ECEN325: Electronics
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Semiconductor pn Junction Diode

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Announcements

• HW4 Due Oct 25
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

Intrinsic Si

p-type Si
doping
(Boron)

n-type Si
doping
(Phosphorous)

Metal contact

Anode

Cathode

[Redacted: Sedra/Smith]
Diffusion, Drift Current, & Barrier Voltage

- **“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

- 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

[Sedra/Smith]
I-V Characteristic

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

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

\[ V_T = \text{Thermal Voltage} = \frac{kT}{q} = \left( 8.63 \times 10^{-5} \right) T \Rightarrow 25.9 \text{mV at } T = 300K \]

\[ n = \text{Ideality Factor (1 - 2), Assume } n = 1 \text{ if not given} \]
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 designed to operate in reverse breakdown and used in applications such as voltage regulators.

[Sedra/Smith]
Constant-Voltage-Drop Model

- Used to simplify analysis
- If $V_d < V_{\text{constant}} \Rightarrow I_d = 0$
  - (Open Circuit)
- If $V_d > V_{\text{constant}} \Rightarrow I_d$ can go to $\infty$, and $V_d$ clamps at $V_{\text{constant}}$
  - (Battery w/ $V_{\text{constant}}$ voltage)
- We will assume $V_{\text{constant}} = 0.7V$
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?
- $V_d=10\text{V}$ and $I_d=0\text{A}$
- 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

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

$V_{OUT}=5.35V$

KCL at $V_{OUT}$

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

$V_{OUT} = 5.35V, I_d = 4.65mA$
Rectifier Circuits

[Karsilayan]
Half-Wave Rectifier

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

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

Maximum Reverse Voltage $= V_p$
Half-Wave Rectifier Transfer Characteristic

• Only rectifies positive half of the input signal
• Lose one diode voltage drop from the peak value
Half-Wave Rectifier w/ a Filter Cap

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

Maximum Reverse Voltage \( \approx 2V_p - V_{D,\text{on}} \)
How Much is the Ripple Voltage?

At \( t = t_3 \) \( V_{out}(t_3) = (V_p - V_{D, on}) e^{\frac{(t_3-t_1)}{R_i C_L}} \)

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

\[ V_{out}(t_3) = (V_p - V_{D, on}) e^{\frac{T_{in}}{R_i C_L}} \]

Also \( R_i C_L \) should be \( >> T \Rightarrow e^{\frac{T_{in}}{R_i C_L}} \approx 1 - \frac{T_{in}}{R_i C_L} \)

Peak - to - Peak Ripple Voltage

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

\[ V_R \approx (V_p - V_{D, on}) \left( \frac{T_{in}}{R_i C_L} \right) = \frac{V_p - V_{D, on}}{R_i C_L f_{in}} \]
What is the Peak Diode Current?

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

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

$$\sin \omega_{\text{in}} t_1 = 1 - \frac{V_R}{V_P}$$

(1)

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

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

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

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

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

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

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

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

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

Maximum Reverse Voltage \( = 2V_P - V_{D,on} \)
Full-Wave Rectifier Transfer Characteristic

- 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

Maximum Reverse Voltage = $V_P - V_{D,on}$
Bridge Rectifier Transfer Characteristic

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

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

\[ V_R = \frac{V_P - 2V_{D,\text{on}}}{2R_LC_1f_{\text{in}}} \]

\[ I_P = \frac{V_P}{R_L}\left(\frac{R_L C_1 \omega_{\text{in}} \sqrt{2V_R \over V_P}}{V_P} + 1\right) \]
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 $\frac{1}{2}$ relative to half-wave
  - - Requires center-tapped transformer
  - - Maximum reverse voltage almost double that of half-wave
- **Bridge Rectifier**
  - + Reduces capacitor size by $\frac{1}{2}$ relative to half-wave
  - + Save maximum reverse voltage as half-wave rectifier
  - - Lose two diode voltage drops in peak value