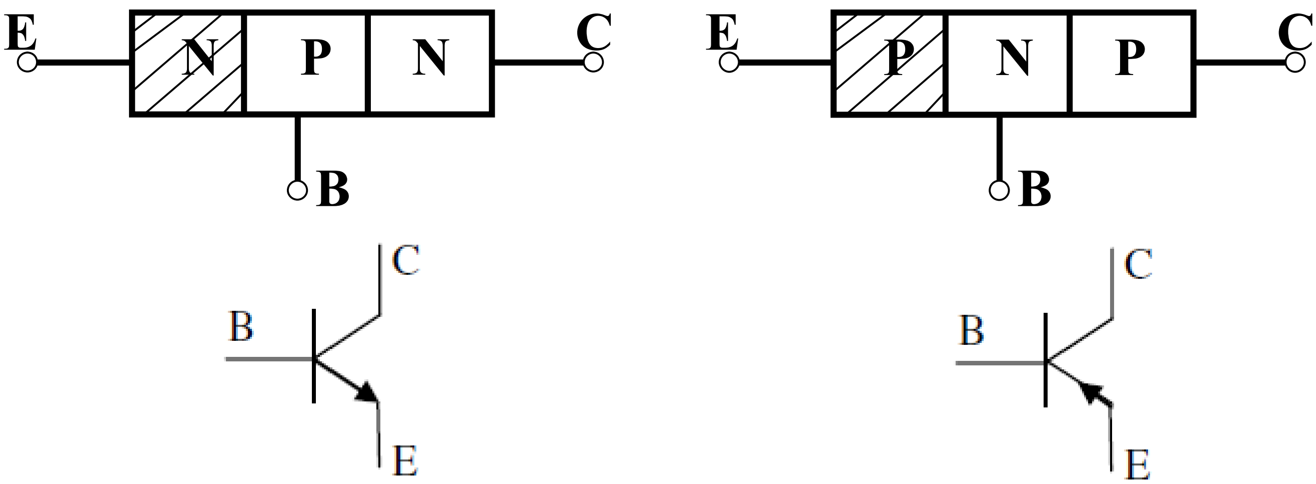
Chapter 4: The Bipolar Transistor

1- Introduction

In electronics, electrical engineering, and control systems, active components are commonly used to perform specific functions such as amplification or switching, and the transistor serves this purpose. The bipolar transistor is a fundamental component of modern electronics, it is built on the basis of two junctions (**PN**) which give it electrical characteristics slightly more complex than those of a diode. It is from these characteristics that we can examine the electrical behavior of the transistor.

A bipolar transistor is formed from a silicon crystal containing three distinct doping regions. Depending on the configuration, transistors are classified as **NPN** or **PNP**.

The three layers (regions) constitute three regions called, in order, **Emitter (E), Base (B),** and **Collector (C).** These consist of two PN junctions sharing a central region called the base.



Transistor NPN **Transistor PNP**

NPN transistors in which a thin layer of type **P** is between two regions of type **N**

PNP transistors in which a thin layer of type **N** is between two regions of type **P**

Figure 1. bipolar Transistor

The structure of a transistor is not symmetrical. Indeed, the region corresponding to the emitter has a higher doping level than the one corresponding to the collector. Therefore, emitter and collector cannot be interchanged in a transistor circuit.

2- Operation of the Transistor

The study will be conducted on an NPN bipolar transistor, which is the most commonly used and easiest to implement. The operation of a PNP type transistor is deduced by exchanging the roles of electrons and holes, as well as reversing the signs of the supply voltages and currents.

2.1 NPN Structure

Let's consider two PN junctions sharing a central region of p-type semiconductor. Figure 2 depicts the cross-section of this structure. Two space-charge regions are formed at the emitter-base ***EB*** and base-collector ***BC*** junctions. The diagram illustrating the distribution of charges and potentials at these two junctions is provided in Figure 2.

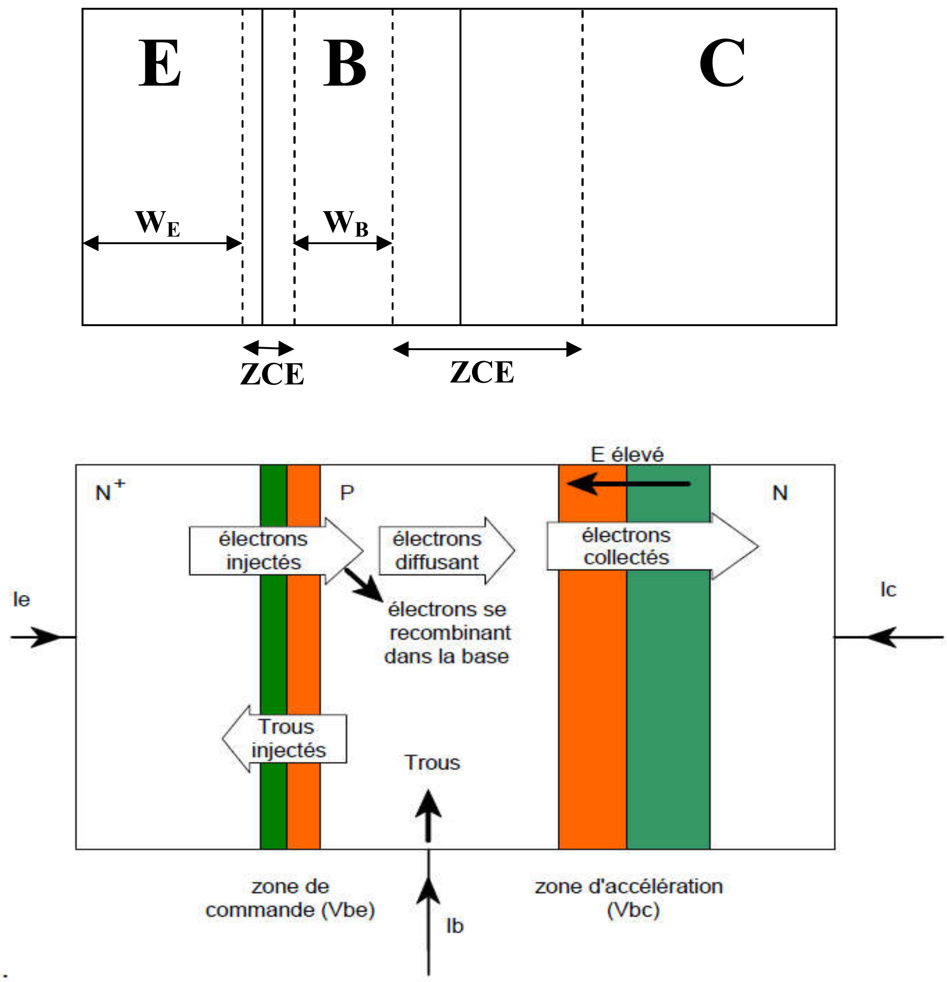


Figure 2. NPN structure of a bipolar transistor

We define the effective thickness of a region as its technological thickness reduced by the thicknesses of the space-charge regions if applicable.

2.2 Conduction mechanism in an NPN Structure

Among the various ways to bias an NPN transistor, only one is of primary interest. If we bias the emitter-base junction forward ($V_{BE} > 0$) and the collector-base junction reverse ($V_{BC} < 0$), we obtain the configuration shown in Figure 3.

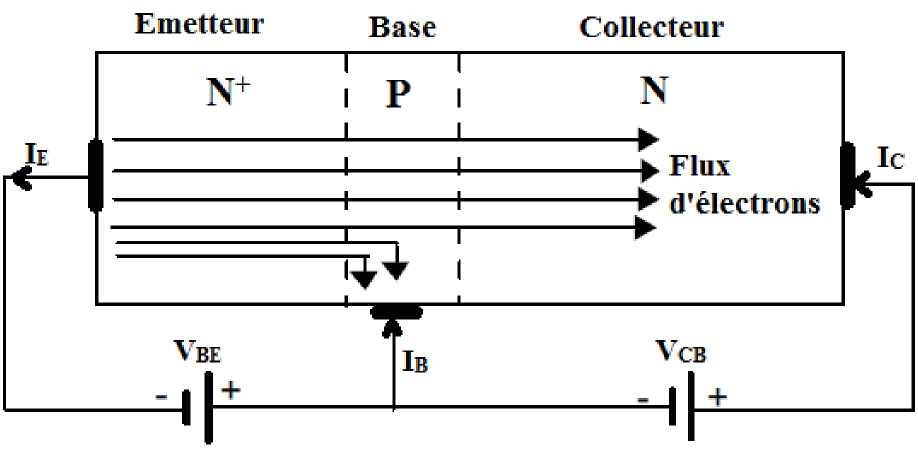


Figure 3. Forward bias and principle of the transistor effect.

Under these conditions, due to the forward bias V_{BE}, the emitter injects electrons into the base. These electrons diffuse perpendicular to the junction, and if the base is thin enough so that recombination is negligible, they reach the boundary of the Depletion Zone of the collector-base junction biased in reverse. There they are captured by the intense electric field, which favors the passage of minority carriers. They are then swept towards the collector, which is an N region, where they become majority carriers again. Figure 4 schematically illustrates the movement of carriers in an NPN structure and the direction of currents.

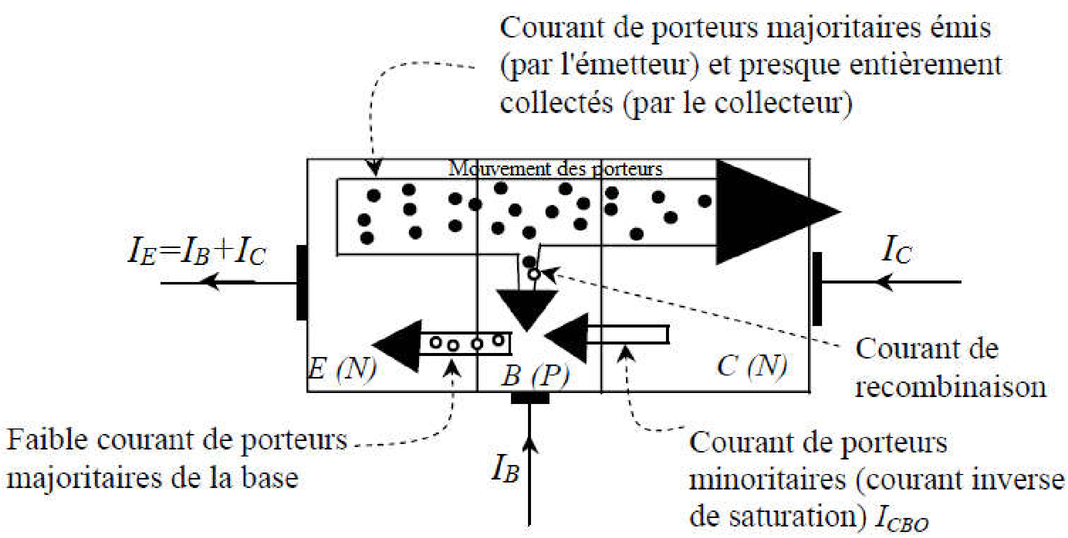


Figure 4. Current balance for a real transistor

The total collector current is slightly less than the emitter current.

The transistor effect therefore consists of injecting carriers from a highly doped emitter towards a fairly thin base, where they become a minority and from where, thanks to the intense reverse field, they are collected towards the collector region. This type of transistor is called a **bipolar transistor** because conduction takes place with both types of carriers.

3- Current Gain of a Bipolar Transistor

3.1 The transistor considered as a quadripole

When the transistor is connected in a circuit, it is generally mounted as a quadripole. Therefore, the convention of signs of the quadripole is applied to it.

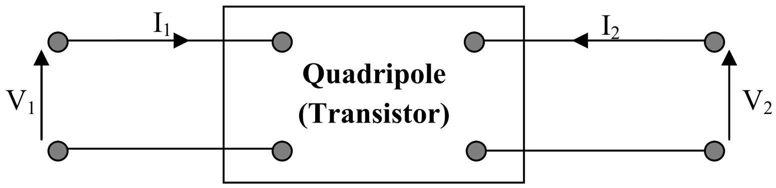


Fig. 5. Quadripole Representation

3.2 The various configurations of a bipolar transistor

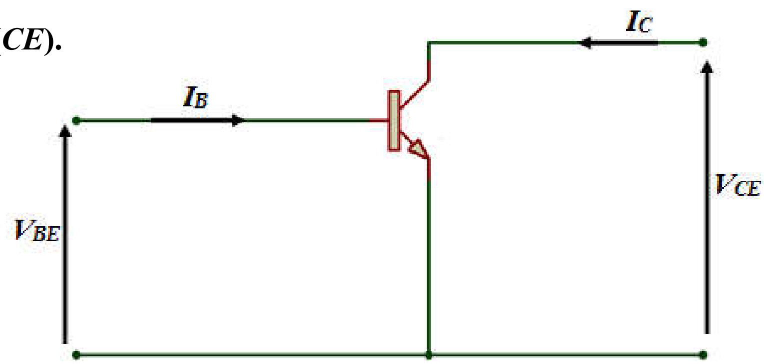
The static characteristics of bipolar transistors consist of the relationships between currents and voltages at the input and output of the transistor. Depending on the type of circuit used, the characteristics will differ for the same component. Since the transistor has three electrodes, one of them will be common to both the input and output. This results in three main configurations:

- Common emitter configuration (***CE***).
- Common base configuration(***CB***).
- Common collector configuration(***CC***).

Figure 6 depicts these three configurations, specifying the input and output voltages and currents.

3.2.1 The Common Emitter configuration (*CE*).

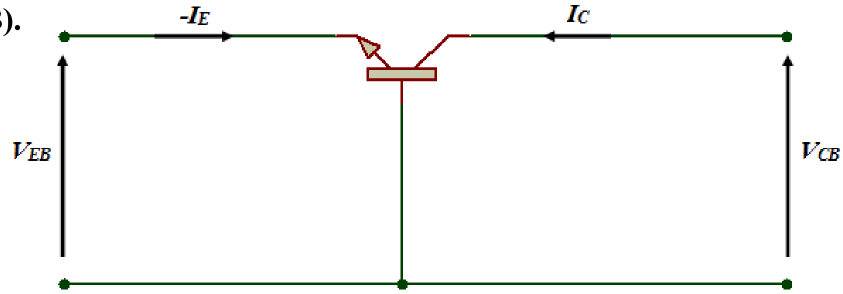
- Input current : I_B
- Output current : I_C
- Input voltage : V_{BE}
- Output voltage : V_{CE}



CE Configuration

3.2.2 The Common Base configuration (CB).

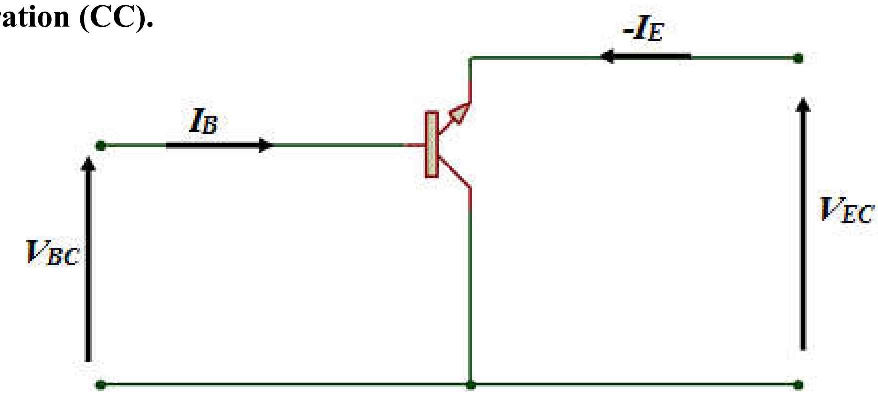
- Input current : $-I_E$
- Output current : I_C
- Input voltage : V_{EB}
- Output voltage : V_{CB}



CB Configuration

3.2.3 The Common Collector configuration (CC).

- Input current : I_B
- Output current : $-I_E$
- Input voltage : V_{BC}
- Output voltage : V_{EC}



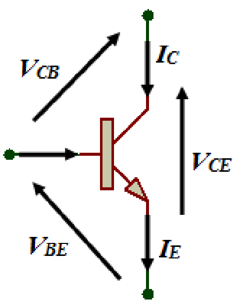
CC Configuration

Figure 6. Different types of transistor configurations

Table 1 shows a summary of the voltages and currents of the different types of transistor configurations.

Parameters	CE Configuration	CB Configuration	CC Configuration
Input terminal	base	emetter	base
Output terminal	collector	collector	emetter
Input current	I_B	I_E	I_B
Output current	I_C	I_C	I_E
Input voltage	V_{BE}	V_{EB}	V_{BC}
Output voltage	V_{CE}	V_{CB}	V_{EC}

Tableau 1 Summary of the voltages and currents of the different types of transistor configurations.



$$I_E = I_B + I_C$$

$$V_{CE} = V_{CB} + V_{BE}$$

Knowing that the transistor effect is to carry a high current from the collector based on a low base current ($I_C >> I_B$), we define the static current gain. $\beta = \frac{I_C}{I_B} \Rightarrow I_C = \beta I_B$

3.3 Fundamental relationships for bipolar transistor

3.2.1 Common-base configuration (current gain in common base)

According to the common-base configuration in Figure 6, we have:

$I_E = I_B + I_C$

$I_C = \alpha I_E + I_{CB0}$

Where I_{CB0} is the reverse saturation current of the Base-Collector junction (also known as the emitter open-circuit leakage current $I_E=0$). In practice, I_{CB0} is a very small constant. As a first approximation, $I_C = \alpha I_E$ with $0.98 < \alpha < 0.99$.

The coefficient $\alpha = I_C/I_E$ is called **the common-base current gain**.

3.2.2 Common-emitter configuration (current gain in common emitter).

In practice, the most commonly used configuration is the common-emitter configuration shown in Figure 6 (notably, the emitter is common to both input and output). According to the common-emitter configuration in Figure 6, we have:

$I_E = I_B + I_C$

$I_C = \beta I_B + I_{CE0}$

Where I_{CE0} is the open base leakage current $I_B=0$.

We have : $\beta = \frac{\alpha}{1-\alpha}$ and $I_{CE0} = (\beta + 1) I_{CB0}$

Since the coefficient α is close to the unit, the coefficient β is in practice between 20 and 900.

Dans la pratique, le courant I_{CE0} est faible et I_C est proportionnel à I_B pour V_{CE}=*constante :*

In practice, the I_{CE0} current is low, and IC is proportional to I_B for V_{CE}=*constant* :

The coefficient $\beta = \frac{I_C}{I_B} \Rightarrow I_C = \beta I_B$ is called **the common-emitter current gain.**

4- Bipolar transistor in circuits

The transistor has two main functions:

- Signal amplification in analog circuits.
- Switching in logic circuits.

4.1 Criterion for choosing a transistor

To choose a transistor for a particular application domain, we primarily consider the following parameters:

- **Breakdown voltage (V_{CEmax}):** Beyond this voltage, the collector current I_C increases rapidly, which can lead to transistor destruction.
- **Maximum collector current (I_{Cmax}):** Exceeding this current is not destructive, but it causes a significant drop in the current gain β, making the transistor less desirable.
- **Maximum power dissipation of the transistor:** $P_{max}=V_{CE}.I_C$. This represents the maximum power the transistor can dissipate without damage.
- **Current gain (β):** Indicates the amplification of current relative to the base current. Higher β may be preferable in certain applications.
- **Saturation voltage (V_{CEsat}):** If the transistor is used in switching applications, saturation voltage is important as it influences power loss and transistor efficiency.
- **Cutoff frequency:** For high-frequency applications, the transistor's cutoff frequency is a crucial parameter to consider.

By considering these parameters, one can select the most suitable transistor for a specific application domain.

4.2 Amplification principle

4.2.1 Static characteristic network

The characteristics are curves that represent the relationships between the currents and voltages of the transistor. They allow delimiting the operating regions of the transistor, determining the optimal operating point, and the hybrid parameters of the transistor.

In principle, four types of characteristic networks can be defined (Figure 7):

- The input characteristics network $I_B(V_{BE})$ **at** V_{CE} **= Cte**;
- The direct transfer characteristics network: $I_C(I_B)$ **at** V_{CE} **= Cte**;
- The output characteristics network: $I_C(I_B)$ **at** V_{CE} **= Cte**;
- The inverse transfer characteristics network: $I_C(I_B)$ **at** V_{CE} **= Cte**.

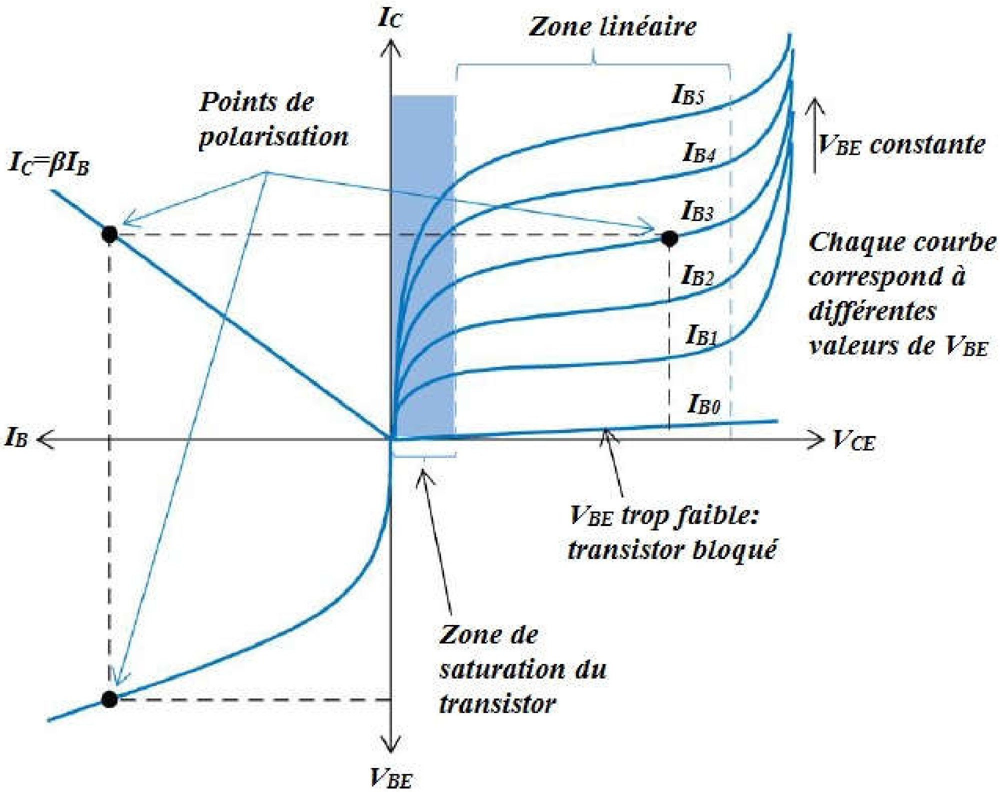


Figure 7. Bipolar transistor characteristic network

4.2.2 Bipolar transistor biasing

Biasing a transistor involves setting a set of values that characterize its operating state. This entails determining the values of the bias voltages V_{BE} and V_{CE}, as well as the base current I_B and the emitter or collector current.

Since the transistor is a three-terminal device, to apply the results observed on quadripoles, one must choose one of the poles common to both the input and output. The most commonly used configuration is the « common emitter » configuration.

Biasing a transistor thus involves inserting this quadripole between an input network, which sets the values of V_{BE} and I_B, and an output network that sets the values of V_{CE} and I_C.

Consider the circuit of Figure 8. At the input we have:

$V_{BB}=R_BI_B+V_{BE}$

At the output we have:

$V_{CC}=R_CI_C+V_{CE}$

If we fix an operating point Q defined by: $Q(I_B,I_C,V_{BE},V_{CE})$, we can set the values of the biasing resistors R_B and R_C.

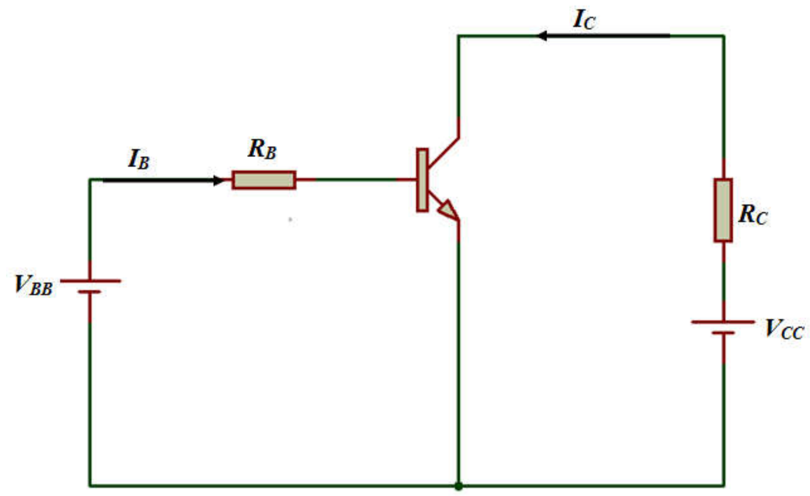


Figure 8. Common emitter configuration

4.2.3 Load line

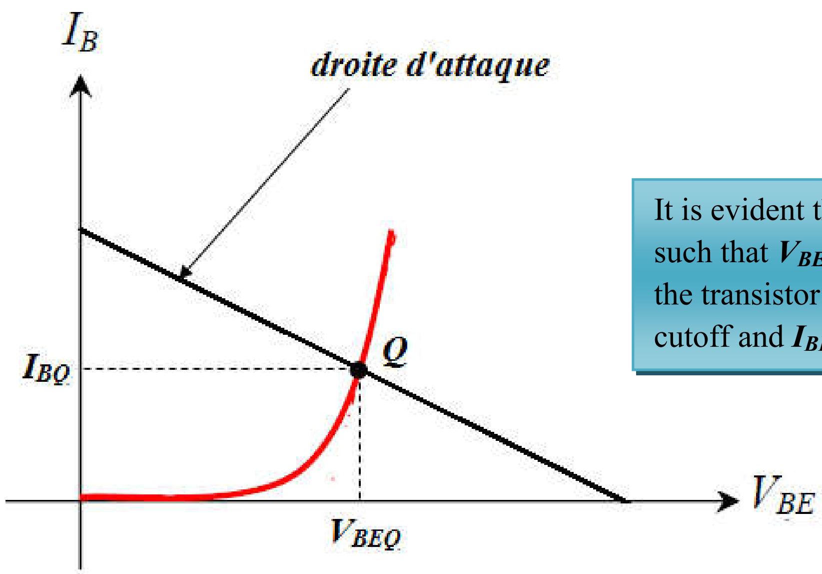
a. Static drive line (droite d'attaque statique) :

It's the equation of a line called the drive line. This line is represented on the transistor's base characteristic. The values of V_{BE} and I_B must satisfy both the transistor's operating equation and the input network's equation. They will be determined by the intersection between the static drive line and the transistor's base characteristic, as shown in Figure 9. The equation of the transistor's static drive line is given by:

$V_{BB}=R_BI_B+V_{BE}$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{V_{BB}}{R_B} - \frac{V_{BE}}{R_B}$$

It's a line with a slope equal to $\frac{1}{R_B}$, figure 9



It is evident that if point Q is such that $V_{BEQ} < 0.6V$, then the transistor will be in cutoff and $I_{BEQ} = 0$.

Figure 9. Drive line

b. Static load line:

The mesh equation of the output circuit gives us: $V_{CC} = V_{CE} + R_C I_C$. The line representing this equation is called the ***static load line***. The intersection of this line with the collector characteristic of the transistor provides the values of V_{CE} and I_C, as shown in Figure 10. The chosen collector characteristic corresponds to the base current I_{B0} determined by the static drive line.

Alors:

$V_{BB}=R_B I_B+V_{BE}$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{V_{CC}}{R_C} - \frac{V_{CE}}{R_C}$$

It's a line with a slope equal to $\frac{1}{R_C}$, figure 10

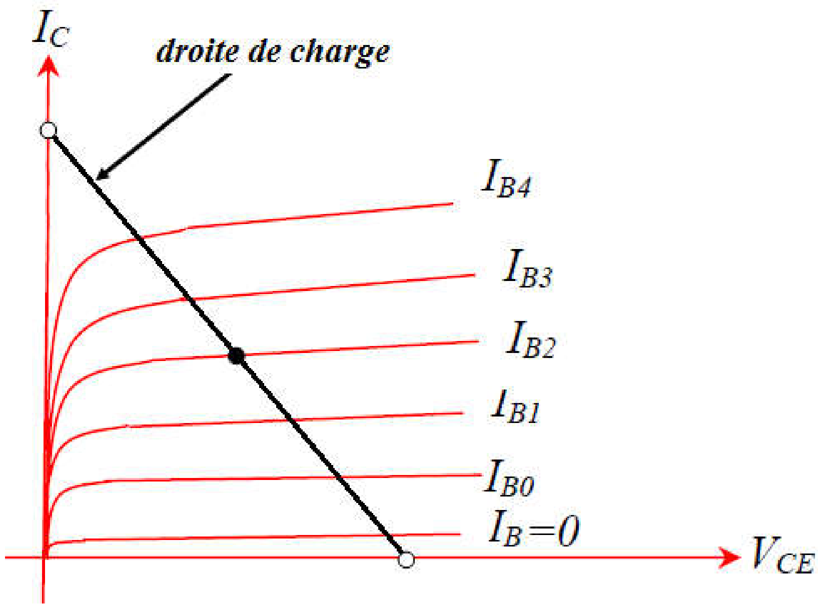


Figure 10. Load line

4.2.4 Amplification

Let's apply a variable signal to the input of the circuit in Figure 8. This voltage will be superimposed on the DC voltage.

Notations :

Continuous quantities will be denoted by uppercase letters with uppercase indices (example: V_{CE}), alternating quantities by lowercase letters with lowercase indices (example: v_{ce}), and the variable quantity will be their sum denoted by lowercase letters with uppercase indices (example: $v_{CE} = V_{CE} + v_{ce}$).

On the load line, the quiescent point Q can vary between points A and B, as shown in Figure 11.

- Point ***A*** corresponds to i_{CMAX} and is the **saturation** point.

$$I_{Csat} = \frac{V_{CC}}{R_C} \;\; et \;\; V_{CEsat} = 0$$

- Point ***B*** corresponds to $\boldsymbol{v_{CE}} = \boldsymbol{V_{CC}}$ and $\boldsymbol{i_C = 0}$, which is the **cutoff** point.

$$I_{CBLO} = 0 \;\; et \;\; V_{CEBLO} = V_{CC}$$

The variable output current and voltage vary around point Q (Figure 11). To allow them to vary over a wide range, the operating point should preferably be placed in the middle of the load line.

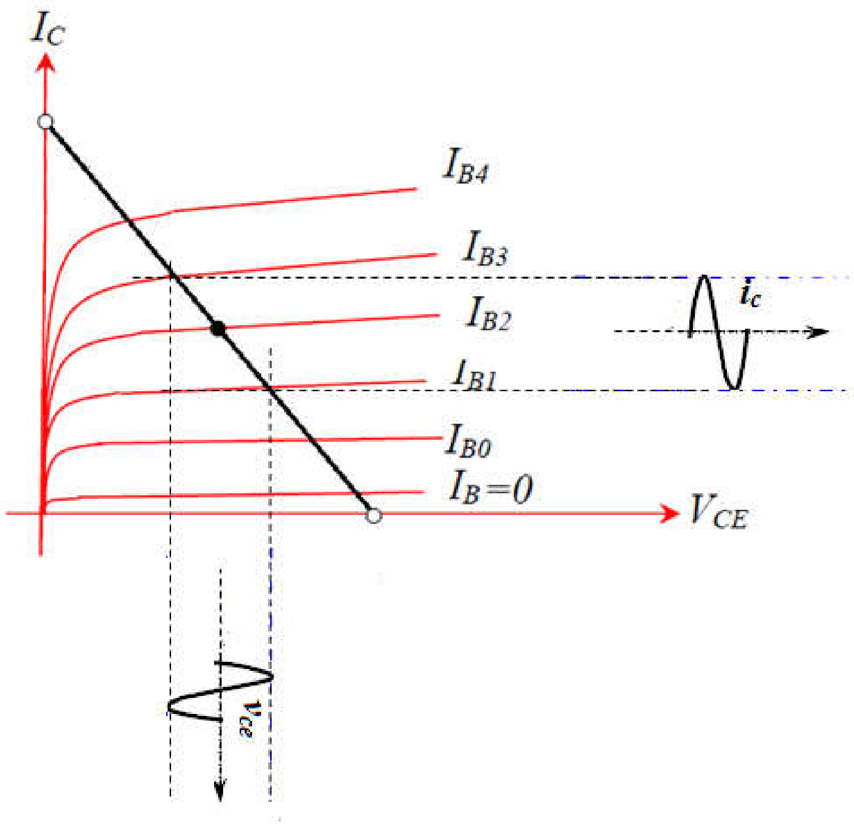


Figure 11. variable output current and voltage around point Q

4.2.4.1 Amplification phenomenon

At the input, there is a low $\boldsymbol{i_B}$ and $\boldsymbol{v_{BE}}$.

At the output, there is a high $\boldsymbol{i_C}$ and large $\boldsymbol{v_{CE}}$.

Therefore, we have a power gain.: $A_P = \frac{v_{CE}\, i_C}{v_{BE}\, i_B}$

4.2.5 Biasing Methods and Stability Factor

We have seen that the collector current is in the form::

$\boldsymbol{I_C = \beta I_B + I_{CE0}}$

$$I_C = \beta I_B + \frac{I_{CB0}}{1 - \alpha}$$

$\boldsymbol{I_{CB0}}$: Leakage current, it is highly sensitive to temperature variations. It doubles every 6°C for a silicon diode. Therefore, any temperature variation results in a change in $\boldsymbol{I_{CB0}}$, which implies a change in the $\boldsymbol{I_C}$ current.

We define a stability factor S:

$$S = \frac{\Delta I_C}{\Delta I_{CB0}}$$

For a circuit to be stable in temperature, the stability factor S must be close to 1.

4.2.5.1 Biasing by imposed base current

An example of a circuit biased by a fixed base current is given in Figure 12. The study of this circuit shows that the base current is given by the following relationship:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

Si $V_{BB} \gg V_{BE}$ alors $I_B = \frac{V_{BB}}{R_B}$

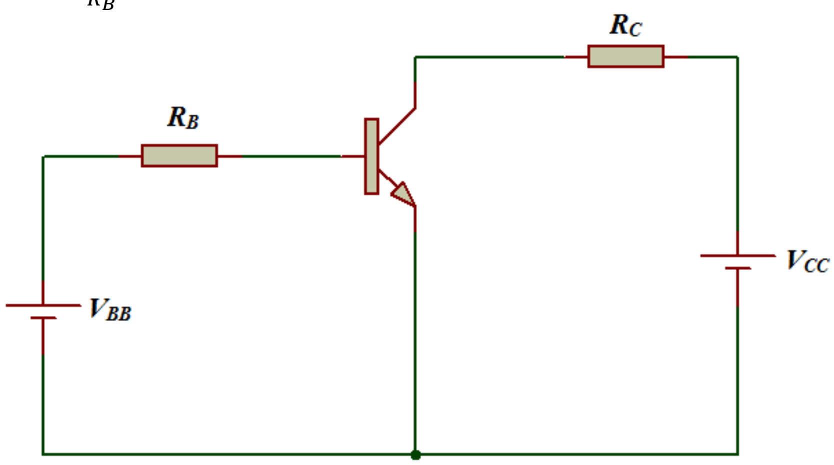


Figure 12. Biasing by imposed base current

Regarding the stability factor, given that:

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CB0}}{1-\alpha}$$

The stability factor accounts for the leakage current in a common emitter configuration..

The calculation of the base current yields:

$$I_B = \frac{1-\alpha}{\alpha} I_C - \frac{I_{CB0}}{\alpha}$$

For our circuit, we have:

$$V_{BB} = R_B I_B + V_{BE}$$

$$V_{BB} = R_{BB}\left[\frac{1-\alpha}{\alpha}I_C - \frac{\Delta I_{CB0}}{\alpha}\right]$$

By differentiating this equation, we find:

$$\Delta V_{BB} = 0 = \frac{1-\alpha}{\alpha}I_C - \frac{\Delta I_{CB0}}{\alpha}$$

Then, the stability factor S is:

$$S = \frac{\Delta I_C}{\Delta I_{CB0}} = \frac{1}{1-\alpha}$$

However,:

$$\beta = \frac{\alpha}{1-\alpha} \Rightarrow \frac{1}{1-\alpha} = \beta + 1$$

So the stability factor is:

$S = \beta + 1$

The value of β, the static gain in a common emitter configuration, is relatively high. Therefore, this configuration gives poor temperature stability.

4.2.5.2 Biasing by collector feedback

In this type of biasing circuit (see Figure 13), a resistor connects the base to the collector. Based on this circuit, we can write:

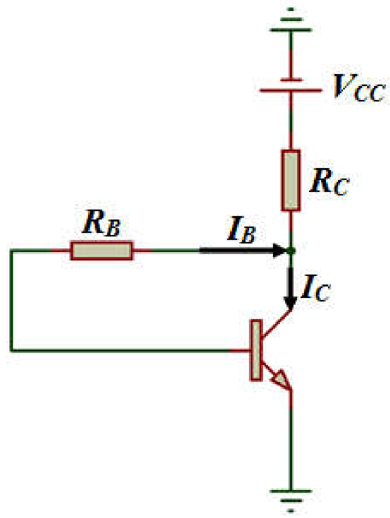


Figure 13. Biasing by collector feedback

$$V_{CC} = R_C(I_B + I_C) + R_B I_B + V_{BE}$$

$$V_{CC} = R_C(I_B + I_C) + V_{CE}$$

$$I_B = \frac{1-\alpha}{\alpha}I_C - \frac{I_{CB0}}{\alpha}$$

Since:

$$V_{BB} \ll V_{CC} \Rightarrow V_{CC} = R_C I_C + (R_B + R_C)I_B$$

$$V_{CC} = R_C I_C + (R_B + R_C)\left[\frac{1-\alpha}{\alpha} I_C - \frac{I_{CB0}}{\alpha}\right]$$

$$V_{CC} = \left[R_C + (R_B + R_C)\frac{1-\alpha}{\alpha}\right] I_C - (R_B + R_C)\frac{I_{CB0}}{\alpha}$$

$$\Delta V_{CC} = 0 = [\alpha R_C + (R_B + R_C)(1-\alpha)]\Delta I_C - (R_B + R_C)\Delta I_{CB0}$$

We deduce the stability factor:

$$S = \frac{\Delta I_C}{\Delta I_{CB0}} = \frac{1}{1 - \alpha \frac{R_B}{R_B + R_C}}$$

By comparing S to $\beta = \frac{\alpha}{1-\alpha}$, we can affirm that it is less than β but still greater than 1. Therefore, this type of biasing also gives poor temperature stability..

4.2.5.3 Biasing by resistor in series with the emitter

Consider the circuit of Figure 14, where the base biasing of the transistor is ensured by the bridge of resistors R_1 and R_2 and that of the collector by the resistors R_C in series with the collector and R_E in series with the emitter.

This circuit can be transformed using Thévenin's theorem, resulting in the following simplified diagram:

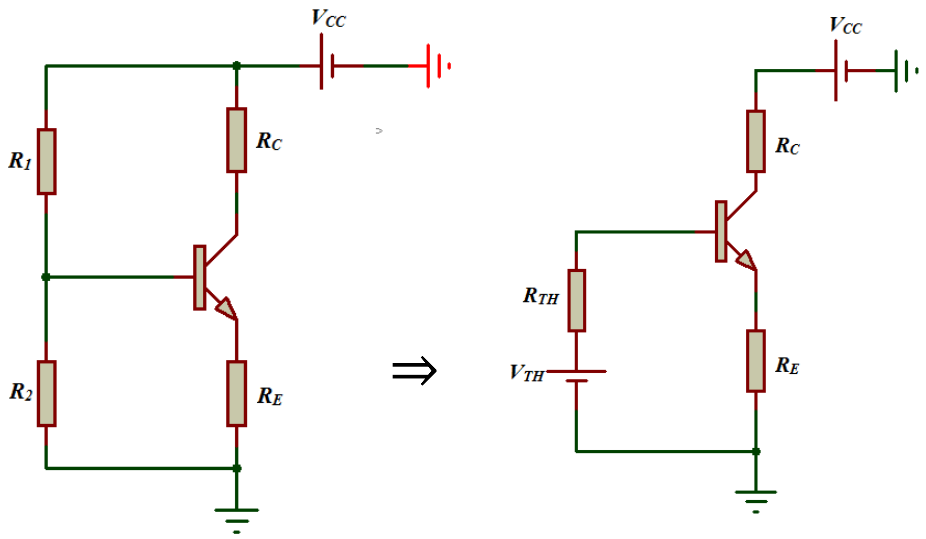


Figure 14. Biasing by resistor in series with the emitter

$$V_{CC} = R_C I_C + R_E I_E + V_{CE}$$

$$V_{TH} = R_{TH} I_B + R_E(I_C + I_B) + V_{BE}$$

This equation can be simplified if we take into account that $V_{BB} \ll V_{CC}$

$$V_{TH} = (R_{TH} + R_E) I_B + R_E I_C$$

Knowing that :

$$I_B = \frac{1-\alpha}{\alpha} I_C - \frac{I_{CB0}}{\alpha}$$

We obtain:

$$V_{TH} = (R_{TH} + R_E)\left[\frac{1-\alpha}{\alpha} I_C - \frac{I_{CB0}}{\alpha}\right] + R_E I_C$$

$$V_{TH} = (R_{TH} + R_E)\left[\frac{1-\alpha}{\alpha} I_C - \frac{I_{CB0}}{\alpha}\right] + R_E I_C$$

$$V_{TH} = \left[R_E + (R_{TH} + R_E)\frac{1-\alpha}{\alpha}\right] I_C - I_{CB0}\frac{R_{TH} + R_E}{\alpha}$$

After differentiation and simplification of this equation we obtain:

$$S = \frac{1 + \frac{R_{TH}}{R_E}}{1 + \frac{R_{TH}}{R_E}(1-\alpha)}$$

The stability factor tends toward 1 if the ratio $\frac{R_{TH}}{R_E}$ is low **,** $\boldsymbol{S\to 1}$.

Therefore, this circuit provides good temperature stability if the values of the biasing resistors are correctly chosen.

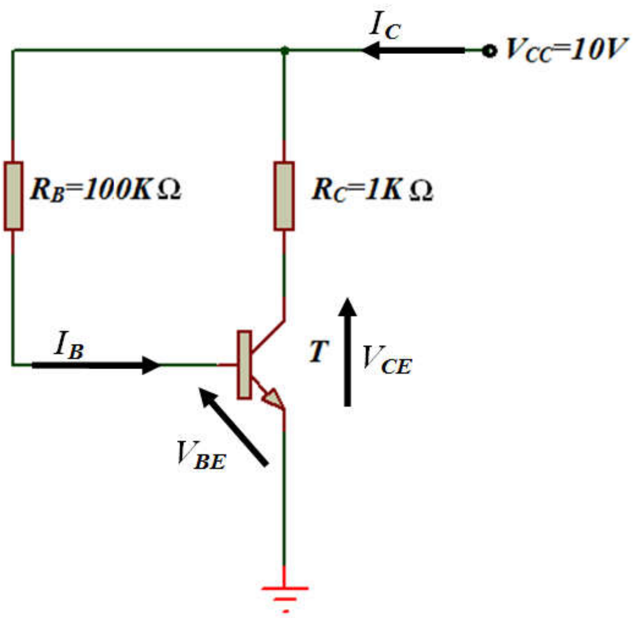
4.3 Examples of Biasing Circuit Calculations

Example 01

Consider the circuit below where:

T is a silicon transistor, with β=50, V_{BE}=0.6V

Find I_C and V_{CE}



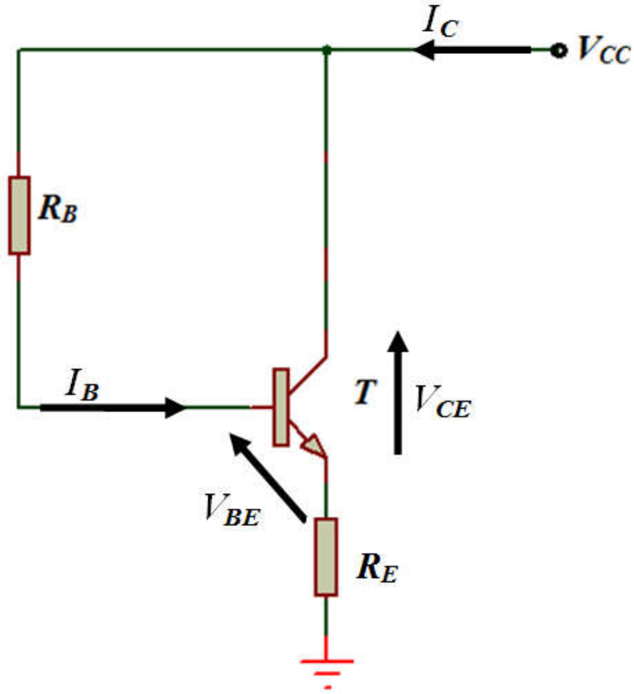
$V_{CC}=R_C I_C+V_{CE}$ **(1)**

$V_{CC}=R_B I_B+V_{BE}$ **(2)**

From (2) we have $I_B = \frac{V_{CC}-V_{BE}}{R_B} = \frac{10-0.6}{100.10^3} \Rightarrow I_B = 9.4\ 10^{-2}$

$I_C=\beta I_B=50\times 9.4\ 10^{-5}$ so $\boldsymbol{I_C=4.7mA}$

From (1) we have : $V_{CE}= V_{CC} - R_C I_C = 10-4.7$ so $\boldsymbol{V_{CE}=5.3V}$



Example 02

Consider the circuit opposite where:

V_{CE}=10V, V_{BE}=0.5V, I_C=5mA and β=100

Knowing that the operating point is in the middle of the load line, let's calculate V_{CC}, R_B and R_E

$V_{CE}=10V$, the operating point is in the middle of the load line, so $\boldsymbol{V_{CC}=2V_{CE}=20V}$

$V_{CC}=R_EI_E+V_{CE}$

$I_E=I_C+I_B \approx I_C$

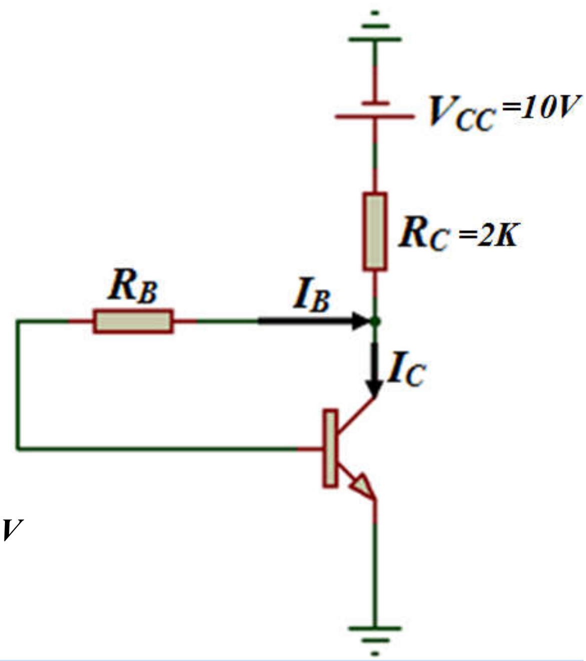
So $R_EI_E = V_{CC}-V_{CE} \Rightarrow R_EI_C = V_{CC}-V_{CE} \Rightarrow R_E = (V_{CC}-V_{CE})/ I_E =(20-10)/ (5\ 10^{-3})$

$\Rightarrow \boldsymbol{R_E = 2K\Omega}$

$I_C=\beta I_B \Rightarrow I_B= I_C/\beta= 5\ 10^{-3}/100 \Rightarrow I_B=5\ 10^{-5}=50\ \mu A$

$V_{CC}= R_BI_B + V_{BE} + R_EI_E \Rightarrow R_B=(V_{CC} - V_{BE} - R_EI_E)/ I_B \Rightarrow R_B=(20 – 0.5 – 2\ 10^3\times 5\ 10^{-3})/ 5\ 10^{-5}$

$R_B= 1.9\ 10^5 \Rightarrow \boldsymbol{R_B= 190\ K\Omega}$



Example 03

Consider the circuit opposite where:

V_{CC}=10V, V_{BE}=0.3V, β=50 and R_C=2KΩ

Knowing that the operating point is in the middle of the load line, let's calculate I_B, R_B, and the stability factor S.

The load line thus $V_{CC}=2V_{CE} \Rightarrow V_{CE} = V_{CC}/2=10/2 \Rightarrow \boldsymbol{V_{CE}=5V}$

$V_{CC}=R_CI_C+V_{CE}$

$I_E=I_C+I_B \approx I_C$

$I_C=(V_{CC}-V_{CE})/R_C=(10-5)/(2\ 10^{-3}) \Rightarrow \boldsymbol{I_C=2.5mA}$

$I_C=\beta I_B \Rightarrow I_B=I_C/\beta=2.5\ 10^{-3}/50 \Rightarrow \boldsymbol{I_B=5\ 10^{-4}=50\ \mu A}$

$V_{CC}=R_C I_C+R_B I_B+V_{BE} \Rightarrow R_B=(V_{CC}-R_C I_C-V_{BE})/I_B=R_B=(10-2\ 10^3\times 2.5\ 10^{-3}-0.3)/(50\ 10^{-6})$

$\Rightarrow \boldsymbol{R_B=94\ K\Omega}$

$$S=\frac{\Delta I_C}{\Delta I_{CB0}}=\frac{1}{1-\alpha\frac{R_B}{R_B+R_C}}$$

$$\beta=\frac{\alpha}{1-\alpha}\Rightarrow\alpha=\frac{\beta}{1+\beta}$$

$$S=\frac{1}{1-\frac{\beta}{1+\beta}\frac{R_B}{R_B+R_C}}$$

$$S=\frac{1}{1-\frac{50}{51}\frac{94\ 10^3}{94\ 10^3+2\ 10^3}}$$

So ***S=25***

4.4 The transistor in dynamic mode

In dynamic mode, at the input of the common emitter transistor circuit, the input and output quantities result from the superposition of continuous or static quantities (V_{BE}, I_B, I_C, and V_{CE}) and alternating quantities which are the effect of alternative sources.

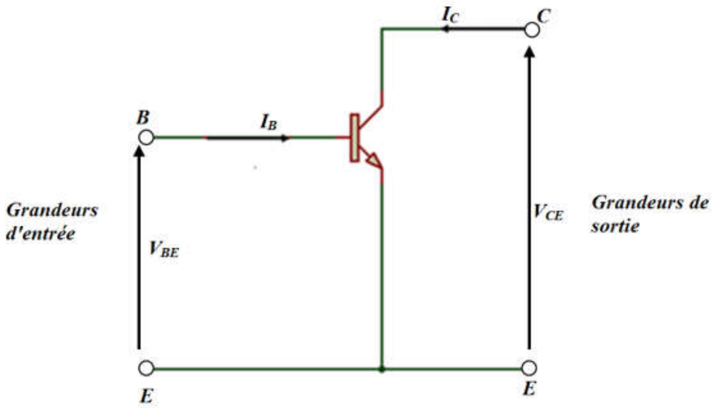


Figure 15. The transistor in static mode

Variable quantity = Continuous quantity + Alternative quantity

Examples : $v_{BE}=V_{BE}+v_{be}$

$i_C=I_C+i_c$

Let's apply an alternating voltage v_e in series with V_{BB} at the input. This variable voltage will produce a variation in the base current, which implies a variation in the collector current. Therefore, the currents in dynamic mode are:

Total base current: $i_B = I_B + i_b$

Total collector current: $i_C = I_C + i_c$

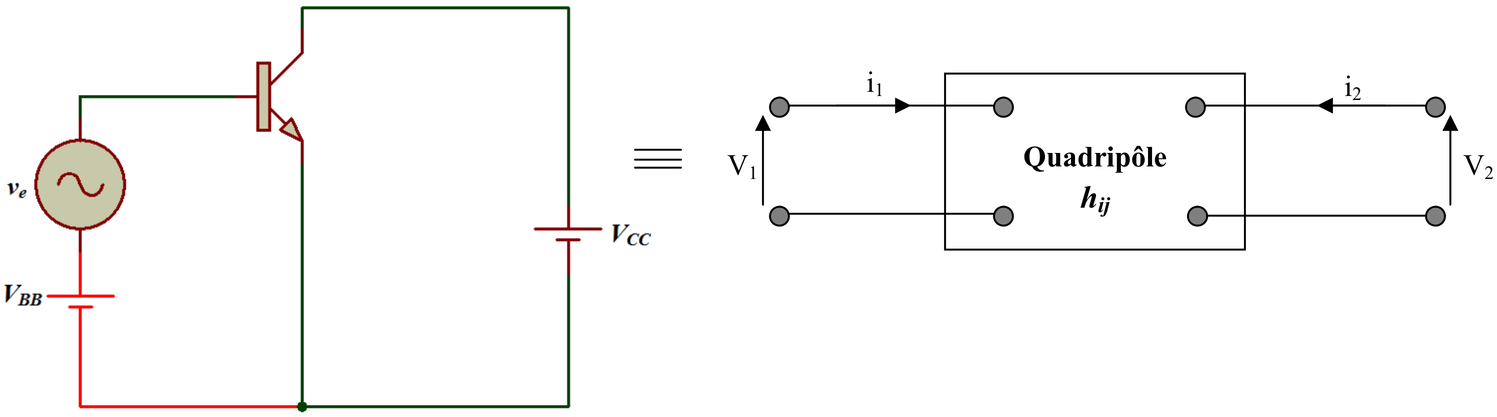


Figure 16. The transistor in dynamic mode

In general, the transistor is considered as a quadripole: it has two input terminals and two output terminals (one terminal of the transistor will therefore be common to both the input and the output). It is convenient to define the transistor's equivalent quadripole by its hybrid parameters "h" such as:

$$\begin{cases} v_1 = h_{11}i_1 + h_{12}v_2 \\ i_2 = h_{21}i_1 + h_{22}v_2 \end{cases} \equiv \begin{cases} v_{BE} = h_{11}i_B + h_{12}v_{CE} \\ i_C = h_{21}i_B + h_{22}v_{CE} \end{cases}$$

This corresponds to the following equivalent electrical scheme :

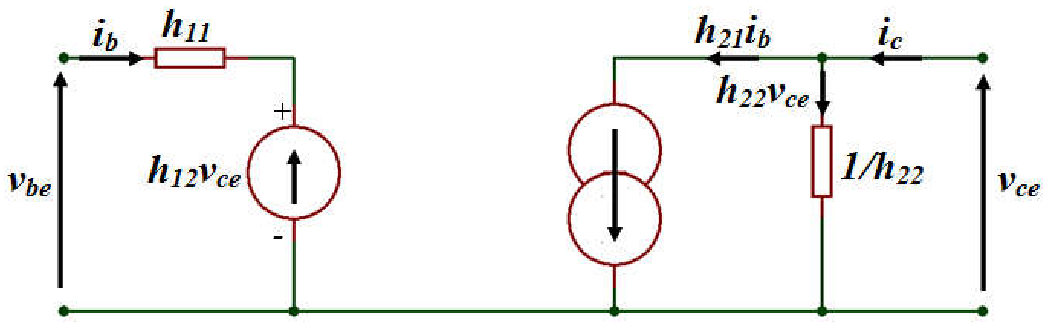


Figure 17. Equivalent circuit of the transistor in common emitter configuration in alternating current

4.4.1 Physical meaning of hybrid parameters

According to the system of equations of the hybrid parameters h_{ij}, we have:

$h_{11} = \frac{v_{be}}{i_b} = \frac{\Delta v_{BE}}{\Delta i_B}\Big|_{v_{CE}=0}$: h_{11} is none other than the dynamic resistance of the base-emitter junction (input impedance), the output being in short circuit. $v_{CE} = V_{CE} + v_{ce}$

$h_{12} = \frac{v_{be}}{v_{ce}} = \frac{\Delta v_{BE}}{\Delta v_{CE}}\Big|_{i_B=0}$: h_{12} is the inverse of the voltage gain (or feedback factor from output to input).

$h_{21} = \frac{i_c}{i_b} = \frac{\Delta i_C}{\Delta i_B}\Big|_{v_{CE}=0}$: h_{21} $=\beta$ It's the current gain of the transistor. The output is short-circuited for the alternating signal.

$h_{22} = \frac{i_c}{v_{ce}} = \frac{\Delta i_C}{\Delta v_{CE}}\Big|_{i_B=0}$: h_{22} It's the output admittance of the transistor with open input for the alternating signal. In practice, its value is low. Later on, we will pose $\rho = \frac{1}{h_{22}}$

Remark: We often have h_{12} very low, of the order of 10^{-4}

h_{22} very low, of the order of $10^{-5}\Omega$ (where ρ is very large).

The equivalent circuit is then reduced to:

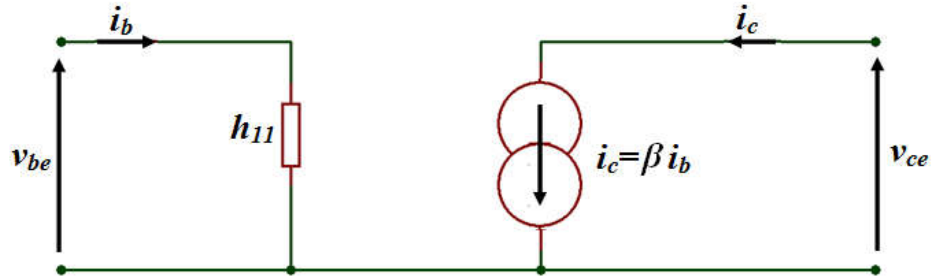


Figure 18. The reduced equivalent circuit of the transistor in common emitter configuration in alternating current

In an equivalent circuit in small-signal regime, only the variable components of the signals are considered. All constant potentials are equivalent to ground.

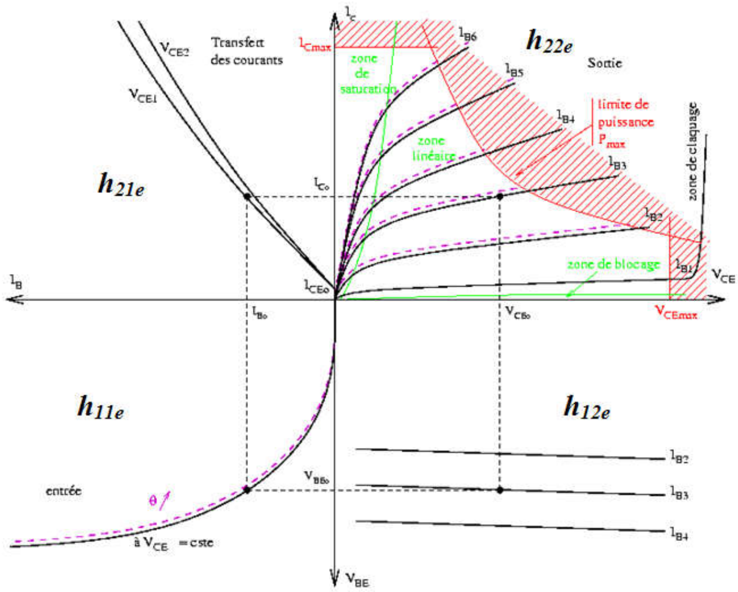


Figure 19. Bipolar transistor characteristic network in small-signal

4.4.2 Transistor Bipolar Amplifiers

The main function of a transistor is signal amplification at its input.

A transistor amplifier may consist of one or multiple stages, with the number of stages equal to the number of transistors present in the amplifier circuit. Figure 20 shows an example of a bipolar transistor amplifier circuit..

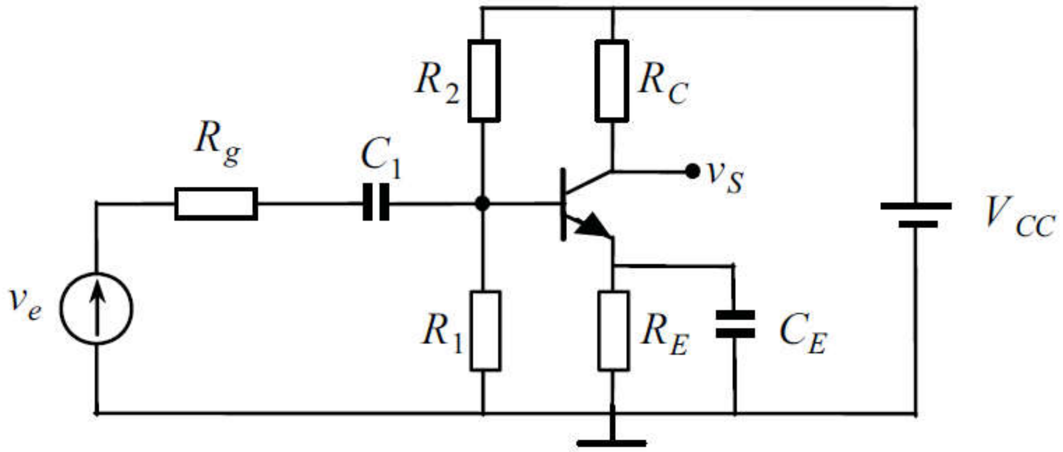


Figure 20. Transistor Bipolar Amplifiers

4.4.2.1 Coupling and Decoupling Capacitors

We have just seen that a transistor circuit comprises a direct current (DC) circuit and an alternating current (AC) circuit. Thanks to the capacitors, we can superimpose the alternating current circuit on the biasing circuit without the latter modifying the direct currents and voltages.

a. Coupling Capacitors

A coupling capacitor transmits (without attenuation) an alternating signal from a point that is not at ground to another point that is also not at ground; it must behave like a short circuit for alternating currents. Therefore, its capacitance should be calculated based on the lowest frequency to be transmitted. To calculate its capacitance, we must transform the circuit to which C_L is connected using Thévenin's theorem (see Figure 21).

In the equivalent circuit of Figure 21, $\boldsymbol{R_{TH}}$ represents the resistance of the circuit located before the capacitor location, and $\boldsymbol{R_L}$ represents the input resistance of the circuit placed after the capacitor. This circuit is equivalent to a low-pass filter, with the lower cutoff frequency $\boldsymbol{f_{cb}}$ given by the following relationship:

$$|Z_C| = \frac{1}{C\omega} = \frac{1}{2\pi f C} \Rightarrow f_{cb} = \frac{1}{2\pi(R_{TH} + R_L)C_L}$$

This gives the value of $\boldsymbol{C_L}$:

$$C_L = \frac{1}{2\pi f_{cb}(R_{TH} + R_L)}$$

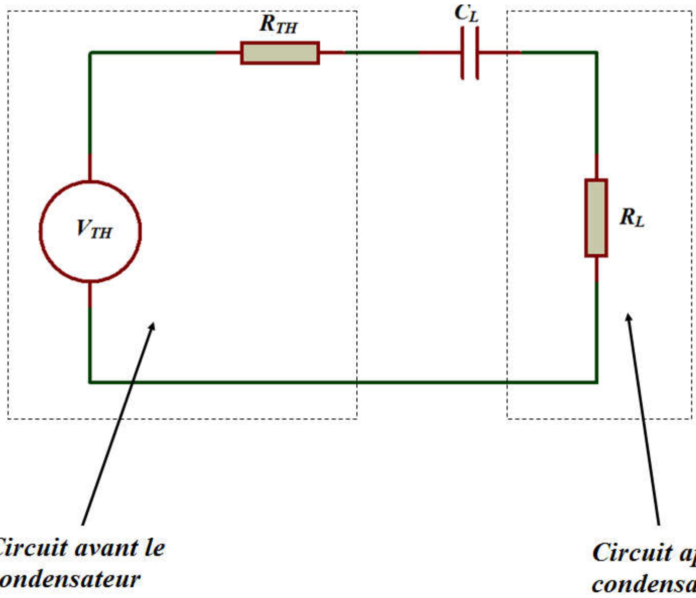
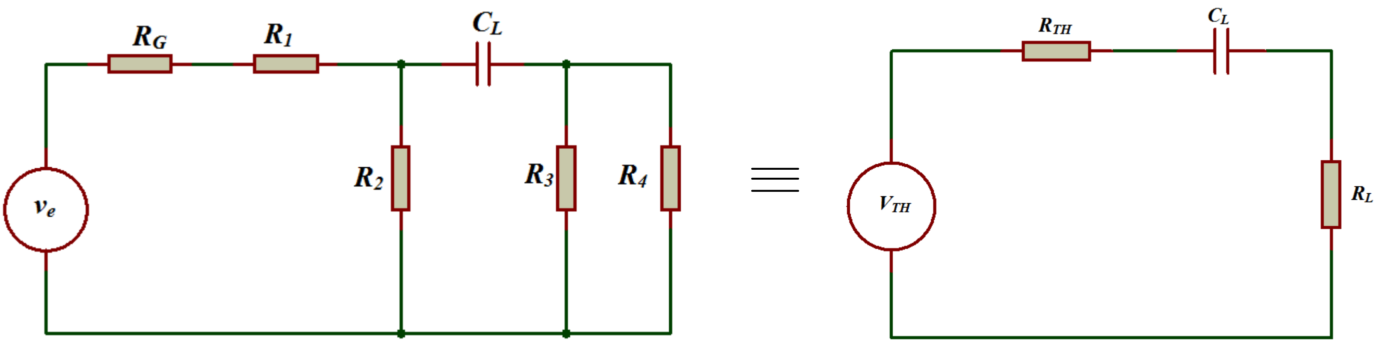


Figure 21. Coupling Capacitors

Example :

Given the following circuit, we apply a sinusoidal signal at its input, with a frequency ranging from 100Hz to 1MHz, coming from a generator with an internal resistance R_G=1KΩ. Calculate the value of the coupling capacitor that allows these frequencies to pass without attenuation.



R_{TH}=(R_1+R_G)//R_2 avec R_1=11KΩ, R_2=6KΩ, R_G=1KΩ.

R_{TH}=(1+11)//6=4KΩ.

R_L=(R3//R4)=3//6=2KΩ.

From there, we can evaluate the minimum value of the coupling capacitor allowing the passage of a low-frequency signal of 100Hz without attenuation.

$$C_{Lmin} = \frac{1}{2\pi 100(6)} = 2.6\mu F$$

b. Decoupling Capacitors

A decoupling capacitor is similar to a coupling capacitor, with the difference that it connects a point that is not connected to ground to ground. These capacitors introduce the concept of ground in alternating current.

Among the circuits we have studied, the one that exhibits better temperature stability is the one where a biasing resistor is placed in series with the transistor's emitter. Therefore, it needs to be decoupled in alternating current by placing a capacitor in parallel with it, which should behave like a short circuit in alternating current. This is called a decoupling capacitor.

To calculate the minimum value of the decoupling capacitor, the same circuit transformation as in the case of the coupling capacitor needs to be done for the circuit before the capacitor. We obtain the following equivalent circuit diagram:

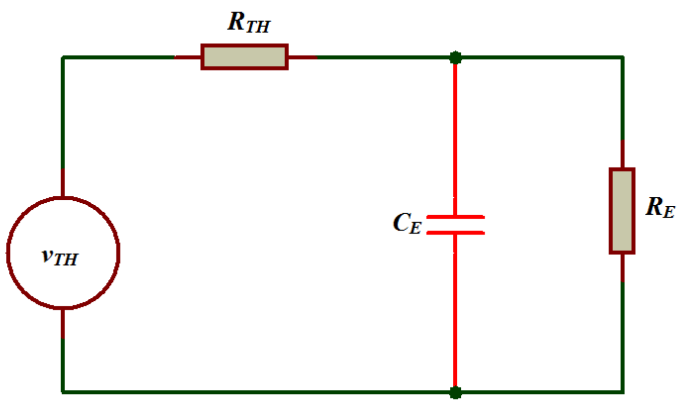


Figure 22. Decoupling Capacitors

$$C_{Emin} = \frac{1}{2\pi f_{cb} R_{TH}}$$

4.4.3 Equivalent circuit of the amplifier in continuous mode and in variable mode

In a transistor amplifier, DC sources establish continuous currents and voltages. The AC source produces fluctuations in the currents and voltages of the transistor. The simplest way to analyze the action of transistor circuits is to divide the analysis into two parts: one for the DC quantities and the other for the AC quantities. In other words, transistor circuits can be analyzed by applying the superposition theorem of electrical states in a somewhat special way. Instead of taking one source at a time, all DC sources are taken simultaneously, and continuous currents and voltages are found using the usual methods from the section on bipolar transistor biasing.

Then, all AC sources are taken simultaneously, and the alternating currents and voltages are calculated. By adding these DC and AC currents and voltages together, the total currents and voltages are obtained.

a. DC Operating Mode

In static mode, coupling and decoupling capacitors are replaced by open circuits. Additionally, the variable voltage generators are turned off. Applying these considerations, the circuit in Figure 20 becomes as follows:

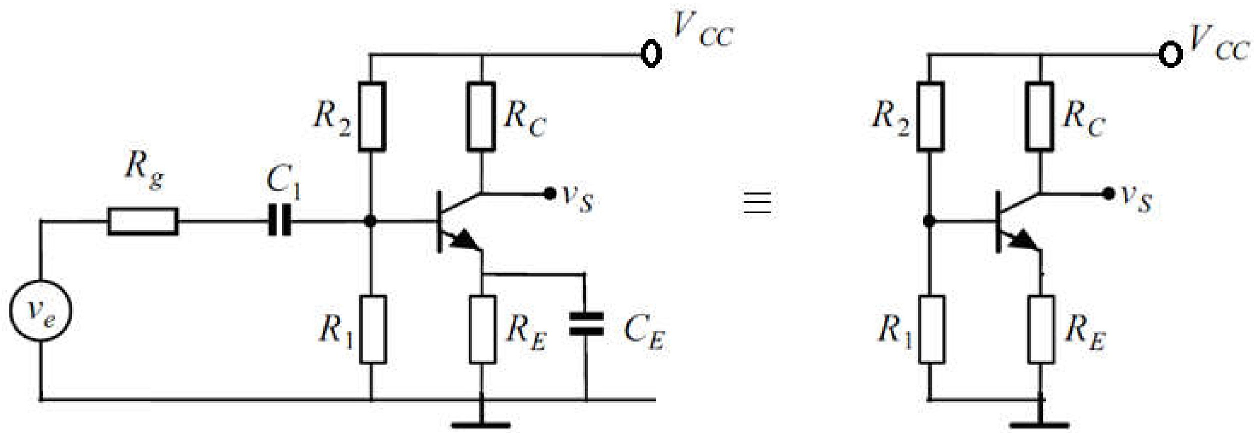


Figure 23. Equivalent circuit in static mode

b. Dynamic Operating Mode

In dynamic mode, DC sources are reduced to zero, and capacitors are replaced by short circuits. Therefore, the equivalent circuit will be as follows:

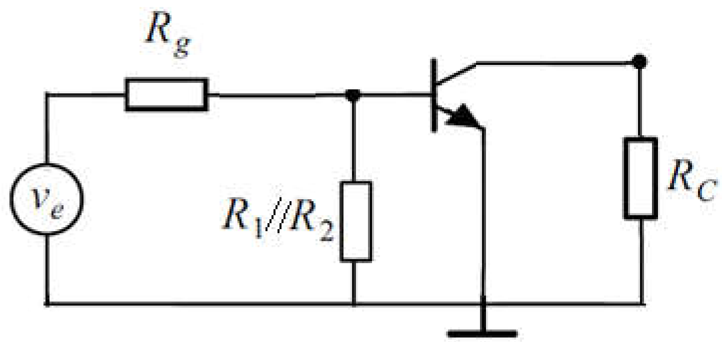


Figure 24. Equivalent circuit in dynamic mode

4.4.4 Fundamental Bipolar Transistor Configurations

The bipolar transistor is the most commonly used component in electronics. This fundamental component is used in discrete circuits but especially in integrated circuits. The three fundamental configurations are the common emitter, the common collector, and the common base.

4.4.4.1 Common Emitter Amplifier

Let's consider the common emitter configuration shown in Figure 20, in which the transistor is biased in its linear operating region. Resistors $\boldsymbol{R_1}$ and $\boldsymbol{R_2}$ are chosen such that $\boldsymbol{h_{11}}$ is much smaller than the equivalent resistance of their parallel combination, $\boldsymbol{R_0}$, and we also assume that resistor $\boldsymbol{R_C}$ is of the same order as $\boldsymbol{h_{11}}$.

Using the hybrid parameters, we recall the following equations:

$$\begin{cases} v_{BE} = h_{11e} i_B + h_{12e} v_{CE} \\ i_C = h_{21e} i_B + h_{22e} v_{CE} \end{cases}$$

Based on the equivalent circuit of the transistor in dynamic mode, we can redefine the parameters $\boldsymbol{h_{ij}}$ as follows:

$h_{11e} = \left.\frac{\Delta v_{BE}}{\Delta i_B}\right|_{v_{CE}=0} = r$: Input resistance of the transistor.

$h_{12e} = \left.\frac{\Delta v_{BE}}{\Delta v_{CE}}\right|_{i_B=0} = \gamma$: Output-to-input reaction rate. $\gamma \approx 0$ (because $\boldsymbol{v_{be}}(\boldsymbol{v_{ce}})$ characteristics are practically horizontal)

$h_{21e} = \left.\frac{\Delta i_C}{\Delta i_B}\right|_{v_{CE}=0} = \beta$: Transistor current gain.

$h_{22e} = \left.\frac{\Delta i_C}{\Delta v_{CE}}\right|_{i_B=0} = \frac{1}{\rho}$, $\boldsymbol{\rho}$: This is the output resistance of the transistor.

Using these parameters and knowing that $\gamma \approx 0$, we can write::

$$v_{be} = r i_b$$

$$i_c = \beta i_b + \frac{v_{ce}}{\rho}$$

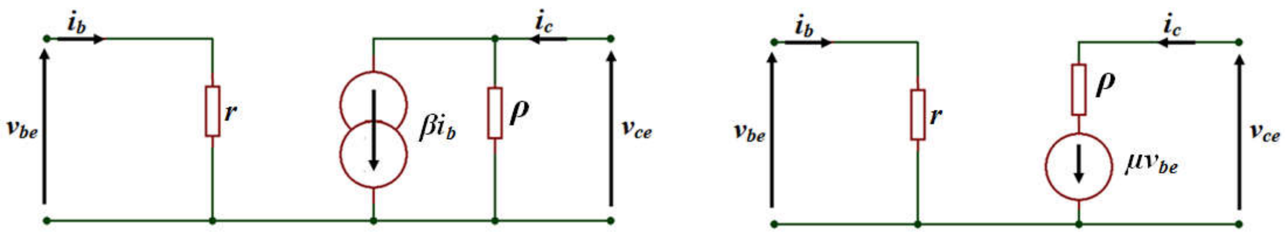
$$\Rightarrow i_b = \frac{v_{be}}{r}$$

$$\Rightarrow i_c = \beta \frac{v_{be}}{r} + \frac{v_{ce}}{\rho}$$

Or, knowing that: $g_m = \frac{\beta}{r}$, we can write:

$$i_c = g_m v_{be} + \frac{v_{ce}}{\rho}$$

From these equations, we can draw the following two equivalent circuits:



$$\mu = \frac{\beta\rho}{r}$$

Figure 25. equivalent circuits Common Emitter Amplifier

By associating an input generator and an output load to this equivalent circuit, we obtain the following equivalent circuit:

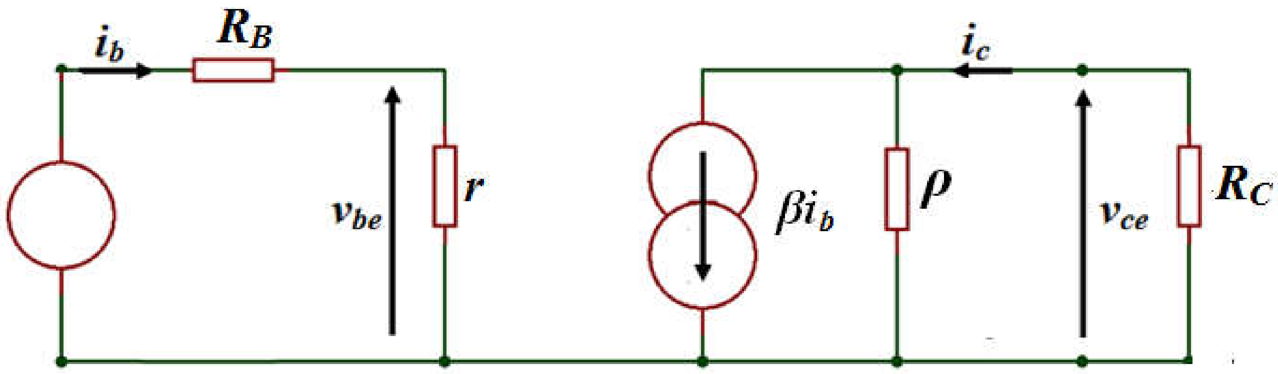


Figure 26. Equivalent circuit by associating an input generator and an output load.

From this equivalent stage circuit, we will calculate the various parameters of the amplifier.

a. Current Gain

The current gain of the common emitter configuration is:

$$G_I = \frac{i_c}{i_b}$$

Which is obtained from the following formulas:

$$v_{ce} = -R_C i_c$$

Where r_c is the collector resistance in dynamic mode. In our case: $r_c=R_C//\rho$

$$v_{ce} = -r_c \beta i_b$$

$$v_{ce} = -\frac{\rho R_C}{\rho + R_C}\beta i_b$$

So,

$$-R_C i_c = -\frac{\rho R_C}{\rho + R_C}\beta i_b$$

$$\frac{i_c}{i_b} = \frac{\beta\rho}{\rho + R_C}$$

Generally, the output resistance of the transistor has a quite high value, and $\rho \gg R_C$. The gain formula can then be simplified, and we can write:

$$G_I \approx \beta$$

The current gain in common emitter configuration is significant.

b. Voltage Gain

The voltage gain is:

$$G_V = \frac{v_{ce}}{v_{be}}$$

$$v_{ce} = -R_C i_c$$

$$v_{be} = r i_b$$

$$\mapsto G_V = -\frac{R_C}{r} G_I$$

$$\mapsto G_V = -\beta \frac{R_C}{r}$$

The negative sign in the formula for gain indicates a phase shift of π radians between the output voltage and the input voltage.

c. Power Gain

Power gain is the product of the absolute values of the current gain and voltage gain.

$$G_P = |G_V||G_I|$$

$$G_P = \beta^2 \frac{R_C}{r}$$

d. Input Impedance

By definition, input impedance is the ratio of input voltage to input current.

$$R_e = \frac{v_{be}}{i_b} = \frac{r i_b}{i_b} \mapsto R_e = r$$

e. Output Impedance

The output impedance of the transistor is:

$$R_s = \rho$$

4.4.4.2 Common Collector Amplifier

The equivalent circuit of this type of circuit is given in figure 27. In this type of configuration, we have:

- Input parameter : $\begin{cases} i_1 = i_b \\ v_1 = v_{bc} \end{cases}$

- Output parameter : $\begin{cases} i_2 = i_e \\ v_2 = v_{ec} \end{cases}$

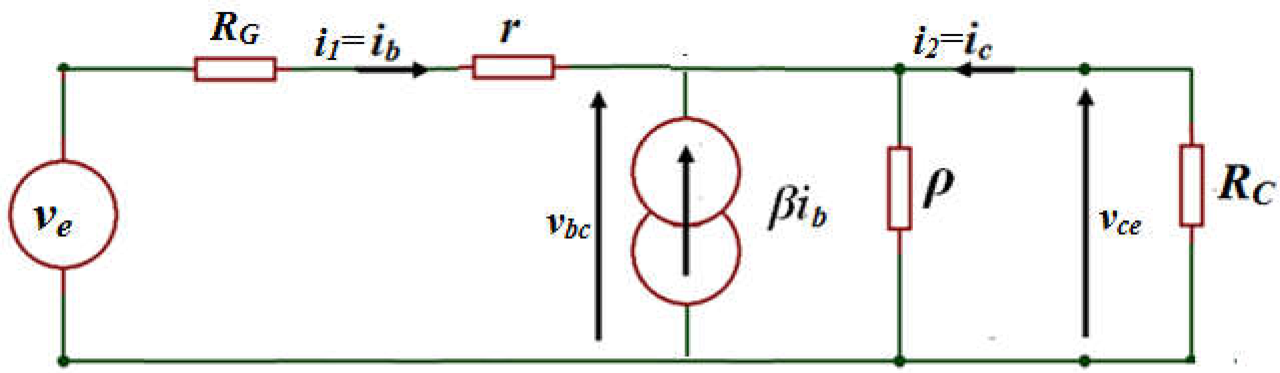


Figure 27. **E**quivalent circuit of Common Collector Amplifier

a. Current gain

The current gain of the common collector configuration is :

$$i_1 = i_b$$
$$i_2 = -(\beta + 1)i_b$$

So the current gain is:

$$G_I = \frac{i_2}{i_1} = -(\beta + 1) \approx -\beta$$

The formula for the gain can then be simplified and we can write:

$$\boldsymbol{G_I \approx -\beta}$$

b. Voltage gain

$$v_2 = (\beta + 1)(\rho//R_C)i_b$$
$$v_1 = ri_b + (\beta + 1)(\rho//R_C)i_b$$

The voltage gain is:

$$G_V = \frac{(\beta + 1)(\rho//R_C)}{r + (\beta + 1)(\rho//R_C)}$$

The resistance value is quite high compared to typical load values. Therefore, the voltage gain simplifies as follows:

$$G_V = \frac{(\beta + 1)R_C}{r + (\beta + 1)R_C}$$

If $r \ll (\beta + 1)R_C$, The gain can be approximated by $\boldsymbol{G_V = 1}$

c. Power gain

Power gain is the product of the absolute values of the current gain and voltage gain.

$$G_P = |G_V||G_I|$$

$$G_P = \beta \frac{(\beta + 1)R_C}{r + (\beta + 1)R_C}$$

Under the previous approximation conditions:

$$G_P = \beta$$

d. Input impedance

By definition, input impedance is the ratio of input voltage to input current.

$$R_e = \frac{v_1}{i_1} = r + (\beta + 1)(\rho // R_C)$$

Using previous approximations:

$$R_e = (\beta + 1)R_C$$

This circuit exhibits a relatively high input impedance compared to the other two circuits.

e. Output impedance

The output impedance of the transistor is :

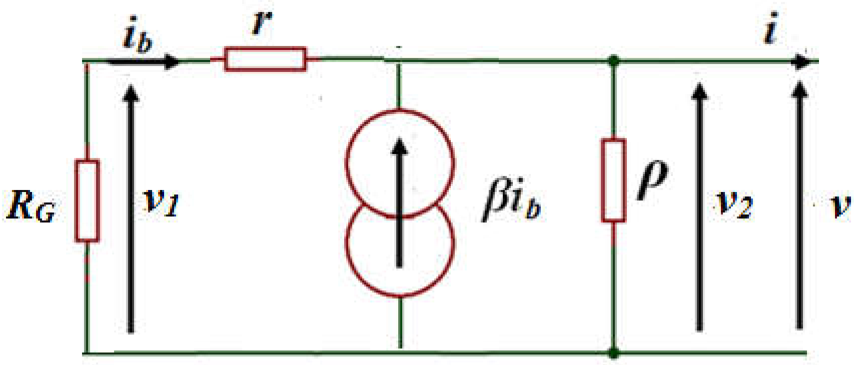


Figure 28. Output impedance scheme

According to Figure 28, we can write the following equations:

$$i = -\frac{v}{\rho} + (\beta + 1)i_b$$

$$v = -(r + R_G)i_b$$

By replacing i_b with its expression:

$$i = -\frac{v}{\rho} - \frac{(\beta + 1)}{r + R_G} v$$

$$\frac{i}{v} = -\frac{1}{\rho} - \frac{(\beta + 1)}{r + R_G}$$

So the output resistance is given by :

$$R_S = \rho // \left(\frac{r + R_G}{\beta + 1}\right)$$

4.4.4.3 Common base amplifier

The equivalent circuit diagram of this type of configuration is provided in Figure 29. In this type of setup, we have:

- Input parameter : $\begin{cases} i_1 = i_e \\ v_1 = v_{eb} \end{cases}$
- Output parameter : $\begin{cases} i_2 = i_c \\ v_2 = v_{cb} \end{cases}$

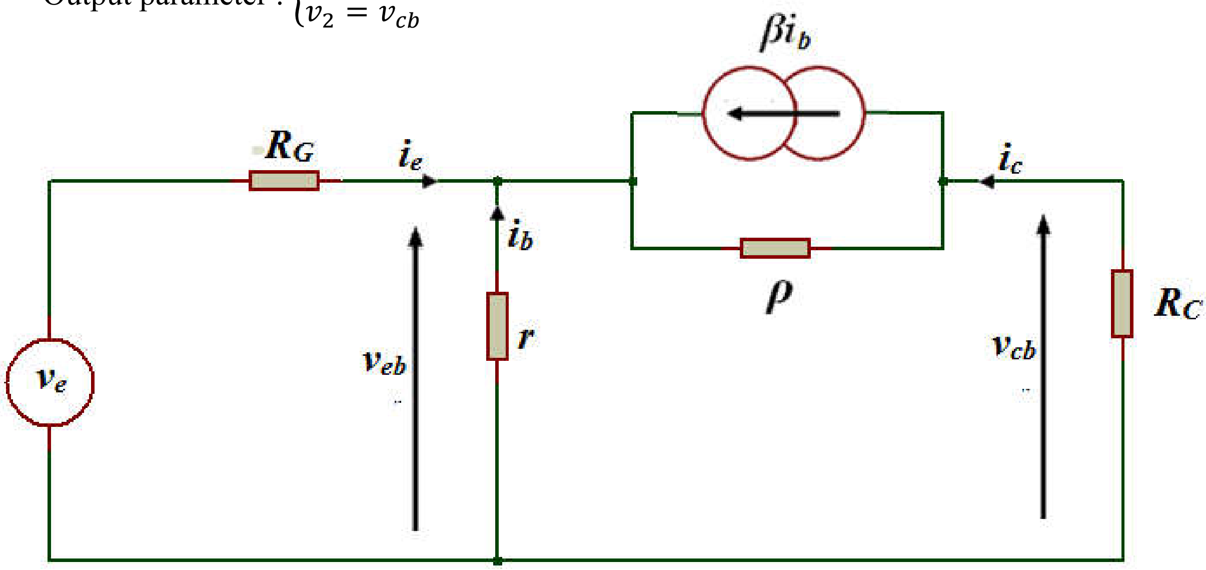


Figure 29. Common base amplifier circuit

For this type of setup, and given that the output resistance of the transistor $\boldsymbol{\rho}$ is of high value, the latter will be neglected except for the calculation of the output resistance of the stage..

a. **Current gain**

The current gain of the common base configuration is:

$$i_1 = -(\beta + 1)i_b$$

$$i_2 = i_c = \beta i_b$$

So the current gain is:

$$G_I = \frac{i_2}{i_1} = -\frac{\beta}{(\beta + 1)} \approx -\alpha$$

The gain formula can then be simplified and we can write:

$$\boldsymbol{G_I \approx - \alpha}$$

Since $\boldsymbol{\alpha}$ is close to 1, the common base configuration has no current gain. Additionally, the negative sign indicates a phase shift between the input current and the output current.

b. **Voltage gain**

$$v_2 = -R_C i_c$$

$$v_1 = -r i_b$$

The voltage gain is:

$$G_V = \frac{R_C i_c}{r i_b} \Rightarrow G_V = \beta \frac{R_C}{r}$$

c. Power gain

The power gain is the product of the absolute values of the current and voltage gains..

$$G_P = |G_V||G_I|$$

$$G_P = \alpha\beta \frac{R_C}{r}$$

In the previous approximation conditions, where α is close to 1:

$$G_P = \beta \frac{R_C}{r}$$

d. Input impedance

By definition, input impedance is the ratio of input voltage to input current.

$$R_e = \frac{v_1}{i_1}$$

Knowing that:

$$v_1 = -r i_b$$

$$i_1 = -(\beta + 1) i_b$$

This circuit exhibits an input impedance of the following form:

$$R_e = \frac{r}{\beta + 1}$$

Generally, β is much greater than 1, so:

$$R_e = \frac{r}{\beta}$$

The input impedance of this type of configuration is β times lower than the input resistance of the common emitter configuration.

e. Output impedance

The output impedance of the transistor is:

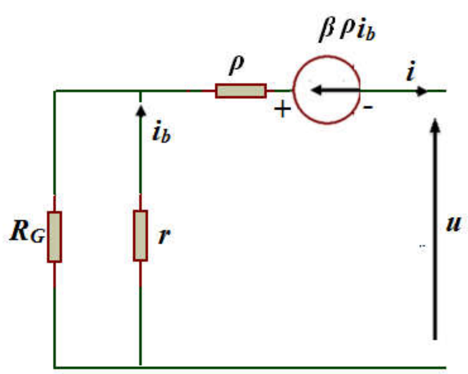


Figure 30. Output impedance scheme

According to Figure 29, we can write the following equations:

$$R_S = \frac{u = v_{2(co)}}{i = i_{2(cc)}}$$

To perform this calculation, we proceed as follows:

- Short-circuit the input generator to calculate $\boldsymbol{i}$.
- Remove the load $\boldsymbol{R_C}$ to calculate the open-circuit output voltage $\boldsymbol{u}$.
- Convert the current generator into a voltage generator to simplify the calculations.

From the circuit in Figure 30, we have:

$$u = \beta\rho i_b + \rho i + r i_b = 0$$

$$R_G(i_b - i) = -r i_b$$

This allows us to write:

$$i_b = -\frac{R_G}{R_G + r} i$$

So the output resistance is given by:

$$R_S = \frac{v}{i} = \rho + \left(\frac{r + \beta\rho}{r + R_G}\right) R_G$$

The output resistance is a function of the internal resistance of the generator, which represents one of the drawbacks of this type of configuration.

4.4.5 Comparison of the three fundamental bipolar transistor configurations

- The common emitter ***C.E*** configuration is the one that offers the best power gain $\boldsymbol{G_p}$, which is why it is the most widely used configuration for amplification. Its main drawback is its input impedance, which is not high enough, requiring impedance matching at the input, hence the need for a preamplifier.
- The common collector ***C.C*** configuration possesses the characteristics required for a preamplifier, as it has a high input impedance and a low output impedance.

The following table provides a summary of the characteristics of the three fundamental bipolar transistor configurations.

Montage	Re		Rs		Gi		Gv	
E.C	$r = h_{11}$	average	ρ	high	β	élevée	$-\beta \frac{R_C}{r}$	average
B.C	$\frac{r}{\beta}$	low	$\rho + \left(\frac{r + \beta\rho}{r + R_G}\right) R_G$	large	-α ≈ -1	faible	$\beta \frac{R_C}{r}$	average
C.C	$\approx \beta R_C$	high	$\rho // \left(\frac{r + R_G}{\beta + 1}\right)$	low	$-\beta$	élevé	≈1	low

4.4.6 Darlington configurations

The Darlington configuration allows achieving a high β. It involves connecting two transistors together as shown in the following figure:

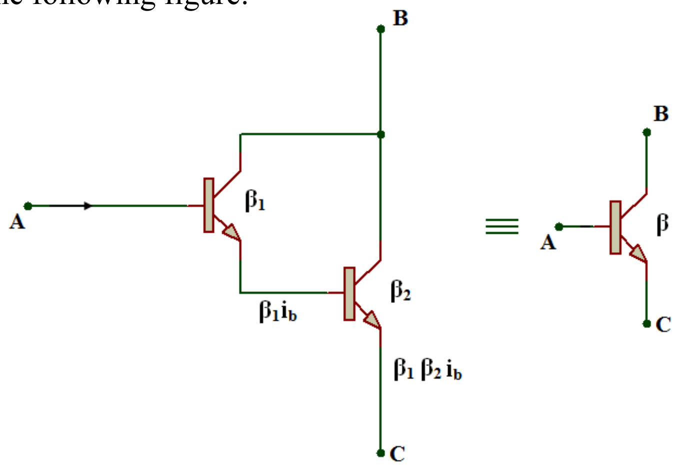


Figure 31. Darlington configurations

The circuit in Figure 31 depicts two transistors connected in cascade within the same package, which can be considered as a single transistor known as a 'Darlington transistor'. The transistors are characterized by current gains β1 and β2, respectively. They are assumed to be biased in their linear region. This configuration allows, using two different transistors, to construct a device with a current gain equal to the product of the two gains β1 and β2. The two transistors in the Darlington configuration are treated as a single transistor with a very high gain (super β).

4.5 The transistor in switching mode.

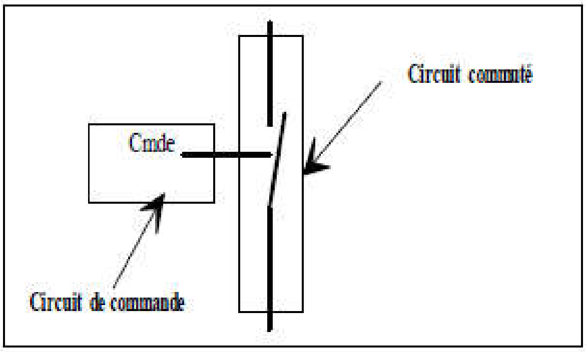
We will now study the transistor in switching mode. If the transistor is not biased in its linear region, then it will only take two states: **cutoff** (V_{BE} and I_B are very low) or **saturated** (V_{CE} very low). There are many systems that rely on this property of transistors.

We can liken the transistor to an electrically controlled switch. The control is the **base**, and the switch is between the **collector** and the **emitter**.

The switching transistor is used to open or close a circuit. Thus, it can control an **LED**, a **RELAY**, a **MOTOR**, etc. Generally, we liken the output circuit of the transistor to a switch that is controlled either by voltage or by current, depending on the type of transistor chosen.

The configuration of a switching transistor can be divided into two circuits:

- Control circuit or Input circuit
- Switched circuit or Output circuit



4.5.1 Cutoff state and saturated state

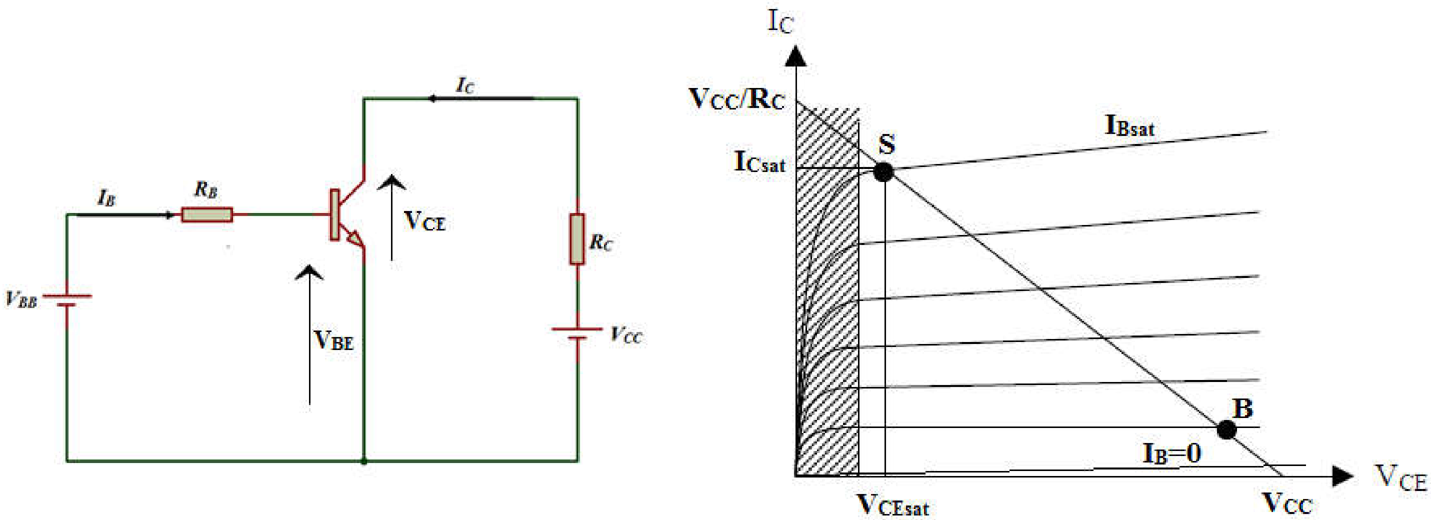


Figure 32. Definition of the operating modes of the bipolar transistor

Consider the circuit in Figure 32, the equations for the input and output loops are:

$V_{BB}=R_BI_B+V_{BE}$

$V_{CC}=R_CI_C+V_{CE}$

In the output plane $I_C=f(V_{CE})$, we consider 3 regions according to the state of the transistor (Figure 32):

- A saturation region characterized by the voltage $V_{CE} = V_{CEsat} \approx 0$ and the current $I_C = I_{Csat} = I_{Cmax}$ given by:

$$I_{Csat} = \frac{V_{CC} - V_{CEsat}}{R_C}$$

Point S of Figure 32.

- A cutoff region characterized by the voltage $V_{CE} \approx V_{CC}$ and the current $I_B \approx 0$ et $I_C \approx 0$

Point B of Figure 32.

- An amplification region, also known as the linear operating region, located between the two previous regions.

When the transistor operates in perfect switching, its operating point is:

- Either at **S**, the transistor is perfectly saturated: $V_{CE} = 0$ et $I_C = I_{Csat} \neq 0$.

The transistor is equivalent to a closed switch.

- Or at **B**, the transistor is perfectly cut off: $V_{CE} = V_{CC} \neq 0$ et $I_C = 0$.

The transistor is equivalent to an open switch.

The saturation condition is expressed as:

$$I_B \geq \frac{1}{\beta}\left(\frac{V_{CC} - V_{CEsat}}{R_C}\right)$$

En réalité on a $V_{CC} >> V_{CEsat}$ d'où la condition de saturation

$$I_B \geq I_{Bsat} \cong \frac{1}{\beta}\frac{V_{CC}}{R_C}$$

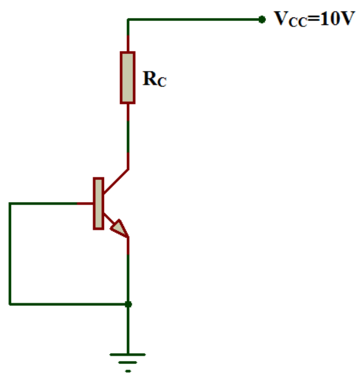
However, the base current I_B is given by:

$$I_B = \frac{V_{BB} - V_{BEsat}}{R_B} \geq I_{Bsat}$$

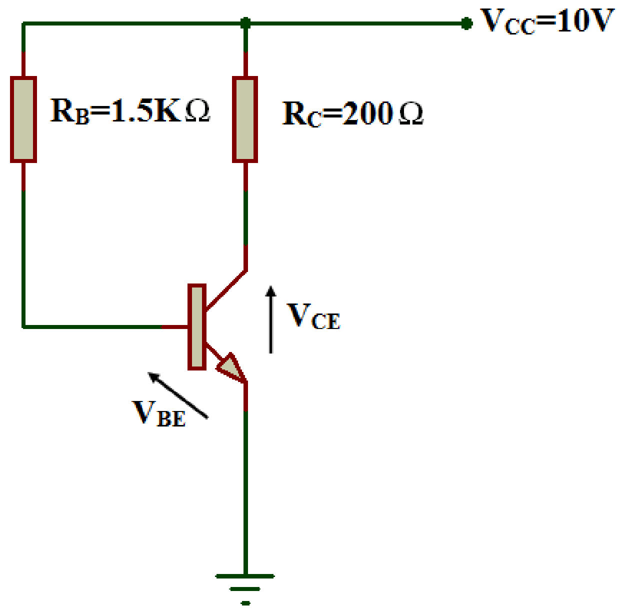
Upon examining this last relation, we observe that the base current I_B is set by the input circuit. However, for $I_B \geq I_{Bsat}$, the collector current I_C almost does not increase anymore. We then say that the transistor operates in the regime of oversaturation. An increase in I_B results in an accumulation of charges consisting of minority carriers in the base. Furthermore, in this type of regime, both the BE and BC junctions are forward biased. The charges stored in the base come from both the emitter and the collector.

4.5.2 Determining the conduction state of a transistor in switching mode

If a transistor is not biased in its linear region, it can either be blocked (V_{BE} and I_B are very low) or saturated (V_{CE} very low). A simple analysis of the operating point is sufficient to determine whether the transistor is blocked or saturated. In the case of the figure below, it is immediately observed that $V_{BE}=0$. Therefore, the transistor is blocked and its collector current is zero.



Consider the following circuit:



The case of this assembly is less obvious and requires a particular method; we assume that it is biased in its linear zone.

If this is not the case, we quickly arrive at a contradiction. Thus, the transistor is biased in its linear region, we have: $V_{BE}=V_B=0.7V$, $\beta=50$.

Hence,:

$I_B = \frac{V_{CC}-V_B}{R_B} = \frac{10-0.7}{1500} \Rightarrow \boldsymbol{I_B = 6.2mA}$

and $I_C=\beta I_B=50\times0.0062 \Rightarrow \boldsymbol{I_C=0.31A}$

Let's calculate now.: $V_{CE}=V_C$, we have : $V_{CC}-V_C=R_CI_C$

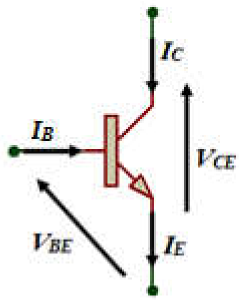
Hence: $V_C = V_{CC} - R_CI_C = 10-200\times0.31 \Rightarrow V_C = -52V$

However, the voltage $\boldsymbol{V_{CE}}$ cannot drop below $\boldsymbol{0V}$. The initial assumption is therefore false. The current $\boldsymbol{I_C}$ will never reach that value of $\boldsymbol{0.31A}$ but will stabilize at a value corresponding to $\boldsymbol{V_C=0V}$.

Let it be:

$I_C = \frac{V_{CC}}{R_C} = \frac{10}{200} \Rightarrow \boldsymbol{I_C = 50mA}$

The transistor is therefore saturated. It should be noted that in this case, the equality $\boldsymbol{I_C=\beta I_B}$ is no longer valid. In reality, we have: $\boldsymbol{I_C<\beta I_B}$.



- Therefore, for an NPN transistor, when VBE=0, the transistor is blocked.
  This means that I_C=I_E=0, et V_{CE} is any positive constant (V_{CE}< V_{CEmax})
- And, when V_{BE}=0.7V (threshold voltage of the base-emitter diode),
  the transistor is conducting. For it to be saturated, we saw that it was necessary that

$$I_B > \frac{I_C}{\beta}$$

This means that $\boldsymbol{V_{CE} = V_{CEsat} = 0.2V}$ for a low-power transistor. The current can then flow through the transistor from the collector to the emitter. What needs to be clearly understood is that the transistor behaves like a switch.

4.5.3 Application

There are numerous applications of transistors operating in switching mode because in this case, they act like switches that can be controlled..

Many logic functions can also be implemented using this principle. For example, the figure below represents the negation logic function: when $\boldsymbol{V_E=0V}$, the base-emitter junction is blocked, no base current, nor collector current. The potential difference across $\boldsymbol{R_C}$ is therefore zero, and we have $\boldsymbol{V_S=V_{CC}=5V}$.

If, on the contrary, $\boldsymbol{V_E=5V}$, the base-emitter junction is correctly biased and, since the emitter is at ground, we have: $\boldsymbol{V_B=0.7V}$. Therefore, the base current is:

$$I_B = \frac{V_1 - V_B}{R_B} = \frac{5-0.7}{10^4} \mapsto I_B = 0.43mA$$

We can deduce the collector current and then the voltageV_S.

$I_C=\beta I_B=100\times 0.43\ 10^{-3} \mapsto \boldsymbol{I_C=43mA}$.

$V_{CC}-V_S=R_C I_C \mapsto V_S= V_{CC} - R_C I_C = 5-1000\times 43\ 10^{-3} \mapsto \boldsymbol{V_S= -38V}$

This value is impossible to obtain; the transistor can only be saturated at the value $\boldsymbol{V_C=V_S=0V}$.