University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

VE 320 – Summer 2012
Introduction to Semiconductor Device

Ideal BJT

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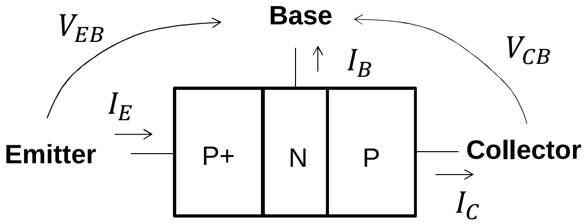
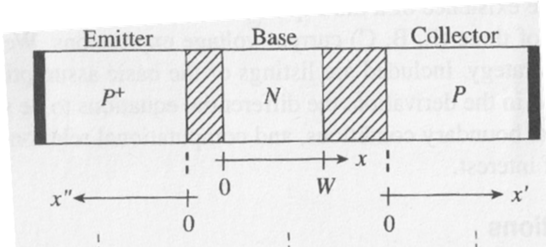
Ideal BJT



Assumptions:

- pnp device, step junction
- Steady state
- One dimensional
- Low-level injection prevails in the quasineutral regions
- No other process other than drift, diffusion, thermal R-G
- Negligible thermal R-G in depleted regions
- Emitter and collector much larger than minority carrier diffusion length

Coordinates and Convention



$N_E = N_{AE}$ $\quad N_B = N_{DB}$ $\quad N_C = N_{AC}$

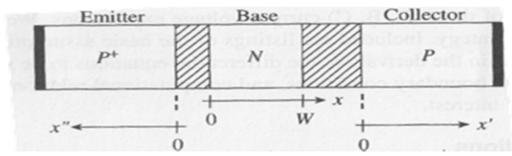
$D_E = D_N$ $\quad D_B = D_P$ $\quad D_C = D_N$

$\tau_E = \tau_n$ $\quad \tau_B = \tau_p$ $\quad \tau_C = \tau_n$

$L_E = L_N$ $\quad L_B = L_P$ $\quad L_C = L_N$

$n_{E0} = n_{p0}$ $\quad p_{B0} = p_{n0}$ $\quad n_{C0} = n_{p0}$

Equations and Boundary Conditions



$$0 = D\frac{d^2\Delta n}{dx^2} - \frac{\Delta n}{\tau} \quad \Rightarrow \quad \Delta n(x) = C_1 e^{-x/L} + C_2 e^{x/L}$$

Boundary Conditions

Emitter: $\Delta n_E(x'' \to \infty) = 0$ $\quad \Delta n_E(x'' = 0) = n_{E0}(e^{qV_{EB}/kT} - 1)$

Base: $\Delta p_B(0) = p_{B0}(e^{qV_{EB}/kT} - 1)$ $\quad \Delta p_B(W) = p_{B0}(e^{qV_{CB}/kT} - 1)$

Collector: $\Delta n_C(x' \to \infty) = 0$ $\quad \Delta n_C(x' = 0) = n_{C0}(e^{qV_{CB}/kT} - 1)$

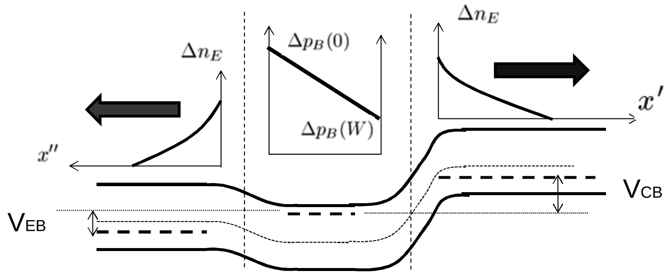
Solutions

It should not be surprising to see the solutions like the following…

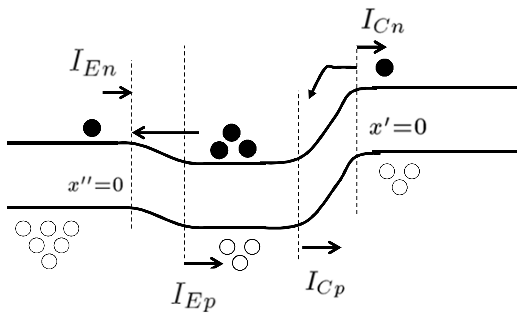
$$\Delta n_E(x'') = n_{E0}(e^{qV_{EB}/kT} - 1)e^{-x''/L_E}$$

$$\Delta n_C(x') = n_{C0}(e^{qV_{CB}/kT} - 1)e^{-x'/L_C}$$

$$\Delta p_B(x) = \Delta p_B(0)\frac{\sinh[(W-x)/L_B]}{\sinh(W/L_B)} + \Delta p_B(W)\frac{\sinh(x/L_B)}{\sinh(W/L_B)}$$



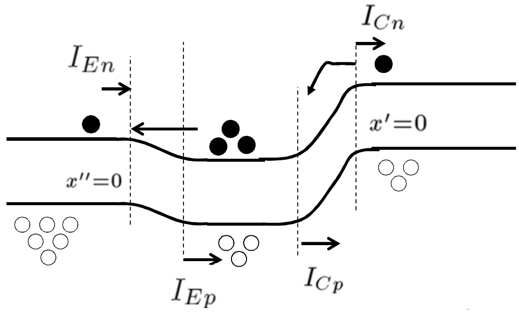
Currents



$$I_{En} = -qAD_E\frac{d\Delta n_E}{dx''}\Big|_{x''=0} = qA\frac{D_E}{L_E}n_{E0}(e^{qV_{EB}/kT} - 1)$$

$$I_{Cn} = qAD_C\frac{d\Delta n_C}{dx'}\Big|_{x'=0} = -qA\frac{D_C}{L_C}n_{C0}(e^{qV_{CB}/kT} - 1)$$

Currents cont'd



$$I_{Ep} = qA\frac{D_B}{L_B}p_{B0}\left[\frac{\cosh(W/L_B)}{\sinh(W/L_B)}(e^{qV_{EB}/kT}-1) - \frac{1}{\sinh(W/L_B)}(e^{qV_{CB}/kT}-1)\right]$$
$$I_{Cp} = qA\frac{D_B}{L_B}p_{B0}\left[\frac{1}{\sinh(W/L_B)}(e^{qV_{EB}/kT}-1) - \frac{\cosh(W/L_B)}{\sinh(W/L_B)}(e^{qV_{CB}/kT}-1)\right]$$

Under active mode biasing, $V_{EB}>0$ and $V_{CB}<0$, therefore the second term is very small comparing to the first term.

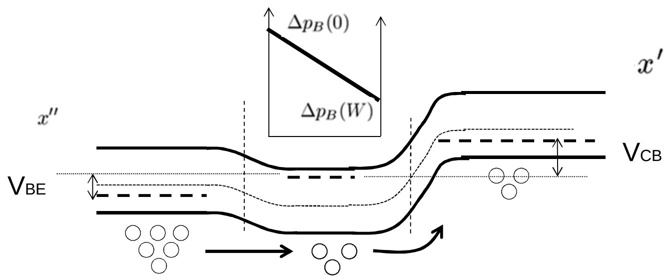
Narrow Base

$$\Delta p_B(x) = \Delta p_B(0)\frac{\sinh[(W-x)/L_B]}{\sinh(W/L_B)} + \Delta p_B(W)\frac{\sinh(x/L_B)}{\sinh(W/L_B)}$$

Base width much smaller than minority carrier diffusion length.

$$W \ll L_B$$

$$\Delta p_B(x) \approx \Delta p_B(0)\left(1-\frac{x}{W}\right) + \Delta p_B(W)\frac{x}{W}$$



Performance Parameters

$$\gamma = \frac{I_{Ep}}{I_E} = \frac{I_{Ep}}{I_{Ep} + I_{En}}$$

$$\alpha_T = \frac{I_{Cp}}{I_{Ep}}$$

$$\alpha_{dc} = \gamma \alpha_T = \frac{I_{Cp}}{I_E} \approx \frac{I_C}{I_E}$$

$$\beta = \frac{I_C}{I_B} = \frac{\alpha_{dc}}{1-\alpha_{dc}}$$

Solution of minority carrier diffusion equation $\xrightarrow{}$ Narrow base

$$\gamma = \frac{1}{1 + \frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E}}$$

$$\alpha_T = \frac{1}{1 + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

$$\alpha_{dc} = \frac{1}{1 + \frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

$$\beta_{dc} = \frac{1}{\frac{D_E}{D_B}\frac{N_B}{N_E}\frac{W}{L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

Ebers-Moll Equations

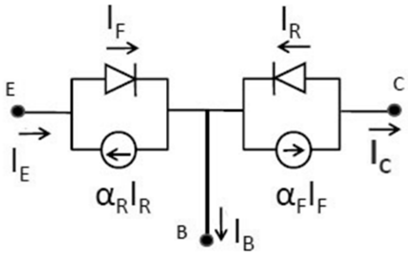
$$I_E = qA\Big[\Big(\overbrace{\tfrac{D_E}{L_E} n_{E0} + \tfrac{D_B}{L_B} p_{B0} \tfrac{\cosh(W/L_B)}{\sinh(W/L_B)}}^{I_{F0}}\Big)\left(e^{qV_{EB}/kT} - 1\right) - \underbrace{\Big(\tfrac{D_B}{L_B} p_{B0} \tfrac{1}{\sinh(W/L_B)}\Big)}_{\alpha_R I_{R0}}\left(e^{qV_{CB}/kT} - 1\right)\Big]$$

$$I_C = qA\Big[\overbrace{\Big(\tfrac{D_B}{L_B} p_{B0} \tfrac{1}{\sinh(W/L_B)}\Big)}^{\alpha_F I_{F0}}\left(e^{qV_{EB}/kT} - 1\right) - \Big(\underbrace{\tfrac{D_C}{L_C} n_{C0} + \tfrac{D_B}{L_B} p_{B0} \tfrac{\cosh(W/L_B)}{\sinh(W/L_B)}}_{I_{R0}}\Big)\left(e^{qV_{CB}/kT} - 1\right)\Big]$$

$$\alpha_F I_{F0} = \alpha_R\, I_{R0} = qA\frac{D_B}{L_B}\frac{p_{B0}}{\sinh(\frac{W}{L_B})}$$

Ebers-Moll Equations

- Node equation for BJT terminals



$$I_F = I_{F0}(e^{qV_{EB}/kT} - 1)$$
$$I_R = I_{R0}(e^{qV_{CB}/kT} - 1)$$

$$I_E = I_{F0}(e^{qV_{EB}/kT} - 1) - \alpha_R I_{R0}(e^{qV_{CB}/kT} - 1)$$
$$I_C = \alpha_F I_{F0}(e^{qV_{EB}/kT} - 1) - I_{R0}(e^{qV_{CB}/kT} - 1)$$

The four parameters can be treated as empirical parameters.