Review for Final

Main topics
- Diodes
- Semiconductor Physics
- MOSFETS
- BJTs

Diodes

exact IV characteristic

\[ I = I_s [\exp \left( \frac{V}{V_T} \right) - 1] \]

3 models

1) Ideal

2) Constant voltage drop

3) Exponential

4) Small signal

\[ I_d = \frac{V_T}{I_d} \]

\[ I_d \propto \text{slope of IV curve} \]

Zener Diode

model

\[ I_Z \]

\[ V_Z \]

\[ R_Z \]
Rectifiers: Full Wave

Output (constant voltage drop model)

Peak inverse voltage: max reverse bias on $D_2 = V_{st} + V_{out} = 2V_s - V_D$

Rectifiers: Bridge

Peak inverse voltage: $V_0 = V_s - V_D$

max reverse bias = $V_{out} + V_{D2} = V_s - V_D$
Rectifier with filter capacitor

1) Small period of time where
   \( V_{in} \approx V_{out} + 0.7 \)
   Diode on, capacitor charges

2) Most of time diode off
   Capacitor discharge through resistor

\[ \Delta V = V_D \exp \left( -t/R_C \right) \]

* Know differences in FWR vs HWR
  (full wave rectifier vs half wave rectifier)

Semi-conductor Physics

Metal: high conductivity, partially full bands

Insulator: no current, bands full

Semiconductor: sometimes electrical conduction, band filling depends on temp
Carrier concentration (in semiconductor) depends on:

1) Probability state occupied with electron

\[ f(E) = \frac{1}{1 + \exp \left( \frac{E - E_F}{kT} \right)} \]

2) # of states available
\[ g(E) = \text{density of states} \]

Concentration of electrons \( n = \int_{E_L}^{\infty} g(E)f(E) \, dE \)

Intrinsic semiconductor (no doping)
\[ n = p = N_i \quad np = N_i^2 \]

Doped semiconductors to increase # of carriers, must dope w/ impurities
\[ np = N_i^2 \]

If \( N_A \gg N_i \), \( p = N_A \quad n = n_i^2/N_A \)

If \( N_D \gg N_i \), \( n = N_D \quad p = p_i^2/N_D \)

Current in PN Junction: Drift & Diffusion

Drift
\[ Q_d = n q v + p q v \]
\[ v = u E, \quad u = \text{mobility} \]

motion of carriers in response to \( E \) field
\[ Q_d = q \left( n u n + p u p \right) E \]
Diffusion current flow in response to nonuniform carrier concentration

\[ J_{\text{diffusion}} = q_0 D_n \frac{\partial n}{\partial x} - q_0 D_p \frac{\partial p}{\partial x} \]

\[ D_n = \frac{kT}{q_0} \mu_n \]

**PN Junction**

<table>
<thead>
<tr>
<th>No bias</th>
<th>Reverse bias</th>
<th>Forward bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V = 0 )</td>
<td>( V &lt; 0 )</td>
<td>( V &gt; 0 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Junction voltage</th>
<th>( U_{\text{bi}} )</th>
<th>( U_{\text{bi}} + U_A )</th>
<th>( U_{\text{bi}} - U_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>0</td>
<td>Drift</td>
<td>Diffusion</td>
</tr>
<tr>
<td>Depletion width</td>
<td>( w )</td>
<td>( \uparrow w ), ( \downarrow ) capacitance</td>
<td>( \downarrow w ), ( \uparrow ) capacitance</td>
</tr>
<tr>
<td>( E ) field</td>
<td>( \uparrow E )</td>
<td>( E )</td>
<td>( \downarrow E )</td>
</tr>
</tbody>
</table>
\[ U_{bi} = V_T \ln \left( \frac{NA \cdot ND}{n_i^2} \right) \]

\[ I = I_S \left( \exp \left( \frac{V}{V_T} \right) - 1 \right)^2 \]

PN junction charge, \( \varepsilon \) field & voltage

\[
\begin{array}{c|c|c}
\text{NA} & \text{ND} \\
\hline
\text{P} & \text{n} \\
\end{array}
\]

\[
\frac{d\varepsilon}{dx} = \varepsilon_0 \left( N_D(x) - N_A(x) \right)
\]

\[
\frac{dV}{dx} = -\varepsilon(x)
\]

MOSFET

NMOS

N MOS

\[ I_{dd} \]

\[ R \]

\[ G \]

\[ S \]

\[ I_D \]

\[ I_D \]
\[ I_D = \begin{cases} 
0 & \text{if } V_{GS} < V_t \text{ Cutoff} \\
R_n \left[ (V_{GS} - V_t) V_{DS} - V_{DS}^2/2 \right] & \text{if } V_{GS} \geq V_t \text{ and } V_{DS} \leq V_{GS} - V_t \\
\frac{k}{2} \left( V_{GS} - V_t \right)^2 & \text{if } V_{GS} \geq V_t \text{ and } V_{DS} \geq V_{GS} - V_t \text{ Saturation} 
\end{cases} \]

\[ R_n = \mu n C_0 x \frac{W}{L} \]

Finite output resistance in saturation

\[ R_0 = \left[ \frac{\delta I_D}{\delta V_{DS}} \right]^{-1} \left|_{V_{GS} \text{ constant}} \right. = \frac{1}{\lambda I_D} = \frac{V_A}{I_D} \]
\( I_D = \text{current w/o channel length modulation} \)

**Body effect** \( s \rightarrow \text{Body of most negative MOSFET on integrated circuit} \) \( \Rightarrow V_{BS} \)

Small Signal model only valid for saturation!

1. Solve DC problem
2. Solve AC problem with small signal model

**Hybrid T1**

[Diagram of Hybrid T1]

**MOSFET amplifier configurations**

Know how to calculate \( R_{in}, R_0, A_v, \) \( 1/G_v \)

Amplifiers are 2-port systems

[Diagram of 2-port system]
Whatever terminal is common to $v_i/v_o$ gives name of amplifier.

Types
- common source
- common gate
- common drain / source follower

Example: CD or source follower

\[ V_{DD} \]
\[ R_L \]
\[ R_o \]

7.4 Current mirrors

Q1 in saturation
Assume Q2 in saturation

\[ I_2 = \frac{(W/L)_2}{I_{ref}(W/L)_1} \]

If Q1 & Q2 identical
### Bipolar Junction Transistor

**NPN**

\[
\begin{array}{ccc}
E & B & C \\
\hline
N & P & N \\
\end{array}
\]

\[
\begin{array}{l}
I_B \\
I_C \\
I_E \\
\end{array}
\]

**PNP**

\[
\begin{array}{ccc}
E & B & C \\
\hline
P & N & P \\
\end{array}
\]

\[
\begin{array}{l}
I_B \\
I_E \\
I_C \\
\end{array}
\]

---

2 PN junctions to consider:

E/B & C/B

4 Regions of Operation

<table>
<thead>
<tr>
<th>BE</th>
<th>BC</th>
<th>Region of Operation</th>
<th>$V_{BE}$</th>
<th>$V_{CE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>F</td>
<td>saturation</td>
<td>0.7 V</td>
<td>0.2 V (0.3 V for edge of saturation)</td>
</tr>
<tr>
<td>F</td>
<td>R</td>
<td>forward active</td>
<td>0.7 V</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>R</td>
<td>cutoff</td>
<td></td>
<td>i = 0</td>
</tr>
<tr>
<td>R</td>
<td>F</td>
<td>reverse active</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\[ R_0 = \left[ \frac{\Delta I_C}{\Delta U_{CE}} \right]^{-1} \quad r_0 = \frac{V_A}{I_c'} \]

\[ I_c' = \text{collector current w/o Early effect} \]

BJT operation in forward active

1) \( \text{BE} = \) forward biased diode, 
   inject carriers into base (NPN: \( e \) to base)
2) minority carriers diffuse across base
   some recombine \( \Rightarrow \) base \( \alpha \) current
3) most swept by reverse bias into collector
   \( I_C = I_s \exp \left( \frac{V_{BE}}{V_T} \right) \)
\[ I_B = I_c / B \]
\[ I_E = I_c / \alpha \]
\[ I_E = I_B + I_C \]
Saturating mode
2 forward biased junctions that produce current in opposite directions

Test for saturation
1. $U_{BC} > 0.4\,V$ ?
2. $I_c/I_B < B$

$V_{CEO} = 0.2\,V$ (saturation)
$0.3\,V$ (edge of saturation)

Small signal models (valid for active region)

Hybrid $\Pi$

$V_{be} + R_T$

$g_m V_{be}$

$T$ model

$i_B$ or $i_c$

$V_{be}$
Amplifiers (active mode)

Common emitter | Common base | Emitter follower

R_in, R_o, A_v, G_v

Note differences between BJT (i_b > 0) & MOSFET (i_g = 0)

BJT high frequency model