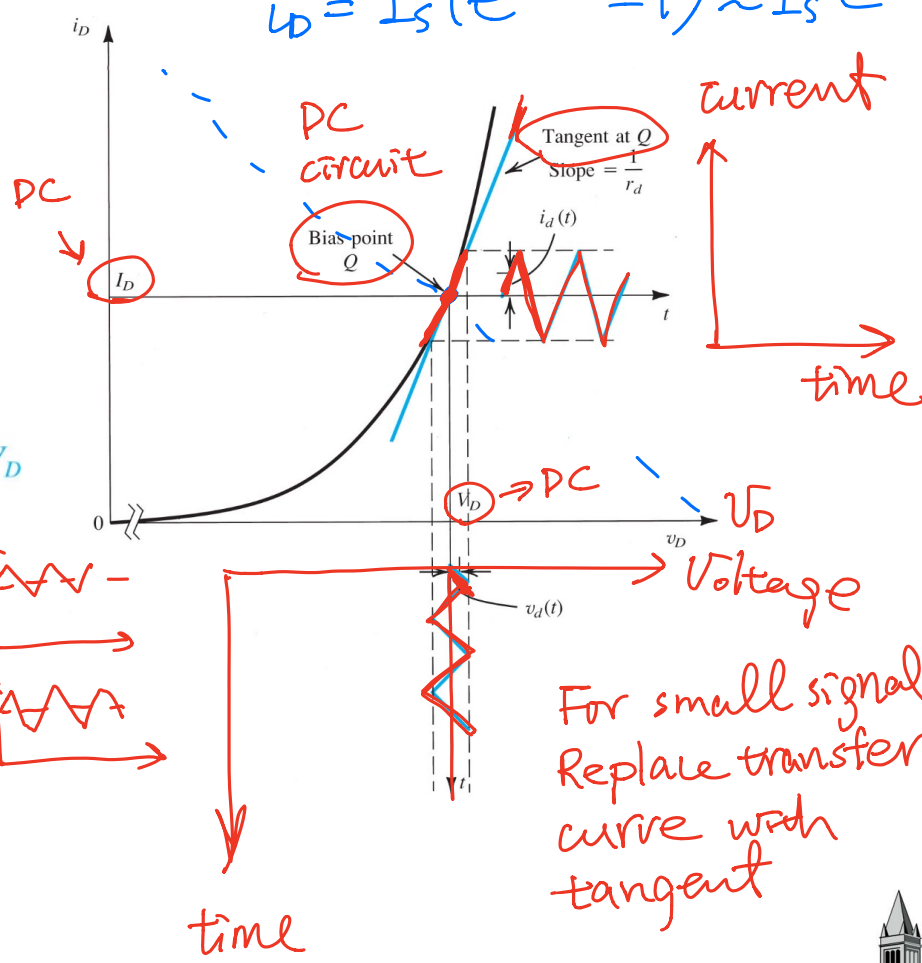
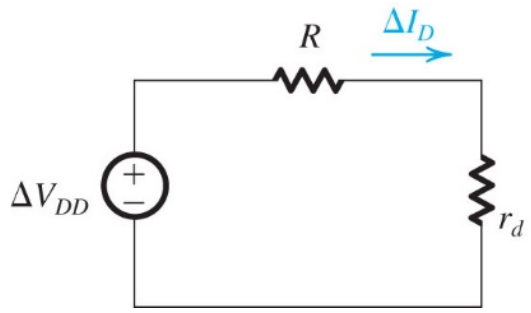
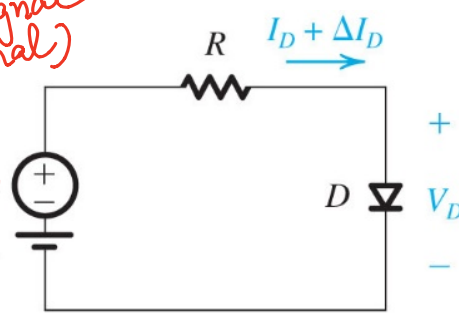


Small Signal Resistance

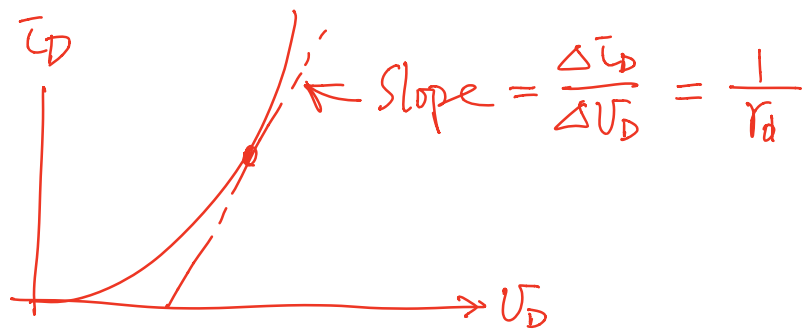
$$i_D = I_S (e^{v_D/V_T} - 1) \approx I_S e^{v_D/V_T}$$



small signal
(ac signal)



For small signal
Replace transfer
curve with
tangent



$$r_d = \frac{\Delta U_D}{\Delta \bar{i}_D} = \frac{1}{\left(\frac{d\bar{i}_D}{dU_D}\right)} = \frac{1}{\left(\frac{I_D}{V_T}\right)} = \frac{V_T}{I_D}$$

$V_T = 26 \text{ mV}$
at room temp

$$\bar{i}_D = I_S e^{\frac{U_D}{V_T}}$$

$$\frac{d\bar{i}_D}{dU_D} = I_S \cdot \frac{1}{V_T} e^{\frac{U_D}{V_T}} = \frac{1}{V_T} (I_S e^{\frac{U_D}{V_T}}) = \frac{I_D}{V_T}$$

Symbol convention

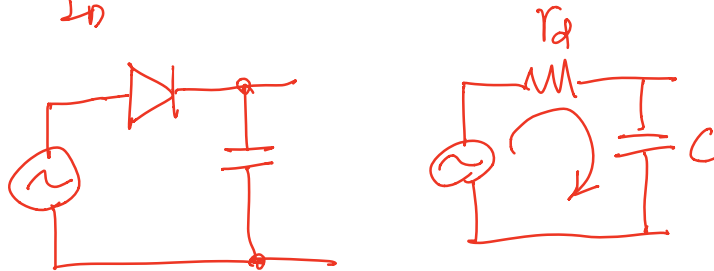
I_D = DC current

\bar{i}_D = AC current

If diode is biased at $I_D = 1 \text{ mA}$

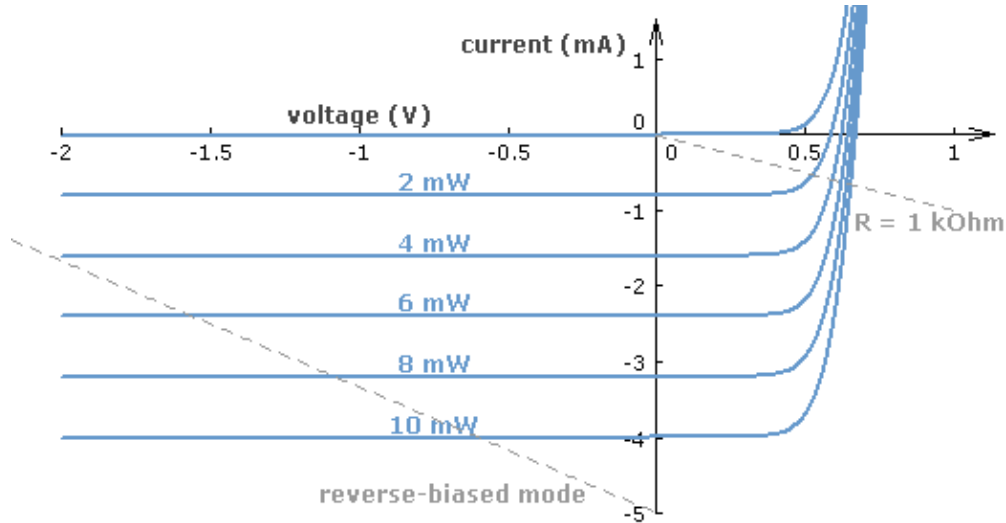
$$r_d = \frac{V_T}{I_D} = 26 \Omega$$

$$RC = r_d \cdot C$$

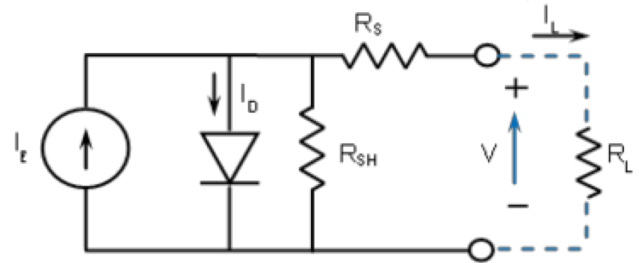
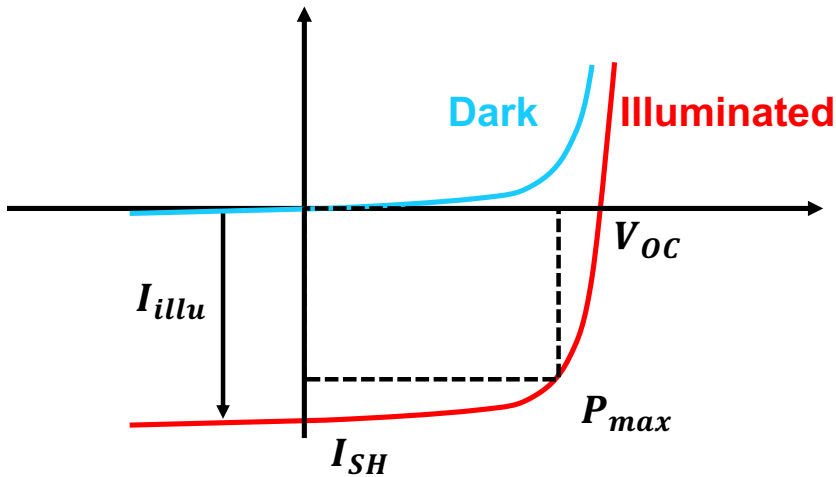


Thu = Video.
No Class

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