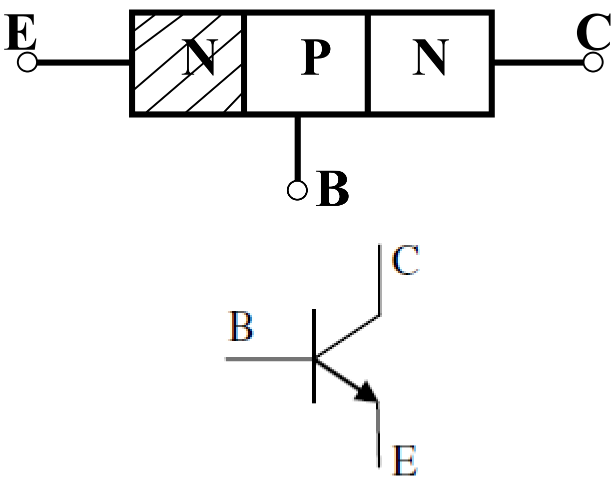
Chapter 4: The Bipolar Transistor

1- Introduction

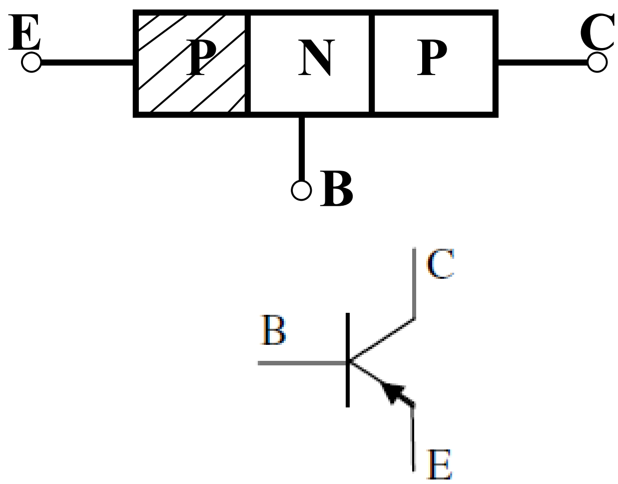
In electronics, electrical engineering, and control systems, active components are commonly used to perform specific functions such as amplification or switching, and the transistor serves this purpose. The bipolar transistor is a fundamental component of modern electronics, it is built on the basis 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.

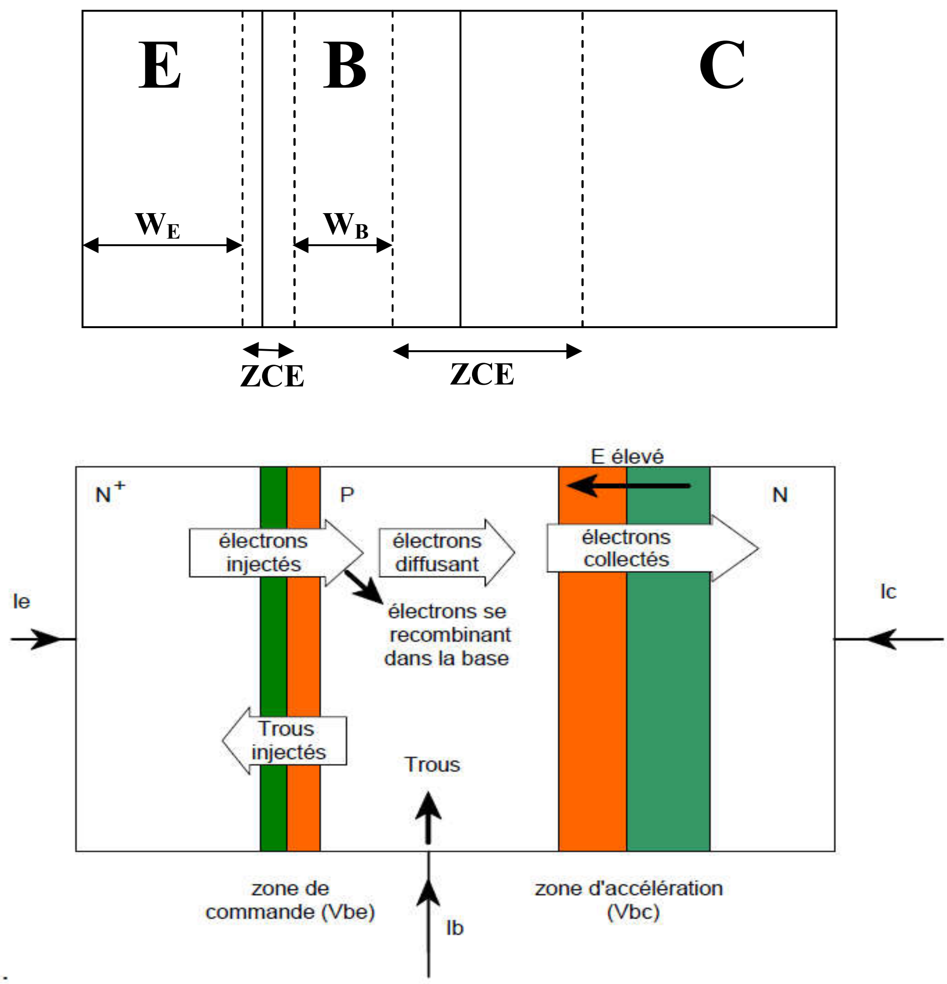


Figure 2. NPN structure of a bipolar transistor

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.

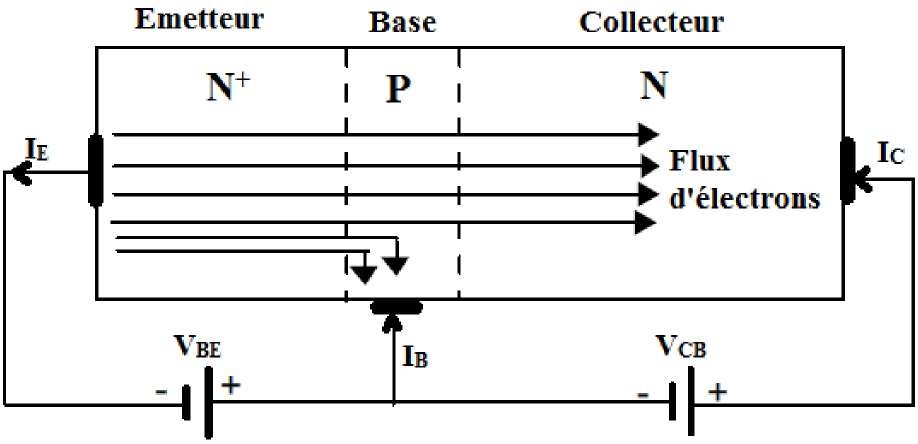


Figure 3. Forward bias and principle of the transistor effect.

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.

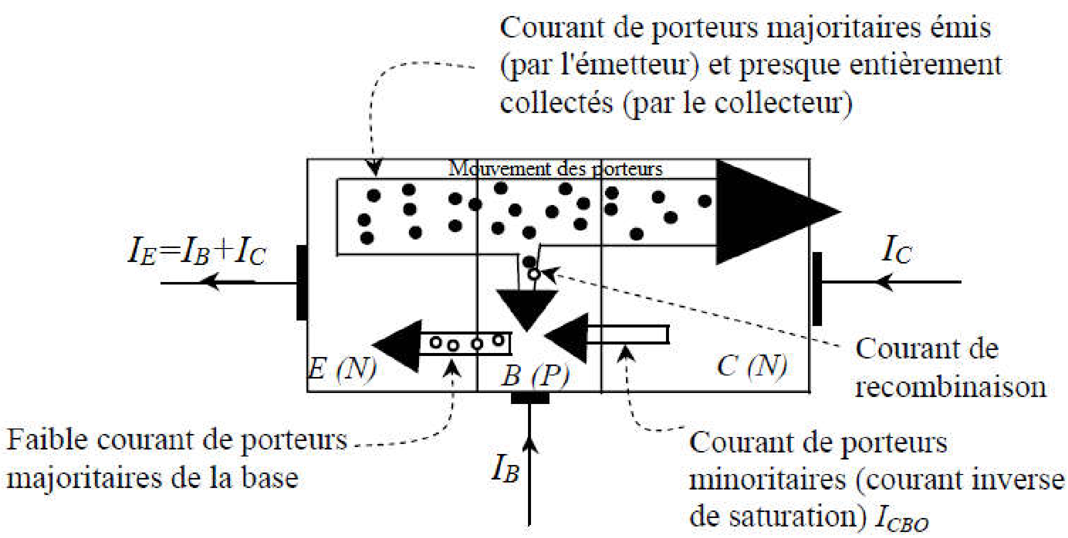


Figure 4. Current balance for a real transistor

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.

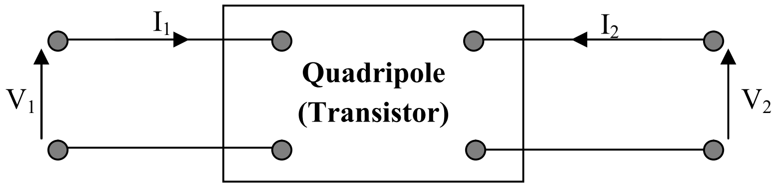


Fig. 5. Quadripole Representation

3.2 The various configurations of a bipolar transistor

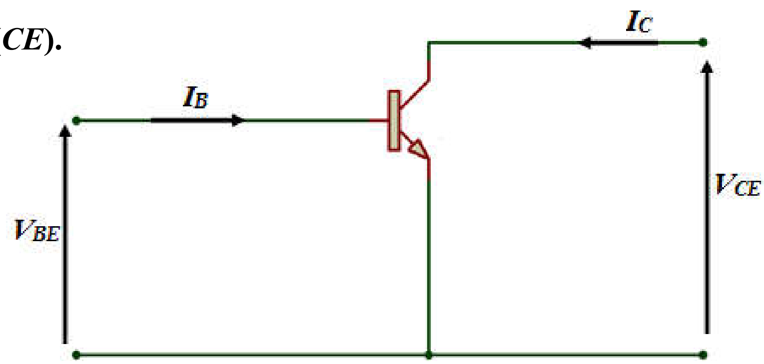
The static characteristics of bipolar transistors consist of the relationships between currents and voltages at the input and output of the transistor. Depending on the type of circuit used, the characteristics will differ for the same component. Since the transistor has three electrodes, one of them 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*).

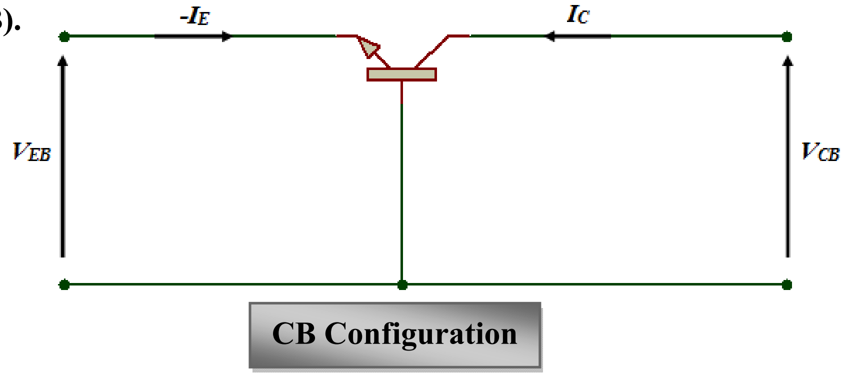
- Input current : I_B
- Output current : I_C
- Input voltage : V_{BE}
- Output voltage : V_{CE}



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}



3.2.3 The Common Collector configuration (CC).

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

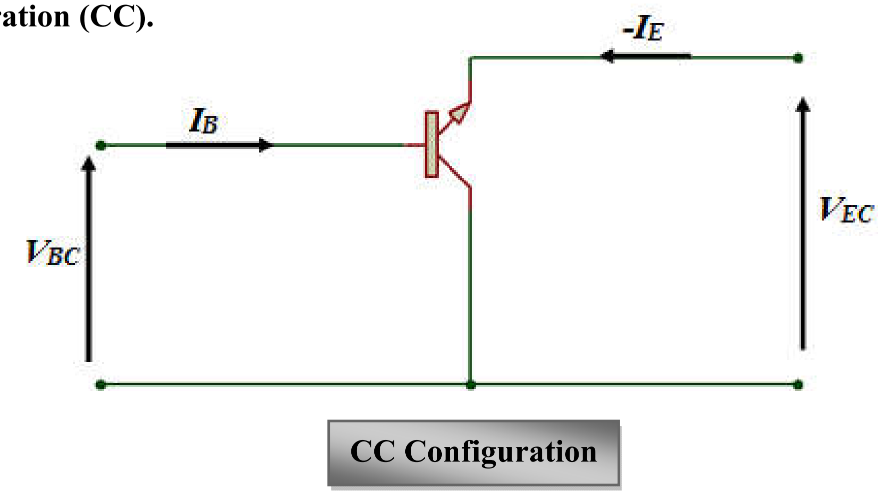
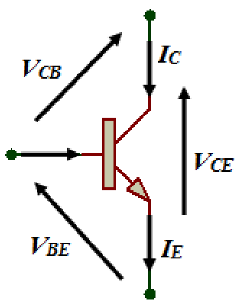


Figure 6. Different types of transistor configurations

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**.

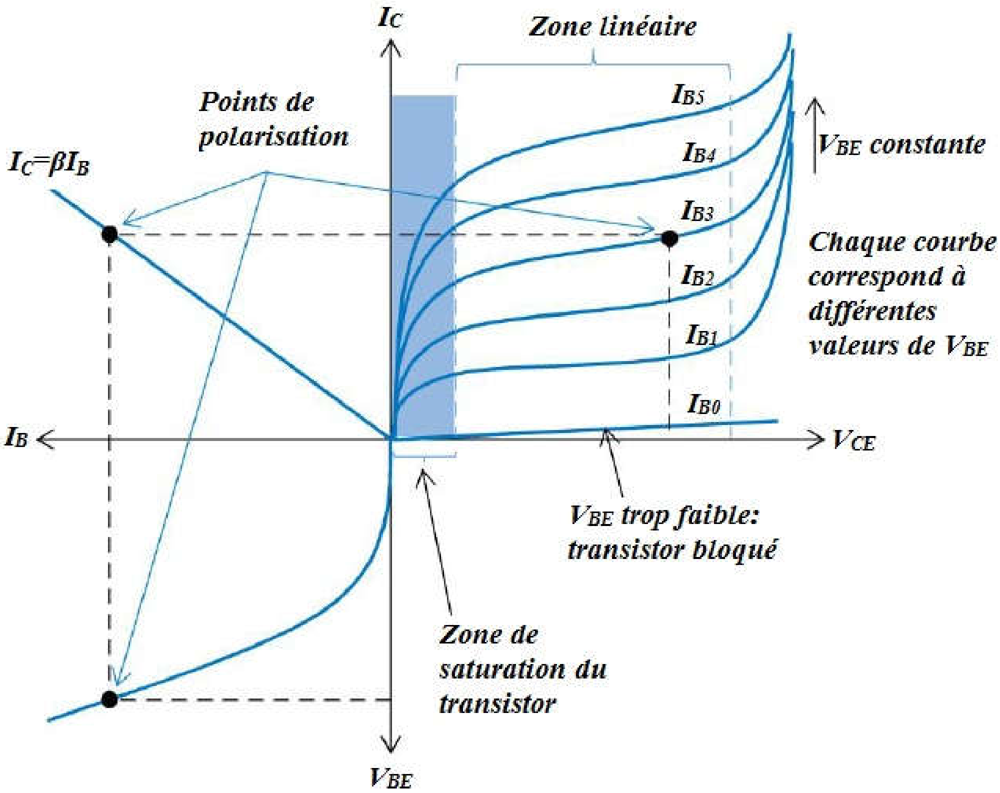


Figure 7. Bipolar transistor characteristic network

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.

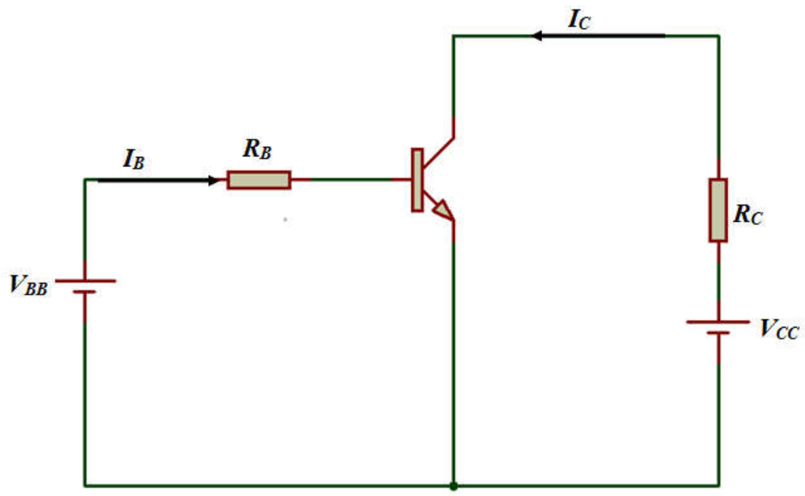


Figure 8. Common emitter configuration

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

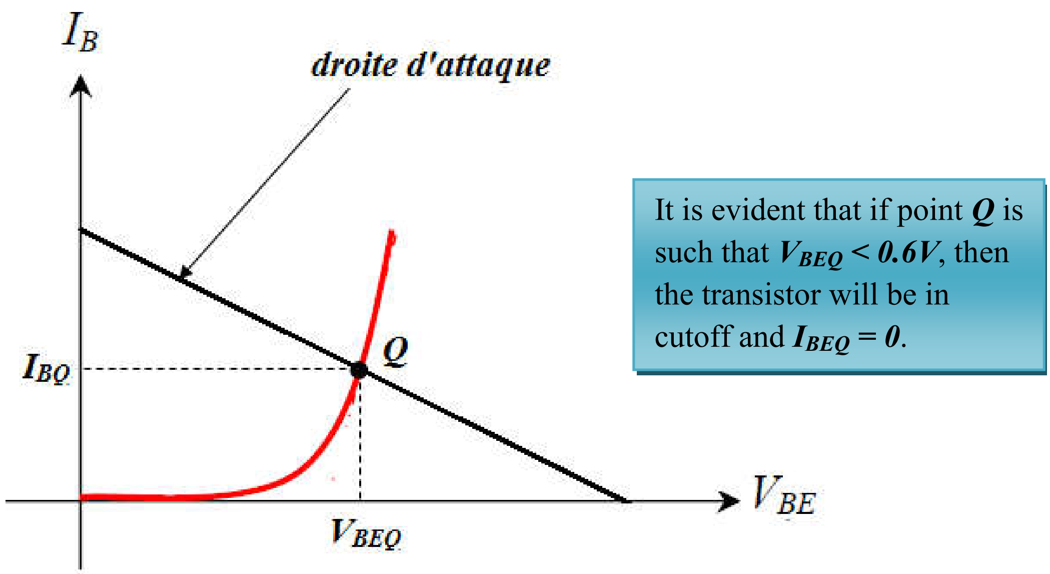


Figure 9. Drive line

b. Static load line:

The mesh equation of the output circuit gives us: $\boldsymbol{V_{CC} = V_{CE} + R_C I_C}$. 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:

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

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

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

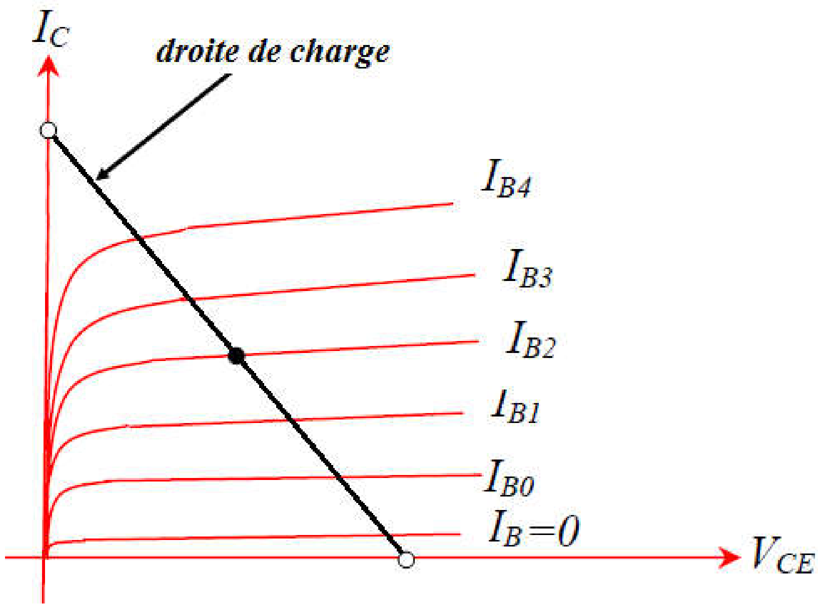


Figure 10. Load line

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.

<u>Notations :</u>

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

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

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

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

- Point ***B*** corresponds to $v_{CE} = V_{CC}$ and $i_C = 0$, 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.

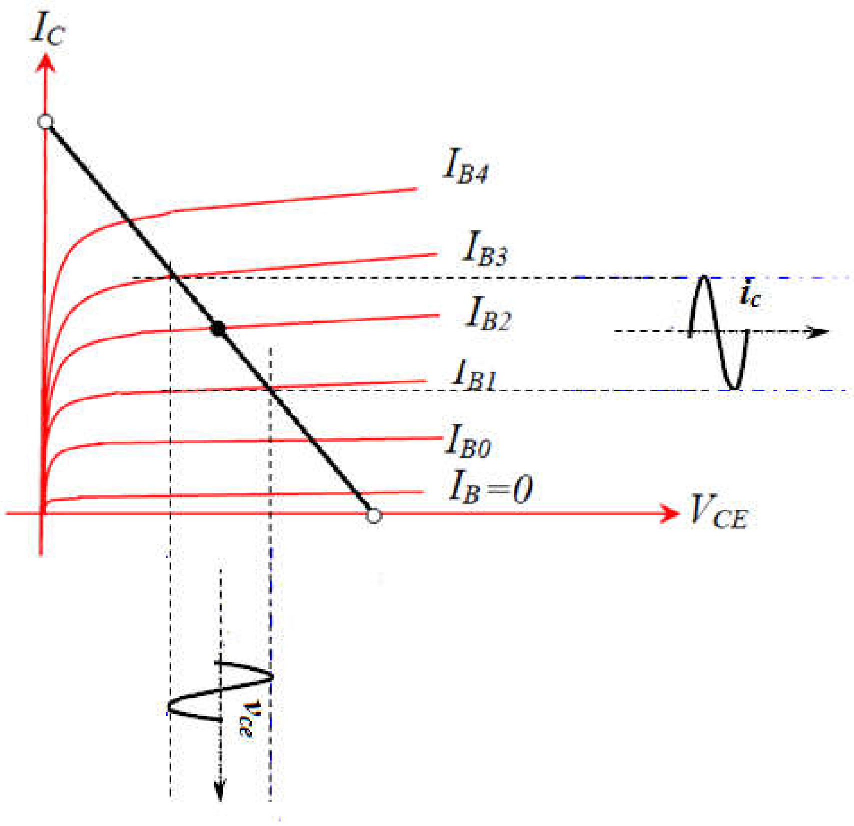


Figure 11. variable output current and voltage around point Q

4.2.4.1 Amplification phenomenon

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

At the output, there is a high i_C and large 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::

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

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

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 I_{CB0}, which implies a change in the 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 $I_B = \frac{V_{BB}}{R_B}$

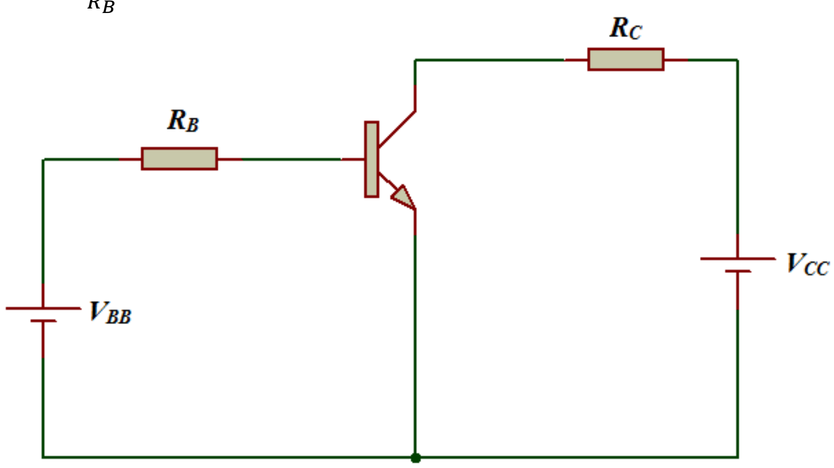


Figure 12. Biasing by imposed base current

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:

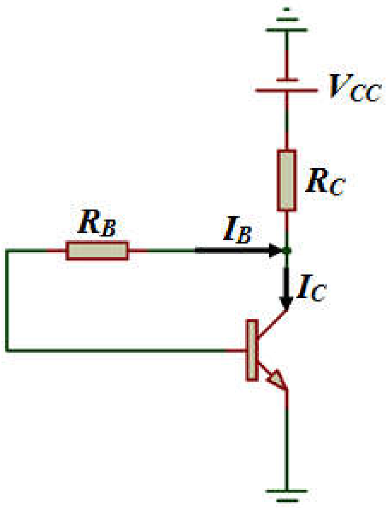


Figure 13. Biasing by collector feedback

$$V_{CC} = R_C(I_B + I_C) + R_B I_B + V_{BE}$$
$$V_{CC} = R_C(I_B + I_C) + V_{CE}$$
$$I_B = \frac{1-\alpha}{\alpha}I_C - \frac{I_{CB0}}{\alpha}$$

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:

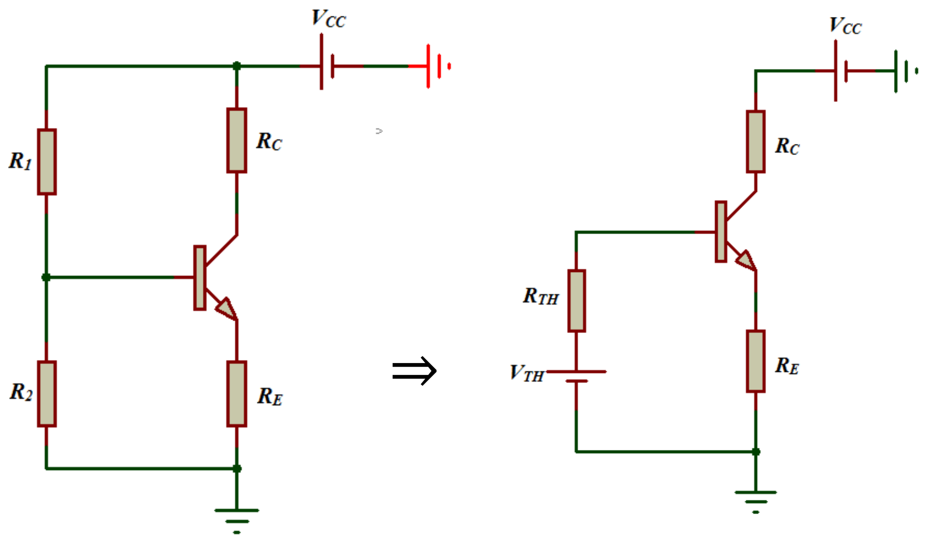


Figure 14. Biasing by resistor in series with the emitter

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

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

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:

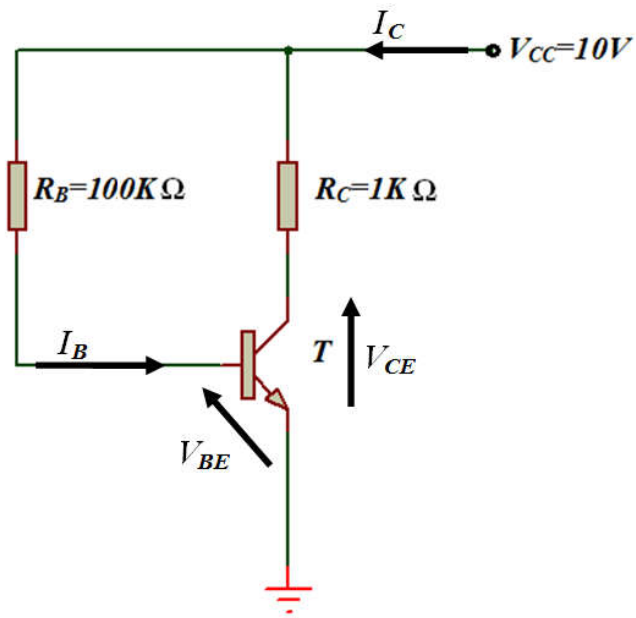
$$S = \frac{1 + \frac{R_{TH}}{R_E}}{1 + \frac{R_{TH}}{R_E}(1-\alpha)}$$

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}

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

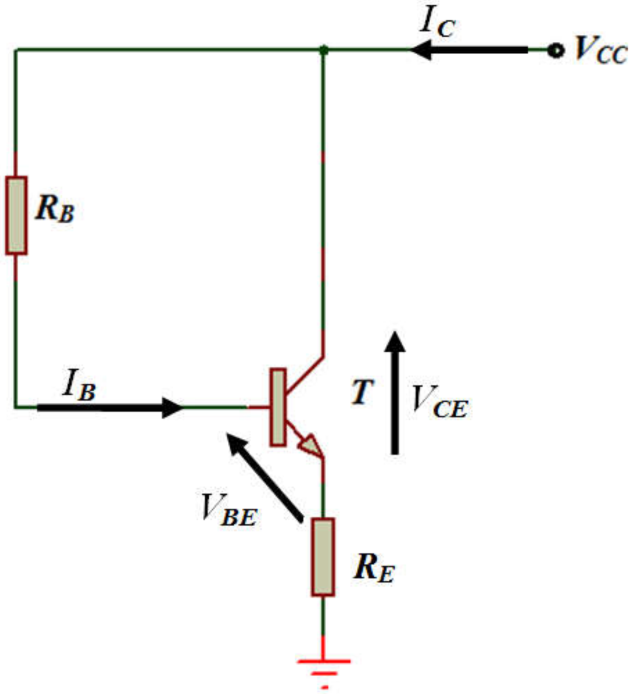
$\boldsymbol{V_{CC}=R_B I_B+V_{BE}}$ **(2)**

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

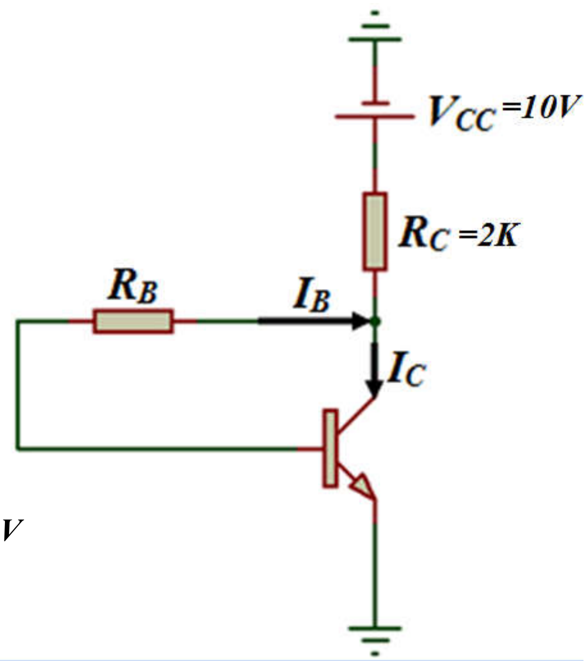
$\Rightarrow \boldsymbol{R_E = 2K\Omega}$

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

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

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

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}) ⇨ **I_C=2.5mA**

$I_C=\beta I_B$⇨I_B= I_C/β= 2.5 10^{-3}/50 ⇨ **I_B=5 10^{-4}=50 μA**

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

⇨ **R_B=94 KΩ**

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

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

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

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

So **S=25**