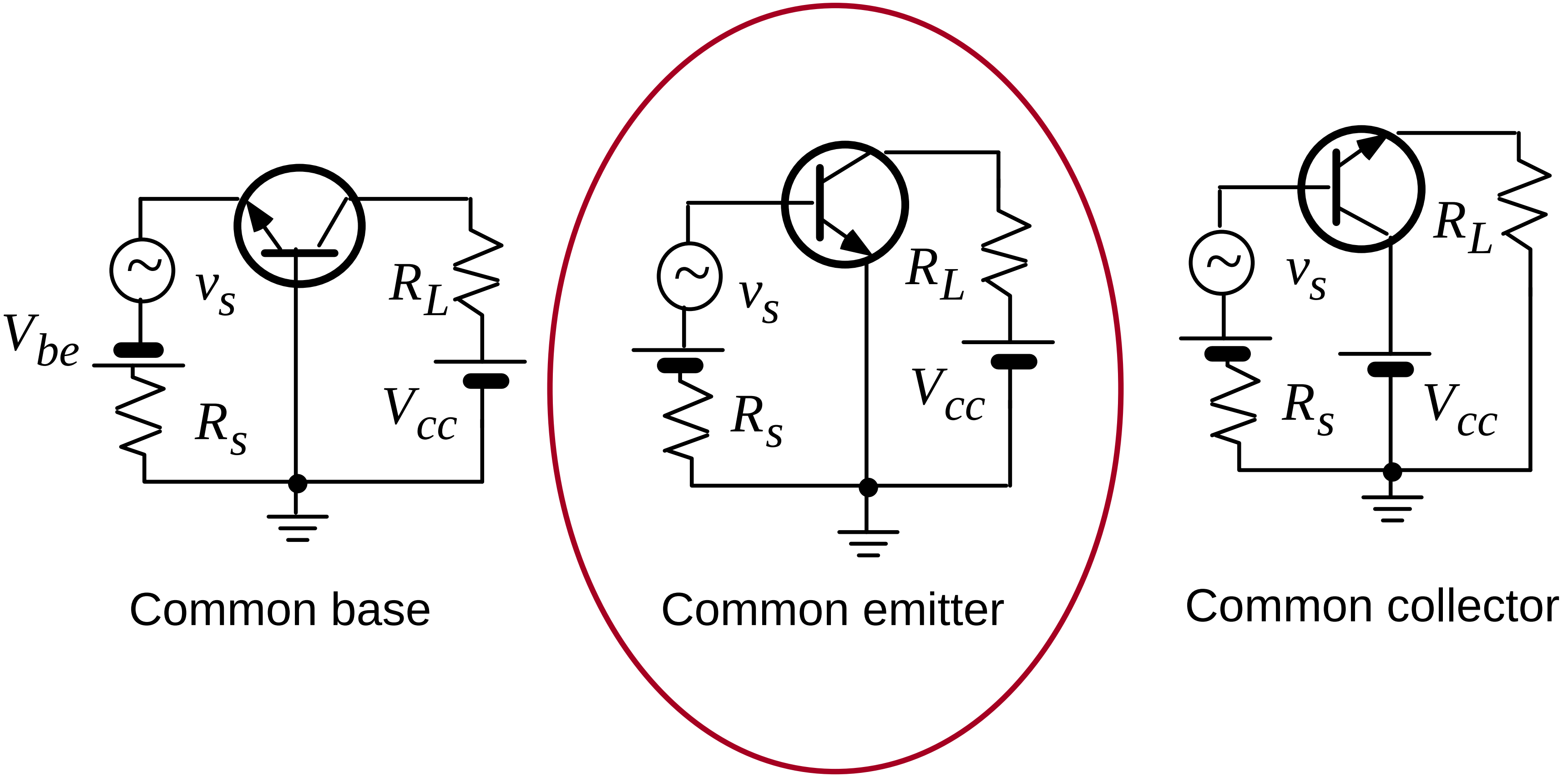
BJT Circuit Configurations

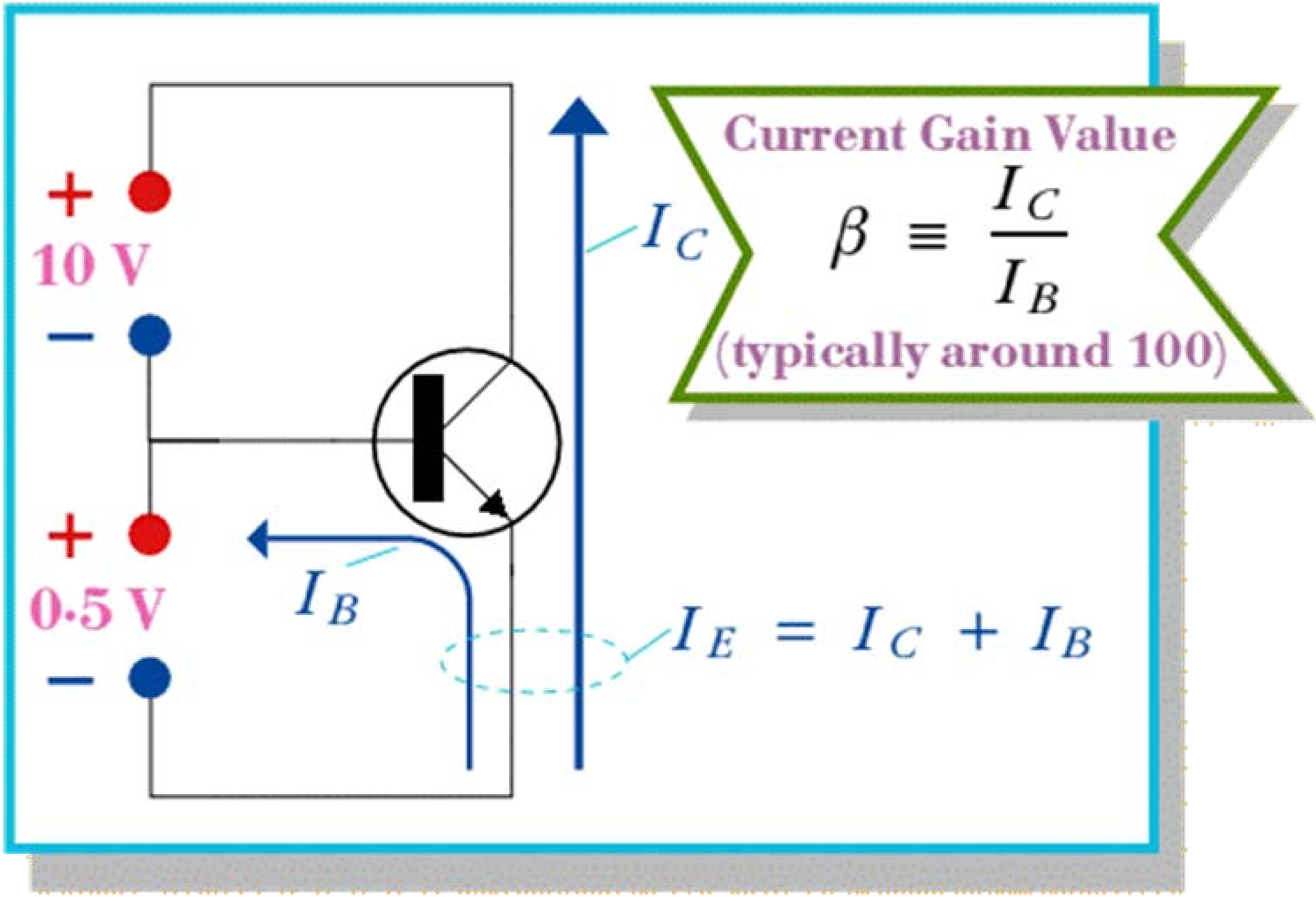


Common base

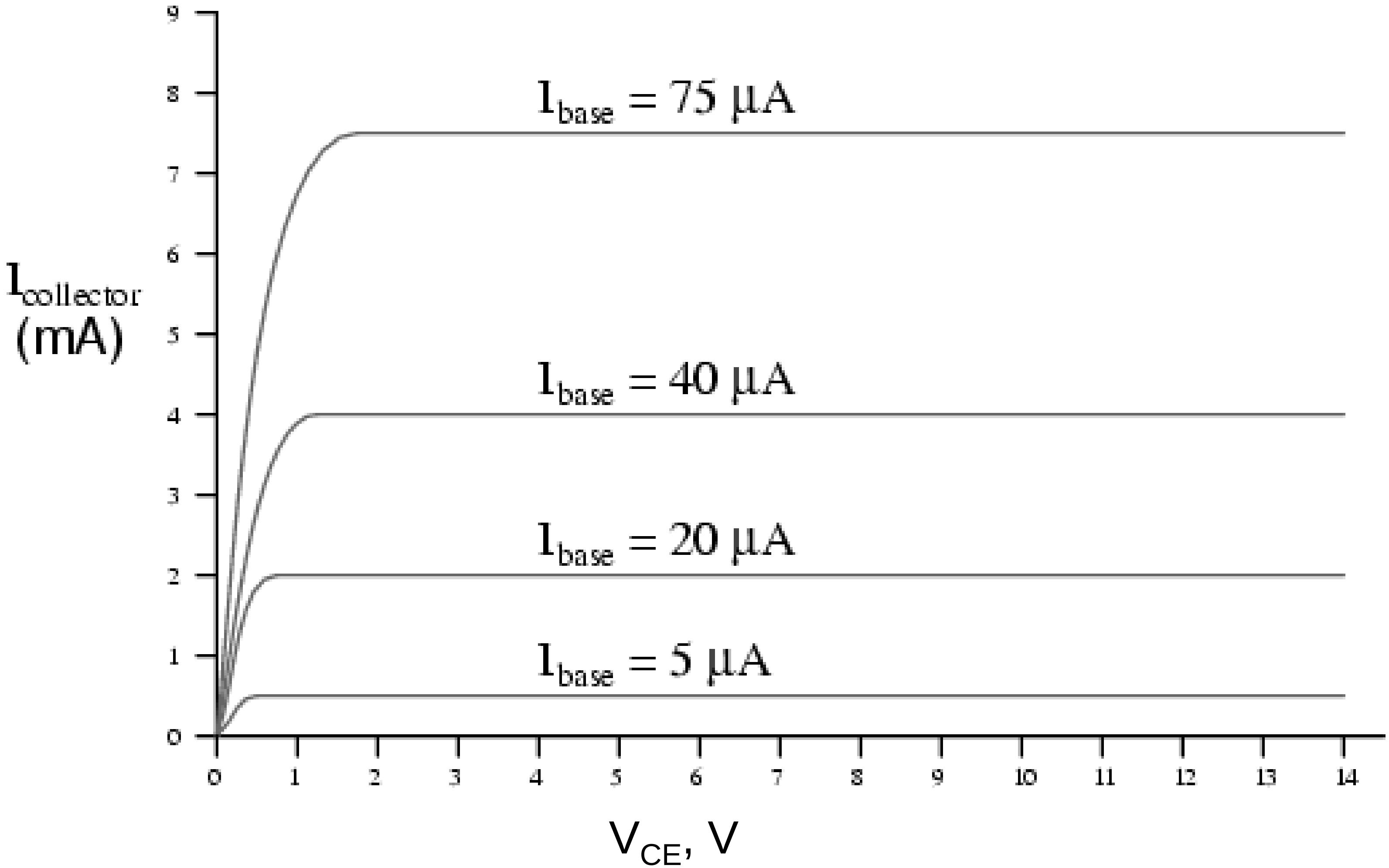
Common emitter

Common collector

Common emitter current gain

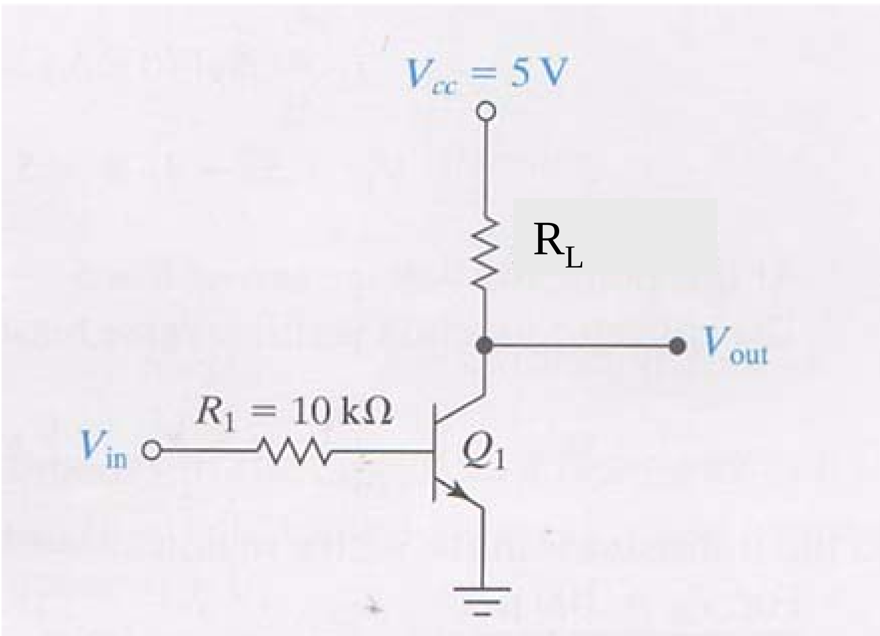


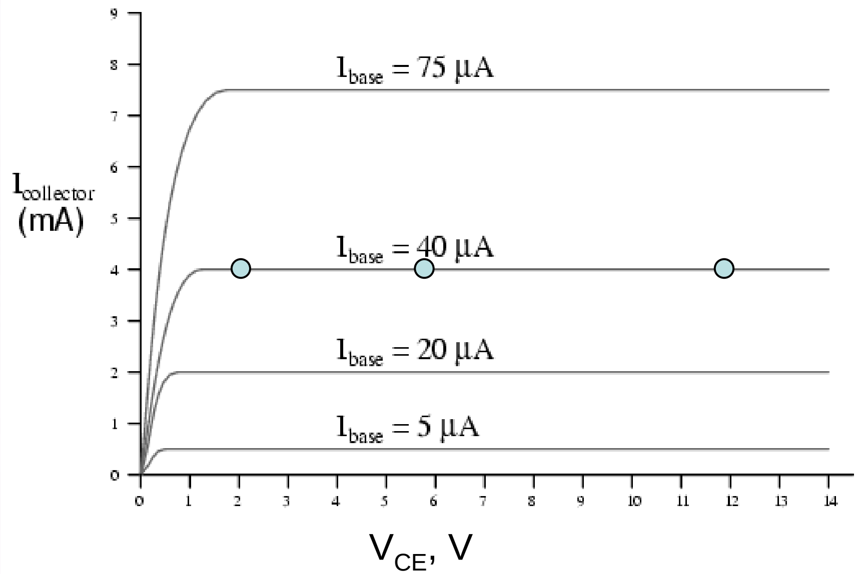
BJT Current-Voltage Characteristics



Very small base current (~5-75 μA)
causes much higher collector current (up to 7.5 mA).
The current gain is ~ 100

BJT amplifier circuit analysis: Operating point





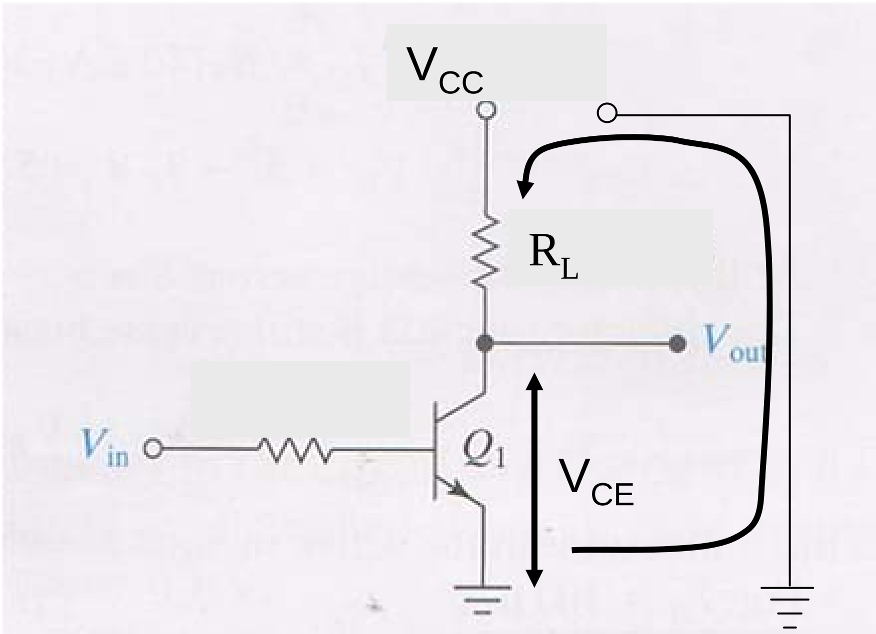
Collector current depends on two circuit parameters:

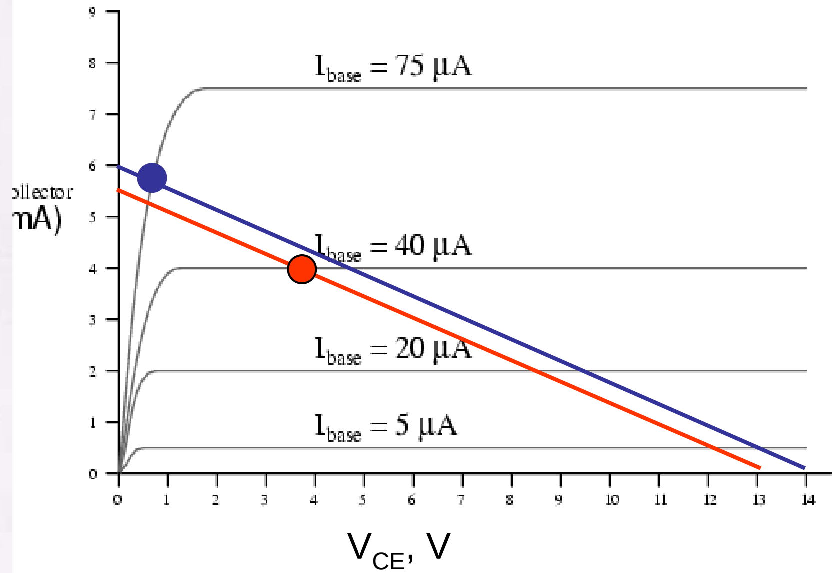
the base current and the collector voltage.

At high collector voltage the collector current depends on the base current only.

For I_{base} = 40 µA, I_{coll} = 4 mA for any $E_{C\text{-}E}$ greater than 1.5 V

BJT amplifier circuit analysis: Operating point





For an arbitrary collector voltage, collector current can be found using the KVL.

The KVL for the collector – emitter circuit, $V_{CC} = I_{RL} \times R_L + V_{CE}$;

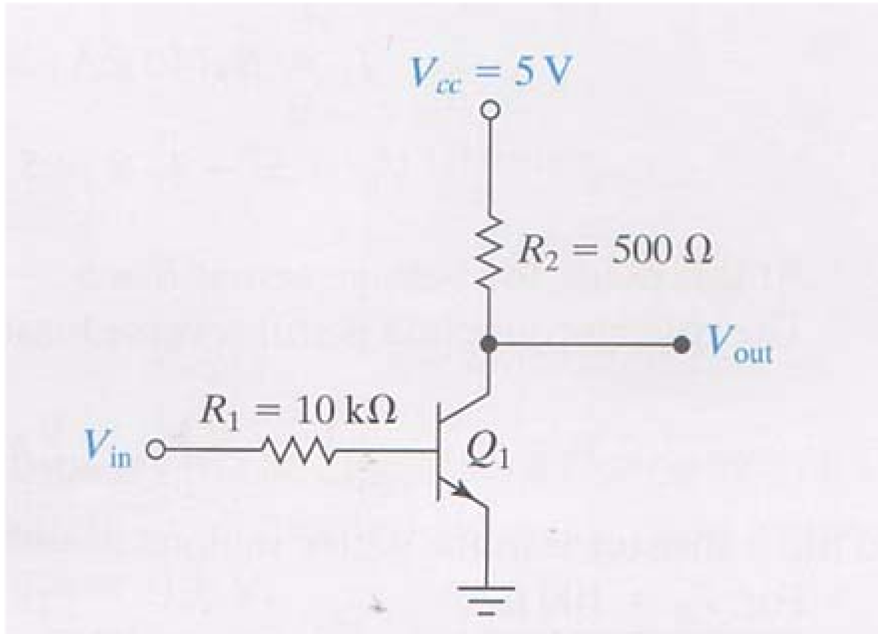
$$I_{RL} = \frac{V_{CC} - V_{CE}}{R_L}$$ The R_L current depends linearly on the collector voltage V_{CE}

Resistor R_L and the C-E circuit of BJT are connected in series, hence $I_{RL} = I_C$

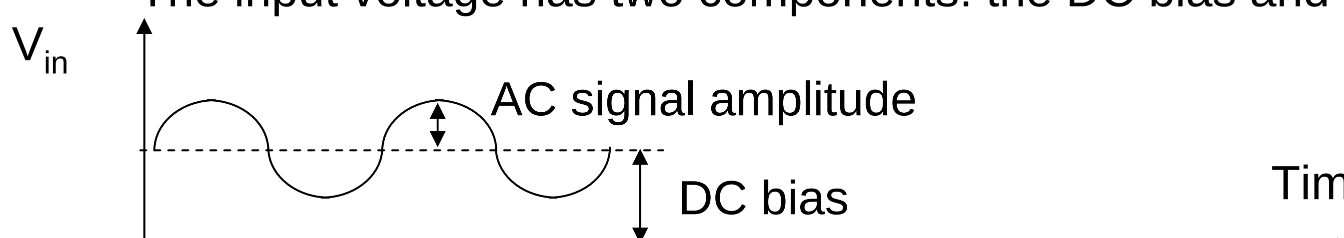
For $I_b = 40\ \mu A$ and $V_{CC} = 13V$, the collector current $I_C = 4$ mA

For $I_b = 75\ \mu A$ and $V_{CC} = 14V$, the collector current $I_C = 4$ mA

BJT amplifier gain analysis: 1

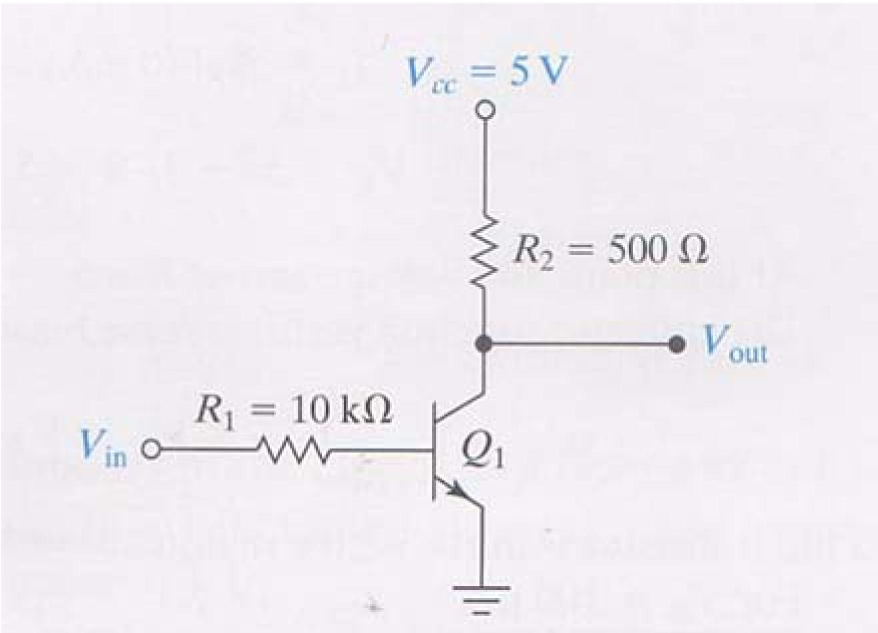


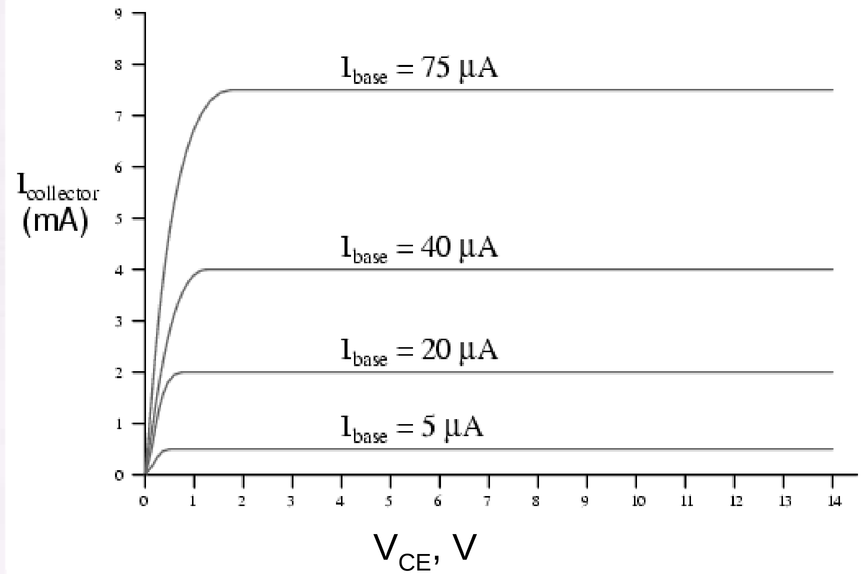
1. Input circuit
The input voltage has two components: the DC bias and the AC signal



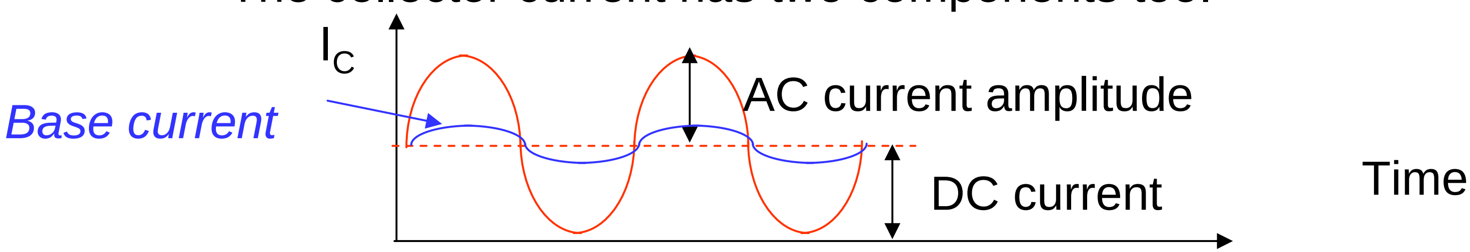
DC voltage component biases the base-emitter p-n junction in the forward direction
AC component is the input signal to be amplified by the BJT.

BJT amplifier gain analysis: 2



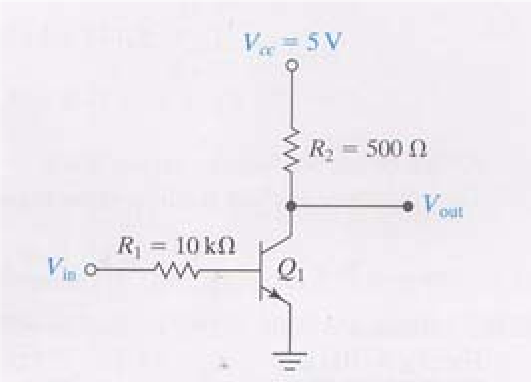


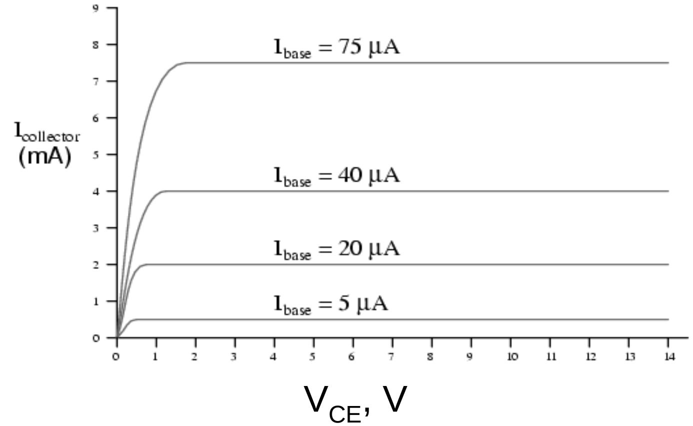
2. Output circuit
The collector current has two components too.



DC and AC collector currents flow through the BJT in accordance with its I-V characteristics

BJT amplifier gain analysis: 3





The resistance of the B-E junction is very low when $V_{BE} \geqslant V_{BE0} \approx V_{bi} \approx 0.7$ V.

Hence the base current $I_B \cong (V_{in}-V_{BE0})/R1 = (V_{inDC}-V_{BE0}+V_{inAC})/R_1$

The collector current I_C does not depend on the collector voltage if the latter is high enough.

Hence, $I_C \cong \beta\ I_B$;

The voltage drop across the load resistance R_2: $V_2 = I_C\ R_2$;

The output voltage $V_{out} = V_{CC} - V_2 = V_{CC} - I_C\ R_2$;

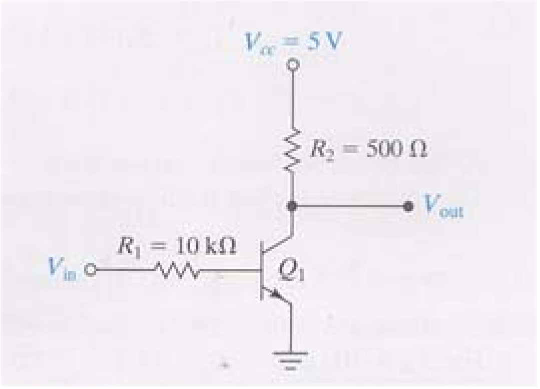
$V_{out} = V_{CC} - I_C\ R_2 = V_{CC} - \beta\ I_B\ R_2 = V_{CC} - \beta\ R_2(V_{inDC}-V_{BE0}+V_{inAC})/R_1$;

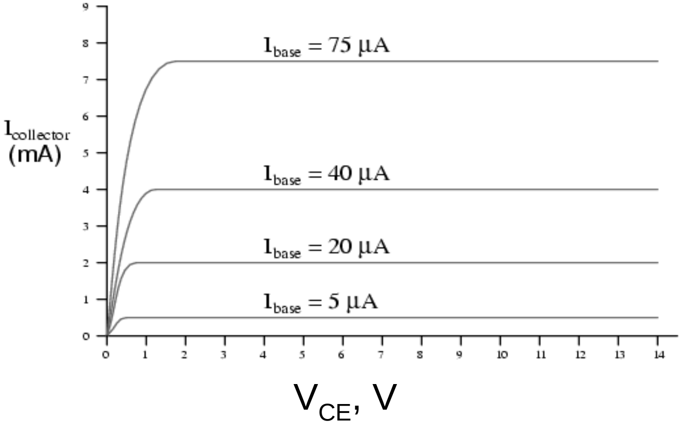
In signal amplifiers only AC component of the output voltage is important:

$$V_{outAC} = -\beta\ R_2 V_{inAC}/R_1;$$

The amplifier voltage gain: $\mathbf{k_V = V_{outAC}/V_{inAC} = -\beta\ R_2/R_1}$;

BJT amplifier gain analysis: 4





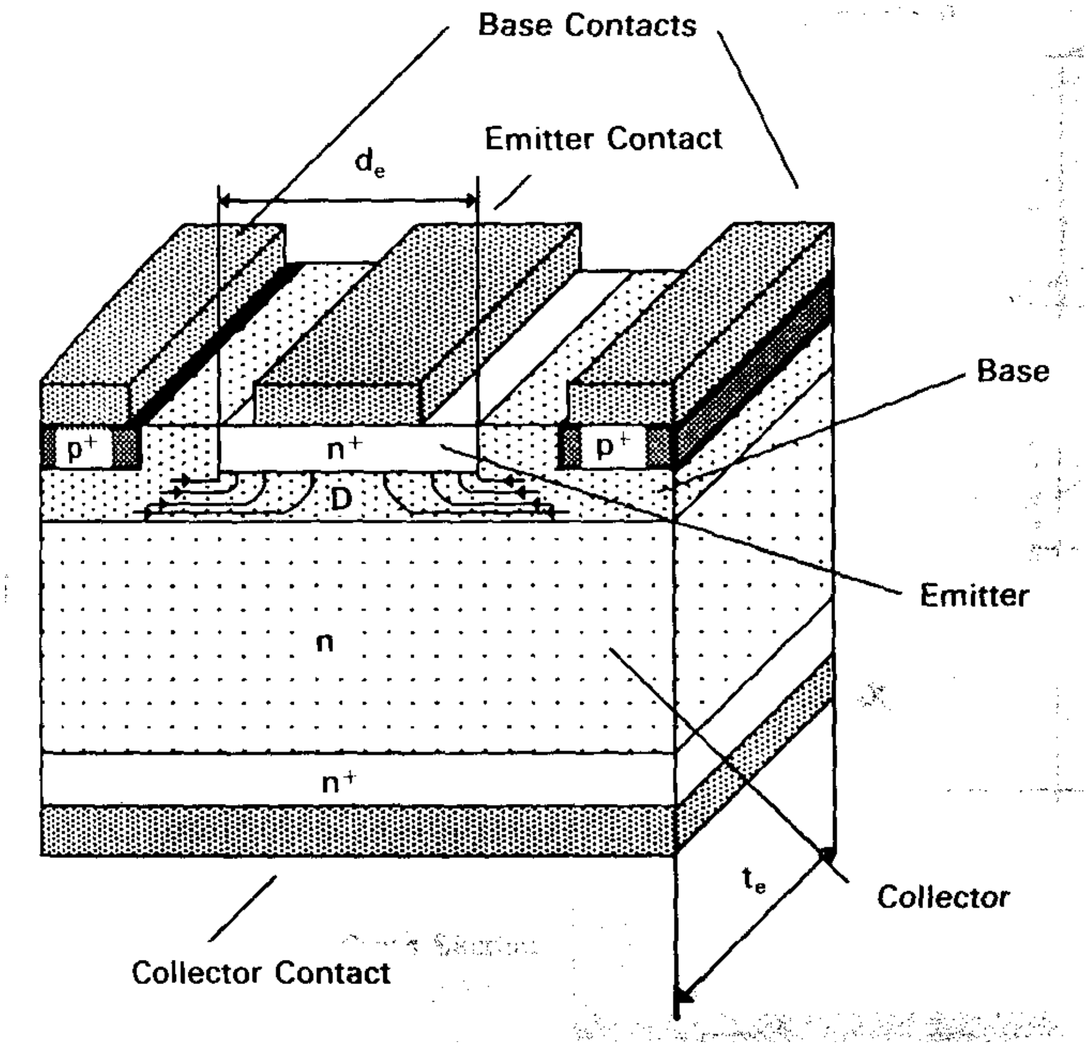
Common emitter gain summary:

Current gain: $\mathbf{k_I = \beta}$

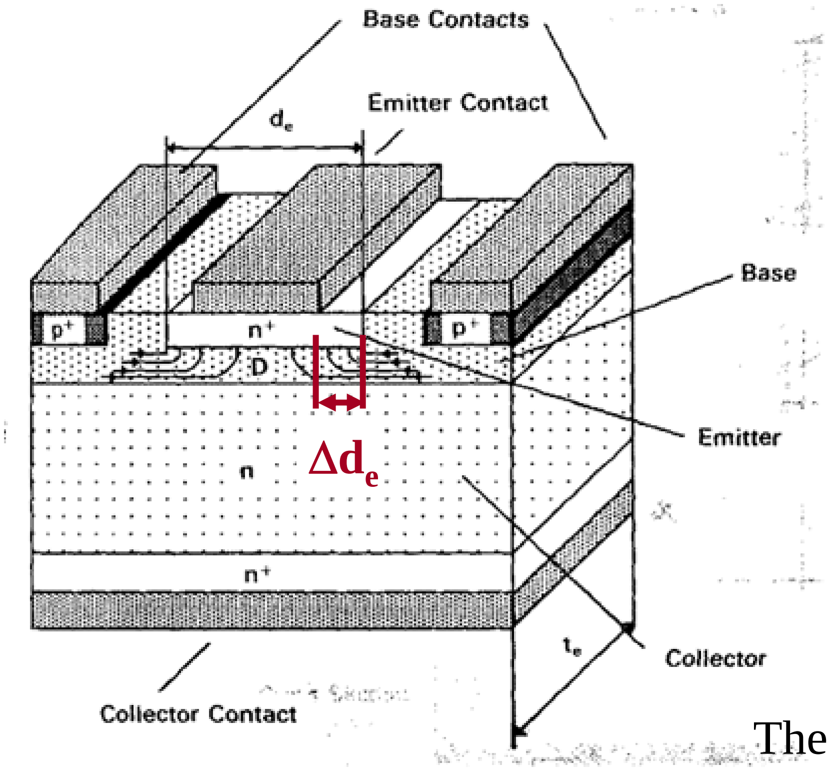
Voltage gain: $\mathbf{k_V = V_{outAC}/V_{inAC} = -\beta\, R_2/R_1}$;

Power gain: $\mathbf{k_P = k_V \times k_I = -\beta^2 \times R_2/R_1}$

BJT design and factors affecting the performance



Base resistance and emitter current crowding in BJTs



The voltage drop along the base layer $\boldsymbol{V_{bb} = r_{bb}\, I_b}$, where r_{bb} is called the base spreading resistance.

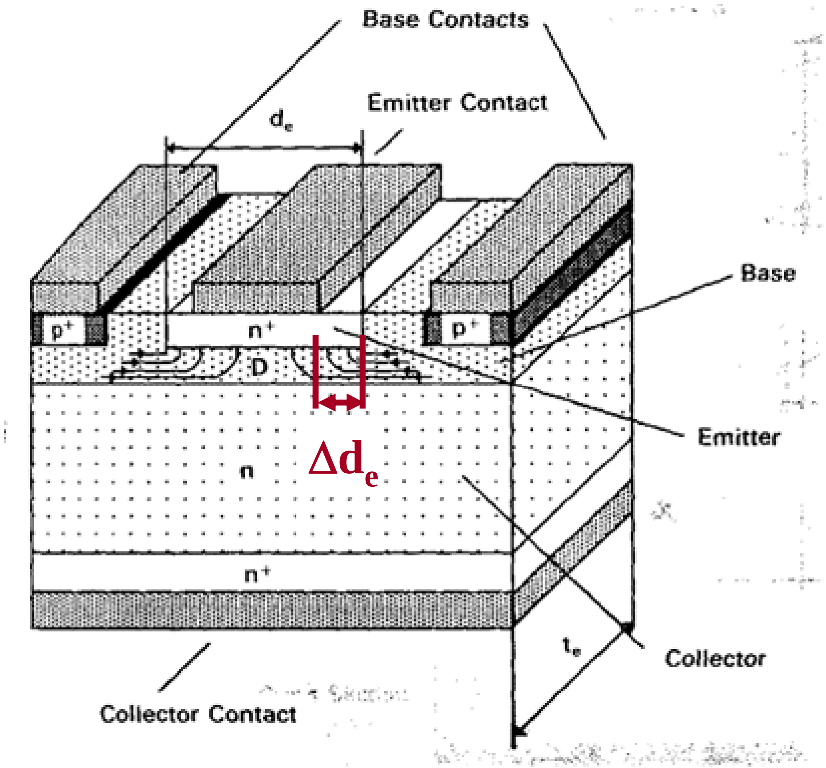
The p-n junction current decreases rapidly when the voltage drops by $\Delta V_{bb} \sim V_{th} = kT/q$

$$I = I_S\left(e^{\frac{qV}{kT}} - 1\right) = I_S\left(e^{\frac{V}{V_{TH}}} - 1\right)$$

The length of the edge region, Δd_e, where most of the emitter current flows may be estimated from:

$$V_{th} = I_b\, R_{b\max} \approx I_b\, \rho_b\, \frac{\Delta d_e}{t_e W}$$

Emitter current crowding in BJTs (cont.)



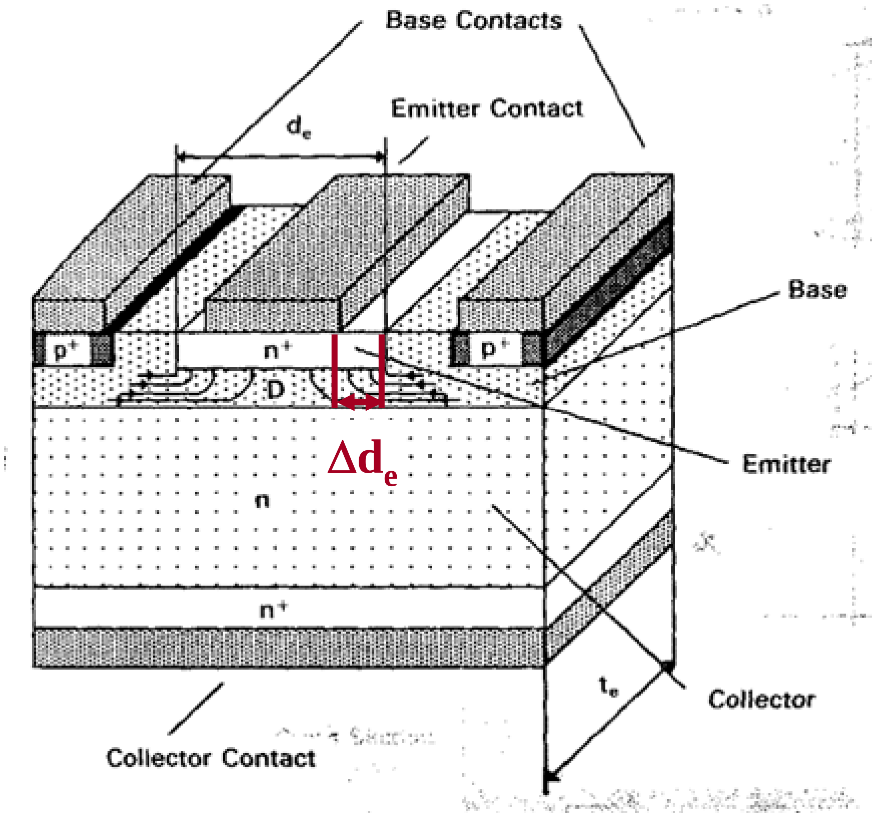
$$V_{th} = I_b\, R_{b\max} \approx I_b\, \rho_b\, \frac{\Delta d_e}{t_e W}$$

$$\rho_b = \frac{1}{q N_b\, \mu_b}$$

From these,

$$\boxed{\Delta d_e \approx \frac{V_{th}\, t_e\, W}{I_b\, \rho_b} = \frac{V_{th}}{I_b}\, q\, N_b \mu_b\, t_e\, W_b}$$

Example



Estimate the effective emitter length, Δd_e for the BJT having the following parameters:

I_b = 50 μA;

$N_b = 10^{17}$ cm^{-3}

μ_b = 400 cm^2/V-s

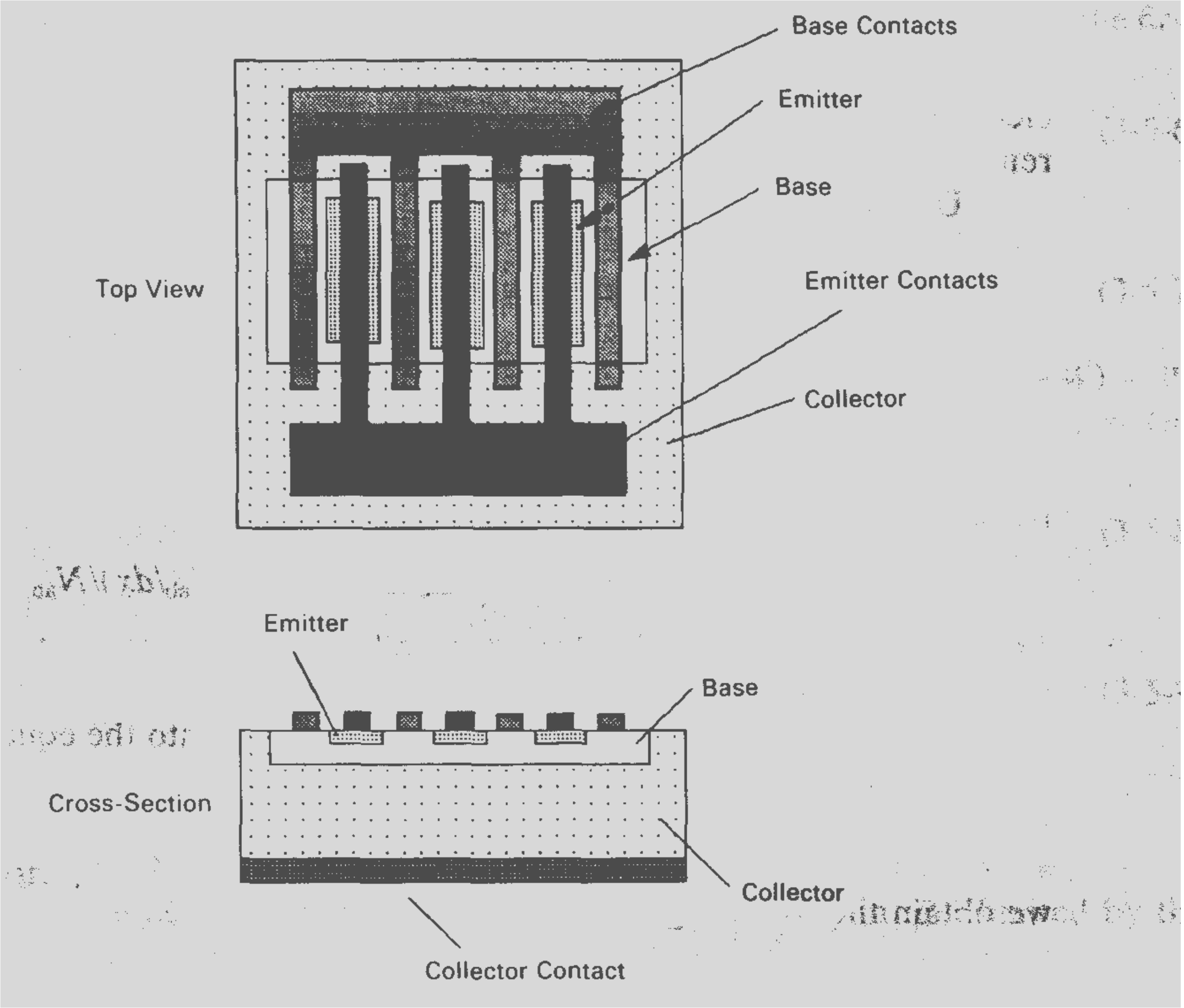
W_b = 0.1 μm

t_e = 100 μm

$$\boxed{\Delta d_e \approx \frac{V_{th}}{I_b} q\, N_b \mu_b\, t_e\, W_b}$$

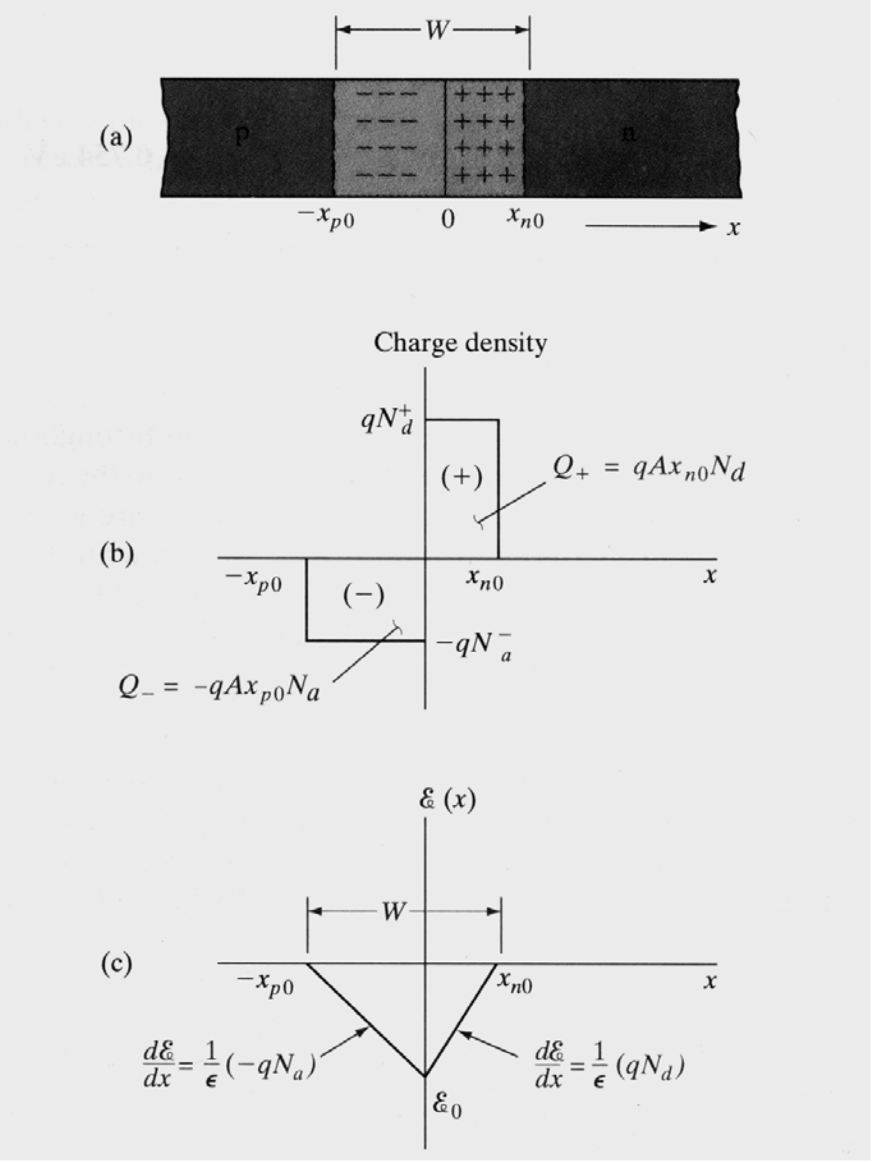
Δd_e = 3.33 e-4 cm = 3.33 μm

Large periphery B JT Design



Base narrowing (Early effect)

The depletion width of the p-n junction depends on the applied voltage:



(Here W is the depletion region width not the width of the base as in BJT!)

In the BJT, this effect means that the effective width of the base is less than W_b:

$\boldsymbol{W_{eff} = W_b - X_{deb} - X_{dcb}}$

where W_b is the physical thickness of the base,

x_{deb} and x_{dcb} are the depletion region widths from the emitter and collector sides.

The depletion widths are given by ($N_e >> N_b$):

$$x_{deb} = \left[\frac{2\varepsilon\varepsilon_0 (V_{bi} - V_{be})}{q N_b} \right]^{1/2}$$

$$x_{dcb} = \left[\frac{2\varepsilon\varepsilon_0 (V_{bi} + V_{cb}) N_c}{q N_b^2} \right]^{1/2}$$

x_{dcb} is usually the most important factor since the voltage applied to collector is high.

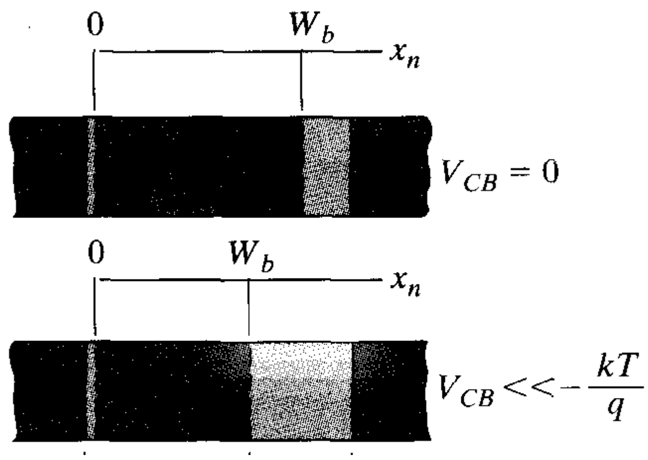
The doping level in collector, N_{DC} has to be lower than that of the base, N_{AB}, to reduce the Early effect:

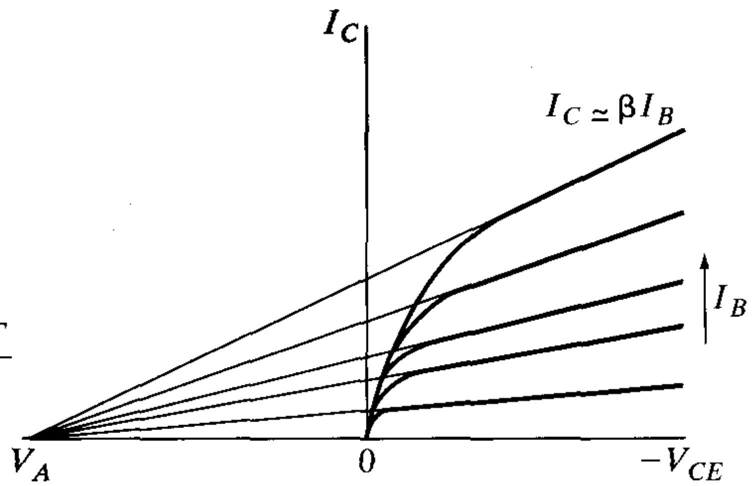
$$\boldsymbol{N_C << N_B}$$

Due to Early effect the effective base thickness depends on the collector voltage.

In the gain expression, W should be replaced with W_{eff}:

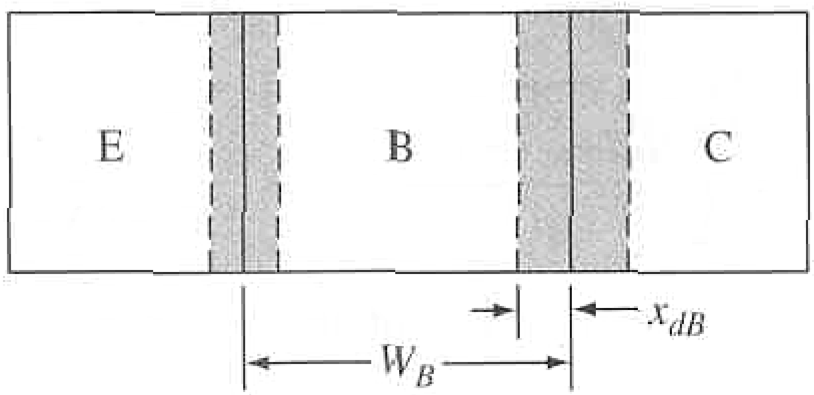
$$\boxed{\beta_{rec} = \frac{2L_p^2}{W_{eff}^2}}$$

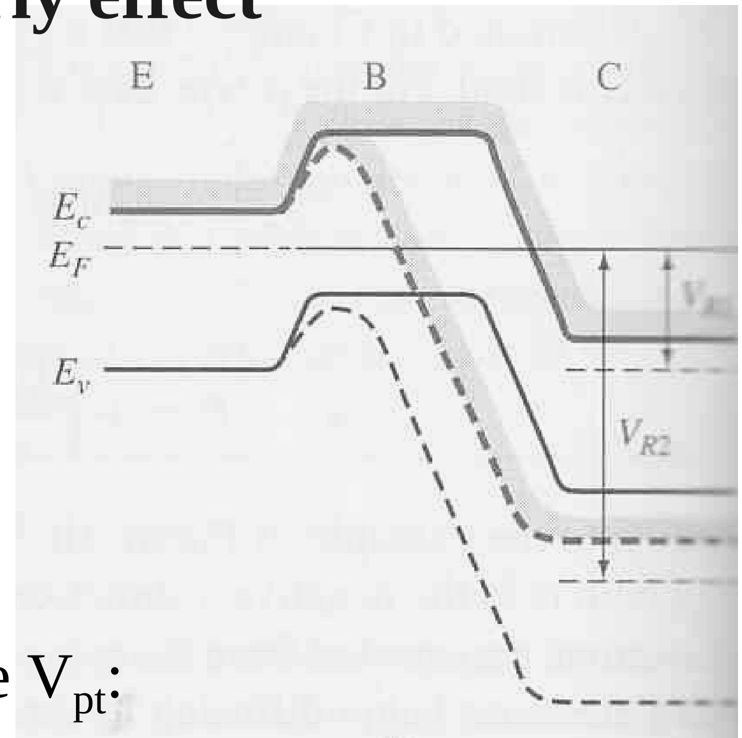




The Early effect decreases the output resistance, and hence the voltage gain of BJTs.

Punch-through breakdown in BJTs -
- the result of the Early effect





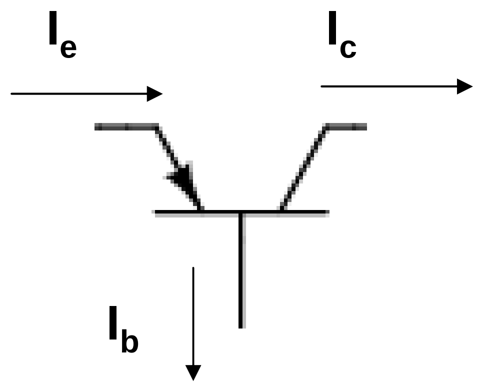
The punch-through breakdown voltage V_{pt}:

$$W = x_{dcb}$$

$$V_{pt} = \frac{qW^2}{2\varepsilon\varepsilon_0}\frac{N_b\left(N_c + N_b\right)}{N_c}$$

BJT Model

- **Gummel-Poon model used in SPICE and other simulators**



Applying KCL to the BJT terminals:

$$I_e = I_c + I_b$$

Collector – emitter current relationship:

$$I_c = \alpha I_e$$

where α is called a common base current gain

Hence, $$I_c = \alpha (I_c + I_b)$$

$$\boxed{I_c = \frac{\alpha}{1-\alpha} I_b}$$

Common emitter current gain is defined as:

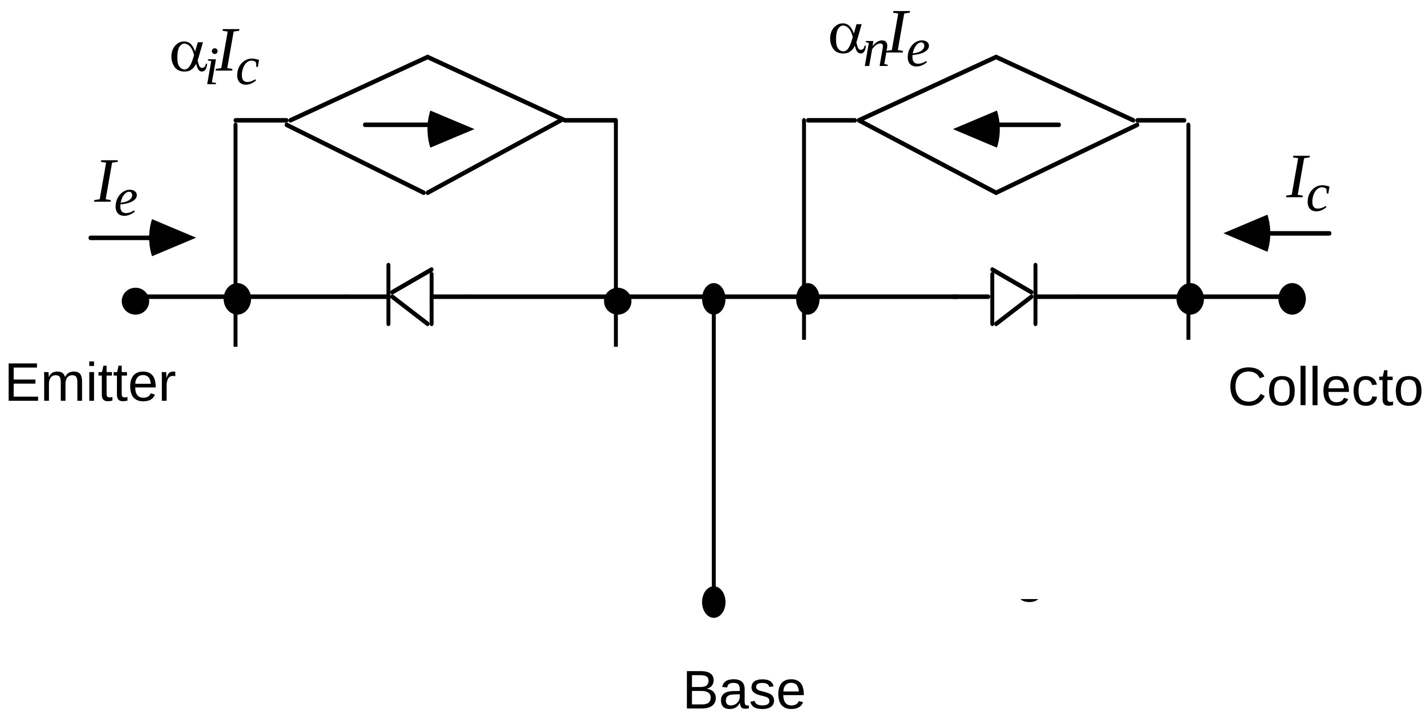
$$\boxed{I_c = \beta I_b}$$

$$\boxed{\beta = \frac{\alpha}{1-\alpha}}$$

$$\boxed{\alpha = \frac{\beta}{1+\beta}}$$

The last two expressions link common emitter and common base current gains

Simplified Gummel-Poon BJT equivalent circuit



- Emitter junction:

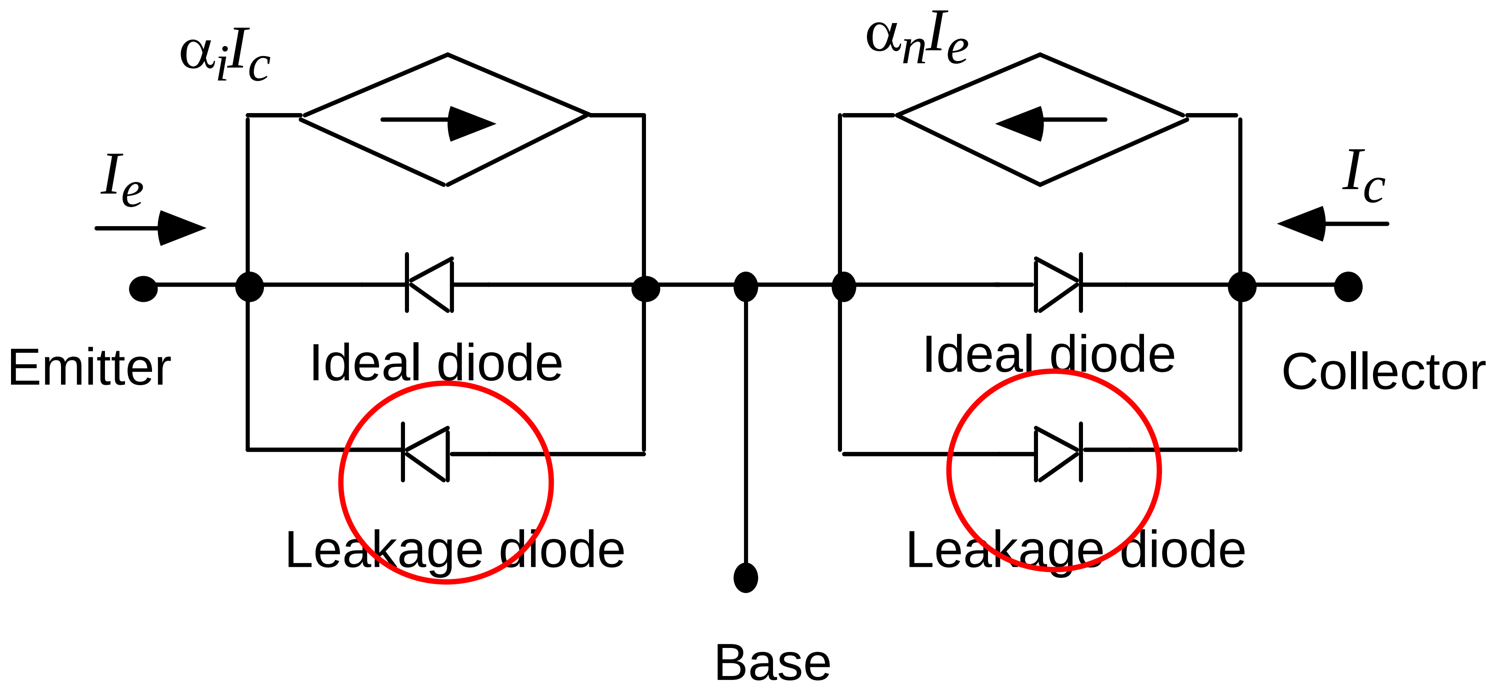
$$I_{be} = \frac{I_{se}}{\beta_F}\left[\exp\left(\frac{V_{be}}{n_F V_{th}}\right) - 1\right]$$

- Collector junction:

$$I_{bc} = \frac{I_{sc}}{\beta_R}\left[\exp\left(\frac{V_{bc}}{n_R V_{th}}\right) - 1\right]$$

V_{th} = kT/q = 0.026 V at 300 K

Gummel-Poon BJT equivalent circuit accounting for the leakage currents



- Emitter –base leakage diode:

$$I_{Leak\_be} = I_{se}\left[\exp\left(\frac{V_{be}}{n_E V_{th}}\right) - 1\right]$$

Collector –base leakage diode:

$$I_{Leak\_bc} = I_{sc}\left[\exp\left(\frac{V_{bc}}{n_C V_{th}}\right) - 1\right]$$