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

VE 320 – Summer 2012
Introduction to Semiconductor Device

Non-ideal Effects

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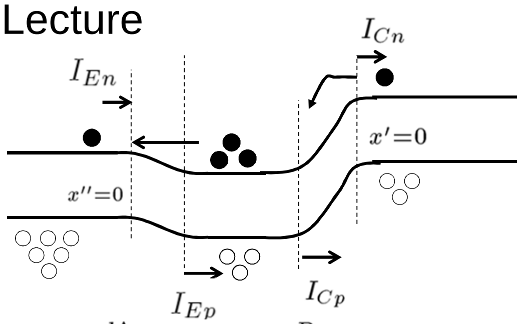
NANO ENERGY LAB

Previous Lecture



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

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

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

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

Terminal Currents

$$I_E = qA\left[\left(\frac{D_E}{L_E}n_{E0} + \frac{D_B}{L_B}p_{B0}\frac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)(e^{qV_{EB}/kT}-1) - \left(\frac{D_B}{L_B}p_{B0}\frac{1}{\sinh(W/L_B)}\right)(e^{qV_{CB}/kT}-1)\right]$$

$$I_C = qA\left[\left(\frac{D_B}{L_B}p_{B0}\frac{1}{\sinh(W/L_B)}\right)(e^{qV_{EB}/kT}-1) - \left(\frac{D_C}{L_C}n_{C0} + \frac{D_B}{L_B}p_{B0}\frac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)(e^{qV_{CB}/kT}-1)\right]$$

- Why BJT is not equivalent to two pn junction diode?
- What happens if W >> L_B ?

Performance Parameters

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

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

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

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

Without narrow base assumption.

$$\gamma = \left[1 + \left(\frac{D_E L_B N_B}{D_B L_E N_E}\right)\frac{\sinh(W/L_B)}{\cosh(W/L_B)}\right]^{-1}$$

$$\alpha_T = [\cosh(W/L_B)]^{-1}$$

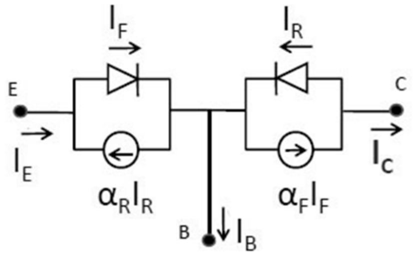
$$\alpha_{dc} = \left[\cosh(W/L_B) + \left(\frac{D_E L_B N_B}{D_B L_E N_E}\right)\sinh(W/L_B)\right]^{-1}$$

$$\beta_{dc} = \left[\cosh(W/L_B) + \left(\frac{D_E L_B N_B}{D_B L_E N_E}\right)\sinh(W/L_B) - 1\right]^{-1}$$

Generally one want large common emitter current gain. Then the doping concentration in the base should be as small as possible. However ...

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.

More about Ebers-Moll Equations

Exercise 11.5 Forward Current Gain

$$\alpha_F = \frac{qA\frac{D_B}{L_B}\frac{p_{B0}}{\sinh(W/L_B)}}{qA\left(\frac{D_E}{L_E}n_{E0} + \frac{D_B}{L_B}p_{B0}\frac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)}$$

$$\alpha_F = \left[\cosh(W/L_B) + \left(\frac{D_E L_B n_{E0}}{D_B L_E p_{B0}}\right)\sinh(W/L_B)\right]^{-1}$$

$$n_{E0}/p_{B0} = N_B/N_E$$

$$\Rightarrow \quad \alpha_F = \alpha_{dc}$$

Input and Output

(1) Common base input $[I_E = I_E(V_{EB}, V_{CB})]$

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

(2) Common base output $[I_C = I_C(V_{CB}, I_E)]$

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

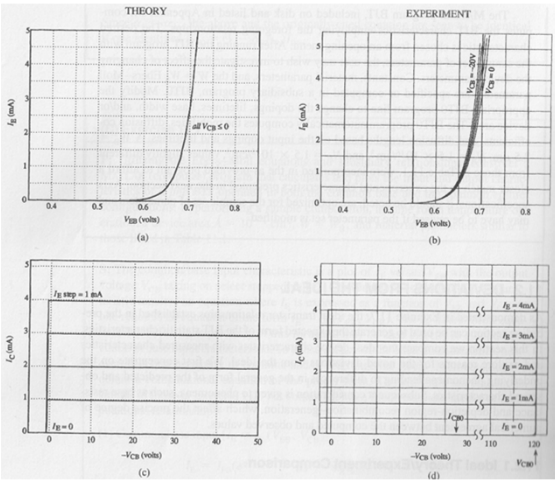
(3) Common emitter input $[I_B = I_B(V_{EB}, V_{EC})]$

$$I_B = [(1 - \alpha_F)I_{F0} + (1 - \alpha_R)I_{R0}e^{-qV_{EC}/kT}]\, e^{qV_{EB}/kT} - [(1 - \alpha_F)I_{F0} + (1 - \alpha_R)I_{R0}]$$

(4) Common emitter output $[I_C = I_C(V_{EC}, I_B)]$

$$I_C = \frac{(\alpha_F I_{F0} - I_{R0}e^{-qV_{EC}/kT})[I_B + (1 - \alpha_F)I_{F0} + (1 - \alpha_R)I_{R0}]}{(1 - \alpha_F)I_{F0} + (1 - \alpha_R)I_{R0}e^{-qV_{EC}/kT}} + I_{R0} - \alpha_F I_{F0}$$

Ideal and Non-ideal

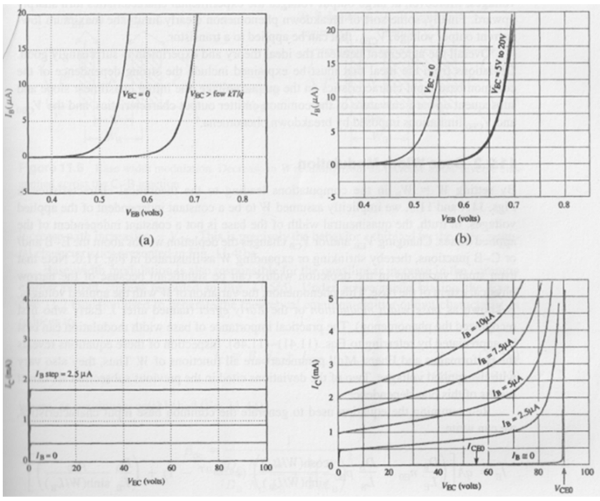


Common base input and output

Input current increases with increasing negative values of V_{CB}

Break down at large $-V_{CB}$

Common Emitter



Theory and experiment are almost consistent

Breakdown voltage is lower than common base breakdown.

Output current increases with V_{EC}

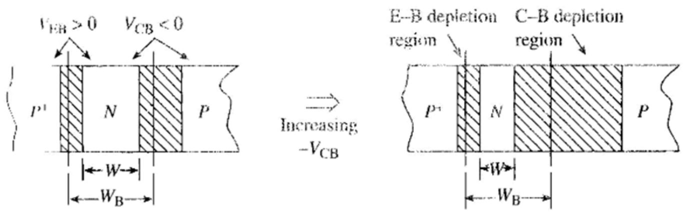
Base Width Modulation

The plots are generated with the assumption of $W = W_B$

$$I_E = qA[\left(\frac{D_E}{L_E}n_{E0} + \frac{D_B}{L_B}p_{B0}\frac{\cosh(W/L_B)}{\sinh(W/L_B)}\right)(e^{qV_{EB}/kT} - 1) - \left(\frac{D_B}{L_B}p_{B0}\frac{1}{\sinh(W/L_B)}\right)(e^{qV_{CB}/kT} - 1)]$$

$$I_E \approx qA\frac{D_B}{W}p_{B0}e^{qV_{EB}/kT}$$

Common base input is dependent on the base width.

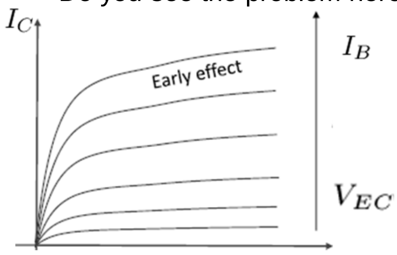


Base Width Modulation (Early Effect)

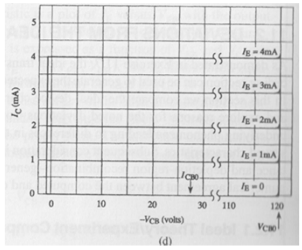
Do you see the problem here?

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

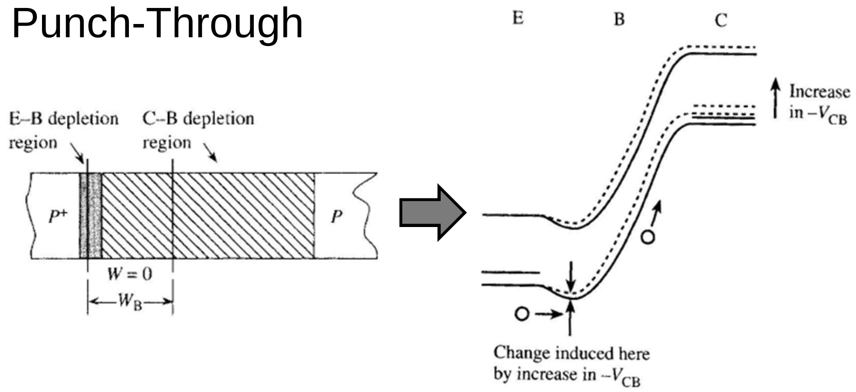
$$\alpha_{dc} = \left[1 + \frac{D_E N_B W}{D_B N_E L_E} + \frac{1}{2} \left(\frac{W}{L_B} \right)^2 \right]^{-1}$$



Common emitter current gain is sensitive to base width but common base current gain is not.



Punch-Through

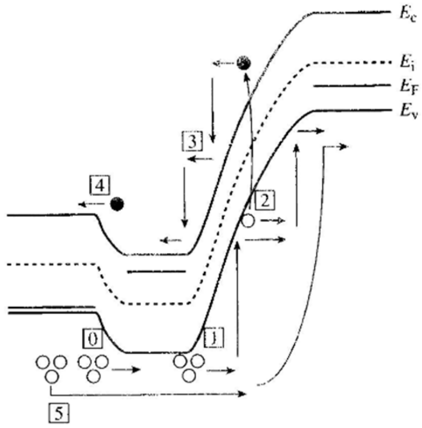


- Base width modulation results in zero quasi-neutral width in the base region.
- The barrier can be reduced by C-B bias.
- **If it occurs**, it limits the maximum voltage can be applied on the C-B diode.

Why the base doping cannot be too low?

Avalanche Breakdown

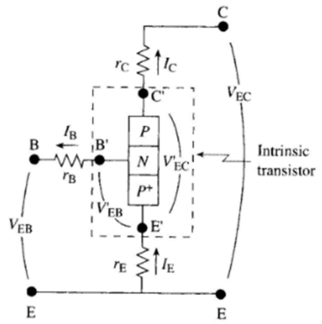
- Common base: breakdown occurs when the C-B diode breakdown
- Common emitter: breakdown occurs at a lower V_{CE} voltage.

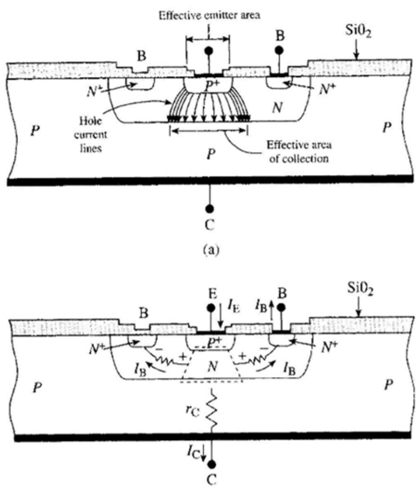


Base current is held constant so that the extra electrons have be injected into the emitter, which creates extra holes injected into the collector.

Geometric Effect

- Emitter area and collector area are not the same
- Series resistance
- Current crowding

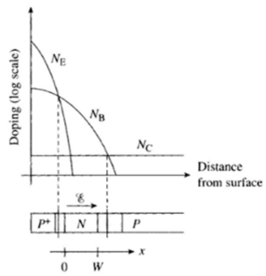




Can you see another reason why base doping cannot be too low?

R-G Current / Graded Base

- In most operation conditions the R-G current is generally not important. For small forward bias of the E-B junction, the R-G current is dominant.
- The doping profile in the base in “graded” and therefore induces an electric field in the base.

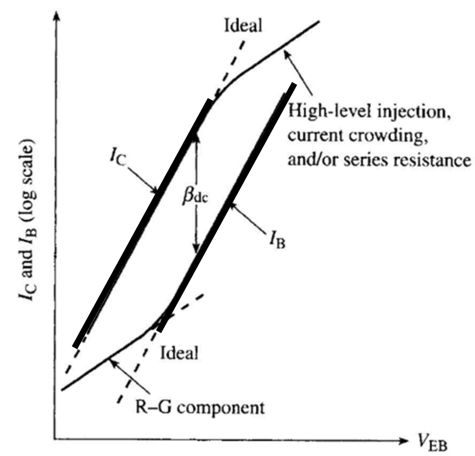


$$J_N = q\mu_n n\mathscr{E} + qD_N \frac{dn}{dx} = 0$$

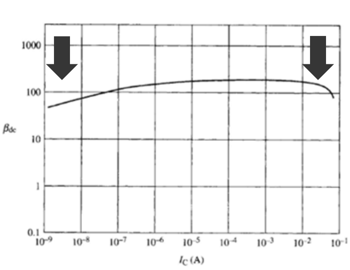
$$\mathscr{E}(x) = -\frac{D_N}{\mu_n}\frac{dn/dx}{n} \cong -\frac{kT}{q}\frac{dN_B(x)/dx}{N_B(x)}$$

The electric field assists the transport of minority carriers in the base, and thus reduces the R-G in the base. This is beneficial.

Gummel Plot



In a certain region, I_C is proportional to I_B and the signal is amplified. Outside this region the non-ideality is due to similar reasons as a non-ideal diode.



Self-test

- How to obtain the ideal BJT current-voltage relationship?
- How can BJT amplify a signal?
- What are the reasons for the nonideality of BJT?