Lecture 17: Bipolar Junction Transistors (BJTs) II

- Announcements:
- HW#6 online and due Friday, Oct. 18 (almost two weeks from now) via Gradescope
- Lab#3 continues this week
  - Prelab due before lab; Lab#3 due next week
- Lab#4 is online, with prelab due next week
- Midterm 1 on Friday, Oct. 11, 7-9 p.m., 160 Kroeber Hall
  - Midterm Info Sheet online
  - Review Session for Midterm, Tuesday, 6-8 p.m., in 293 Cory
  - For the review session, please post on Piazza specific problems you would like covered
- My Monday Office Hours will move to 5-6 p.m. on Oct. 14 and thereafter
- I am traveling today
  - This lecture is pre-recorded
  - I will be back on Wednesday, Oct. 9
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- Lecture Topics:
  - BJT Forward-Active Region
    - —Physics
    - —Large Signal Circuit Model
    - —Operating Pt. Example
  - Reverse Active Region
  - Saturation Region
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- Last Time:
- Went through BJT physics

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

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

*

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

make emitter doping large to reduce

③: $I_{rB} = \frac{Q_e}{\tau_b}$ ← minority carrier charge in the base; τ_b ← minority carrier lifetime in base

$$= \frac{1}{\tau_b}\Big[\underbrace{\tfrac{1}{2} n_{pB}(0) W_B qA}_{\text{area under the minority carrier } (e^-) \text{ charge curve}}\Big]$$

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

Define: $\boxed{\text{Forward Current Gain} = \beta_F}$

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

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

To maximize β_F, want:

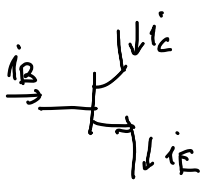
① W_B = small

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?



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

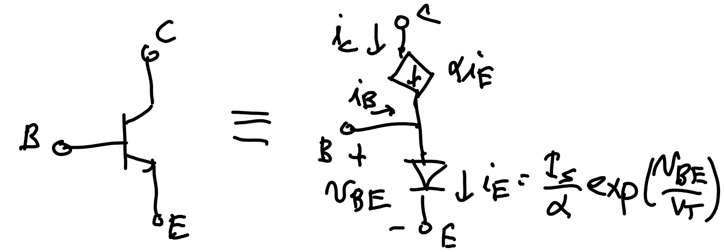
$$i_C = \left(\frac{1}{1+\frac{1}{\beta}}\right) i_E = \left(\frac{\beta}{\beta+1}\right) i_E = \boxed{\alpha i_E = i_C}$$

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

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

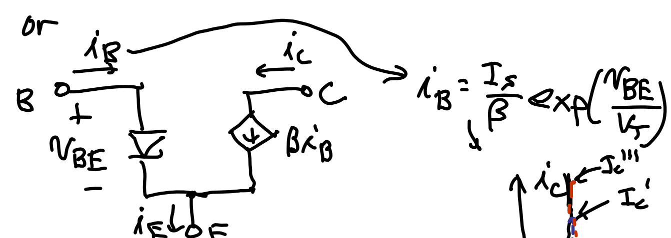
Equiv. Large Signal Ckt. Models for BJT's (in Forward-Active)

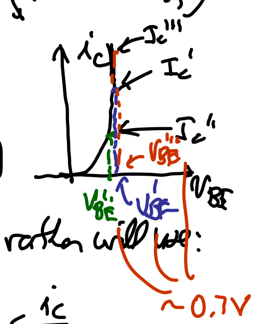
⇒ several of them → two most popular accurate ones:



Common-Base (CCCS)

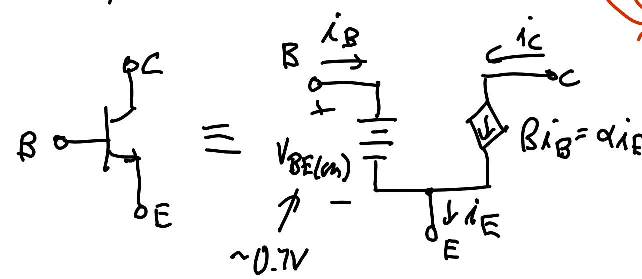
or



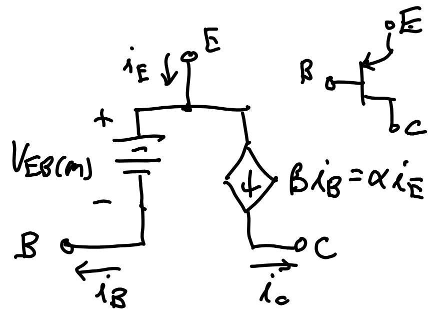


Common-Emitter (CCCS)

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

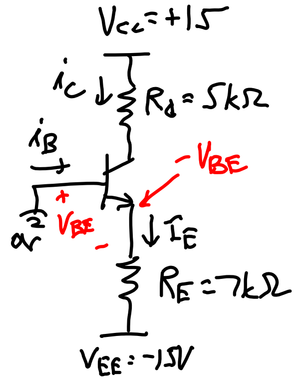


npn



(for pnp)

Example. (exactitude)



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

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

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

For npn Xsistor:
$\beta = 100$
$I_S = 2\times10^{-15}A$

$$I_S \exp\left(\frac{V_{BE}}{V_T}\right) = \underbrace{\frac{\beta}{\beta+1}}_{\alpha} \frac{(-V_{EE} - V_{BE})}{R_E}$$

25mV (nonlinear equation)

→ iteration, numerical → painful...

⇒ Get $V_{BE} = 0.717V$

⇒ $I_E = \frac{15 - 0.717}{7K} = 2.04mA$

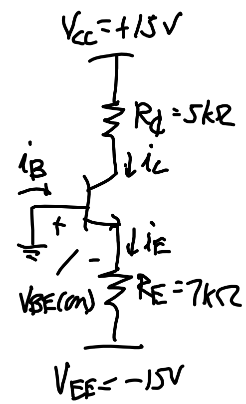
⇒ $I_C = \alpha I_E = \left(\frac{100}{101}\right) I_E = 2.02mA$

⇒ $I_B = \frac{I_C}{\beta} = 0.02\ mA$

$V_B = 0V$
$V_E = -0.717V$
$V_C = 15 - I_C(5K) = 4.9V$

⇒ What if we don't know β & I_S accurately? → No need to be so accurate!

⇒ Do the problem again using approximations.
↳ esp. the model.



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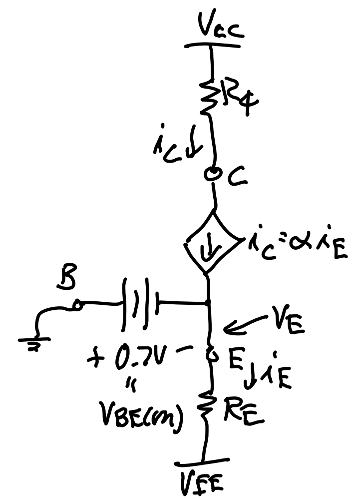


⇒ no exponential
⇒ easy to solve!

$V_B = 0V$, $V_E = -0.7V = -V_{BE(on)}$

$$I_E = \frac{-0.7 - (-15)}{7k} \simeq 2.04mA$$

$$I_C = \alpha I_E \cong I_E = 2.04mA$$

$$I_B = \frac{I_C}{\beta} = 0.02mA$$

$$V_C = 15 - (\underset{10^{-3}}{2.04m})(\underset{10^{3}}{5K}) \simeq 4.8V$$

③ Reverse-Active Region:

BEJ reverse-biased

BCJ forward-biased

$\Rightarrow$ similar to forward-active region w/ one important difference:

$\beta_R \propto \dfrac{N_{dC} W_E D_p}{N_{aB} W_B D_n} \leftarrow N_{dC} < N_{aB}$ (collector is n-)

reverse

$\therefore \beta_R \ll \beta_F$ forward

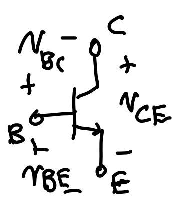
Thus, avoid using the device in reverse-active!

④ Saturation Region:

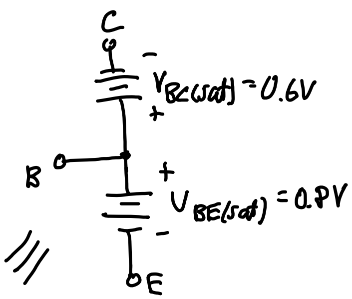
higher than 0.7V in saturation

BEJ forward-biased $\rightarrow V_{BE(on)} \sim 0.8V$

BCJ forward-biased $\rightarrow V_{BC(on)} \sim 0.6V$



$\Longrightarrow$



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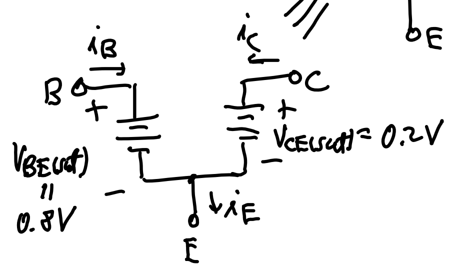
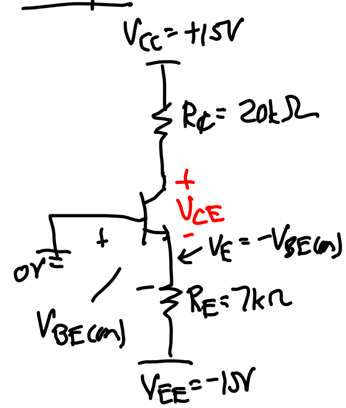


(All for npn; come up w/ pnp yourself)

- When determining DC operating point:
  1. First, assume forward-active, then check for cut-off, i.e., is there enough V_{BE}?
  2. Assume forward-active, then determine V_{CE}.
  3. If $V_{CE} > V_{CE(sat)}$, then okay … otherwise, must do analysis using the device saturation model.

Example.



① $i_E = \dfrac{15 - 0.7}{7k} = 2.04mA$

$\Rightarrow$ enough voltage to turn on BEJ ✓

② Assume forward-active

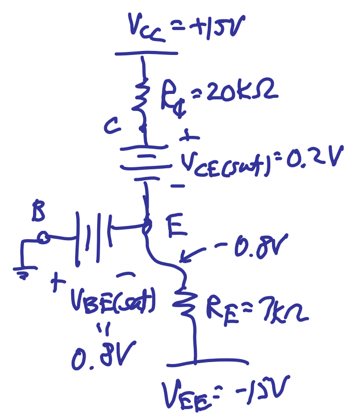
$V_C = 15 - (2.04m)(20k) = -25.8V$

$\therefore V_{CE} = V_C - V_E = -25.8 - (-0.7)$

$= -25.1V < 0.2V = V_{CE(sat)}$

$\therefore$ saturated BJT

③ Analyze assuming saturation:



$V_B = 0V,\ V_E = -0.8V$

$I_E = \dfrac{-0.8 + 15}{7k} = 2.03mA$

$I_C = \dfrac{15 - (-0.8) - 0.2}{20k} = 0.78mA$

$I_B = I_E - I_C = 1.25mA$

(Note: no longer $I_B = \dfrac{I_C}{\beta}$.)

$V_C = 15 - (0.78m)(20k) = -0.6V$