Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

Dr. P. Stamenov

School of Physics and CRANN, Trinity College,
Dublin 2, Ireland

Hilary Term, TCD
27th of Jan ‘14

BJT - Current Components

$$-\frac{p - p_B}{\tau_B} + D_{pB}\frac{\partial^2 p}{\partial x^2} = 0$$

Continuity Equation for the base region

Conventional Diffusion of the minority carriers

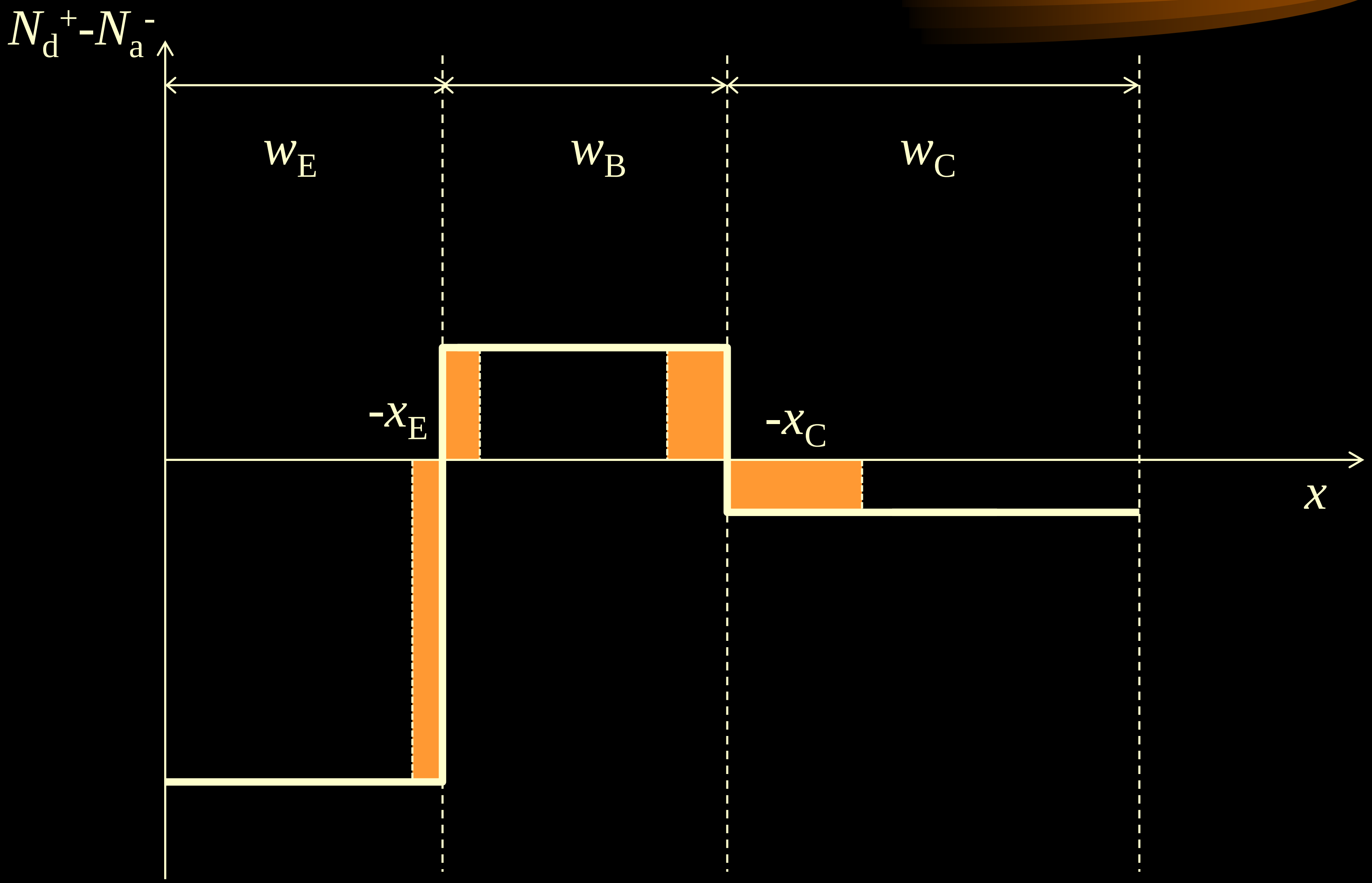
$$J_p = -qD_{pB}\frac{\partial p}{\partial x}$$

$$J_{tot} = J_n + J_p$$

Total Current

- All voltage drop concentrated in the junction depletion regions. Neutral base approximation
- No surface generation or recombination (to be lifted later)
- Continuity and current density equations govern the transport.
- Furthermore – ideal diode equations for both the emitter and the collector junctions

BJT – Schematic 1D Diagram



Excess Carrier Balance

$$p'(0) = p(0) - p_{\mathrm{B}} = p_{\mathrm{B}} \left[\exp\left(\frac{V_{\mathrm{EB}}}{V_{\mathrm{t}}} \right) - 1 \right]$$

$$n'(-x_{\mathrm{E}}) = n(-x_{\mathrm{E}}) - n_{\mathrm{E}} = n_{\mathrm{E}} \left[\exp\left(\frac{V_{\mathrm{EB}}}{V_{\mathrm{t}}} \right) - 1 \right]$$

At the emitter depletion-layer edges.

$$p'(w_{\mathrm{B}}) = p(w_{\mathrm{B}}) - p_{\mathrm{B}} = p_{\mathrm{B}} \left[\exp\left(\frac{V_{\mathrm{CB}}}{V_{\mathrm{t}}} \right) - 1 \right]$$

$$n'(-x_{\mathrm{C}}) = n(-x_{\mathrm{C}}) - n_{\mathrm{C}} = n_{\mathrm{C}} \left[\exp\left(\frac{V_{\mathrm{CB}}}{V_{\mathrm{t}}} \right) - 1 \right]$$

At the collector depletion-layer edges.

- p_B, n_E and n_C are the equilibrium carrier concentrations in the base, emitter and collector, respectively.
- Ideal diode equations.
- The most important contribution is, the minority holes in the base.

Non-equilibrium Carrier Distributions

$$p(x) = p_\mathrm{B} + \left[\frac{p\prime(w_\mathrm{B} - p\prime(0)e^{-w_\mathrm{B}/L_B}}{2\sinh\left(w_\mathrm{B}/L_\mathrm{B}\right)}\right]\left[\exp\left(x/L_\mathrm{B}\right) - \exp\left(-x/L_\mathrm{B}\right)\right]$$

Depends on the injected hole density, mostly

Holes within the base region

$$L_\mathrm{B} = \sqrt{\tau_\mathrm{B} D_\mathrm{pB}}$$

hole diffusion length in base

$$n(x) = n_\mathrm{E} + n\prime(-x_\mathrm{E})\exp\left[\frac{x + x_\mathrm{E}}{L_\mathrm{E}}\right]$$

Electrons within the emitter region

Minority carriers in the corresponding regions

$$n(x) = n_\mathrm{C} + n\prime(x_\mathrm{C})\exp\left[-\frac{x - x_\mathrm{C}}{L_\mathrm{C}}\right]$$

Electrons within the collector region

Transistor Currents

$$I_\mathrm{E} = AJ_\mathrm{p}(x=0) + AJ_\mathrm{n}(x=-x_\mathrm{E})$$

Emitter Current

$$I_\mathrm{C} = AJ_\mathrm{p}(x=w_\mathrm{B}) + AJ_\mathrm{n}(x=x_\mathrm{C})$$

Collector Current

$$I_\mathrm{B} = I_\mathrm{E} - I_\mathrm{C}$$

Base Current (by continuity)

$$I_\mathrm{E} = A\left(-qD_\mathrm{pB}\left.\frac{\partial p}{\partial x}\right|_{x=0}\right) + A\left(-qD_\mathrm{nC}\left.\frac{\partial n}{\partial x}\right|_{x=-x_\mathrm{E}}\right)$$

$$I_\mathrm{C} = A\left(-qD_\mathrm{pB}\left.\frac{\partial p}{\partial x}\right|_{x=w_\mathrm{B}}\right) + A\left(-qD_\mathrm{nC}\left.\frac{\partial n}{\partial x}\right|_{x=x_\mathrm{C}}\right)$$

- Remember the principle of the computation only.
- The actual expressions are rather cumbersome and not very applicable

h-Parameters - Definitions

$$\begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix}$$

$$h_{11} \equiv \left. \frac{V_1}{I_1} \right|_{V_2=0} \qquad h_{21} \equiv \left. \frac{I_2}{I_1} \right|_{V_2=0}$$

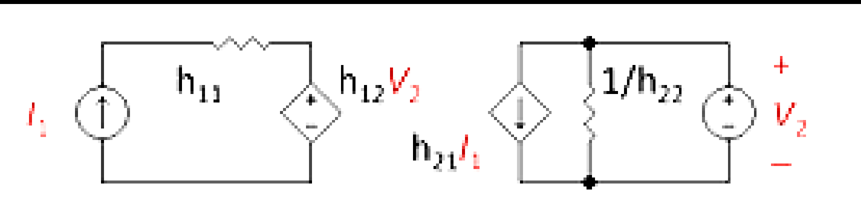
$$h_{12} \equiv \left. \frac{V_1}{V_2} \right|_{I_1=0} \qquad h_{22} \equiv \left. \frac{I_2}{V_2} \right|_{I_1=0}$$

Off-diagonal Dimensionless

Diagonal ones Reciprocal

Input Impedance

Output Conductance



Simplified Effective Circuit

Very useful - Current Gain

- A hybrid set of parameters is useful, as BPT are current-controlled.
- This is all within a linear approximation, however can be differential.
- Unilateral approximation if $h_{12} = 0$. If $h_{12} = h_{21} = 0$ – Not a transistor.
- Everything is the same if linear impedances are used instead .

Current Gain – Related Parameters

F – Forward direction

B – Common Base

$$\alpha_0 \equiv h_{\mathrm{FB}} = \frac{\partial I_{\mathrm{C}}}{\partial I_{\mathrm{E}}}$$

Current gain in common base mode

$$\alpha_0 = \frac{\partial I_{\mathrm{pE}}}{\partial I_{\mathrm{E}}} \frac{\partial I_{\mathrm{pC}}}{\partial I_{\mathrm{pE}}} \frac{\partial I_{\mathrm{C}}}{\partial I_{\mathrm{pC}}}$$

Collector Multiplication - M

Emitter Efficiency - γ

Base Transport Factor- α_{T}

Current gain in common emitter configuration

$$\beta_0 \equiv h_{FE} = \frac{\partial I_{\mathrm{C}}}{\partial I_{\mathrm{B}}}$$

Likely the most popular choice

$$\beta_0 = \frac{\alpha_0}{1 - \alpha_0}$$

It is easy to convert between the different modes in the low-bias case.

Typical Values:

$\alpha_0 > 0.99$

$\beta_0 > 100$

How to Estimate the Current Gain?

$$\alpha_0 = \gamma \alpha_T M$$

Common base current gain

Emitter efficiency

$$\gamma = \frac{\partial A J_p(x=0)}{\partial I_E} \approx \left[1 + \frac{n_E}{p_B}\frac{D_E}{D_B}\frac{L_B}{L_E}\tanh\left(\frac{w_B}{L_b}\right)\right]^{-1}$$

Base transport factor

$$\alpha_T = \frac{J_p(x=w_B)}{J_p(x=0)} = \frac{1}{\cosh\left(w_B/L_B\right)} \approx 1 - \frac{w_B^2}{2L_B^2}$$

Collector Multiplication

$$M \approx 1$$

The Famous h_{FE}

$$h_{FE} \approx \frac{\gamma}{1-\gamma}$$

Rough Estimate of the Current Gain...

$$w_\mathrm{b} = 1\ \mu\mathrm{m}$$

Effective base width has to be thin to achieve high gains

$$L_\mathrm{b} = 100\ \mu\mathrm{m}$$

Base diffusion length – the longer – the better

$$M = 1$$

Collector Multiplication

Can be higher in real transistors and at high collector bias

$$\gamma \approx \frac{1}{1 + \tanh\left(\frac{w_\mathrm{b}}{L_\mathrm{b}}\right)} \approx 0.99$$

Emitter efficiency would normally be the dominant factor

$$\alpha_\mathrm{T} \approx 1 - \frac{w_\mathrm{b}^2}{2L_\mathrm{b}^2} \approx 1.00$$

The base transport factor would typically be very close to unity

$$\alpha_0 = \gamma \alpha_\mathrm{T} M \approx 0.99$$

The common base current gain

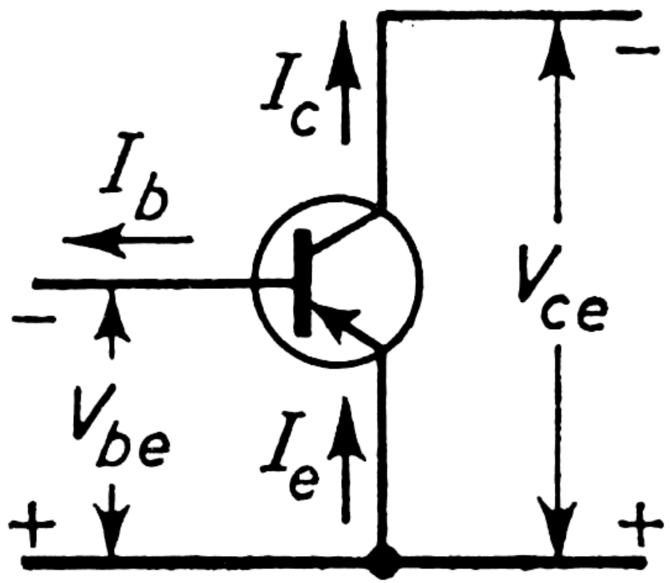
$$h_\mathrm{FE} = \beta_0 = \frac{\alpha_0}{1 - \alpha_0} \approx 100$$

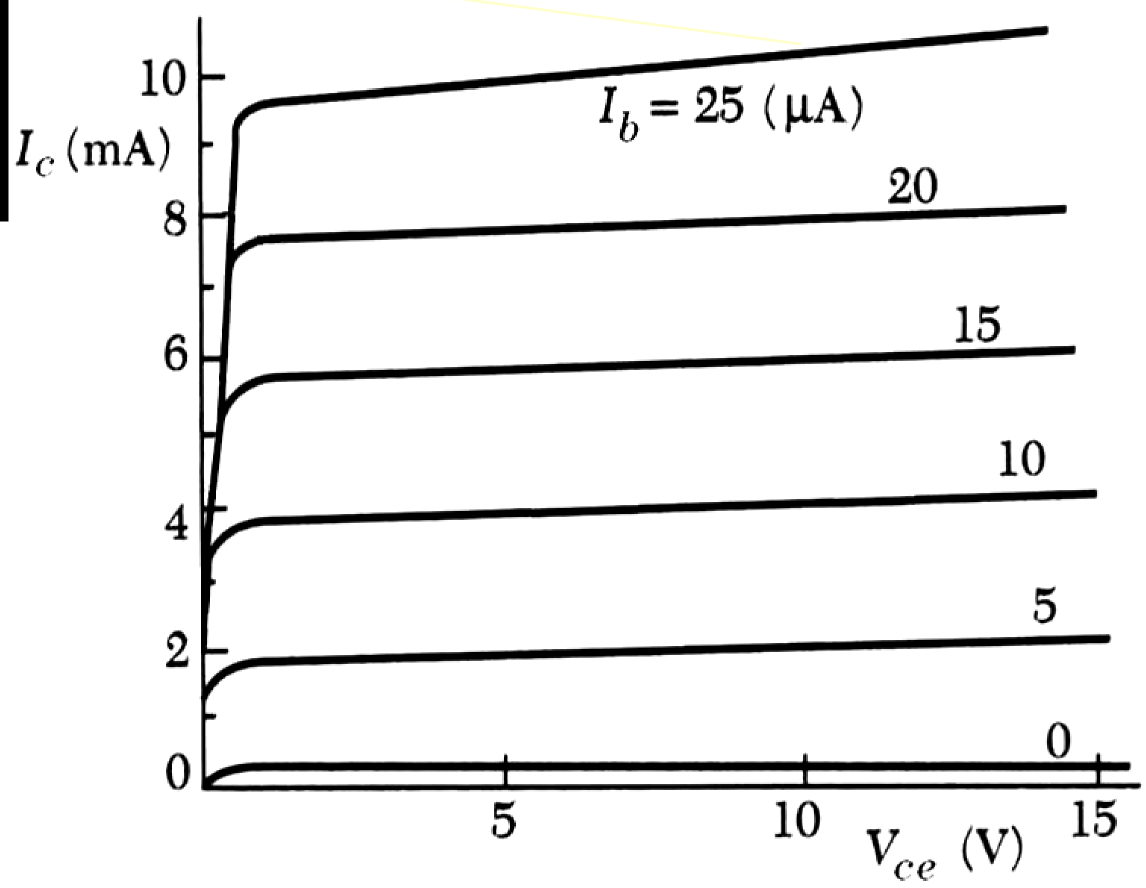
Typical of popular bipolar transistors

Output Characteristics

A typical set of characteristics is shown (right) for the output current I_c vs output voltage V_{ce} for different base currents I_b for the case of the BPT 'common emitter' circuit configuration (left – *p-n-p* shown).

Note the almost linear dependence of the Saturation current on I_b





The Early Effect - (J. M. Early 1952)

(i) Common emitter current gain of this transistor ≈ 400 (from fig. !)

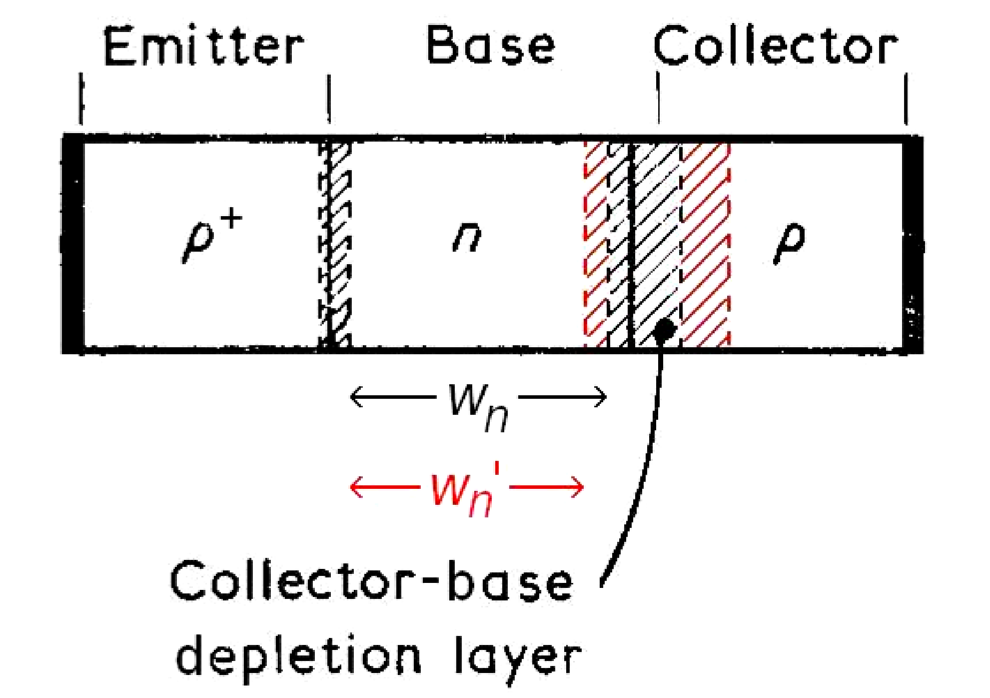
(ii) $I_c \neq 0$ for $I_b = 0$ because of leakage effects at the collector-base junction (neglected in this analysis).

(iii) The characteristics slope upwards, i.e. the gain increases with increasing V_{ce}.

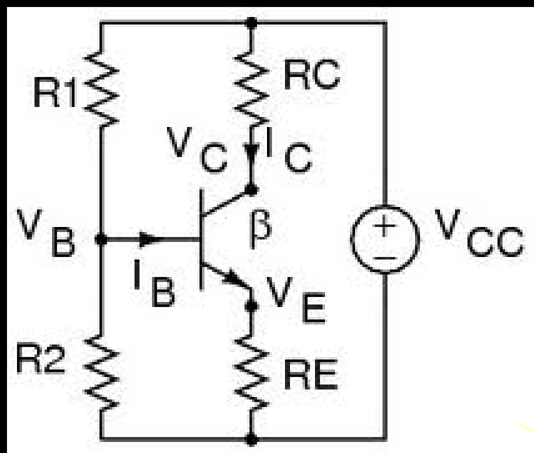
This is because the reverse voltage V_{cb} across the collector-base junction $= V_{ce} - V_{be} \approx V_{ce} - 0.6$ V and is therefore also increasing.

∴ The collector-base depletion layer width is increasing.

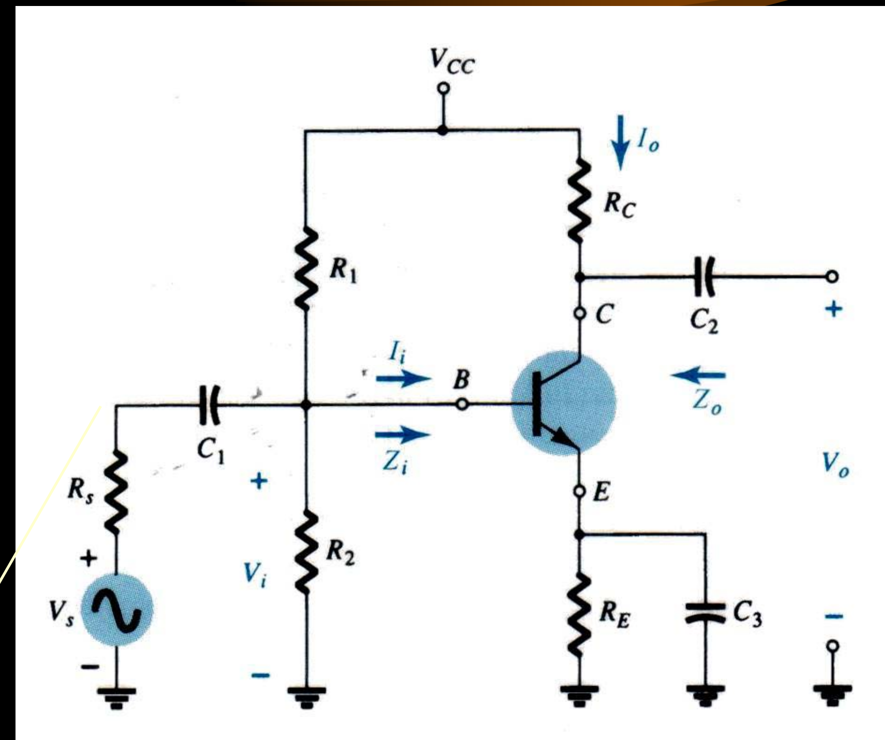
∴ The effective base width, w_n, is decreasing to w_n' (see figure).



Bipolar Transistors - Usage



Basic DC biasing concept



Basic AC decoupling

- Common emitter is the most abundant circuit connection type.
- Typically Resistor dividers are used for DC biasing.
- Decoupling capacitors are used extensively for AC decoupling.
- There is no direct way to provide for bipolar amplification (later other examples will be provided within unipolar devices)

Thanks and Acknowledgements

Thank You Very Much for Your Attention!