Lecture 17: Bipolar Junction Transistors (BJTs) II

- Announcements:
  - HW#6 online soon and due Friday Oct. 12 via Gradescope
  - Lab#4 will be online soon and its prelab is due next week (as is Lab#3)
  - By popular demand, lab sections run this week
  - Midterm 1: Friday, Oct. 5, from 5-6:30 p.m., in 277 Cory
  - Midterm Info Sheet online with updates from what we discussed last week
  - Department has the list of those needing access to 125 Cory - hopefully, they act on it

- Lecture Topics:
  - BJT Forward-Active Region
    - Physics
    - Large Signal Circuit Model
    - Operating Pt. Example
  - Reverse Active Region
  - Saturation Region

- Last Time:
  - Finished MOS physics (for now)
Regions of BJT Operation

<table>
<thead>
<tr>
<th>EBJ</th>
<th>CBJ</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>R</td>
<td>Cutoff (both diodes off)</td>
<td>widely used in analog amplifiers</td>
</tr>
<tr>
<td>F</td>
<td>R</td>
<td>Forward Active</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>F</td>
<td>Reverse Active</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>Saturation</td>
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</tbody>
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⇒ Or graphically:

- npn
  - Reverse Active
  - Saturation
  - Cut-off

- npn
  - Reverse Active
  - Saturation
  - Cut-off

⇒ BOTH diodes reverse-biased

⇒ No current flows:

- $i_B = 0$, $i_C = 0$, $i_E = 0$
BEJ Forward-Biased:

1. Get diffusion current as in diode
2. Forward-biasing of a BJT → three current components:
   - Electron injection from emitter to base:
     \[ I_{EB} = A J_{N_{EB}} \]
   - Hole injection from base to emitter:
     \[ I_{P_{PE}} = A J_{P_{PE}} \]
   - Recombination of e⁻⁻ and h⁺⁺ in the base:
     \[ I_{Re} \sim \exp \left( \frac{N_{BE}}{N_{V_{T}}} \right) \]

3. Currents:
   - Collector current:
     \[ I_C = I_{EB} = \frac{1}{1} \]
   - Emitter current:
     \[ I_E = I_{EB} + I_{P_{PE}} + I_{Re} = 1 + 2 + 3 \]
   - Base current:
     \[ I_B = I_{P_{PE}} + I_{Re} = 2 + 3 \]
**Current Formulations**

1. \( I_{NB} = -A \int_{NB} \frac{\partial n_{PB}(x)}{\partial x} dx \)

   - Diffusion constant
   - Slope of minority carrier concentration in base

\[ n_{PB}(x) \approx 0 \]

\[ n_{PB}(0) = \frac{n_i^2}{N_{aB}} \exp \left( \frac{V_{BE}}{V_T} \right) \]

\[ I_{NB} = qA D_{NB} \frac{n_i^2}{N_{aB} W_B} \exp \left( \frac{V_{BE}}{V_T} \right) \]

\[ i_C = 0 = I_S \exp \left( \frac{V_{BE}}{V_T} \right) \]

2. \( I_{PE} = A \int_{PE} \frac{d^2 n_{PB}}{dx^2} dx \)

   - Diffusion constant
   - Slope of emitter

\[ I_{PE} = qA D_{PE} \left[ P_{CE}(0) - P_{CE}(-WE) \right] \]

\[ P_{CE}(x) \rightarrow \text{from large emitter} \]

\[ P_{CE}(0) \rightarrow \text{passing large emitter} \]

\[ P_{CE}(-WE) \rightarrow \text{passing large emitter} \]

3. \( I_{P(E)} = \frac{qA D_{PE} n_i^2}{N_{aB} W_B} \exp \left( \frac{V_{BE}}{V_T} \right) \)

   - Minority carrier charge in base

\[ I_{P(E)} = \frac{qA D_{PE} n_i^2}{N_{aB} W_B} \exp \left( \frac{V_{BE}}{V_T} \right) \]

Define: Forward Current Gain \( \beta_F \)

\[ \beta_F = \frac{i_C}{i_B} = \frac{1}{3} + \frac{qA D_{NE} n_i^2}{N_{aB} W_B} \left[ \frac{1}{2} n_{PB}(0) W_B qA \right] \]

\[ \beta_F = \left[ \frac{W_B}{2 \tau_b D_{PB}} + \frac{D_{PE} W_B N_{aB}}{D_{PB} W_E N_{aE}} \right]^{-1} \]
To maximize $V_E$, want:

1. $W_E$ is small
2. $N_{pe} \gg N_{eb} \rightarrow D_{pe} \ll D_{ne}$
3. $T_b = \text{large} \rightarrow \text{base Si should be free of impurity/doped to prevent recombination of } e^- \text{ and } h^+$

This is why emitter is not impurity/doped.

So, $\beta \neq \frac{i_B}{i_C}$. How about $i_C \neq i_E$?

$$i_C = i_B + i_C = \frac{i_C}{\beta} + i_C = \left(1 + \frac{1}{\beta}\right) i_C$$

$$i_E = \left(\frac{1}{1 + \beta}\right)i_E = \left(\frac{\alpha}{1-\alpha}\right)i_E = \beta i_E = i_C$$

where $\frac{\beta}{\beta + 1} \Rightarrow \beta = \frac{\alpha}{1 - \alpha}$

If $\beta$ is large, $\alpha \approx 1 \Rightarrow i_C \approx i_E$
Example. (Exactitude)

\[
V_{cc} = +15 \quad \text{Find the DC operating pt.}
\]

\[
\begin{align*}
\text{(i.e., find the DC voltages at} \quad \\
\text{each node and the currents} \quad \\
\text{through each branch)}
\end{align*}
\]

\[
\begin{align*}
I_E &= \frac{V_{BE} - V_{EE}}{R_E} \\
I_C &= \alpha I_E = \frac{\alpha (V_{RE} V_{BE})}{R_E}
\end{align*}
\]