ELEN E3106/4106 Lecture 17

BJTs Part III: Modes of Operation and Secondary Effects

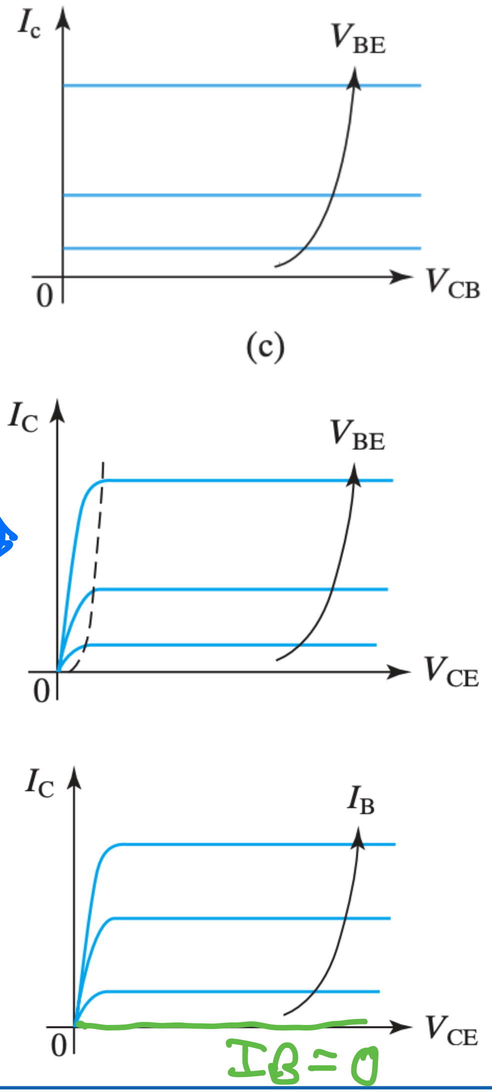
Outline

- 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.. active (normal) mode)

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



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

Modes of Operation

- Previously, we saw that each p-n junction can have **3** possible modes of operation:
  - Forward biased
  - Reverse biased
  - Breakdown

And equilibrium

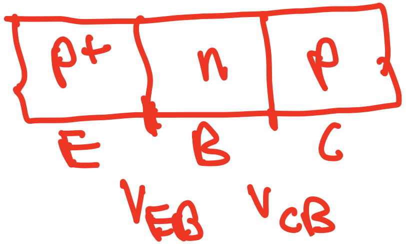
- A BJT has 4 modes of operation
- So far, we have discussed just one mode of operation for a BJT

1. Normal (forward) **active** mode (V_{EB} > 0 (FB); V_{CB} < 0 (RB)) for p-n-p

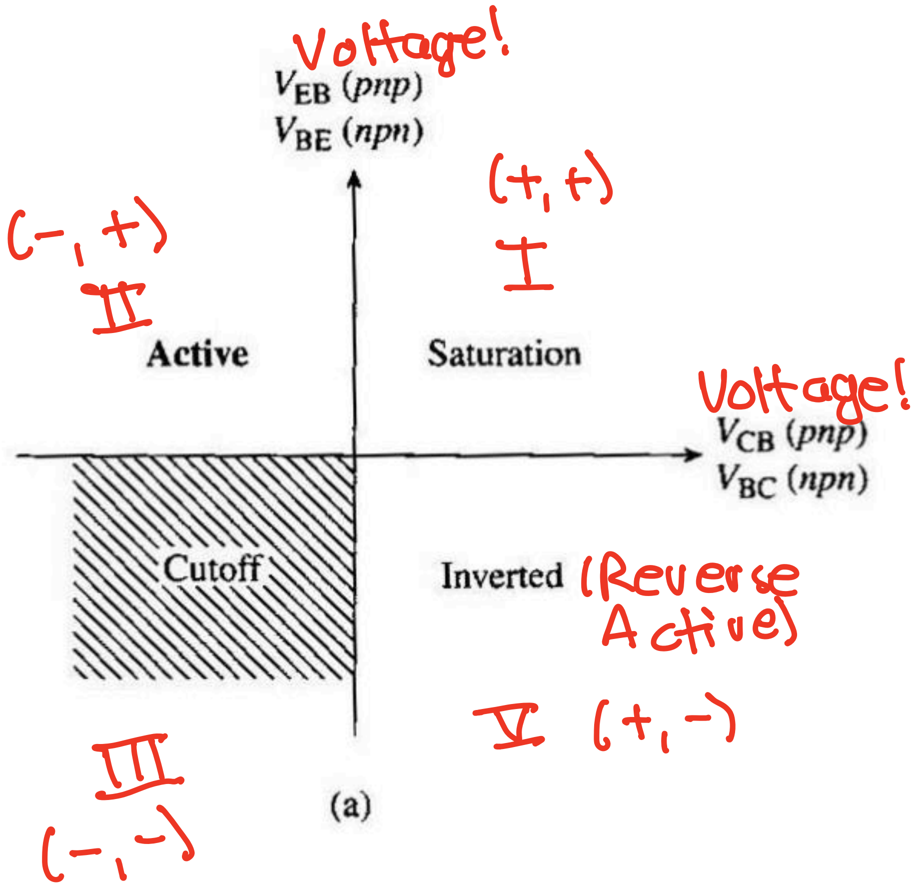
- But, there are other modes of operation when the transistor is not biased in the "normal" way, particularly in switching applications:

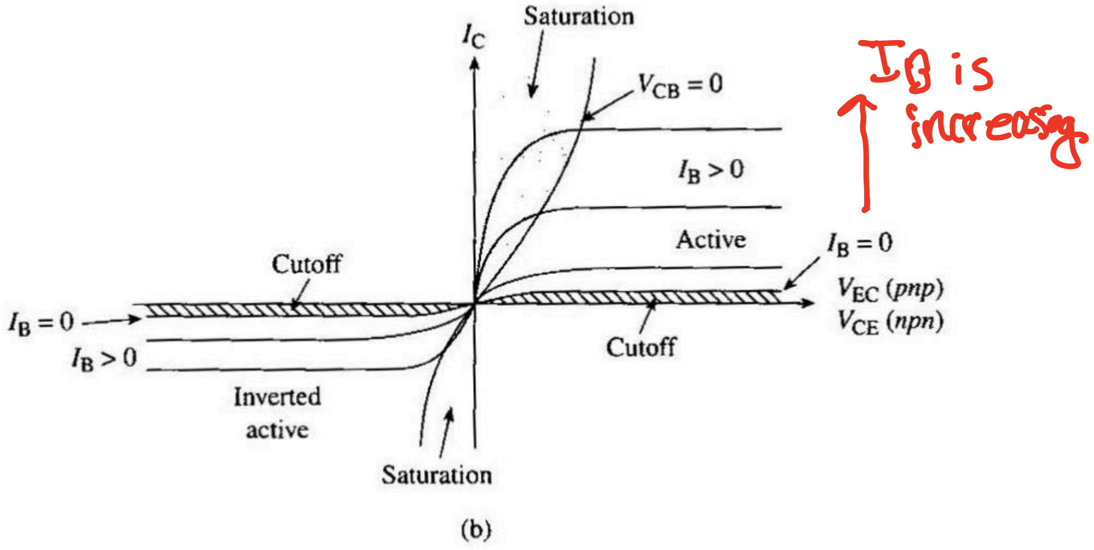
Mode	EB Junction	CB Junction	Applications
Cut-off	Reverse biased	Reverse biased	Open-switch
Active	Forward biased	Reverse biased	Amplifiers
Reverse Active	Reverse biased	Forward biased	Attenuators
Saturation	Forward biased	Forward biased	Short-switch

Full picture of *I-V* Characteristics



I_c vs. V_{EC} curve





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.

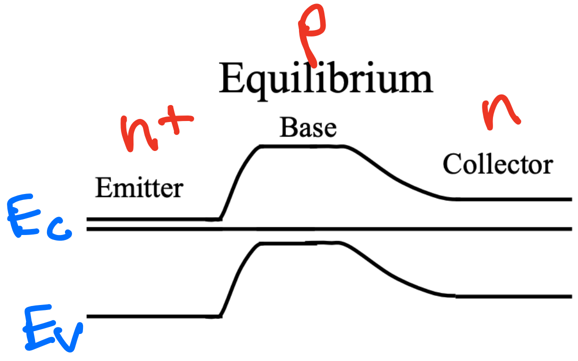
Sources: A. Doolittle ECE 3040 Slides

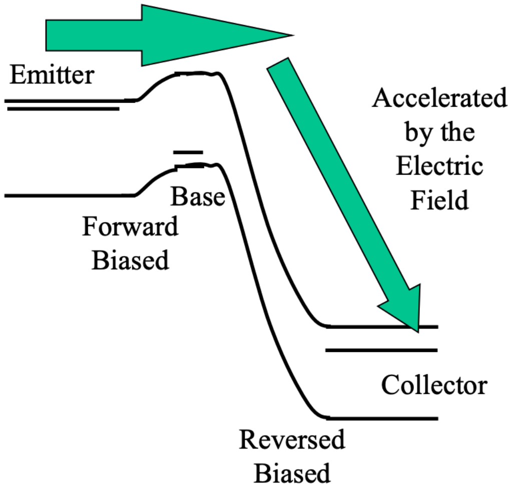
Normal/Active Mode: Band Diagram

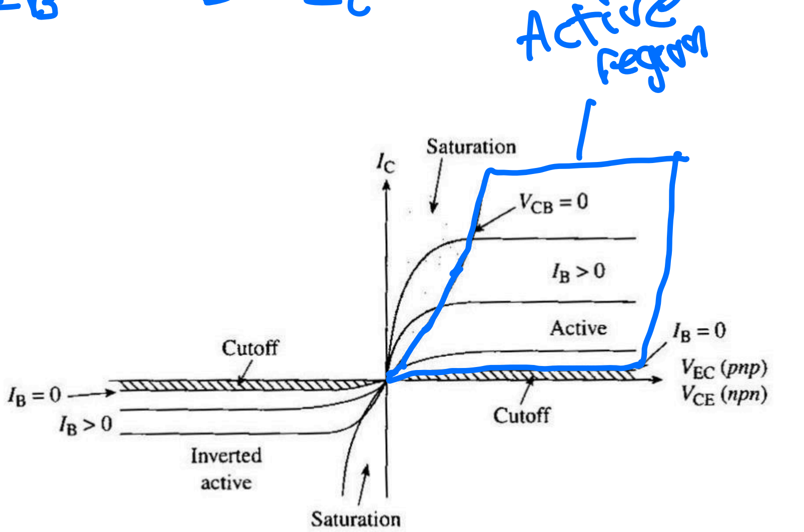
- This is is normal mode of operation for amplifiers
- For pnp (npn): EB (BE) junction is FB, CB (BC) junction is RB
- Collector current nearly matches I_E current
- The curves are practically flat at a given I_B

$I_E = I_C + I_B$ ← typically very small

$I_E \approx I_C$



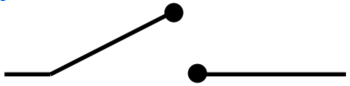


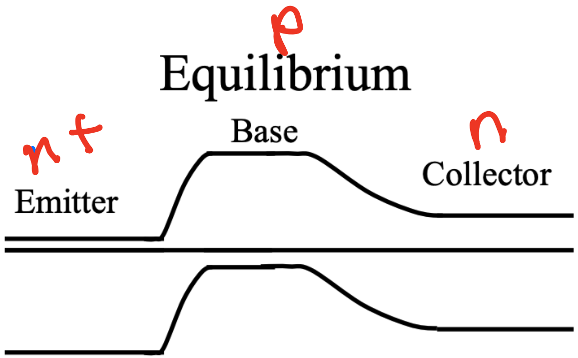


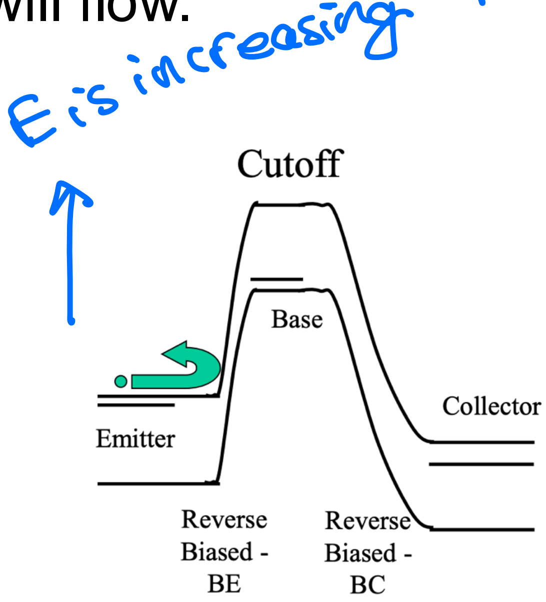
Sources: A. Doolittle ECE 3040 Slides

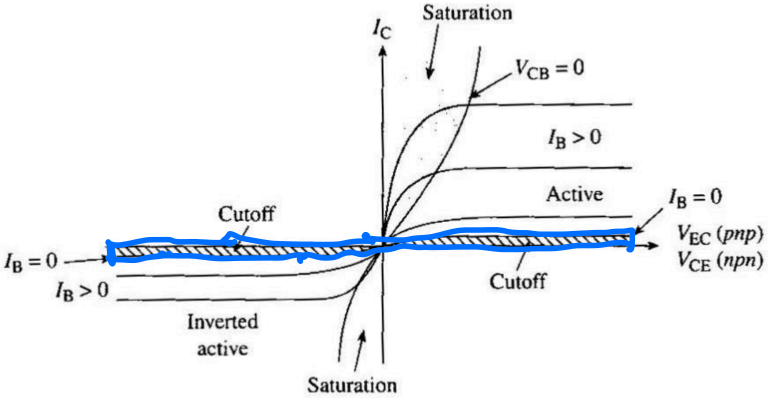
Cut-off Mode: Band Diagram

- This is the "off" state (open-circuit) condition when transistor is used as a switch. Very little current flow!
- Both junctions are RB, so barriers to particle flow are very high. Only a small leakage current will flow. (IR from p-n junction)





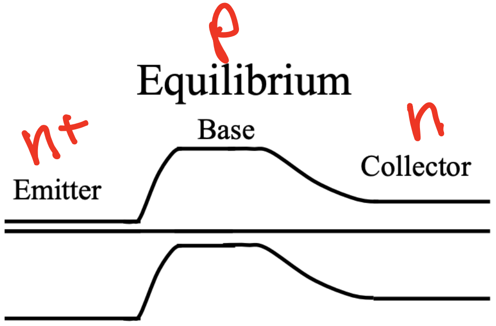


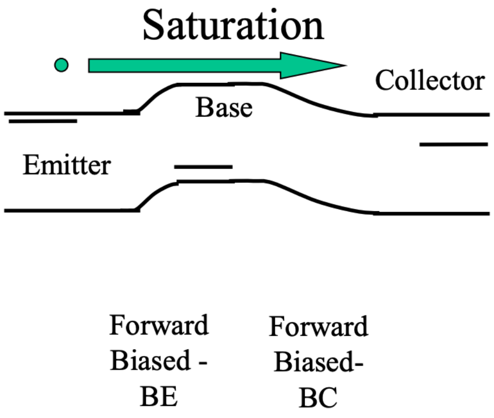


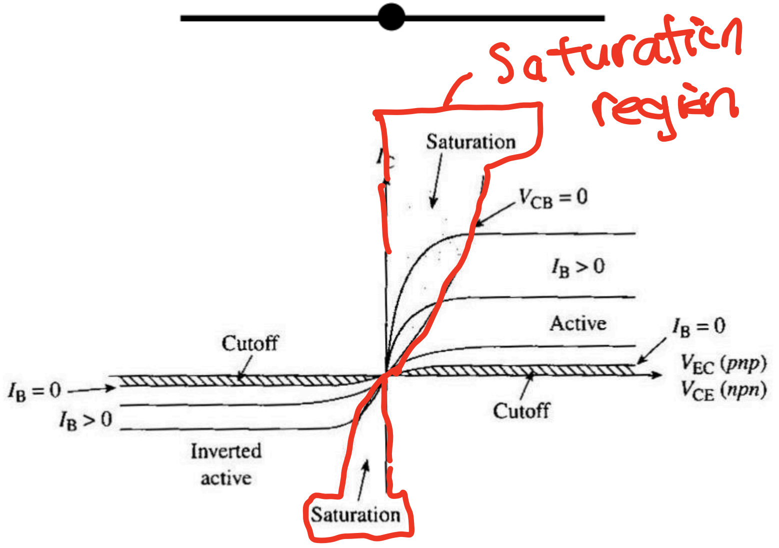
Sources: A. Doolittle ECE 3040 Slides

Saturation Mode: Band Diagram

- This is the "on" state (short-circuit) condition when transistor is used as a switch. High current flow!
- Both junctions are FB, so barriers to particle flow are lowered, allowing large currents to flow.





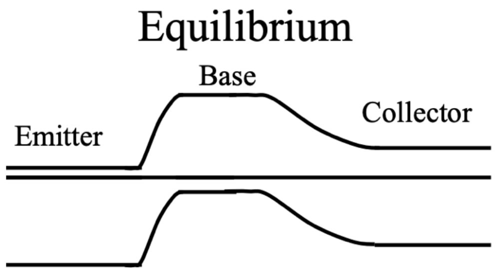


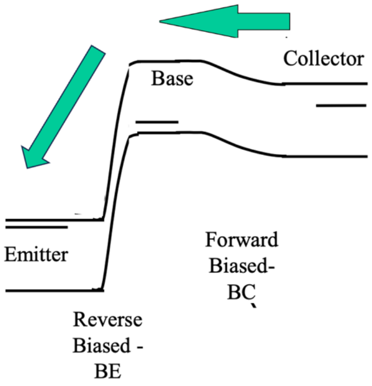
Sources: A. Doolittle ECE 3040 Slides

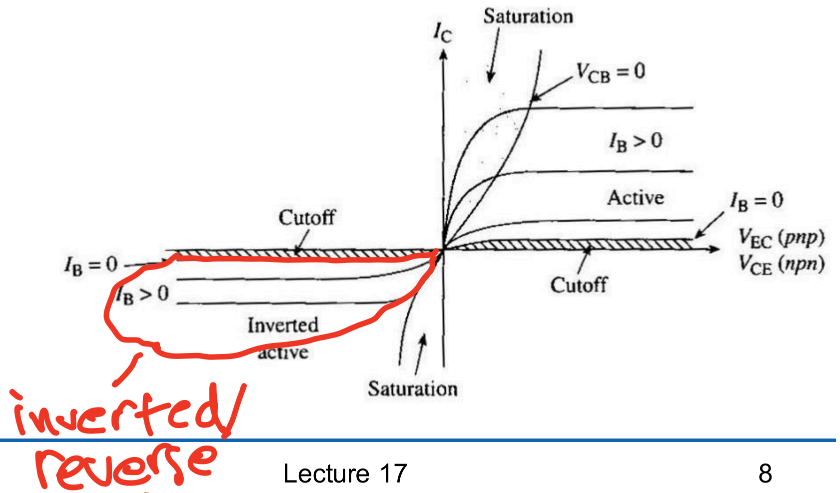
Reverse Active Mode: Band Diagram

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

$\beta_R << \beta$







Sources: A. Doolittle ECE 3040 Slides

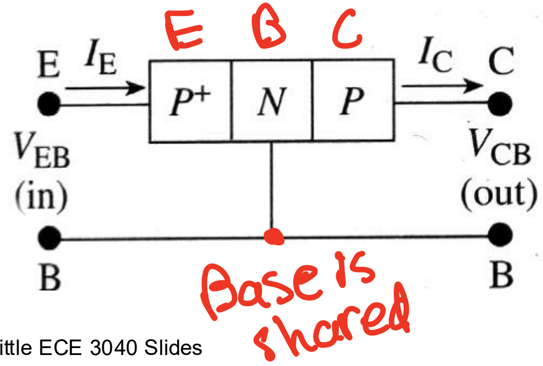
active

Biasing Configurations (Topologies)

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

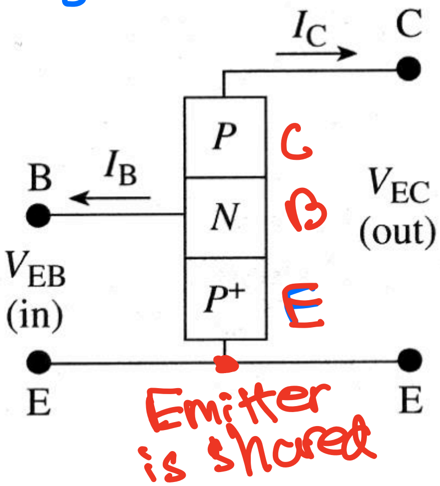
1. Common-Base

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



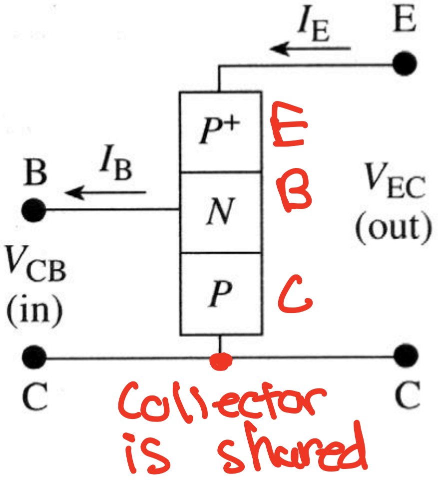
2. Common-Emitter

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



3. Common-Collector

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



Sources: A. Doolittle ECE 3040 Slides

Additional Terminology for Gain

$I_E = I_C + I_B$

- In previous lectures, we introduced these 2 parameters:
  - α (current transfer ratio, representing emitter-to-collector current amplification) not significant amplification
  - β (Base-to-collector current amplification) significant amplification
- α is also called the *common-base current gain* (typically ≥ 0.98)
- β is also called the *common-emitter current gain* (typically ≈ 20-200)
  - Ex. If β = 100, 1 e- will flow from base terminal for every 100 e- flowing between EC in an npn BJT
- They are related by the following identities:

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

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

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

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

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

Emitter Bandgap Narrowing

- How do we raise β? Typically, we increase the emitter doping, N_E
- But, when N_E increases, $n_{iE}^2 \gg$ $n_{i,typical}^2$
- This is called the *heavy doping effect*, AKA bandgap narrowing
- Why? Heavy doping can decrease E_g, and $n_i^2 \propto \exp(-E_g)$

$$n_i^2 = N_c N_v e^{-E_g/kT} \qquad n_{iE}^2 = n_i^2 e^{\Delta E_{gE}/kT}$$

- 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 10^{20} cm^{-3}, $\Delta E_{gE} < 140$ meV at 10^{21} cm^{-3}

$E_{g,typical} \approx 1.1$ eV

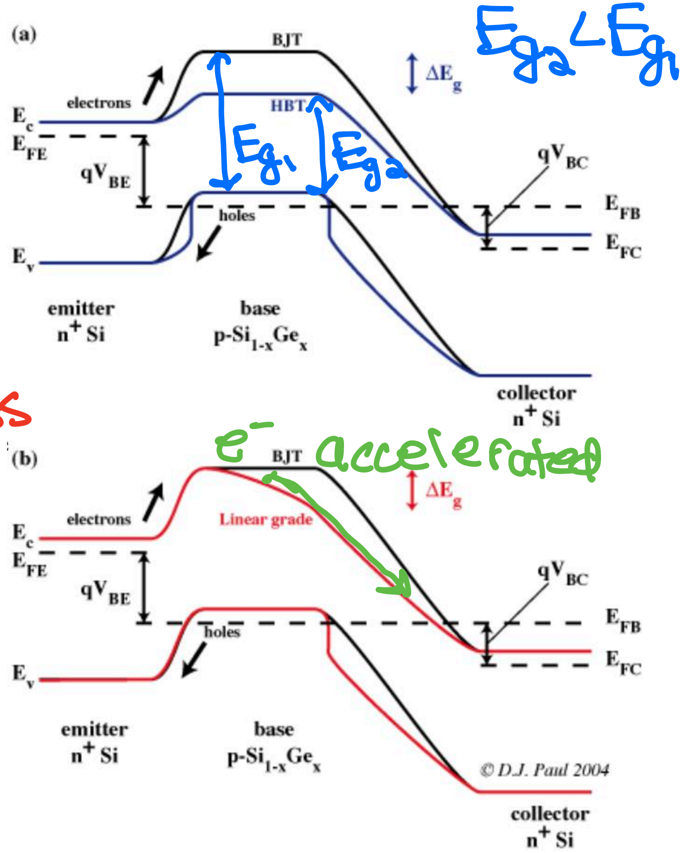
$N_E = 10^{19}\ cm^{-3} \rightarrow E_g \approx 1.05$ eV

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

Heterojunction BJT and Compositional Grading

- Another method to raise β: raise n_{iB} by using smaller bandgap base material ($E_{gE} > E_{gB}$)
  - Si emitter + SiGe base ← narrower E_g in base
  - InP emitter + InGaAs base
  - GaAlAs emitter + GaAs base
- Device is known as a heterojunction bipolar transistor, HBT $Ga_{0.2}Al_{0.8}As \rightarrow Ga_{0.8}Al_{0.2}As$
- We can further improve HBT by compositionally grade the base
  - Creates a built-in E-field, which reduces transit time τ_t (e.g. improves speed) 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, Q_p, due to excess carriers

1 A = 1 C/s

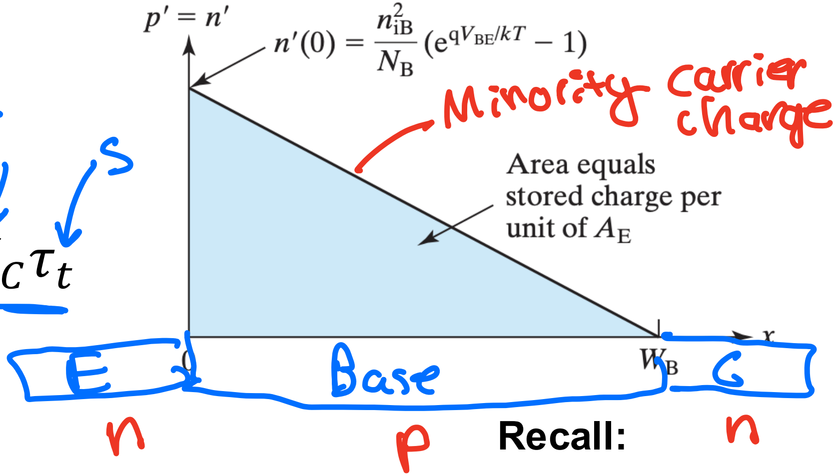
- We found

units: C

- $Q_p = \frac{1}{2}(base\ x\ height) = \frac{qA\frac{n_i^2}{N_B}(e^{\frac{qV_{EB}}{kT}}-1)W_B}{2} = I_C\tau_t$

- Where

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



Recall:

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

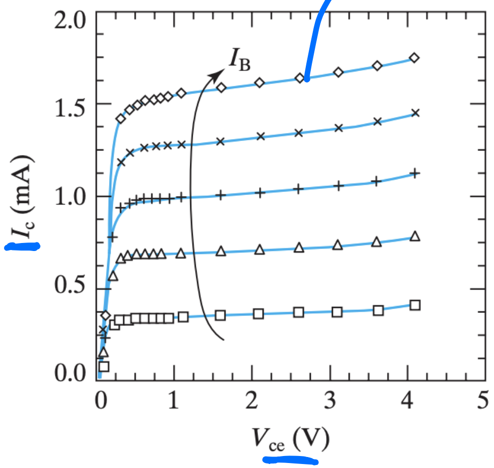
- Hence, to reduce (i.e., to make a faster BJT), we can either use a compositionally graded HBT OR reduce W_B

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 forward active (normal) mode
  - Known as the *early effect*
  - Not desired. Hight output conductance (dI_C/dV_{CE}) is deleterious to voltage gain in circuits
- The flatness of the I-V curve is described by the early voltage, V_A
- Large output resistance, r_o, (large V_A) are desired for high voltage gain

not flat

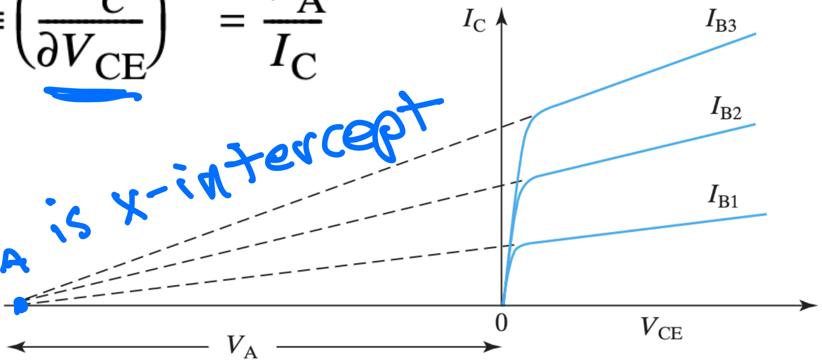


(a)

Not your applied bias

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

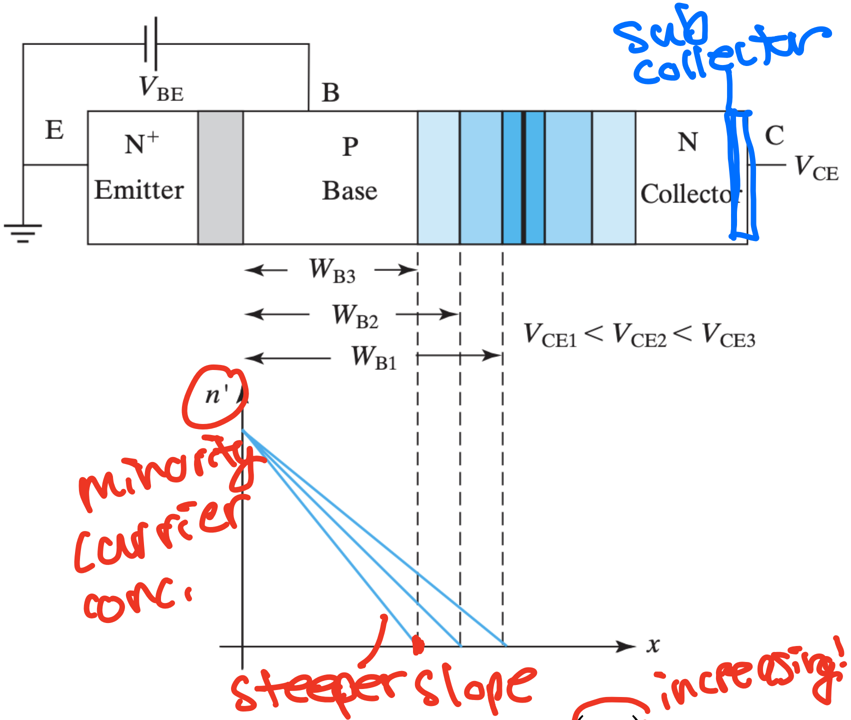
V_A is x-intercept



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 SCR width (depletion)
- This decreases neutral base region width, W_B
- I_C subsequently increases! (e.g. excess carrier conc. slope increases) I_C is diff. driven
- In reality, $N_C \ll N_B$ so that way most of the CB depletion region is on the collector side to suppress the Early effect
- What about series resistance? A heavily doped subcollector 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*