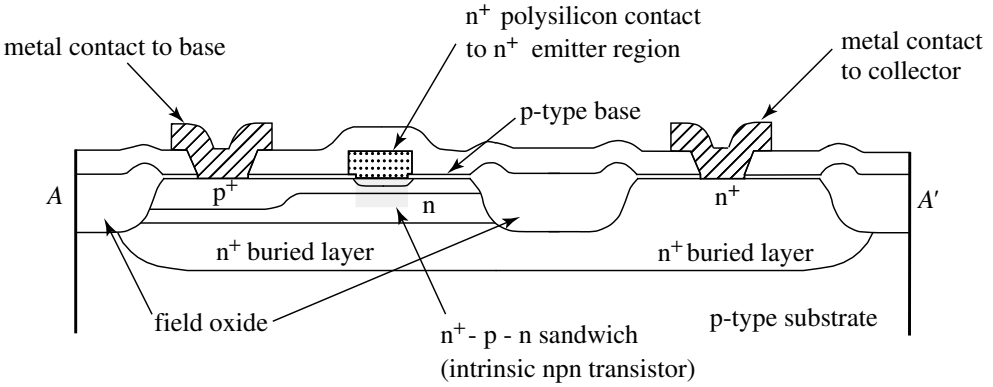
I. The Bipolar Junction Transistor

A. Physical Structure:

- oxide-isolated, low-voltage, high-frequency design
- typical of the bipolar transistor found in a BiCMOS process,



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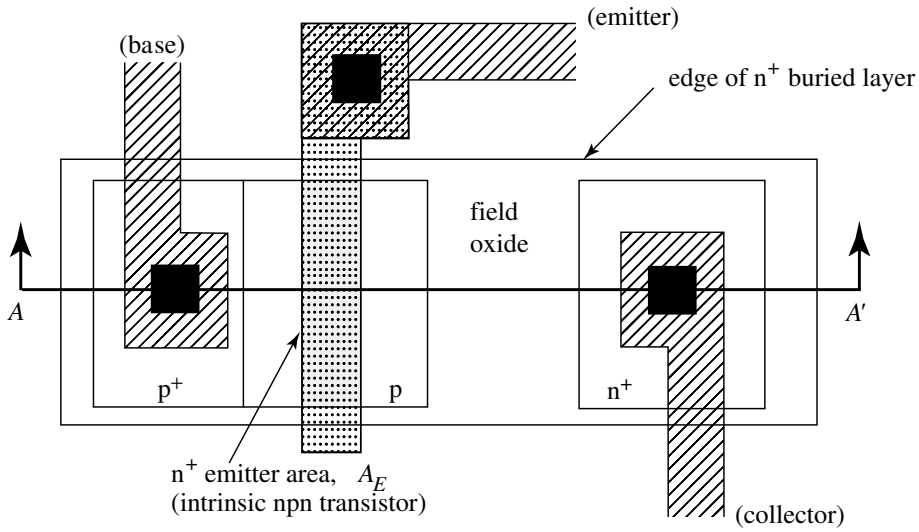

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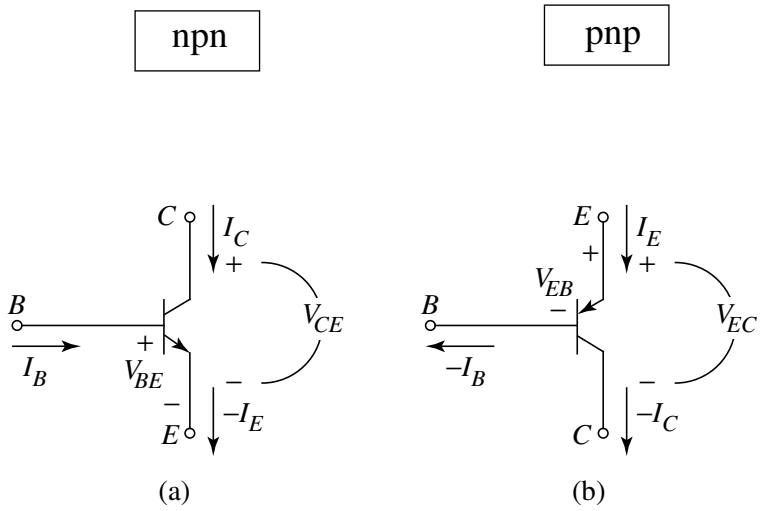
B. Circuit Symbol and Terminal Characteristics

- Two devices that have complementary characterisitics npn transistor and the pnp transistor
- The direction of the diode arrow indicates device type



Normal operation:

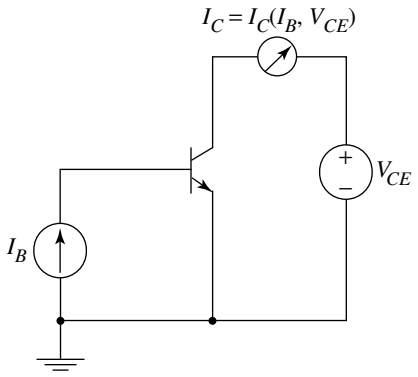
I_C positive V_{CE} positive
I_B positive $V_{BE} = 0.7$
$-I_E$ positive

Normal operation:

$-I_C$ positive V_{EC} positive
$-I_B$ positive $V_{EB} = 0.7$
I_E positive

C. npn BJT Collector Characteristics

- Similar test circuit as for n-channel MOSFET ... except I_B is controlled instead of V_{BE}



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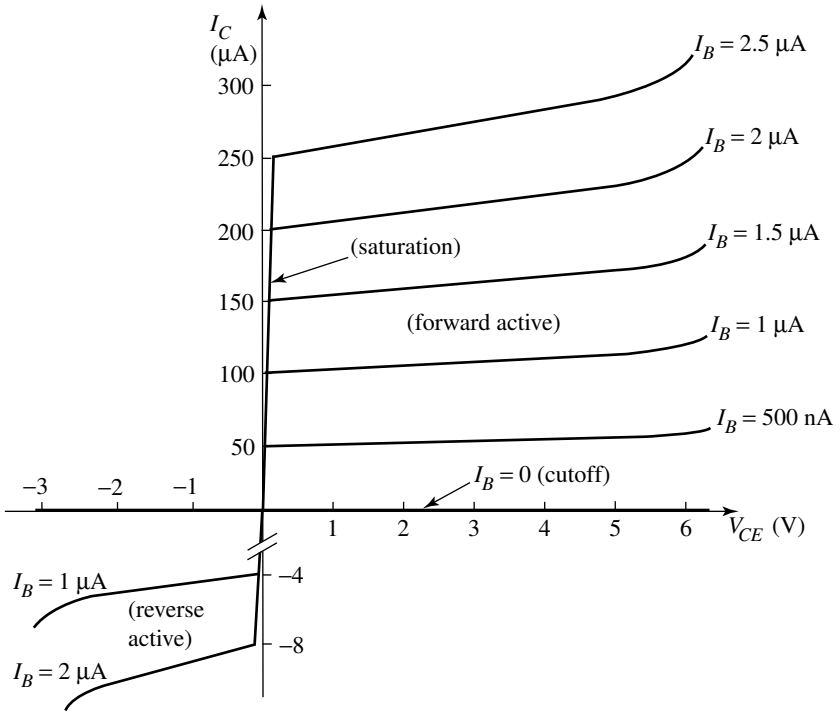


(b)

D. Regions of Operation

- Constant-current region is called *forward active* ... corresponds to **MOSFET saturation region (!!!)**

$$I_C = \beta_F I_B$$

$$I_C \propto e^{\frac{V_{BE}}{V_{th}}}$$

- Bipolar *saturation* region (modeled as a constant voltage) corresponds to **MOSFET triode region**

$$V_{CE} \approx V_{CE(sat)} = 0.1V$$

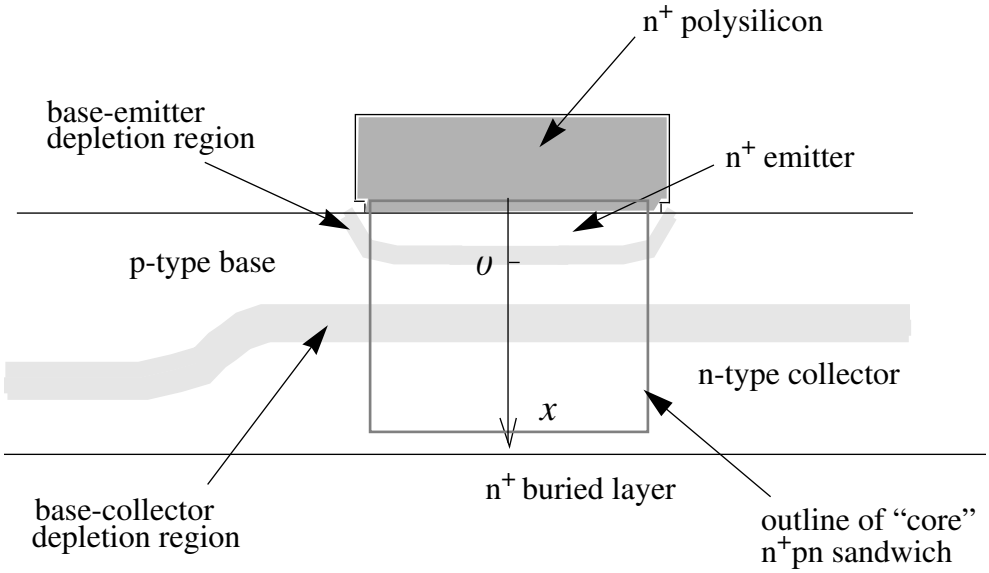
- *Cutoff* ... corresponds to MOSFET cutoff region
- *Reverse active* ... terminal voltages for npn sandwich are flipped so that V_{CE} is negative and $V_{BC} = 0.7$ V. Only occasionally useful.

- Boundary between saturation and forward-active regions:

$$V_{CE} > V_{CE(sat)} \qquad \text{and} \qquad I_B > 0$$

II. Bipolar Transistor Physics

A. Forward Active Region of Operation

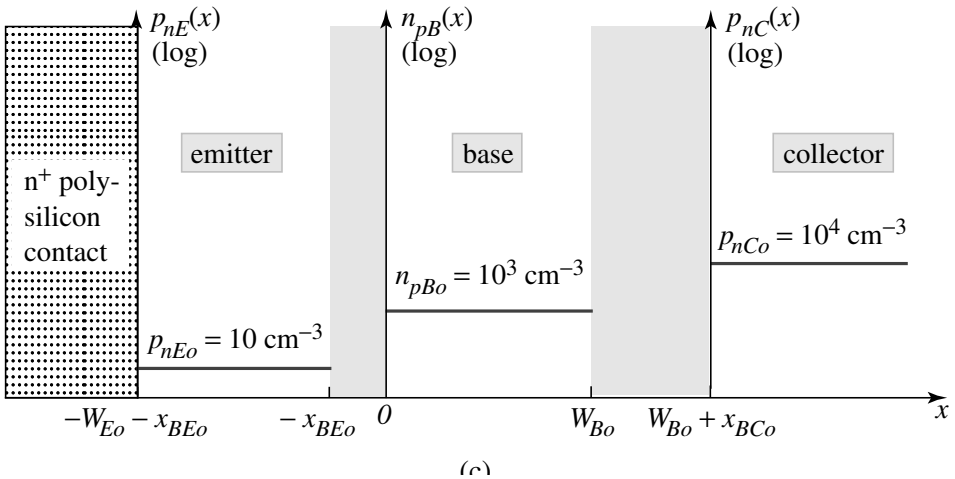


B. Game Plan

- Understand thermal equilibrium potential and carrier concentrations.
- Apply the Law of the Junction with $V_{BE} \approx 0.7$ V and $V_{BC} < 0$ (typical forward-active bias point) to find the minority carrier concentrations at the depletion region edges.
- Assume that the emitter and the base regions are "short" (**no recombination**) and find the diffusion currents.

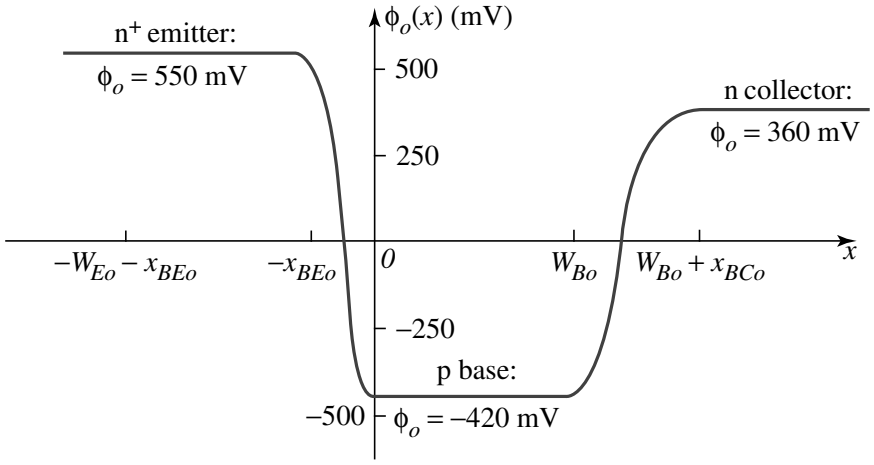
C. Thermal Equilibrium

- Typically emitter is doped two orders of magnitude (at least) more heavily than the base; the collector is an order of magnitude more lightly doped than the base.
- Minority carrier concentrations:



(c)

- Electrostatic potential:

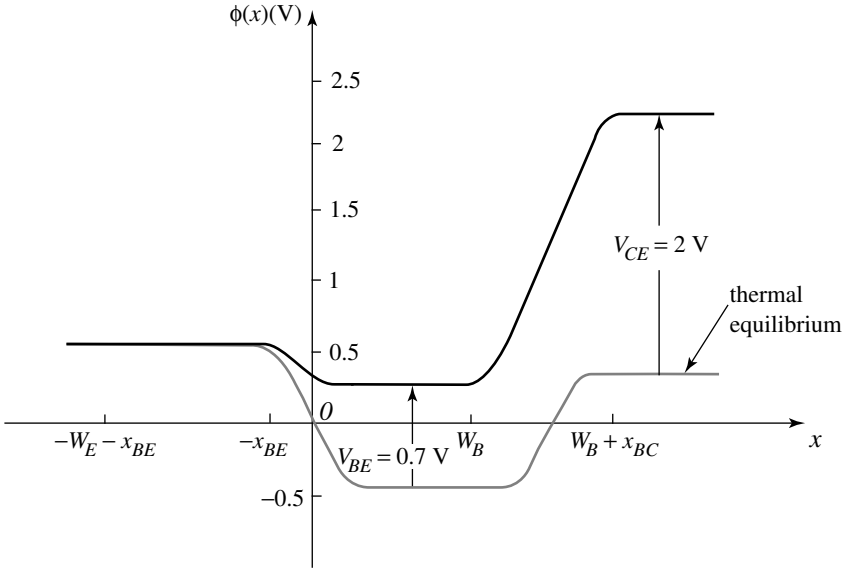


D. Carrier Concentrations under Forward Active Bias

- Boundary conditions at the edges of the depletion region are:

Emitter-Base: $\exp[V_{BE} / V_{th}] >> 0$.....Base-Collector: $\exp[V_{BC} / V_{th}] = 0$

- Ohmic contacts return carrier concentration to equilibrium



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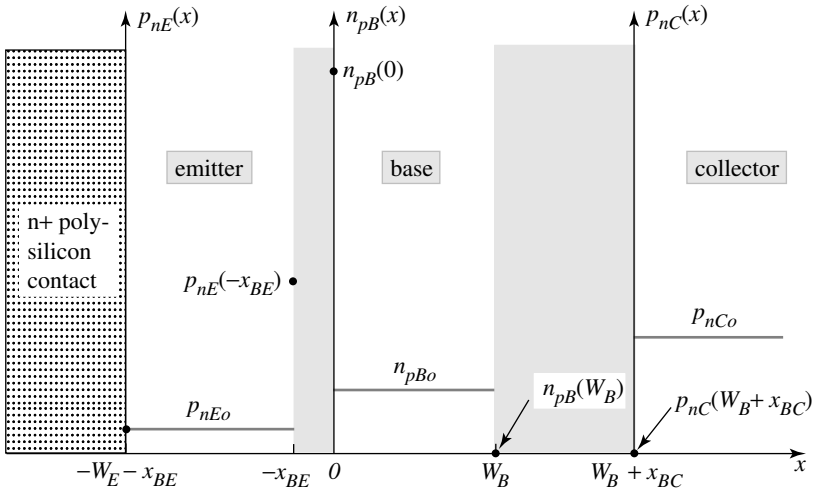

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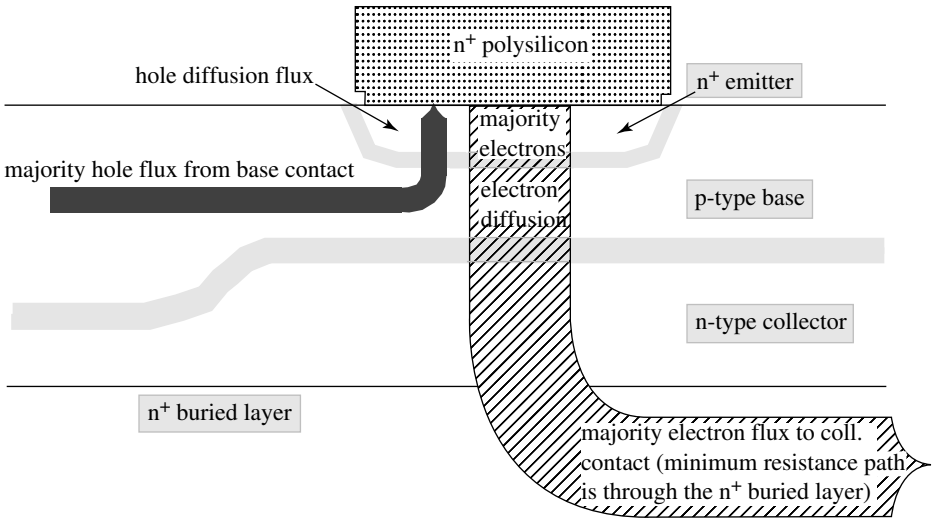
E. The Flux Picture - Forward Active Bias

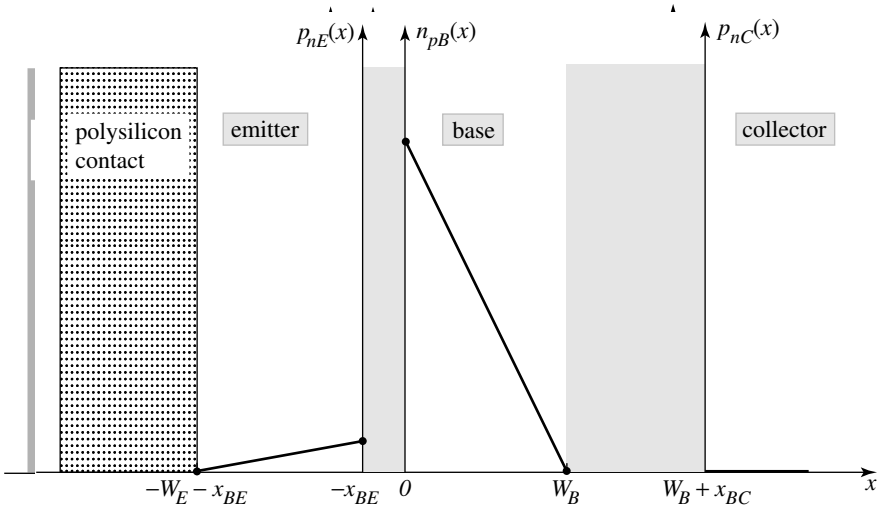
- Rather than current densities, we use the concept of *flux* [# per cm^2 per second]
- The width of the electron flux "stream" is greater than the hole flux stream.



(b)

- The electrons are supplied by the emitter contact and diffuse across the base
- Electric field in the collector depletion region sweeps electrons into the collector
- n^+ buried layer provides a low resistance path to the collector contact
- The holes are supplied by the base contact and diffuse across the emitter
- The reverse injected holes are recombined at the polysilicon ohmic contact

III. Forward-Active Terminal Currents



A. Collector current:

- Electron diffusion current density X emitter area

$$J_{nB}^{diff} = qD_n\left(\frac{n_{pB}(W_B) - n_{pB}(0)}{W_B}\right) = qD_n\frac{n_{pBo}\left(e^{V_{BC}/V_{th}} - e^{V_{BE}/V_{th}}\right)}{W_B}$$

$$I_C = -J_{nB}^{diff}A_E = \left(\frac{qD_n n_{pBo}A_E}{W_B}\right)e^{V_{BE}/V_{th}} \quad where \quad n_{pBo} = \frac{n_i^2}{N_{aB}}$$

B. Base current

- Reverse-injected hole diffusion current density X emitter area

$$J_{pE}^{diff} = -\left(\frac{qD_p p_{nEo}}{W_E}\right)(e^{V_{BE}/V_{th}} - 1) \quad where \quad p_{nEo} = \frac{n_i^2}{N_{dE}}$$

$$I_B = -J_{pE}^{diff} A_E = \left(\frac{qD_p p_{nEo} A_E}{W_E}\right)\left(e^{V_{BE}/V_{th}} - 1\right)$$

C. Emitter current

- Sum of I_B and I_C according to KCL (negative ... reference is positive-in)

$$I_E = \left(J_{nB}^{diff} + J_{pE}^{diff}\right)A_E = -\left[\left(\frac{qD_p p_{nEo} A_E}{W_E}\right) + \left(\frac{qD_n n_{pBo} A_E}{W_B}\right)\right] e^{V_{BE}/V_{th}}$$

IV. Forward-Active Current Gains

A. Alpha-F - $I_C/|I_E| = \alpha_F$

- The ratio of collector current to the magnitude of the emitter current

$$\frac{I_C}{|I_E|} = \frac{\left(\frac{qD_n n_{pBo} A_E}{W_B}\right)}{\left(\frac{qD_p p_{nEo} A_E}{W_E}\right) + \left(\frac{qD_n n_{pBo} A_E}{W_B}\right)} = \alpha_F$$

$$\boxed{\alpha_F = \frac{1}{1 + \left(\frac{D_p N_{aB} W_B}{D_n N_{dE} W_E}\right)}}$$

- α_F --> 1 ... typically, $\alpha_F = 0.99$.

B. Beta Forward Current Gains - $I_C/I_B = \beta_F$

- The ratio of collector current to base current

$$I_B = -I_E - I_C = \frac{I_C}{\alpha_F} - I_C = I_C\left(\frac{1-\alpha_F}{\alpha_F}\right)$$

$$\boxed{I_C = \left(\frac{\alpha_F}{1-\alpha_F}\right) I_B = \beta_F I_B.}$$

- A typical value is $\beta_F = 100$