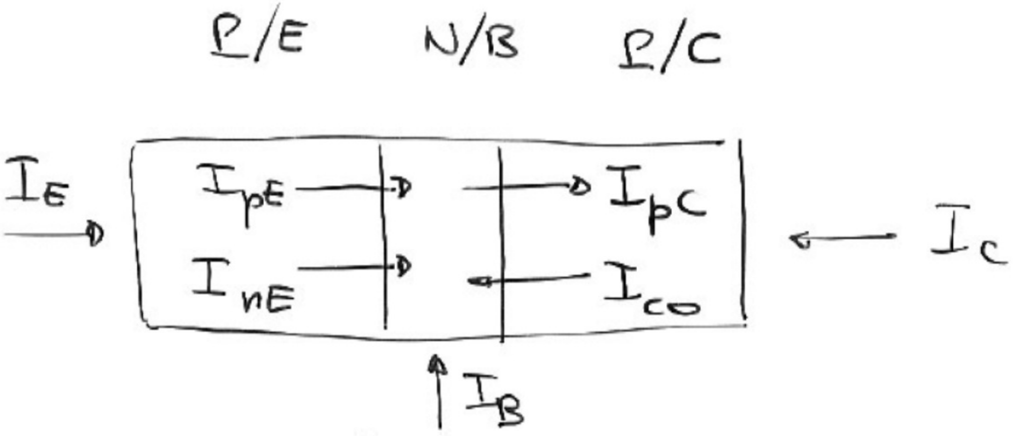
BJT

[Fonstad, Ghione]

Currents in the BJT



- Let us consider a PNP
- $I_E = I_{pE} + I_{nE}$
- We want $I_{pE} >> I_{nE}$
- → higher doping in E than in B, $\gamma \sim 1$

$$\boxed{\gamma \triangleq \frac{I_{pE}}{I_E}}$$

- we also want that (almost) all the holes reach the collector without recombining:

  $I_{pC} \sim I_{pE}$

- → B has to be *short* (and not too strongly doped);

  $\beta^* \sim 1$

$$\boxed{\beta^* \triangleq \frac{I_{pC}}{I_{pE}}}$$

Currents in the BJT

- We have

$$I_C = -I_{pC} + I_{C0} = -\beta^* I_{pE} + I_{C0} = -\beta^* \gamma I_E + I_{C0}$$

- and with

$$\boxed{\alpha_N \triangleq \beta^* \gamma}$$

- we get

$$\boxed{I_C = -\alpha_N I_E + I_{C0}}$$

- Then, being $I_E+I_C+I_B=0$ we get

$$I_C = -\alpha_N(-I_C - I_B) + I_{C0} \qquad I_C(1-\alpha_N) = \alpha_N I_B + I_{C0}$$

$$I_C = \frac{\alpha_N}{1-\alpha_N} I_B + \frac{1}{1-\alpha_N} I_{C0}$$

- and, with $\beta_N=\alpha_N/(1-\alpha_N)$

$$\boxed{I_C = \beta_N I_B + (\beta_N + 1) I_{C0}}$$

Currents in the BJT

- In the NPN transistor, all currents and voltages are reversed. The “good” current is carried by electrons, again from E to C
- Dependences on the temperature:

  \- I_{C0} doubles for each 10 °C increment

  \- V_{BE} decreases by 2.5 mV/°C

  \- β increases with T

Currents in the BJT

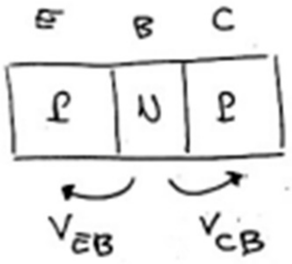
- To compute the currents, we follow the same approach we used for the pn junction
- but with an extra hypothesis: no recombination in the base (i.e. $I_{PE}=I_{PC}$)
- And we get the Ebers-Moll equations

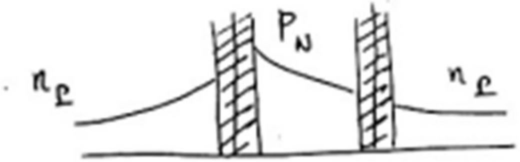
$$\boxed{\begin{aligned} I_E &= a_{11}\left(e^{V_{EB}/V_T}-1\right)+a_{12}\left(e^{V_{CB}/V_T}-1\right) \\ I_C &= a_{21}\left(e^{V_{EB}/V_T}-1\right)+a_{22}\left(e^{V_{CB}/V_T}-1\right) \end{aligned}}$$

- where the a_{ij} depend on doping, dimensions, carriers...

Currents in the BJT

- we start from the diffusion equations
- we neglect ohmic effects
- we consider a PNP with both junctions directly biased (this is *not* the usual condition!!)

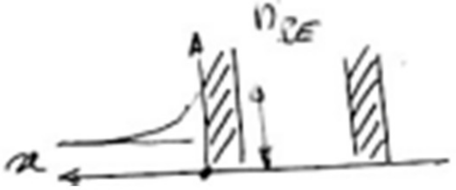




$$\frac{d^2(n_p - n_{p0})}{dx^2} = \frac{n_p - n_{p0}}{L_n^2}$$

$$n_p - n_{p0} = A e^{-x/L_n} + B e^{x/L_n}$$

- In the emitter



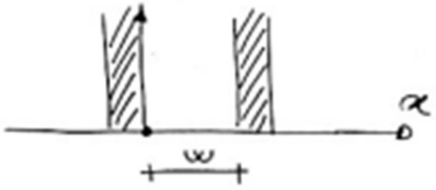
$$x \to \infty \Rightarrow n_{pE} - n_{pE0} = 0 \to B = 0$$

$$x = 0 \Rightarrow n_{pE} = n'_{pE} = n_{pE0} e^{V_{EB}/V_T}$$

$$n_{pE} - n_{pE0} = n_{pE0}\left(e^{V_{EB}/V_T} - 1\right) e^{-x/L_{nE}}$$

- in the base (*w* is the base width (actually, length))

$$\frac{d^2(p_{NB} - p_{NB0})}{dx^2} = \frac{p_{NB} - p_{NB0}}{L_{pB}^2}$$



$$p_{NB} - p_{NB0} = A e^{-x/L_{pB}} + B e^{x/L_{pB}}$$

$$\begin{cases} p_{NB}(0) - p_{NB0} = A + B \\ p_{NB}(w) - p_{NB0} = A\,e^{-w/L_{pB}} + B\,e^{w/L_{pB}} \end{cases}$$

$$\begin{cases} p_{NB}(0) = p_{NB0}\,e^{V_{EB}/V_T} \\ p_{NB}(w) = p_{NB0}\,e^{V_{CB}/V_T} \end{cases}$$

$$\begin{cases} p_{NB0}\left(e^{V_{EB}/V_T} - 1\right) = A + B \\ p_{NB0}\left(e^{V_{CB}/V_T} - 1\right) = A\,e^{-w/L_{pB}} + B\,e^{w/L_{pB}} \end{cases}$$

hypothesis: thin (actually, short) base

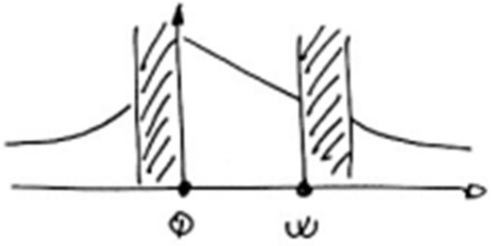
- so $I_{pE}=I_{pC}$
- *and* $p_{NB}(x) - p_{NB0} = A\left(1 - \frac{x}{L_{pB}}\right) + B\left(1 + \frac{x}{L_{pB}}\right)$

with

$$\begin{cases} p_{NB0}\left(e^{V_{EB}/V_T} - 1\right) = A + B \\ p_{NB0}\left(e^{V_{CB}/V_T} - 1\right) = A\left(1 - \frac{W}{L_{pB}}\right) + B\left(1 + \frac{W}{L_{pB}}\right) \end{cases}$$

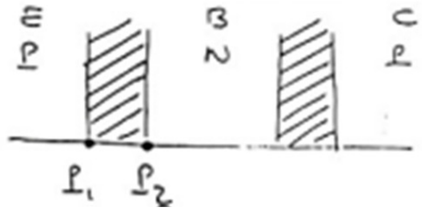
$$= A + B - \frac{W}{L_{pB}}(A - B)$$

note the linear profile of p_B



In the collector: as in the emitter

$$n_{pC} - n_{pC0} = n_{pC0}\left(e^{V_{CB}/V_T} - 1\right) e^{-x/L_{nC}}$$



Current are computed as in the diode

$$J_E = J_{nd}(\ell_1) + J_{pd}(\ell_2)$$

$$= -q D_{pB} \frac{dp_{NB}}{dx}\Big|_{\ell_2}$$

$$= q D_{nE} \frac{dn_{pE}}{dx}\Big|_{\ell_1}$$

and we get

$$J_{ndE} = \frac{q D_{nE} n_{pE0}}{L_{nE}}\left(e^{V_{EB}/V_T} - 1\right)$$

In the base

$$J_{pdB} =$$

$$= -q\,D_{pB}\,\frac{d}{dx}\left[(A+B) + (B-A)\frac{x}{L_{pB}}\right]\Bigg|_{x=0}$$

$$= -\frac{q\,D_{pB}}{L_{pB}}(B-A)$$

$$= -\frac{q\,D_{pB}}{\cancel{L_{pB}}}\cdot\frac{\cancel{L_{pB}}}{w}\left[p_{NBo}\left(e^{\frac{V_{CB}}{V_T}}-1\right) - p_{NBo}\left(e^{\frac{V_{EB}}{V_T}}-1\right)\right]$$

So

$$J_E = \left(\frac{q D_{nE} n_{PE0}}{L_{nE}} + \frac{q D_{pB} p_{NB0}}{W} \right) \cdot \left(e^{V_{EB}/V_T} - 1 \right) -$$

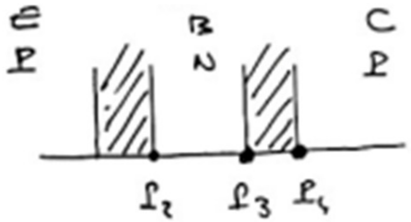
$$- \frac{q D_{pB} p_{NB0}}{W} \left(e^{V_{CB}/V_T} - 1 \right)$$

Normally, doping is lower in B than in E => $p_{NB0} >> n_{PE0}$; moreover, in normal bias

$$\exp\left(V_{CB}/V_T \right) \cong 0$$

so that

$$J_E \simeq \frac{q D_{pB} p_{NB0}}{W} \left(e^{''} - 1 - 0 + 1 \right) = \frac{q D_{pB} p_{NB0}}{W} e^{V_{EB}/V_T}$$



Similarly for the collector

$$J_c = J_{pd}(\ell_3) + J_{nd}(\ell_4)$$

and we get

$$J_c = -\frac{q D_{pB} p_{NB0}}{w}\left(e^{V_{EB}/V_T} - 1\right) +$$

$$+\left(\frac{q D_{pB} p_{NB0}}{w} + \frac{q D_{nC} n_{PC0}}{L_{nC}}\right)\left(e^{V_{CB}/V_T} - 1\right)$$

If we assume a constant section *S*, we get the currents

$$\boxed{\begin{aligned} I_E &= a_{11}\left(e^{V_{EB}/V_T}-1\right)+a_{12}\left(e^{V_{CB}/V_T}-1\right) \\ I_C &= a_{21}\left(e^{V_{EB}/V_T}-1\right)+a_{22}\left(e^{V_{CB}/V_T}-1\right) \end{aligned}}$$

with

$$a_{12}=a_{21}=-\frac{q\,D_{pB}\,p_{NB0}}{w}\cdot S$$

In normal bias

$$\begin{cases} I_E = a_{11}\left(e^{V_{EB}/V_T}-1\right)-a_{12} \\ I_C = a_{21}\left(e^{V_{EB}/V_T}-1\right)-a_{22} \end{cases}$$

Currents in the BJT

- and, by substituting *(*exp*(V_{EB}/V_T)-1)*

$$\boxed{I_C = -\alpha_N I_E + I_{CO}\left(1 - e^{V_{CB}/V_T}\right)}$$

- with

$$\boxed{\alpha_N = -\frac{a_{21}}{a_{11}}} \qquad \boxed{I_{CO} = -\frac{a_{11}a_{22} - a_{21}a_{12}}{a_{11}}}$$

- Also:

$$I_C = \beta_N I_B + (\beta_N + 1) I_{CO}\left(1 - e^{V_{CB}/V_T}\right)$$

The (small) base current…

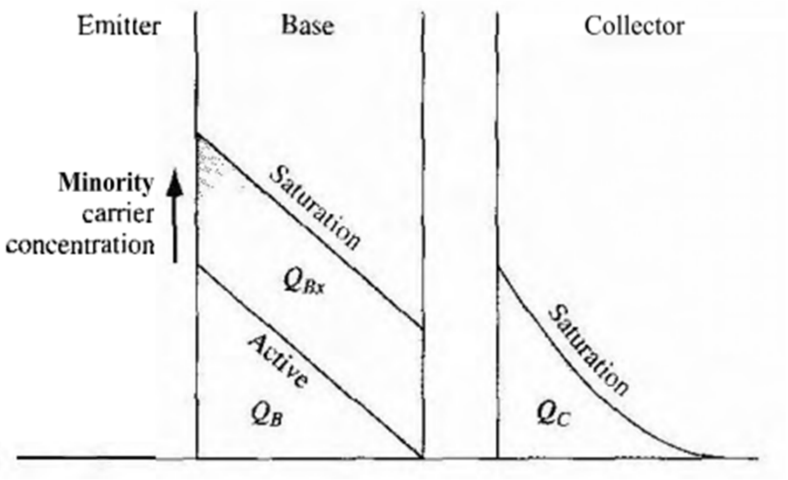
has 3 main components

- the “wrong” part of the emitter current (I_{nE} for a pnp)
- the carriers (electrons for a pnp) which enter from the base terminal to recombine with the minority carriers in the base
- the inverse saturation current of the BC junction (I_{CO})

and 2 other minor components

- the recombination of carriers in the depletion region of the forward-biased BE junction
- the generation of carriers in the depletion region of the reverse-biased BC junction

BJTs in saturation and Schottky transistors



charge storage in the base and collector at saturation and in active mode

Schottky-clamped transistor and its symbol