ECE 340 Lectures 40
Semiconductor Electronics

Spring 2022
10:00-10:50am

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Today’s Discussion

- **Analytical model of the Bipolar Junction Transistor (BJT)**
- **Transistor as amplifier**

BJT results so far

$$\gamma = \frac{i_{Ep}}{i_E} = \frac{i_{Ep}}{i_{Ep} + i_{En}}$$

emitter injection efficiency

$$i_C = \boldsymbol{B}\, i_{Ep}$$

base transport factor

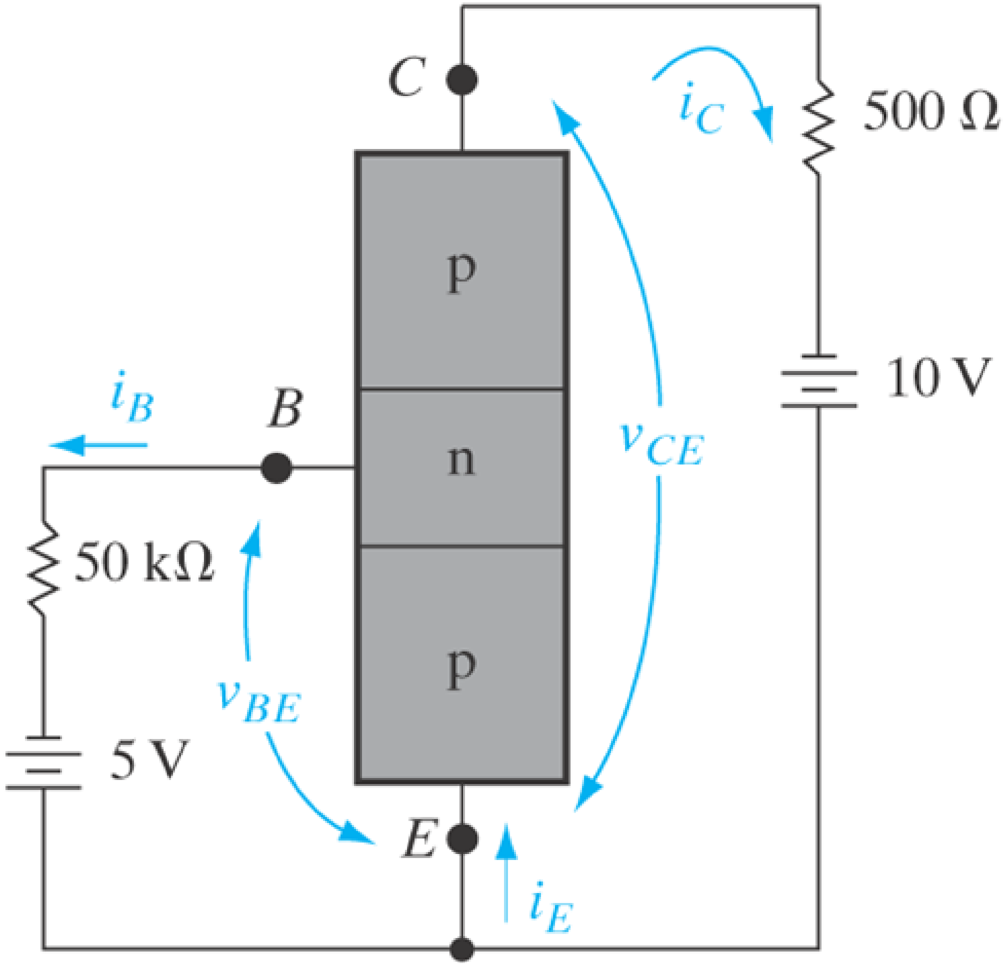
$$\frac{\boldsymbol{i_C}}{\boldsymbol{i_E}} = B\gamma = \boldsymbol{\alpha}$$

current transfer ratio

$$\frac{i_C}{i_B} = \frac{\alpha}{1-\alpha} = \beta$$

amplification factor

Example



Base recombination time

$$\tau_n = \tau_p = 10\ \mu s$$

Base transit time

$$\tau_t = 0.1\ \mu s$$

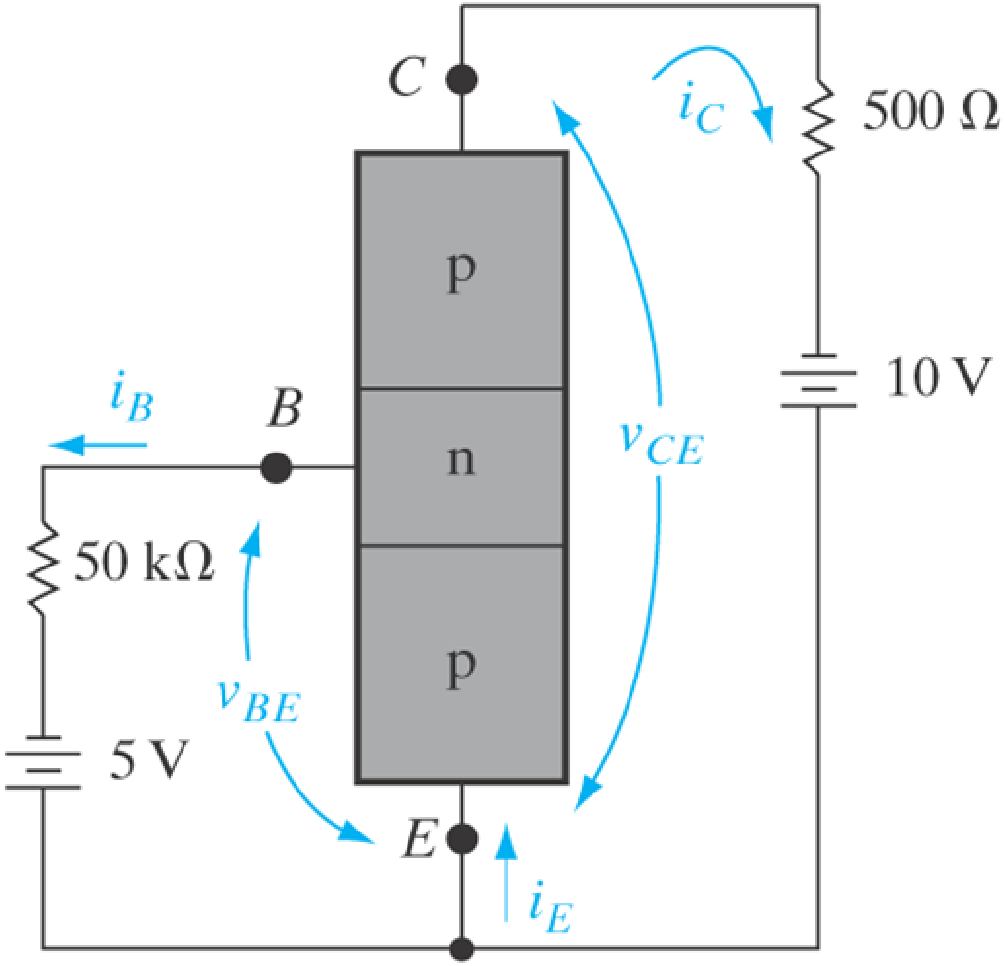
Amplification factor

$$\beta = \frac{i_C}{i_B} = \frac{\tau_n}{\tau_t} = 100$$

Current Transfer ratio

$$\alpha = \frac{\beta}{1+\beta} = \frac{100}{101} = 0.99$$

Example



Amplification factor

$$\beta = 100$$

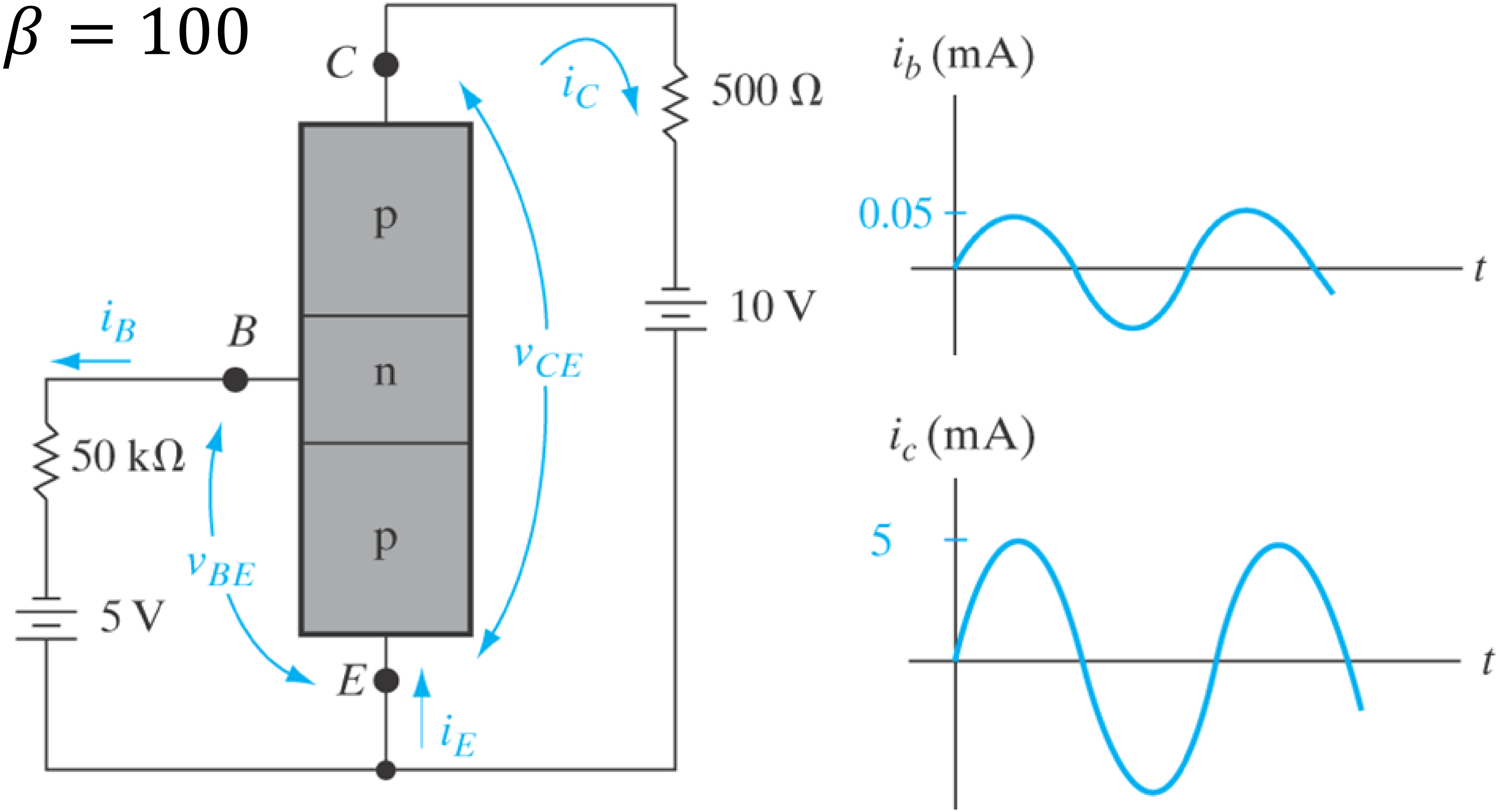
Assume $v_{BE} \approx 0$

$$I_B = \frac{5\text{V}}{50\text{k}\Omega} = 0.1\text{ mA}$$

$$I_C = \beta I_B = 10\text{ mA}$$

Example

$\beta = 100$



For the curious ones:

- Video by Bill Hammack on the first transistor invented by Bardeen and Brattain at Bell Labs (point-contact transistor)

  https://www.youtube.com/watch?v=RdYHljZi7ys

The book by Shockley contains an extensive description of the point-contact transistor, based on metal-semiconductor junctions rather than p-n junctions
https://archive.org/details/ElectronsAndHolesInSemiconductors

- AT&T Archives video: Genesis of the Transistor:
  https://www.youtube.com/watch?v=WiQvGRjrLnU

Mathematical analysis of the *p-n-p* BJT

- **Some simplifying assumptions are necessary in order to develop a manageable model which is general and valid for general bias conditions:**

1. **Negligible drift in the base region (holes move by diffusion)**
2. **Emitter injection efficiency $\gamma = 1$ (emitter is highly doped *p*+)**
3. **Reverse saturation current at the collector is negligible**
4. **Uniform cross-sectional area A (1-D model)**
5. **Steady-state conditions**

Posted handout on NBD and BJT:

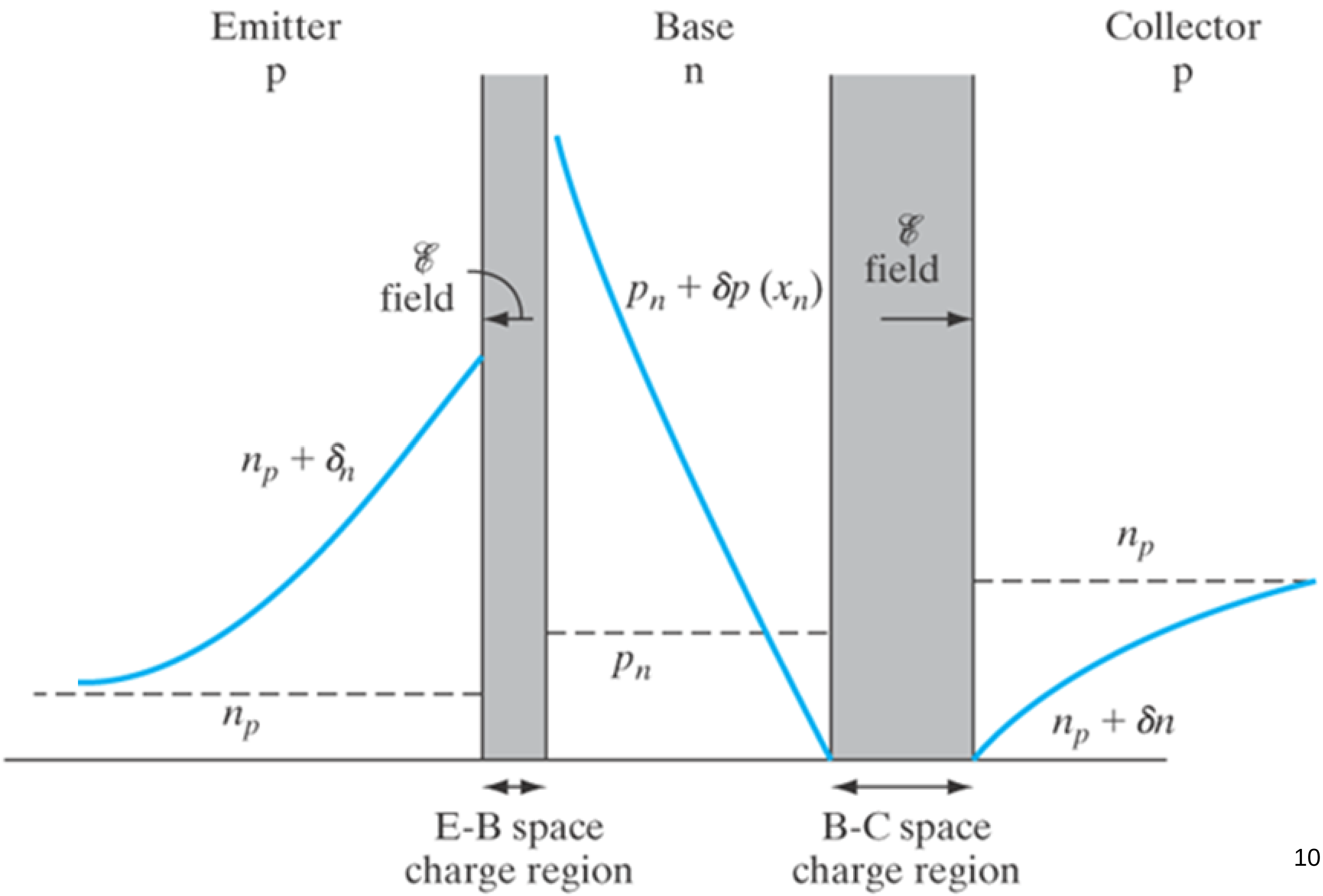
We are going to focus on the significance of the results and on physical understanding of physical behavior.

Details of the analytical solution for the 1-D model BJT are outlined in the posted handout and are left as optional reading for the interested students.

Actual complete simulations of realistic devices are carried out by numerical solution of the coupled system of semiconductor equations consisting of:

- **continuity equations for electrons and holes based on the drift-diffusion current model**
- **Poisson equation to obtained self-consistent space dependent electric fields**

Excess carriers in the whole device



Results obtained from analytical solution

$$I_{Ep} = qA\frac{D_p}{L_p}\left[\Delta p_E \operatorname{ctnh}\frac{W_B}{L_P} - \Delta p_C \operatorname{csch}\frac{W_B}{L_P}\right]$$

$$I_C = qA\frac{D_p}{L_p}\left[\Delta p_E \operatorname{csch}\frac{W_B}{L_P} - \Delta p_C \operatorname{ctnh}\frac{W_B}{L_P}\right]$$

$$I_B = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\frac{W_B}{2L_P}\right]$$

For the narrow base diode

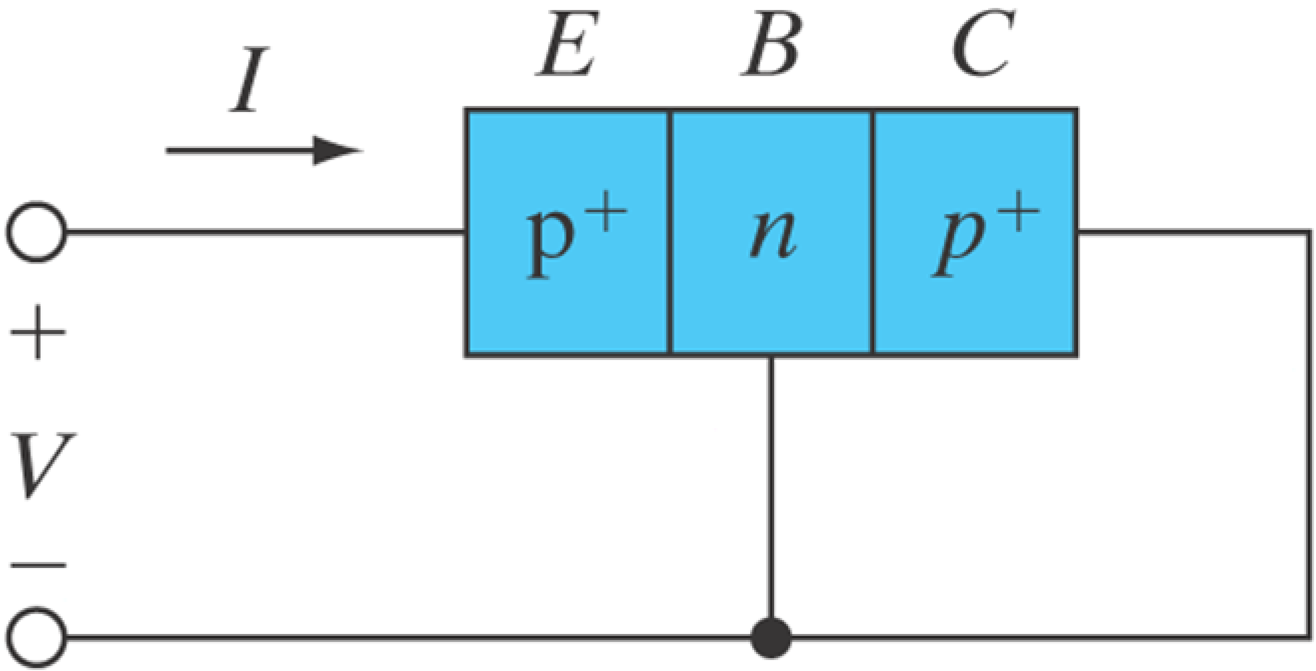
$$I_p(x_n = 0) = qA\frac{D_p}{L_p}\Delta p_n \operatorname{ctnh}\frac{\ell}{L_P}$$

$$I_p(x_n = \ell) = qA\frac{D_p}{L_p}\Delta p_n \operatorname{csch}\frac{\ell}{L_P}$$

$$I_n(\text{recomb}) = qA\frac{D_p}{L_p}\Delta p_n \tanh\frac{\ell}{2L_P}$$

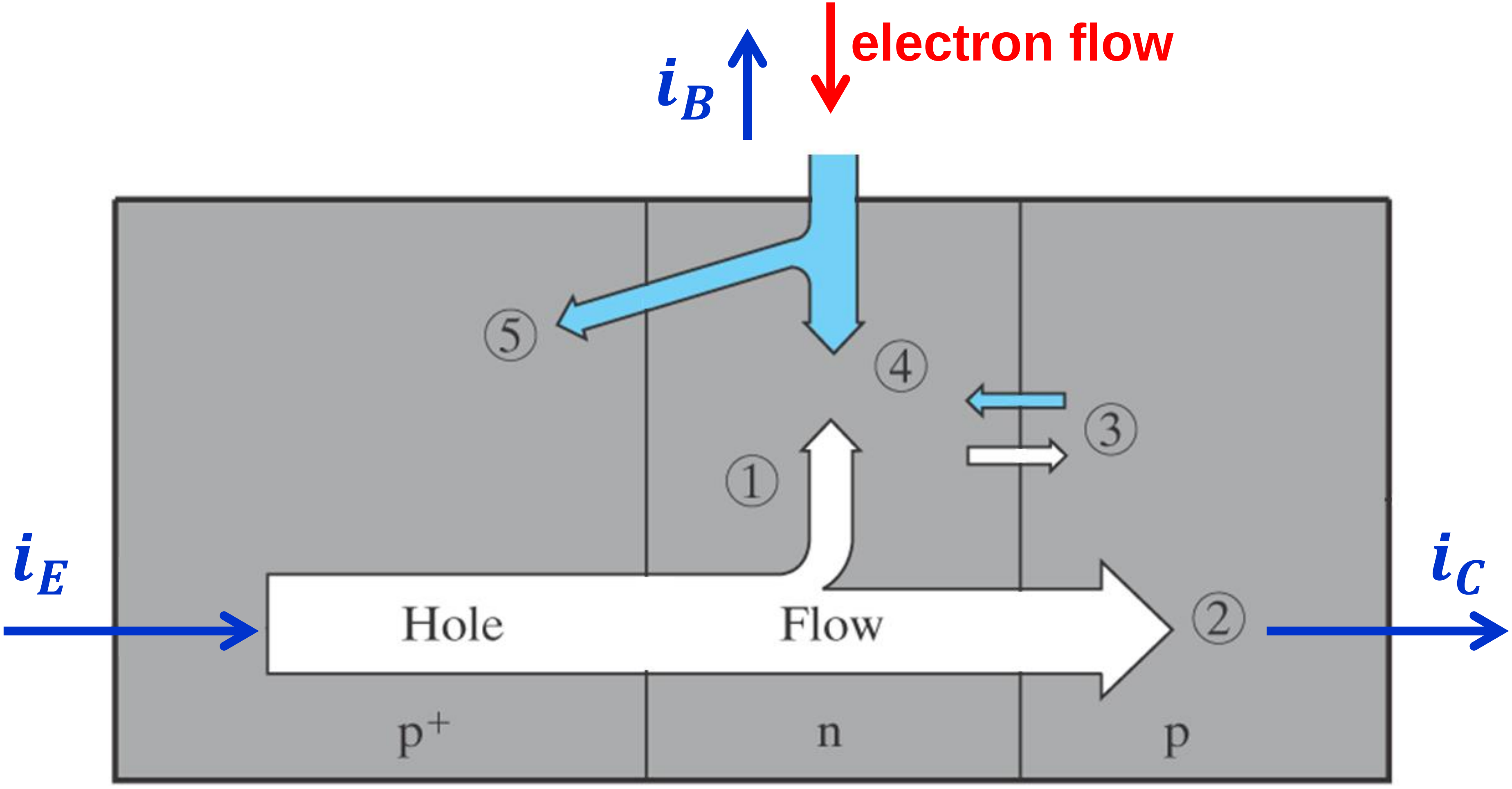
With $\Delta p_c \approx 0$ essentially the same result obtained for BJT

In fact, NBD is equivalent to this BJT



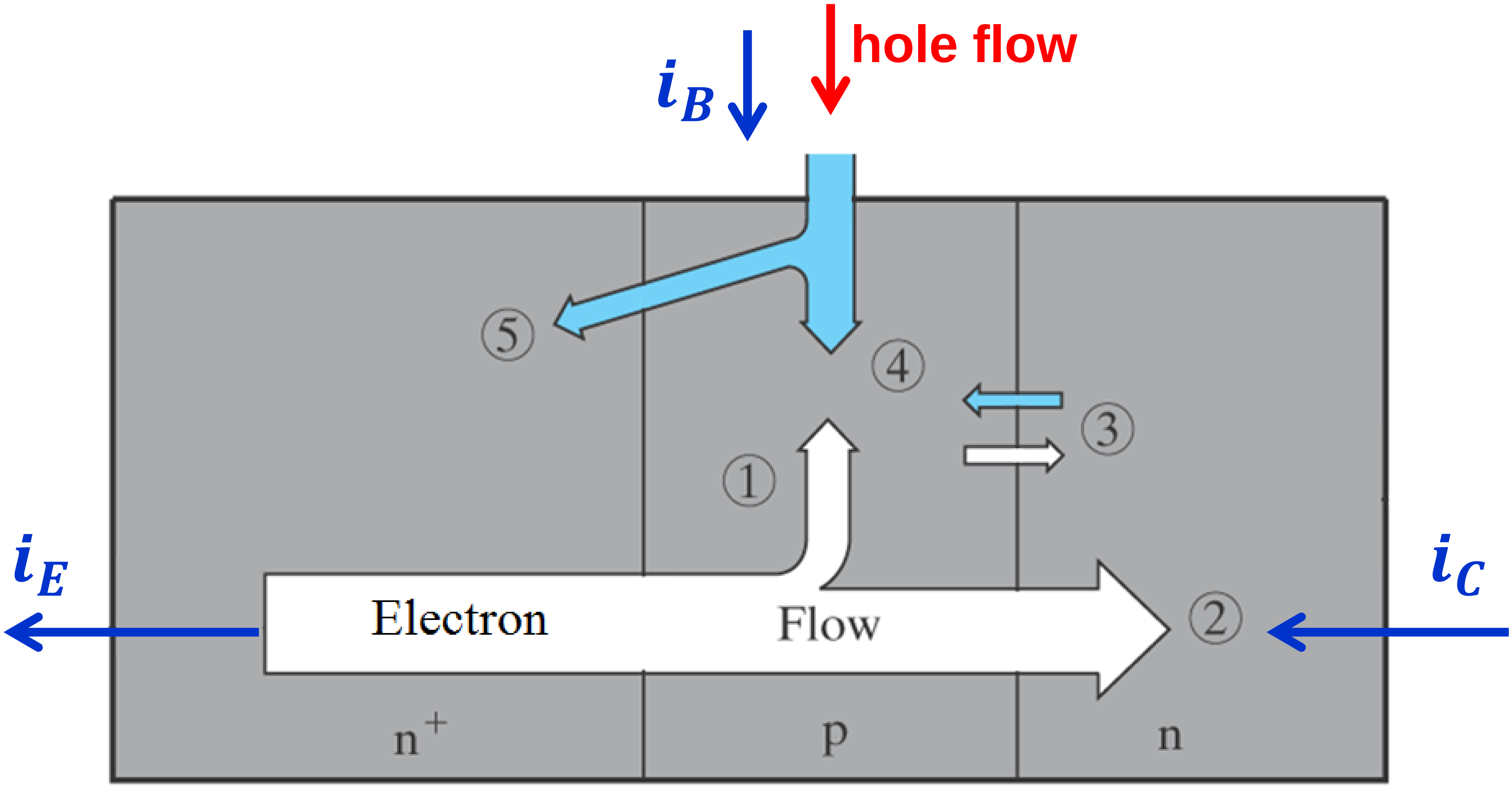
$$V_{CB} = 0 \quad \rightarrow \quad \Delta p_C = 0$$

Recall the carrier flow for p^+-n-p



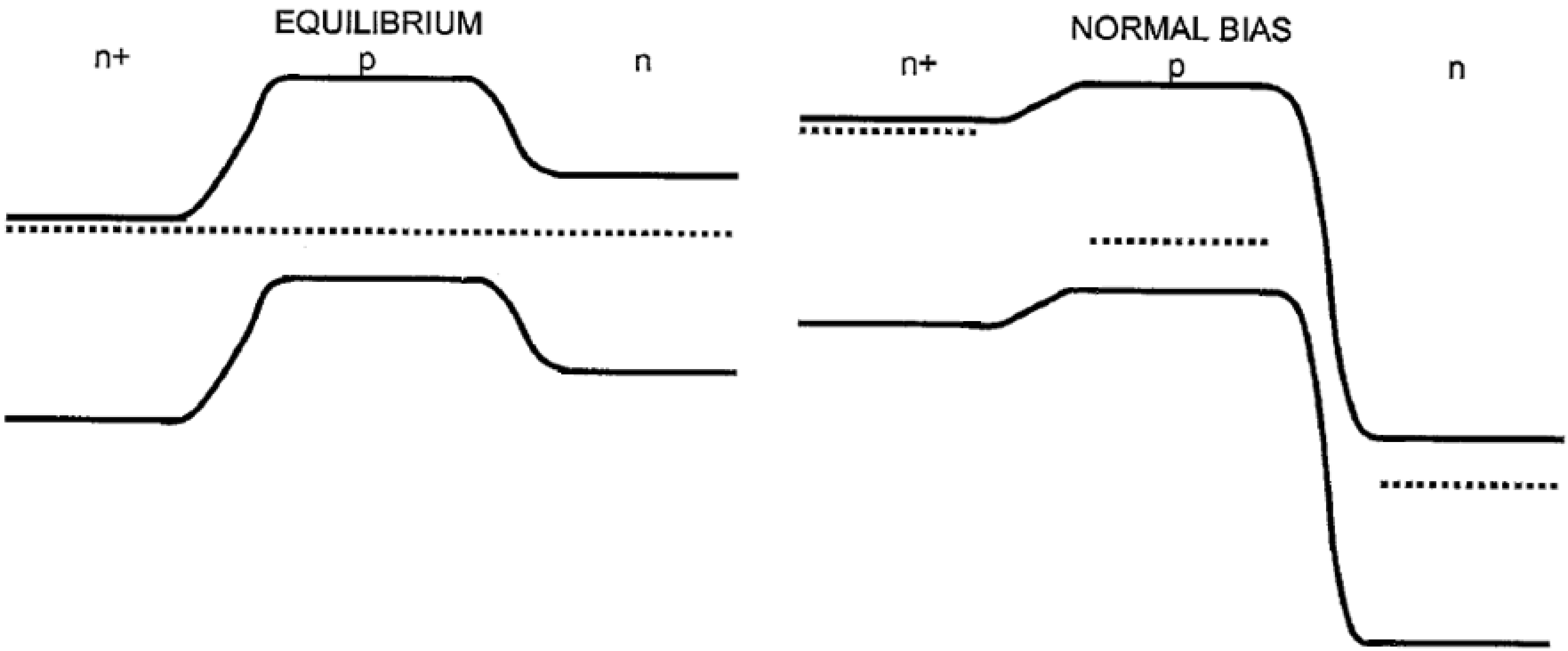
$$\overrightarrow{i_E} = \begin{cases} \overrightarrow{i_{Ep}} \\ \overrightarrow{i_{En}} \end{cases} \qquad \overrightarrow{i_C}$$

Redraw carrier flow for n$^+$-p-n

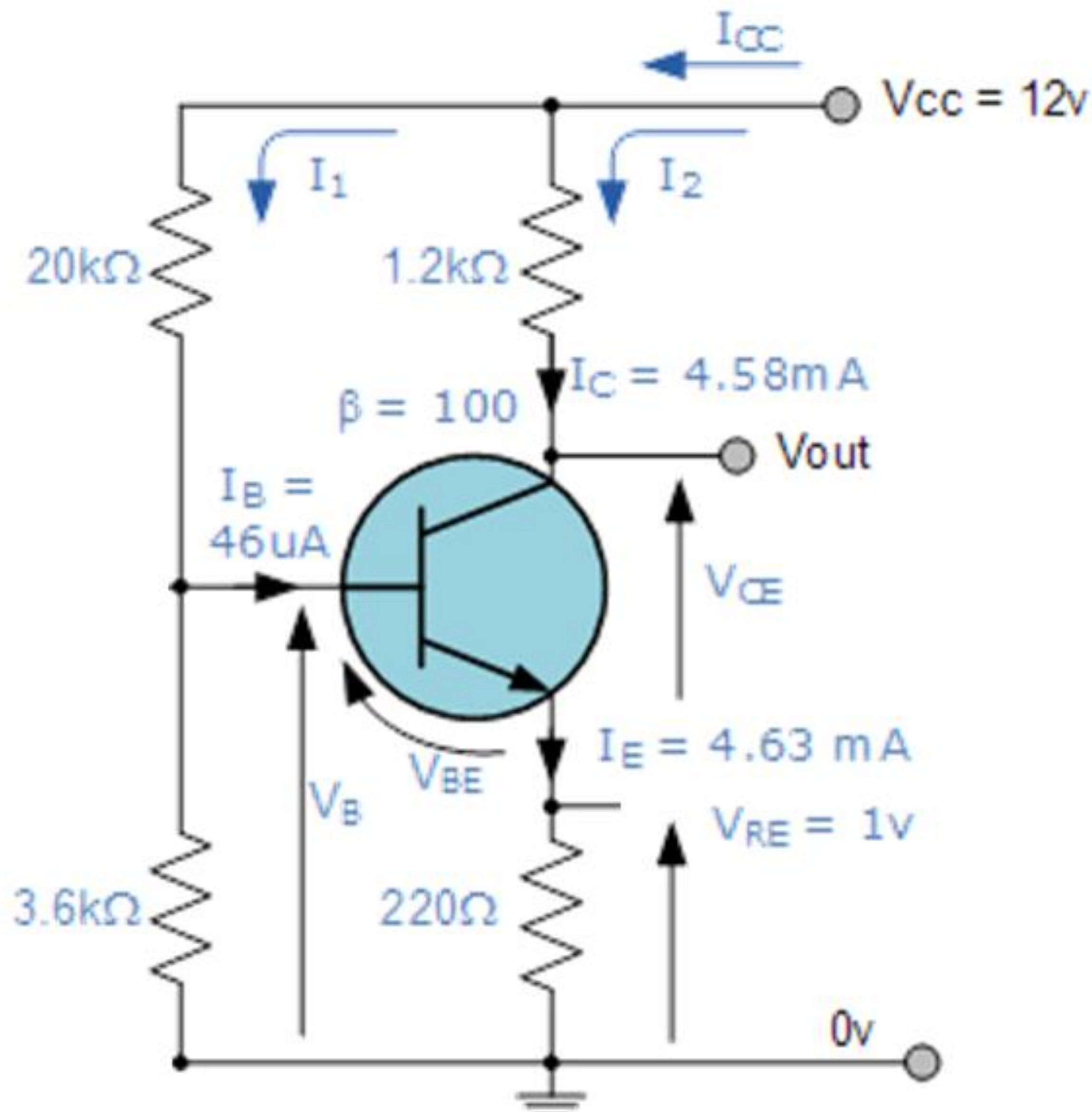


$$i_E = \left\{ \begin{array}{l} i_{En} \\ i_{Ep} \end{array} \right. \qquad i_C$$

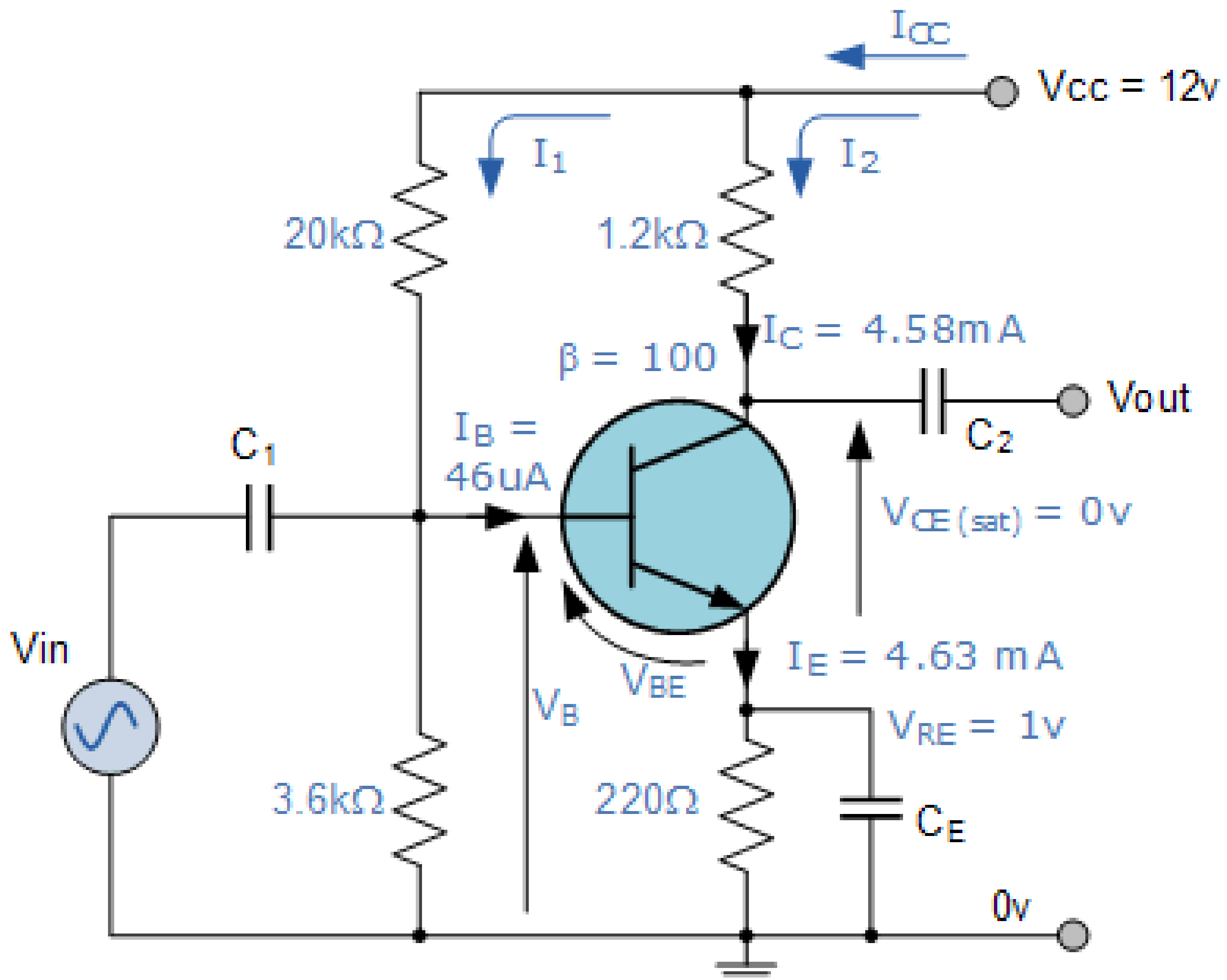
Redraw band diagram for n^{+}-p-n



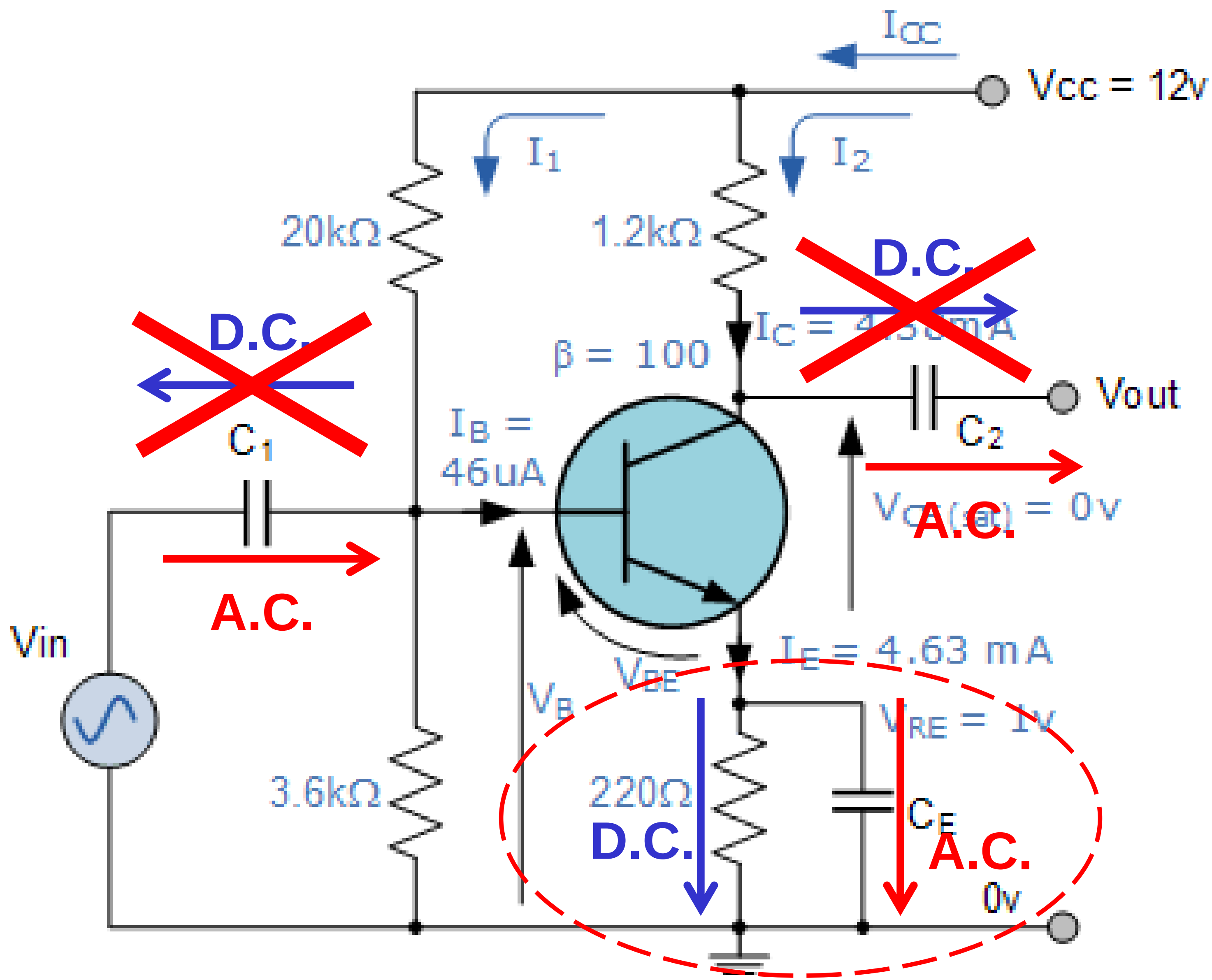
Single battery bias for n-p-n BJT

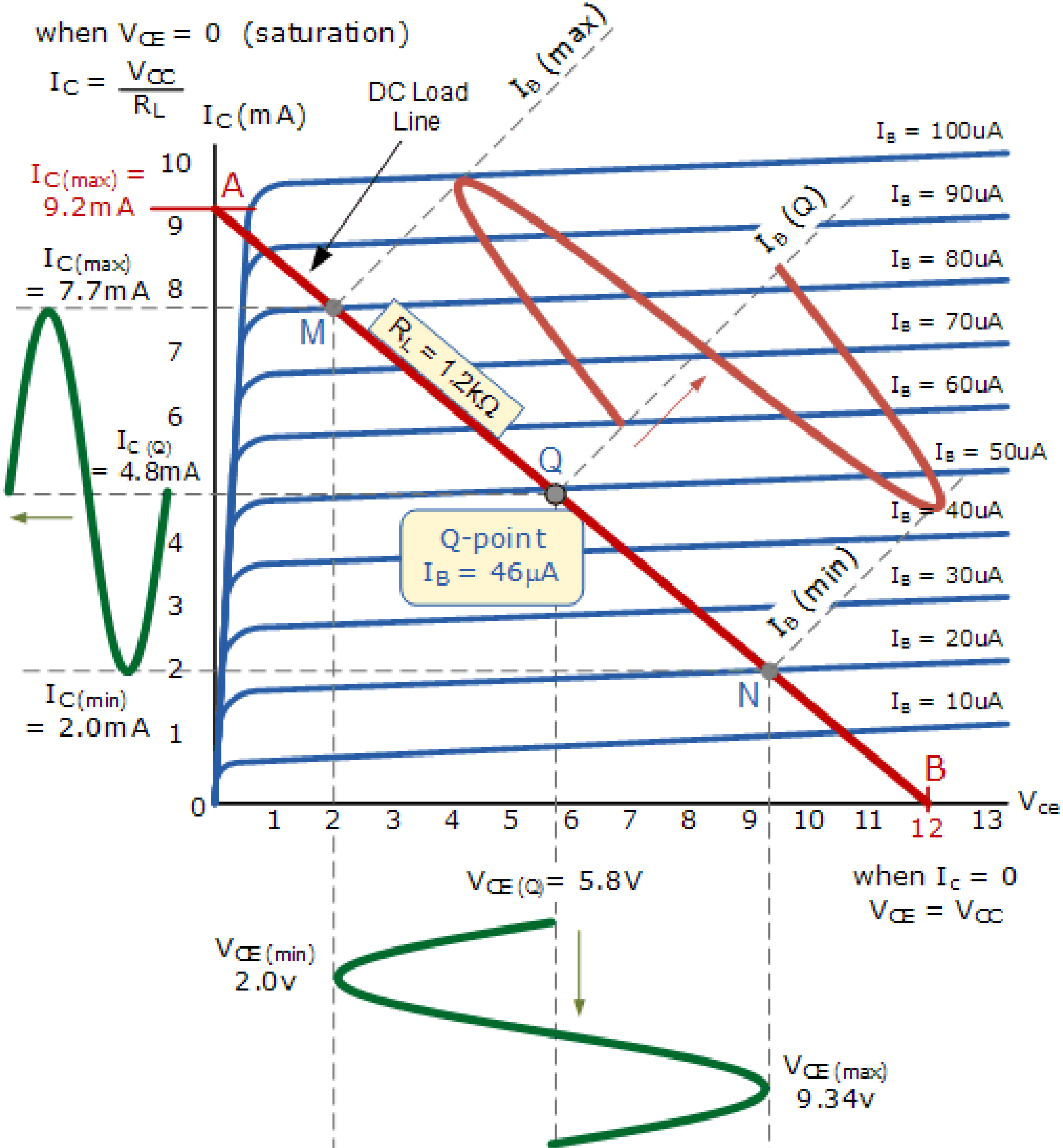


Amplifier stage based on n-p-n BJT



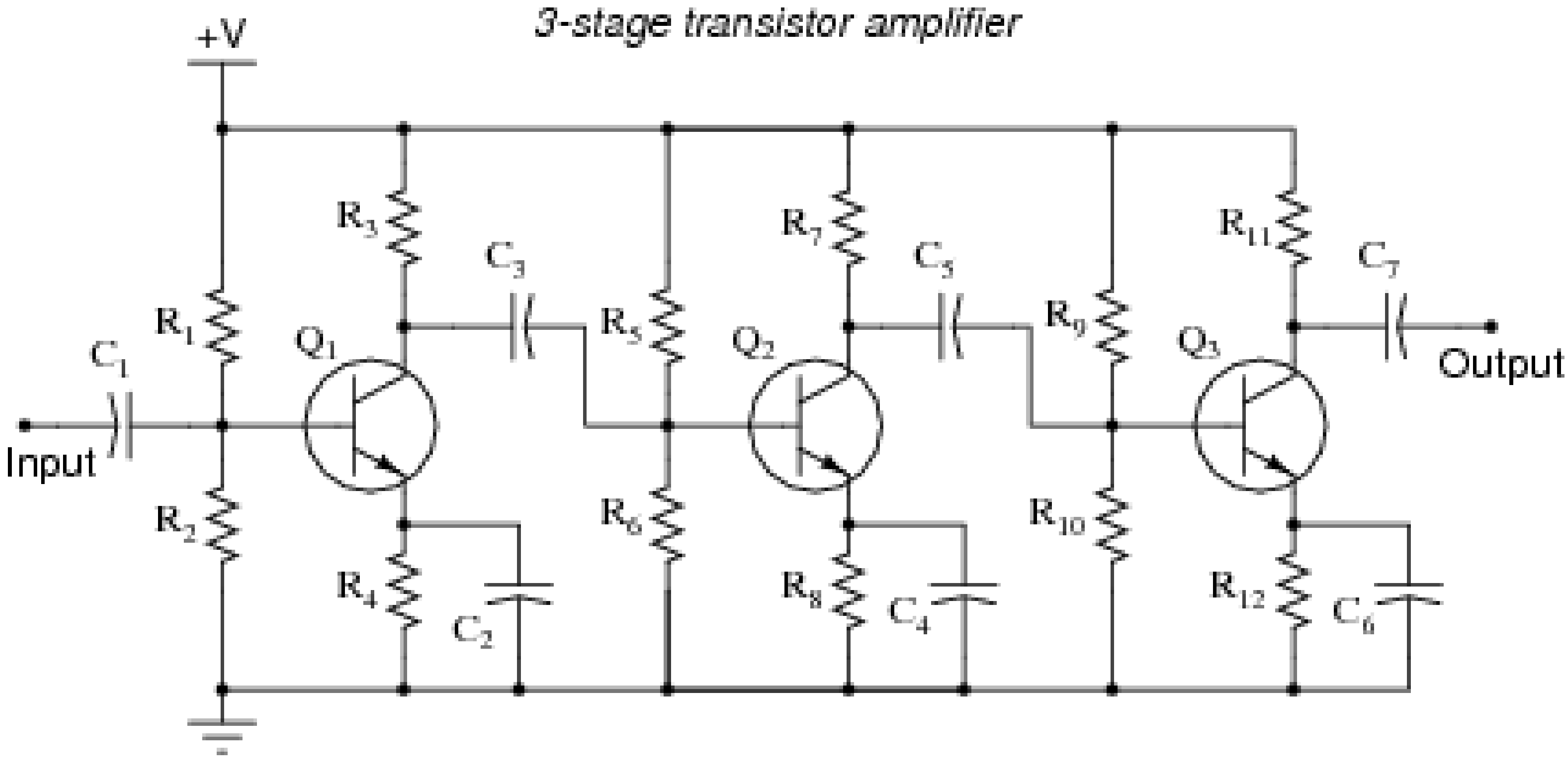
Amplifier stage based on n-p-n BJT



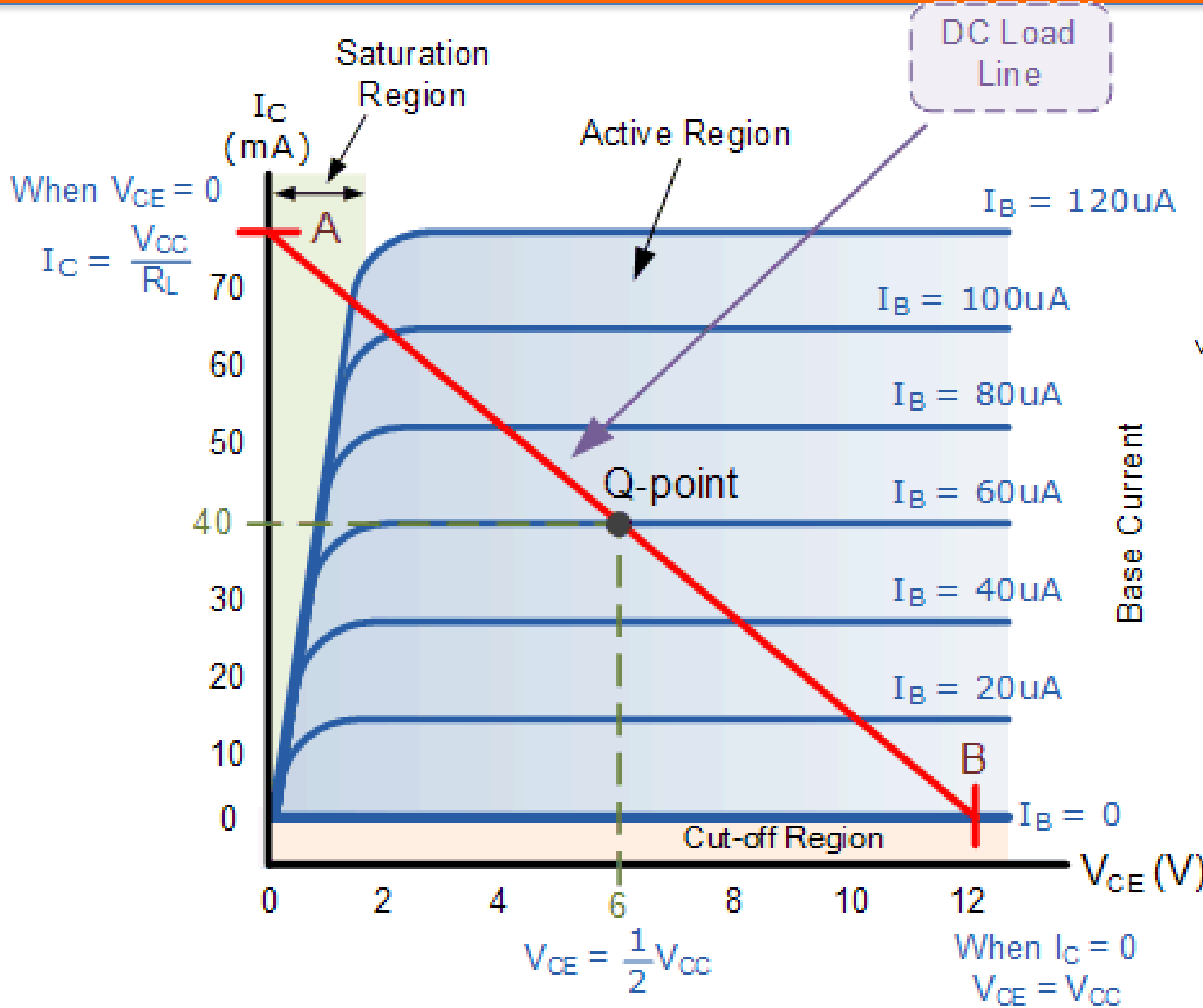


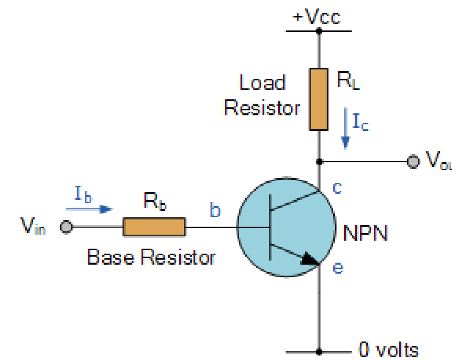
when VCE = 0 (saturation)
IC = VCC / RL
IC (mA)
DC Load Line
IB (max)
IB = 100uA
IB = 90uA
IB = 80uA
IB = 70uA
IB = 60uA
IB = 50uA
IB = 40uA
IB = 30uA
IB = 20uA
IB = 10uA
IB (Q)
IB (min)
IC(max) = 9.2mA
IC(max) = 7.7mA
IC (Q) = 4.8mA
IC(min) = 2.0mA
A
M
Q
N
B
RL = 1.2kΩ
Q-point IB = 46µA
Vce
0 1 2 3 4 5 6 7 8 9 10 11 12 13
10 9 8 7 6 4 3 2 1
VCE (Q) = 5.8V
when Ic = 0
VCE = VCC
VCE (min) 2.0v
VCE (max) 9.34v

Multi-stage amplifier example



BJT as amplifier or as switch

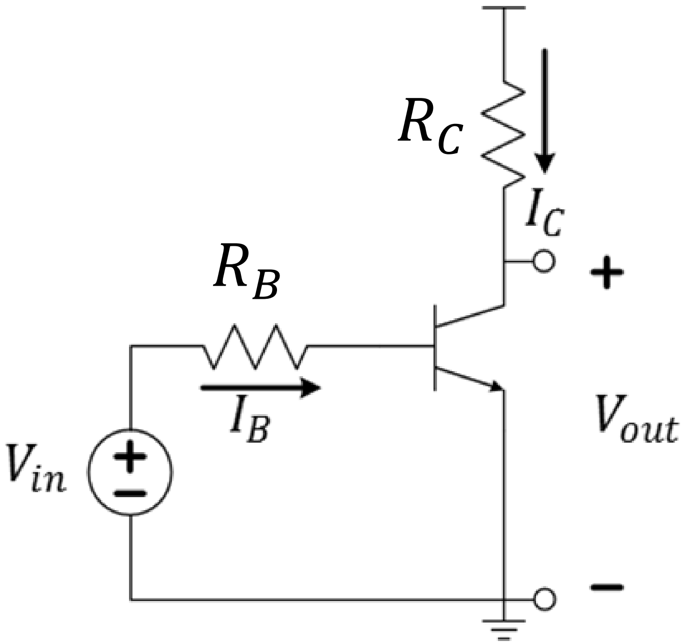


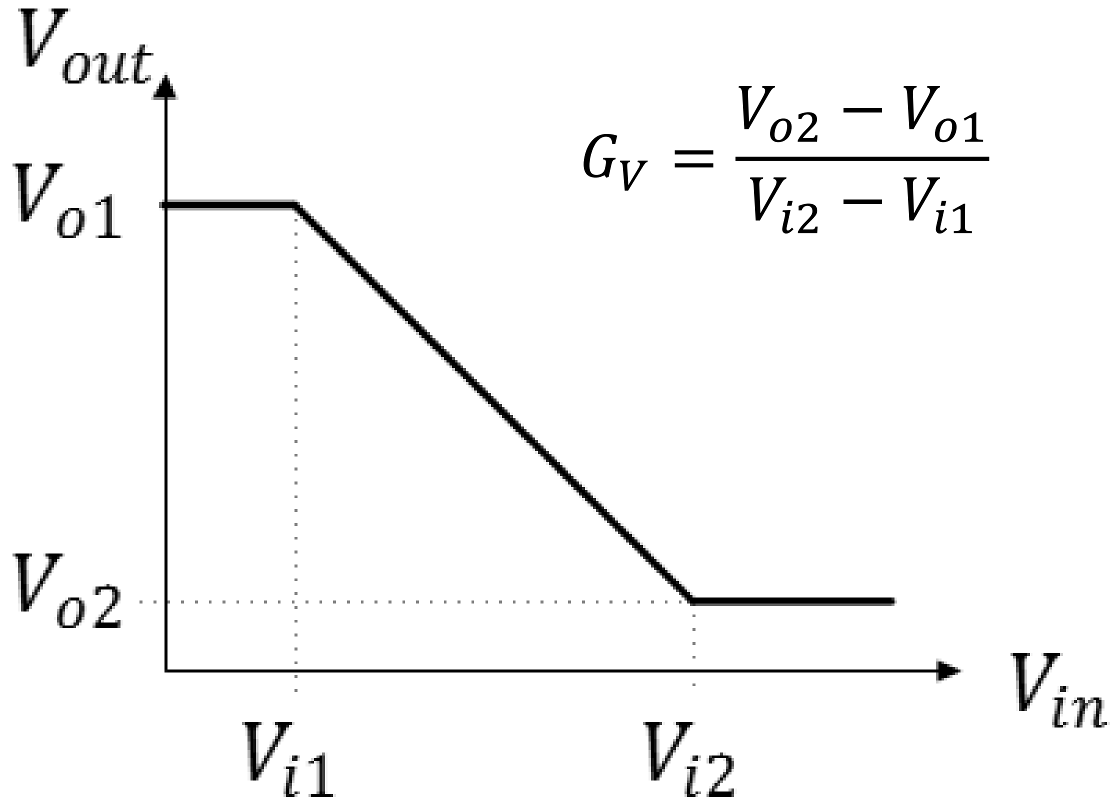


Q bias point
Amplifier

A and B points
Logic Inverter

Voltage Transfer Characteristics

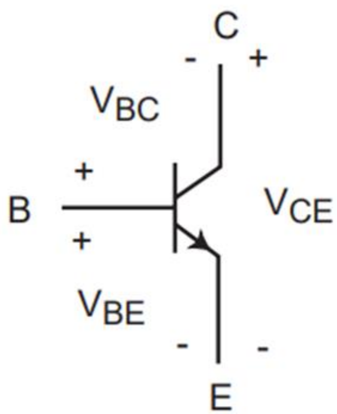


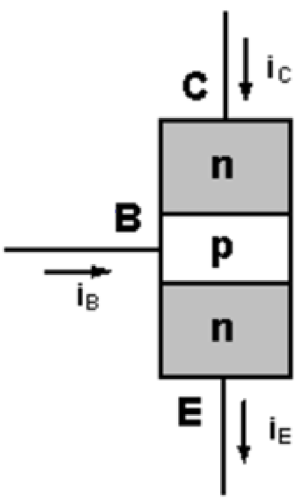


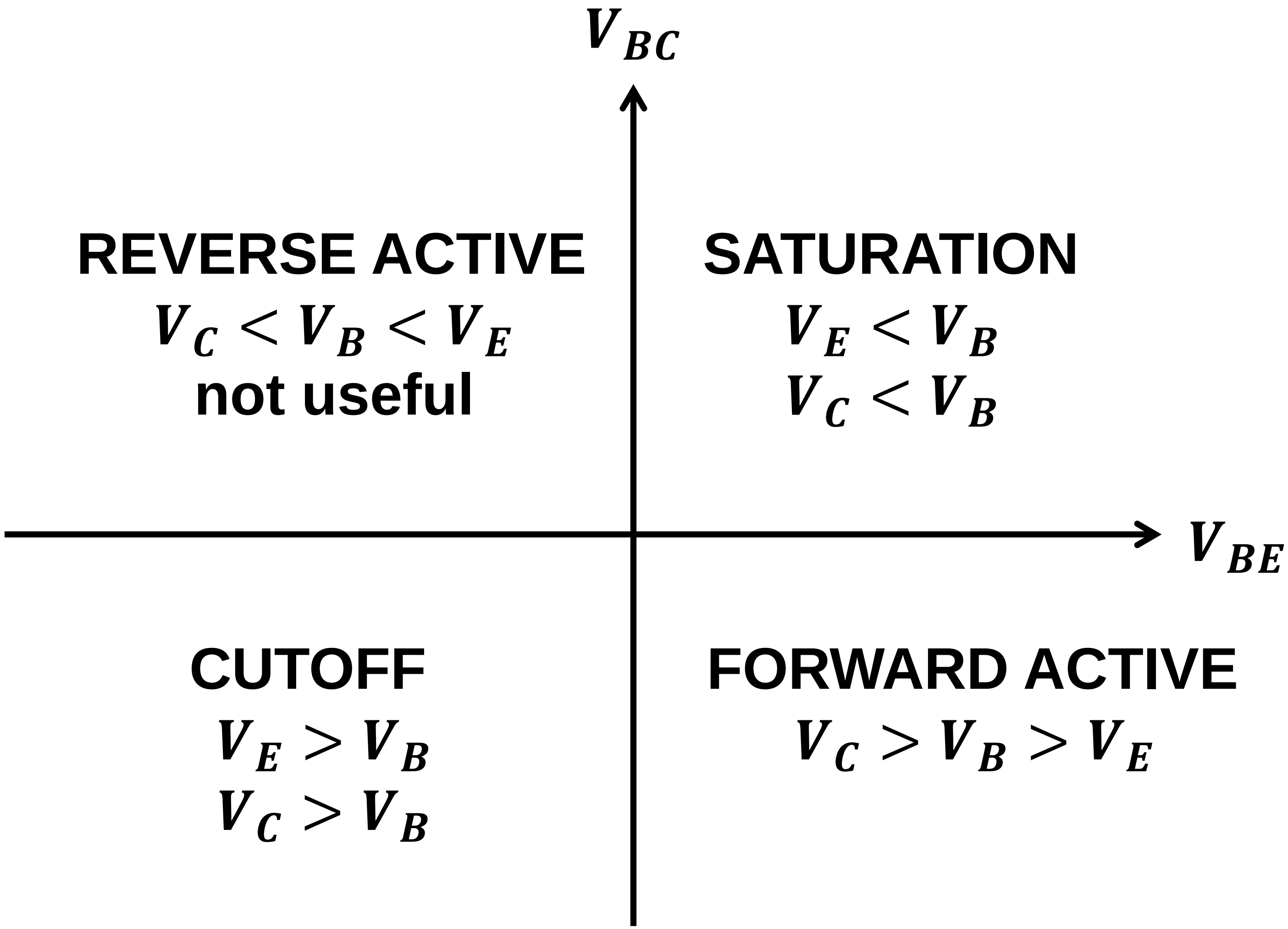
incremental voltage gain

$$G_V = \frac{\Delta V_{out}}{\Delta V_{in}} = \frac{-\Delta I_C R_C}{\Delta I_B R_B} = -\beta \frac{R_C}{R_B}$$

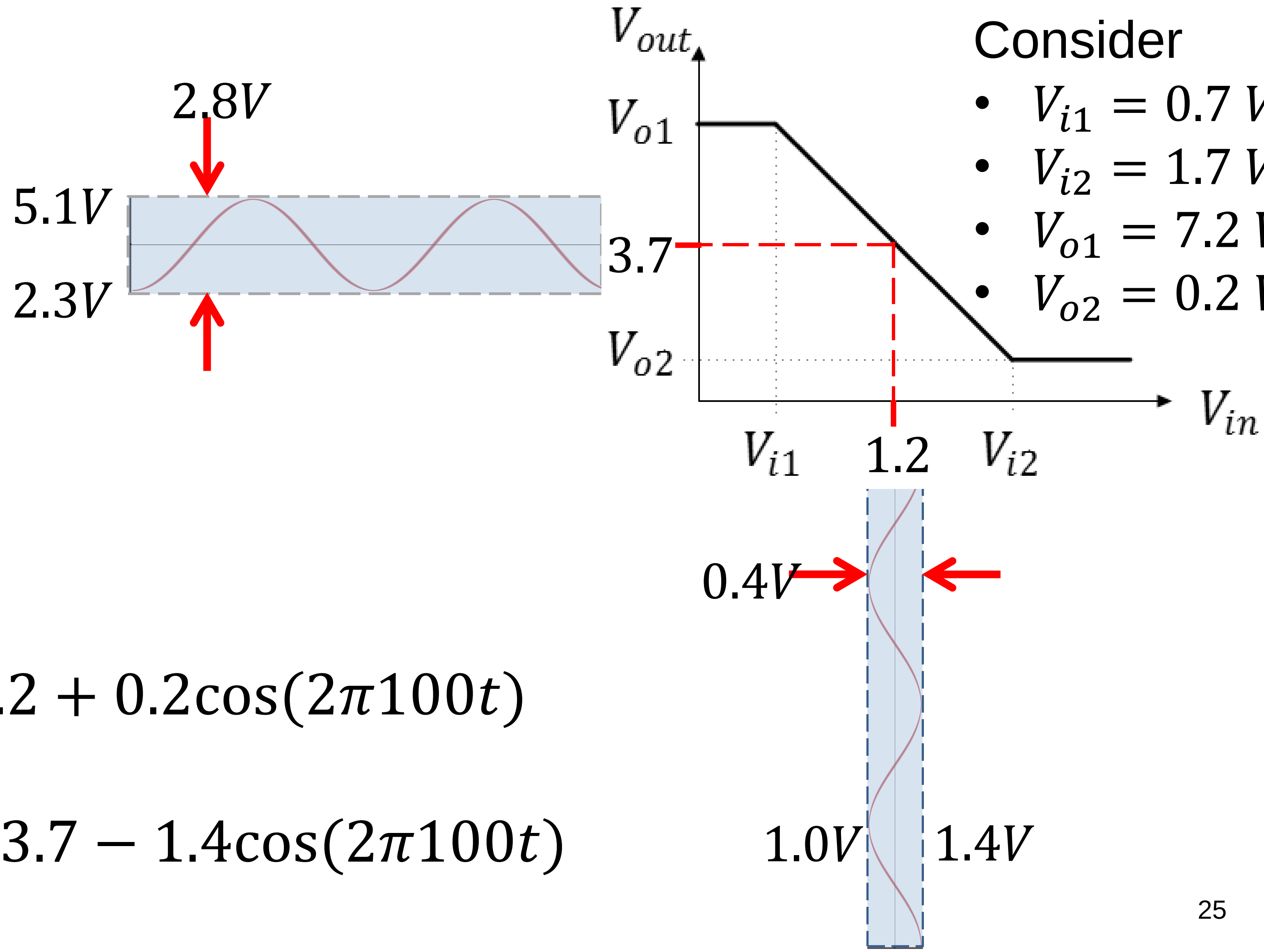
Summary of n-p-n BJT regimes







Amplification Example



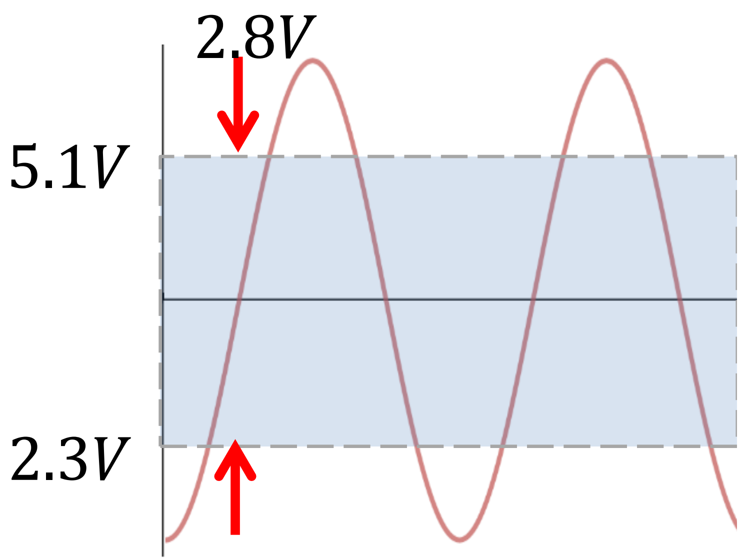
Consider

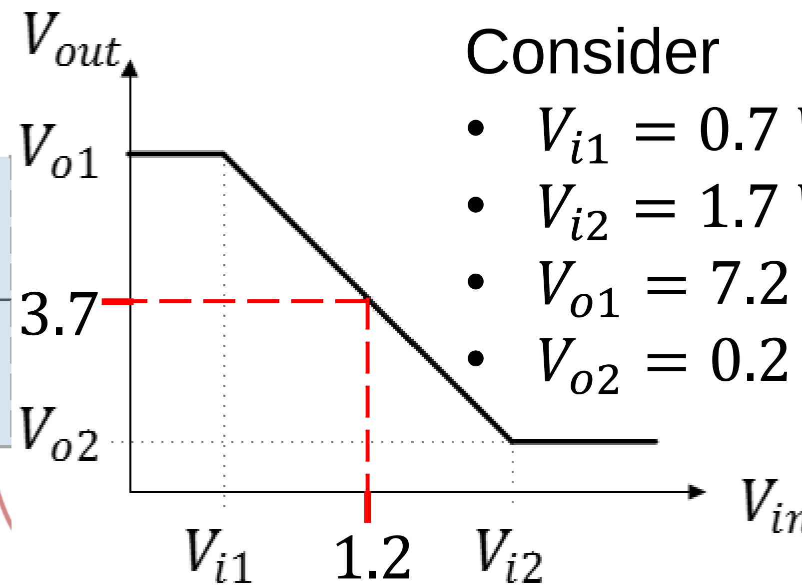
- $V_{i1} = 0.7\ V$
- $V_{i2} = 1.7\ V$
- $V_{o1} = 7.2\ V$
- $V_{o2} = 0.2\ V$

$$V_{IN} = 1.2 + 0.2\cos(2\pi 100t)$$

$$V_{OUT} = 3.7 - 1.4\cos(2\pi 100t)$$

Example





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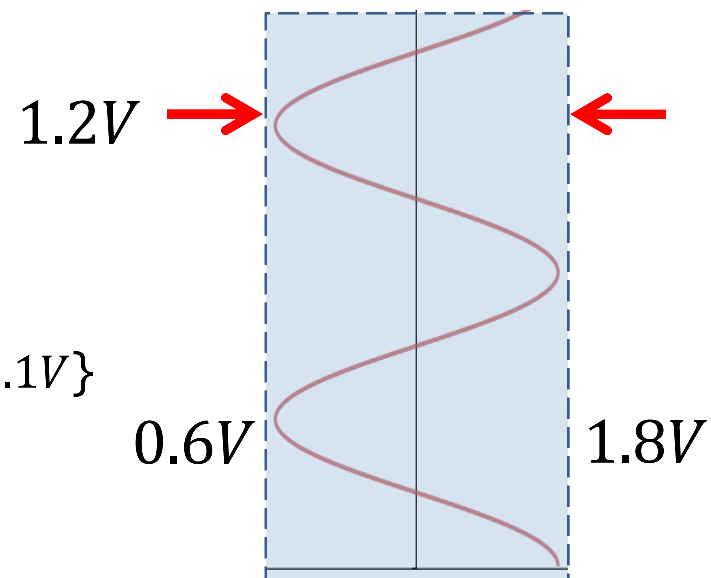


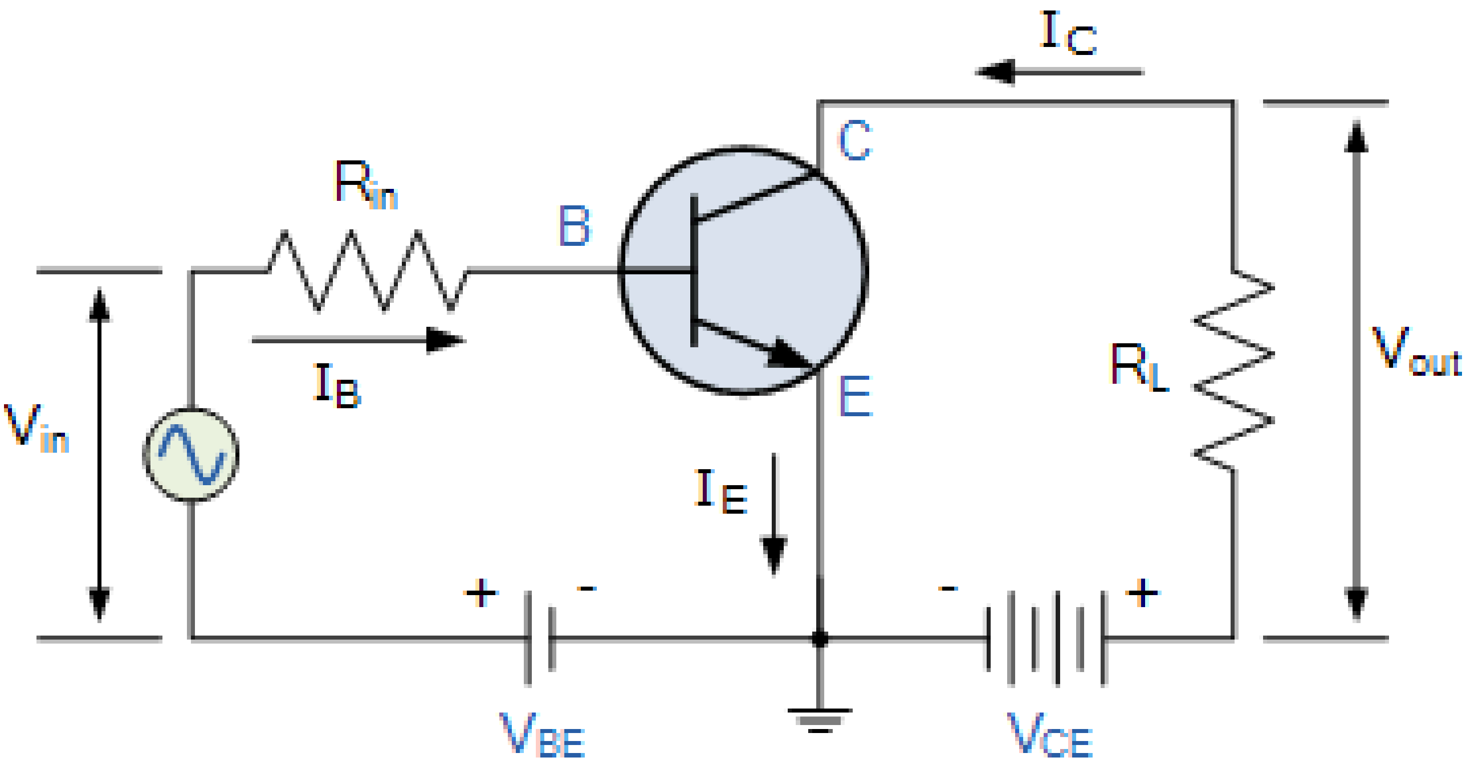
$$V_{IN} = 1.2 + 0.6\cos(2\pi 100t)$$

$V_{OUT} = 2.3$ $\{V_{in} \leq 0.7V\}$

$V_{OUT} = 3.7 - 4.2\cos(2\pi 100t)$ $\{2.3 \geq V_{out} \leq 5.1V\}$

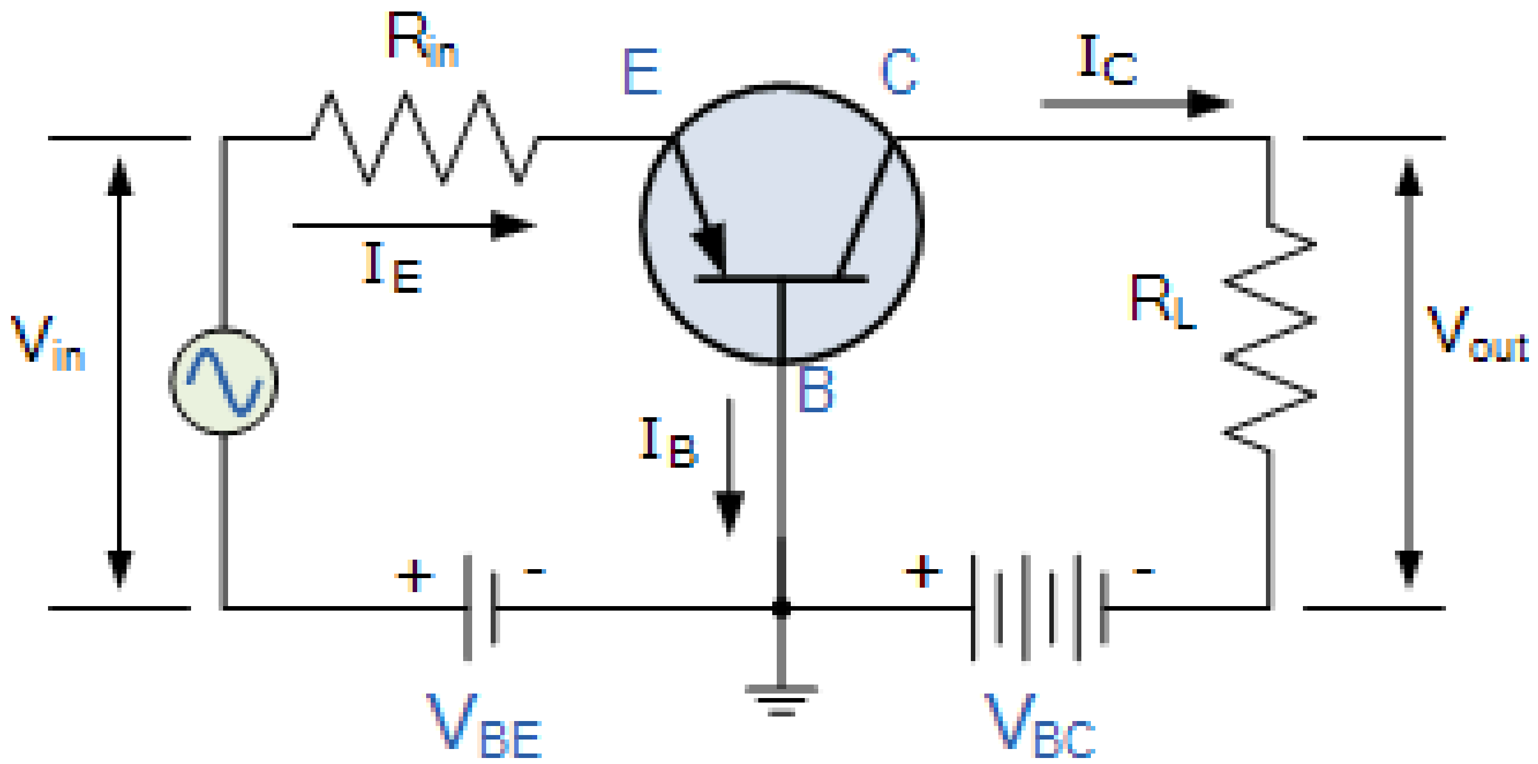
$V_{OUT} = 5.1V$ $\{V_{in} \geq 1.7V\}$

Transistor circuit configurations



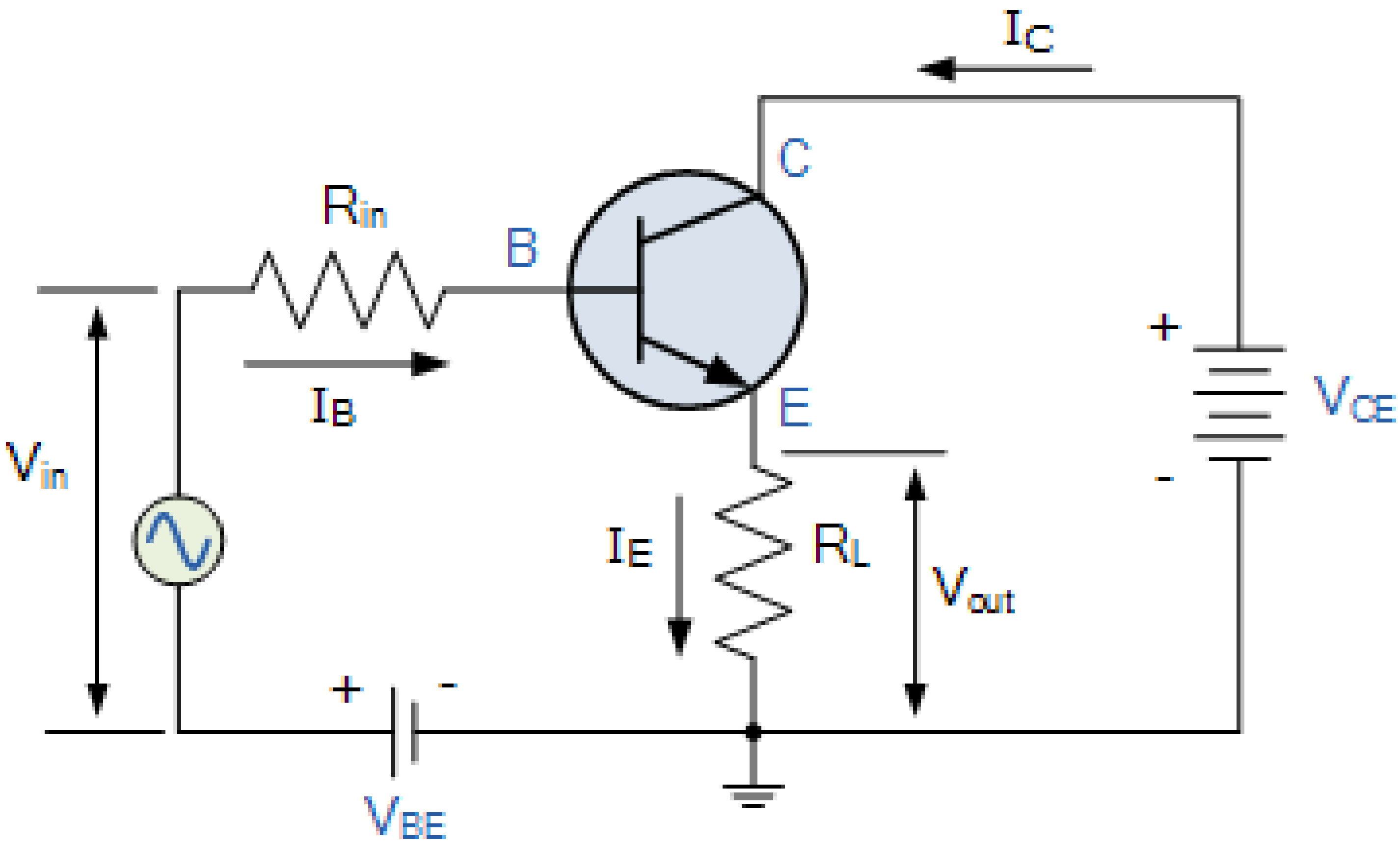
Common Emitter
- **Current gain**
- **Voltage gain**

Transistor circuit configurations



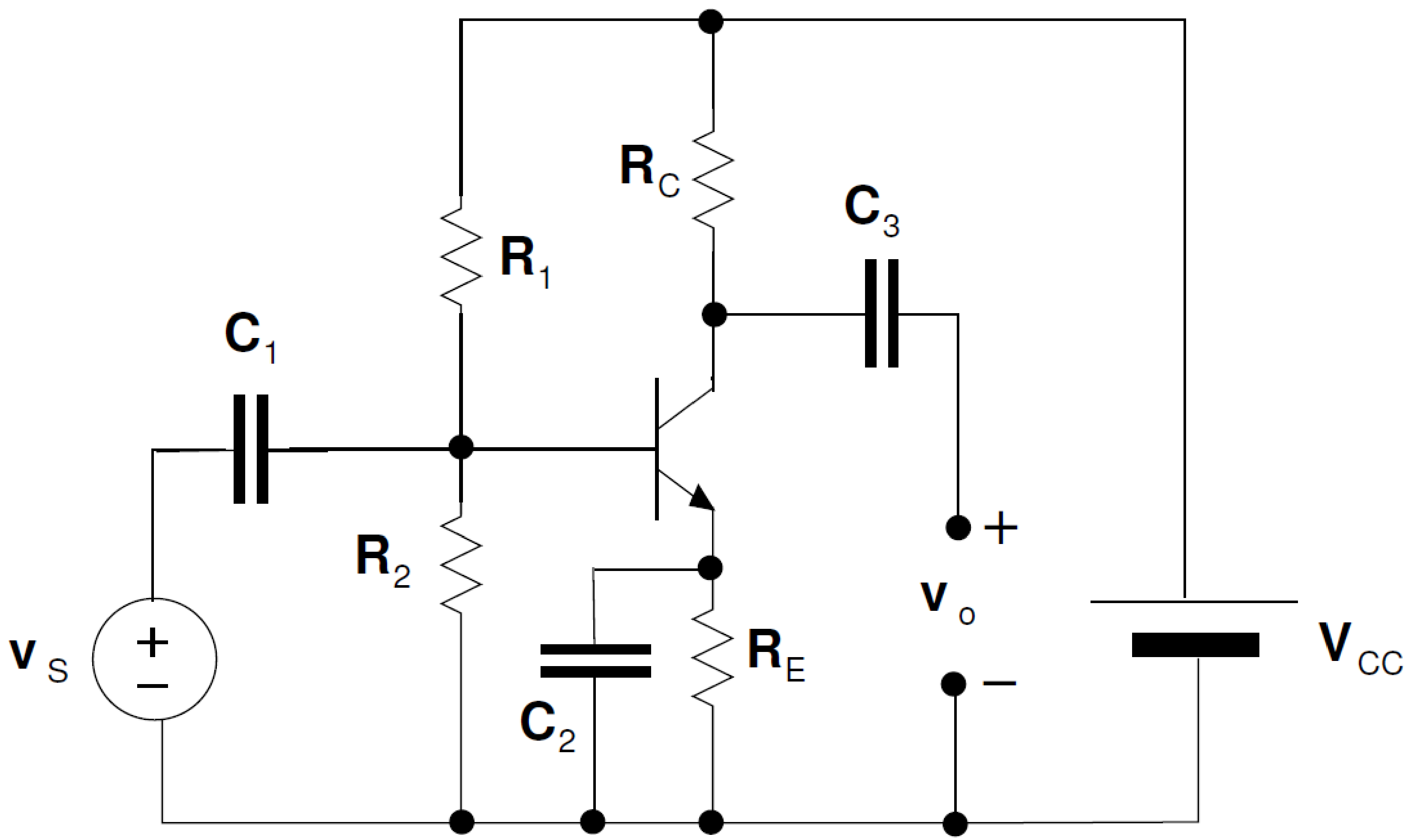
Common Base
- Voltage gain

Transistor circuit configurations



Common Collector
- Current gain

Common Emitter Amplifier Stage



Small signals equivalent circuit