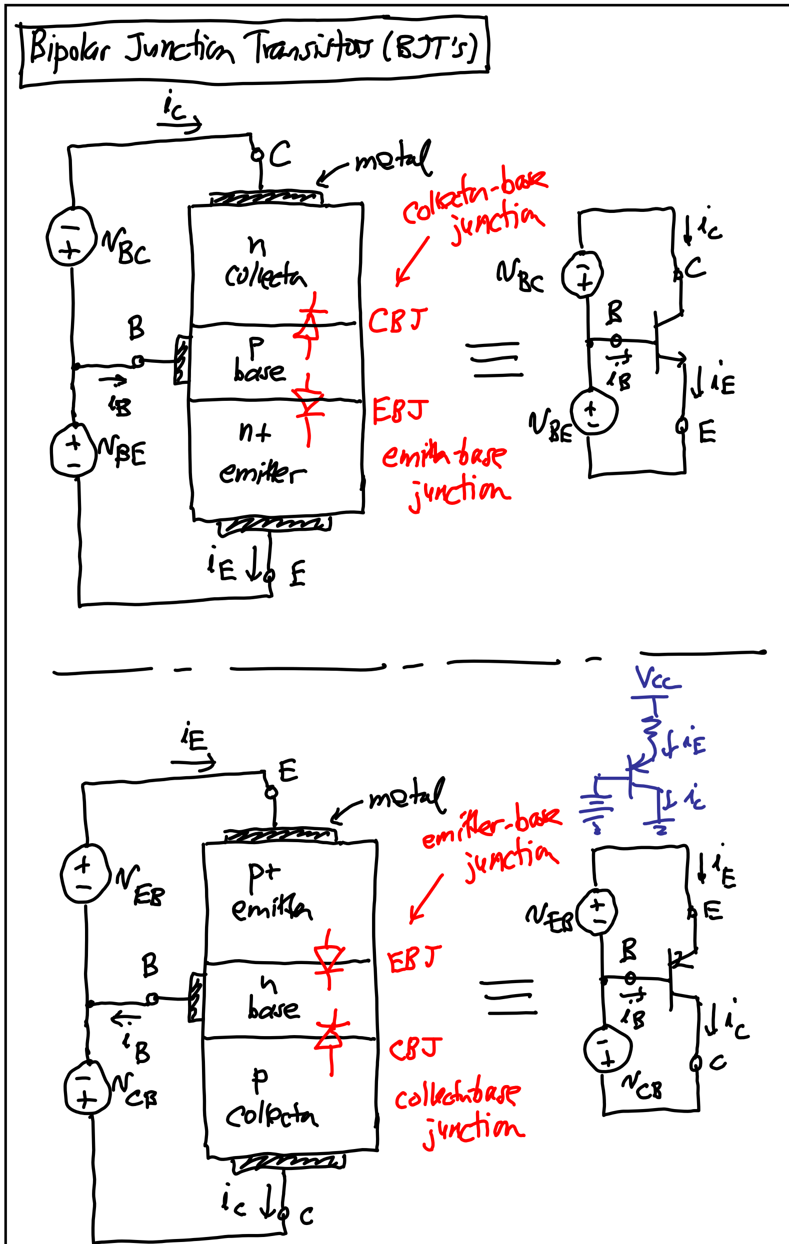
Lecture 17: Bipolar Junction Transistors (BJTs) II

- 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)

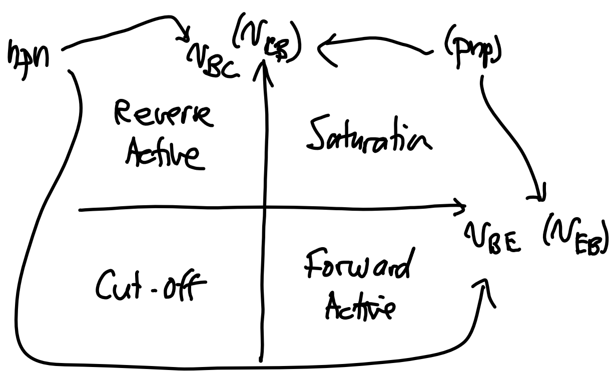


Regions of BJT Operation

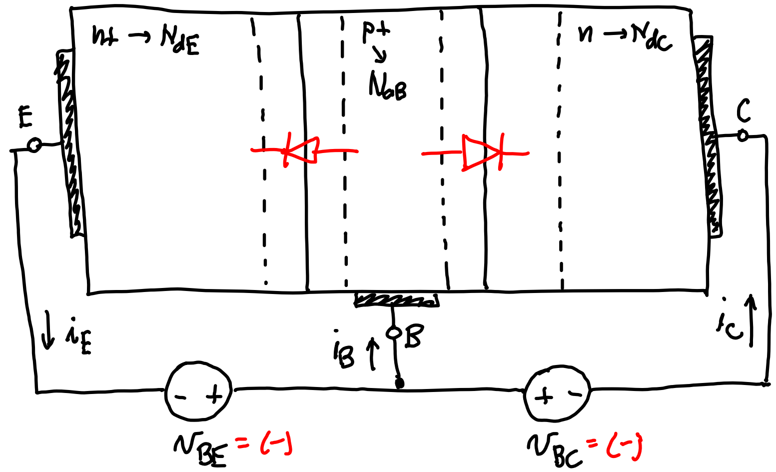
F ← forward bias, R ← reverse bias

EBJ	CBJ	Mode
R	R	Cutoff (both diodes off)
F	R	Forward Active (widely used in analog amplifiers)
R	F	Reverse Active
F	F	Saturation

⇒ Or graphically:



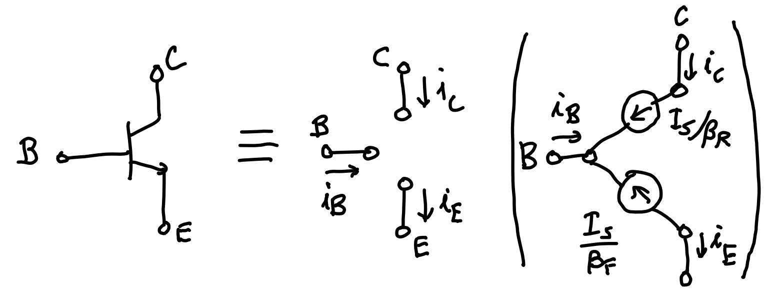
① Cutoff Region: (npn transistor)



⇒ Both diodes reverse-biased

↳ No current flows.

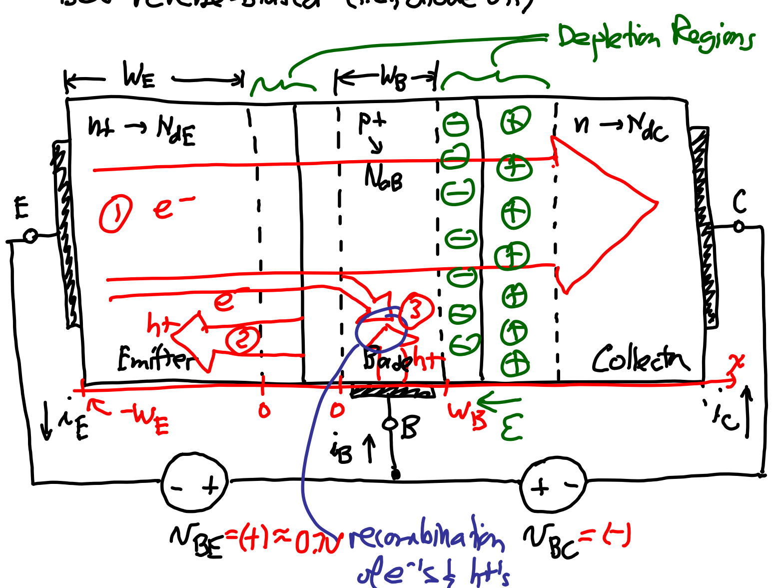
$i_B = 0$, $i_C = 0$, $i_E = 0$



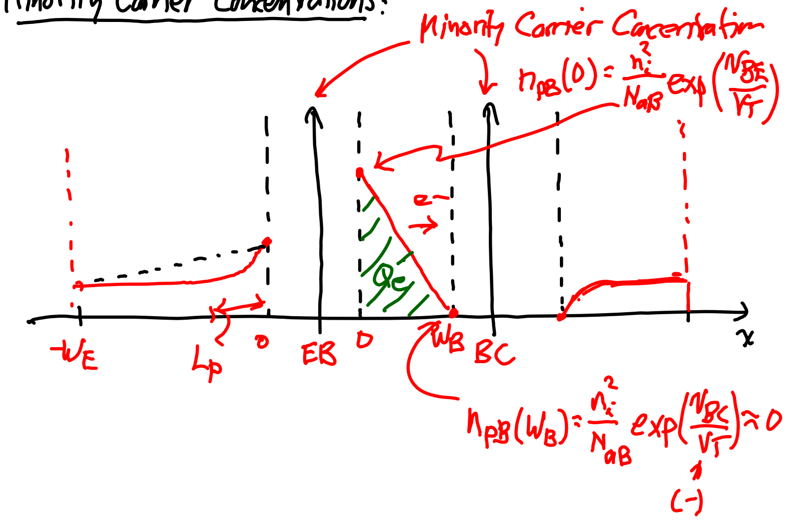
② Forward-Active Region: (npn transistor)

BEJ forward-biased (i.e., diode on)

BCJ reverse-biased (i.e., diode off)



Minority Carrier Concentrations:



BEJ Forward-Biased:

⇒ get diffusion current as in diode

⇒ forward-biasing of a BJT → three current components:

① e⁻'s injected from emitter to base:

$$I_{nB} = -A J_{nB}^{diff}$$

② h⁺s injected from base to emitter:

$$I_{pE} = -A J_{pE}^{diff}$$

③ recombination of e⁻'s & h⁺'s in the base

$$I_{rB} \propto \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$i_C = I_{nB} = ①$$

$$i_E = I_{nB} + I_{pE} + I_{rB} = ① + ② + ③$$

$$i_B = I_{pE} + I_{rB} = ② + ③$$

Diffusion Current:

$$I_{nB} = -A J_{nB}^{diff} = -A q D_{nB} \frac{dn_p(x)}{dx}$$

cross-sectional area

diffusion constant for e⁻'s in base

e⁻ conc. in p-type region

$$= -qAD_{nB} \frac{[n_{pB}(W_B) - n_{pB}(0)]}{W_B}$$

Current Formulations

① : $I_{nB} = -A J_{nB}^{diff} = -A q D_{nB} \dfrac{dn_p(x)}{dx}$

cross-sectional area

D_{nB}: diffusion constant for e⁻'s in base

$\dfrac{dn_p(x)}{dx}$: slope of minority carrier concentration

* $= -qAD_{nB} \dfrac{[n_{pB}(W_B) - n_{pB}(0)]}{W_B}$

$$n_{pB}(W_B) = \frac{n_i^2}{N_{aB}} \exp\left(\frac{v_{BC}}{V_T}\right) \approx 0$$

$$n_{pB}(0) = \frac{n_i^2}{N_{aB}} \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$\boxed{I_{nB} = qAD_{nB} \frac{n_i^2}{N_{aB} W_B} \exp\left(\frac{v_{BE}}{V_T}\right) = ①}$$

$$\boxed{i_C = ① = I_S \exp\left(\frac{v_{BE}}{V_T}\right)}$$

② : $I_{pE} = A J_{pE}^{diff} = qAD_{pE} \dfrac{dp_n(x)}{dx}$

D_{pE}: diffusion constant for ht's in emitter

$\dfrac{dp_n(x)}{dx}$: slope

$= qAD_{pE} \dfrac{[p_{nE}(0) - p_{nE}(-W_E)]}{W_E}$

W_E ← (or L_p) ← for long emitter

for a short emitter

*

$$p_{nE}(0) = \frac{n_i^2}{N_{dE}} \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$p_{nE}(-W_E) \cong 0$$

$$\boxed{I_{pE} = qAD_{pE} \frac{n_i^2}{N_{dE} W_E} \exp\left(\frac{v_{BE}}{V_T}\right) = ②}$$

make emitter doping large to reduce

③ : $I_{rB} = \dfrac{Q_e}{\tau_b}$

Q_e ← minority carrier charge in the base

τ_b ← minority carrier lifetime in base

$= \dfrac{1}{\tau_b} \Big[\underbrace{\tfrac{1}{2} n_{pB}(0) W_B q A}_{\text{area under the minority carrier (e⁻) charge curve}} \Big]$

$$\therefore \boxed{I_{rB} = \frac{1}{2} \frac{n_i^2 W_B q A}{N_{aB} \tau_b} \exp\left(\frac{v_{BE}}{V_T}\right) = ③}$$

Define: Forward Current Gain $= \beta_F$

$$\beta_F = \frac{i_C}{i_B} = \frac{①}{③ + ②} = \frac{\dfrac{qAD_{nB} n_i^2}{N_{aB} W_B}}{\dfrac{1}{2}\dfrac{n_i^2 W_B q A}{N_{aB} \tau_b} + \dfrac{qAD_{pE} n_i^2}{N_{dE} W_E}}$$

$$\therefore \beta_F = \left[\frac{W_B^2}{2 \tau_b D_{nB}} + \frac{D_{pE} W_B N_{aB}}{D_{nB} W_E N_{dE}} \right]^{-1}$$

To maximize β_F, want:

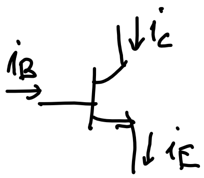
① W_B = small

② $N_{dE} \gg N_{aB} \xrightarrow[\text{to}]{\text{leads}} D_{pE} \ll D_{nE}$

③ τ_b = large → base Si should be free of impurities/defects to prevent recombination of e^-'s & h^+'s

This is why emitter is n+.

So, β relates i_B & i_C. How about i_C & i_E?



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

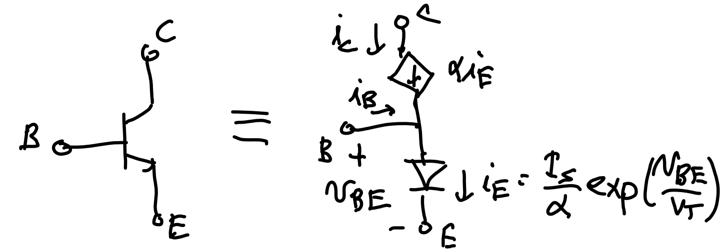
$$i_C = \left(\frac{1}{1+\frac{1}{\beta}}\right) i_E = \left(\frac{\beta}{\beta+1}\right) i_E = \boxed{\alpha i_E = i_C}$$

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

↳ if β = large → $\alpha \cong 1$ & $i_C \cong i_E$

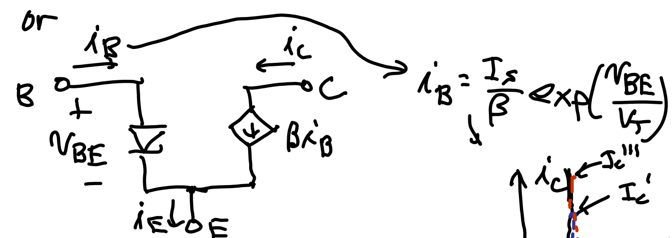
Equiv. Large Signal Ckt. Models for BJT's (in Forward-Active)

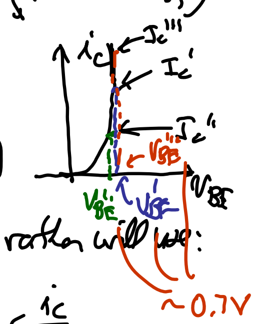
⇒ several of them → two most popular accurate ones:



Common-Base (CCCS)

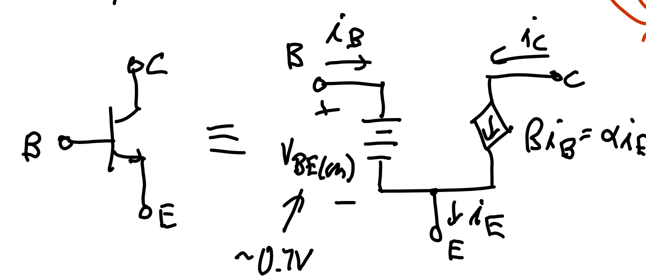
or



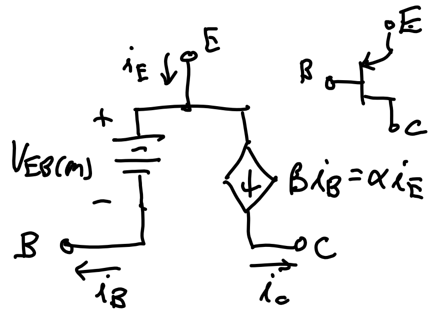


Common-Emitter (CCCS)

↳ usually, won't use the above, but rather will use:

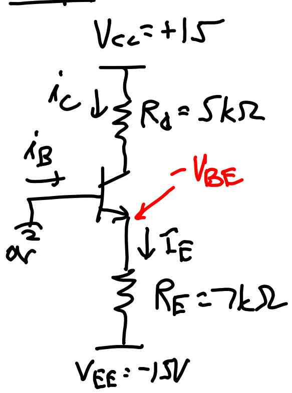


npn



(for pnp)

Example. (exactitude)



Find the DC operating pt.
(i.e., Find the DC voltages at each node and the currents through each branch)

$$I_E = \frac{-V_{BE} - V_{EE}}{R_E}$$

$$I_C = \alpha I_E = \frac{\alpha(-V_{EE} - V_{BE})}{R_E}$$