

ELEN E3106/4106 Lecture 16

BJTs Part II

Outline

- Cross-Section of fabricated BJT
- Minority carrier concentrations
- Approximations of current in the 3 regions
- Gummel numbers and plots
- High-level injection & Knee Current
- Current Gain

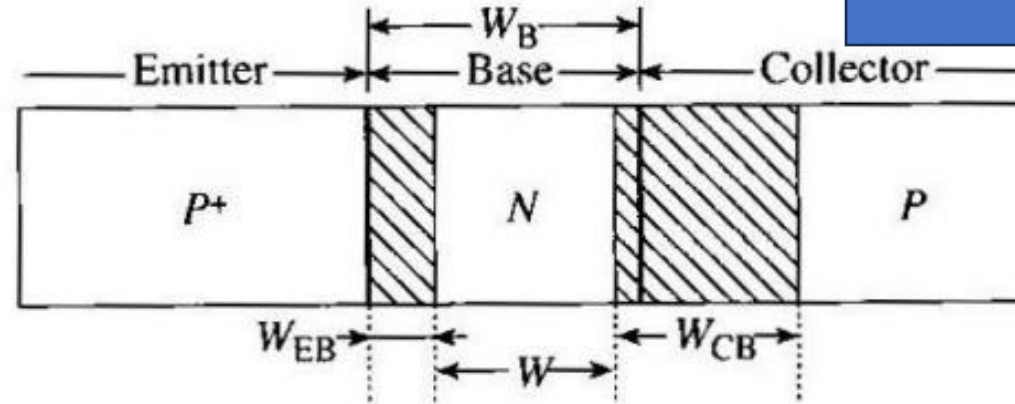
Assignments:

Reading: Streetman and Banerjee §7.1-7.4

Reading: C. Hu §8.1-8.4

Terminology and Notation ()

Note: For n-p-n, the subscripts on the right sides of the equal signs will flip from n to p or vice verse (ex. $D_E = D_p$ in n-p-n) Why? Because we are focusing on the minority carrier types in each region!



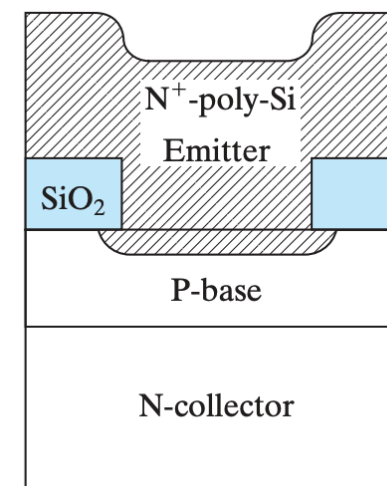
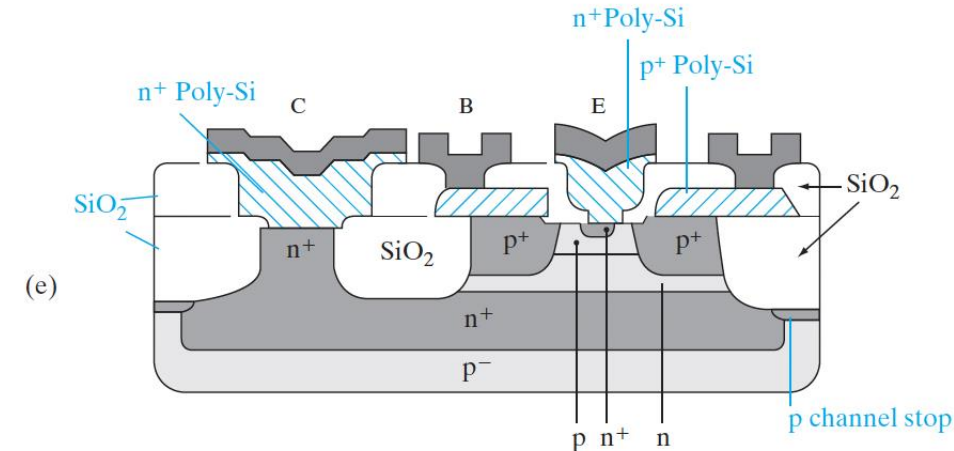
$$\begin{aligned} I_E \\ W_E \\ N_E = N_{a,E} \\ D_E = D_n \\ \tau_E = \tau_n \\ L_E = L_n \\ n_E = \frac{n_{iE}^2}{N_E} \end{aligned}$$

$$\begin{aligned} I_B \\ W_B \\ N_B = N_{d,B} \\ D_B = D_p \\ \tau_B = \tau_p \\ L_B = L_p \\ n_B = \frac{n_{iB}^2}{N_B} \end{aligned}$$

$$\begin{aligned} I_C \\ W_C \\ N_C = N_{a,C} \\ D_C = D_n \\ \tau_C = \tau_n \\ L_C = L_n \\ n_C = \frac{n_{iC}^2}{N_C} \end{aligned}$$

Cross-Section of a Realistic BJT

- What type of BJT is this?
- Why are there extra n^+ and p^+ regions?
- Why do we need the SiO_2 ?



Assumptions for Simplified BJT Analysis

- Back to our simplified analysis of a p-n-p. We will assume:
 1. Holes diffuse from _____ (ignore drift)
 2. I_E made up entirely of holes (emitter injection efficiency $\gamma = 1$)
 3. Collector saturation current is negligible
 4. Ignore _____ (for now, then add it back in)
 5. All currents and voltages are steady-state
 6. Cross-sectional area of both junctions is _____ and current flow is essentially _____

- What ratio of dimensions constitute narrow (short) vs. long base?
 - Short: $W_B \ll 3L_B$
 - Long: $W_B \gg 3L_B$

Sources: Textbook

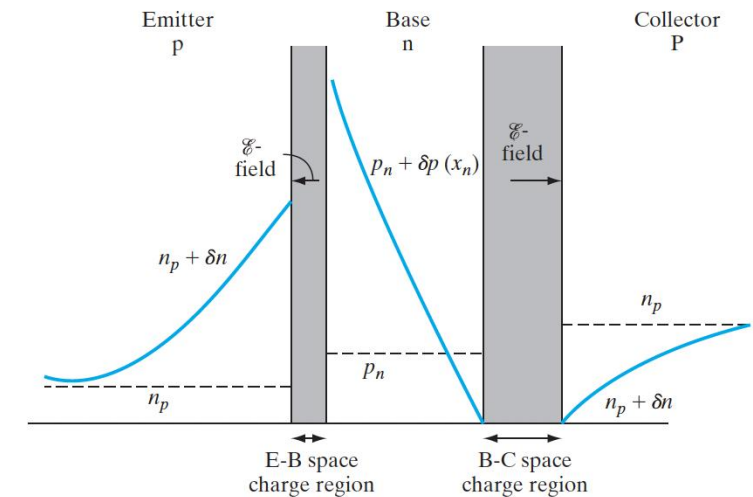
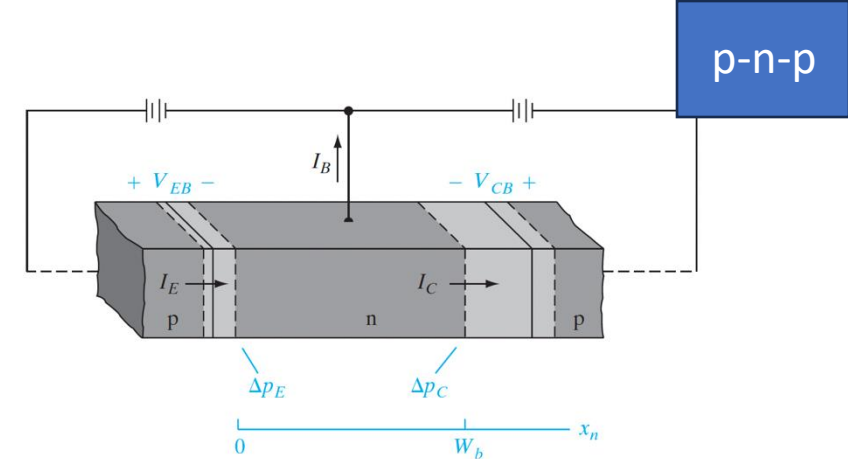
Narrow Base Minority Carrier Concentrations

- +x-dir: Current entering base: ____; current leaving base: ____
- A is cross-sectional ____, W_B is ____ of the base
- Recalling our equation for excess minority carrier concentrations injected at the edge of the depletion region ($\Delta p_n = p_n (e^{\frac{qV}{kT}} - 1)$), we can write the excess h+ concentrations at the edge of the ____ and ____ depletion regions:

$$\Delta p_E = p_n (e^{qV_{EB}/kT} - 1) \simeq$$

$$\Delta p_C = p_n (e^{qV_{CB}/kT} - 1) \simeq$$

- Which simplify when EB is strongly ____ ($V_{EB} \gg kT/q$) and CB is strongly ____ ($V_{CB} \ll 0$)
- Also recall we denote excess carrier concentrations as a function of distance $\delta p(x_n)$ where $\delta p(0) = \underline{\hspace{1cm}}$; $\delta p(W_b) = \underline{\hspace{1cm}}$



p-n-p

Approximation of Collector Current

- Now, we can *almost* find the collector (hole) current (assuming _____):

$$I_C \approx -qAD_p \left. \frac{dp}{dx} \right|_{x=W_B}$$

- From our discussion of narrow-base diodes ($W_b \ll L_p$), $\frac{dp}{dx}$ varies linearly with the _____ approximation, and the slope is:

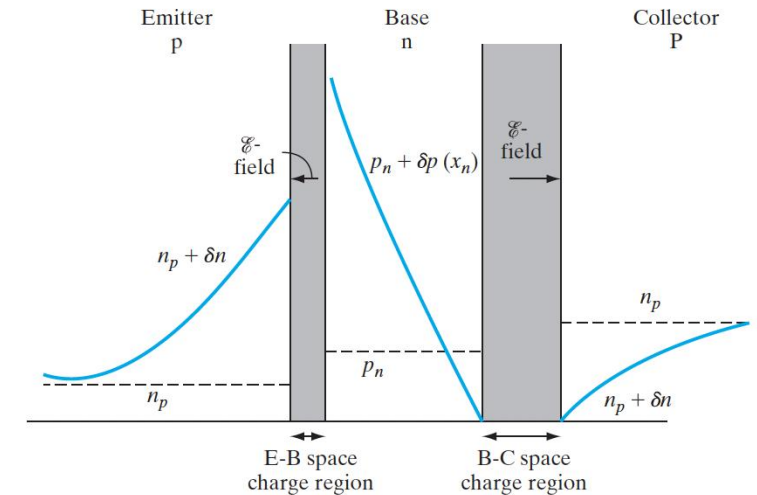
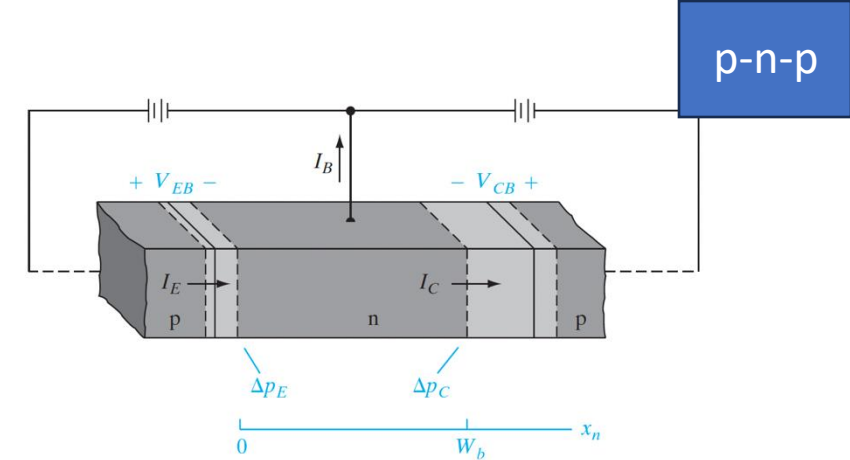
$$\frac{dp}{dx} \approx \frac{\cdot}{W_B} \approx \frac{\cdot}{W_B} (e^{\frac{qV_{EB}}{kT}} - 1)$$

- Then, our current becomes:

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

- Which we can rewrite in terms of the _____, _____

$$I_C = I_S (e^{\frac{qV_{EB}}{kT}} - 1)$$



Base Gummel Number

- We can rewrite the collector current $I_C = I_S(e^{\frac{qV_{EB}}{kT}} - 1)$, as $I_C = A \frac{qn_i^2}{G_B} (e^{\frac{qV_{EB}}{kT}} - 1)$

- Where _____, the _____ (units: s/cm⁴) is:

$$G_B = \frac{n_i^2}{n_{iB}^2} \frac{N_B}{D_B} W_B = \frac{n_i^2}{n_{iB}^2} \frac{n}{D_B} W_B$$

n_{iB} is the intrinsic carrier concentration of the base material. The subscript, B, is added to n_i because the base may be made of a different semiconductor than the emitter and collector material!

- The more general definition valid even for _____ in the base and high-level conditions:

$$G_B \equiv \int_0^{W_B} \frac{n_i^2}{n_{iB}^2} \frac{n}{D_B} dx$$

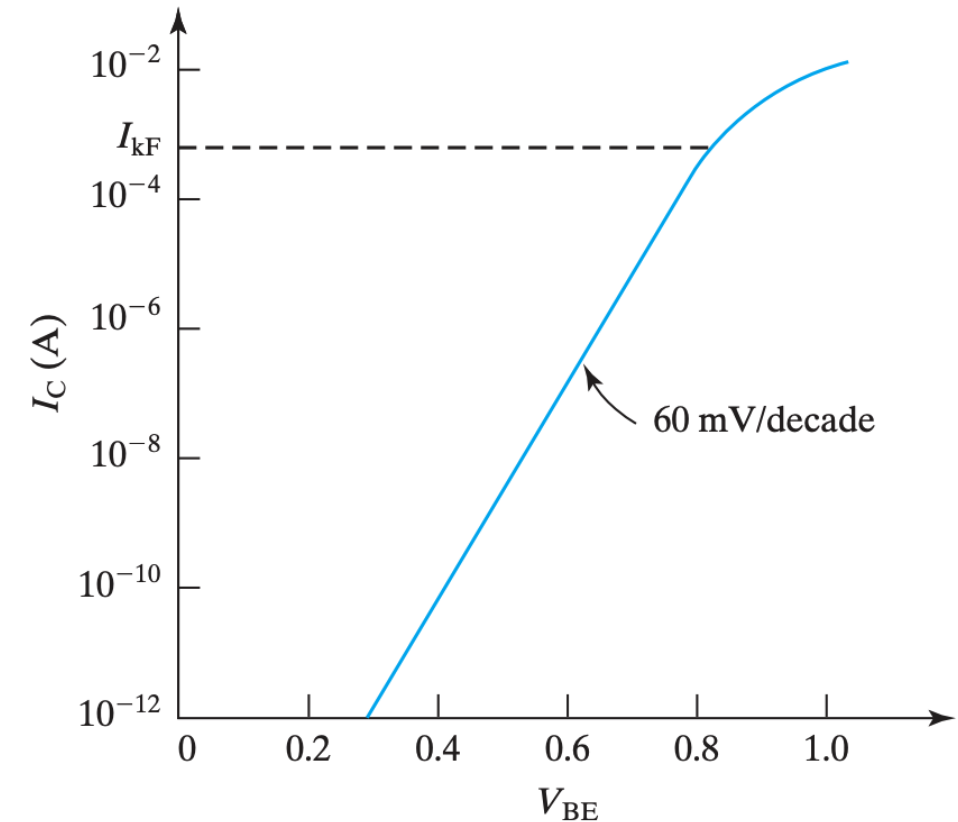
- In the special case where $n_i = n_i^B$, D_B is constant, and low-level injection (_____):

$$G_B = \frac{1}{D_B} \int_0^{W_B} N_B(x) dx = \frac{1}{D_B} \times \text{base dopant atoms per unit area}$$

Gummel Plots

n-p-n. How can we tell? Plot in terms of V_{BE} instead of ____ !

- So, now we know the base gummel number is basically _____ to the base dopant density per area
 - The _____ the base dopant density, the _____ I_C will be for a given V_{BE}
 - G_B contains all of the subtleties of transistor design that impact _____
 - And... G_B can be easily experimentally determined from the _____ (semilog of I_C and sometimes I_B versus _____)
1. Extrapolate straight line to find the y-intercept. This is I_S .
 2. $G_B = Aqn_i^2/I_S$



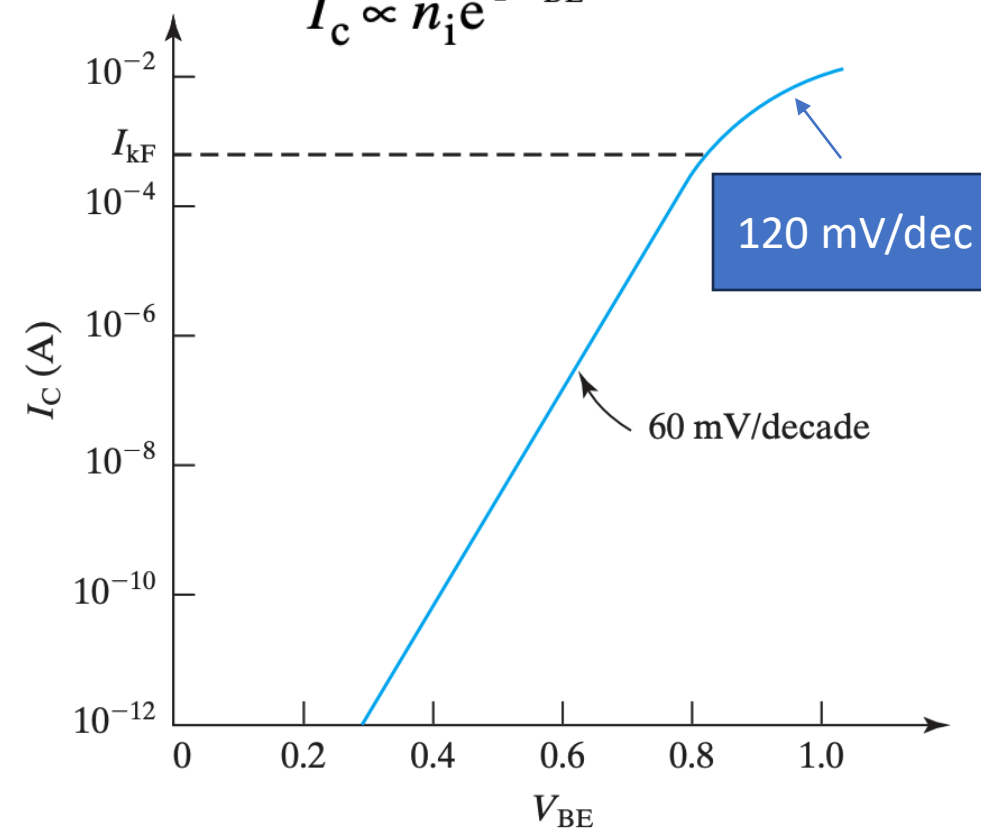
High Level Injection and Knee Current

- Why does the slope decrease at high I_C ?
- At large V_{BE} , $\delta n(x_p)$ in the base can become larger than the base doping concentration:
 $\delta n(x_p) = \delta p(x_p)$ _____
- Recall in H.L.I., minority AND _____ carrier concentrations are changed substantially in base region
- Thus, the _____ is increased by a factor of 2 and becomes 120 mV/dec
- The current at which the slope changes is called the _____, _____

$$n \approx p \approx n_i e^{\frac{qV}{2kT}}$$

$$G_B \propto n_i e^{qV_{BE}/2kT}$$

$$I_C \propto n_i e^{qV_{BE}/2kT}$$



Approximation of Base Current

What about the base current?

- From our last discussion on _____, base current exists primarily due to e- which

(a) are _____ into the emitter across the _____ biased EB junction

(b) recombine with a small fraction (____) of the h+ transiting the base

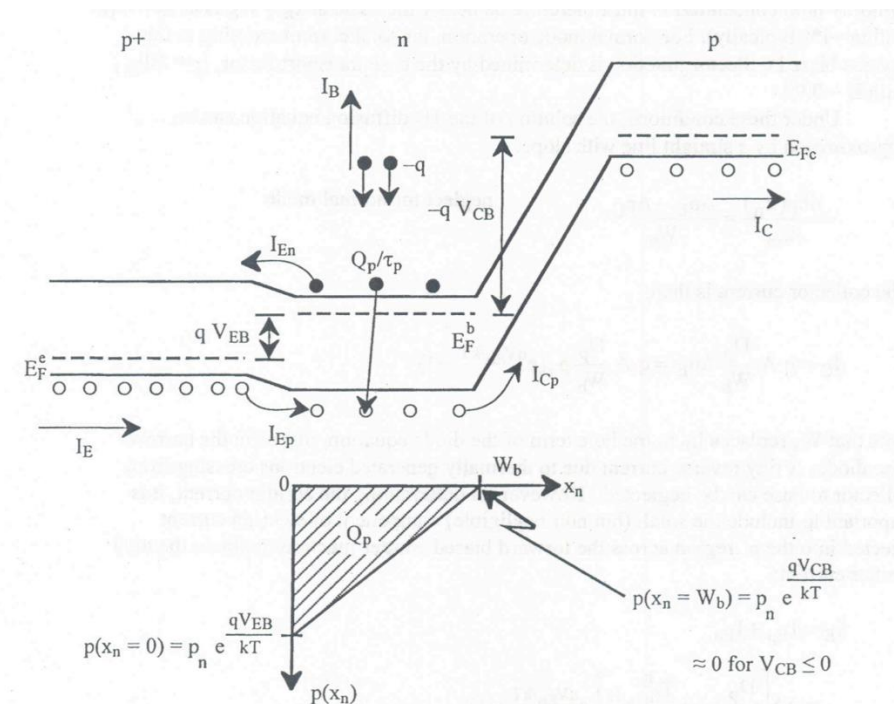
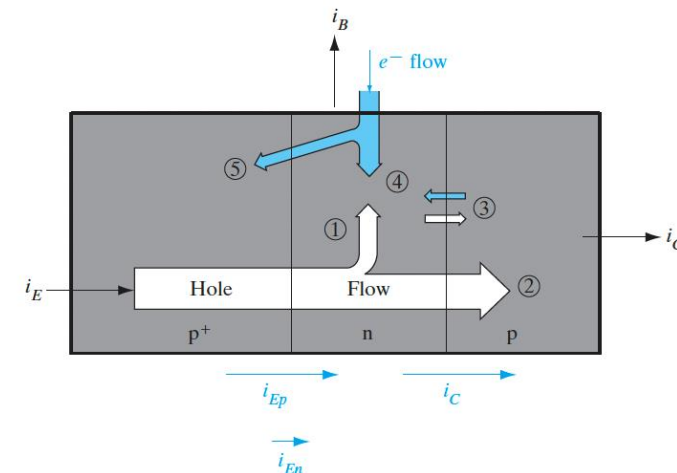
$$I_B = I_B(\text{inj. to E}) + I_B(\text{recomb. with excess holes})$$

$$I_B \approx I_{En} + Q_p/\tau_p$$

$$I_B \approx I_{En} + \frac{1}{2\tau_p} AW_B p_n \left(e^{\frac{qV_{EB}}{kT}} - 1 \right)$$

- The current _____ can then be written:

$$\beta = \frac{I_C}{I_B} \approx \frac{I_{Ep}}{I_{En} + I_{B,rec.}}$$



Emitter Gummel Number and Base Current

- Conveniently, we can express the base current in terms of another Gummel number the _____, _____

$$I_B = A_E \frac{qn_i^2}{G_E} (e^{qV_{BE}/kT} - 1)$$

$$G_E = \int_0^{W_E} \frac{n_i^2}{n_{iE}^2} \frac{n}{D_E} dx$$

Similarly, n_{iE} is the intrinsic carrier concentration of the emitter material. The subscript, E, is added to n_i because the base may be made of a different semiconductor than the emitter.

- In the case where the emitter is _____, and D_E is constant:

$$I_B = A_E q \frac{D_E n_{iE}^2}{W_E N_E} (e^{qV_{BE}/kT} - 1)$$

Expressions for Current Gain

β can be simplified in 2 ways:

1. If we assume _____ in the base,

$$\beta(\text{no recomb.}) \approx \frac{I_C}{I_{En}} \approx \frac{D_B L_E N_E}{D_E W_B N_B}$$

2. If emitter injection efficiency is perfect, _____, $I_{B,rec.} \gg I_{B,inj.}$ and

$$\beta(\gamma \rightarrow 1) \approx \frac{I_C}{I_{B,rec.}} \approx 2 \left(\frac{L_B}{W_B} \right)^2$$

Where $L_B^2 = D_B \tau_B$, and $W_B \ll L_B$

- Where did the square and factor of 2 come from?
- How do you find $D_{E,B}$? Recall _____: _____

Approximation of Emitter Current

- Now, we can find the emitter (hole) current (diffusion only), considering there is a small _____ from the n-type base (#____ on diagram)
- If emitter is long _____) minority carrier concentration _____ decays. If emitter is short, ($W_E \ll L_E$), straight line approximation applies.
- If emitter is long, expression for long-base diode:

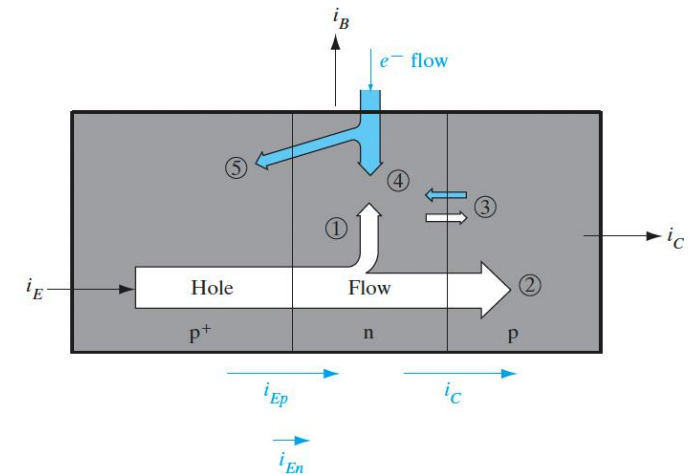
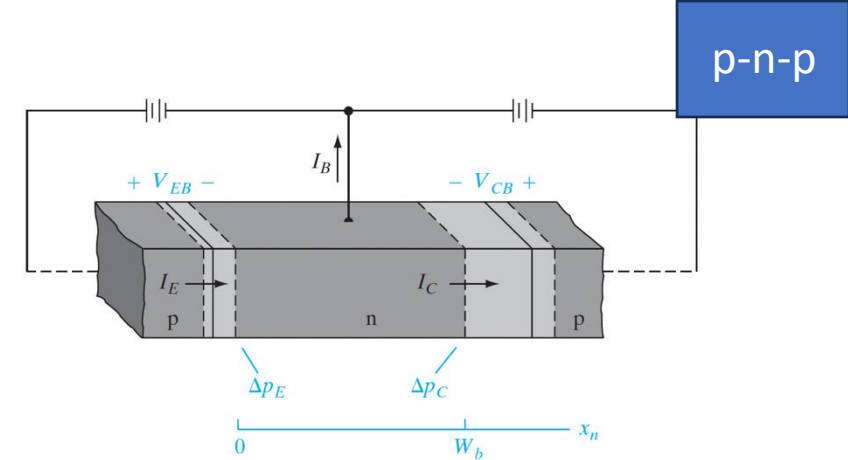
$$I_{En} = qA \frac{D_n^E}{L_n^E} \frac{n_i^2}{N_E} (e^{qV_{EB}/kT} - 1)$$

- We can finally write total emitter current,

$$I_E = I_{Ep} + I_{En} \approx I_C + I_{En} \approx qAn_i^2 \left[\frac{D_p^B}{W_B N_B} + \frac{D_n^E}{L_n^E N_E} \right] (e^{\frac{qV_{EB}}{kT}} - 1)$$

And, now we can calculate the FOM emitter injection efficiency, $\gamma = I_{Ep}/I_E$

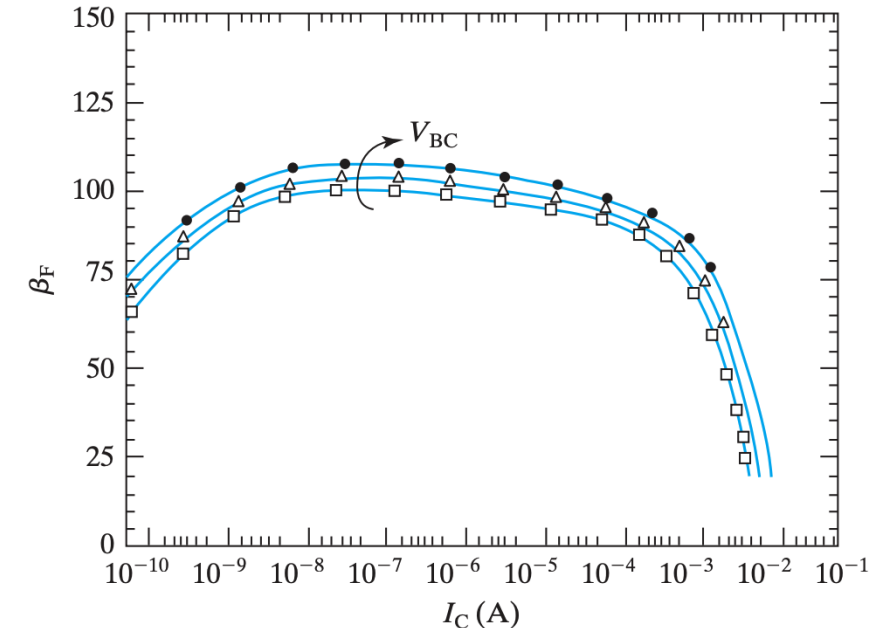
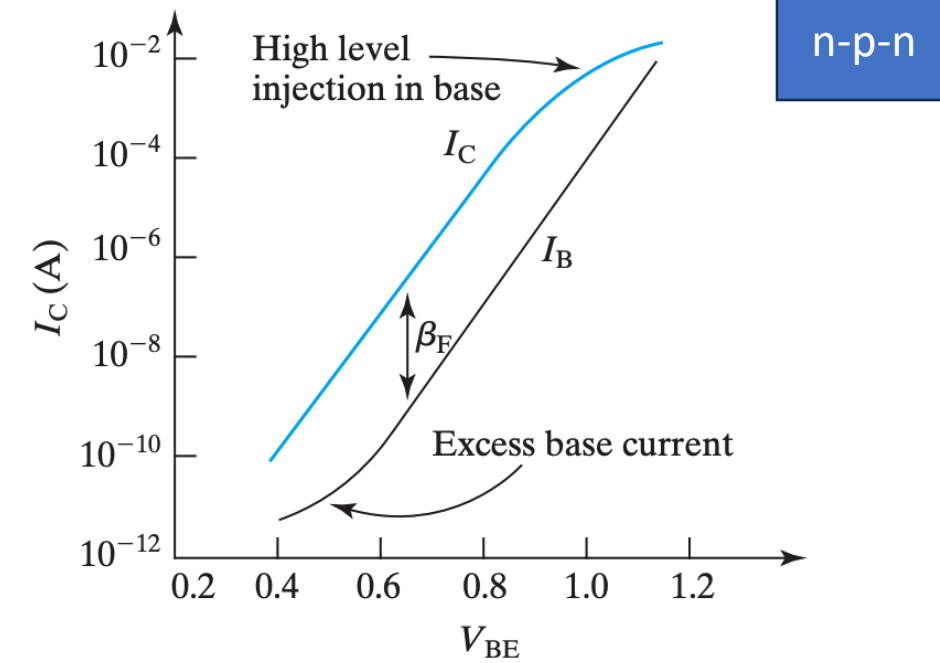
Sources: Textbook, E. Pop ECE 340 Lecture Slides



Gummel Plot and β Fall-Off at High and Low I_C

- Slide 10 recap: High I_C (used for _____)
 - _____ effect in the base flattens I_C
 - I_B injected into emitter is _____ because emitter is very heavily doped (it's practically impossible to inject more _____ than N_E)
- Low I_C (used for low-power circuits)
 - Non-idealities such as _____ in the EB _____ can dominate at low current levels

$$I_B = I_B(\text{inj. to E}) + I_B(\text{recomb. with excess holes})$$
 - Recall we accounted for this with the diode ideality factor, _____
- Summary: Current gain, $\beta = \frac{I_C}{I_B}$ is degraded in _____ high, low I_C cases



Transit Time and Charge Storage

- By design, $\beta \gg ______$ for current *amplification*. Let's discuss the essential features of current amplification effects (neglecting $I_{B,inj.}$)
- In a properly designed amplification circuit, I_B can be $______$
- The junction voltages are not clamped and will adjust themselves accordingly to changes I_B
- Due to space charge neutrality, the stored minority hole charge is determined by the $______$:

$$Q_p = I_{B,rec.} \tau_p$$

- I_C depends on the stored charge, and an average $______$, $______$, which is much less than the average recombination lifetime ($\tau_t \ll \tau_p$)

$$I_C = Q_p / \tau_t$$

$$\beta(\gamma \rightarrow 1) \approx \frac{I_C}{I_{B,rec.}} \approx 2 \left(\frac{L_p}{W_B} \right)^2 = ______ \gg 1$$

- Transit time: average time it takes for excess carrier to move from emitter to collector
- Charge storage and transit time are crucial factors in determining the $______$ and $______$ of a BJT, as we will see

