Lecture #16

OUTLINE

The Bipolar Junction Transistor

- Narrow-emitter and/or narrow-collector
- Ebers-Moll model
- Base-width modulation, Early voltage

Reading: Chapter 11.2

Narrow-Emitter and Narrow-Collector

$$I_{En} = qA \tfrac{D_E}{L_E} n_{E0} \frac{\cosh(W_E'/L_E)}{\sinh(W_E'/L_E)} (e^{qV_{EB}/kT} - 1)$$

$$I_{Cn} = -qA \tfrac{D_C}{L_C} n_{C0} \frac{\cosh(W_C'/L_C)}{\sinh(W_C'/L_C)} (e^{qV_{CB}/kT} - 1)$$

$$I_E = qA\left[\left(\tfrac{D_E}{W_E'} n_{E0} + \tfrac{D_B}{L_B} p_{B0} \tfrac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)(e^{qV_{EB}/kT} - 1) - \left(\tfrac{D_B}{L_B} p_{B0} \tfrac{1}{\sinh(W/L_B)}\right)\left(e^{qV_{CB}/kT} - 1\right)\right]$$

$$I_C = qA\left[\left(\tfrac{D_B}{L_B} p_{B0} \tfrac{1}{\sinh(W/L_B)}\right)(e^{qV_{EB}/kT} - 1) - \left(\tfrac{D_C}{W_C'} n_{C0} + \tfrac{D_B}{L_B} p_{B0} \tfrac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)\left(e^{qV_{CB}/kT} - 1\right)\right]$$

Performance Parameters (revisited)

$$\gamma = \frac{1}{1 + \frac{n_{iE}^{2}}{n_{iB}^{2}} \frac{D_E}{D_B} \frac{N_B}{N_E} \frac{W}{L_E}}$$

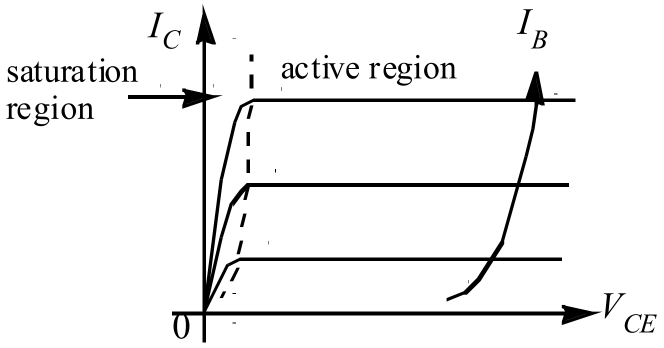
← Replace with W_E' if short emitter

$$\alpha_T = \frac{1}{1 + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

$$\alpha_{dc} = \frac{1}{1 + \frac{n_{iE}^{2}}{n_{iB}^{2}} \frac{D_E}{D_B} \frac{N_B}{N_E} \frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

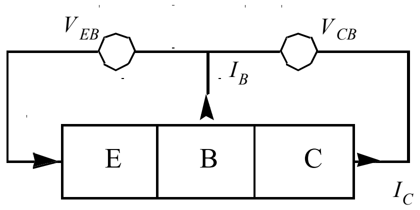
$$\beta_{dc} = \frac{1}{\frac{n_{iE}^{2}}{n_{iB}^{2}} \frac{D_E}{D_B} \frac{N_B}{N_E} \frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

Ebers-Moll Model



The Ebers-Moll model is a **large-signal** equivalent circuit which describes both the active and saturation regions of BJT operation.

I_C is driven by two forces, V_{EB} and V_{CB}.



If only V_{EB} is applied (V_{CB} = 0):

$$I_E = I_{F0}(e^{qV_{EB}/kT} - 1)$$
$$I_C = \alpha_F I_{F0}(e^{qV_{EB}/kT} - 1)$$
$$I_B = (1-\alpha_F)I_{F0}(e^{qV_{EB}/kT} - 1)$$

α_R : reverse common base gain
α_F : forward common base gain

If only V_{CB} is applied (V_{EB} = 0): :

$$I_C = -I_{R0}(e^{qV_{CB}/kT} - 1)$$
$$I_E = -\alpha_R I_{R0}(e^{qV_{CB}/kT} - 1)$$
$$I_B = I_{R0}(1-\alpha_R)(e^{qV_{CB}/kT} - 1)$$

In the general case, both V_{EB} and V_{CB} are non-zero:

$$I_C = \alpha_F I_{F0}(e^{qV_{EB}/kT} - 1) - I_{R0}(e^{qV_{CB}/kT} - 1)$$

I_C: C-B diode current + fraction of E-B diode current that makes it to the C-B junction

$$I_E = I_{F0}(e^{qV_{EB}/kT} - 1) - \alpha_R I_{R0}(e^{qV_{CB}/kT} - 1)$$

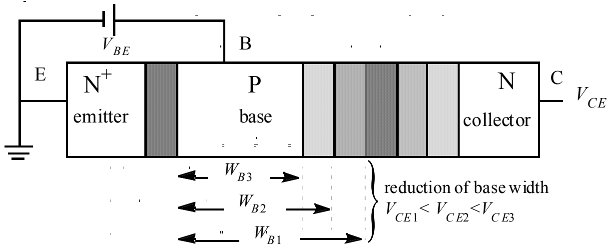
I_E: E-B diode current + fraction of C-B diode current that makes it to the E-B junction

V_{CE} (V)

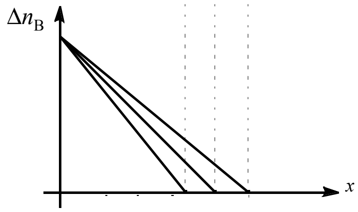
Reciprocity Relationship

$$\alpha_F I_{F0} = \alpha_R I_{R0} \equiv qA\frac{D_B}{L_B}\frac{p_{B0}}{\sinh(W/L_B)}$$

Base-Width Modulation



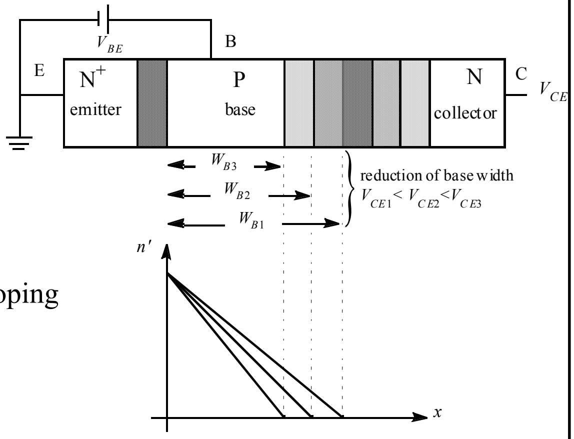
$$\beta_{dc} = \frac{1}{\frac{n_{iE}^2}{n_{iB}^2}\frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$



How can we reduce the base-width modulation effect?

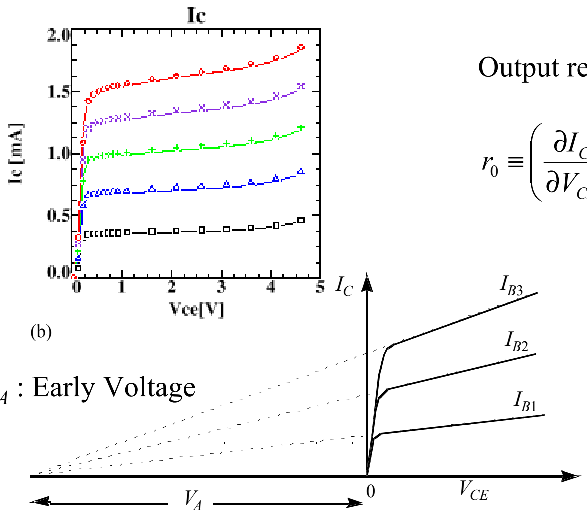
The base-width modulation effect is reduced if we

(A) Increase the base width,
(B) Increase the base doping concentration, N_B, or
(C) Decrease the collector doping concentration, N_C.



Which of the above is the most acceptable action?

Early Voltage



(b)

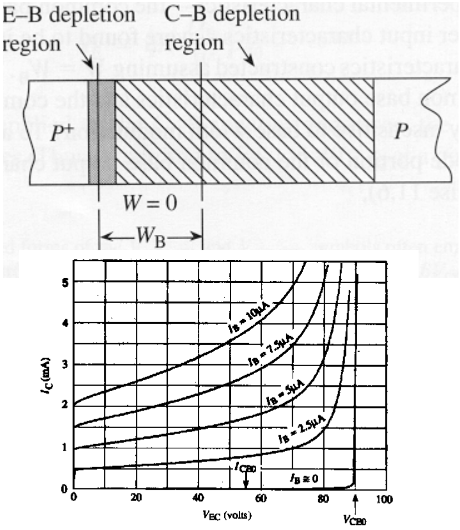
V_A : Early Voltage

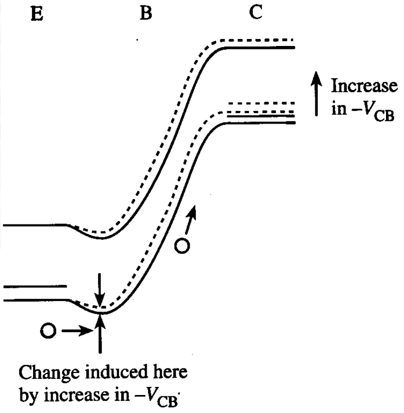
Output resistance :

$$r_0 \equiv \left(\frac{\partial I_C}{\partial V_{CE}}\right)^{-1} = \frac{V_A}{I_C}$$

A large V_A (*i.e.* a larger r_o) is desirable

Punchthrough





Summary: BJT Performance Requirements

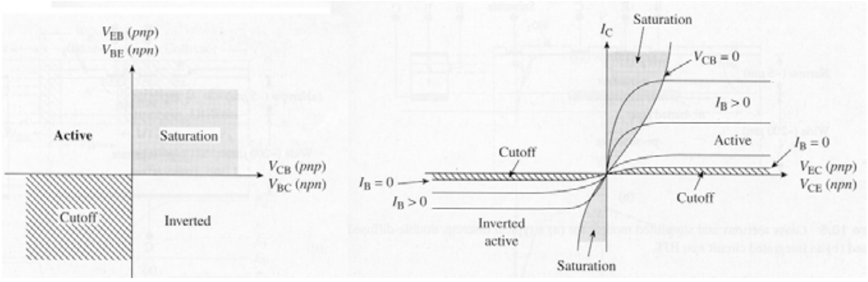
- **High gain** ($\beta_{dc} >> 1$)
  - → <u>One-sided emitter junction</u>, so emitter efficiency $\gamma \approx 1$
    - Emitter doped much more heavily than base ($N_E >> N_B$)
  - → <u>Narrow base</u>, so base transport factor $\alpha_T \approx 1$
    - Quasi-neutral base width << minority-carrier diffusion length ($W << L_B$)

- **I_C determined only by I_B** ($I_C \neq$ function of V_{CE}, V_{CB})
  - → <u>One-sided collector junction</u>, so quasi-neutral base width W does not change drastically with changes in V_{CE} (V_{CB})
    - Based doped more heavily than collector ($N_B > N_C$)

($W = W_B - x_{nEB} - x_{nCB}$ for PNP BJT)

Review: Modes of Operation

Common-emitter output characteristics
(I_C *vs.* V_{CE})



Note that $\beta_{dc} = \frac{I_C}{I_B}$ is lower for inverted mode operation. Why?