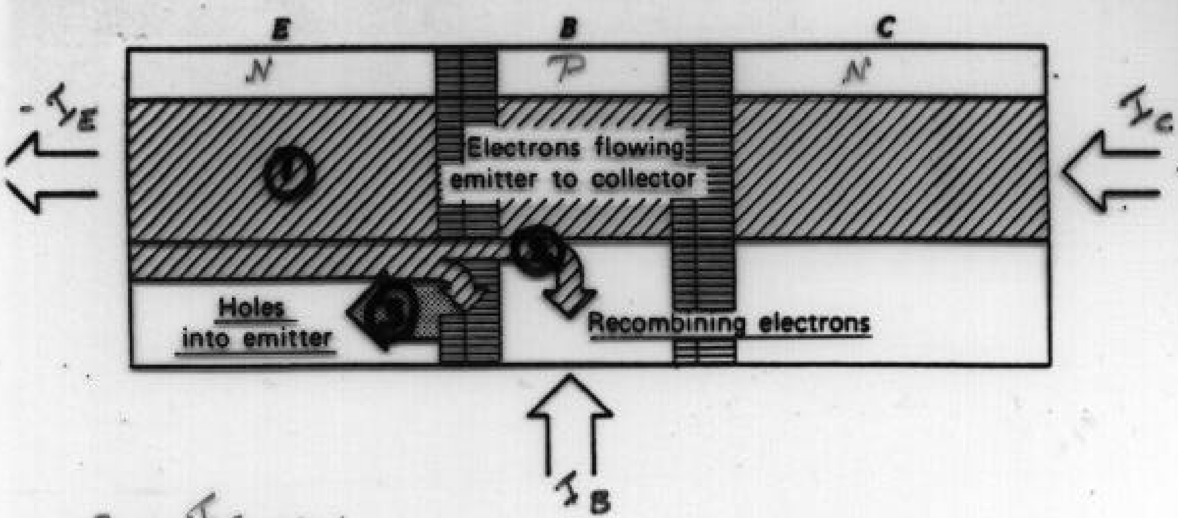
CURRENT GAIN



$$\beta = \frac{I_C}{I_B} \gg 1$$

FACTORS INFLUENCING β:

- RECOMBINATION IN THE BASE : BASE TRANSPORT FACTOR: α_T
- HOLE INJECTION INTO THE EMITTER – NON-UNIFORM DOPING
  - EMITTER INJECTION EFFIC. γ
- $\alpha_F = \frac{I_C}{I_E}$

CURRENT GAIN

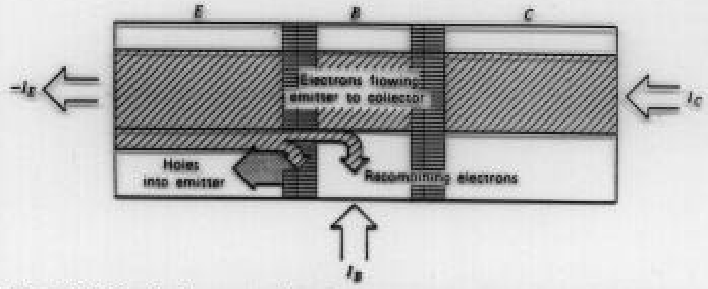


Figure 6.5 Terminal currents and major current components in an active-biased transistor. Not shown is the collector leakage current (J_1 in Figure 6.4).

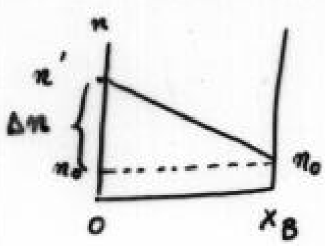
$$\beta = \frac{I_C}{I_B} \gg 1$$

RECOMBINATION IN THE BASE

$$R = \frac{n' - n_0}{\tau_n} \Longrightarrow I_{rB} = qA\int_0^{x_B} R(x)\,dx$$

(RECOMBINATION CURRENT)

$$\boxed{n' - n_0 = \underbrace{n_0\left(e^{\frac{qV_{BE}}{kT}} - 1\right)}_{\Delta n}\left(1 - \frac{x}{x_B}\right)} \quad n_0 = \frac{n_i^2}{N_a}$$



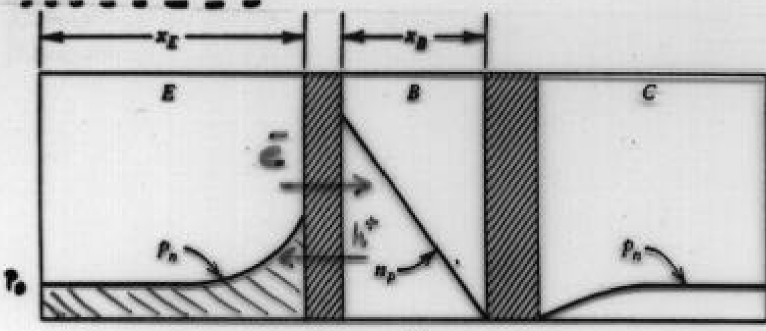
$$I_{rB} = \frac{qA\,n_i^2}{N_a \tau_n}\left(e^{\frac{qV_{BE}}{kT}} - 1\right)\overbrace{\int_0^{x_B} dx\left(1 - \frac{x}{x_B}\right)}^{\frac{x_B^2}{2}}$$

BASE TRANSPORT FACTOR

UNIFORMLY DOPED BASE →
$$\alpha_T = \frac{|I_{nE}| - |I_{rB}|}{|I_{nE}|} = 1 - \left|\frac{I_{rB}}{I_{nE}}\right| = 1 - \frac{x_B^2}{2L_n^2}$$

HOLE INJECTION INTO THE EMITTER (BASE CURRENT)

LONG EMITTER



(a)

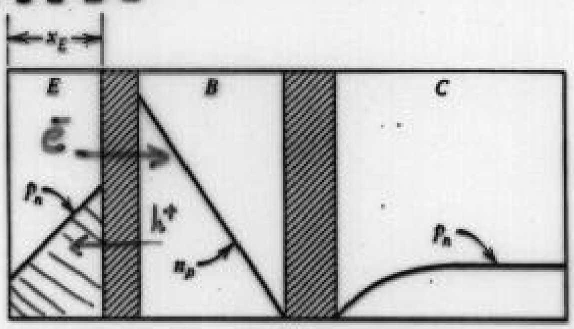
$x_E \gg \sqrt{D_p \tau_p}$

$$I_{pE} = -\frac{qA_E n_i^2 D_{pE}}{N_E \underbrace{L_{pE}}}\left(e^{\frac{qV_{BE}}{kT}} - 1\right)$$

RECOMBINATION

VALID FOR UNIFORM DOPING IN THE EMITTER

SHORT EMITTER



(b)

$x_E \ll \sqrt{D_p \tau_p}$

$$I'_{pE} = -\frac{qA_E n_i^2 D_{pE}}{N_E \underbrace{x_E}}\left(e^{\frac{qV_{BE}}{kT}} - 1\right)$$

TRANSIT

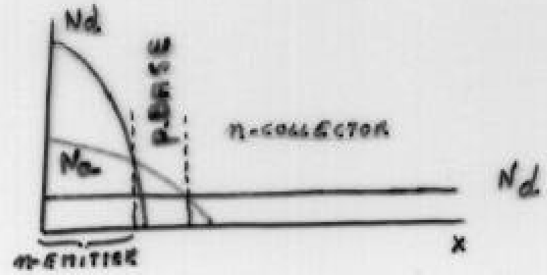
VALID FOR UNIFORM DOPING IN THE EMITTER

Figure 6.6 Minority-carrier distributions in the prototype transistor of Figure 6.1 under active bias. (*a*) $x_E \gg$ hole diffusion length in emitter. (*b*) $x_E \ll$ hole diffusion length.

FOR SHORT EMITTER, I_{pE} INFLUENCED BY THE BUILT-IN FIELD ARISING FROM THE EMITTER GRADED DOPING

$\Rightarrow$ MODIFY I_{pE} !

EMITTER INJECTION: NON-UNIFORM DOPING



GRADED DOPING BUT QUASI NEUTRALITY $\Longrightarrow n \simeq N_d$

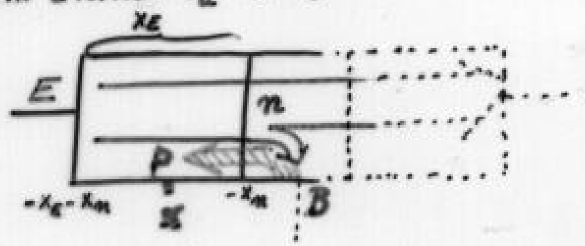
EQUILIBRIUM :

$$\begin{cases} J_n = 0 = q\mu_n n \mathcal{E}_0 + qD_n \dfrac{dn}{dx} \\ \mathcal{E}_0 = -\dfrac{D_n}{\mu}\dfrac{1}{n}\dfrac{dn}{dx} = -\dfrac{kT}{q}\dfrac{1}{N_E(x)}\dfrac{dN_E(x)}{dx} = -\dfrac{kT}{q}\dfrac{d}{dx}\ln\dfrac{N_E(x)}{N_E(0)} \end{cases}$$

$\mathcal{E}_0$: BUILT-IN FIELD IN THE QUASI-NEUTR. EMITTER REGION

WHEN EMITTER-BASE JUNCTION IS FORWARD BIASED : RESIDUAL APPLIED ELECTRIC FIELD IN EMITTER $\mathcal{E}_a \ll \mathcal{E}_0$

HOLE CURRENT IN EMITTER



$$J_p = q\mu_p p_n'(\mathcal{E}_0 + \mathcal{E}_a') - qD_p\frac{dp_n'}{dx}$$

$$= -\frac{qD_p}{N_E(x)}\left(p_n'\frac{d}{dx}N_E(x) + N_E(x)\frac{d}{dx}p_n'\right) = -\frac{qD_p}{N_E(x)}\frac{d}{dx}\left(p_n'(x)N_E(x)\right)$$

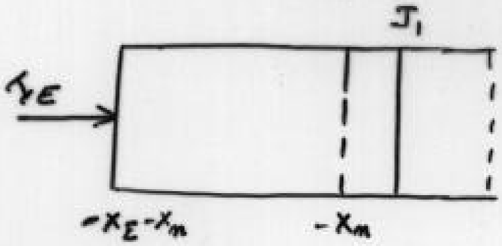
NEGLECTING HOLE RECOMBINATION IN SHORT EMITTER $x_E \ll L_{pE}$

$$J_p\int_x^{-x_E-x_n}\frac{N_E(x')dx'}{qD_p} = \text{[redacted]} + p_n'(x)N_E(x) - p_n'(-x_E-x_n)N_E(-x_E-x_n)$$

BUT $\underline{p_n'(-x_E-x_n) = 0} \Longrightarrow$

$$\boxed{J_p = \frac{q\,p_n'(x)\,N_E(x)}{\displaystyle\int_x^{-x_E-x_n}\frac{N_E(x')dx'}{D_p}} = \text{CONSTANT!}}$$

FROM $$J_p = \frac{q\, p_n'(x)\, N_E(x)}{\displaystyle\int_x^{x_E - x_m} \frac{N_E(x)}{D_p}\, dx}$$



$$I_{pE} = -J_p(-x_m)\, A_E$$

$$\begin{cases} p_n'(-x_m) = p_{no}\left(e^{\frac{qV_{BE}}{kT}} - 1\right) \\ p_{no} = \dfrac{n_i^2}{N_E(-x_m)} \end{cases}$$

$$\boxed{I_{pE} = -\frac{q\, n_i^2\, \tilde{D}_p\, A_E \left(e^{\frac{qV_{BE}}{kT}} - 1\right)}{\displaystyle\int_{-x_m}^{x_E - x_m} N_E(x)\, dx}}$$

IF $N_E(x)$ = CONSTANT

$$I_{pE} = -\frac{q\, n_i^2\, D_p\, A_E}{N_E\, x_E}\left(e^{\frac{qV_{BE}}{kT}} - 1\right)$$

USUAL CURRENT EXPRESSION FOR SHORT BASE DIODE

EMITTER JUNCTION EFFICIENCY

$$\gamma = \frac{I_{nE}}{I_{nE} + I_{pE}} = \frac{1}{1 + \left|\frac{I_{pE}}{I_{nE}}\right|}$$

$$\begin{cases} I_{pE} = -\dfrac{q n_i^2 \tilde{D}_{pE} A_E}{\int_{-x_E - x_m}^{-x_m} N_E(x)\,dx}\left(e^{\frac{qV_{BE}}{kT}} - 1\right) = -\dfrac{q n_i^2 \tilde{D}_{pE} A_E}{GN_E}\left(e^{\frac{qV_{BE}}{kT}} - 1\right) \\[2ex] I_{nE} = -\dfrac{q n_i^2 \tilde{D}_{nB} A_E}{\int_{0}^{x_B} N_B(x)\,dx}\left(e^{\frac{qV_{BE}}{kT}} - 1\right) = -\dfrac{q n_i^2 \tilde{D}_{nB} A_E}{GN_B}\left(e^{\frac{qV_{BE}}{kT}} - 1\right) \end{cases}$$

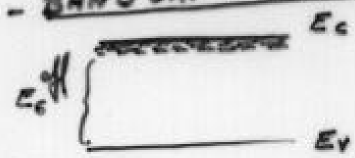
$$\boxed{\gamma = \frac{1}{1 + \frac{GN_B\,\tilde{D}_{pE}}{GN_E\,\tilde{D}_{nB}}}} \longrightarrow \frac{1}{1 + \frac{x_B N_a D_{pE}}{x_E N_d D_{nB}}}$$

if $\left.\begin{matrix} N_a(x) \\ N_d(x) \end{matrix}\right\}$ uniform

x_E : EMITTER WIDTH

WARNING : NOT VALID FOR HEAVY DOPING IN THE EMITTER

- BAND GAP NARROWING $\longrightarrow$ n_i^2 INCREASES IN THE EMITTER

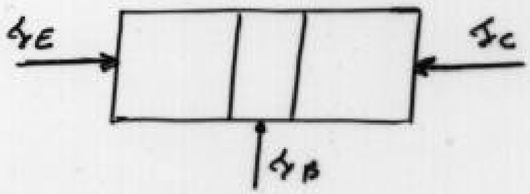


MINORITY CARRIERS $\uparrow$

$\boxed{\gamma \downarrow}$

- AUGER RECOMBINATION

CURRENT GAIN



$$\alpha_F = -\frac{I_C}{I_E} \longrightarrow \alpha_F = \gamma\alpha_T = \overbrace{\frac{I_{mE}}{I_E}}^{\gamma}\ \overbrace{\frac{I_C\,(= I_{mE} - I_{rB})}{I_{mE}}}^{\alpha_T}$$

$$I_B + I_E + I_C = 0$$

$$I_B - \frac{I_C}{\alpha_F} + I_C = 0 \longrightarrow \boxed{I_C = \frac{\alpha_F}{1-\alpha_F} I_B = \beta_F I_B}$$

$$\alpha_F \lesssim 1 \rightarrow \beta_F \gg 1$$

FROM γ AND α_T, $\underline{\gamma}$ IS GENERALLY THE CRITICAL FACTOR LIMITING THE GAIN β