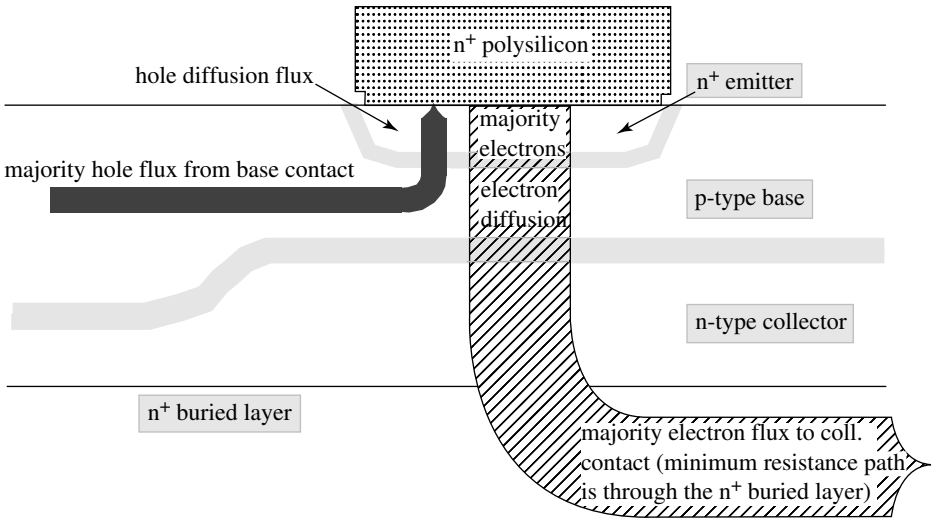
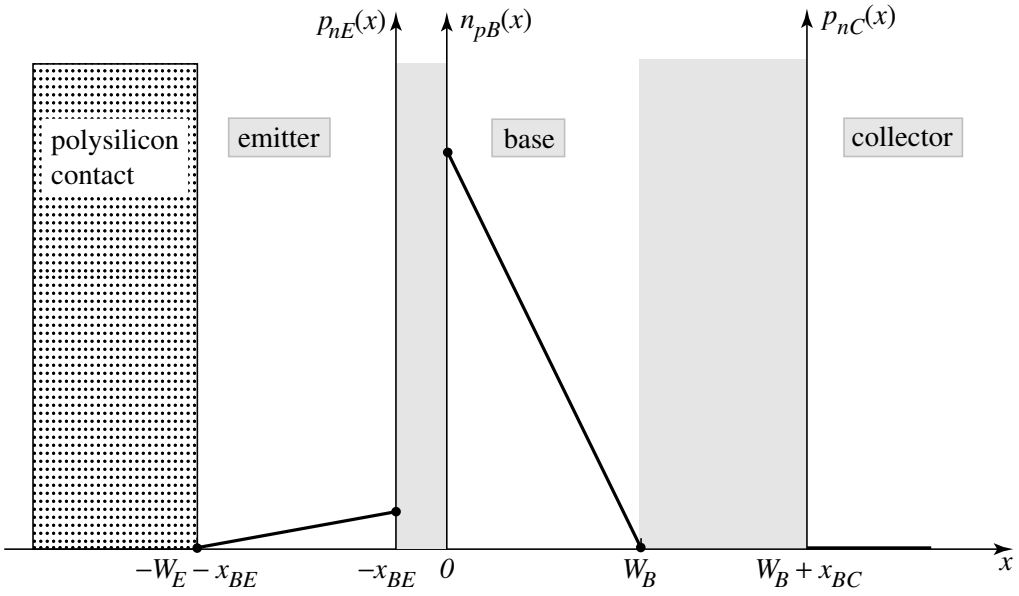
I. Regions of Operation

A. Forward Active Bias - The Flux Picture



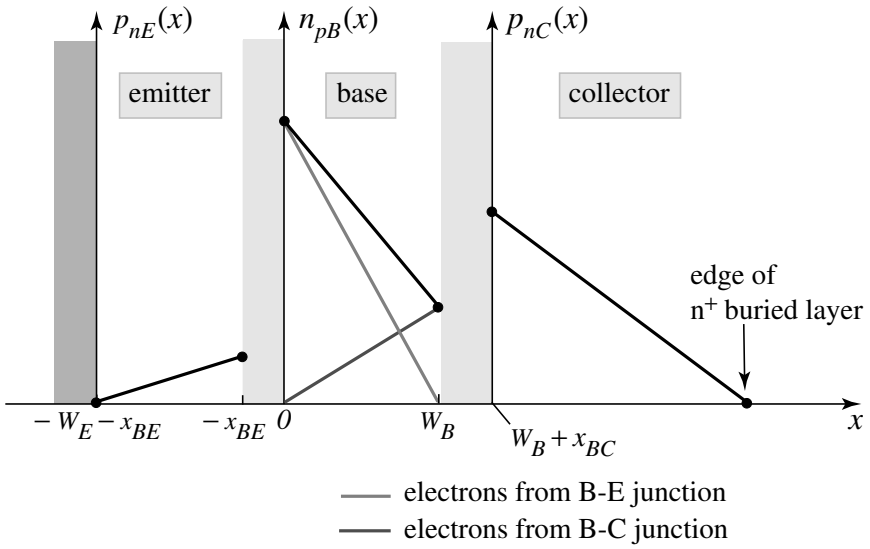
(b)

B. Minority Carrier Concentration



C. Saturation Region - Minority Carrier Concentration

- $V_{CE(sat)} \approx 0.1$ V from the characteristics --> both the emitter-base and the base-collector junctions are forward-biased
- Find minority carrier concentrations in the emitter, base, and collector

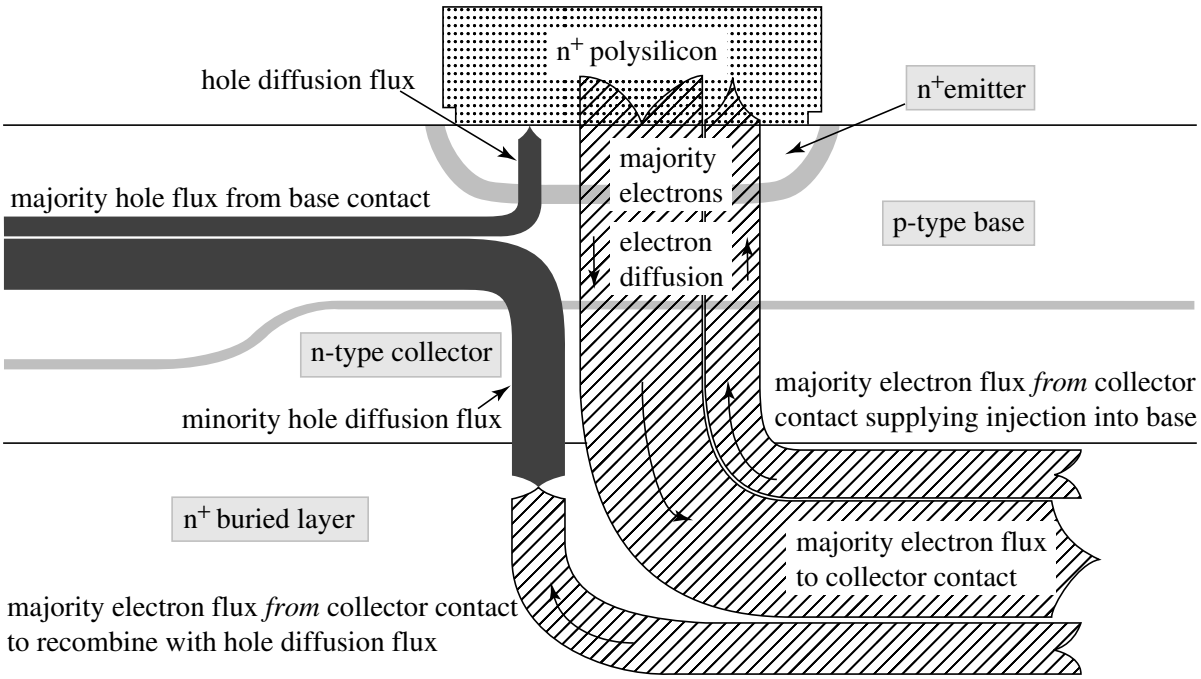


- Both junctions are injecting and both are also collecting ... since the electric field in the depletion region remains in the same direction under forward bias.
- Separate the electron diffusion current in the base into two components: one due to the emitter-base junction and the other due to the base-collector junction

$$J_{nB}^{diff} = -qD_n \frac{n_{pBo}(e^{V_{BE}/V_{th}} - 1)}{W_B} + qD_n \frac{n_{pBo}(e^{V_{BC}/V_{th}} - 1)}{W_B}$$

D. Saturation - The Flux Picture

- Both junctions injecting and collecting
- Electrons injected from emitter into the base are collected by the collector as in the forward active case
- Electrons injected from the collector are injected into the base and collected by the emitter
- Holes injected into emitter recombine at polysilicon ohmic contact as in the forward active case
- Holes injected into collector recombine with electrons upon reaching the n^+ buried layer



II. Ebers-Moll Model

A. Electron diffusion current in the base

$$I_{diff} = -I_S(e^{V_{BE}/V_{th}} - 1) + I_S(e^{V_{BC}/V_{th}} - 1) = -I_1 + I_2$$

B. Emitter current I_E Three components

- $-I_1$ due to injection of electrons from the emitter-base junction,
- $-I_1 / \beta_F$ due to reverse injection of holes into the emitter, and
- I_2 due to collection of electrons injected by base-collector junction.

$$I_E = -I_1 + (-I_1/\beta_F) + I_2 = -\left(1 + \frac{1}{\beta_F}\right)I_1 + I_2 = -\left(\frac{1}{\alpha_F}\right)I_1 + I_2$$

C. Collector current I_C Three components (by symmetry)

- $-I_2$ due to injection of electrons from the base-collector junction,
- $-I_2 / \beta_R$ due to reverse injection of holes into the collector, and
- I_1 due to collection of electrons injected by emitter-base junction
- $\beta_R = \alpha_R / (1 - \alpha_R)$ is the reverse current gain

$$I_C = I_1 - I_2 - \frac{I_2}{\beta_R} = I_1 - \left(1 + \frac{1}{\beta_R}\right)I_2 = I_1 - \left(\frac{1}{\alpha_R}\right)I_2$$

D. "Standard form" for Ebers-Moll equations

- Define two new constants

$$I_{ES} = I_S / \alpha_F \text{ and } I_{CS} = I_S / \alpha_R,$$

$$\alpha_F I_{ES} = \alpha_R I_{CS}$$

- Emitter current:

$$I_E = -I_{ES}(e^{V_{BE}/V_{th}} - 1) + \alpha_R I_{CS}(e^{V_{BC}/V_{th}} - 1)$$

- Collector current:

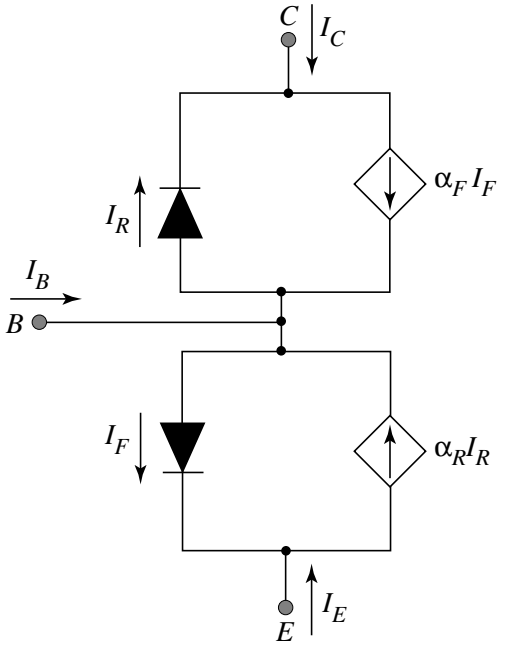
$$I_C = \alpha_F I_{ES}(e^{V_{BE}/V_{th}} - 1) - I_{CS}(e^{V_{BC}/V_{th}} - 1)$$

- Base current: By KCL

$$I_B = -I_C - I_E$$

E. Ebers-Moll Equivalent Circuit

- The collector current and the emitter current represent two diodes with current-controlled current sources coupling the emitter and the collector branches



Diode Currents:

$I_F = I_{ES}(e^{V_{BE}/V_{th}} - 1)$

$I_R = I_{CS}(e^{V_{BC}/V_{th}} - 1)$

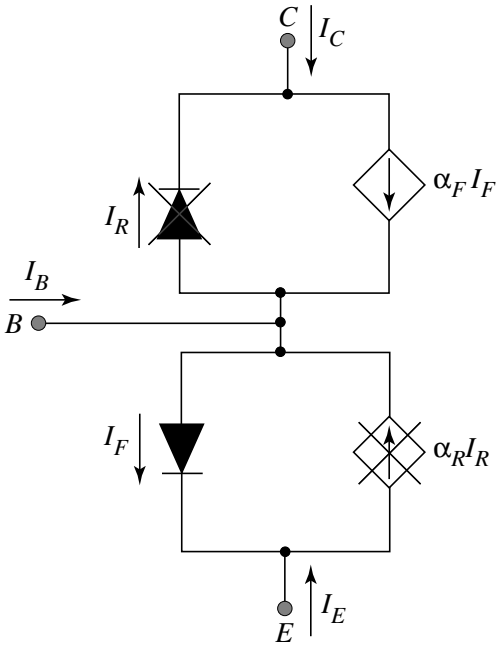
- This model for the BJT applies to general device structures, with the four parameters I_{ES}, I_{CS}, α_F, and α_R being linked by "reciprocity"

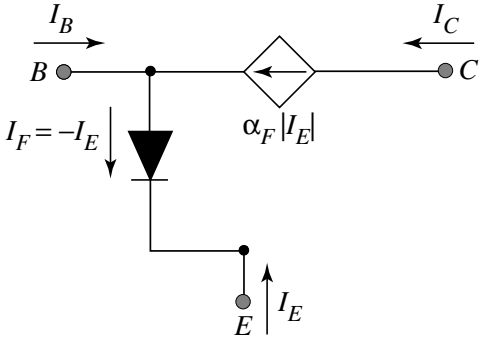
$$\alpha_F I_{ES} = \alpha_R I_{CS} = I_S$$

III. Simplification of Ebers Moll Model

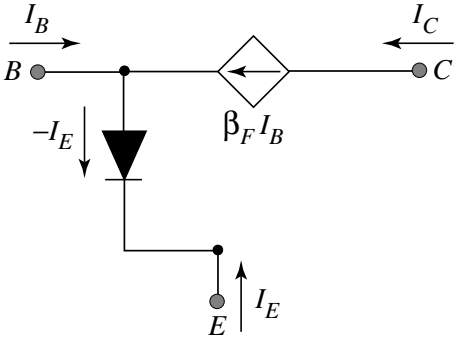
A. Forward Active Model

- I_R is negligible --> can neglect current through B-C diode



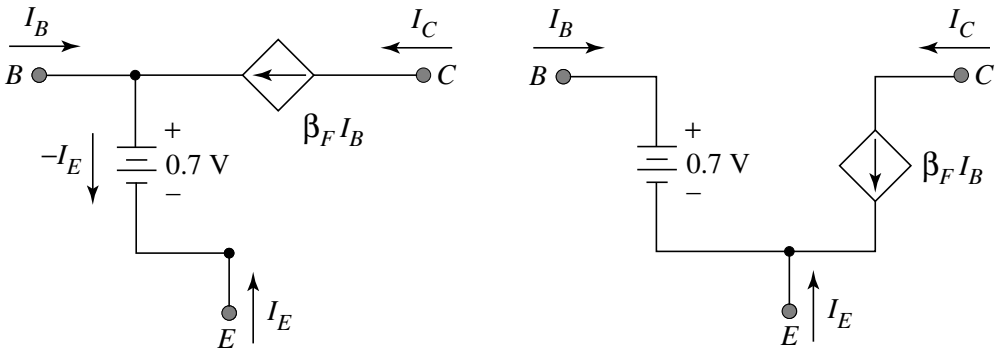


Emitter current control



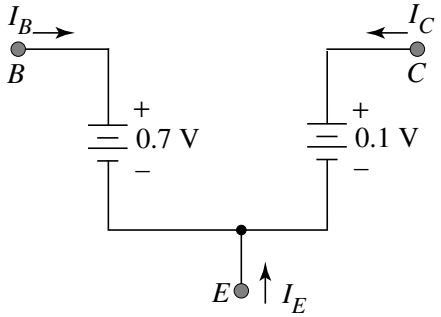
Base current control

- Eliminate forward-biased diode by replacing with a 0.7 V battery (a)
- Current controlled current source can have any voltage across it so we eliminate 0.7V source to yield a more convenient form (b)



B. Saturation

- Include both diodes in the circuit ... both as batteries



- Note that the batteries make the controlled current sources irrelevent to the circuit.