ECEN325: Electronics
Spring 2024

Semiconductor pn Junction Diode

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Announcements

- HW3 Due Feb 22
- Exam 1 Feb 29
  - One double-sided 8.5x11 notes page allowed
  - Bring your calculator
  - Covers Linear Circuit Analysis & Opamps

Reading

- Razavi Ch2 (optional)
  - Basic semiconductor device physics, which is useful to understand how diodes work
  - Covered in more detail in ECEN 370

- Razavi Ch3
  - Diode models and circuits

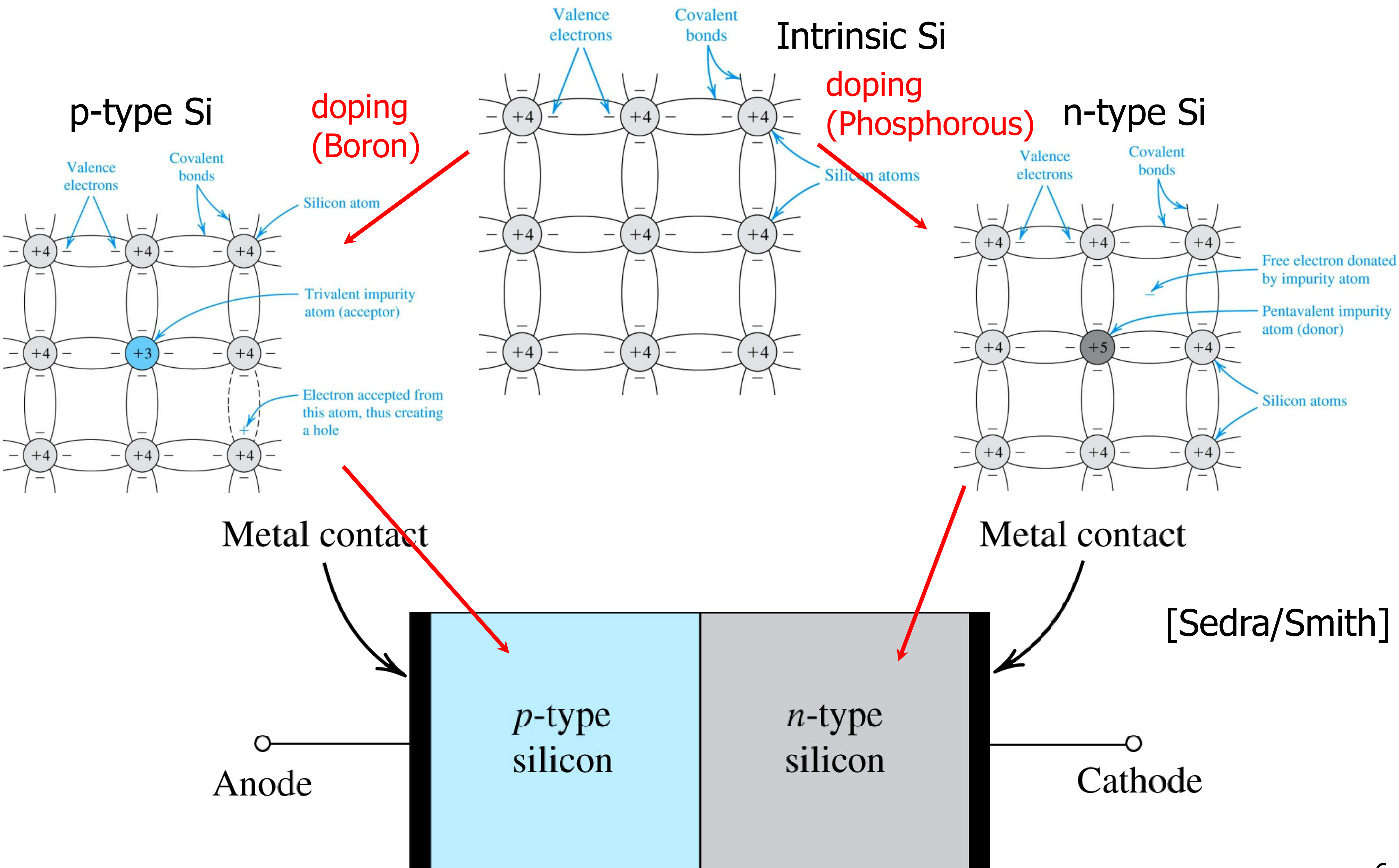
Agenda

- Semiconductor pn junction diodes
- Diode current-voltage (I-V) characteristics
- Constant voltage drop model
- Solving circuits with diodes
- Diode rectifier circuits

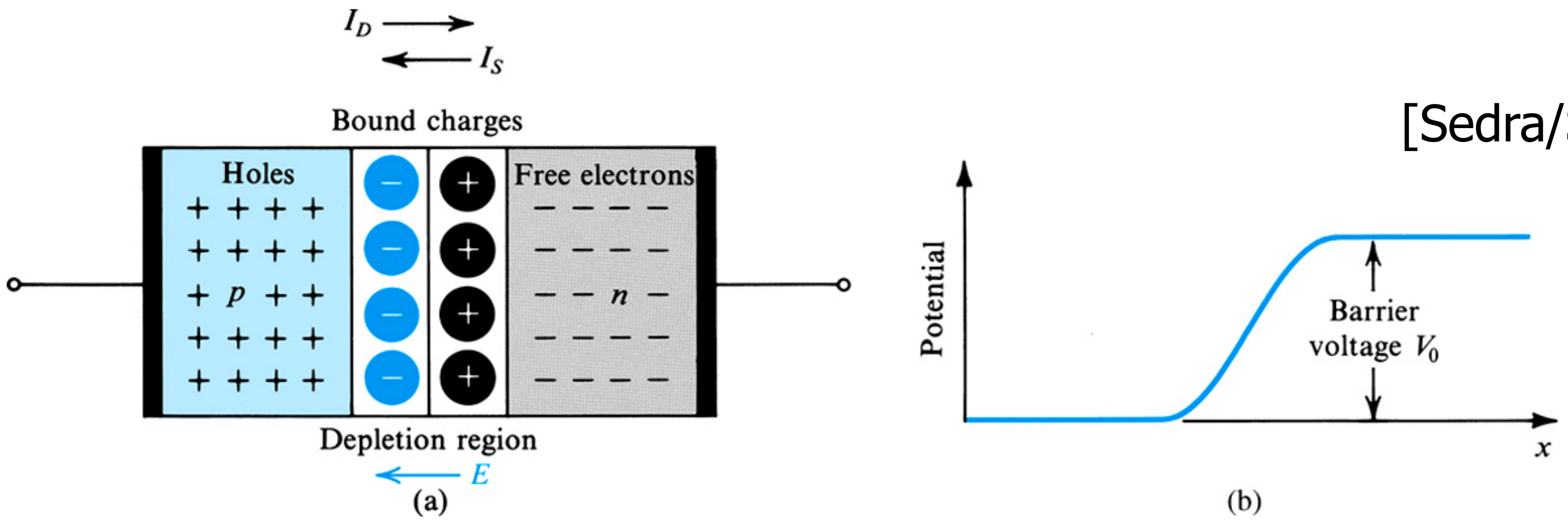
Semiconductors

- A semiconductor is a material whose conductivity lies somewhere between an insulator and a conductor
- Example: Pure or “intrinsic” Silicon (Si) has 4 valence electrons and is not a very good conductor
- A semiconductor’s conductive properties can be changed by “doping” the material with either n-type dopants (Phosphorous) or p-type dopants (Boron)
- A diode is formed at the boundary or junction of a p and n type semiconductor

Semiconductor pn Junction Diode Physical Schematic



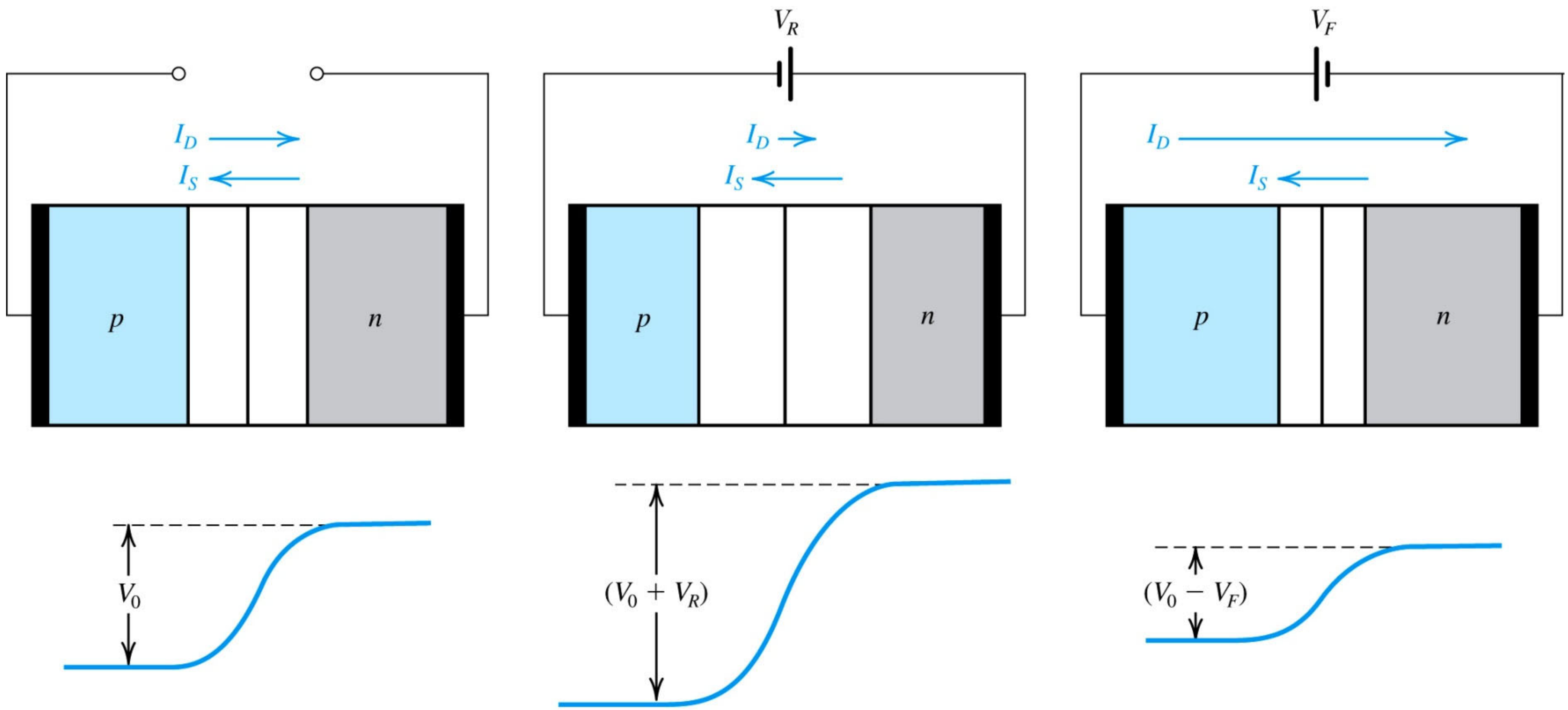
Diffusion, Drift Current, & Barrier Voltage



[Sedra/Smith]

- "Majority-Carrier" Diffusion Current, I_D
  - Caused by majority carriers diffusing into other region
  - Near the junction, holes diffusing into the n-region recombine with free electrons, deplete the carriers close to the junction, and form a positive charged region
  - Similarly, electrons diffusing into the p-region recombine with free holes, deplete the carriers close to the junction, and form a negative charged region
- This charge separation creates a "Barrier Voltage" which limits the diffusion current
- "Minority-Carrier" Drift Current, I_S
  - Caused by thermally generated minority carriers sweeping across the junction due to the E-field

Operation w/ Different Biases



(a) Open-circuit (Equilibrium)

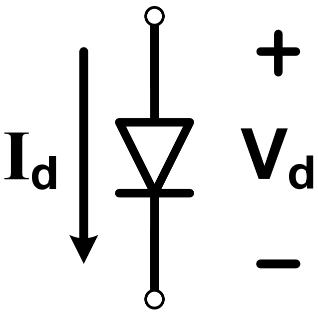
(b) Reverse Bias

(c) Forward Bias

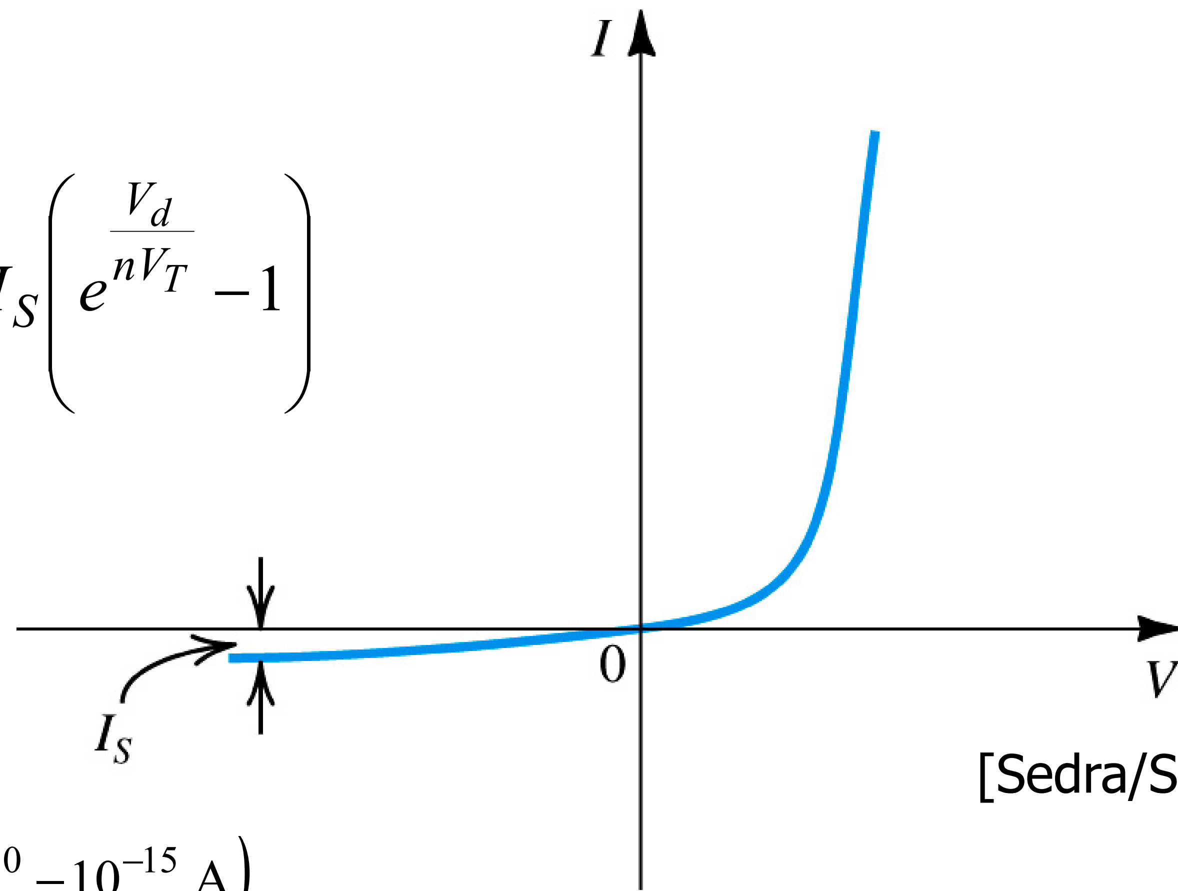
[Sedra/Smith]

- Open Circuit, $I_D = I_S$
- Reverse-Biased, $I_S > I_D$, Weak Minority Carrier Drift Current
- Forward-Biased, $I_D >> I_S$, Strong Majority Carrier Diffusion Current

I-V Characteristic



$$I_d = I_S\left(e^{\frac{V_d}{nV_T}} - 1\right)$$



[Sedra/Smith]

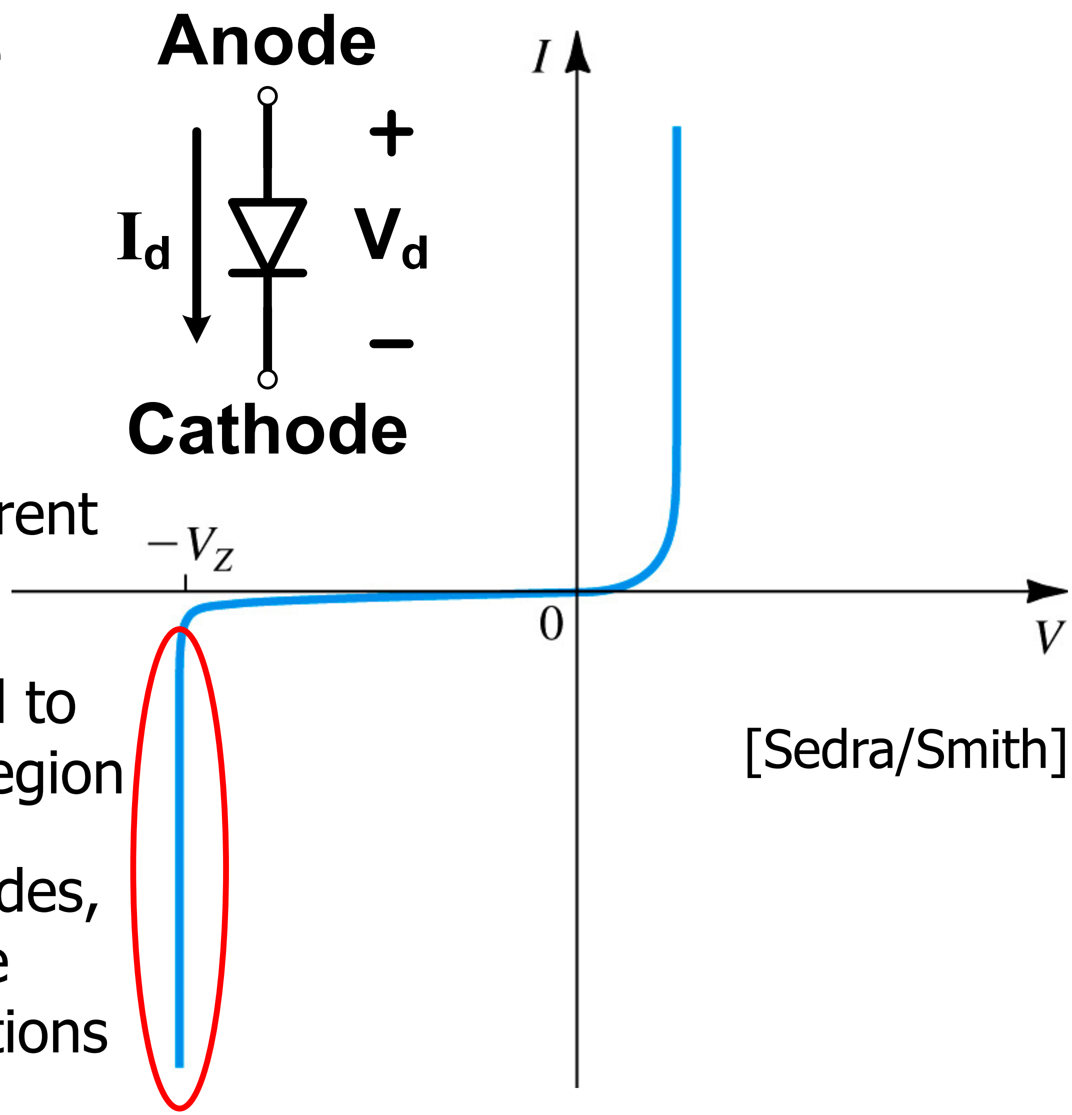
I_S = Saturation Current $\left(10^{-10} - 10^{-15}\ \text{A}\right)$

V_T = Thermal Voltage $= \dfrac{kT}{q} = \left(8.63\times10^{-5}\right)T \Rightarrow 25.9\text{mV at } T = 300K$

n = Ideality Factor $(1 - 2)$, Assume n = 1 if not given

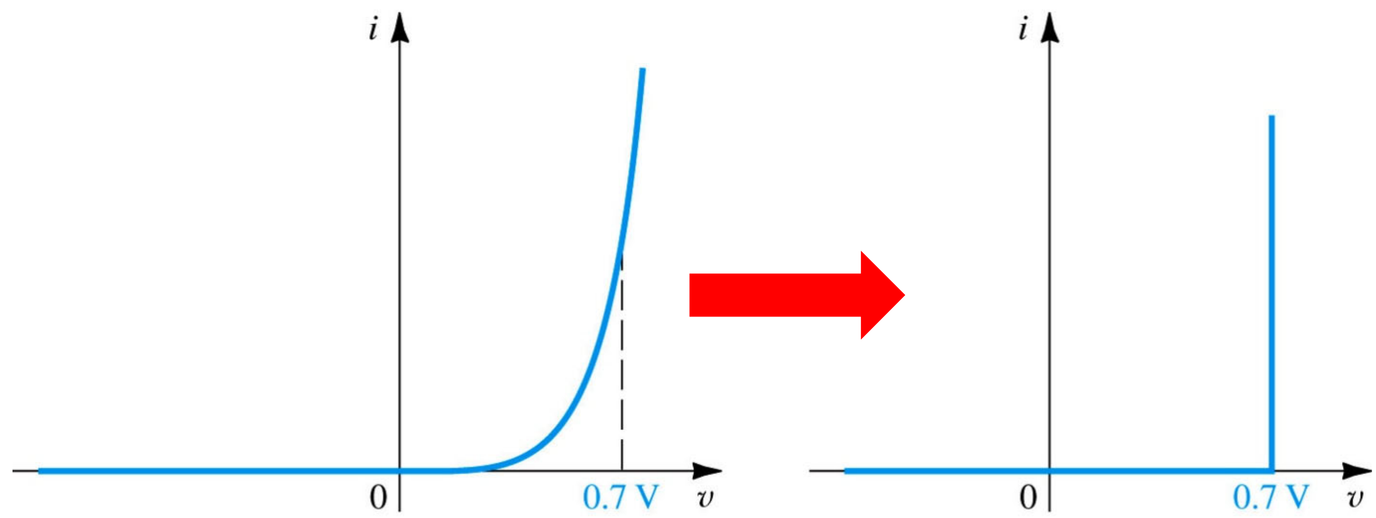
Reverse Breakdown

- For large negative voltages, the previous exponential equation predicts that the reverse bias current should saturate at $-I_S$
- However, with a large negative voltage "-V_Z" the diode "breaks down" and a large negative current exists
- Most diodes should be designed to avoid this reverse-breakdown region
- Special diodes, called Zener diodes, are design to operate in reverse breakdown and used in applications such as voltage regulators

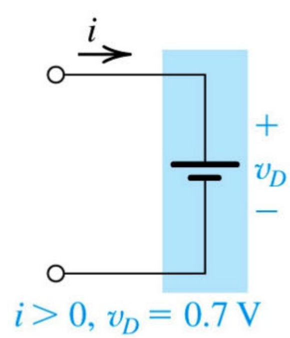


[Sedra/Smith]

Constant-Voltage-Drop Model



(a) (b)



(c)

[Sedra/Smith]

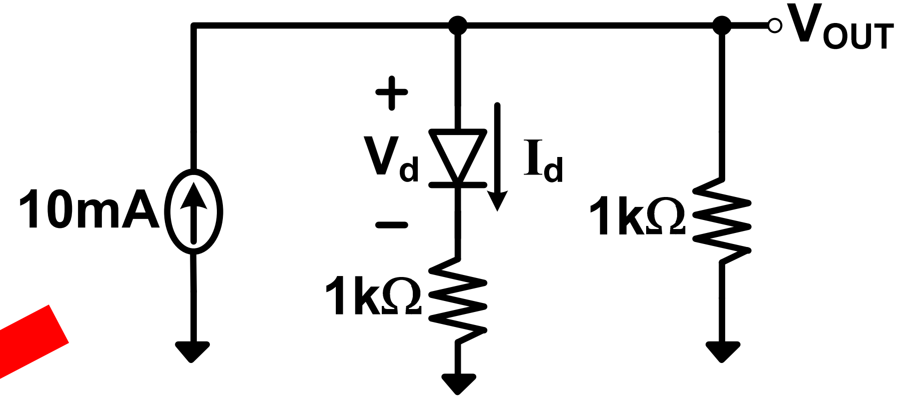
- Used to simplify analysis
- If $V_d < V_{constant} \Rightarrow I_d = 0$
  - (Open Circuit)
- If $V_d > V_{constant} \Rightarrow I_d$ can go to ∞, and V_d clamps at $V_{constant}$
  - (Battery w/ $V_{constant}$ voltage)
- We will assume $V_{constant}$ = 0.7V

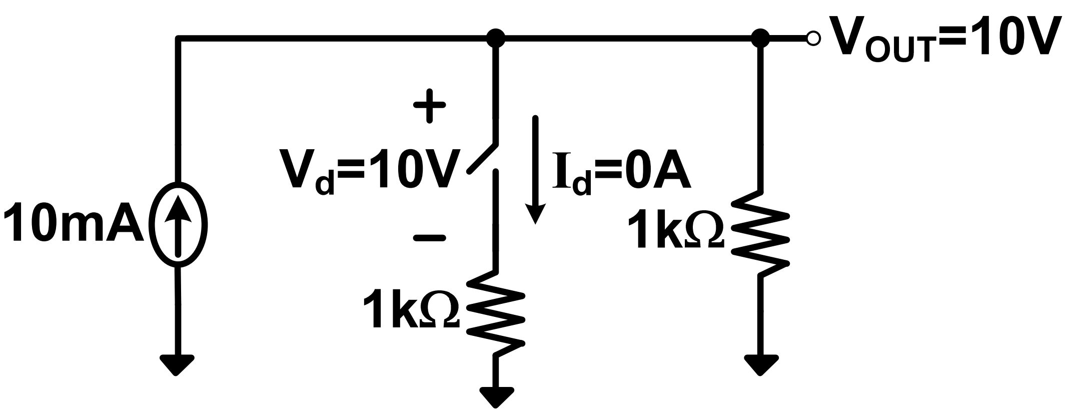
Solving Circuits with Diodes

1. A diode will either be “on” or “off”, resulting in 2 possibilities for each diode in the circuit
2. Assume 1 condition and solve the circuit
3. Check solution for consistency with the diode model
4. If it is consistent, the solution is correct and you are done
5. If not consistent, you need to solve the circuit with another possible condition

Diode Circuit Example #1

- Solve for Vout and Id
- First assume that the diode is "OFF", i.e. an open circuit

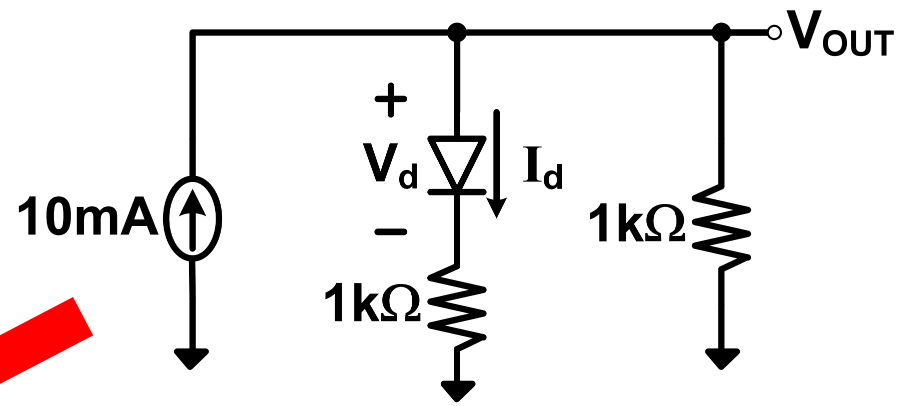


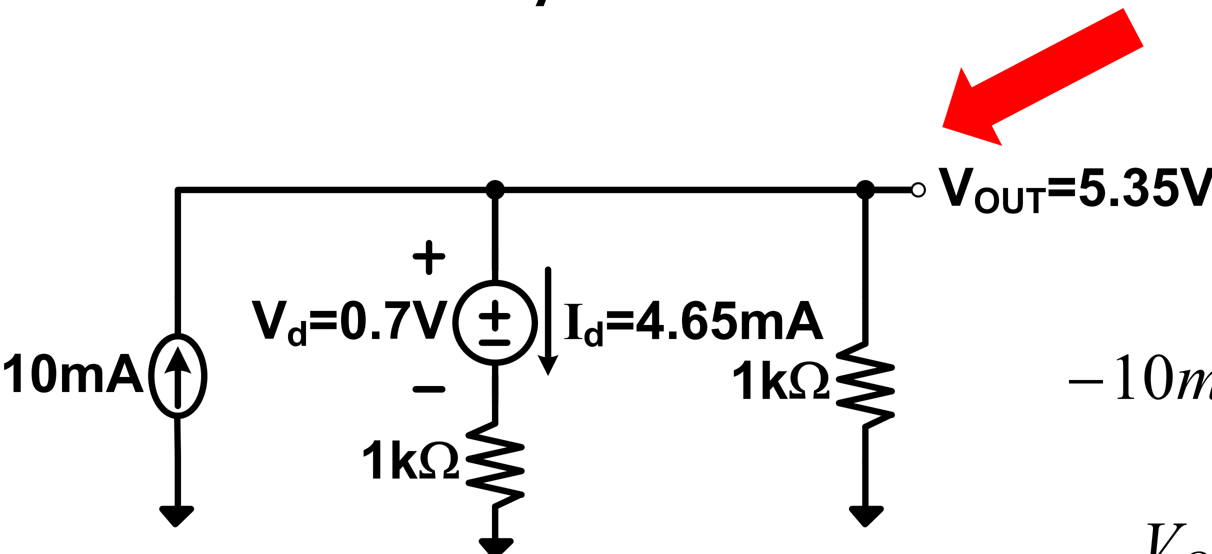


- Are the diode I-V conditions consistent with the constant-voltage-drop model?
- V_d=10V and I_d=0A
- This is not consistent with the diode model!
- We need to try another diode condition

Diode Circuit Example #1 (cont.)

- Now assume that the diode is "ON", i.e. a 0.7V battery





KCL at V_{OUT}

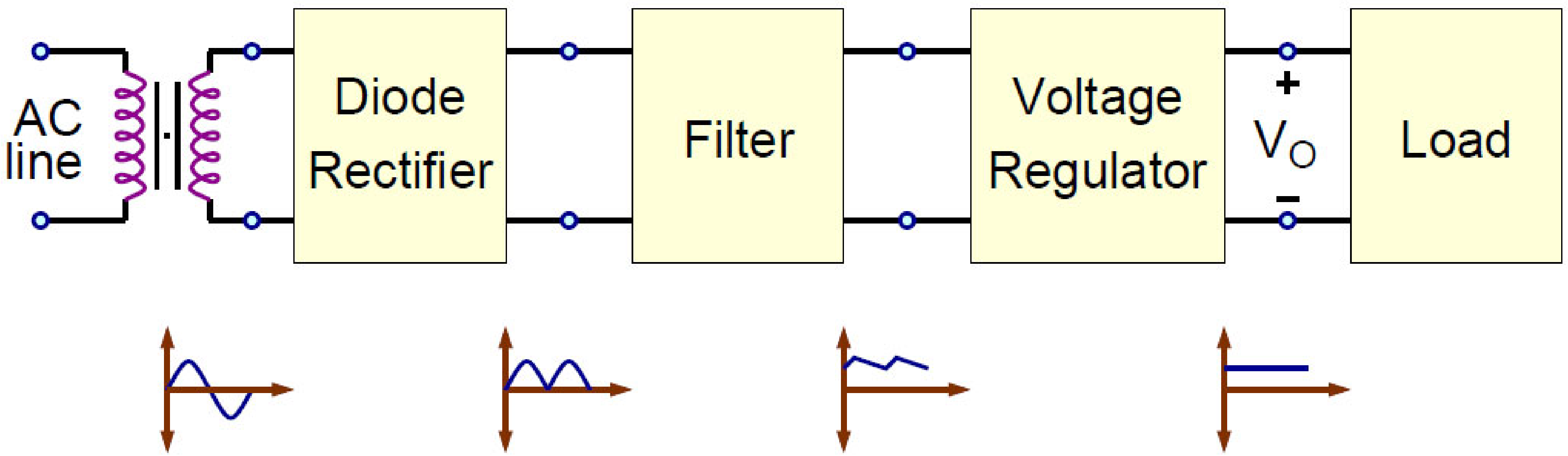
$$-10mA + \frac{V_{OUT} - 0.7V}{1k\Omega} + \frac{V_{OUT}}{1k\Omega} = 0$$

$$V_{OUT} = 5.35V, \;\; I_d = 4.65mA$$

- Now, V_d=0.7V and I_d=4.65mA
- This is consistent with the diode model!
- This is the correct solution

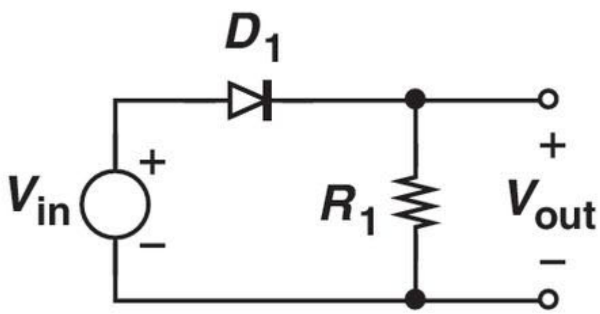
Rectifier Circuits

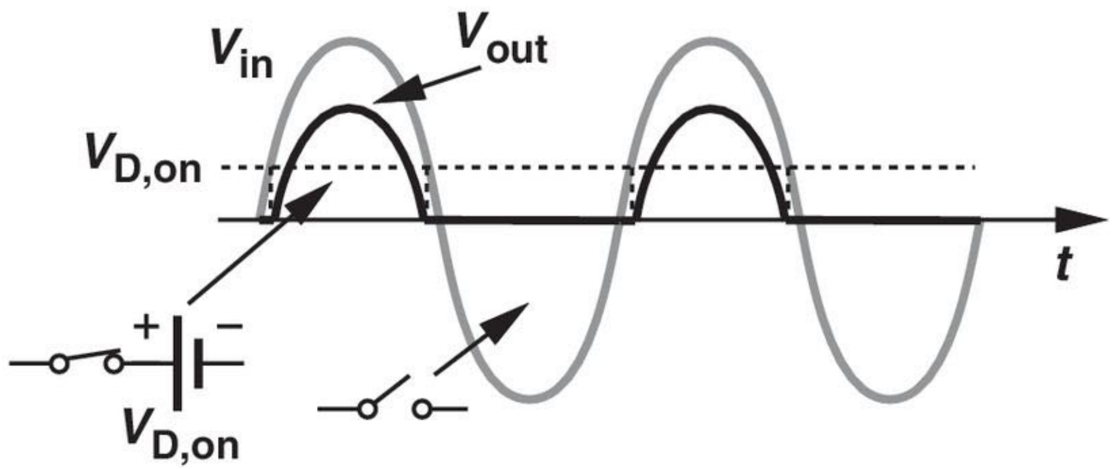
[Karsilayan]



Half-Wave Rectifier

[Razavi]





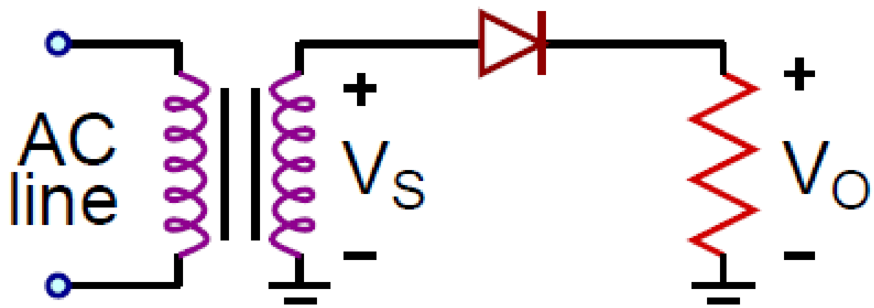
$$\text{For } V_{in} = V_p \sin \omega t$$

$$\text{Peak } V_{out} = V_p - V_{D,on}$$

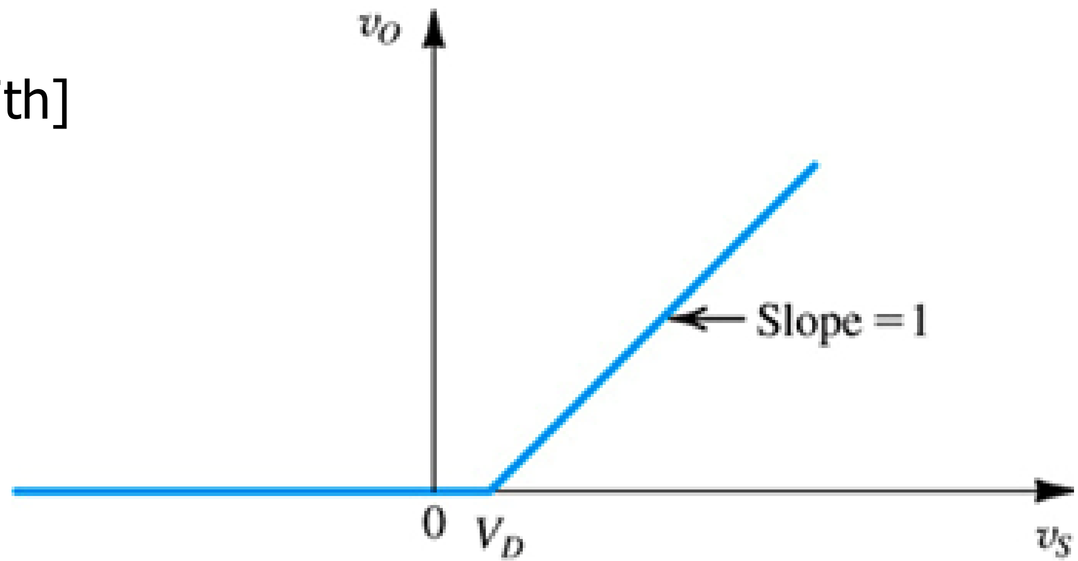
$$\text{Maximum Reverse Voltage} = V_p$$

Half-Wave Rectifier Transfer Characteristic

[Karsilayan]



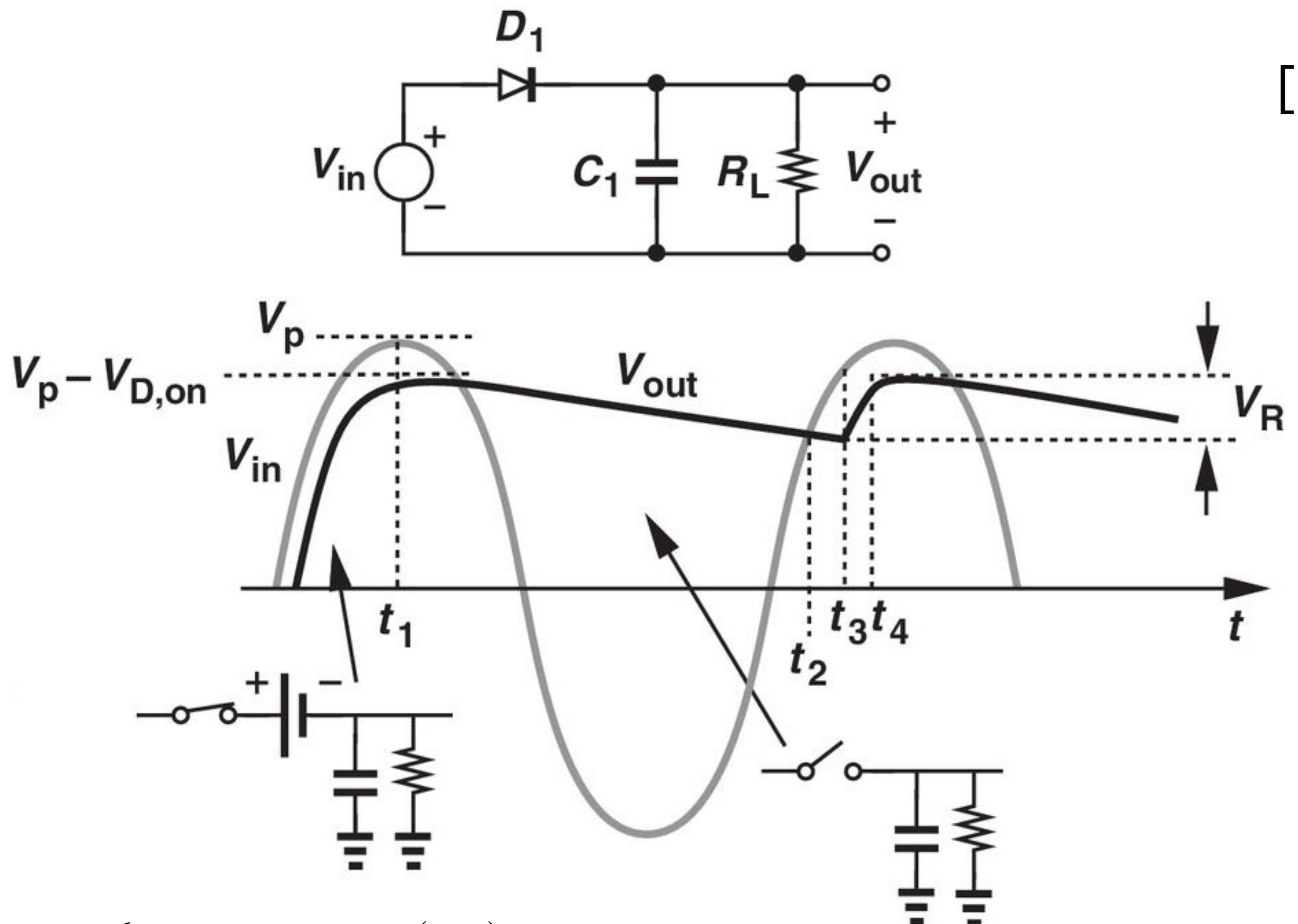
[Sedra/Smith]



- Only rectifies positive half of the input signal
- Lose one diode voltage drop from the peak value

Half-Wave Rectifier w/ a Filter Cap

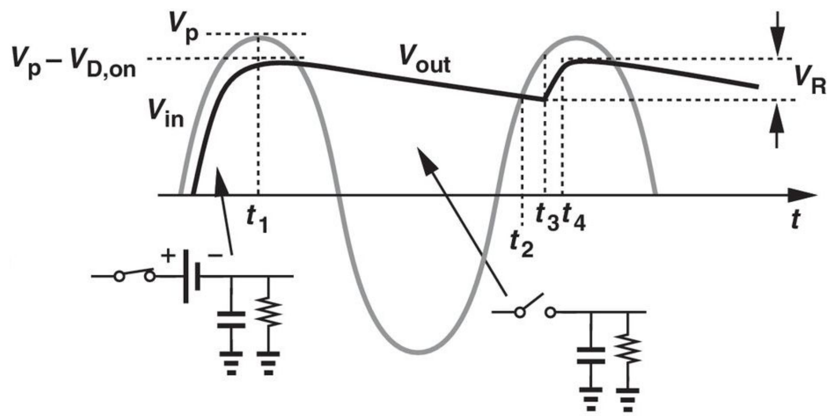
[Razavi]



$$V_{out}(t) = \begin{cases} (V_p - V_{D,on})e^{-\frac{(t-t_1)}{R_1C_L}}, & t_1 < t < t_3 \\ V_{in} - V_{D,on}, & t_3 < t < t_4 \end{cases} \Rightarrow V_{out}(t_3) = (V_p - V_{D,on})e^{-\frac{(t_3-t_1)}{R_1C_L}}$$

$$\text{Maximum Reverse Voltage} \approx 2V_P - V_{D,on}$$

How Much is the Ripple Voltage?



[Razavi]

$$\text{At } t = t_3 \quad V_{out}(t_3) = \left(V_p - V_{D,on}\right) e^{-\frac{(t_3 - t_1)}{R_1 C_L}}$$

For a properly designed filter: $t_3 - t_1 \approx T_{in}$ where T_{in} is the input period

$$V_{out}(t_3) = \left(V_p - V_{D,on}\right) e^{-\frac{T_{in}}{R_1 C_L}}$$

Also $R_1 C_L$ should be $>> T \Rightarrow e^{-\frac{T_{in}}{R_1 C_L}} \approx 1 - \frac{T_{in}}{R_1 C_L}$

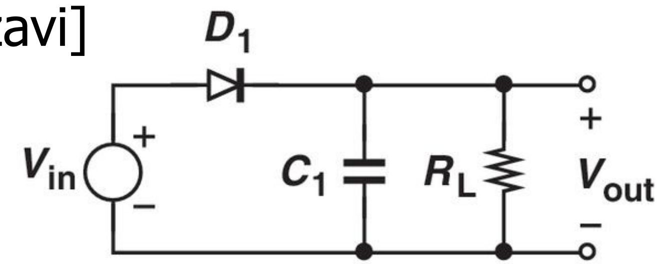
Peak - to - Peak Ripple Voltage

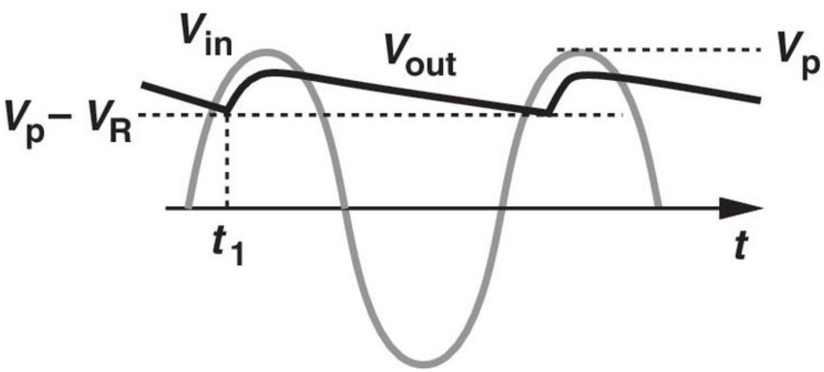
$$V_R \approx \left(V_p - V_{D,on}\right)\left(1 - e^{-\frac{T_{in}}{R_1 C_L}}\right) \approx \left(V_p - V_{D,on}\right)\left(\frac{T_{in}}{R_1 C_L}\right)$$

$$\boxed{V_R \approx \left(V_p - V_{D,on}\right)\left(\frac{T_{in}}{R_1 C_L}\right) = \frac{V_p - V_{D,on}}{R_1 C_L f_{in}}}$$

What is the Peak Diode Current?

[Razavi]





To simplify this analysis, let's assume that $V_{D,on} \approx 0$

$$V_{out}(t_1) = V_P \sin \omega_{in} t_1 = V_P - V_R - V_{D,on} \approx V_P - V_R$$

$$\sin \omega_{in} t_1 = 1 - \frac{V_R}{V_P} \qquad (1)$$

$$I_{D1}(t) = I_{C1} + I_{R1} \approx C_1 \frac{dV_{out}}{dt} + \frac{V_P}{R_L} = C_1 \omega_{in} V_P \cos \omega_{in} t + \frac{V_P}{R_L}$$

This will reach a peak value at $t = t_1$

$$I_p = C_1 \omega_{in} V_P \cos \omega_{in} t_1 + \frac{V_P}{R_L}$$

Using $\cos^2 x + \sin^2 x = 1 \Rightarrow \cos x = \sqrt{1 - \sin^2 x}$ and (1)

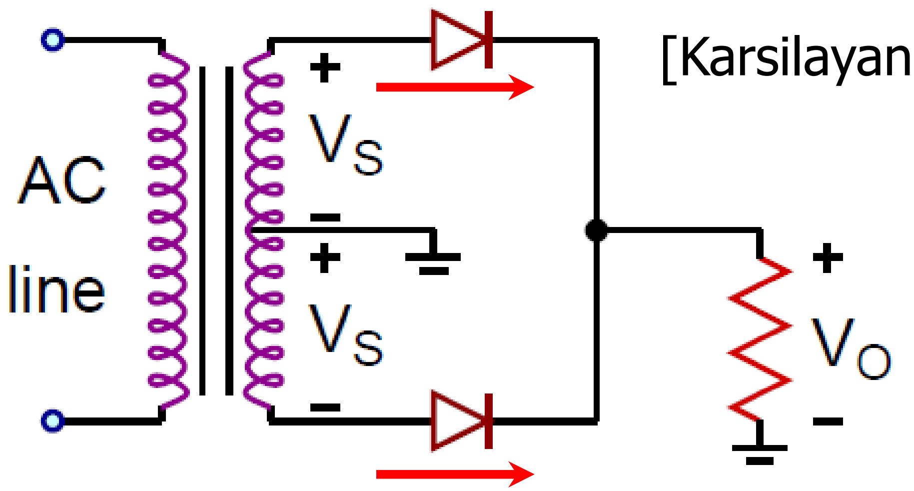
$$I_p = C_1 \omega_{in} V_P \sqrt{1 - \left(1 - \frac{V_R}{V_P}\right)^2} + \frac{V_P}{R_L} = C_1 \omega_{in} V_P \sqrt{\frac{2V_R}{V_P} - \left(\frac{V_R}{V_P}\right)^2} + \frac{V_P}{R_L}$$

$$I_p \approx C_1 \omega_{in} V_P \sqrt{\frac{2V_R}{V_P}} + \frac{V_P}{R_L}$$

- The peak current is proportional to the product of the RC time constant and the input frequency

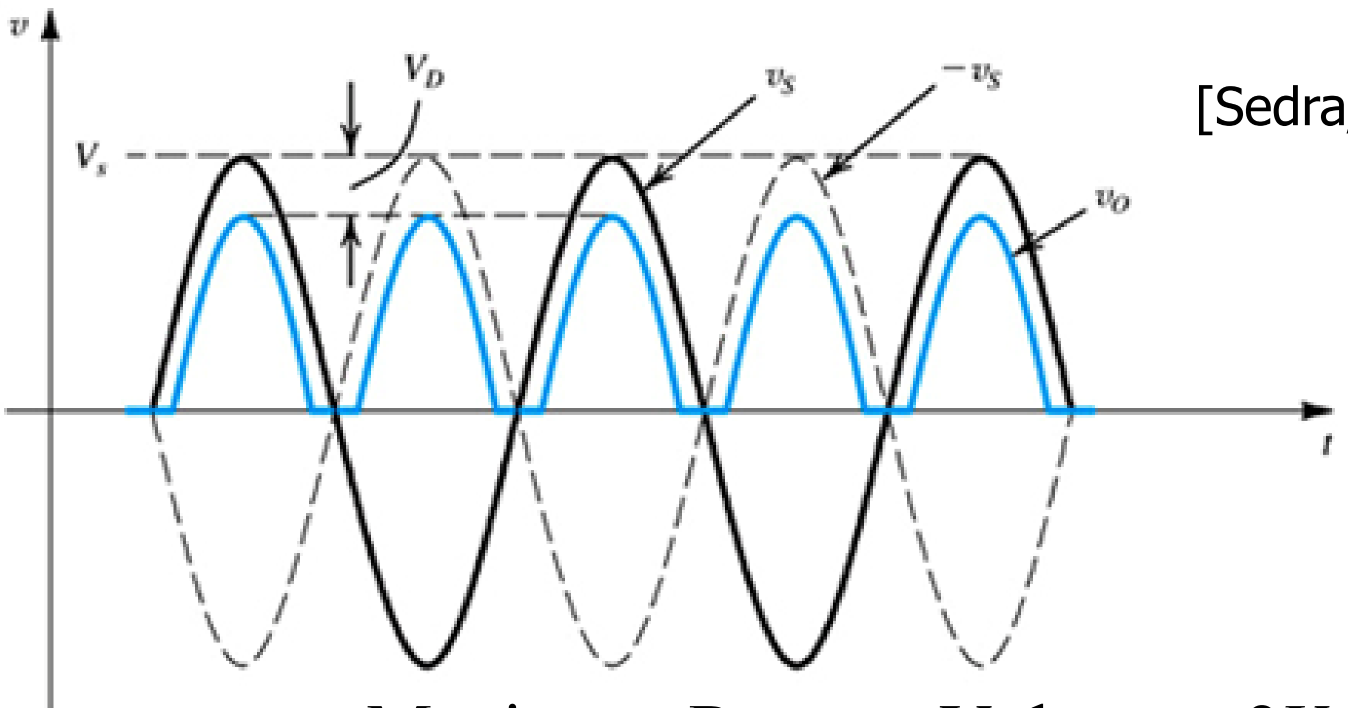
$$I_p = \frac{V_P}{R_L}\left(R_L C_1 \omega_{in} \sqrt{\frac{2V_R}{V_P}} + 1\right)$$

Full-Wave Rectifier



[Karsilayan]

- Positive ½ cycle
  - Top diode on
- Negative ½ cycle
  - Bottom diode on

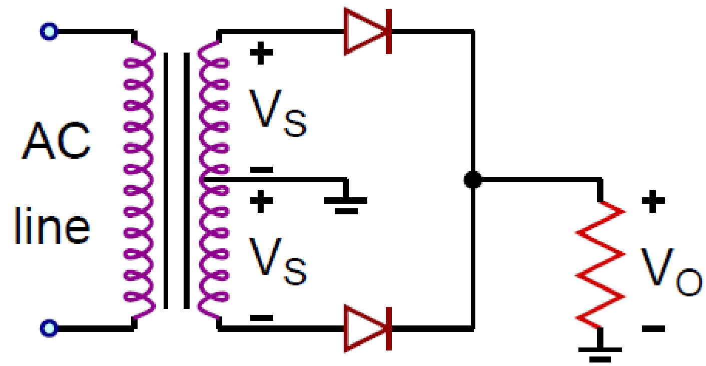


[Sedra/Smith]

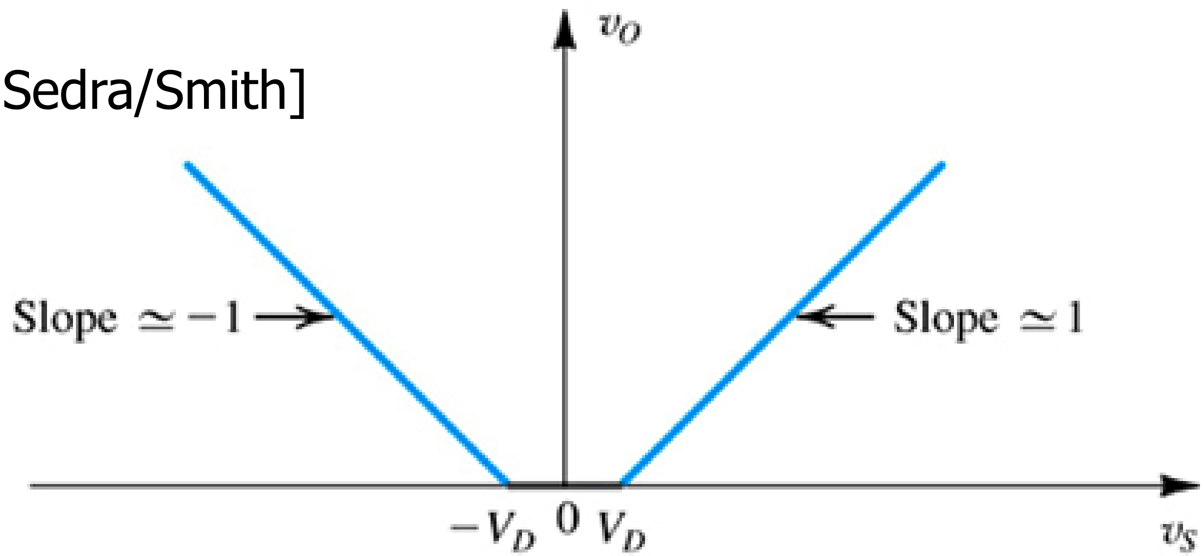
$$\text{Maximum Reverse Voltage} = 2V_P - V_{D,on}$$

Full-Wave Rectifier Transfer Characteristic

[Karsilayan]

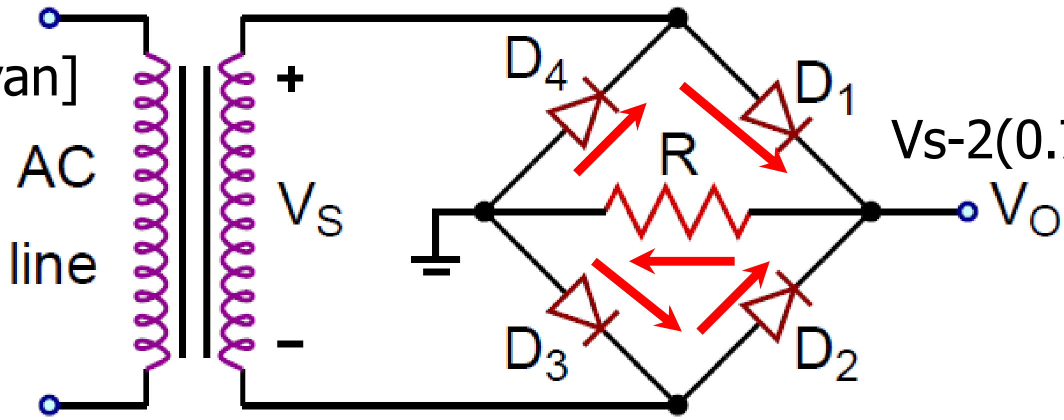


[Sedra/Smith]

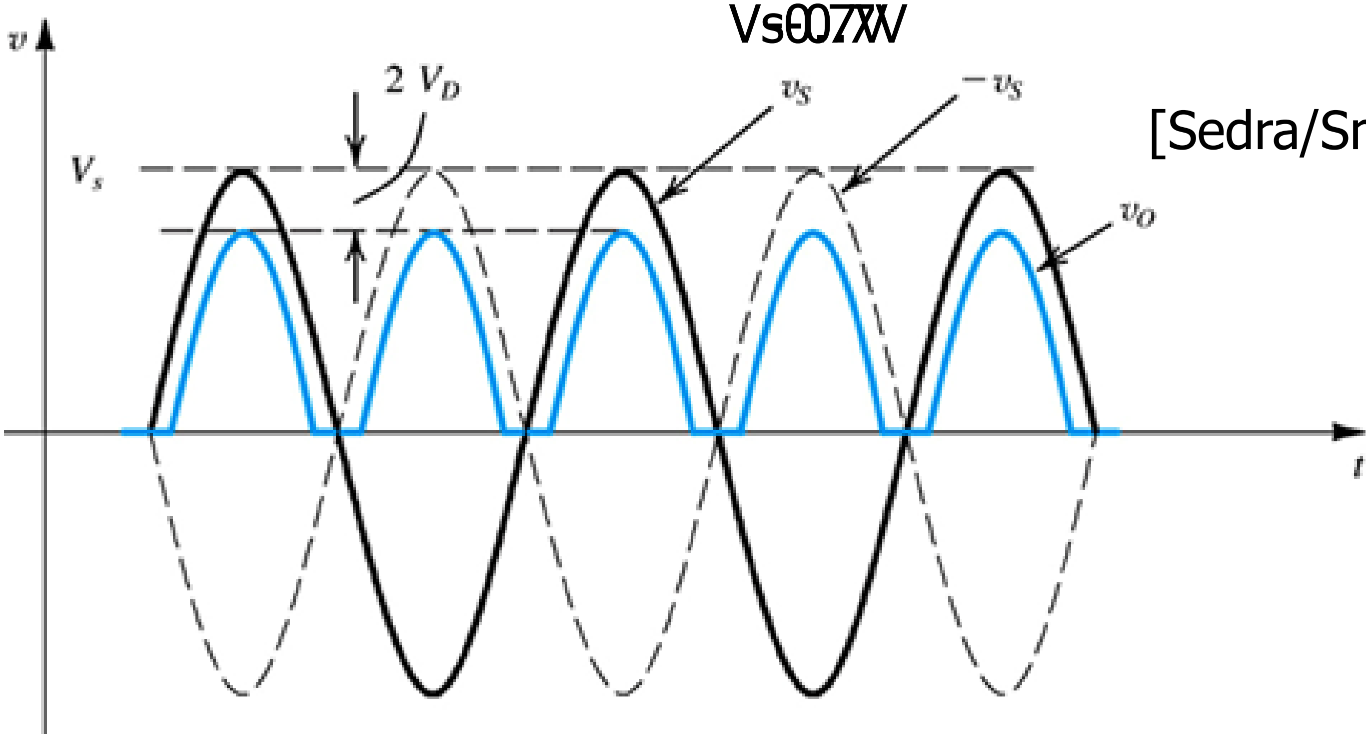


- Rectifies all of the input signal
- Lose one diode voltage drop from the peak value

Bridge Rectifier



- Positive ½ cycle
  - D1 & D3 on
- Negative ½ cycle
  - D2 & D4 on

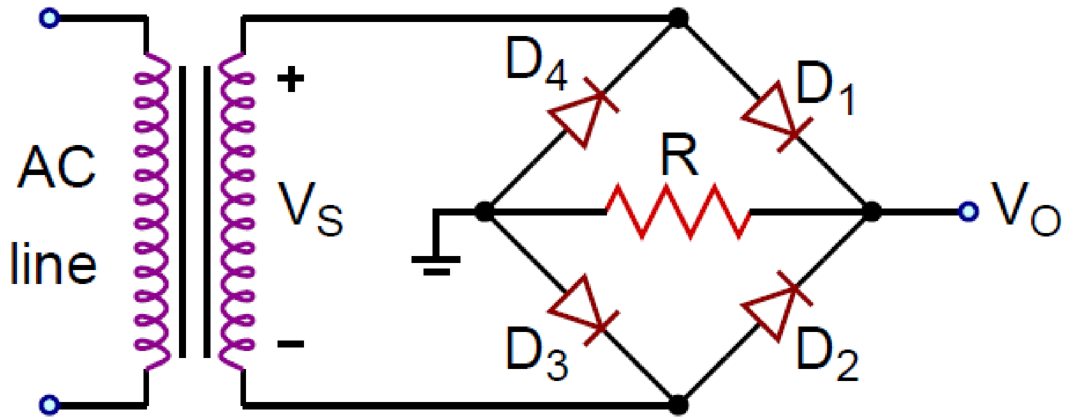


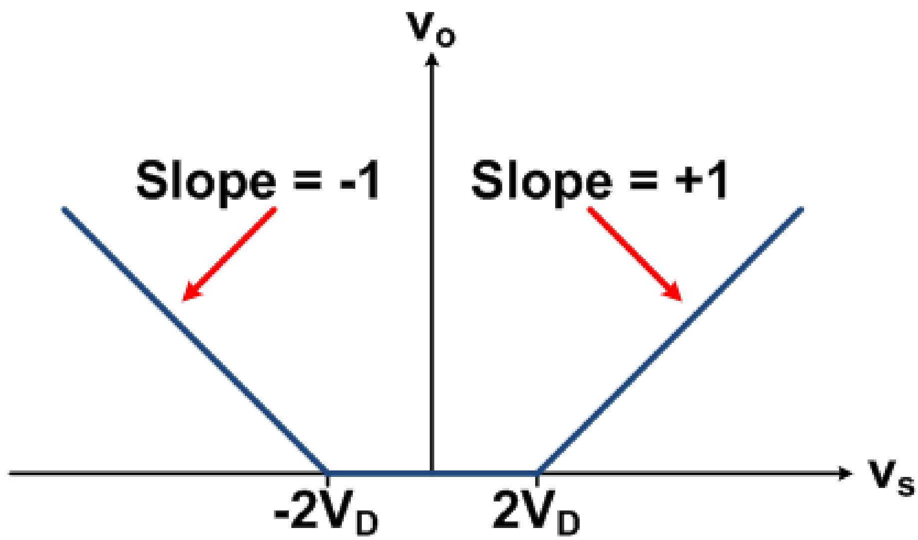
[Sedra/Smith]

$$\text{Maximum Reverse Voltage} = V_P - V_{D,on}$$

Bridge Rectifier Transfer Characteristic

[Karsilayan]

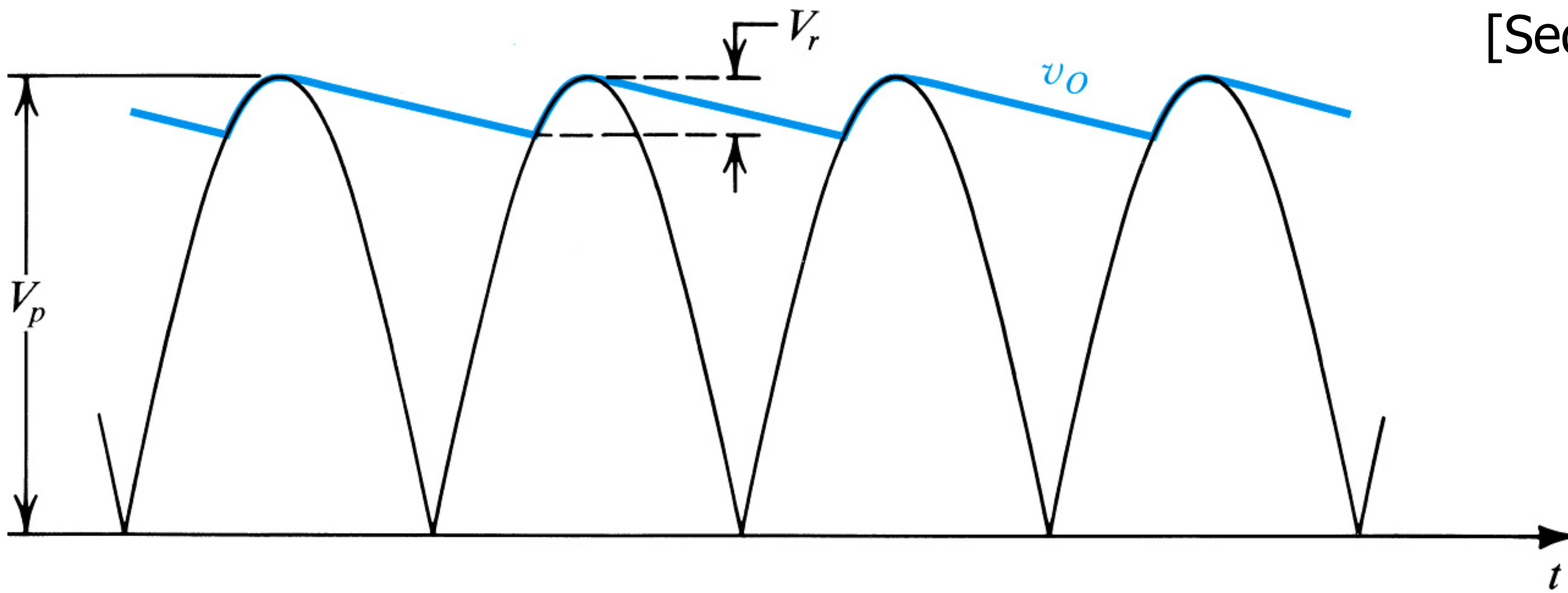




- Rectifies all of the input signal
- Lose two diode voltage drops from the peak value

Full-Wave & Bridge Rectifier w/ a Filter Cap

[Sedra/Smith]



- The capacitor only discharges for T/2
  - Results in ½ Cap size for a given ripple
  - Roughly ½ diode current due to smaller Cap

$$V_R = \frac{V_P - 2V_{D,on}}{2R_L C_1 f_{in}} \qquad I_P = \frac{V_P}{R_L}\left(R_L C_1 \omega_{in}\sqrt{\frac{2V_R}{V_P}} + 1\right)$$

Rectifier Trade-Offs

- Half-Wave Rectifier
  - + Simplest design with fewest components
  - - Requires largest capacitor for a given ripple
- Full-Wave Rectifier
  - + Reduces capacitor size by ½ relative to half-wave
  - - Requires center-tapped transformer
  - - Maximum reverse voltage almost double that of half-wave
- Bridge Rectifier
  - + Reduces capacitor size by ½ relative to half-wave
  - + Save maximum reverse voltage as half-wave rectifier
  - - Lose two diode voltage drops in peak value