ECEN325: Electronics
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Semiconductor pn Junction Diode

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Announcements

- HW3 due today
- HW4 due Mar. 10
- Exam 1 Mar. 3
  - Closed-notes, but 1 standard note sheet (front-and-back)
  - Bring your calculator
  - We will have 10 extra minutes, until 9:25AM
- Next week (2/23 – 2/27)
  - No lecture on Tuesday and Thursday
  - Normal Wednesday recitation and lab sessions
Diode Reading

• Diode Applications (Silva)
• Sedra/Smith Text: Ch3 (optional), 4.2, 4.3, 4.5, 4.6
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
Valance electrons
Covalent bonds
Silicon atom
Trivalent impurity atom (acceptor)
Electron accepted from this atom, thus creating a hole

Valence electrons
Covalent bonds
Silicon atoms
doping (Boron)

n-type Si
Valence electrons
Covalent bonds
Silicon atoms
Pentavalent impurity atom (donor)
Free electron donated by impurity atom

Metal contact
Anode
p-type silicon
n-type silicon
Cathode

[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

[Image: Diagram of a diode showing charge distribution and potential profile with a barrier voltage $V_0$.]
Operation w/ Different Biases

- **Open Circuit,** $I_D = I_S$
- **Reverse-Biased,** $I_S > I_D$
- **Forward-Biased,** $I_D >> I_S$

[Sedra/Smith]
I-V Characteristic

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

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

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

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

[Sedra/Smith]
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.
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 $V_{\text{constant}} = 0.7V$

[Image of current-voltage graphs]

[Sedra/Smith]
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 V_{out} and I_d
• 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

\[
V_{d} = 0.7V, \quad I_{d} = 4.65mA
\]

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

\[ PIV = \hat{V}_S \]
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

\[ V_o(t) = \begin{cases} 
  V_s(t) - 0.7V, & t_1 < t < t_2 \\
  V_p e^{-\frac{t}{RC}}, & 0 < t < t_1
\end{cases} \Rightarrow V_o(t_1) = V_p e^{-\frac{t_1}{RC}} \]
How Much is the Ripple Voltage?

For a properly designed filter:

\[
\begin{align*}
t_1 &\approx T \quad \Rightarrow \quad V_O(t_1) \approx V_p \ e^{-\frac{T}{RC}} \\
RC &\gg T \quad \Rightarrow \quad e^{-\frac{T}{RC}} \approx 1 - \frac{T}{RC}
\end{align*}
\]

\[
\Rightarrow \quad V_O(t_1) = V_p \left(1 - \frac{T}{RC}\right)
\]

Peak-to-peak ripple voltage:

\[
V_r = V_p - V_O(t_1) = V_p - V_p \left(1 - \frac{T}{RC}\right) \quad \Rightarrow \quad V_r = V_p \ \frac{T}{RC}
\]
How Much Current Flows Through the Diode?

• First, we need to figure out how long the diode is on, $\Delta t$

\[ V_p \cos(\omega \Delta t) = V_p - V_r \]

$\omega \Delta t$ is small $\Rightarrow \cos(\omega \Delta t) \approx 1 - \frac{1}{2}(\omega \Delta t)^2$

$\Rightarrow \omega \Delta t \approx \sqrt{\frac{2V_r}{V_p}} \Rightarrow \Delta t \approx \frac{T}{2\pi} \sqrt{\frac{2V_r}{V_p}}$
How Much Current Flows Through the Diode?

- The diode current consists of the current to the resistor and the capacitor
  - Approximate the resistor current as constant
  - The capacitor current must replace the lost charge, and is assumed to have a triangular profile

During conduction \((t_1-t_2)\):

\[ Q_{\text{supplied}} = Q_{\text{lost}} \]

\[ I_{Cav}\Delta t = CV_r \]
How Much Current Flows Through the Diode?

Substitute $\Delta t$ in $I_{Cav} \Delta t = CV_r$

$$I_{Cav} \frac{T}{2\pi} \sqrt{\frac{2V_r}{V_p}} = CV_r \Rightarrow I_{Cav} = \frac{2\pi CV_r}{T} \sqrt{\frac{V_p}{2V_r}}$$

$$I_{Dav} = I_R + I_{Cav} = I_R + \frac{2\pi CV_r}{T} \sqrt{\frac{V_p}{2V_r}}$$

$$V_r = V_p \frac{T}{RC}, \quad V_p \approx I_R R \Rightarrow V_r = I_R \frac{T}{C}$$

$$I_{Dav} = I_R + 2\pi I_R \sqrt{\frac{V_p}{2V_r}} = I_R \left( 1 + \pi \sqrt{\frac{2V_p}{V_r}} \right)$$

$$I_{Dmax} = I_R \left( 1 + 2\pi \sqrt{\frac{2V_p}{V_r}} \right) \text{ (assuming a triangular capacitive current profile)}$$
Full-Wave Rectifier

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

\[ PIV = 2\hat{V}_s - 0.7V \]

[Sedra/Smith]
[Karsilayan]
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

\[ PIV = \hat{V}_s - 0.7V \]
Bridge Rectifier Transfer Characteristic

- Rectifies all of the input signal
- Lose two diode voltage drops from the peak value
The capacitor only discharges for $T/2$

- Results in $1/2$ Cap size for a given ripple
- Roughly $1/2$ diode current

\[ V_r = V_p \frac{T}{2R_L C_L} \quad I_{D_{avg}} = I_R \left(1 + \pi \sqrt{\frac{V_p}{2V_r}}\right) \quad I_{D_{max}} = I_R \left(1 + 2\pi \sqrt{\frac{V_p}{2V_r}}\right) \]
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
  - - PIV almost double that of half-wave

- **Bridge Rectifier**
  - + Reduces capacitor size by ½ relative to half-wave
  - + Save PIV as half-wave rectifier
  - - Lose two diode voltage drops in peak value