

Physics of Electronics:

8. Bipolar Junction Transistor

July – December 2009

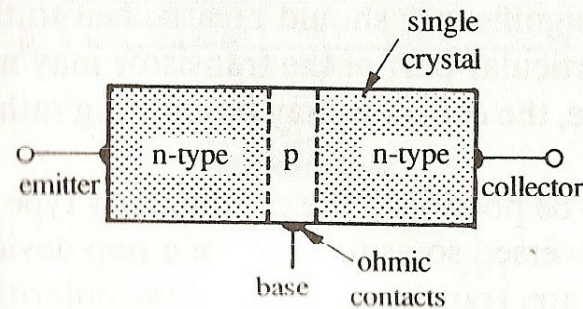
Contents overview

- Basics
- Bipolar junction transistor
- Gain parameters
- Non-ideal structures

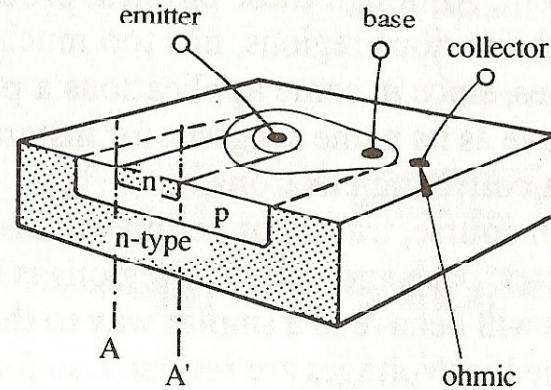
Ideal Bipolar Junction Transistor

- Basics

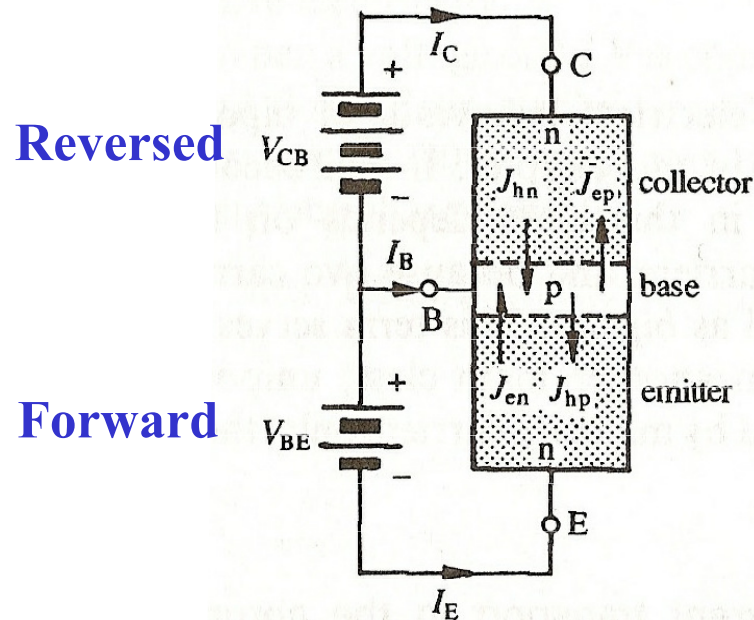
Schematic representation



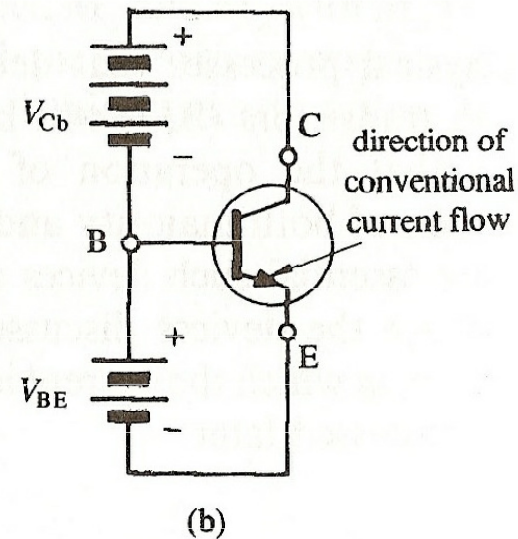
Actual realization



Normal biasing

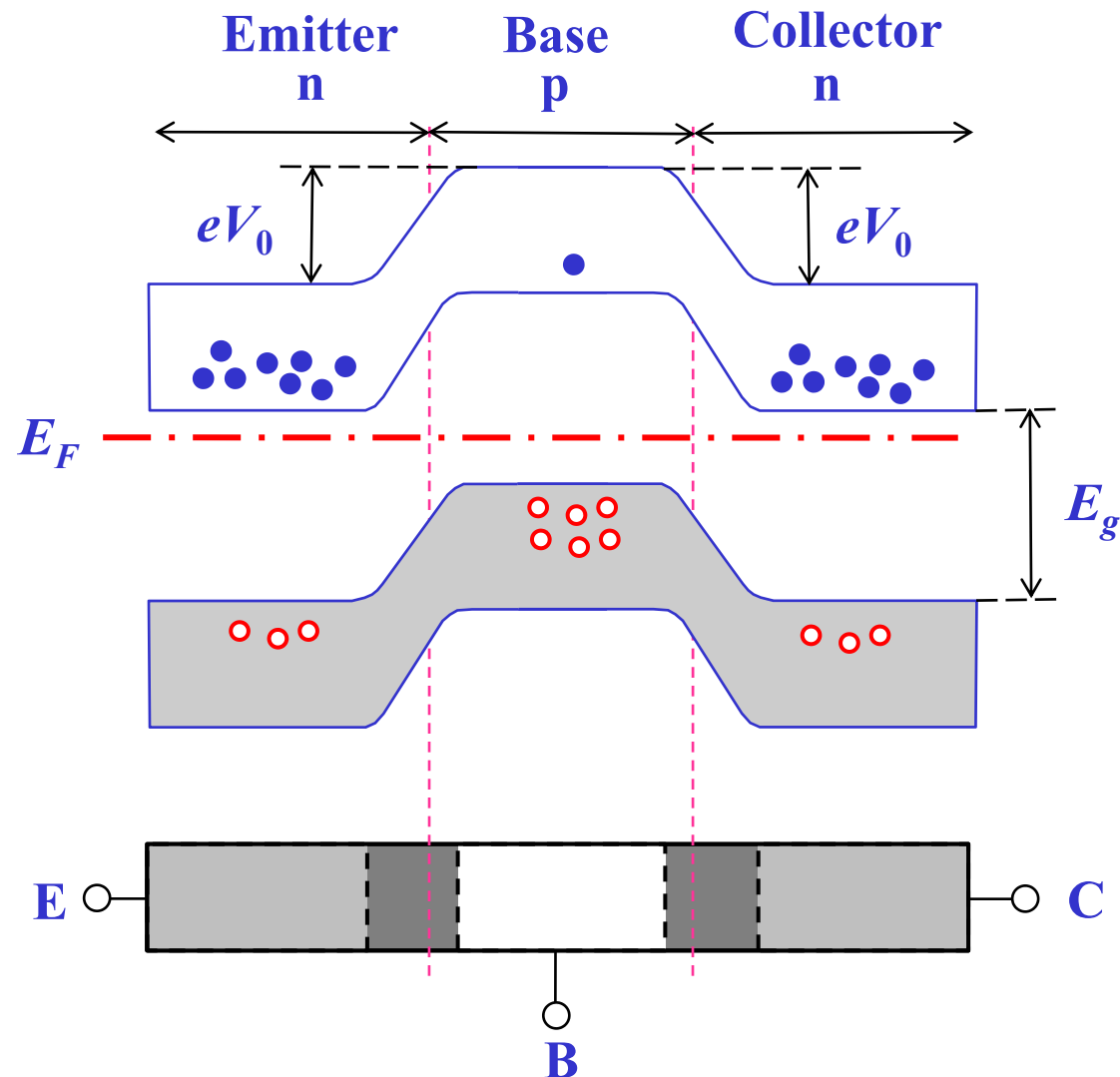


Circuit representation



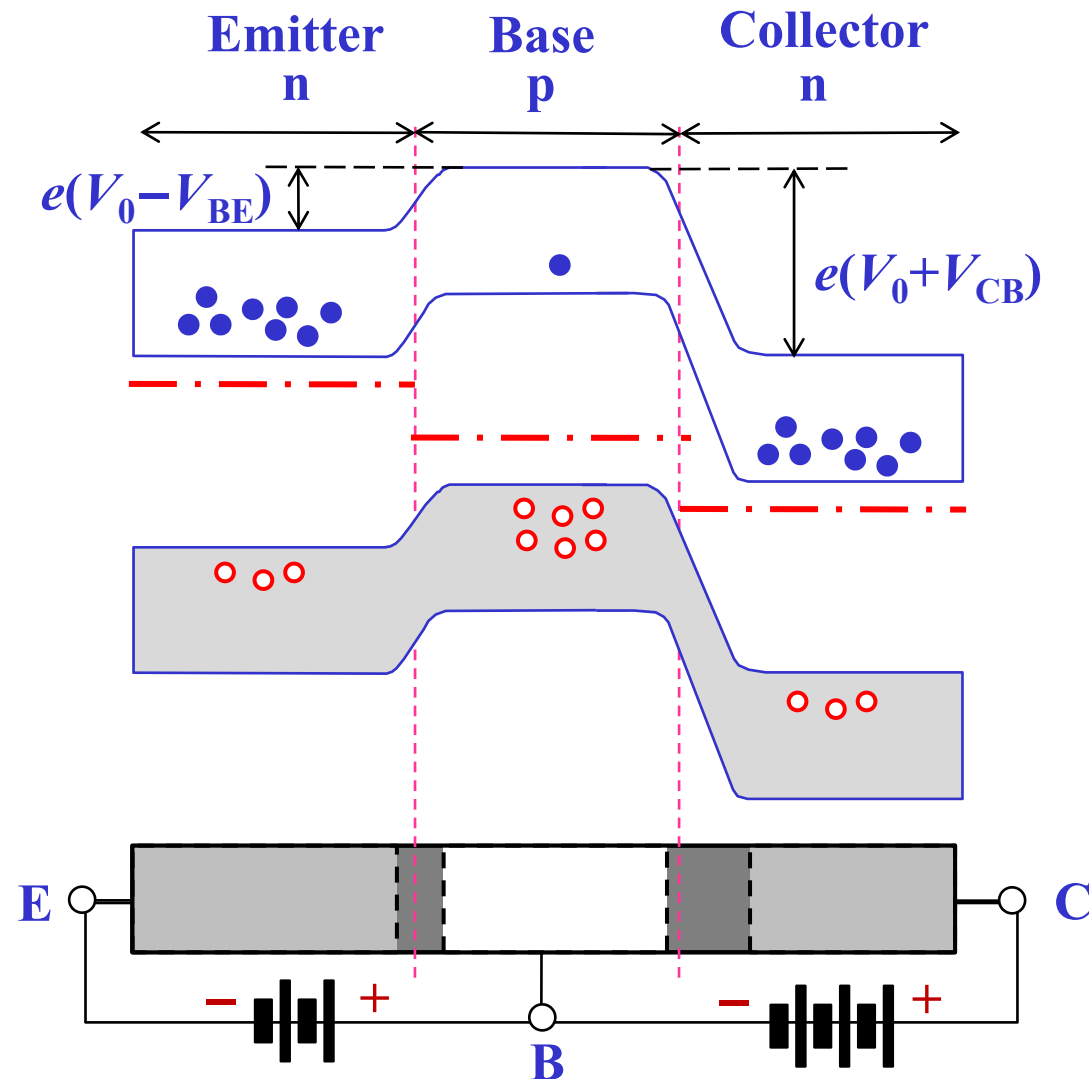
Ideal Bipolar Junction Transistor

- Phenomenological description - unbiased:



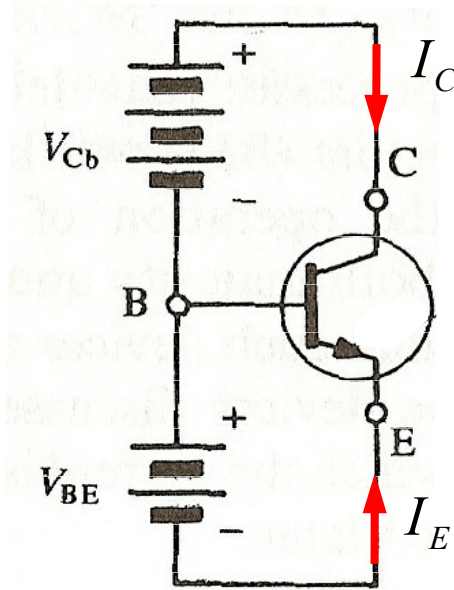
Ideal Bipolar Junction Transistor

- Phenomenological description - biased:



Gain Parameters in a BJT

- Common-base configuration:



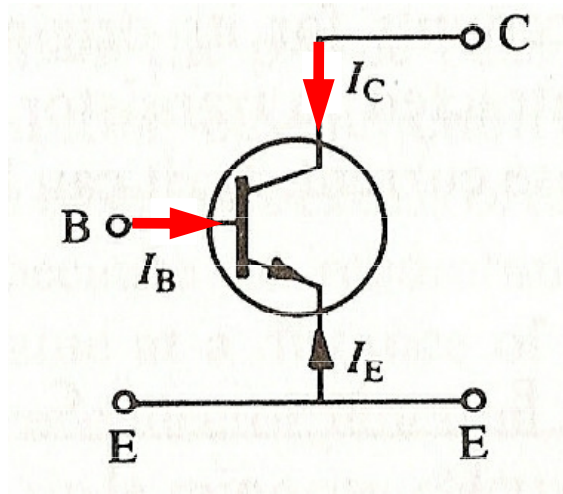
Common-base gain:

$$\frac{\text{change in collector current}}{\text{change in emitter current}} = \left(\frac{-\Delta I_C}{\Delta I_E} \right) \bigg|_{V_{CB} \text{ const.}} = \alpha_B$$

$$\alpha_B \approx 0.9 - 0.99$$

Gain Parameters in a BJT

- Common-emitter configuration:



Common-emitter gain:

$$\alpha_E = \left(\frac{\Delta I_C}{\Delta I_B} \right) \bigg|_{V_{CE} \text{ const.}}$$

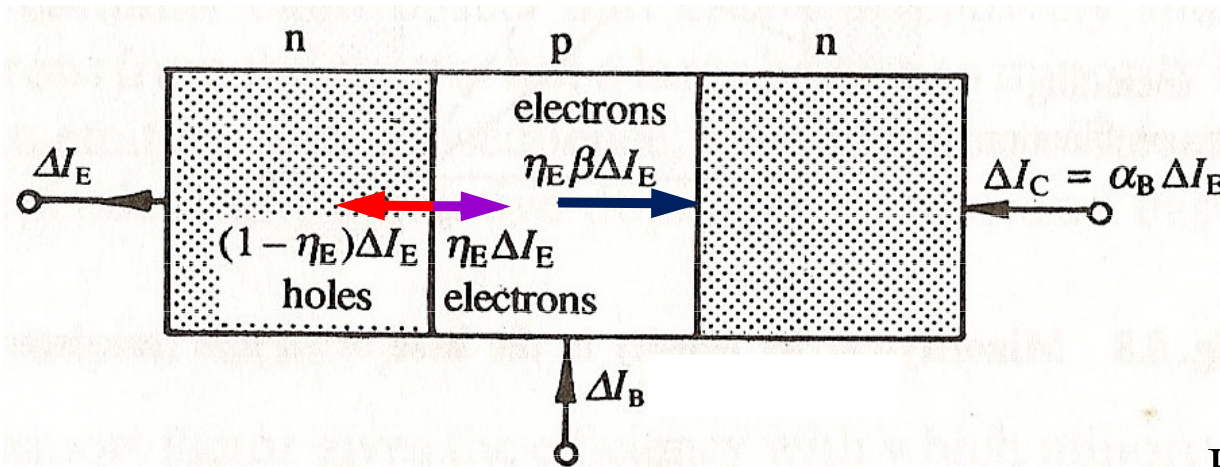
- Relation between gains:

$$I_B + I_C + I_E = 0 \Rightarrow \Delta I_B = -(\Delta I_C + \Delta I_E) \Rightarrow \Delta I_B = -\Delta I_C \left[1 - \frac{1}{\alpha_B} \right]$$

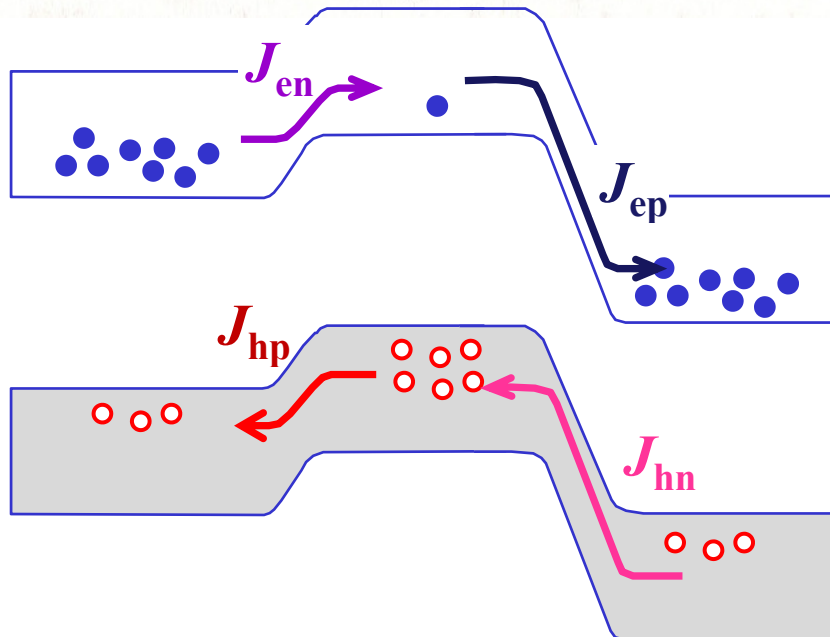
$$\Rightarrow \boxed{\frac{1}{\alpha_E} = \frac{1}{\alpha_B} - 1} \quad \alpha_E \approx 10 - 100$$

Gain Parameters in a BJT

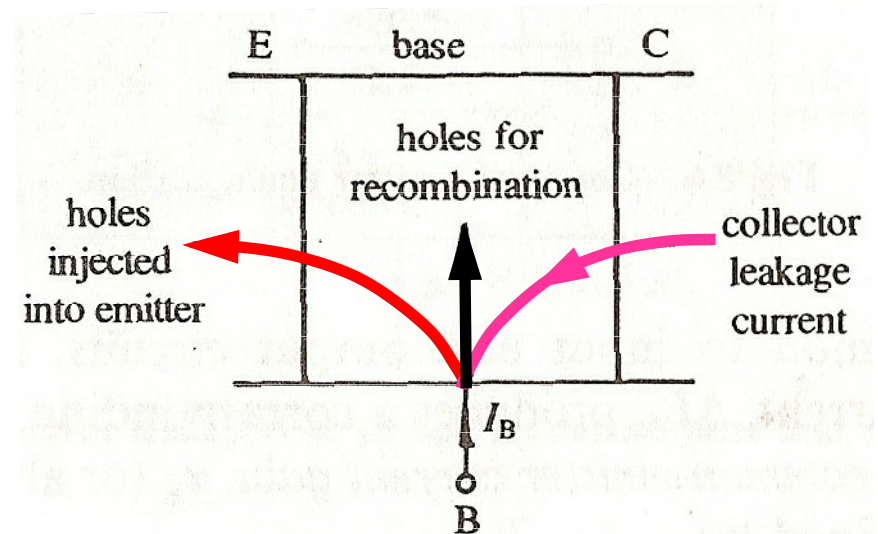
- α_B in terms of the base current:



η_E : injection efficiency
 β : base transport factor

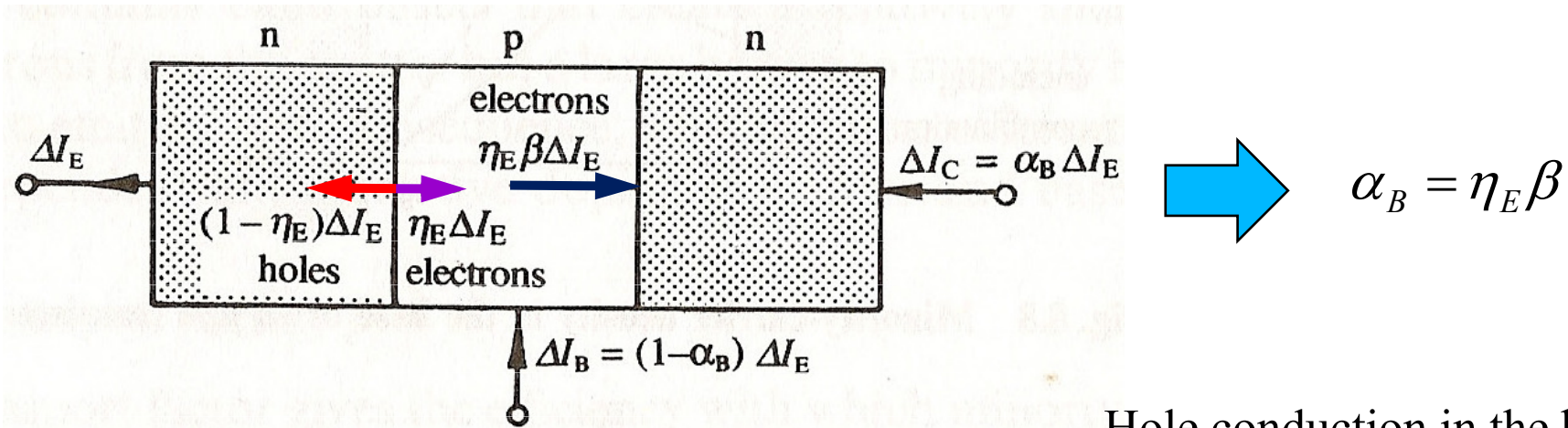


Hole conduction in the base:



Gain Parameters in a BJT

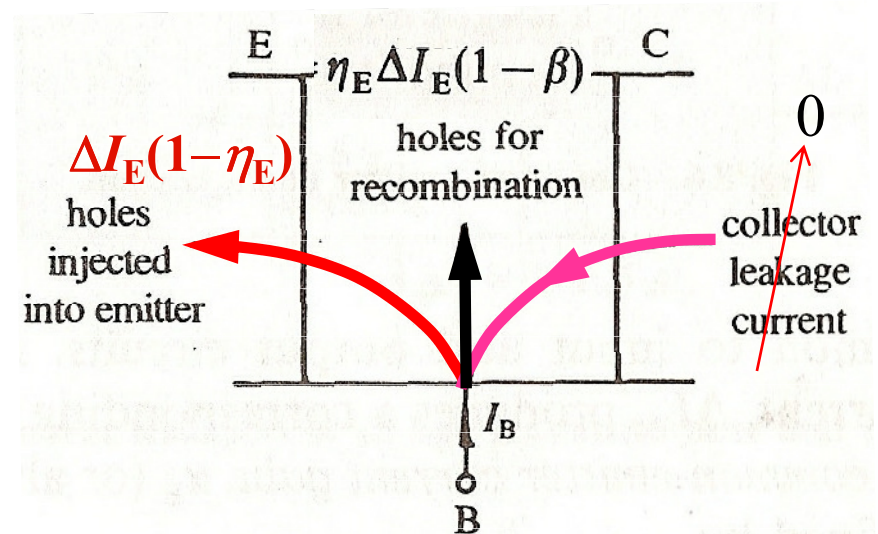
- α_B in terms of the base current:



Hole conduction in the base:

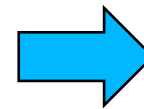
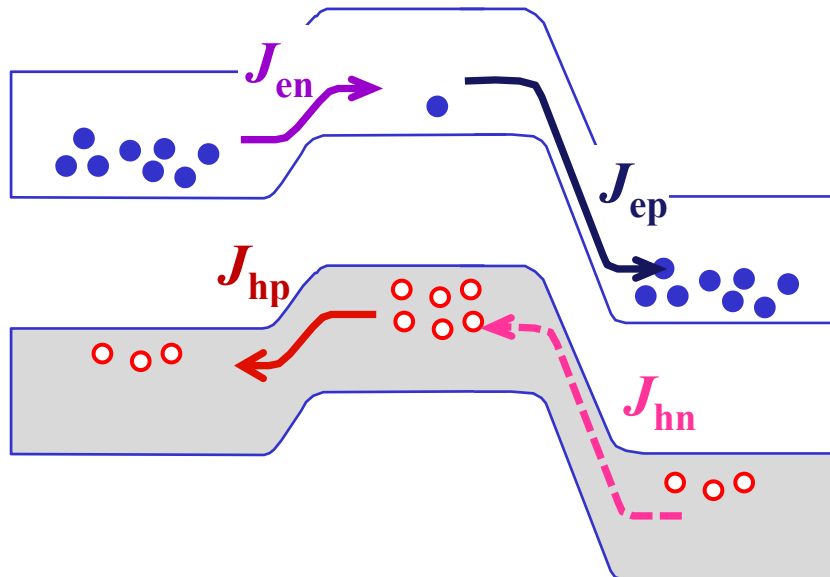
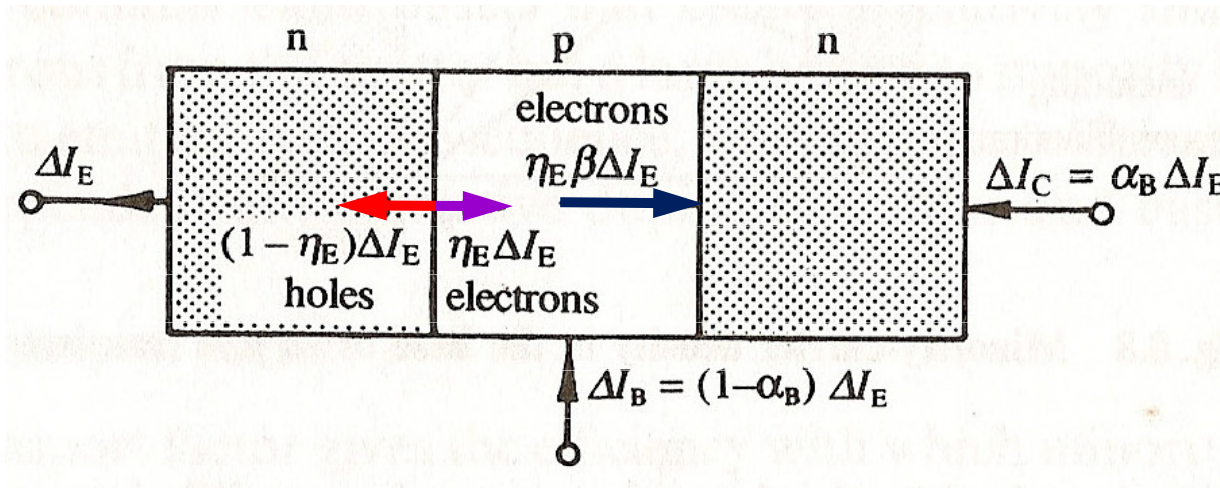
$$\begin{aligned}\Delta I_B &= \eta_E\Delta I_E(1 - \beta) + \Delta I_E(1 - \eta_E) \\ &= (1 - \alpha_B)\Delta I_E\end{aligned}$$

All currents are related!



Gain Parameters in a BJT

- Derivation of η_E :

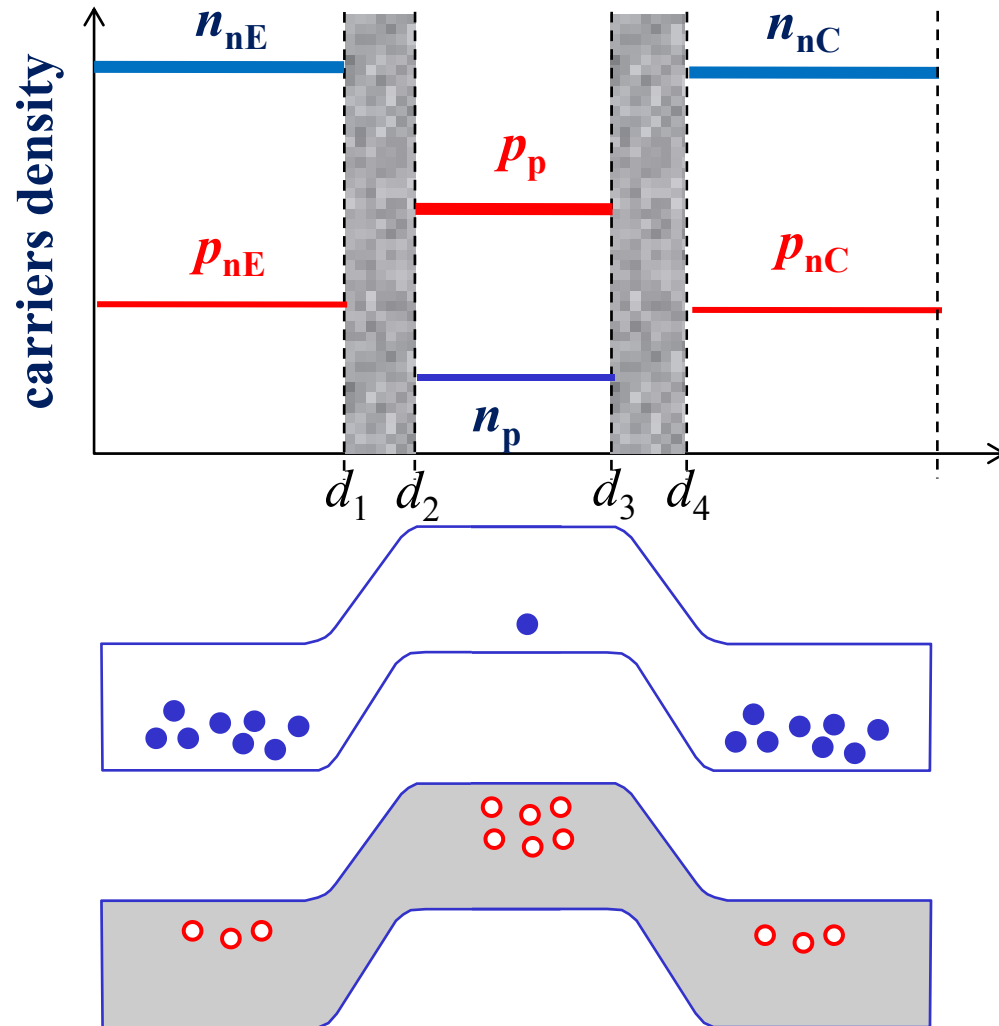


$$\eta_E = \frac{J_{en}}{J_{en} + J_{hp}}$$

$$= \left(1 - \frac{J_{en}}{J_{hp}} \right)^{-1}$$

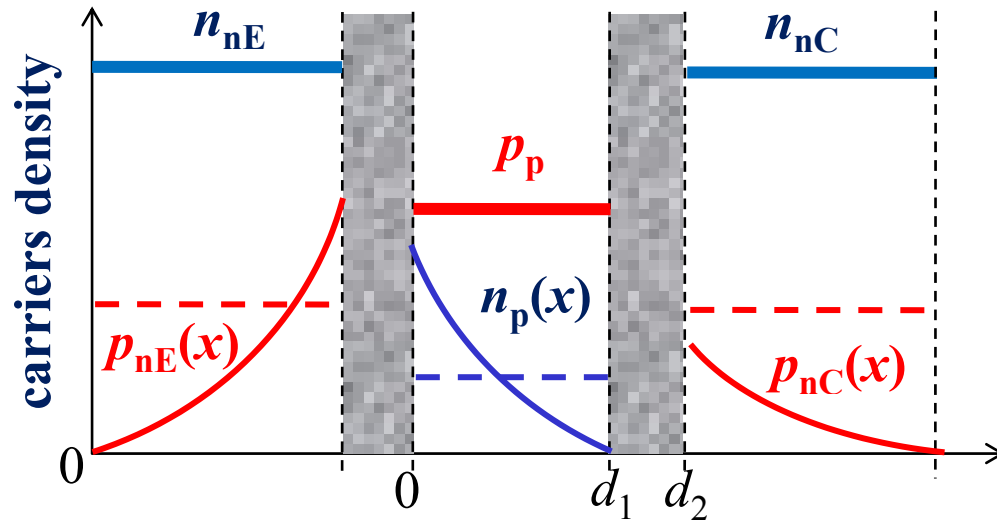
Gain Parameters in a BJT

- Derivation of η_E :

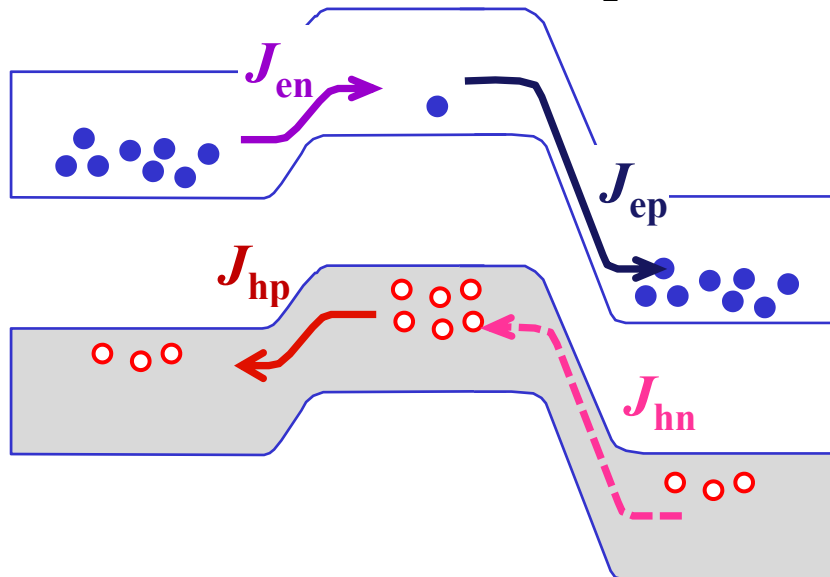


Gain Parameters in a BJT

- Derivation of η_E :



$$J_{en} = eD_e \left. \frac{dn_p}{dx} \right|_{x=0}$$



$$n_p(0) = n_{p0} = n_p \exp(eV_{BE}/kT)$$

$$n_p(d_1 \approx l_B) = n_p \exp(-eV_{BC}/kT)$$

linear approx.

$$n_p(x) = n_{p0} \left(1 - \frac{x}{l_B} \right)$$

Gain Parameters in a BJT

- Derivation of η_E :

$$J_{en} = eD_e \left. \frac{dn_p}{dx} \right|_{x=0} \quad \Rightarrow \quad J_{en} = eD_e \frac{n_{p0}}{l_B} = \frac{eD_e}{l_B} n_p \exp(eV_{BE}/kT)$$

$$J_{hp} = \frac{eD_h}{l_E} p_{nE} \exp(eV_{BE}/kT)$$

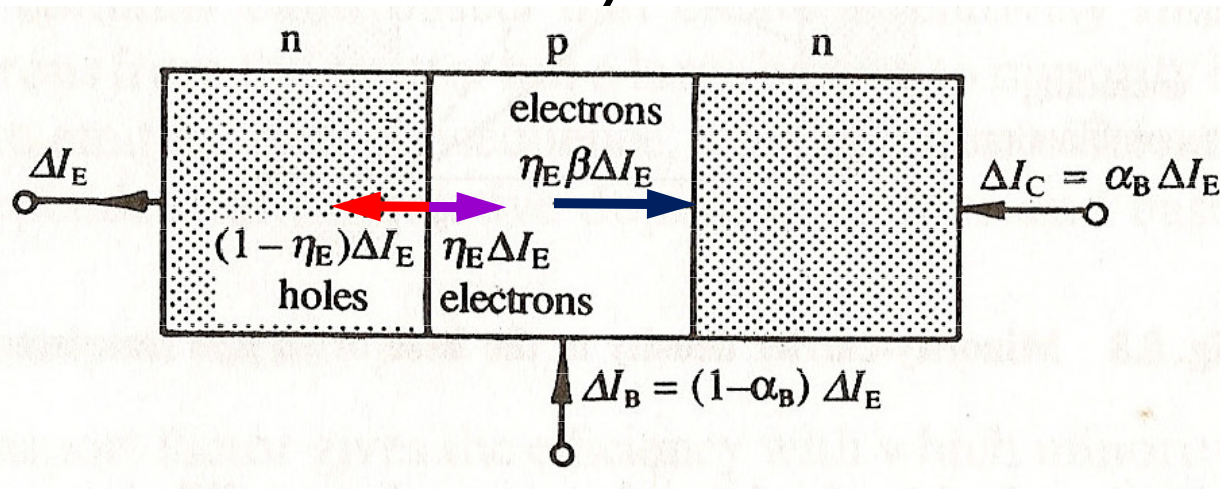
$$\Rightarrow \frac{J_{en}}{J_{hp}} = \frac{eD_e n_p}{l_B} \div \frac{eD_h p_{nE}}{l_E} \quad \text{But} \quad n_p \cancel{p_p}^{N_A} = n_i^2 = n_{nE} \cancel{p_{nE}}^{N_{DE}}$$

$$\Rightarrow \boxed{\frac{J_{en}}{J_{hp}} \approx \frac{D_e N_{DE} l_E}{D_h N_A l_B}}$$

- Currents controlled by doping and lengths.
- Doping and lengths are usually selected such that $\eta_E > 0.99$

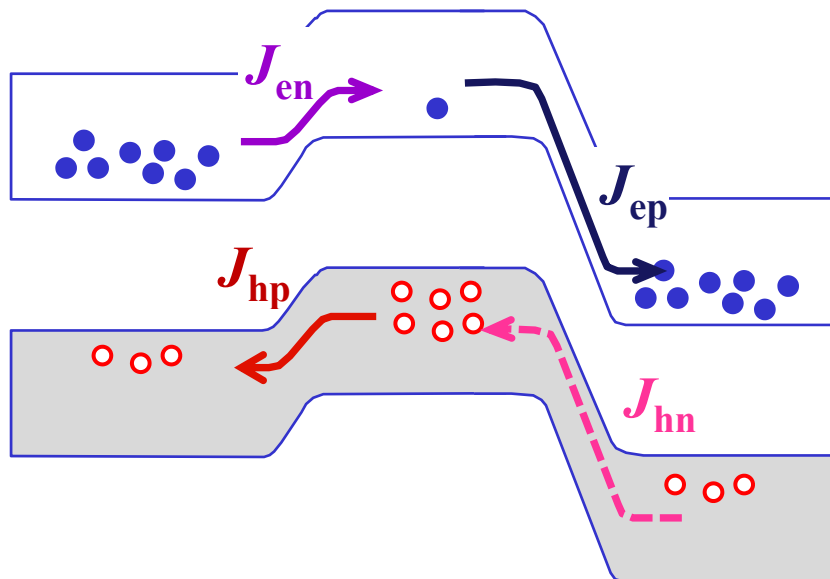
Gain Parameters in a BJT

- Derivation of β :



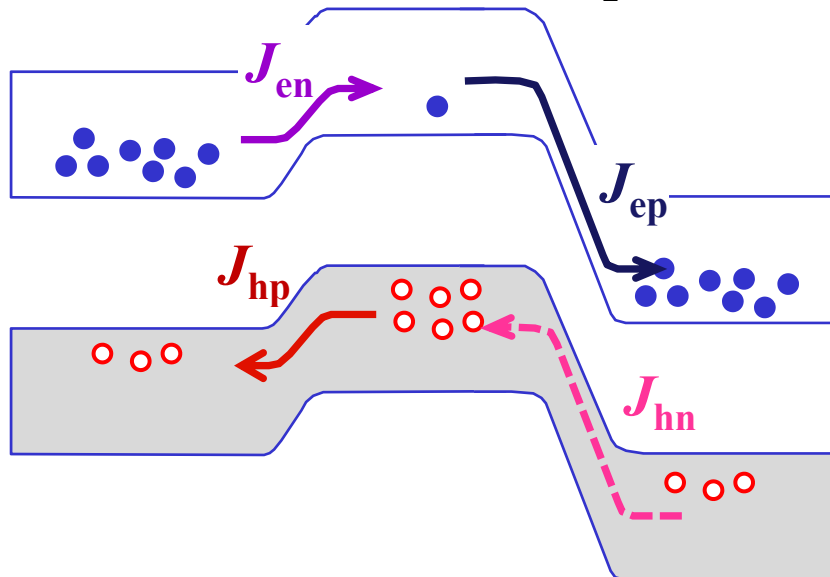
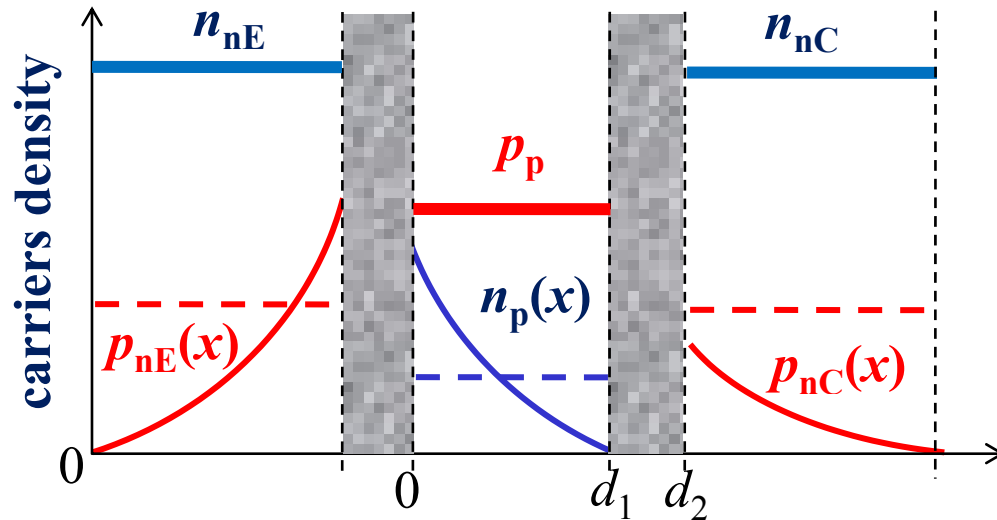
$$\beta = \frac{J_e|_{\text{collector junction}}}{J_e|_{\text{emitter junction}}}$$

$$\beta = \frac{J_{ep}}{J_{en}}$$



Gain Parameters in a BJT

- Derivation of β :



$$J_{en} = eD_e \left. \frac{dn_p}{dx} \right|_{x=0}$$

$$J_{ep} = eD_e \left. \frac{dn_p}{dx} \right|_{x=d_1}$$

To determine n_p we apply the continuity equation with the following boundary conditions:

$$n_p(0) = n_{p0} = n_p \exp(eV_{BE}/kT)$$

$$n_p(d_1 \approx l_B) = 0$$

Gain Parameters in a BJT

- Derivation of β :

$$\cancel{\frac{\partial(\delta n)}{\partial t}} = -\frac{\delta n}{\tau_{Le}} + \mu_e \cancel{\mathcal{E}_x} \frac{\partial(\delta n)}{\partial x} + D_e \frac{\partial^2(\delta n)}{\partial x^2} \quad \Rightarrow \quad \frac{d^2(\delta n)}{dx^2} = \frac{\delta n}{L_e^2}$$

$$\Rightarrow \delta n = C_1 \exp(-x/L_e) + C_2 \exp(+x/L_e) \quad \text{With:} \quad \begin{array}{ll} \delta n = n_{p0} - n_p & \text{at } x=0 \\ \delta n = -n_p \simeq 0 & \text{at } x=l_B \end{array}$$

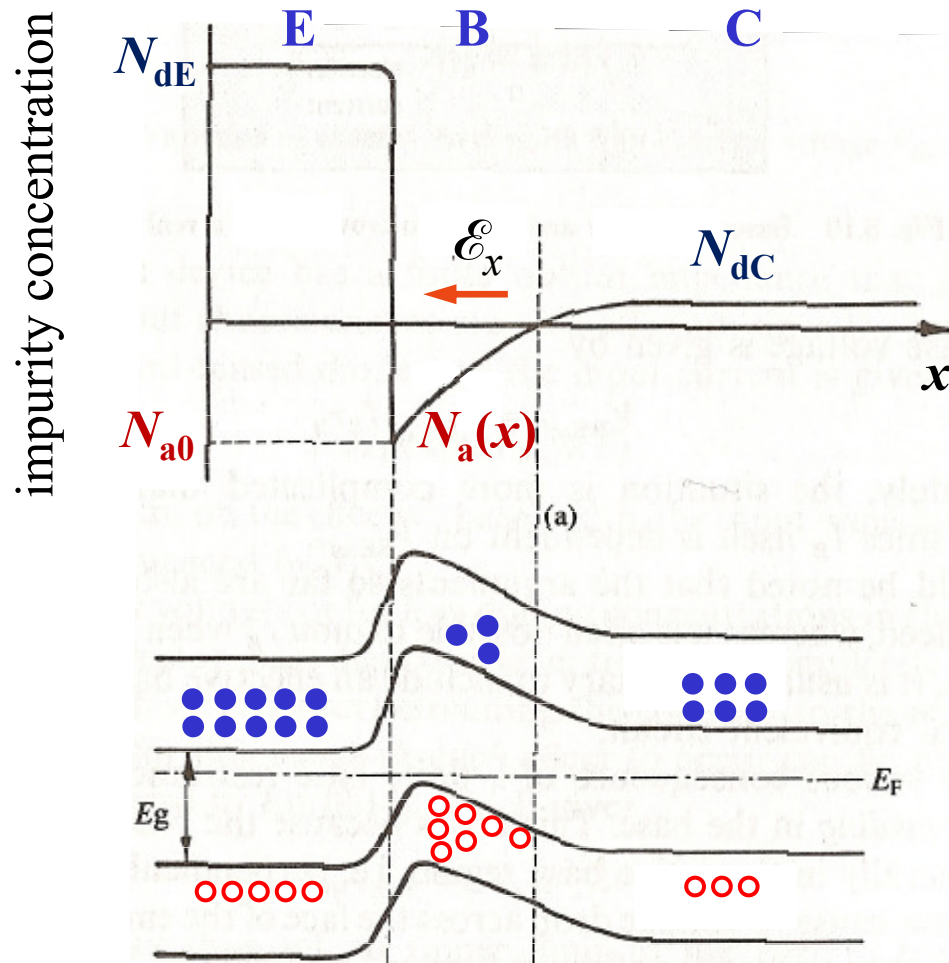
$$\Rightarrow \delta n = \frac{n_{p0} - n_p}{1 - \exp(2l_B/L_e)} [\exp(x/L_e) - \exp(2l_B/L_e) \exp(-x/L_e)]$$

$$\Rightarrow \boxed{\beta \simeq 1 - \frac{1}{2}(l_B/L_e)^2}$$

- Usually, $\beta > 0.95$

Non-ideal Transistor Structures

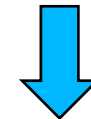
- Graded base
 - Base doped non-uniformly. \mathcal{E} field along all the base.



Hole current in the base:

$$J_h = e\mu_h p \mathcal{E}_x - eD_h \frac{dp}{dx}$$

But: $J_h = 0$ & $p(x) \approx N_a(x)$



$$\mathcal{E}_x = \frac{D_h}{\mu_h N_a} \frac{dN_a(x)}{dx} = \frac{kT}{e} \frac{1}{N_a} \frac{dN_a}{dx}$$



$$J_e = \boxed{e\mu_n n \mathcal{E}_x} + eD_n \frac{dn}{dx}$$

Conclusions

- The BJT was introduced.
- Gain parameters were defined and calculated from the processes occurring inside the BJT.
- The graded BJT was studied.