

# **EE105**

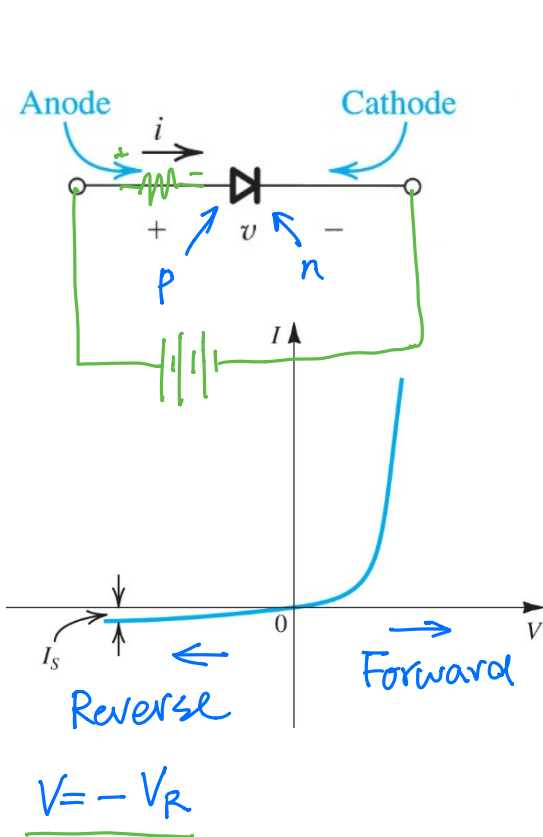
## **Microelectronic Devices and Circuits: Diode Circuits**

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

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)



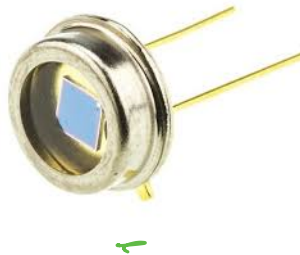
LED Lighting



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



- 1.4Mp IR Camera
- ToF Proximity sensor
- Flood IR Illuminator
- DOT IR Projector

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



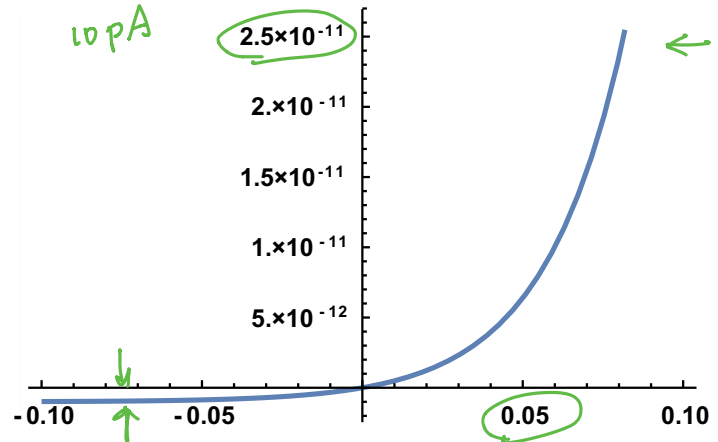
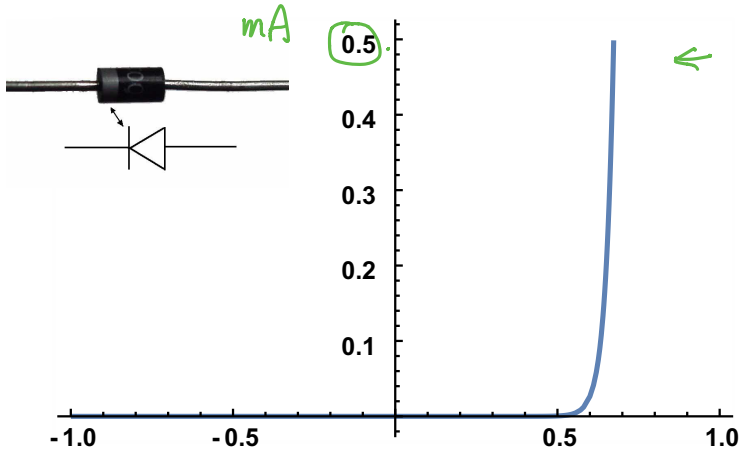
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<http://image-sensors-world.blogspot.com/2017/09/yole-on-iphone-x-3d-innovations.html>



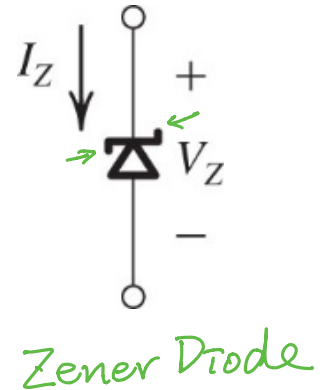
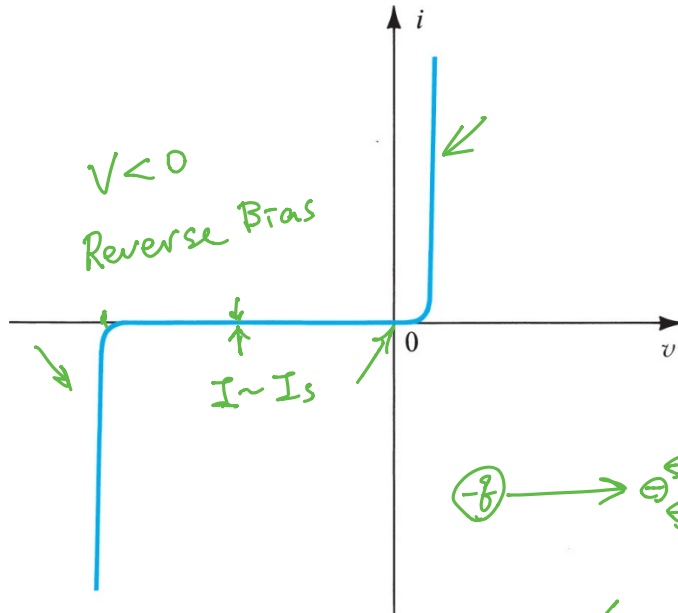
# Diode I-V Curve (Forward)



- 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,  $I_S$

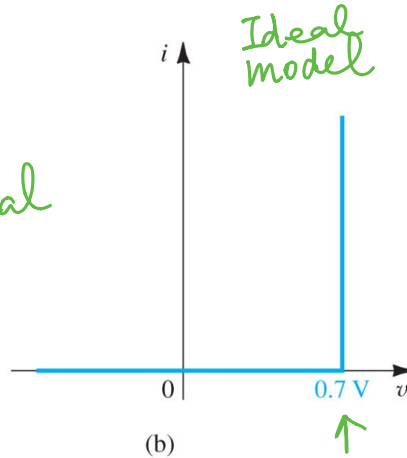
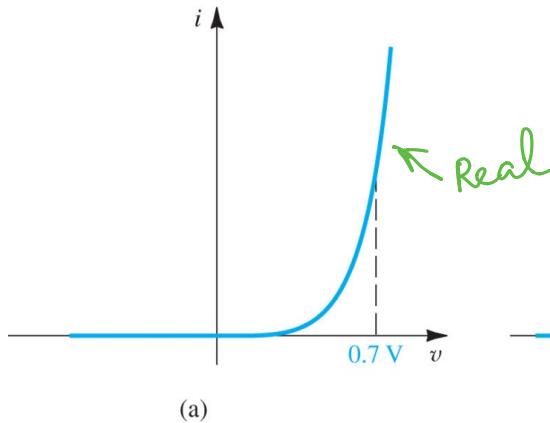
# Reverse Breakdown



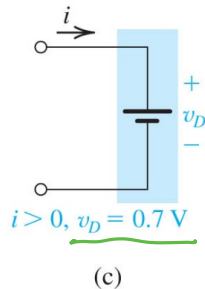
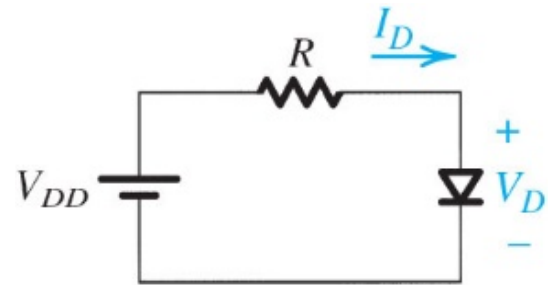
- At sufficiently large reverse bias voltage, current starts to increase dramatically
  - Due to avalanche breakdown or quantum mechanical tunneling
  - Breakdown voltage can be designed
  - Sometimes used as a voltage limiter



# Ideal Diode Model

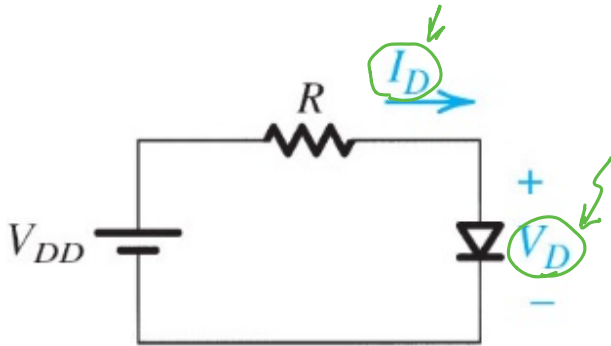


Example:



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

# Exact Solution with Real Diode I-V



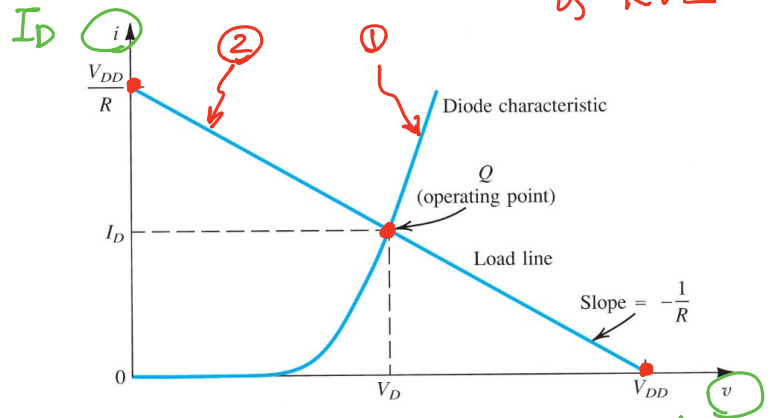
Simple model =  $V_D = 0.7V$   
 $I_D = \frac{V_{DD} - 0.7}{R}$

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

Load Line  $\Rightarrow$  Graphic Represent of KVL



Load line

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

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

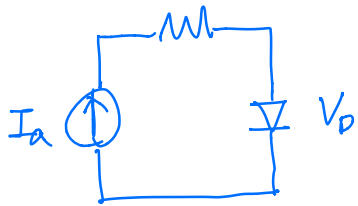
Iterative:

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

② Find  $V_D$  so  $I_D = 1.3mA$

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

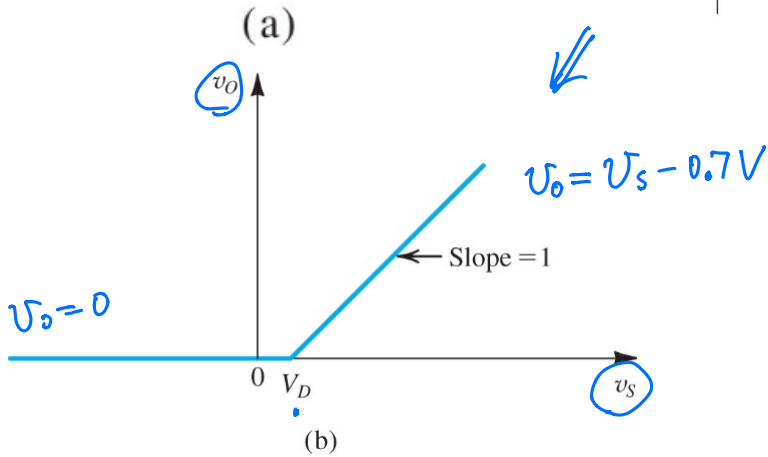
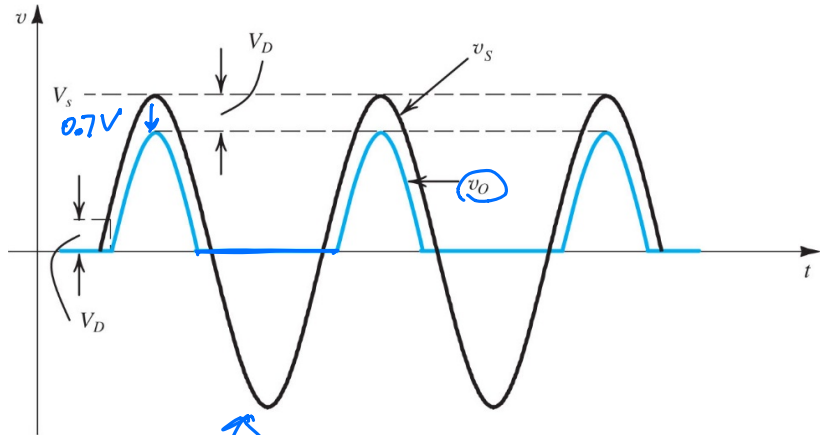
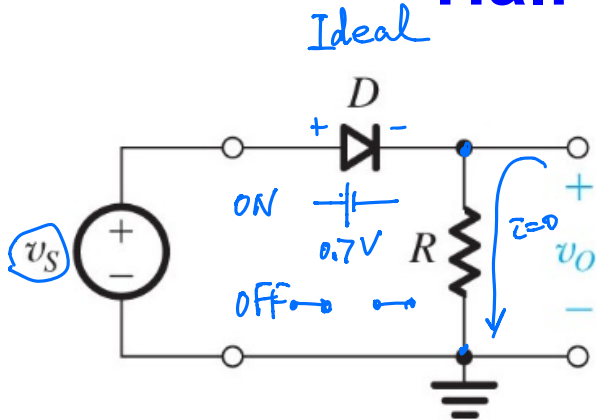
③  $I_D = \frac{2 - 0.72}{1k\Omega} = 1.28mA$



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

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

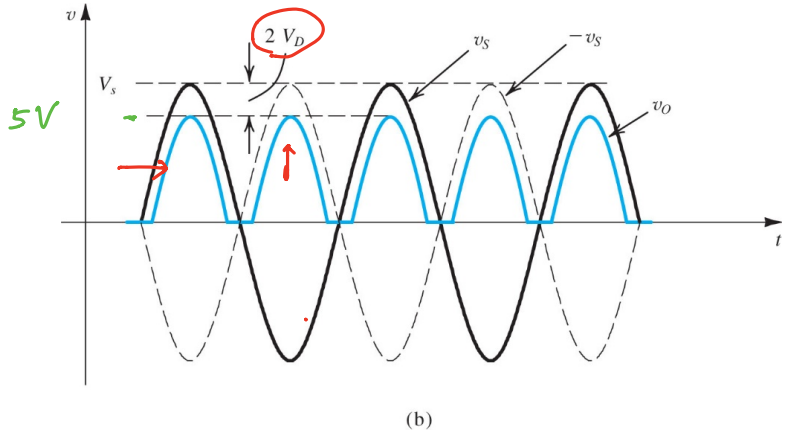
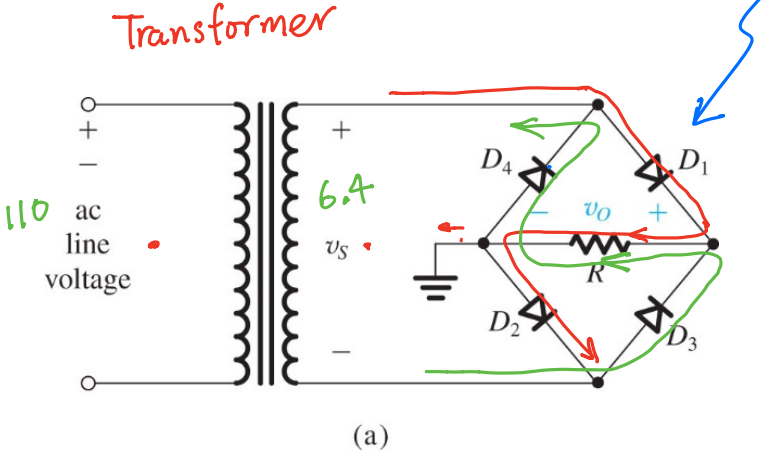
# Half-Wave Rectifier



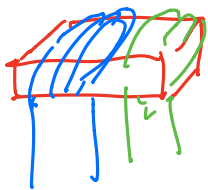
(c)

Throw away

# Full-Wave Bridge Rectifier

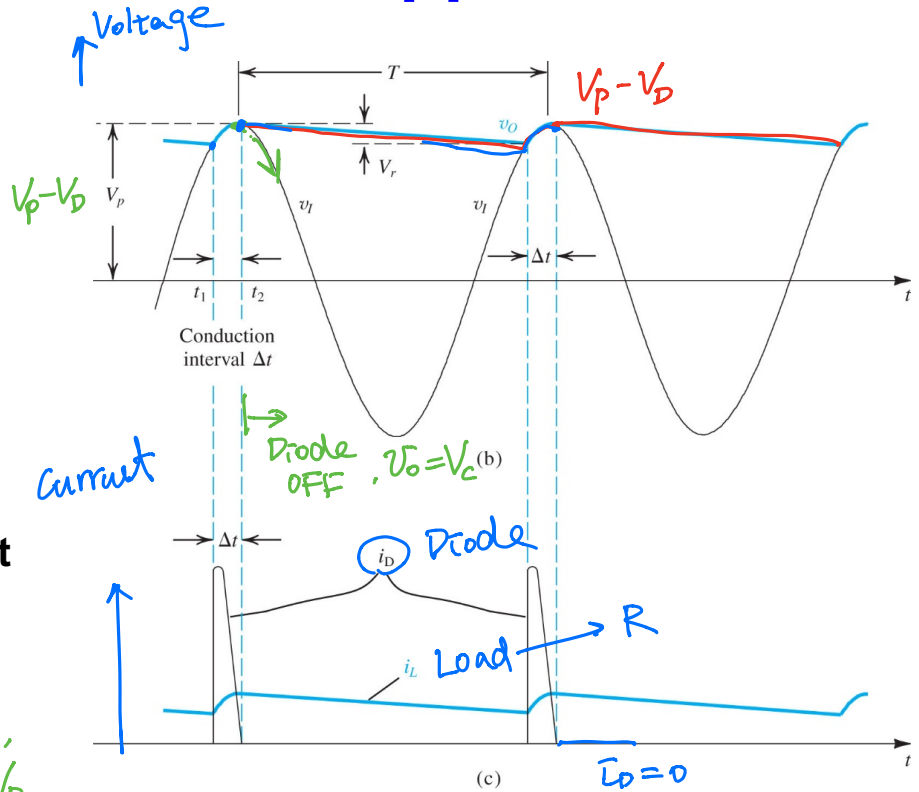
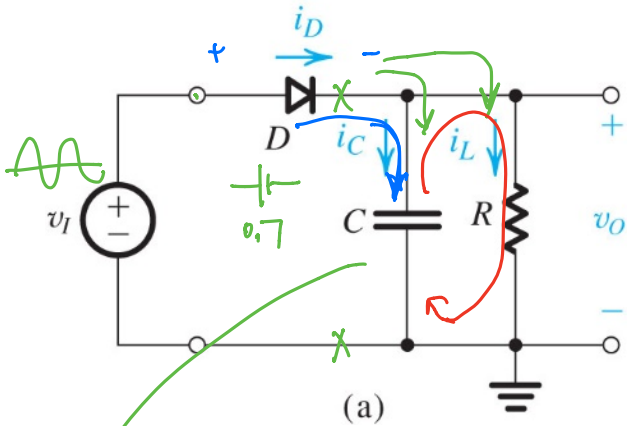


Positive cycle  $D_1, D_2$  ON  
 Negative cycle  $D_3, D_4$  ON



← select transformer with desired turn ratio

# Filter to Remove Ripples



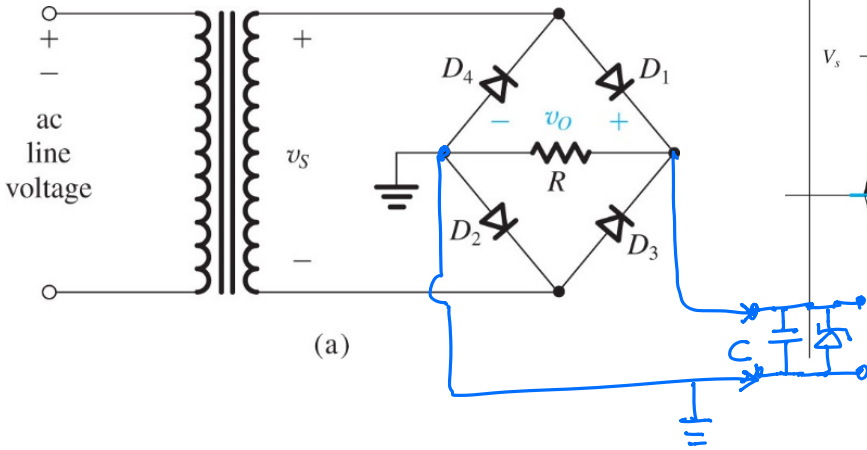
What is the RC time constant in forward bias?

What is RC in reverse bias?

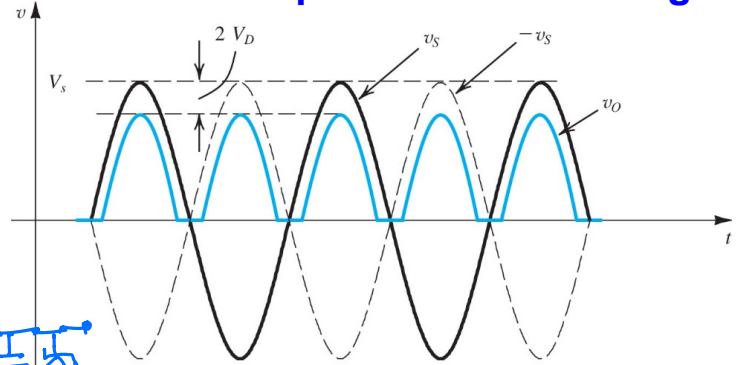
In positive cycle, charged to  $V_p - V_b$   
 $V_c = \frac{Q}{C}$

# Full-Wave Bridge Rectifier with Smoothing Capacitor

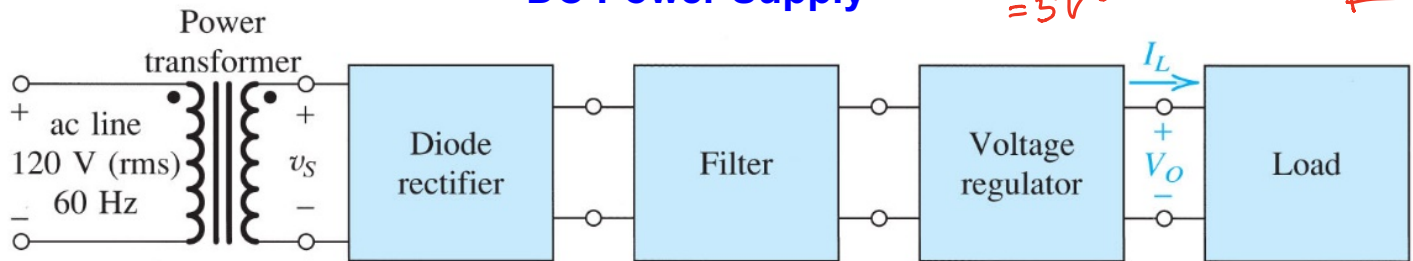
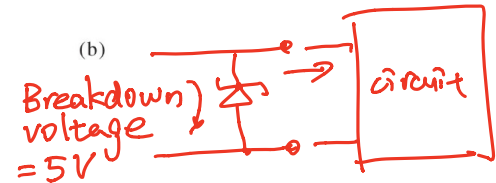
Where do you add capacitor?



How does output waveform change?



## DC Power Supply



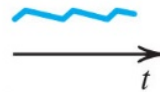
110V



6.4V

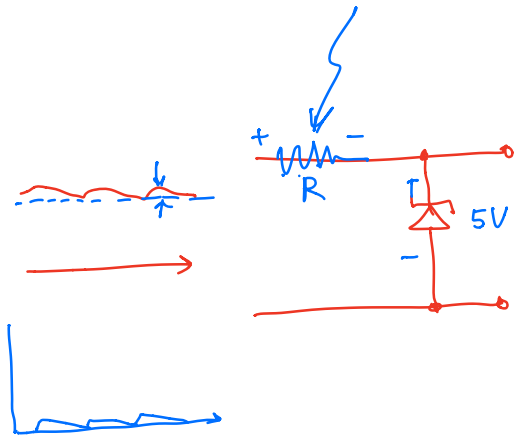


5V + Large ripple



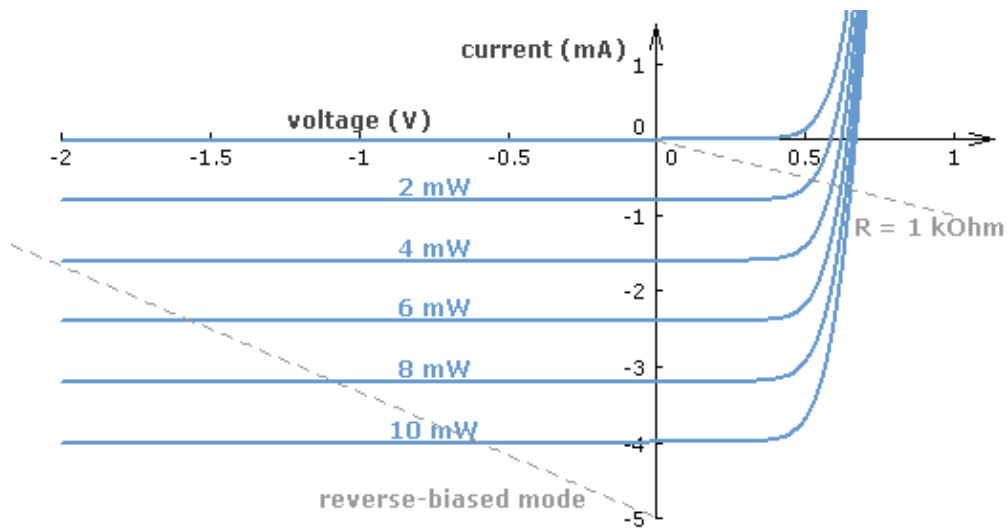
5V + ripple small



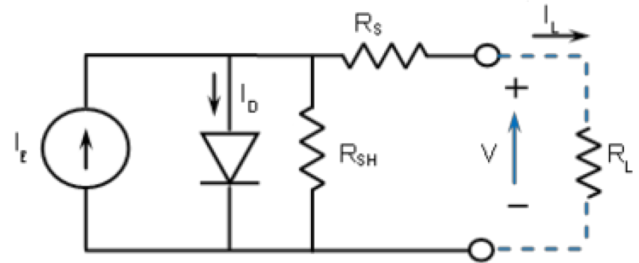
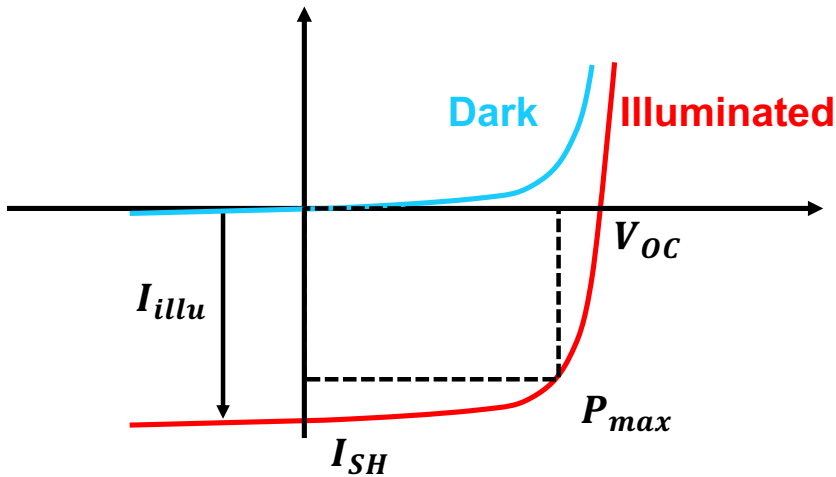




# Photodiodes



# Solar (Photovoltaic, or PV) Cells

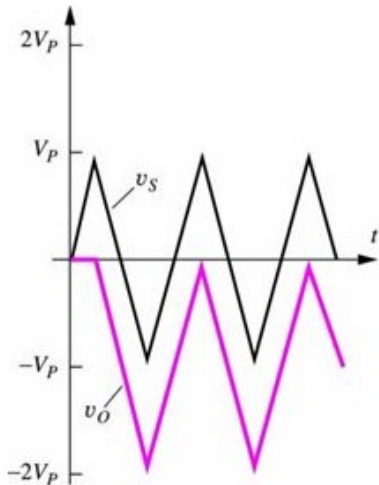
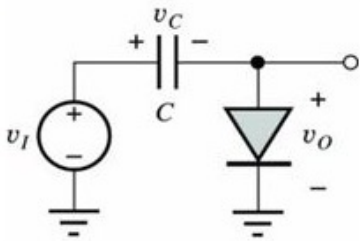


- Operating in the 4<sup>th</sup> quadrant of the I-V curve  
→ It generates power !
- Key parameters:
  - Open circuit voltage,  $V_{OC}$
  - Short-circuit current,  $I_{sh}$
  - Fill factor

# Peak Detector

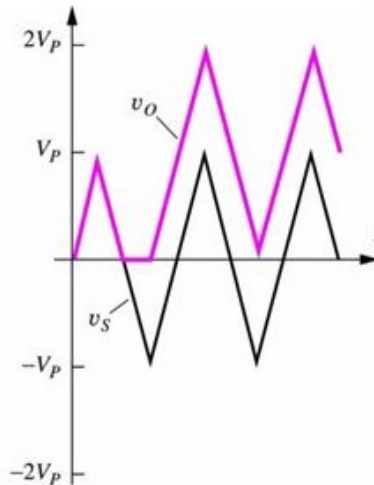
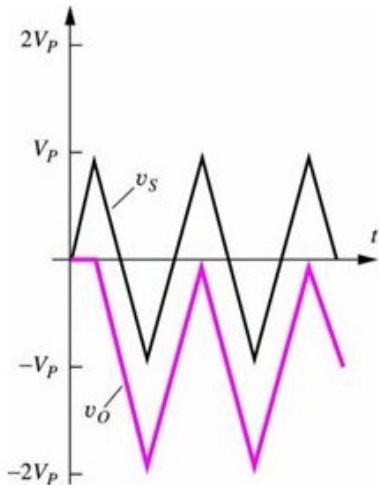
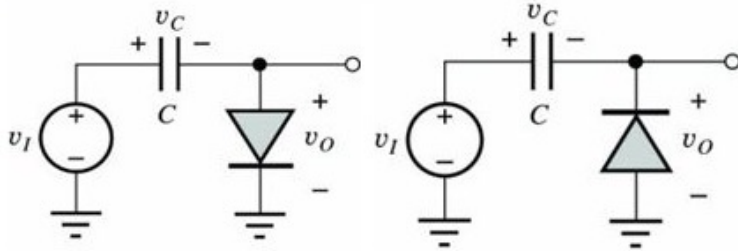
- **The capacitor is charged to the peak voltage and the output is held at the peak**
  - When input  $>$  output, diode is ON, charge capacitor to new peak
  - When input  $<$  output, diode is OFF. Capacitor holds output at peak
- **If you flip the direction of the diode, you get a negative peak detector.**

# Level Restorers



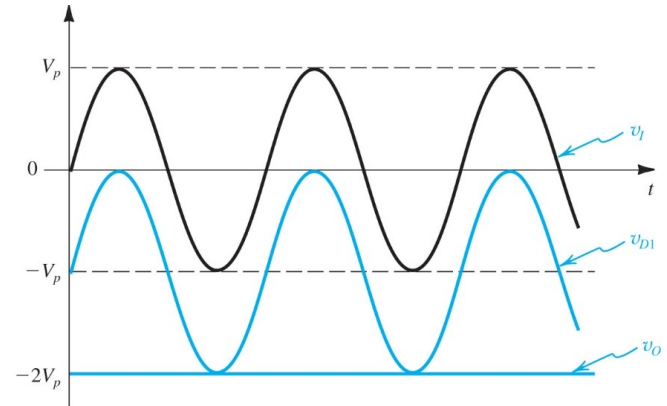
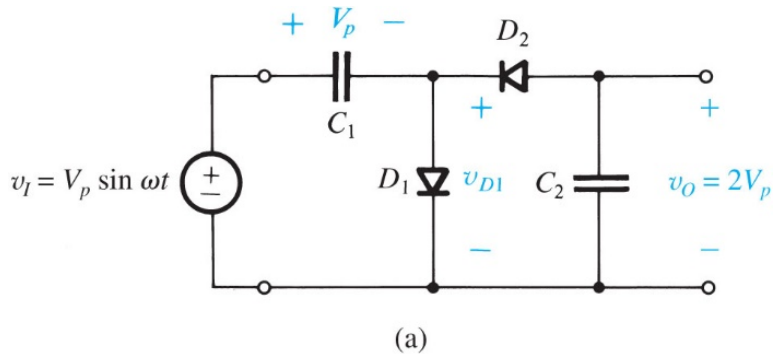
- Diode turns on initially and charges the capacitor to the AC voltage.
  - Note that once the voltage starts to drop, the diode turns off
- The output voltage is therefore level shifted by the DC voltage held on the capacitor
- In this case the voltage excursions are now negative and never rise above 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!

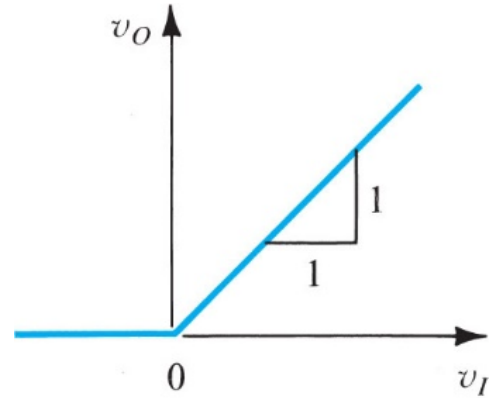
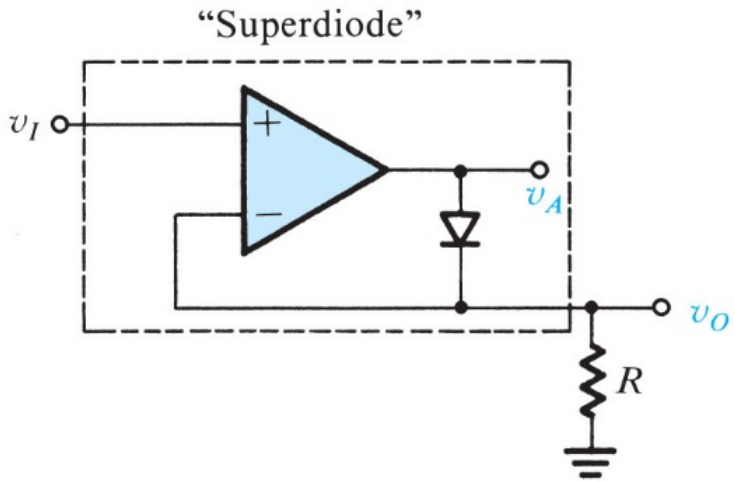
# Voltage Doubler



(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”



Use an op-amp to make circuit precise

# Small Signal Resistance

