COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

ELEN E3106/4106 Lecture 17

BJTs Part III: Modes of Operation and Secondary Effects

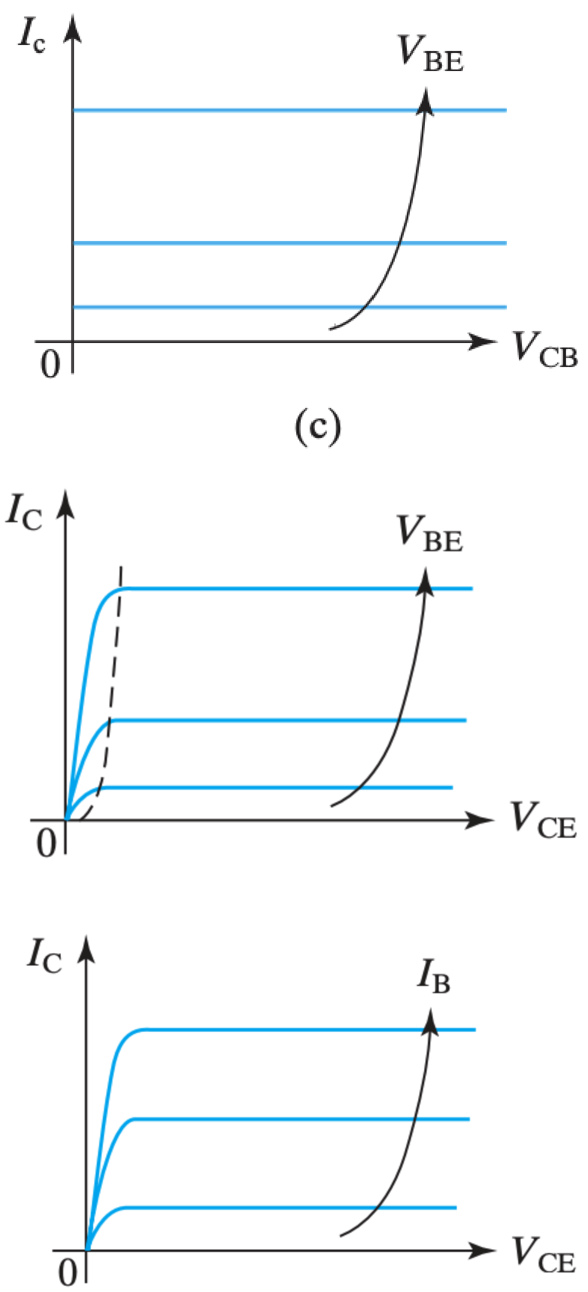
Outline

- BJT *I-V* Characteristics
- Modes of Operation
- Biasing Configurations
- Secondary Effects

Assignments:
Reading: C. Hu §8.4, 8.6, 8.7
Homework 7 due Friday Nov. 15th by 5pm

Recap of *I-V* Characteristics (so far..________________mode)

- Recall that I_C is essentially independent of _____, as long as _____ is RB (top)
- I_C is instead determined by rate of carrier injection from the __________ (e.g. ______) (middle)
- _____ is commonly used as the parameter instead of V_{BE} because IR drops make it difficult to know the true value V_{BE} while ______ can be easily measured (bottom)
- When there is no ____, there is almost no I_C



Sources: C. Hu *Modern Semiconductor Devices for Integrated Circuits*

Modes of Operation

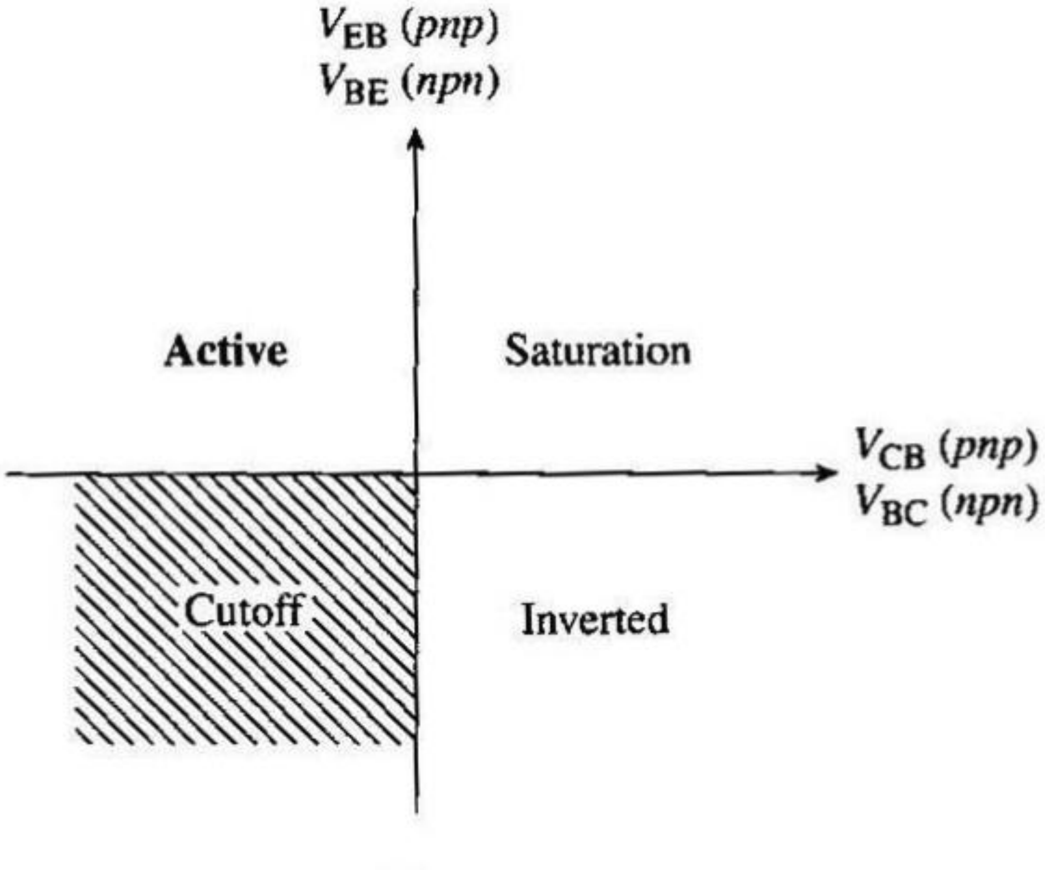
- Previously, we saw that each ___________ can have **3** possible modes of operation:
  - Forward biased
  - Reverse biased
  - ____________
- A BJT has _____ modes of operation
- So far, we have discussed just one mode of operation for a BJT

1. Normal (forward) **active** mode (V_{EB} __ 0; V_{CB} __ 0) for ________

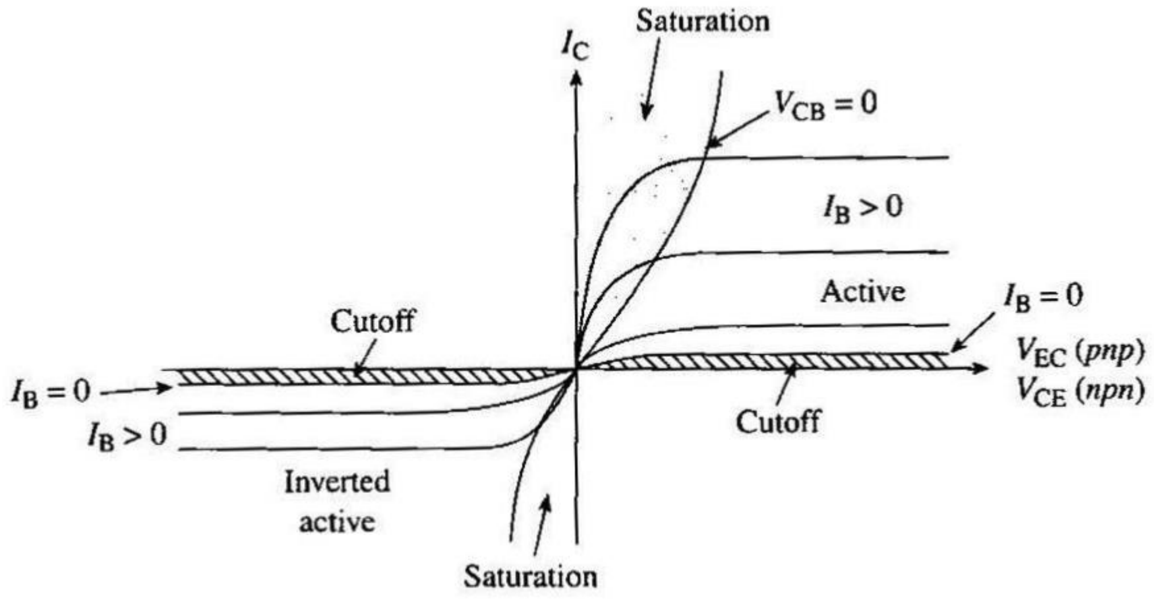
- But, there are other modes of operation when the transistor is not biased in the “normal” way, particularly in switching applications:

Mode	EB Junction	CB Junction	Applications
	Reverse biased	Reverse biased	Open-switch
Active	Forward biased	Reverse biased	Amplifiers
	Reverse biased	Forward biased	Attenuators
	Forward biased	Forward biased	Short-switch

Full picture of *I-V* Characteristics



(a)



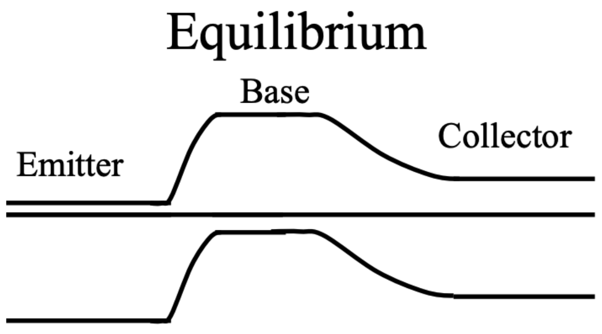
(b)

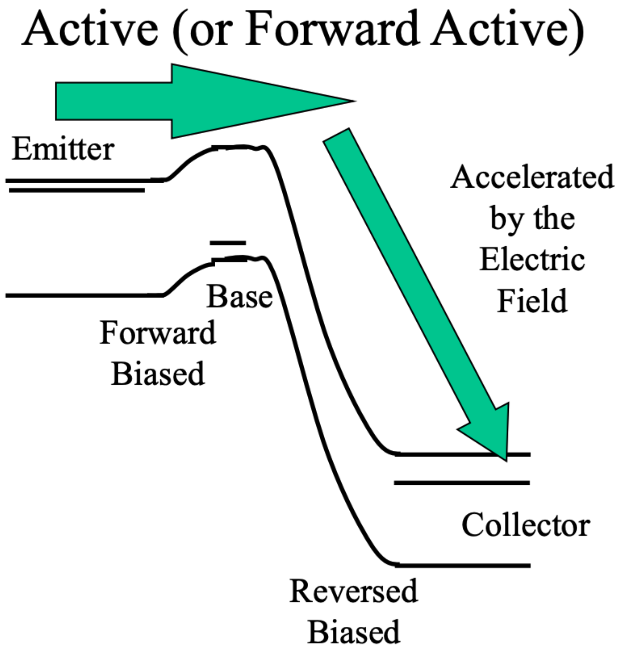
re 10.5 (a) Combinations of the BJT input and output voltages resulting in the four biasing s. (b) Regions of the BJT common emitter output characteristics associated with the four biasing s.

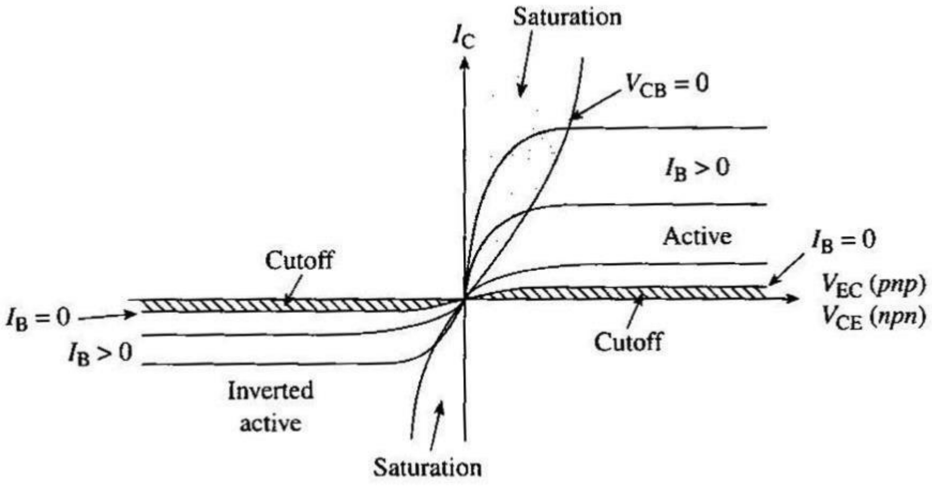
Sources: A. Doolittle ECE 3040 Slides

Normal/Active Mode: Band Diagram

- This s is normal mode of operation for __________
- For pnp (npn): EB (BE) junction is _____, CB (BC) junction is _____
- Collector current nearly matches _________ current
- The curves are practically _______



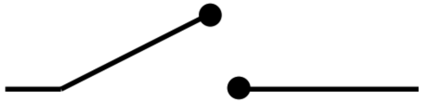


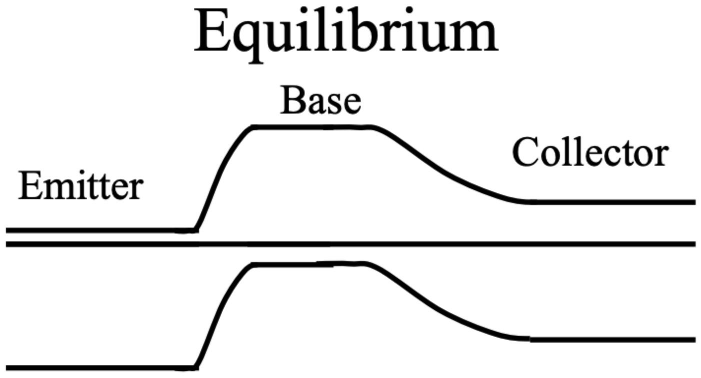


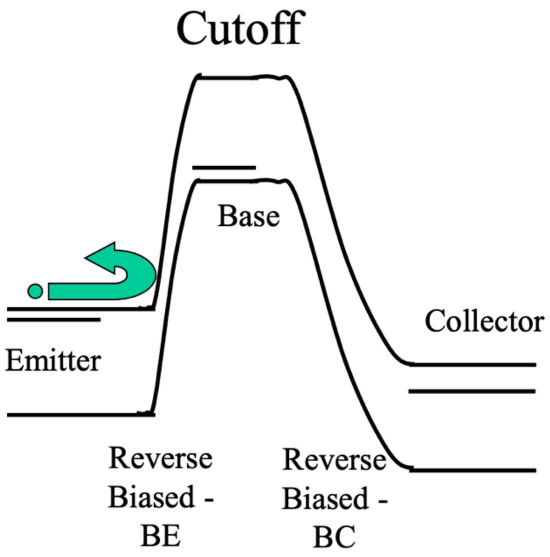
Sources: A. Doolittle ECE 3040 Slides

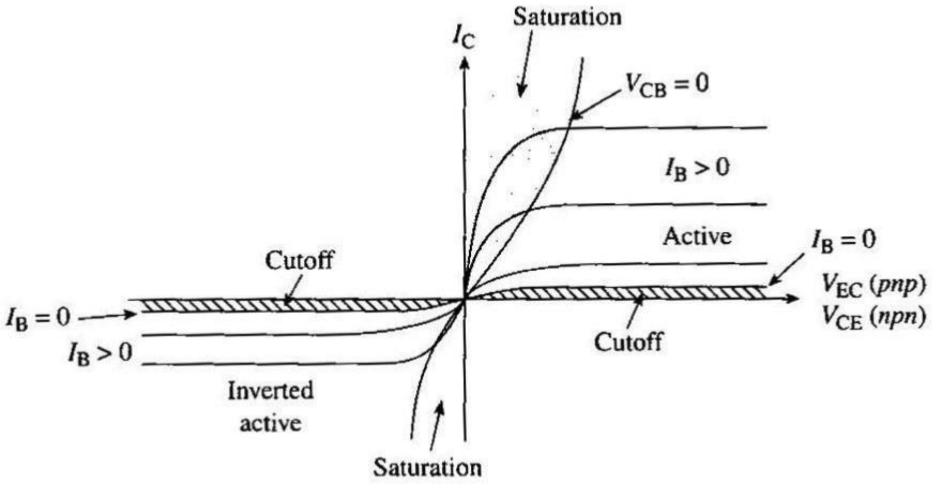
Cut-off Mode: Band Diagram

- This is the _____ state (open-circuit) condition when transistor is used as a switch. Very little current flow!
- Both junctions are _____, so barriers to particle flow are very high. Only a small _______ current will flow.





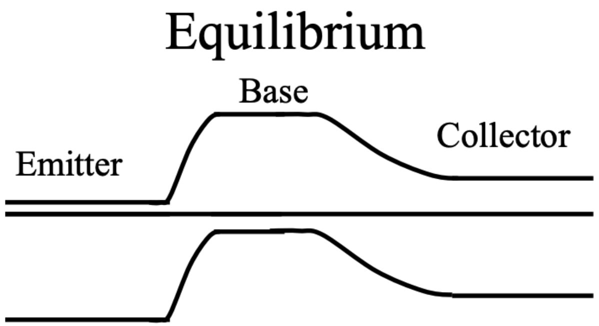


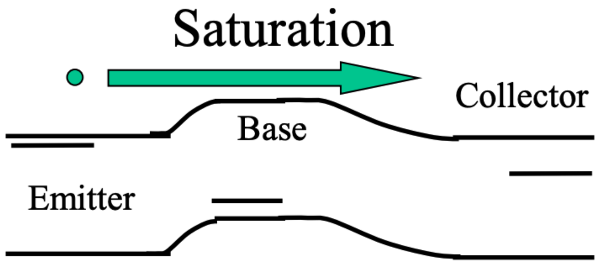


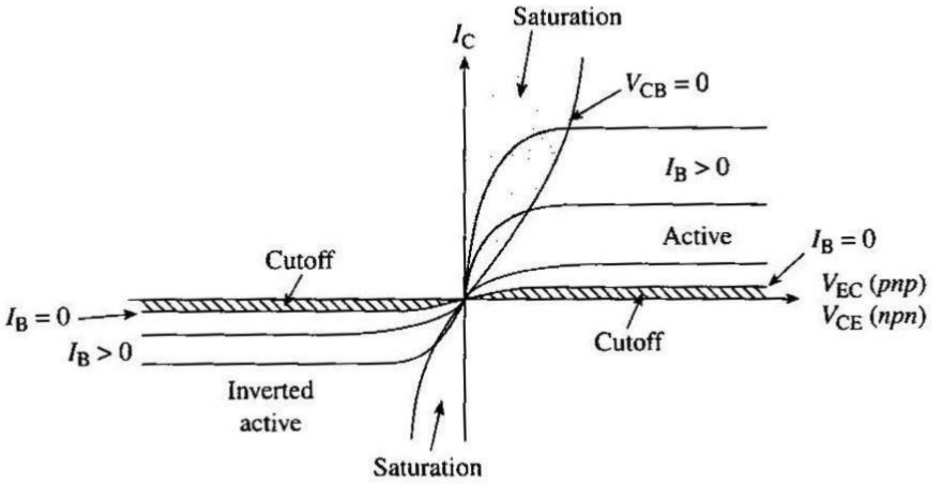
Sources: A. Doolittle ECE 3040 Slides

Saturation Mode: Band Diagram

- This is the _______state (short-circuit) condition when transistor is used as a switch. High current flow!
- Both junctions are ______, so barriers to particle flow are lowered, allowing _______ currents to flow.



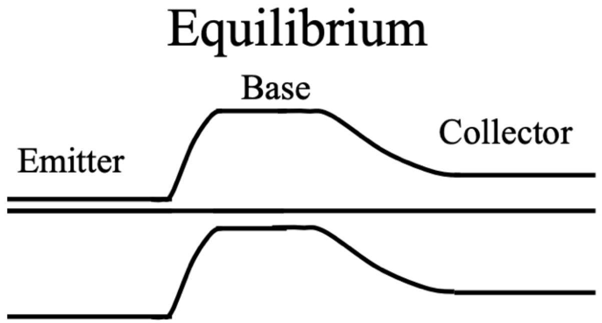


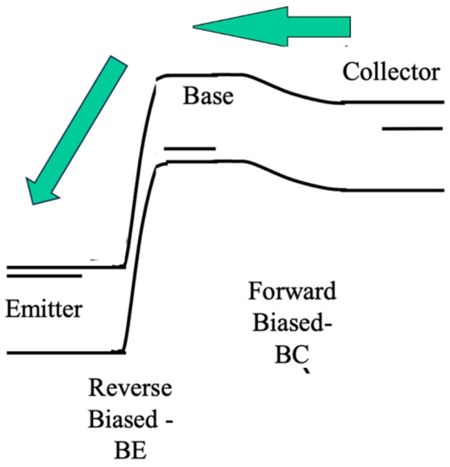


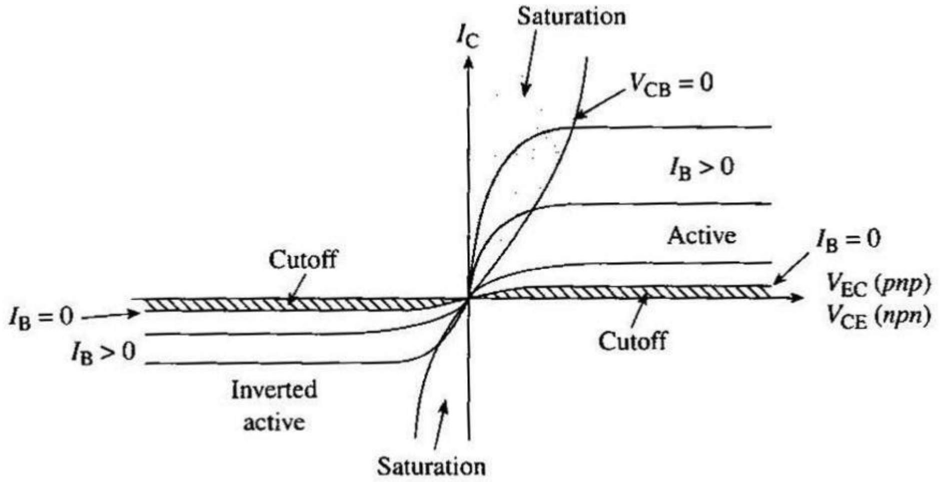
Sources: A. Doolittle ECE 3040 Slides

Reverse Active Mode: Band Diagram

- This mode is not commonly used. It is the ________ of active mode.
- For pnp (npn): EB (BE) junction is ______, CB (BC) junction is ______
- BJT will conduct current in the opposite direction of active mode, and amplify, but β, denoted ____ for reverse active mode, is much smaller
- Why? BJT ______________ are chosen to maximize β in forward active mode.







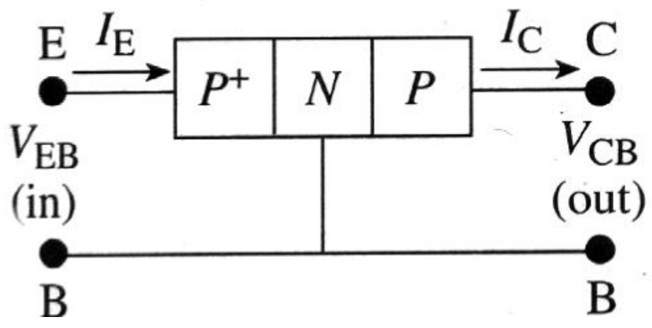
Sources: A. Doolittle ECE 3040 Slides

Biasing Configurations (Topologies)

- The BJT is commonly used as a _________ network (that is, 1 of the terminals is ________ between 2 ports)

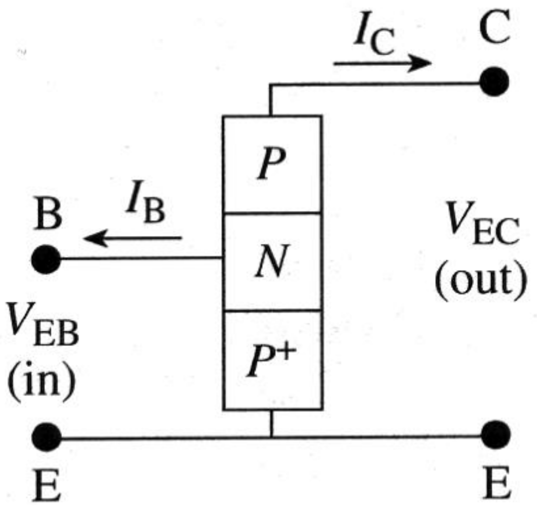
1. **Common-Base**

Input & output share the base "in common". Not very frequently used (gain is near ________). Exceptions are cascode, ultra high frequency.



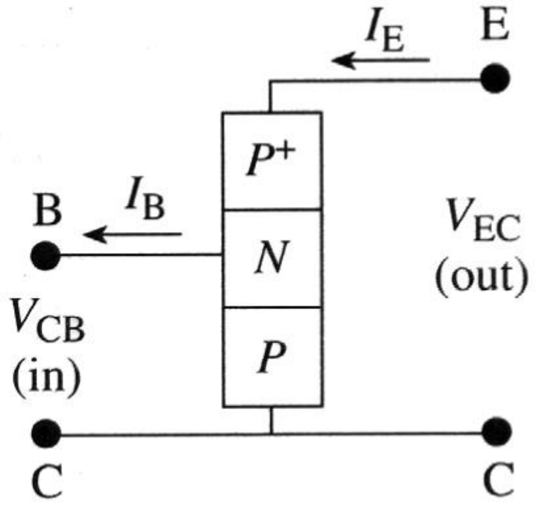
2. **Common-Emitter**

Input & output share the emitter "in common". Widely used, for example in ________________



3. **Common-Collector**

Input & output share the collector "in common". Widely used, for example in ____________________ and voltage buffering.



Sources: A. Doolittle ECE 3040 Slides

Additional Terminology for Gain

- In previous lectures, we introduced these 2 parameters:
  - ____ (current transfer ratio, representing emitter-to-collector current amplification)
  - ____ (Base-to-collector current amplification)
- α is also called the *common-base current gain* (typically ≥ ____)
- β is also called the *common-emitter current gain* (typically ≈ ______)
  - Ex. If β = 100, 1 e- will flow from base terminal for every ______ e- flowing between EC in an npn BJT
- They are related by the following identities:

$$\alpha = \frac{I_C}{I_E} \Leftrightarrow I_C = \alpha I_E \qquad \beta = \frac{I_C}{I_B} = \frac{G_E}{G_B} = \frac{D_B W_E N_E n_{iB}^2}{D_E W_B N_B n_{iE}^2} \Leftrightarrow I_C = \beta I_B$$

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

Note: emitter ejection efficiency can now be rewritten in terms of ____________________:

$$\gamma = \frac{I_E - I_B}{I_E} = \frac{I_C}{I_C + I_B} = \frac{1}{1 + G_B/G_E}$$

Sources: Textbook, C. Hu *Modern Semiconductor Devices for Integrated Circuits*

Emitter Bandgap Narrowing

- How do we raise β? Typically, we increase the emitter doping, ___
- But, when N_E increases, $n_{iE}^2 \gg$ ____
- This is called the *heavy doping effect,* AKA _______________
- Why? Heavy doping can decrease _____, and __________

$$n_{\mathrm{i}}^2 = N_{\mathrm{c}} N_{\mathrm{v}} \mathrm{e}^{-E_{\mathrm{g}}/kT} \qquad n_{\mathrm{iE}}^2 = n_{\mathrm{i}}^2 \mathrm{e}^{\Delta E_{\mathrm{gE}}/kT}$$

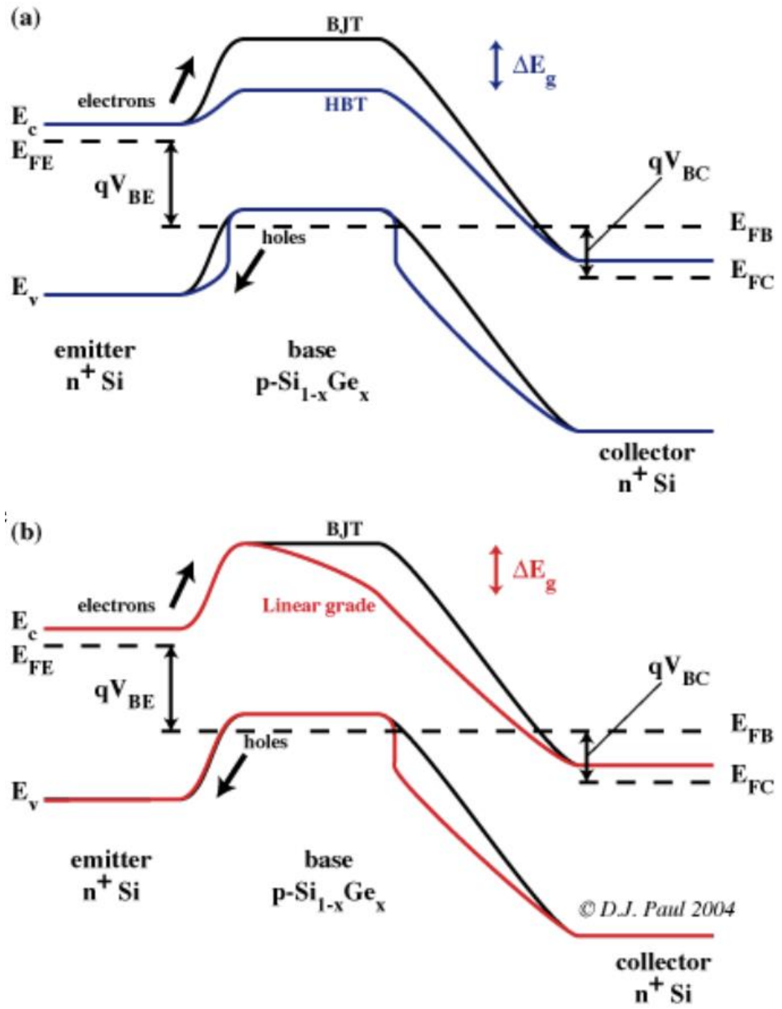
- This effect is negligible for $N_E < 10^{18}\ cm^{-3}$, and $\Delta E_{gE} < 50$ meV at $10^{19}\ cm^{-3}$, $\Delta E_{gE} < 95$ meV at ______ cm^{-3}, $\Delta E_{gE} < 140$ meV at ______ cm^{-3}

Sources: C. Hu *Modern Semiconductor Devices for Integrated Circuits*

Heterojunction BJT and Compositional Grading

- Another method to raise β: raise ___ by using smaller bandgap base material ($E_{gE} > E_{gB}$)
  - Si emitter + ____ base
  - InP emitter + I______ base
  - GaAlAs emitter + ______ base
- Device is known as a heterojunction bipolar transistor, ______
- We can further improve HBT by ________________________
  - Creates a built-in E-field, which reduces transit time ____ (e.g. improves ______) as carriers are accelerated across the base

Energy band diagram of npn (a) HBT and (b) compositionally graded base region HBT. Linear variation in the base material bandgag.



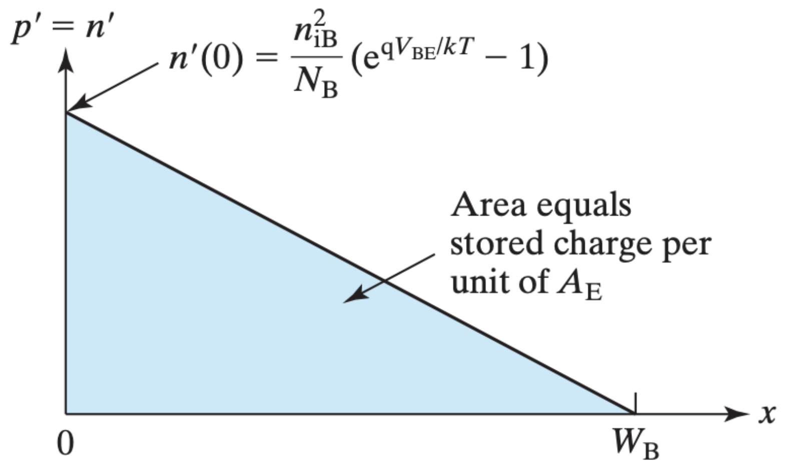
Sources: C. Hu *Modern Semiconductor Devices for Integrated Circuits,* D. J. Paul University of Glasglow https://userweb.eng.gla.ac.uk/douglas.paul/SiGe/HBT.html

Another look at Base Charge Storage and Transit Time

- Last lecture we discussed the stored charge in the base, ____, due to excess carriers
- We found
- $Q_p = \frac{1}{2}(base\ x\ height) = \frac{qA\frac{n_i^2}{N_B}(e^{\frac{qV_{EB}}{kT}}-1)W_B}{2} = I_C\tau_t$
- Where

$$\tau_t = \frac{W_B^2}{2D_B} = \frac{Q_p}{I_C}$$

- Hence, to ________ (i.e., to make a _____ BJT), we can either use a compositionally graded HBT OR ________



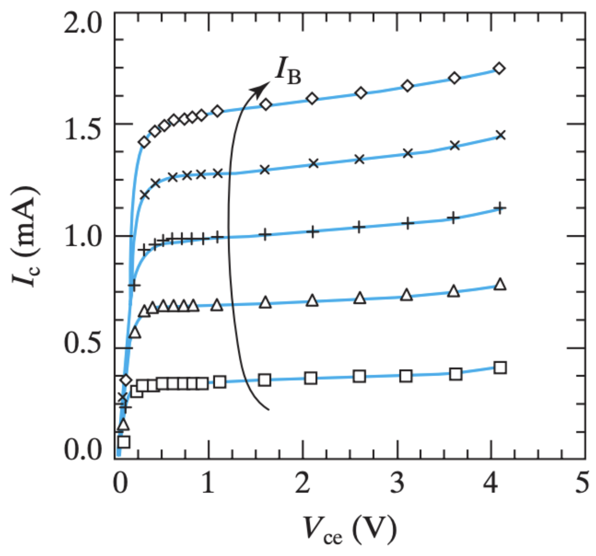
Recall:

$$I_C \approx qA\frac{D_B}{W_B}\frac{n_i^2}{N_B}(e^{\frac{qV_{EB}}{kT}} - 1)$$

Sources: C. Hu *Modern Semiconductor Devices for Integrated Circuits*

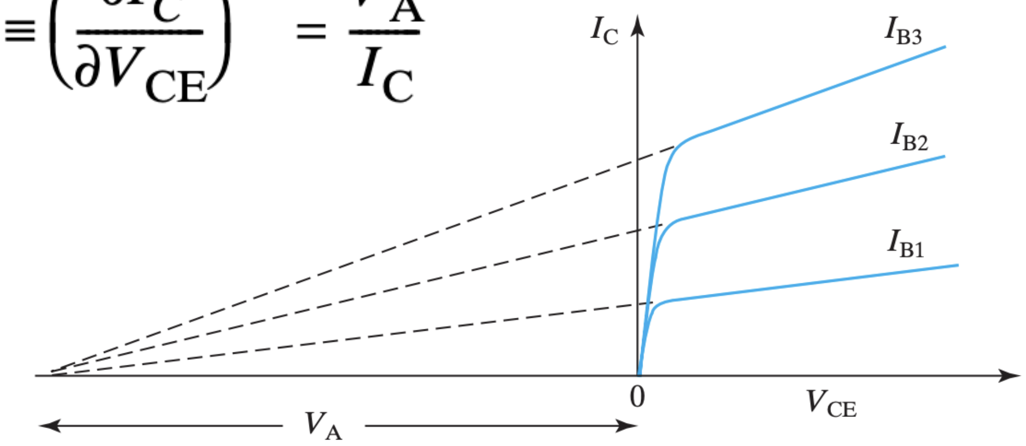
The Early Effect and Early Voltage

- In reality, $I_C - V_{CE}$ curves are not totally flat in the __________
  - Known as the *early effect*
  - Not desired. Hight output conductance (dI_C/dV_{CE}) is deleterious to _________ in circuits
- The flatness of the I-V curve is described by the early voltage, ___
- Large output resistance, ____, (large V_A) are desired for high voltage gain



(a)

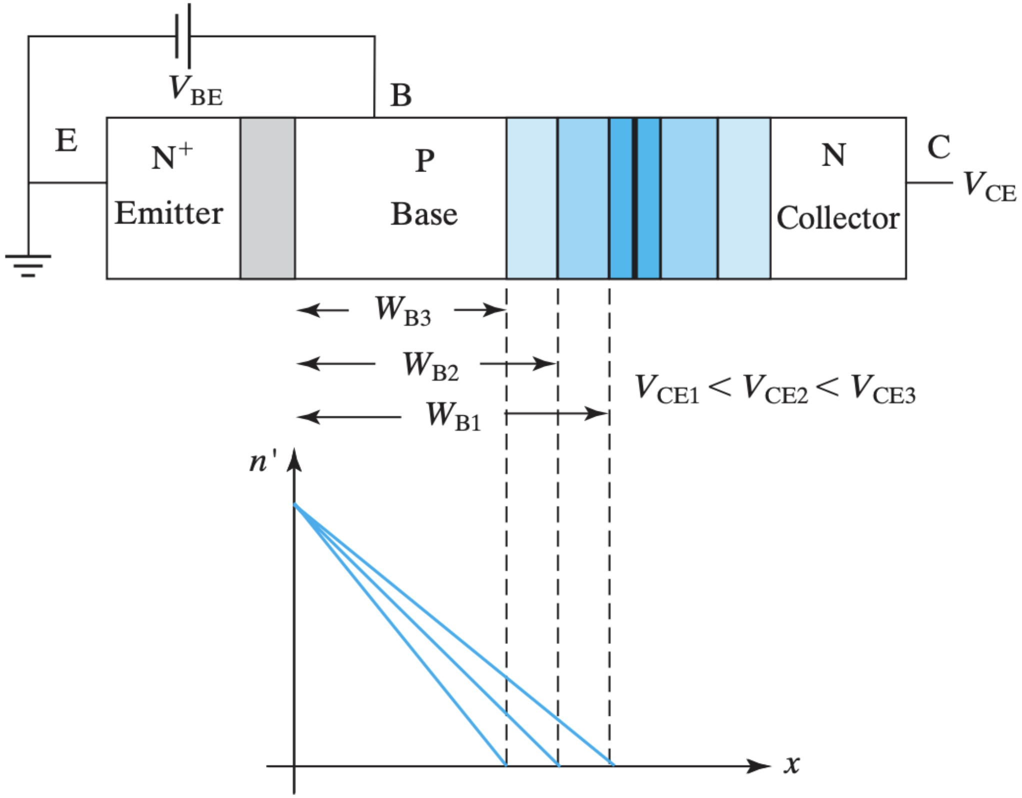
$$r_0 \equiv \left(\frac{\partial I_C}{\partial V_{CE}}\right)^{-1} = \frac{V_A}{I_C}$$



Sources: C. Hu *Modern Semiconductor Devices for Integrated Circuits*

Base Width Modulation

- Why aren't the curves flat anyways?
- Large V_{CE} increases CB junction ________
- This decreases neutral base region width, __
- I_C subsequently increases! (e.g. excess carrier conc. slope _______)
- In reality, $N_C \gg N_B$ so that way most of the CB depletion region is on the ______ side to suppress the Early effect
- What about series resistance? A heavily doped _________ is frequently added



Recall: $I_C = -qAD_B\left(\frac{dn}{dx}\right)$

$$I_C \approx qA\frac{D_B}{W_B}\frac{n_i^2}{N_B}(e^{\frac{qV_{EB}}{kT}} - 1)$$

Sources: C. Hu *Modern Semiconductor Devices for Integrated Circuits*