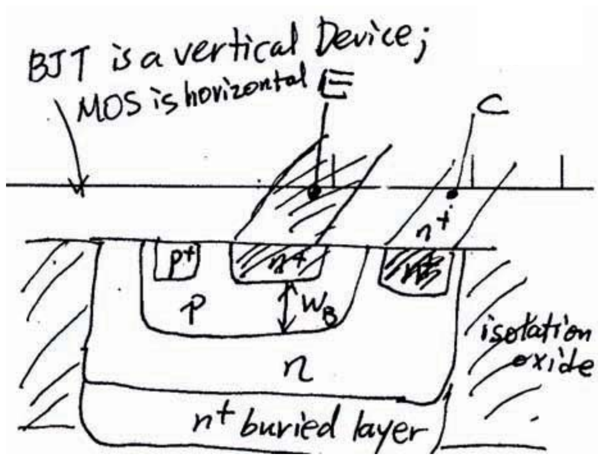
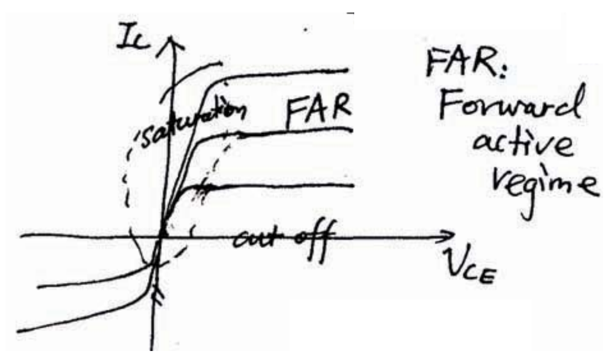
Recitation 17: BJT-Basic Operation in FAR

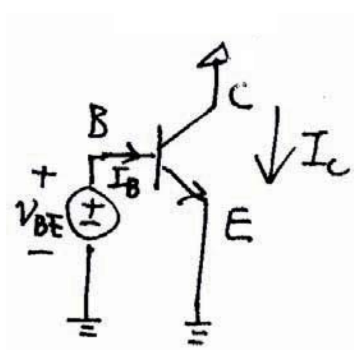
BJT stands for Bipolar Junction Transistor

1. Can be thought of as two p-n junctions back to back, you can have pnp or npn.





In analogy to MOSFET small current I_{B} or voltage V_{BE}, controls large current I_{c}



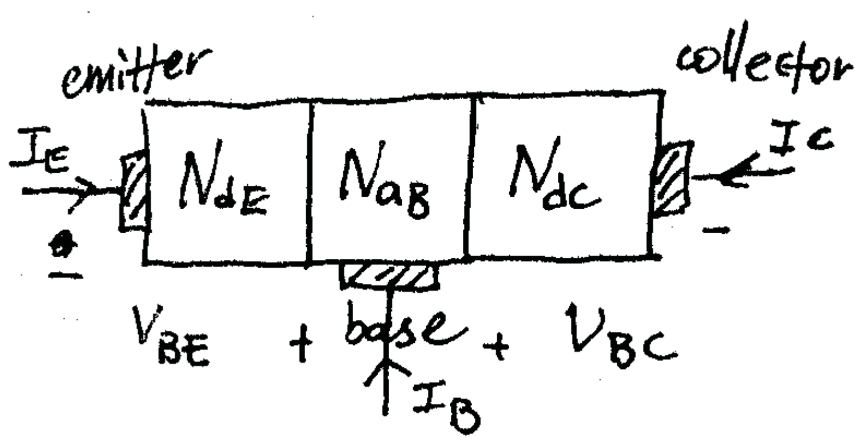
2. How does it work?

- As we learned previously, for an asymmetric pn junction:

$$\begin{aligned}
I_\mathrm{D} &= I_\mathrm{Dn} + I_\mathrm{Dp} \quad \text{electron \& hole diffusion currents} \\
a &= qAn_\mathrm{i}^2 \times \underbrace{\frac{D_\mathrm{n}}{N_\mathrm{a}(w_\mathrm{p}-x_\mathrm{p})}}_{\text{contribution from (1) e}^- \text{ diffusion in p-region}} \times (\mathrm{e}^{\mathrm{qV_D/kT}}-1) \\
b &= qAn_\mathrm{i}^2 \times \underbrace{\frac{D_\mathrm{p}}{N_\mathrm{d}(w_\mathrm{n}-x_\mathrm{n})}}_{\text{contribution (2) from hole diffusion in n-region}} \times (\mathrm{e}^{\mathrm{qV_D/kT}}-1) \\
I_\mathrm{D} &= a+b
\end{aligned}$$

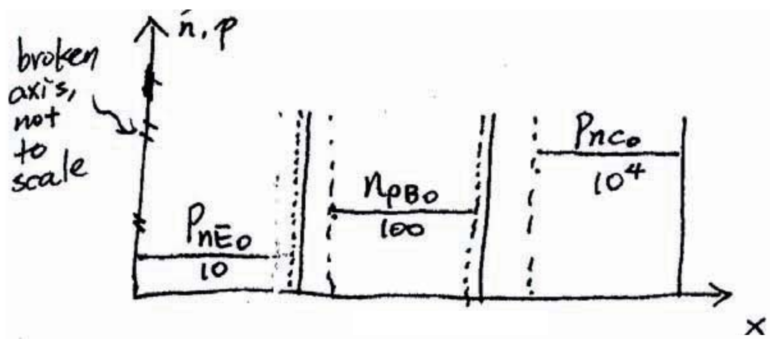
If $N_\mathrm{d} \gg N_\mathrm{a}$, the contribution from hole (2) is much lower than that from electron (1)

- For BJT, the doping profiles are very asymmetric



$$\begin{aligned}
N_\mathrm{dE} &\gg N_\mathrm{aB} \gg N_\mathrm{dC} \\
\text{For example, } N_\mathrm{dE} &= 10^{20}\,\mathrm{cm}^{-3}, \mathrm{N_{aB}} = 10^{18}\,\mathrm{cm}^{-3} \\
N_\mathrm{dC} &= 10^{16} \quad \text{this is critical for BJT to function well. Why?}
\end{aligned}$$

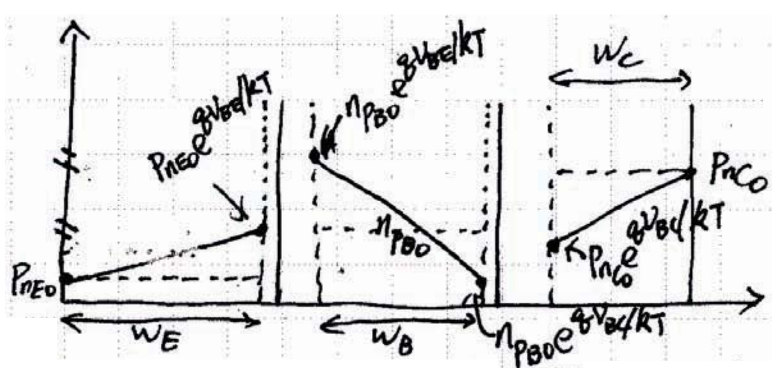
Minority carriers concentration under T.E.



Now FAR means

$V_{BE} > 0$ but $V_{BC} < 0$

- Minority carrier concentration under FAR: (broken linear y axis)



(a) At contacts, equilibrium concentration ($P_{\mathrm{nEO}}, P_{\mathrm{nCO}}$)

(b) BE junction forward biased: minority carrier concentration increased by $e^{qV_{BE}/kT}$

(c) Base-collector (BC) junction reverse biased: minority carrier concentration decreased by $e^{qV_{BC}/kT} \longrightarrow 0$

(d) No recombination in QNR $\Longrightarrow$ linear profile

(e) These profiles result in *diffusion currents* (In BJT, the current we calculate are diffusion currents; in contrast, for MOSFET, the currents we calculate (I_D) are drift currents).

Electrons diffuse across Base

$$\begin{aligned}J_{\mathrm{nB}} &= qD_{\mathrm{n}}\frac{dn_{pB}}{dx} = qD_{\mathrm{n}}\frac{n_{\mathrm{pBo}}(\mathrm{e}^{\mathrm{qV_{BE}/kT}} - \overbrace{\cancel{\mathrm{e}^{\mathrm{qV_{BC}/kT}}}}^{\because \mathrm{V_{BC}} \leq 0} \to 0)}{0 - w_{\mathrm{B}}} \\ &= -\frac{qD_{\mathrm{n}}n_{\mathrm{pBo}}\mathrm{e}^{\mathrm{qV_B/kT}}}{w_{\mathrm{B}}} = -\frac{qD_{\mathrm{n}}n_{\mathrm{i}}^2}{w_{\mathrm{B}} \cdot N_{\mathrm{aB}}}\mathrm{e}^{\frac{\mathrm{V_{BE}}}{\mathrm{V_{th}}}}\end{aligned}$$

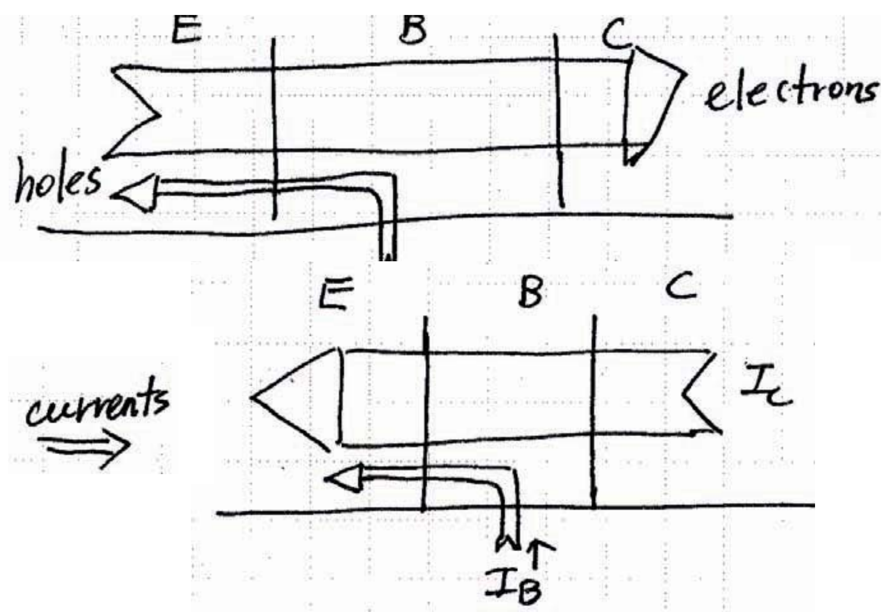
All electrons swept into C by large E field: (BC reverse biased)

$$\begin{aligned}I_{\mathrm{c}} &= -J_{\mathrm{nB}} \cdot A_{\mathrm{E}} \quad \text{to make positive into } c \text{ terminal; } A_{\mathrm{E}} \text{ is the area of Emitter/Base interface} \\ &= \frac{qA_{\mathrm{E}}D_{\mathrm{n}}n_{\mathrm{i}}^2}{N_{\mathrm{aB}}w_{\mathrm{B}}}\mathrm{e}^{\mathrm{qV_{BE}/kT}} = \mathrm{I_S}\mathrm{e}^{\mathrm{qV_B/kT}} \\ I_{\mathrm{S}} &= \frac{qA_{\mathrm{E}}D_{\mathrm{n}}n_{\mathrm{i}}^2}{N_{\mathrm{aB}}w_{\mathrm{B}}} \quad \text{similar to } I_{\mathrm{o}} \text{ in diode, remember on the order of } 10^{-15} - 10^{-20}\,\mathrm{A}\end{aligned}$$

Holes diffuse across Emitter

$$\begin{aligned}J_{\mathrm{pE}} &= -qD_{\mathrm{p}}\frac{p_{\mathrm{nE}}}{dx} = -qD_{\mathrm{p}}\frac{p_{\mathrm{nEo}}(\mathrm{e}^{\mathrm{qV_{BE}/kT}} - \cancel{1})}{O_(- w_{\mathrm{E}})} \quad V_{\mathrm{BE}} > \frac{kT}{q} \\ I_{\mathrm{B}} &= -J_{\mathrm{PE}} \cdot A_{\mathrm{E}} = \frac{qA_{\mathrm{E}}D_{\mathrm{p}}n_{\mathrm{i}}^2}{N_{\mathrm{dE}}w_{\mathrm{E}}}\mathrm{e}^{\mathrm{qV_{BE}/kT}} \quad \text{to make positive into B terminal}\end{aligned}$$

Because E-B we have n-p from left to right, but we define positive direction left → right, the current we calculate will be from p-n which will be right → left.
Now let us draw a flux picture.



1. For current in the base terminal, it is only the *hole* current. (in base, this will be majority carrier current (drift-diffusion); in emitter, this becomes minority carrier diffusion current, as we calculated). Look at Fig. 1, the base is so thin that all the electron current is directly swept to the collector, can not reach hole contact

2. Current in the collector terminal, is only the *electron* current, and do not depend on V_{BC}. What happened to the hole diffusion current due to the doping file in collection region in Fig. 5, $I_{\mathrm{C}} = I_{\mathrm{S}} \cdot \mathrm{e}^{\mathrm{qV_{BE}/kT}}$.

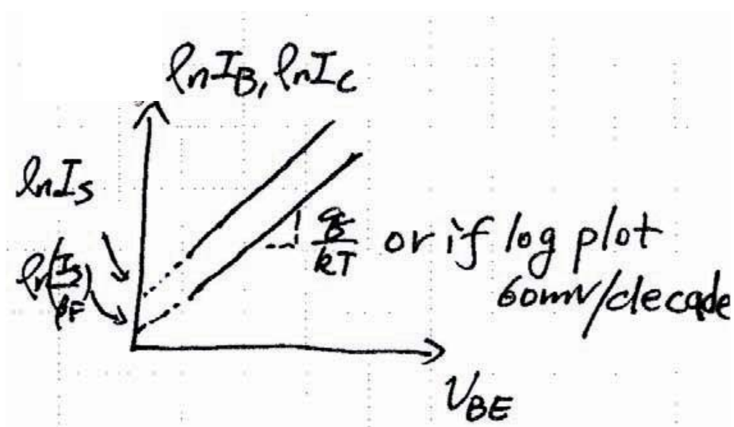
   It is too small to be counted.

   V_{BC} is reverse biased, $I_{\mathrm{D}} = I_{\mathrm{o}}(\mathrm{e}^{\mathrm{qV_{BC}/kT}} - 1) \simeq -\mathrm{I_o}$

3. What about I_{E}?

$$I_{\mathrm{E}} = -(I_{\mathrm{B}} + I_{\mathrm{C}})$$

4. Relationship between I_{B} and I_{C}. We see that both I_{B} and $I_{\mathrm{C}} \propto \mathrm{e}^{\mathrm{qV_{BE}/kT}}$



$$\begin{aligned}
\beta_{\mathrm{F}} &= \frac{I_{\mathrm{C}}}{I_{\mathrm{B}}} = \frac{D_{\mathrm{n}}/N_{\mathrm{aB}}w_{\mathrm{B}}}{D_{\mathrm{p}}/N_{\mathrm{dE}}w_{\mathrm{E}}} = \left(\frac{D_{\mathrm{n}}}{D_{\mathrm{p}}}\right)\left(\frac{N_{\mathrm{dE}}}{N_{\mathrm{aB}}}\right)\left(\frac{w_{\mathrm{E}}}{w_{\mathrm{B}}}\right) \\
\therefore I_{\mathrm{C}} &= I_{\mathrm{S}}\mathrm{e}^{\mathrm{qV_{BE}/kT}}; \quad \mathrm{I_B} = \frac{\mathrm{I_S}}{\beta_{\mathrm{F}}}\mathrm{e}^{\mathrm{qV_{BE}/kT}}
\end{aligned}$$

(a) We would like large β_{F}. To make β_{F} large, we need $N_{\mathrm{dE}} \gg N_{\mathrm{aB}}$, and $w_{\mathrm{E}} > w_{\mathrm{B}}$. D_{n} in the background of N_{aB}

(b) D_{p} in the background of $N_{\mathrm{dE}} \implies D_{\mathrm{n}}$ will be larger than $D_{\mathrm{p}}, \because N_{\mathrm{aB}} \ll N_{\mathrm{dE}}$ plus e vs. hole

(c) If we make pnp, then

$$\beta_{\mathrm{F}} = \left(\frac{D_{\mathrm{p}}}{D_{\mathrm{n}}}\right)\left(\frac{N_{\mathrm{aE}}}{N_{\mathrm{dB}}}\right)\left(\frac{w_{\mathrm{E}}}{w_{\mathrm{B}}}\right)$$

The advantage of D_{n} vs. D_{p} will be gone

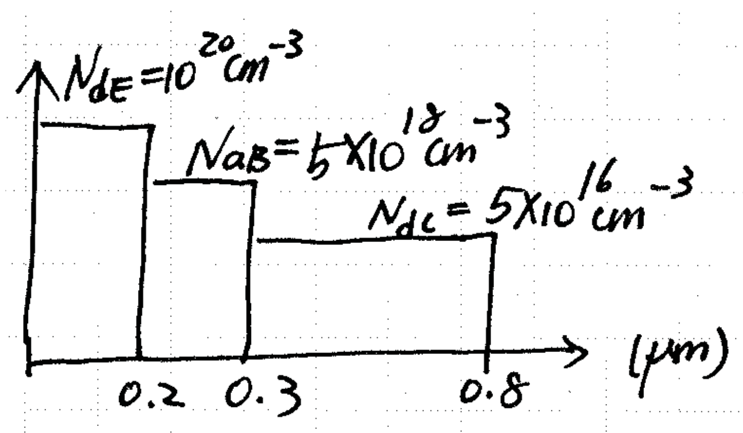
5. Why $N_{\mathrm{aB}} \gg N_{\mathrm{dC}}$?

   When we apply negative V_{BC}, the depletion layer will increase. Effectively, w_{B} will decrease. ($\Longrightarrow$ base width modulation similar to channel length modulation in MOSFET case) $\Longrightarrow$ undesirable

   In addition, if depletion layers in the base region touch each other from both sides (emitter $\rightarrow$ collector) $\Longrightarrow$ punch through $\Longrightarrow$ undesirable $\Longrightarrow$ high enough doping in base compared to collector

Exercise

See figure below:



$$
\begin{aligned}
A_{\mathrm{E}} &= 10\,\mu\mathrm{m} \times 1\,\mu\mathrm{m} \\
&= 10\mu m^2 \\
&= 10 \times (10^{-4})^2\,\mathrm{cm}^2 \\
&= 10^{-7}\,\mathrm{cm}^2 \\
D_{\mathrm{nB}} &= 4\,\mathrm{cm}^2/\mathrm{s}, \quad \mathrm{D_{PE}} = 1.3\,\mathrm{cm}^2/\mathrm{s} \\
\beta_{\mathrm{F}} &= \frac{I_{\mathrm{C}}}{I_{\mathrm{B}}} = \left(\frac{D_{\mathrm{n}}}{D_{\mathrm{p}}}\right)\left(\frac{N_{\mathrm{dE}}}{N_{\mathrm{aB}}}\right)\left(\frac{w_{\mathrm{E}}}{w_{\mathrm{B}}}\right) \\
&= \left(\frac{4}{13}\right)\left(\frac{10^{20}}{5 \times 10^{18}}\right)\left(\frac{0.2}{0.1}\right) = 3 \times 20 \times 2 = 120 \\
I_{\mathrm{S}} &= \frac{qA_{\mathrm{E}}D_{\mathrm{n}}n_{\mathrm{i}}^2}{N_{\mathrm{aB}} \cdot w_{\mathrm{B}}} = \frac{1.6 \times 10^{-19}\,(\mathrm{C}) \times 10^{-7}\,(\mathrm{cm}^2) \times 4\,(\mathrm{cm}^2/\mathrm{s}) \cdot 10^{20}\,(\mathrm{cm}^{-6})}{5 \times 10^{18}\,\mathrm{cm}^{-3} \times 0.1 \times 10^{-4}\,\mathrm{cm}} = 1.28 \times 10^{-19}\,\mathrm{A} \\
\frac{I_{\mathrm{S}}}{\beta_{\mathrm{F}}} &= 1.07 \times 10^{-21}\,\mathrm{A}
\end{aligned}
$$

The $\mathrm{e}^{\mathrm{qV_B/kT}}$ will make $I_{\mathrm{c}}, I_{\mathrm{B}}$ into $10^{-6}\,\mathrm{A} \simeq 1\,\mu\mathrm{A}$.

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