ECE606: Solid State Devices
Lecture 28: BJT Design (I)

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Outline

1) Current gain in BJTs
2) Considerations for base doping
3) Considerations for collector doping
4) Conclusions

REF: SDF, Chapter 10
Ebers Moll Model

\[ I_B = A \frac{qD_p}{W_E} \frac{n_{i,E}^2}{N_E} (e^{qV_{BE}\beta} - 1) + A \frac{qD_p}{W_C} \frac{n_{i,C}^2}{N_C} (e^{qV_{BC}\beta} - 1) \]

\[ I_E = -A_E \left( \frac{qD_n}{W_B} \frac{n_{i,B}^2}{N_B} + \frac{qD_p}{W_E} \frac{n_{i,E}^2}{N_E} \right) (e^{qV_{BE}\beta} - 1) + A_E \frac{qD_n}{W_B} \frac{n_{i,B}^2}{N_B} (e^{qV_{BC}\beta} - 1) \]

\[ = I_{F0} (e^{qV_{BE}\beta} - 1) - \alpha_R I_{R0} (e^{qV_{BC}\beta} - 1) \]

\[ I_F = I_{F0} (e^{qV_{BE}\beta} - 1) \]

\[ I_R = I_{R0} (e^{qV_{BC}\beta} - 1) \]

\[ I_C = -A_C \frac{qD_n}{W_B} \frac{n_{i,B}^2}{N_B} (e^{qV_{BE}\beta} - 1) + A_C \left[ \frac{qD_n}{W_B} \frac{n_{i,B}^2}{N_B} + \frac{qD_n}{W_C} \frac{n_{i,C}^2}{N_C} \right] (e^{qV_{BC}\beta} - 1) \]

\[ = \alpha_F I_{F0} (e^{qV_{BE}\beta} - 1) - I_{R0} (e^{qV_{BC}\beta} - 1) \]
Gummel Plot and Output Characteristics

\[
\frac{I_C}{A} \approx -\frac{qD_n}{W_B} \frac{n_i^2}{N_B} (e^{qV_{BE}/kT} - 1) + \frac{qD_n}{W_B} \frac{n_i^2}{N_B} (e^{qV_{BC}/kT} - 1)
\]

\[
\frac{I_B}{A} = \frac{qD_p}{W_E} \frac{n_i^2}{N_E} (e^{qV_{BE}/kT} - 1)
\]

\[
\beta_{DC} = \frac{I_C}{I_B}
\]

Common emitter Current Gain
Current Gain

Common Emitter current gain ..

\[ \beta_{DC} = \frac{I_C}{I_B} \]

\[ = \frac{qD_n n_{i,B}^2}{W_B N_B} \left( e^{qV_{BE}/kT} - 1 \right) + \frac{qD_n n_{i,B}^2}{W_B N_B} \left( e^{qV_{BC}/kT} - 1 \right) \]

\[ = \frac{qD_n n_{i,E}^2}{W_E N_E} \left( e^{qV_{BE}/kT} - 1 \right) \]

Common Base current gain ..

\[ \alpha_{DC} = \frac{I_C}{I_E} \quad \beta_{DC} = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha_{DC}}{1 - \alpha_{DC}} \]

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Current Gain

\[ \beta_{DC} \approx \frac{D_n}{W_B} \frac{W_E}{D_p} \frac{n_{i,B}^2}{n_{i,E}^2} \frac{N_E}{N_B} \]
How to make a Good Silicon Transistor

For a given Emitter length

\[ \beta_{DC} \approx \frac{D_n W_E}{W_B D_p} \frac{n_{i,B}^2}{n_{i,E}^2} \frac{N_E}{N_B} \]

\(~1, \text{ same material}\)

Make-Base short ...
(few mm in 1950s, 200 A now)

Emitter doping higher than Base doping
Doping for Gain ...

\[ \beta_{DC} \approx \frac{D_n W_E n_{i/B}^2 N_E}{W_B D_p n_{i,E}^2 N_B} \]
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Problem of Low Base Doping: Current Crowding

\[ \beta = \frac{I_C}{I_B} = \frac{\int J_C(x)\,dx}{\int J_B(x)\,dx} = \frac{\int qD_n \frac{n_{i,B}^2}{N_B} (e^{qV_{BE}(x)\beta} - 1)\,dx}{\int qD_p \frac{n_{i,E}^2}{N_E} (e^{qV_{BE}(x)\beta} - 1)\,dx} \]
Low Base Doping: Non-uniform Turn-on
Problem of Low Base Doping: Punch-through

\[ x_{p,BE} = \sqrt{\frac{2k_s \varepsilon_0}{q} \frac{N_E}{N_B(N_E + N_B)}(V_{bi} - V_{BE})} \]

\[ x_{p,BC} = \sqrt{\frac{2k_s \varepsilon_0}{q} \frac{N_C}{N_B(N_C + N_B)}(V_{bi} - V_{BC})} \]
Problem of low Base-doping: Base Width Modulation

\[ \beta_{DC} \approx \frac{D_n}{W_B - x_{p,B} - x_{p,c}} \frac{W_E}{D_p} \frac{n^{2/3}_{i,B} N_E}{n^{2/3}_{i,E} N_B} \]

\[ x_{p,BE} = \sqrt{\frac{2k_s \varepsilon_0}{q} \frac{N_E}{N_B (N_E + N_B)} (V_{bi} - V_{BE})} \]

\[ x_{p,BC} = \sqrt{\frac{2k_s \varepsilon_0}{q} \frac{N_C}{N_B (N_C + N_B)} (V_{bi} - V_{BC})} \]

Gain depends on collector voltage (bad) ...
Problem of Low Base-doping: Early Voltage

\[ \beta_{DC} \approx \frac{D_n}{W_B - x_{p,B} - x_{p,C}} \frac{W_E}{D_p} \frac{n_{i,B}^2}{n_{i,E}^2} \frac{N_E}{N_B} \]

\[ I_{n,C} = -\frac{qD_n}{W_B^'} \frac{n_{i,B}^2}{N_B} (e^{(qV_{BE}/kT)} - 1) + \frac{qD_n}{W_B^'} \frac{n_{i,B}^2}{N_B} (e^{(qV_{BC}/kT)} - 1) \]

\[ \frac{dI_C}{dV_{BC}} = \frac{I_C}{V_{BC} + V_A} \approx \frac{I_C}{V_A} \]

In practice

Ideally
Punch-through and Early Voltage

\[
\frac{dI_C}{dV_{BC}} = \frac{I_C}{V_{BC} + V_A} \approx \frac{I_C}{V_A}
\]

\[
\frac{dI_C}{dV_{BC}} = \frac{dI_C}{d(qN_B W_B)} \frac{d(qN_B W_B)}{dV_{BC}}
\]

\[
= \frac{1}{qN_B} \left( \frac{dI_C}{dW_B} \right) \frac{dQ_B}{dV_{BC}}
\]

\[
= - \frac{1}{qN_B} \left( \frac{I_C}{W_B} \right) C_{CB}
\]

\[
I_C = \frac{qD_n}{W_B} \frac{n_{i,B}^2}{N_B} \left( e^{qV_{BE}/\beta} - 1 \right) + \frac{qD_n}{W_B} \frac{n_{i,B}^2}{N_B} \left( e^{qV_{BC}/\beta} - 1 \right)
\]

\[
\Rightarrow V_A = - \frac{qN_B W_B}{C_{CB}} \to \infty
\]

Need higher \(N_B\) and \(W_B\) or ...
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Collector Doping

\[ \beta \approx \frac{D_n}{W_B - x_{p,B} - x_{p,C}} \frac{W_E}{D_p} \frac{n^2_{i,B}}{n_{i,E}} \frac{N_E}{N_B} \]

\[ V_A = -\frac{qN_B W_B}{C_{CB}} \]

\[ C_{CB} = \frac{\kappa_s \epsilon_0}{x_{n,C} + x_{p,B}} \]

If you want low base doping then reduce collector doping even more to increase Collector depletion.....
... but (!) Kirk Effect and Base Pushout

\[ N_B x_B = N_C x_C \]

\[ V_{bi} - V_{BC} = \frac{q}{2\kappa_s\varepsilon_0} \left[ N_B x_B^2 + N_C x_C^2 \right] \]

\[ J_C = q\nu_{sat} n \]
Kirk Effect and Base Pushout

Space-Charge Density

\[ \text{p-Base} \quad \text{n-Collector} \quad \text{n+} \]

\[ \text{W}_{B} \quad \text{W}_{C} \]

\[ \text{E} \]

\[ \text{W}_{CIB} \quad \text{W}_{SC} \]

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Kirk Effect and Base Pushout

\[ x'_C = x_C \sqrt{1 + \frac{J_C}{q \nu_{sat} N_B}} \]

\[ J_{C, crit} = q \nu_{sat} N_C \equiv J_K \]

Can not reduce collector doping arbitrarily without causing base pushout
Perhaps High Doping in Emitter?

Band-gap narrowing reduces gain significantly ...

\[
\beta \approx \frac{D_n W_E n_{i,B}^2 N_E}{W_B D_p n_{i,E}^2 N_B} = \frac{D_n W_E N_C N_V e^{-E_{g,B}/kT}}{W_B D_p N_C N_V e^{-E_{g,E}/kT}} N_E \approx e^{-\Delta E_{g}/kT} \frac{N_E}{N_B}
\]

(Easki-like) Tunneling cause loss of base control ...
Summary

While basic transistor operation is simple, its optimum design is not.

In general, good transistor gain requires that the emitter doping be larger than base doping, which in turn should be larger than collector doping.

If the base doping is too low, however, the transistor suffers from current crowding, Early effects. If the collector doping is too low, then we have kirk effect (base push out) with reduced high-frequency operation and if the emitter doping is too high then the gain is reduced.