Semiconductor Devices - Hour 30  BJT Example: Part II  (MCD: Entire Bipolar Calculation)

Last Time: Started with the physical structure of a bipolar transistor 

**N** Emitter  
|  | P Base  |  | **N** Collector  

Picked the doping of each layer: 

\[ N_{d,E} = 10^{19} \text{ cm}^{-3} \]  

\[ N_{a,B} = 10^{17} \text{ cm}^{-3} \]  

\[ N_{d,C} = 10^{15} \text{ cm}^{-3} \]

Picked the full ("metallurgical") thickness of each layer: 

0.2 micron  

0.2 micron  

250 micron

Immediately ran into a problem - what are the "effective" layer thicknesses? 

\[ x_E_{eff} = ? \]  

\[ x_B_{eff} = ? \]  

\[ x_C_{eff} = ? \]

Effective thicknesses depend on depletion layers - which depend on voltages applied to junctions

So next I had decide how I was going to USE the transistor! 

Chose: 

- "Common emitter" amplifier circuit  
- Power supply voltage of 5 volts  
- Emitter-base forward bias of 0.5 volts  
- Small enough load resistor that could ignore its voltage drop => collector at ~ 5 volts

Note, final choice (small load R) may not be good circuit sense but allowed me to simplify OUR problem

\[ V_{applied\_left} \neq V_{p\_layer} - V_{n\_layer} \neq V_{BE} \neq 0 \]  

\[ V_{applied\_right} = V_{p\_layer} - V_{n\_layer} = V_{BC} < 0 \]

\[ V_{BE} = 0.5 \text{ volt} \]  

\[ V_{BC} = -4.5 \text{ volt} \]

Signs on voltages are EXTREMELY important and follow from diagram and \( V_{xy} = V_x - V_y \)

THEN able to calculate full depletion widths, penetrations each direction, & EFFECTIVE LAYER THICKNESSES

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**Choice 1:** Complex hyperbolic equations with both \( V_{BE} \) and \( V_{BC} \) voltage factors (book/my earlier lectures):

Completely general: Any layer thickness / Any junction bias  

However: A bear to use!

**Choice 2:** "Straight-line" approximations for emitter and base layers 

Appropriate if: Emitter & base layers are << thinner than their minority carrier's diffusion length  

AND  

E-B junction slightly forward biased / B-C junction strongly reverse biased

This is exactly what you will want anyway; if are trying to design an amplifying transistor!

So we WANT a transistor that will obey simpler equations - just need to check to see if we DO satisfy conditions:

Voltage bias conditions WERE chosen to satisfy requirements!  

Are our emitter and base layers thinner than diffusion lengths?  

Had to fully evaluate parameters of MINORITY CARRIER in each layer
Equilibrium minority carrier concentration in each layer is \( n_i^2 \) / (majority carrier concentration):

\[
\begin{align*}
\frac{n_{p0_E}}{n_{n0_E}} &= \frac{n_{n0_B}}{n_{p0_B}} &= \frac{n_{p0_C}}{n_{n0_C}} \\
\frac{n_{p0_E}}{n_{n0_E}} &= 22.5 \times 10^3 \ \text{cm}^{-3} \quad \frac{n_{p0_B}}{n_{n0_B}} &= 2.25 \times 10^5 \ \text{cm}^{-3} \quad \frac{n_{p0_C}}{n_{n0_C}} &= 2.25 \times 10^5 \ \text{cm}^{-3}
\end{align*}
\]

Then to get minority carrier diffusion lengths \((L = \sqrt{D \tau})\) needed minority diffusivity and lifetime.

Assumed for all minority carriers: \( \tau = 10^6 \) sec

To get the diffusivities, used Einstein's Relationship:

\[
D = \frac{kT}{\mu q}
\]

For which we needed the minority carrier mobilities in each layer - based on ion concentration in each layer:

<table>
<thead>
<tr>
<th>Doping</th>
<th>Emitter</th>
<th>Base</th>
<th>Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doping = Ions:</td>
<td>( N_d_E = 1 \times 10^{19} \ \text{cm}^3 )</td>
<td>( N_a_B = 1 \times 10^{17} \ \text{cm}^3 )</td>
<td>( N_d_C = 1 \times 10^{15} \ \text{cm}^3 )</td>
</tr>
</tbody>
</table>

NOTE: Getting the last step right = "One of 10 Favorite Test Errors" in ECE 303

For which we needed the minority carrier mobilities in each layer - based on ion concentration in each layer:

- Emitter: \( \mu_p_E = 70 \ \text{cm}^2 \ \text{volt sec}^{-1} \)
- Base: \( \mu_n_B = 801 \ \text{cm}^2 \ \text{volt sec}^{-1} \)
- Collector: \( \mu_p_C = 458 \ \text{cm}^2 \ \text{volt sec}^{-1} \)

 anonymous show of hands: Does this minority stuff make sense yet?

Should we go over more carefully or are you content with screwing up on final?

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For the minority carrier profiles in NPN bipolar transistor (from later part of lecture 27):

\[
\delta_{\text{PNP}}(x) = \frac{qV_BE}{kT}(e^{qV_BE/kT} - 1) \frac{x - x_E}{x_E - x} \quad \text{Emitter}
\]

\[
\delta_{\text{PNP}}(x) = \frac{qV_BE}{kT}(e^{qV_BE/kT} - 1) \frac{x - x_B}{x_B - x} \quad \text{Base}
\]

\[
L_{p_E} = 13.461 \ \text{micron} \quad L_{n_B} = 45.539 \ \text{micron} \quad L_{p_C} = 34.435 \ \text{micron}
\]

Which we compared with the layer's effective thicknesses:

\[
\begin{align*}
X_{E_{\text{eff}}} &= 0.199 \ \text{micron} \\
X_{B_{\text{eff}}} &= 0.1 \ \text{micron} \\
X_{C_{\text{eff}}} &= 247.42 \ \text{micron}
\end{align*}
\]

For emitter and base: Effective layer thickness ARE << minority diffusion lengths Use Straight lines

For collector: Effective thickness >> minority diffusion length Use exponential / hyperbolic
NOW (finally) from these profiles, let's compute currents:

1) Emitter hole current:

\[ J_{pE} = q \, D_{pE} \, n_{p_E(x)} \frac{d n_{p_E(x)}}{dx} \]

Mathcad input:

\[ q \approx 1.6 \times 10^{-19} \text{coul} \]
\[ eV = q \text{ volt} \]
\[ k \approx 8.63 \times 10^{-5} \text{ eV/K} \]
\[ T = 300K \]

Holes flowing into thin emitter N-emitter of an NPN bipolar transistor

2) Electrons recombination inside the base:

\[ J_{RB} = \frac{q \, \chi_{B_{eff}} \, n_{p_B(x)}^2 \, \tau}{e} \]

Electrons recombining in thin base of an NPN bipolar transistor

3) Electrons flowing through the base:

\[ J_{nE} = q \, D_{nE} \, n_{n_E(x)} \frac{d n_{n_E(x)}}{dx} \]

Electrons flowing through the thin base of an NPN bipolar transistor
Which in the thin base / low recombination / straight-line model this is ∼ \( J_{nC} \) 

\( J_{nC} := \tilde{J}_{nE} \)

4) Holes leaking in from collector:

- P-Base
- N-Emitter
- N-Collector

δ

\[ \bar{p}_{n,C} \approx \tilde{p}_{no,C} \tilde{L}_{p,C} \]

Which plugging slope into diffusion current expression gives:

\[ J_{pC} := q \frac{D_{p,C} p_{no,C}}{L_{p,C}} \]

\[ J_{pC} = 1.24 \times 10^{-10} \text{ A/cm}^2 \]

Holes flowing out of a thick collector

Can now calculate this transistor's operating parameters (with our choices of voltages)

\( \alpha_T = \text{"Base Transport Factor"} = \text{fraction of minority carriers making it across the base.} \)

\[ \alpha_T = 1 - 2.411 \times 10^{-6} \]

or for more precision:

\[ \alpha_T = 1 - 2.411 \times 10^{-6} \]

So:

\[ \alpha_T = 0.9999975 \]

Using calculator (which doesn’t round off) = 0.9999975

Can also calculate from definition in terms of currents (but play a little to retain precision):

\[ \beta := \frac{J_C}{J_B} = \frac{1}{D_{p,E} N_{a,B} x_{B \text{ eff}}} \frac{1}{2} \left( \frac{x_{B \text{ eff}}}{L_{n,B}} \right)^2 \]

Calculating from the formula:
We have a pretty high gain transistor!!

\[ \beta := \frac{1}{\frac{D_{p,E} N_{a,B} \gamma_{B,\text{eff}}}{D_{n,B} N_{d,E} \gamma_{E,\text{eff}}} \left( \frac{\gamma_{B,\text{eff}}}{\gamma_{E,\text{eff}}} \right)^2} \quad \beta = 2.265 \times 10^3 \]

Calculating from currents:

\[ \beta := \frac{J_C}{J_B} = \frac{J_{nC} + J_{pC}}{J_{pE}^+ - J_{RB} - J_{pC}} \]

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"Emitter Injection Efficiency" = desirable E-B current / all E-B current

\[ \left( \frac{J_{nE}}{J_{pE}} \right) \]

Don’t want \( J_{pE} \) because adds to \( J_B \) input I must provide

\[ \gamma := \frac{J_{nE}}{J_{nE} + J_{pE}} = \frac{1}{1 + \frac{D_{p,E} N_{a,B} \gamma_{B,\text{eff}}}{D_{n,B} N_{d,E} \gamma_{E,\text{eff}}}} \]

\[ \gamma = \frac{1}{1 + 4.391 \times 10^{-4}} = 0.99956 \]

From currents (playing around to get more accuracy):

\[ \gamma = \frac{1}{1 + 4.391 \times 10^{-4}} = 0.99956 \]

\[ \gamma = 1 - 4.391 \times 10^{-4} = 0.99996 \]

NOTE could have turned up Mathcad’s precision setting (menu: Math/Options/Precision) but then precision of EVERY equation in lecture would have increased!