Lecture 21

Bipolar Junction Transistors (BJT): Part 5
Hand Example, SPICE Example, and Limits on output swing imposed by having to stay within Forward Active Mode

Reading:
Notes
An Example that puts it all together!

Consider an Integrated Circuit npn BJT with:
Emitter Doping, $N_{DE}=7.5 \times 10^{18} \text{ cm}^{-3}$
Base Doping, $N_{AB}=10 \times 10^{17} \text{ cm}^{-3}$
Collector Doping, $N_{DC}=1.5 \times 10^{16} \text{ cm}^{-3}$
Substrate doping $N_{Sub}=5 \times 10^{15} \text{ cm}^{-3}$
Minority Carrier Diffusion coefficient in the emitter, $D_{pE-\text{(holes)}}=5 \text{ cm}^{2}/\text{s}$
Minority Carrier Diffusion coefficient in the base, $D_{nB-\text{(electrons)}}=10 \text{ cm}^{2}/\text{s}$
Base Quasi-neutral width, $W=300 \text{ nm}$
Minority Carrier Diffusion length in the emitter, $L_E=250 \text{ nm}$
Minority Carrier Diffusion length in the base, $L_B=100 \text{ um}$
Areas:
$A_{\text{emitter-base}} = 25 \text{ um}^{2}$, $A_{\text{collector-base}} = 100 \text{ um}^{2}$, $A_{\text{substrate-collector}} = 500 \text{ um}^{2}$
Resistances and Early Voltage: $r_b = 250 \Omega$, $r_c = 200 \Omega$, $r_{ex} = 5 \Omega$, $V_A = 35 \text{ V}$

Find the complete small- signal model for:
$I_C = 100 \text{ mA}$, $V_{CE} = 2 \text{ V}$, and $V_{CS} = 2 \text{ V}$ and $V_{be} = 0.5 V_{\text{bi}}$ For the emitter-base
An Example that puts it all together!

First recognize that $W << L_B$ so we can use the simplest form of the transport parameters.

Next, recognize that our choice of generic labeling allows us to use the equations developed for the pnp transistor here even though you were given a npn transistor.

\[
\beta_{DC} = \frac{1}{D_E W N_B + 1} \left( \frac{W}{L_B} \right)^2 \Rightarrow \frac{D_B L_E N_E}{D_E W N_B} = \frac{\alpha_{DC}}{1 - \alpha_{DC}} = 125
\]

\[
\alpha_{DC} = \frac{1}{1 + \frac{D_E W N_B}{D_B L_E N_E} + \frac{1}{2} \left( \frac{W}{L_B} \right)^2} \Rightarrow \frac{1}{1 + \frac{D_E W N_B}{D_B L_E N_E}} = \frac{\beta_{DC}}{1 + \beta_{DC}} = 0.992
\]

Note: The formulas here were derived in the optional material but are not considered optional.
An Example that puts it all together!

Transconductance:

\[ g_m = y_{21} = \frac{I_C}{V_T} = 3.86 \, mS \]

Input Resistance:

\[ r_\pi = \frac{1}{y_{11}} = \frac{\beta_o V_T}{I_C} = \frac{\beta_o}{g_m} = 32.4 \, k\Omega \]

Output Resistance:

\[ r_o = \frac{1}{y_{22}} = \frac{V_A + V_{CE}}{I_C} = 370 \, k\Omega \]

or using the approximate solution,

\[ r_o = \frac{1}{y_{22}} \approx \frac{V_A}{I_C} = 350 \, k\Omega, \quad (\text{still a large value}) \]
An Example that puts it all together!

Forward Base Transport Time:

\[ \tau_F = \frac{W^2}{2D_B} = 45 \text{ pS} \]

Watch the units!

Maximum base transport limited operational frequency ~ 3.5 GHz!

Base-Emitter Diffusion Capacitance:

\[ C_B = g_m \tau_F = 173 \text{ fF} \quad C_\pi = C_B + C_{jE} \]
An Example that puts it all together!

**General Zero-Bias Depletion Capacitance:**

\[
C_{j?o} = \frac{C_{j?o}}{\sqrt{1 + \frac{V_{bi}}{V_{bi} for that junction}}} \\
\text{where,} \\
\begin{align*}
\{ & \text{C}_{j?o} \equiv \text{zero bias depletion capacitance} \\
V_{bi} \text{ for that junction} & \equiv \text{built in voltage for the E \text – B junction} \\
\}
\end{align*}
\]

\[
C_{j?o} = C_{\text{junction}} \bigg|_{V_A=0} = A \sqrt{\frac{qK_S\varepsilon_o}{2}} \frac{N_A N_D}{(N_A + N_D) (V_{bi})} \frac{1}{V_{bi}} \\
V_{bi} = \frac{kT}{q} \ln \left[ \frac{N_A N_D}{n_i^2} \right]
\]

<table>
<thead>
<tr>
<th>Junction</th>
<th>V_{Bi}</th>
<th>Area (cm^2)</th>
<th>C_{j?o} fF</th>
<th>Applied Voltage</th>
<th>C_{j?o} fF</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-B</td>
<td>0.947</td>
<td>2.50E-07</td>
<td>23.335</td>
<td>-0.473</td>
<td>33.000</td>
</tr>
<tr>
<td>B-C</td>
<td>0.786</td>
<td>1.00E-06</td>
<td>37.248</td>
<td>2.000</td>
<td>19.782</td>
</tr>
<tr>
<td>C-Substrate</td>
<td>0.768</td>
<td>5.00E-06</td>
<td>177.201</td>
<td>2.000</td>
<td>93.332</td>
</tr>
</tbody>
</table>

Thus,

\[
C_{\pi} = C_B + C_{jE} = 206 \text{ fF} \\
C_{\mu} = 19.8 \text{ fF} \\
C_{CS} = 93.3 \text{ fF}
\]
SPICE BJT Modeling

SPICE models capacitors slightly different than we have discussed.

Consider for example the Base-Collector capacitance:

\[ C_\mu = \frac{C_{JC}}{\left(1 - \frac{V_{BC}}{V_{JC}}\right)^{MJC}} \]

where,
\[ \begin{align*}
C_{JC} & \equiv \text{zero bias depletion capacitance} \\
V_{JC} & \equiv \text{built in voltage for the B–C junction} \\
MJC & \equiv \text{B–C exponential factor related to the doping profile}
\end{align*} \]

Note the negative sign here
# SPICE BJT Modeling

## Most Common Model Parameters

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>PSPICE Name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Transport saturation current (I_S)</em></td>
<td>IS</td>
<td>A</td>
</tr>
<tr>
<td>Ideal maximum forward bias beta (β_F)</td>
<td>BF</td>
<td>-</td>
</tr>
<tr>
<td>Forward Early voltage (V_A)</td>
<td>VAF</td>
<td>V</td>
</tr>
<tr>
<td>Ideal maximum reverse bias beta (β_R)</td>
<td>BR</td>
<td>-</td>
</tr>
<tr>
<td>Base resistance (r_b)</td>
<td>RB</td>
<td>Ω</td>
</tr>
<tr>
<td>Emitter resistance (r_ex)</td>
<td>RE</td>
<td>Ω</td>
</tr>
<tr>
<td>Collector resistance (r_c)</td>
<td>RC</td>
<td>Ω</td>
</tr>
<tr>
<td>B- E zero- bias depletion capacitance (C_{jE0})</td>
<td>CJE</td>
<td>F</td>
</tr>
<tr>
<td>B- E built- in potential (V_{bi} or φ_{BE})</td>
<td>VJE</td>
<td>V</td>
</tr>
<tr>
<td>B- E junction exponential factor</td>
<td>MJE</td>
<td>-</td>
</tr>
<tr>
<td>B- C zero- bias depletion capacitance (C_{jC0})</td>
<td>CJC</td>
<td>F</td>
</tr>
<tr>
<td>B- C built- in potential (V_{bi} or φ_{BC})</td>
<td>VJC</td>
<td>V</td>
</tr>
<tr>
<td>B- C junction exponential factor</td>
<td>MJC</td>
<td>-</td>
</tr>
<tr>
<td>Substrate zero- bias depletion capacitance (C_{CS0})</td>
<td>CJS</td>
<td>F</td>
</tr>
<tr>
<td>Substrate built- in potential (V_{bi} or φ_{BS})</td>
<td>VJS</td>
<td>V</td>
</tr>
<tr>
<td>Substrate junction exponential factor</td>
<td>MJS</td>
<td>-</td>
</tr>
<tr>
<td>Ideal forward transit time (τ_F)</td>
<td>TF</td>
<td>seconds</td>
</tr>
</tbody>
</table>

*The Transport saturation current (I_S) results from the simplified model which assumes forward active operation. This can optionally be replaced with the Ebers-Moll parameters:*

- Base-collector leakage saturation current (I_{R0α_R})  | ISC         | A       |
- Base-emitter leakage saturation current (I_{F0α_F})   | ISE         | A       |
- Substrate-collector leakage saturation current         | ISS         | A       |
In class example: Simulate this circuit using $V_s = 1$ mV and determine the voltage gain via a transient analysis, and an AC analysis.

What happens to the gain when $C_3$ is removed? Why?

What happens when you do a transient analysis using $V_{inAC} = 1 \mu$V and when $V_{inAc} = 1$ V? Why is there a difference?
What sets the Maximum Limits of operation of the BJT Circuit?

Forward active mode lies between saturation and cutoff. Thus, the maximum voltage extremes that one can operate an amplifier over can easily be found by examining the **boundaries between forward active and cutoff** and ....

\[ V_{C_{\text{max}}} = + \text{Supply} \]
\[ V_{E_{\text{min}}} = - \text{Supply/Gnd} \]
What sets the Maximum Limits of operation of the BJT Circuit?

... and the *boundaries between forward active and saturation*

\[ V_{C\text{ min}} = +0.7 \, \text{V} \]

\[ V_{CB} = 0 \, \text{V} \quad V_{CE} = 0.7 \, \text{V} \]

\[ V_{BE} = 0.7 \]
What sets the Maximum Limits of operation of the BJT Circuit?

Putting the two limits together...

\[ V_{C\text{ max}} = +\, \text{Supply} \]

Output signals that exceed the voltage range that would keep the transistor within its Forward active mode will result in “clipping” of the signal leading to distortion. (Example: “Distortion found in loud Rock Music” - Heavy Metal)

*Unclipped Signal*

\[ V_{C\ @\text{DC}} \]

*Clipped Signal at Active-Saturation boundary*

\[ V_{C\ min} = +\, 0.7 \, \text{V} \]

*Clipped Signal at both Active-Saturation and Active-Cutoff boundary*

The maximum voltage swing allowed without clipping depends on your choice of DC bias points.