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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

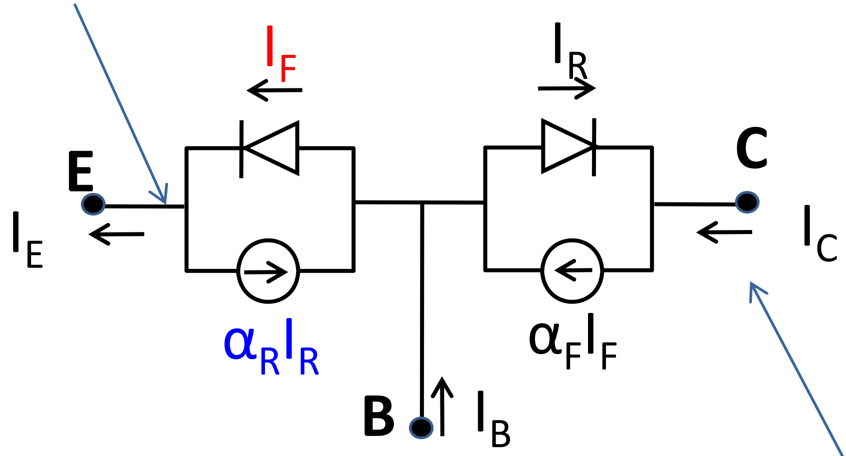
REF: SDF, Chapter 10

Ebers Moll Model

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

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

$$= I_{F0}\left(e^{qV_{BE}\beta}-1\right)-\alpha_R I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$



$$I_F = I_{F0}\left(e^{qV_{BE}\beta}-1\right)$$

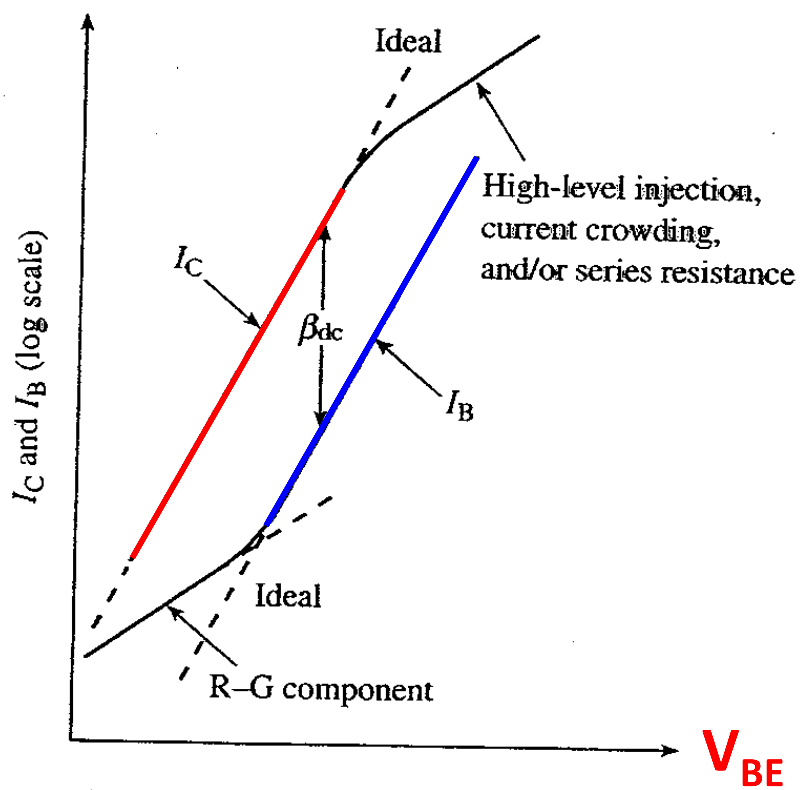
$$I_R = I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

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

$$= \alpha_F I_{F0}\left(e^{qV_{BE}\beta}-1\right)-I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

Gummel Plot and Output Characteristics

$$\frac{I_C}{A} \simeq -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}(e^{qV_{BE}/kT}-1)+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}(e^{qV_{BC}/kT}-1)$$

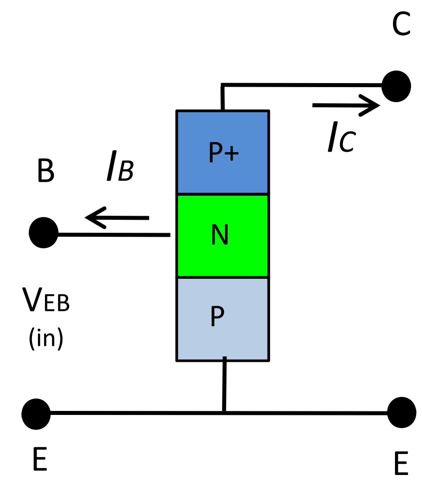


$$\frac{I_B}{A} = \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}(e^{qV_{BE}/kT}-1)$$

$$\beta_{DC} = \frac{I_C}{I_B}$$

$\beta_{DC} \longrightarrow$ Common emitter Current Gain

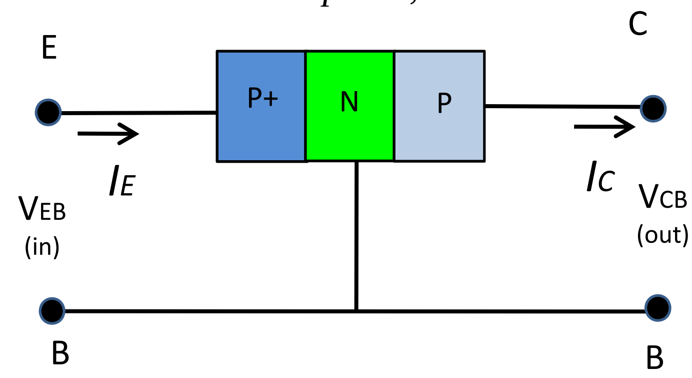
Current Gain



Common Emitter current gain ..

$$\beta_{DC} = \frac{I_C}{I_B}$$

$$= \frac{\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}(e^{qV_{BE}/kT}-1) + \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}(e^{(qV_{BC}/kT)}-1)}{\frac{qD_n}{W_E}\frac{n_{i,E}^2}{N_E}(e^{qV_{BE}/kT}-1)} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

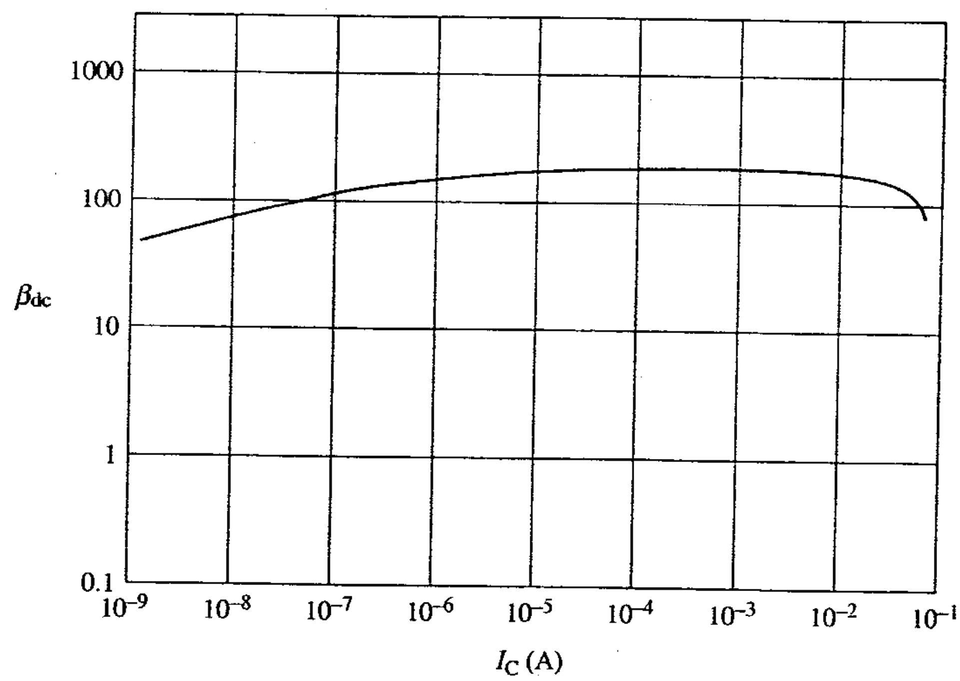


Common Base current gain ..

$$\alpha_{DC} = \frac{I_C}{I_E} \Rightarrow \beta_{DC} = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha_{DC}}{1-\alpha_{DC}}$$

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

~1, same material

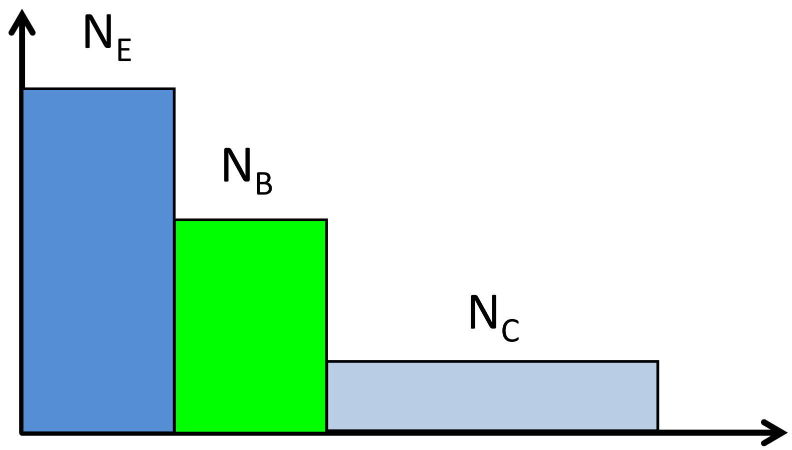
$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

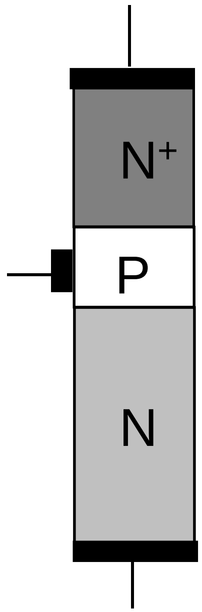
Make-Base short …
(few mm in 1950s, 200 A now)

Emitter doping higher than Base doping

Doping for Gain …

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





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1) Current gain in BJTs
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3) Considerations for collector doping
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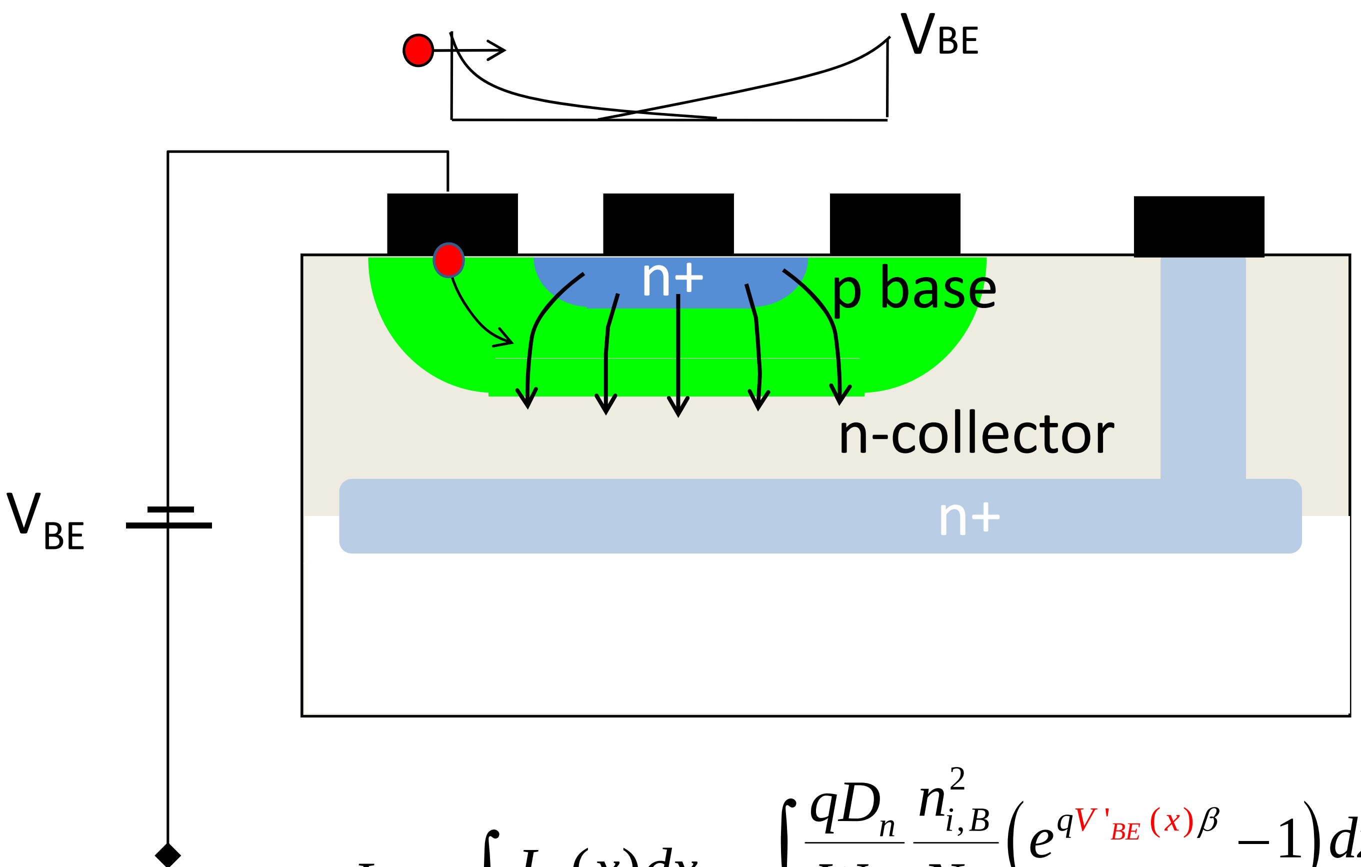
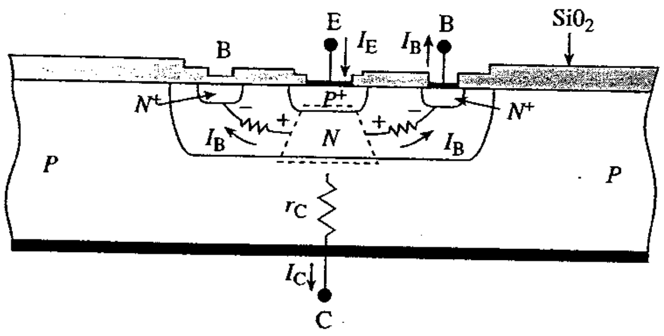
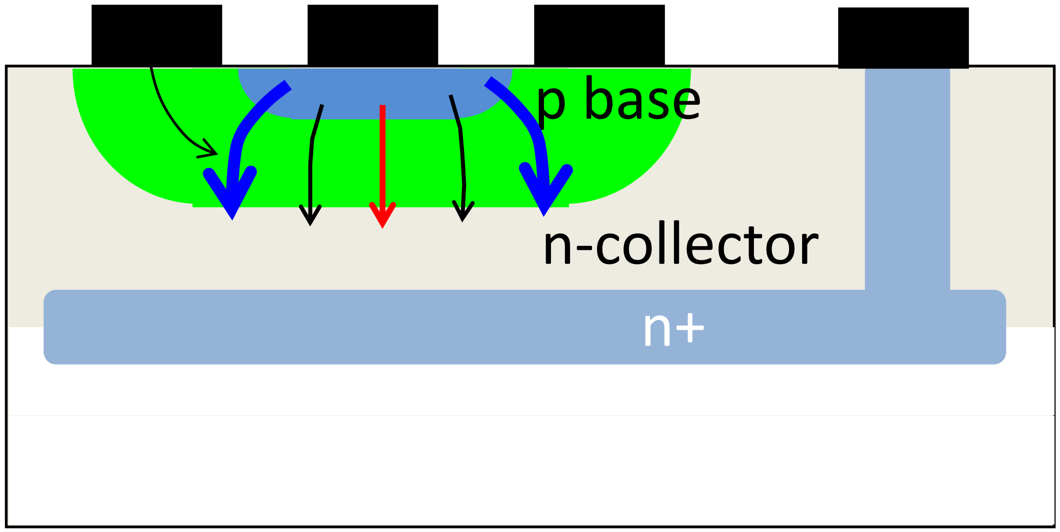
Problem of Low Base Doping: Current Crowding

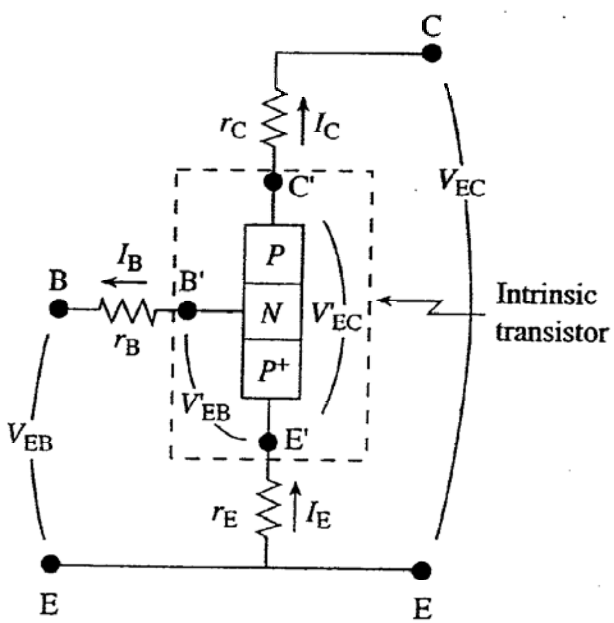


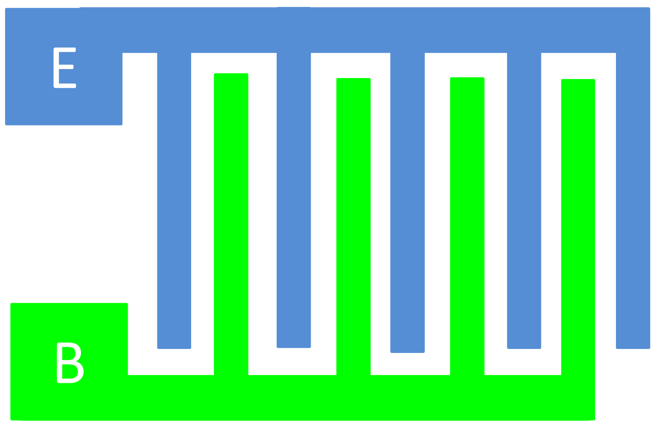
$$\beta = \frac{I_C}{I_B} = \frac{\int J_C(x)dx}{\int J_B(x)dx} = \frac{\int \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV'_{BE}(x)\beta}-1\right)dx}{\int \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV'_{BE}(x)\beta}-1\right)dx}$$

Low Base Doping: Non-uniform Turn-on

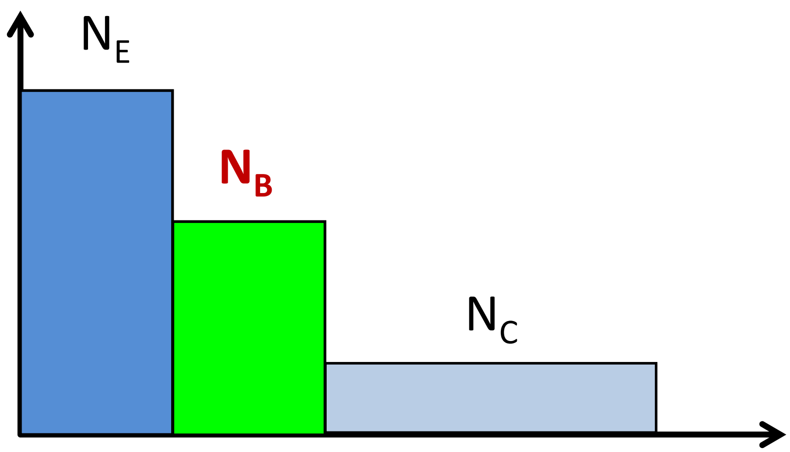


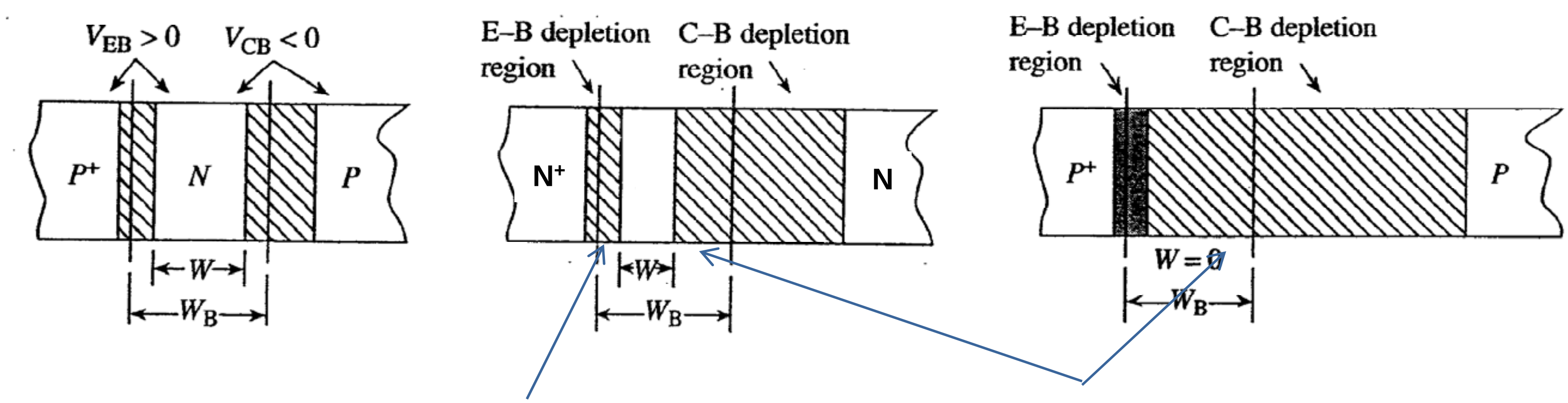






Problem of Low Base Doping: Punch-through



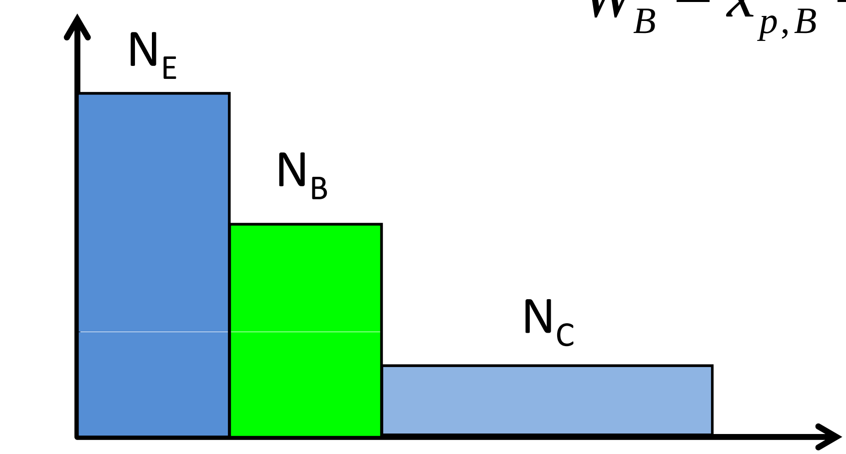


$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E + N_B\right)}\left(V_{bi} - V_{BE}\right)}$$

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

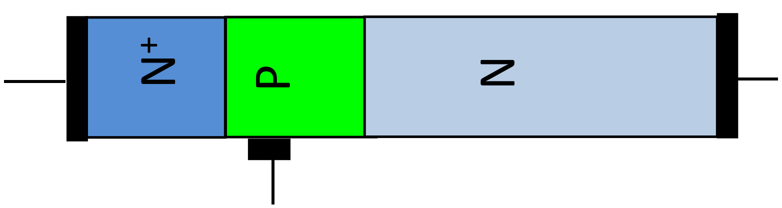
Problem of low Base-doping: Base Width Modulation

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



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

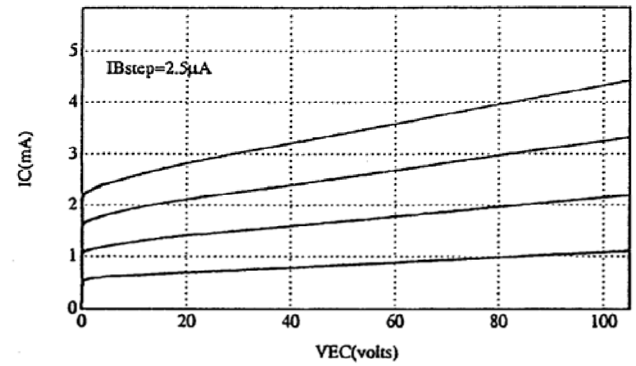
$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q} \frac{N_C}{N_B(N_C + N_B)} (V_{bi} - V_{BC})}$$



Gain depends on collector voltage (bad) …

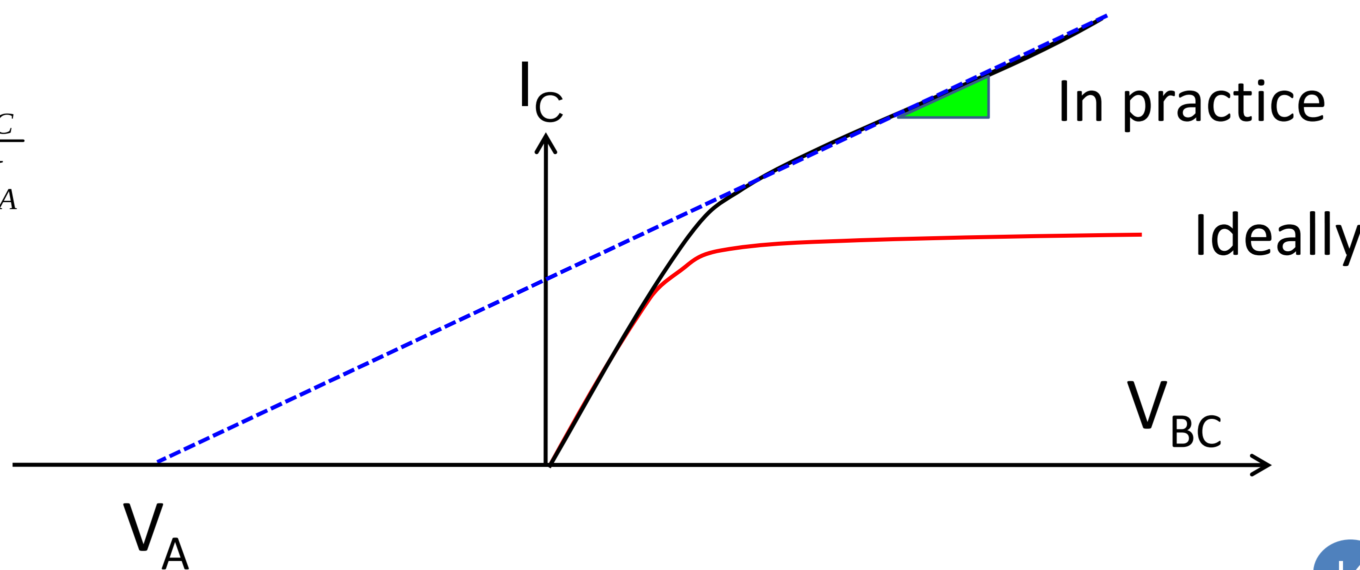
Problem of Low Base-doping: Early Voltage

$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p.B} - x_{p.C}} \frac{W_E}{D_p} \frac{n^2_{i,B}}{n^2_{i,E}} \frac{N_E}{N_B}$$



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

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



Punch-through and Early Voltage

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

$$\frac{dI_C}{dV_{BC}} = \frac{dI_C}{d\left(qN_BW_B\right)} \frac{d\left(qN_BW_B\right)}{dV_{BC}}$$

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

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

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

$$-\frac{C_{CB}}{qN_B}\frac{I_C}{W_B} \approx \frac{I_C}{V_A}$$

$$\Rightarrow V_A = -\frac{qN_BW_B}{C_{CB}} \quad \to \infty$$

Need higher N_B and W_B or …

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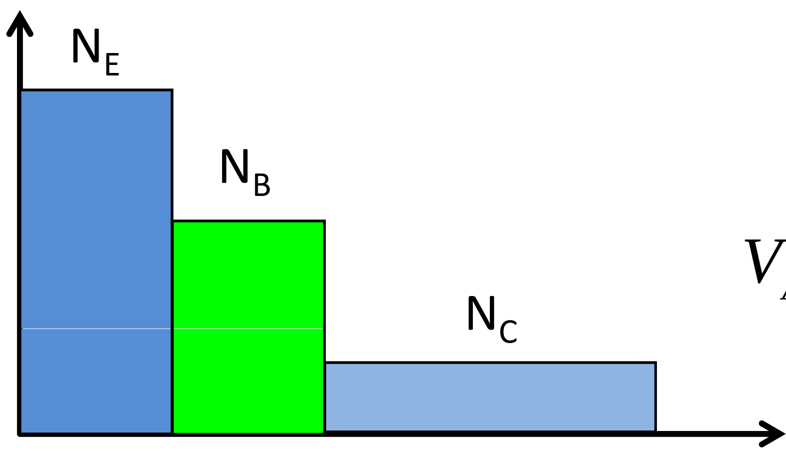
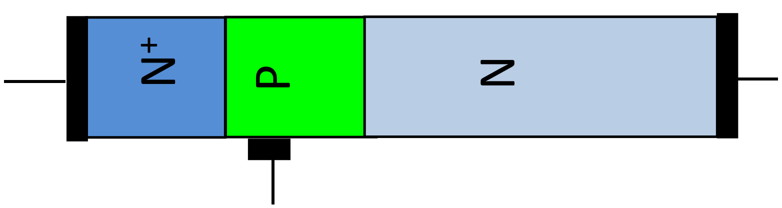
Collector Doping

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

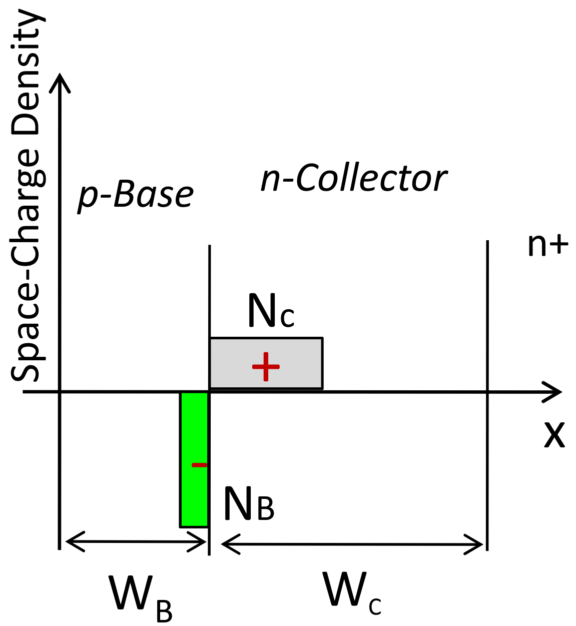


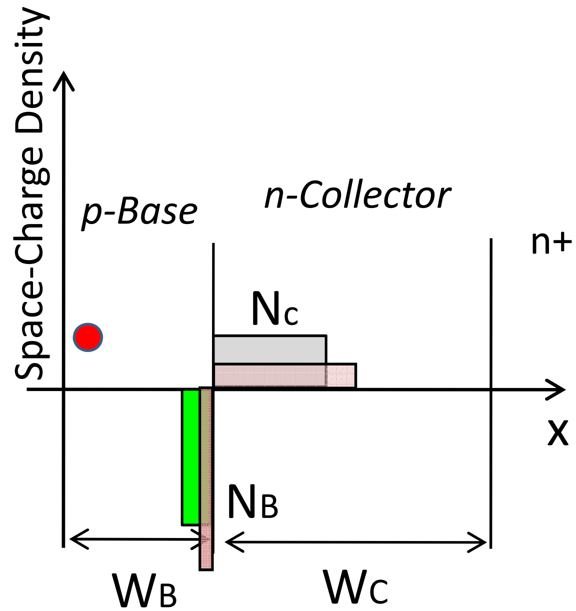
$$V_A = -\frac{qN_B W_B}{C_{CB}} \qquad C_{CB} = \frac{\kappa_s \varepsilon_0}{x_{n,C} + x_{p,B}}$$



If you want low base doping then reduce collector doping even more to increase Collector depletion.....

… but (!) Kirk Effect and Base Pushout





$$N_B x_B = N_C x_C$$

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

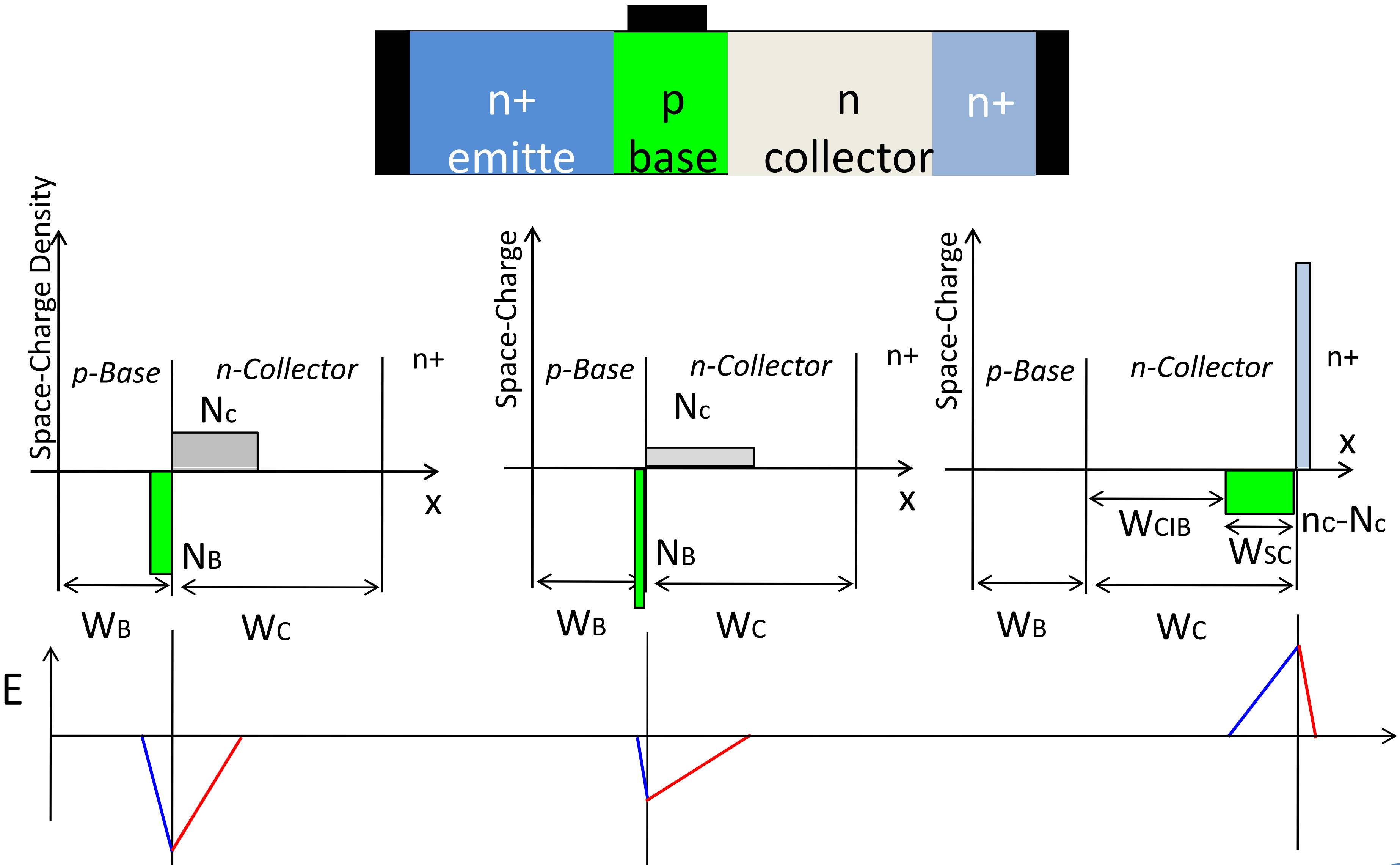
$$J_C = q\upsilon_{sat} n$$

$$\left(N_B + n\right) x_B' = \left(N_C - n\right) x_C'$$

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

$$x_C' = x_C \sqrt{\frac{1 + \frac{n}{N_B}}{1 - \frac{n}{N_C}}} = x_C \sqrt{\frac{1 + \frac{J_C}{q\upsilon_{sat} N_B}}{1 - \frac{J_C}{q\upsilon_{sat} N_C}}}$$

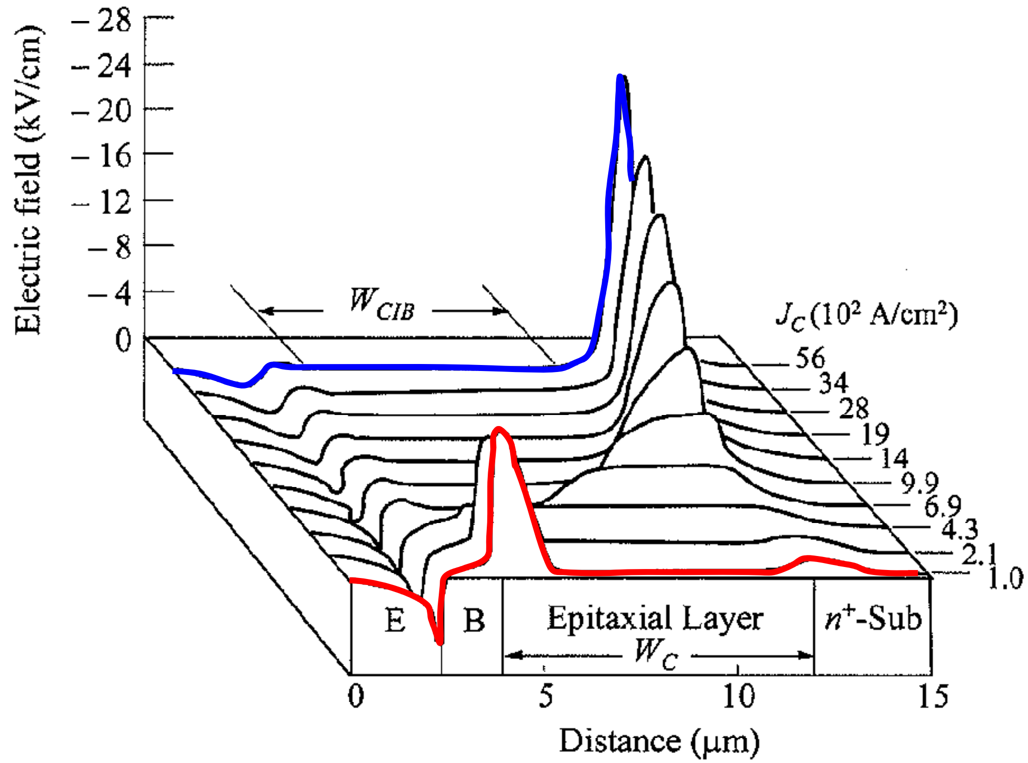
Kirk Effect and Base Pushout



Kirk Effect and Base Pushout

$$x_C' = x_C \sqrt{\frac{1+\dfrac{J_C}{q\upsilon_{sat}N_B}}{1-\dfrac{J_C}{q\upsilon_{sat}N_C}}}$$

$$J_{C,crit} = q\upsilon_{sat}N_C \equiv J_K$$



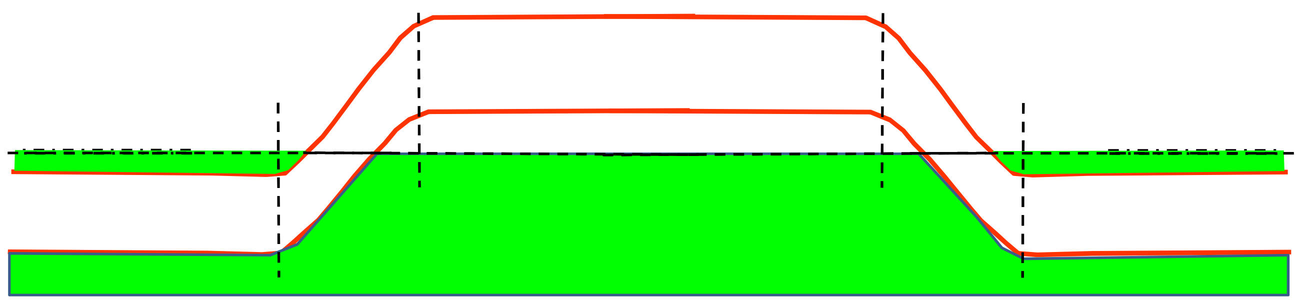
Can not reduce collector doping arbitrarily without causing base pushout

Perhaps High Doping in Emitter?

Band-gap narrowing reduces gain significantly …

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

(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.