Lecture #18

ANNOUNCEMENTS

• Lowest quiz score will be dropped for each student
• No Discussion and Office Hours next week
• Design Project will be posted online tomorrow

OUTLINE

The Bipolar Junction Transistor
  – Gummel numbers
  – Charge-control model
  – Base transit time

Current Formulas for NPN BJT

Long Emitter and Long Collector:

\[ I_E = qA \left( \frac{D_e}{L_e} p_E + \frac{D_a}{L_a} n_{B0} \frac{\cosh(W/L_a)}{\sinh(W/L_a)} \right) e^{\frac{V_{BE}}{kT}} - 1 - \left( \frac{D_e}{L_e} n_{B0} \frac{1}{\sinh(W/L_a)} \right) e^{\frac{V_{AC}}{kT}} - 1 \]

\[ I_C = qA \left( \frac{D_a}{L_a} n_{B0} \frac{1}{\sinh(W/L_a)} \right) e^{\frac{V_{AC}}{kT}} - 1 - \left( \frac{D_e}{L_e} p_C + \frac{D_a}{L_a} n_{B0} \frac{\cosh(W/L_a)}{\sinh(W/L_a)} \right) e^{\frac{V_{AC}}{kT}} - 1 \]

Short Emitter and Short Collector:

\[ I_E = qA \left( \frac{D_e}{L_e} p_E + \frac{D_a}{L_a} n_{B0} \frac{\cosh(W/L_a)}{\sinh(W/L_a)} \right) e^{\frac{V_{BE}}{kT}} - 1 - \left( \frac{D_e}{L_e} n_{B0} \frac{1}{\sinh(W/L_a)} \right) e^{\frac{V_{AC}}{kT}} - 1 \]

\[ I_C = qA \left( \frac{D_a}{L_a} n_{B0} \frac{1}{\sinh(W/L_a)} \right) e^{\frac{V_{AC}}{kT}} - 1 - \left( \frac{D_e}{L_e} p_C + \frac{D_a}{L_a} n_{B0} \frac{\cosh(W/L_a)}{\sinh(W/L_a)} \right) e^{\frac{V_{AC}}{kT}} - 1 \]
Review: BJT Breakdown Mechanisms

- In the common-emitter configuration, for high output voltage $V_{CE}$, the output current $I_C$ will increase rapidly due to one of two mechanisms:
  - punch-through
  - avalanche

Review: Punch-Through

E-B and E-B depletion regions in the base touch, so that $W = 0$

As $|V_{CB}|$ increases, the potential barrier to hole injection decreases and therefore $I_C$ increases.
Review: Avalanche

- Holes are injected into the base, then collected by the B-C junction
  - Some holes in the B-C depletion region have enough energy to generate EHP [1]
  - The generated electrons are swept into the base [3], then injected into the emitter [4]
  - Each injected electron results in the injection of \( I_{Ep}/I_{En} \) holes from the emitter into the base [0]

\[ \frac{I_{Ep}}{I_{En}} + 1 > \beta_{dc} \]

For each EHP created in the C-B depletion region by impact ionization, \( I_{Ep}/I_{En} + 1 > \beta_{dc} \) additional holes flow into the collector

\[ V_{CE0} = \frac{V_{CB0}}{(\beta_{dc} + 1)^{1/m}} \]

where \( V_{CB0} \) = reverse breakdown voltage of the C-B junction

\[ 2 \leq m \leq 6 \]

Base Gummel Number

Base Gummel number:

\[ G_B \equiv \int_0^w \frac{n_i^2}{N_B} \frac{N_B}{D_B} dx \]

= total integrated base dopant dose (atoms/cm\(^2\)) divided by \( D_B \)

For a uniformly doped base with negligible band-gap narrowing,

\[ G_B = \frac{N_B W}{D_B} \]

\[ I_C \approx \frac{q n_i^2 A}{G_B} \left( e^{q V_{CE}/kT} - 1 \right) \]
Emitter Gummel Number w/ Poly-Si Emitter

Emitter Gummel number \( G_E \equiv \int_0^{W_E} \left( \frac{n_i^2}{n_{iE}^2} \frac{N_E}{D_E} dx + \frac{n_i^2}{n_{iE}^2} \frac{N_E}{D_E} (-W_E') \right) \)

where \( S_p = D_{E_{\text{poly}}}/W_{E_{\text{poly}}} \) is the surface recombination velocity

For a uniformly doped emitter,

\[
G_E = N_E \frac{n_i^2}{n_{iE}^2} \left( \frac{W_E'}{D_E} + \frac{1}{S_p} \right)
\]

\[
I_B \equiv \frac{qn_i^2 A}{G_E} \left( e^{qV_B/kT} - 1 \right)
\]

Charge Control Model

A PNP BJT biased in the forward-active mode will have excess minority-carrier charge \( Q_B \) stored in the quasi-neutral base:

\[
\Delta p_B(x,t) = \Delta p_B(0,t) \left( 1 - \frac{x}{W} \right)
\]

\[
Q_B = qA \int_0^W \Delta p_B(x,t) dx = \frac{qAW\Delta p_B(0,t)}{2}
\]

\[
\frac{dQ_B}{dt} = i_B - \frac{Q_B}{\tau_B}
\]
Base Transit Time $\tau_t$

$$Q_B = qA \int_0^W \Delta p_B(x,t) \, dx = \frac{qAW\Delta p_B(0,t)}{2}$$

$$i_c = -qAD_B \frac{\partial \Delta p_B(x,t)}{\partial x} \bigg|_{x=W} = \frac{qAD_B \Delta p_B(0,t)}{W} = \frac{Q_B}{W^2 / 2D_B} = \frac{Q_B}{\tau_t}$$

$$\tau_t = \frac{W^2}{2D_B}$$

- time required for minority carriers to diffuse across the base
- sets the switching speed limit of the transistor

Relationship between $\tau_t$ and $\tau_B$

$$\tau_B \equiv \beta_{dc} \tau_t$$
Drift Transistor: Built-in Base Field

The base transit time can be reduced by building into the base a drift field that aids the flow of electrons.

- Fixed $E_{gB}$, $N_B$ decreases from emitter end to collector end.

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\[
\frac{\partial}{\partial x} = \frac{1}{q} \frac{dE_C}{dx}
\]