Lecture 18: Bipolar Junction Transistors (BJTs) II

- Announcements:
  - HW#6 online and due Friday via Gradescope
    - Slight change to problem 2a and 2b to make things easier
    - Basically, 2b no longer asks for Cgs with the device in the saturation region; we can do this later when we discuss small-signal C
  - Lab#3 prelab due next week
  - Lab#3 experimental part due the week of 10/19

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

- Last Time:
  - Going through BJT physics
  - Now, continue with this …
Bipolar Junction Transistors II

**BEJ Forward-Biased:**

- Get diffusion current as in diode

  \[ I_{BE} = A J_{diff} \]

- Forward-biasing of a BJT \( \rightarrow \) three current components:

  1. **E**'s injected from emitter to base:
     \[ I_{EB} = -A J_{diff} \]

  2. **H**'s injected from base to emitter:
     \[ I_{PE} = -A J_{diff} \]

  3. Recombination of **E**'s \& **H**'s in the base
     \[ I_{RB} \propto \exp \left( \frac{N_{BE}}{VT} \right) \]

- \[ I_C = I_{EB} + \]
- \[ I_E = I_{EB} + I_{PE} + I_{RB} = 1 + 2 + 3 \]
- \[ I_B = I_{PE} + I_{RB} = 2 + 3 \]

**Diffusion Current:**

\[ I_{EB} = -A J_{diff} = -A q p_{nB} \frac{d p_{nB}}{dx} \]

**Cross-sectional Area:**

\[ = -2A p_{nB} \frac{\left( N_{BE} \right) \cdot \left( N_{BE} \right)}{W_B} \]
Current Formulations

1. \( I_{NB} = -A J_{NB} = -A q D_{NB} \frac{dN_{PB}(x)}{dx} \)

   - Diffusion constant
   - Slope of minority carriers
   - \( e^{-x} \) in base
   - Concentration

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

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

\[ I_{NB} = qA D_{NB} \frac{n_i^2}{N_{PB} W_B} \exp \left( \frac{V_{PB}}{V_T} \right) = 1 \]

\[ i_C = 1 = I_s \exp \left( \frac{V_{BE}}{V_T} \right) \]

2. \( I_{PE} = A J_{PE} = qA D_{PE} \frac{dP_{PE}(x)}{dx} \)

   - Diffusion constant
   - Slope
   - \( e^{-x} \) in emitter

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

\[ I_{PE} = qA D_{PE} \frac{n_i^2}{N_{PB} W_E} \exp \left( \frac{V_{PE}}{V_T} \right) = 2 \]

\[ I_{PE}(-W_E) = 0 \]

3. \( I_{RB} = \frac{q \tau_b}{N_{PB} W_B} \exp \left( \frac{V_{PB}}{V_T} \right) \)

   - Minority carrier charge in the base

\[ \tau_b = \frac{1}{q \tau_b} \left[ \frac{1}{2} n_{PB}(0) W_B q A \right] \]

Define Forward Current Gain \( \beta_F \)

\[ \beta_F = \frac{i_C}{i_B} = \frac{1}{1 + 2} = \frac{qA D_{NB} n_i^2}{N_{PB} W_B} \]

\[ \beta_F = \frac{W_B^2}{2 \tau_B D_{NB} + \frac{D_{PE} W_B N_{PB}}{W_E N_{DE}}} \]

\[ \beta_F = \left[ \frac{W_B^2}{2 \tau_B D_{NB} + \frac{D_{PE} W_B N_{PB}}{W_E N_{DE}}} \right]^{-1} \]

\[ \text{in log dB} \]
To maximize $\beta_E$, want:

1. $W_E$ = Small
2. $N_{DE} >> N_{AB}$ leads to $D_{PE} << D_{NE}$
3. $T_b$ = large → bare Si should be free of impurities/diffusion to prevent recombination of $e^-$ and $h^+$

This is why emitter is npn.

So $\beta$ relates $i_b$ to $i_c$.

$\beta$ = control variable, want to control $i_c$.

$\Delta N_{ab}$ small to $\Delta N_{ic}$ large.

So how do we relate $i_c$ and $i_e$?

$$i_c = I_c \frac{1 + \beta}{\beta} = \frac{i_e}{\frac{\alpha}{1 + \beta}}$$

Where $\alpha = \frac{\beta}{1 + \beta}$

$$\beta = \frac{\alpha}{1 - \alpha}$$

If $\beta$ is large, $\alpha \approx 1$, $\approx i_c \approx i_e$

---

Equiv. Large-Signal Ckt. Models for BJTs (in Forward-Active)

-> Several of them → two most popular ones:

- Common-Base (ccs)
  - $i_b = I_C \exp(-\frac{N_{BE}}{V_T})$
  - $i_c = I_C \frac{1 + \beta}{\beta} = \frac{i_e}{\frac{\alpha}{1 + \beta}}$

- Common-Emitter (ccs)
  - $i_c = I_C \frac{1 + \beta}{\beta} = \frac{i_e}{\frac{\alpha}{1 + \beta}}$

All quite close $\approx 0.7V$
Usually we use the above complicated models, but when we use this: (for Forward Active BJT)

For npn:

For pnp:

= the dual of npn
= good exercise: redo this model but for pnp.