COURSE CODE: *ELE 307*

COURSE TITLE: *Electronic Circuit I*

NUMBER OF UNITS: *3 Units*

COURSE DURATION: *Three hours per week*

COURSE DETAILS:

Course Coordinator: **Dr. A. O. Fakolujo**
Email:
Office Location: **Elect./Elect. Engineering Building**
Other Lecturers: **None**

COURSE CONTENT:

Review of two port network theory applied to transistor circuit. Transistor characteristics (bipolar and FET). Analysis of single and multistage transistor amplifier, frequency response analysis. Power amplifier: Class A,B, C and push-pull amplifier. Feedback amplifiers. Oscillators. Introduction to operational amplifiers. Stabilized power supply. Use of electronic device in voltage regulation. Review of elementary digital concept. Switching properties of electronic device.

COURSE REQUIREMENTS:

This is a compulsory course for all 200 level students in the College of Engineering. In view of this, students are expected to participate in all the course activities and have minimum of 75% attendance to be able to write the final examination.

READING LIST:

1. M.Razeghi - Fundamentals of Solid State Engineering. 2nd edition
2. Botslestad and Nashelesky . Electronic Devices and Circuit Theory Botslestad and Nashelesky
3. Theraja, B.L. and Theraja, A.K. "A textbook of Electrical Technology". S. Chard & Company Ltd, Ram Nagar, New Delhi – 110055 (2005).

4. Basavaraj, B. and Shi Vashankar, H.N. "Basic Electronics". 2nd Edition. Gajendra Printin Press, Delhi (2004).

5. Jimmie, J.C. "Electronic devices and Circuits".2nd edition. Schaum's Outline Series. Mc Graw-Hill (2002).

LECTURE NOTES

1.0 Review of 2-port network theory applied to transistor circuits.

2.0 Transistor Characteristics

2.1 The Transistor

There are two basic types of transistors. They are :

1. The bipolar junction transistor (BJT)
2. The field-effect transistor (FET)

2.1.1 The bipolar transistor

This is used in two broad areas of electronics namely :

a. As linear amplifiers to boost an electrical signal
b. As an electronic switch.

The bipolar transistor can be viewed as two P-N junctions connected back to back. There are two types of bipolar transistors as shown in figure 2-1

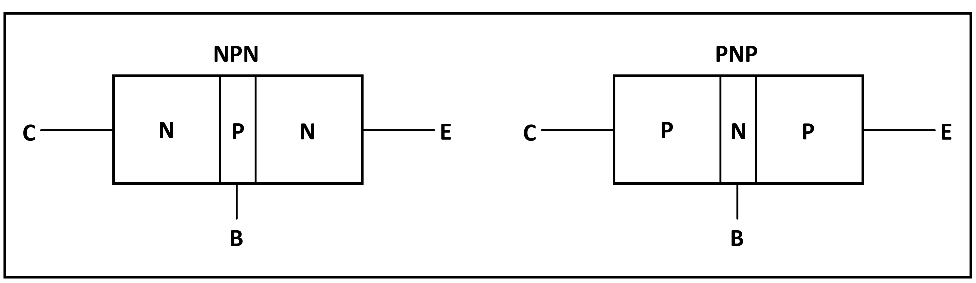

Figure 2-1

The transistor has three terminals: **C -Collector, B - Base, E -Emitter**

Its symbols are:

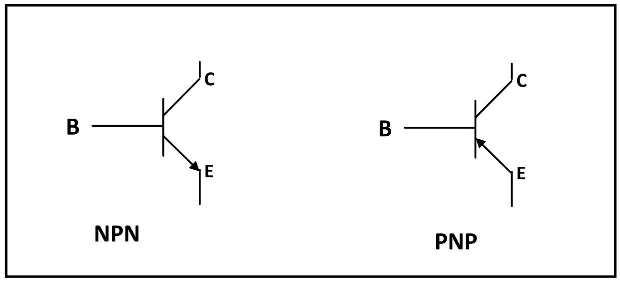

Figure 2-2

The PNP transistor works the same way as NPN only in opposite current flow and voltage bias. . However let us consider the explanation using NPN. Some students feel that they can remember whether the arrow of the device symbol in pointing in or out by matching the letters of the transistor type with the appropriate letters of the phrases "pointing in" or "not pointing in." For instance, there is a match between the letters ***npn*** and the italic letters of ***n**ot **p**ointing i**n*** and the letters ***pnp*** with ***p**ointing i**n***.

2.1.2 Transistor biasing

It is essential to apply voltages of correct polarity across the two junctions of transistor for it to work properly. For normal operation; **emitter-base junction** is always **forward biased** and **collector-base junction** is always **reverse biased.**

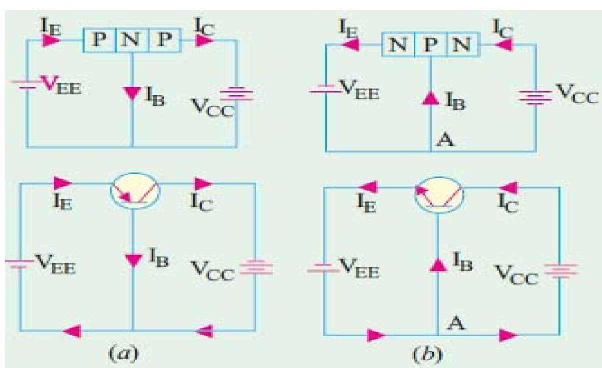

Figure 2-3

The transistor is connected in two electrical circuits. One is using the C_E junction and the V_{CC} voltage source. The second one is using the B_E junction and a V_{BB} voltage source as shown in the following figure.

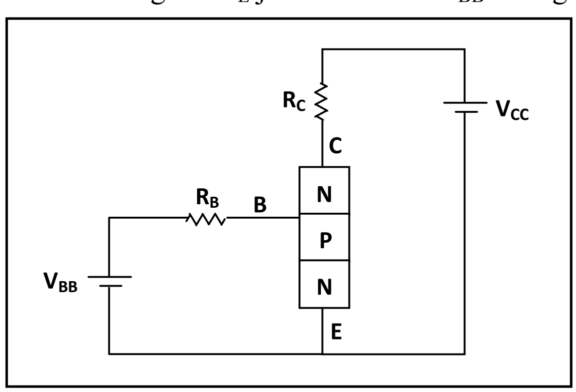

Figure 2-4

The C_E junction may viewed as two diodes back to back:

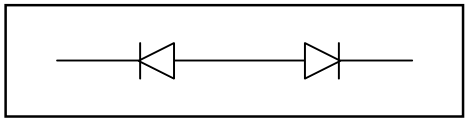

Figure 2-5

If B_E circuit is not activated, the C_E resistance is very high and current is very low.

In B_E circuit the B_E junction is in forward bias and electrons flow from E to B. Because the base is very thin, more electrons flow through the B_E junction than can be absorbed by the base. The base is filled by free electrons, which are pulled by the positive potential of the C (collector) terminal. That's the reason why we get current through the collector and why we can't implement a transistor with two separate diodes.

The current through the emitter (I_E) is divided into two currents - the base current (I_B) and the collector current (I_C).

$$\mathbf{I_E = I_C + I_B} \qquad \textbf{(2.1)}$$

The collector current, however, is comprised of two components—the majority and minority carriers. The minority-current component is called the *leakage current* and is given the symbol I_{CO} (I_C current with emitter terminal *O*pen). The collector current, therefore, is determined in total by Eq. (2.2).

$$I_C = I_{C\text{majority}} + I_{CO\text{minority}} \qquad \textbf{(2.2)}$$

Because of the thin layer of the base, **I_B is much smaller than the I_C.** The ratio between I_C and I_B is fixed and is one of the transistor parameters - β.

$$\boxed{\beta = \frac{I_C}{I_B}} \qquad \textbf{(2.3)}$$

2.1.3 Transistor Amplifying Action

Typical values of voltage amplification for the common-base configuration vary from 50 to 300. The current amplification (I_C / I_E) is always less than 1 for the common-base configuration. This latter characteristic should be obvious since $\boldsymbol{I_C = \alpha I_E}$ and α is always less than 1.

The basic amplifying action was produced by transferring a current *I* from a low to a high-*resistance* circuit. The combination of the two terms in italics results in the label *transistor;* that is,

Transfer+ resistor –> transistor

2.1.4 Transistor Circuit Configuration

There are basically three types of configurations for operating a transistor:

1. Common base (CB)
2. Common emitter (CE)
3. Common collector (CC)

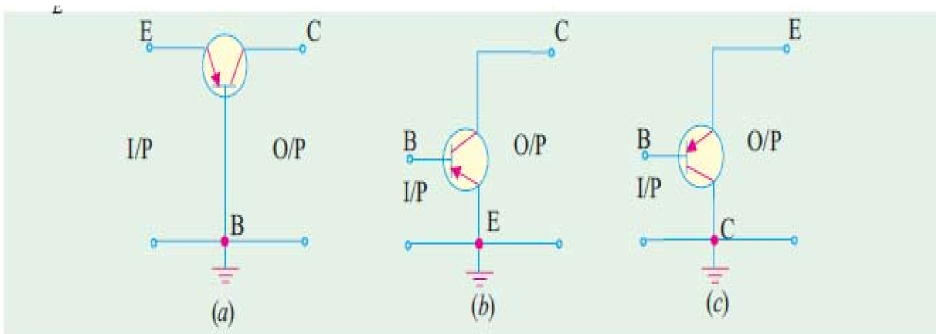

Figure 2-6

2.1.5 The transition characteristic

The transistor transition characteristic describes the relationship between I_C and I_B shown in the following figure:

The base of the transistor is significantly thinner than its collector and its emitter. A small change of the base current, significantly affects the collector current as shown in the graph below. Figure
2-7

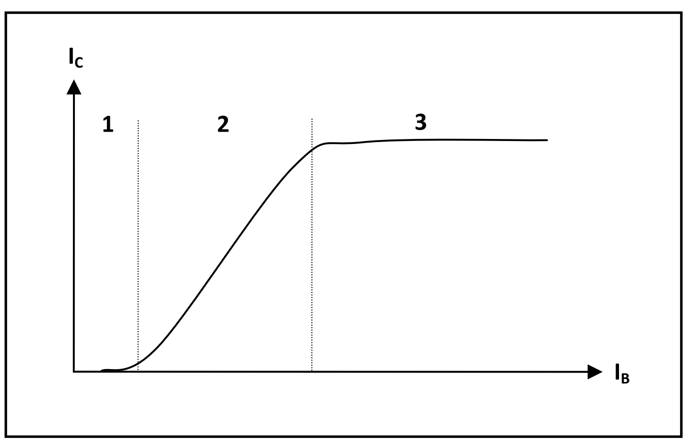

Figure 2-7

This graph has 3 regions:

1) The **CUTOFF** region. In this range $V_{BE} < 0.5V$ and I_B and I_C are very small.

2) The **LINEAR** region. In this range the transistor acts as a linear current amplifier and $I_C = \beta \cdot I_B$. β is one of the transistor's parameters, depending on the base width. Typical values are in the range 50 - 200 but can be as high as 800. In the linear range $V_{BE} = 0.6 - 0.7V$.

3) The **SATURATION** region. In this region, changes in I_B do not affect the I_C current. In this range $V_{BE} = 0.7 - 0.8V$.

Another important characteristic is the output characteristic, which describes the relationship between I_C and V_{CE} for a certain I_B.

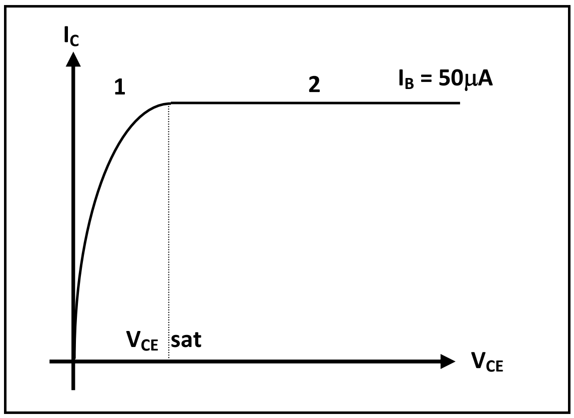

Figure 2-8

In the output characteristic, we can find two regions.

1) The **SATURATION** region. In this range $V_{CE} < 0.2V$ (V_{CE} sat) and the relationship between I_C and I_B is **not** $I_C = \beta \cdot I_B$.

2) The **LINEAR** region. In this range, I_C is constant and depends on I_B only and **not** on V_{CE}.

If we change I_B, we will get another output characteristic. The different output characteristics may be drawn on a graph to show the relationship between I_C, I_B and V_{CE} as shown in figure 2-9:

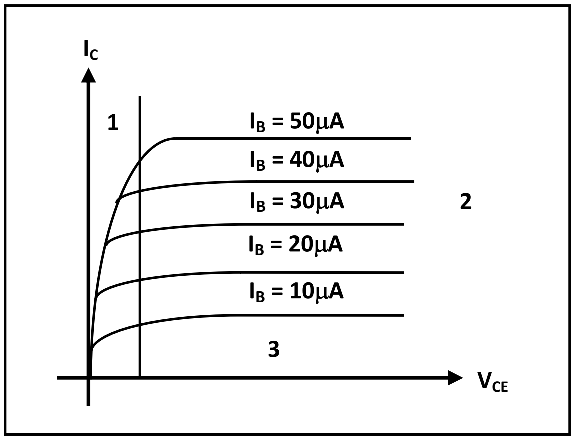

Figure 2-9

We can see how I_C depends on I_B and on V_{CE}. In this graph, we can find three regions:

1) The **SATURATION** region. In this range $V_{CE} < 0.2V$ (V_{CE} sat) and $I_C = \beta \cdot I_B$.

2) The **LINEAR** region. In this range I_C does not depend on V_{CE}, but on I_B according to the formula $I_C = \beta \cdot I_B$.

3) The **CUTOFF** region. In this range, I_B and I_C are very small.

2.1.6 Input or driving point characteristics for a common-base silicon transistor amplifier

To fully describe the behavior of a three-terminal device such as the common-base amplifiers requires two sets of characteristics—one for the ***driving point*** or ***input*** parameters and the other for the ***output*** side. The input set for the common-base amplifier as shown in Fig. 2-10 will relate an input current (I_E) to an input voltage (V_{BE}) for various levels of output voltage (V_{CB}).

The output set will relate an output current (I_C) to an output voltage (V_{CB}) for various levels of input current (I_E). The output or *collector* set of characteristics has three basic regions of interest. Input or driving point characteristics for a common-base silicon transistor amplifier is shown in figure 2-10.

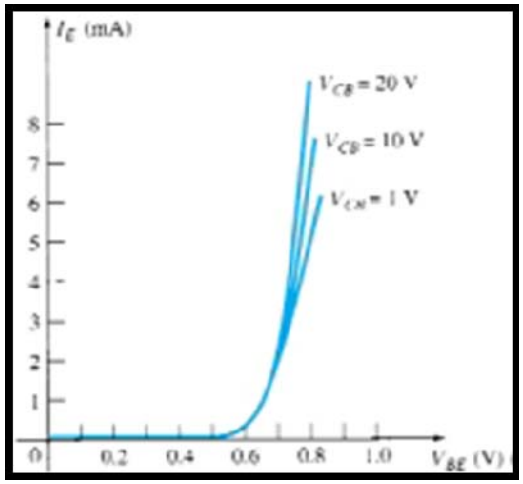

Figure 2-10

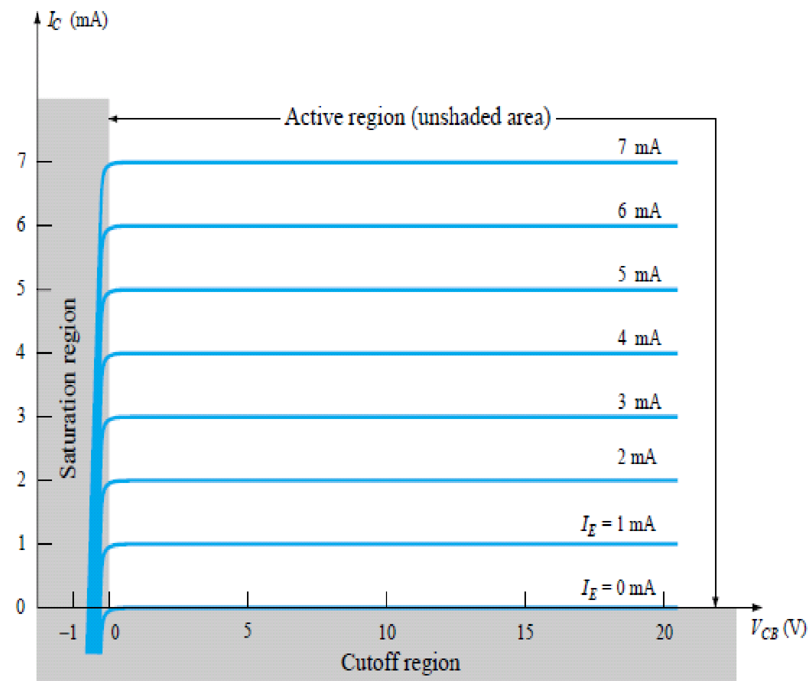

Figure 2-11

The active region is the region normally employed for linear (undistorted) amplifiers. In particular:

In the active region the collector-base junction is reverse-biased, while the base-emitter junction is forward-biased.

The curves clearly indicate that *a first approximation to the relationship between IE and IC in the active region is given by*

$I_C \cong I_E$ (3.3)

increases so rapidly with temperature. Note in Fig. 2-11 that as the emitter current increases above zero, the collector current increases to a magnitude essentially equal to that of the emitter current as determined by the basic transistor-current relations. Note also the almost negligible effect of *VCB* on the collector current for the active region.

As inferred by its name, the cutoff region is defined as that region where the collector current is 0 A, as revealed on Fig. 2-11. In addition:

In the cutoff region the collector-base and base-emitter junctions of a transistor are both reverse-biased.

The saturation region is defined as that region of the characteristics to the left of V_{CB} _ 0 V. The horizontal scale in this region was expanded to clearly show the dramatic change in characteristics in this region. Note the exponential increase in collector current as the voltage V_{CB} increases toward 0 V.

In the saturation region the collector-base and base-emitter junctions are forward-biased.

The input characteristics of Fig. 3.7 reveal that for fixed values of collector voltage (V_{CB}), as the base-to-emitter voltage increases, the emitter current increases in a manner that closely resembles the diode characteristics.

In other words, the effect of variations due to V_{CB} and the slope of the input characteristics will be ignored as we strive to analyze transistor networks in a manner that will provide a good approximation to the actual response without getting too involved with parameter variations of less importance.

2. 2 Analysis of single and multistage transistor amplifiers, frequency response analysis

2.2.1 Load line and operating point

The idea is to determine the transistor operating point in the linear region. In this way, small changes in I_B will create big changes in I_C.

In the following circuits, we will show NPN and PNP circuits in parallel. The calculations are the same. Later we will use the NPN only because it is more popular in circuits. We will also use the silicon parameters.

The basic bias circuit is the following one:

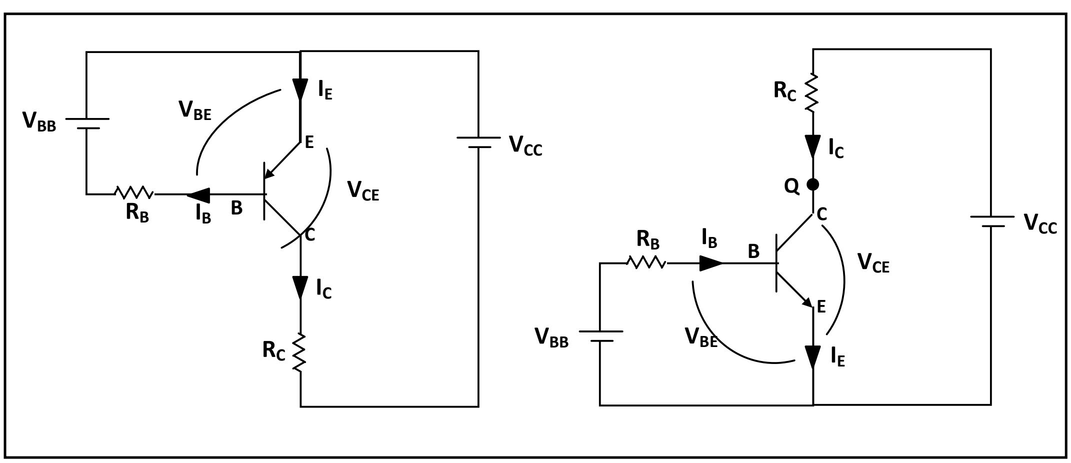

Figure 2-12

Example 1
Find the operating point (usually called the Q point) of the circuit above using the parameters below
V_{CC} = 12V, R_C= 2KΩ, RB=40KΩ, V_{BB}=3V, β =50

SOLUTION: To find the operating point (usually called the Q point) means to calculate or to measure I_C and V_{CE}.

I_C and V_{CE} are parameters in a circuit called the output circuit and its equation is:

$$V_{CC} = I_C \cdot R_C + V_{CE}$$

$$\Uparrow V_{CE} = V_{CC} - I_C \cdot R_C$$

This is a line equation, which describes the dependency between I_C and V_{CE}. R_C is called the circuit load and that's why this line is called the load line.

When I_C = 0, then:

$$V_{CE} = V_{CC}$$

When V_{CE} = 0, then:

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

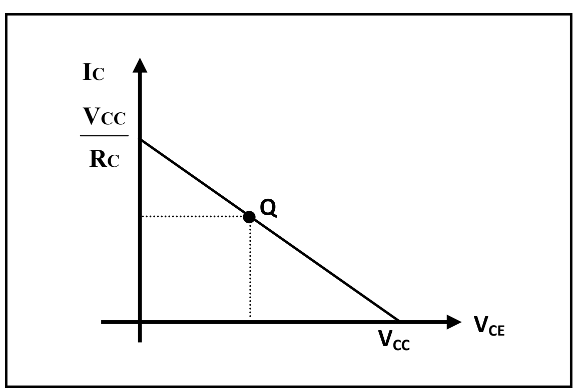

Figure 2-13

The solution starts with the input circuit equation:

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

We may assume $V_{BE} = 0.7V$ for silicon and 0.1V for germanium.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3-0.7}{40K} = 0.0575mA$$
$$I_C = \beta I_B = 50 \cdot 0.0575 = 2.875mA$$
$$V_{CE} = V_{CC} - I_C \cdot R_C = 12 - 2.875m \cdot 2K = 6.25V$$

Note:

If for example R_C is equal 4KΩ then:

$$V_{CE} = 12 - 5.75m \cdot 4K = -11V$$

V_{CE} cannot be negative. When it is, it means that the transistor is in the saturation region and I_C is not equal to $\beta \cdot I_B$.
In a saturation region:

$V_{CE} = 0.2V$

$$\Uparrow \quad \mathbf{I_C = \frac{V_{CC} - V_{CE}\,sat}{R_C} = \frac{12-0.2}{4K} = 2.95mA}$$

2.1.5 Fix bias circuit

In the above circuit, we use two voltage sources, which is unusual in transistor circuit. Instead, we can connect R_B to V_{CC} and use V_{CC} as V_{BB}.

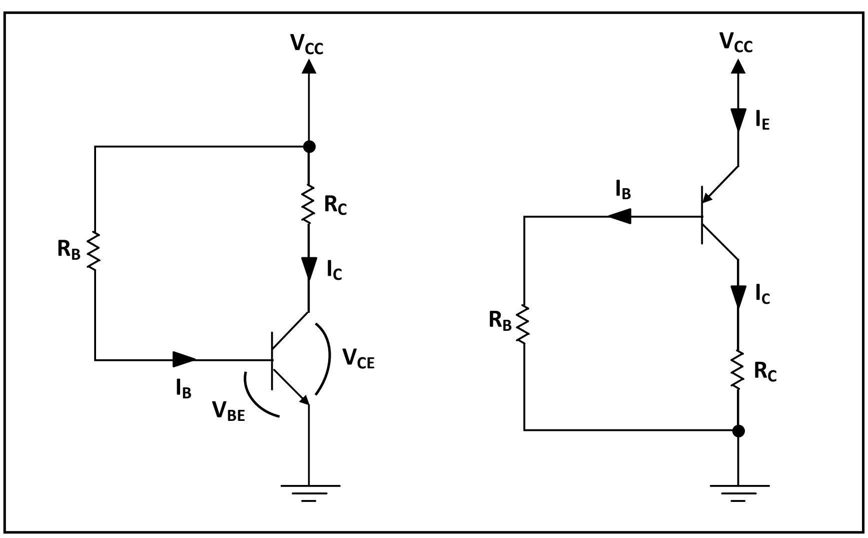

Figure 2-14

Observe the way we use to indicate the power supply terminals.

The input circuit equation is:

$$\mathbf{V_{CC} = I_B \cdot R_B + V_{BE}}$$
$$\mathbf{I_B = \frac{V_{CC} - V_{BE}}{R_B}}$$

The rest is the same as before.

$$\mathbf{I_C = \beta\, I_B}$$
$$\mathbf{V_{CE} = V_{CC} - I_C R_C}$$

We will design the system and calculate R_B. R_C is the load resistor and determined according to the output impedance and the amplifier gain we want to get .Usually is 1K-2KΩ. Let's assume R_C is 2KΩ as before.

Usually we want that the Q point will be in the middle of the load line so:

$$\mathbf{V_{CE} = \frac{V_{CC}}{2} = 6V}$$
$$\mathbf{I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{12-6}{2K} = 3mA}$$
$$\mathbf{I_B = \frac{I_C}{\beta} = \frac{3m}{50} = 0.06mA}$$

The input circuit equation is:

$$\mathbf{V_{CC} = I_B \cdot R_B + V_{BF} \Rightarrow R_B = \frac{V_{CC} - V_{BE}}{I_B B} = \frac{12-0.7}{0.06m} \cong 188K\Omega}$$

We need larger resistance than before in order to achieve the same operating point.

This circuit is called fix bias because I_B has a constant value.

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

The problem is that I_C depends on β and V_{CE} depends on I_C.

$$I_C = \beta I_B$$
$$V_{CE} = V_{CC} - I_C \cdot R_C$$

That means that the operating point depends on β.

When we use a bipolar transistor we can't know its β.

β has a very wide range (may reach 50-400 or 100-800). Also, if we have a circuit that works properly and we have to replace the transistor, the operating point may change significantly.

If we double β from 50 to 100 I_C will be doubled and the transistor will enter into saturation mode. Check this.

The fix bias is used when we use the transistor as a switch .In this application, the transistor is applied in two states only - the cutoff state and the saturation state.

2.1.6 Self bias circuit

When we use the transistor as an amplifier, which amplifies small changes in the input circuit into large changes of V_{CE} and I_C in the output circuit, it is very important that the operating point will be in the center of the load line.

In order to solve the fix bias problem we add resistor R_E to the emitter.
R_C = 2KΩ , R_E=500Ω , R_B =? , β =50
The input circuit equation is

$$V_{CC} = I_B \cdot R_B + V_{BE} + I_E \cdot R_E$$
$$I_E = I_B + I_C = I_B + \beta \cdot I_B = (\beta + 1) I_B$$
$$\Rightarrow V_{CC} = I_B \cdot R_B + V_{BE} + I_B(\beta + 1) \cdot R_E$$
$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1) R_E}$$

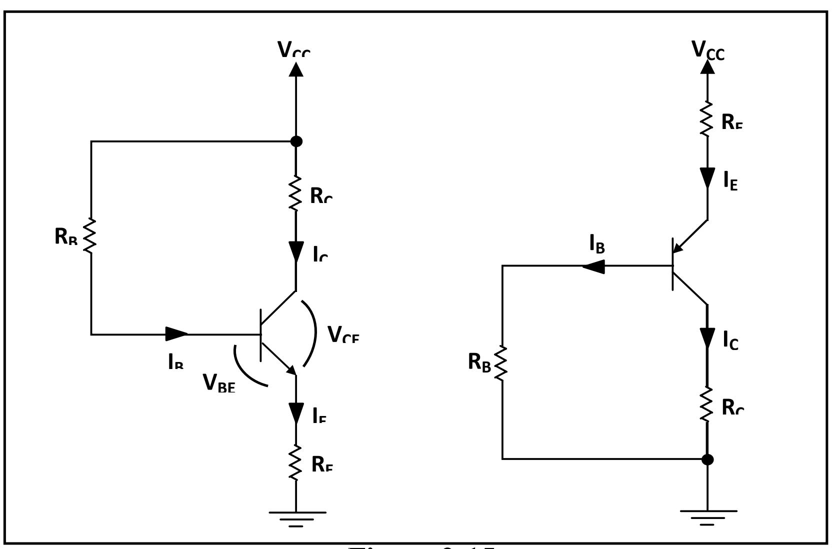

Figure 2-15

We can see that if β increases, I_B decreases and vice versa.

$$\mathbf{I_C = \beta \cdot I_B = \frac{\beta(V_{CC} - V_{BE})}{R_B + (\beta+1)R_E}}$$

If $R_B << (\beta + 1) R_E$ we may assume:

$$\mathbf{I_C} \cong \frac{\mathbf{\beta(V_{CC} - V_{BE})}}{\mathbf{(\beta+1)R_E}} \approx \frac{V_{CC} - V_{BE}}{R_E}$$

I_C is no more depended on β and so is the operating point.

$$V_{CE} = V_{CC} - I_C \cdot R_C - I_E \cdot R_E$$
$$I_E \approx I_C$$
$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

In order to get:

$$V_{CE} = \frac{V_{CC}}{2} = 6V$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C + R_E} = \frac{12 - 6}{2.5K\ \Omega} = 2.4 mA$$

$$I_B = \frac{I_c}{\beta} = \frac{2.4m}{50} = 0.048\ mA$$

$$V_{CC} = I_B \cdot R_B + I_B(\beta + 1)R_E$$

$$R_B = \frac{V_{CC} - V_{BE} - I_B(\beta+1)R_E}{I_B} = \frac{12 - 0.7 - 1.2}{0.048\ m} = 210\ K$$

Let’s double β from 50 to 100.

$$I_B = \frac{V_{CE} - V_{BE}}{R_B + (\beta+1)R_E} = \frac{12 - 0.7}{210K + 101 \cdot 0.5K} = 0.043 mA$$
$$I_C = \beta \cdot I_B = 4.3mA$$
$$V_{CE} = V_{CC} - I_C(R_C + R_E) = 12 - 4.3m \cdot 2.5K = 1.25V$$

The change was less than without R_E but still there is a change.

In order to increase the stability of the circuit we have to reduce the R_B resistance. We can do it by using V_{BB} or voltage divider as shown in the following figure.

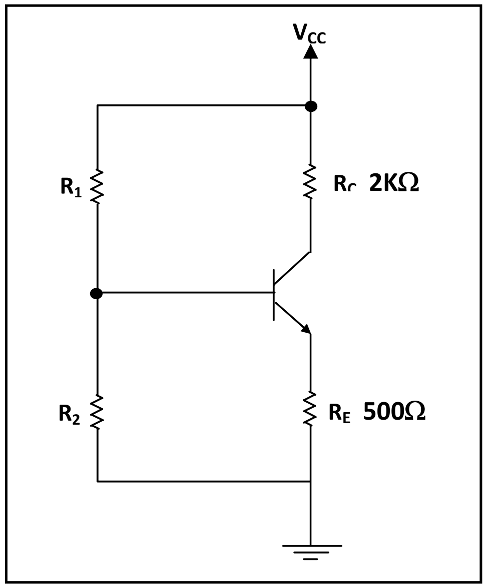

Figure 2-16

To reach the same operating point V_{CE} = 6V and I_C = 2.4mA we have to do the following steps:

$$V_{RE} \cong I_C \cdot R_E = 2.4 \cdot 0.5K = 1.2V$$
$$V_B = V_{BE} + V_{RE} = 0.7 + 1.2 = 1.9V$$
$$I_B = \frac{I_C}{\beta} = \frac{2.4}{50} = 0.48mA$$

If $I_B << I_2$ then changes in I_B will not affect the voltage on $R_2(V_{R2})$ so $V_{R2} = V_B$ = constant.

We may choose:

$$I_2 = 10I_B = 0.48mA$$
$$R_2 = \frac{V_B}{I_2} = \frac{1.9}{0.48m} = 4K\Omega$$
$$I_1 = I_2 + I_B = 0.48m + 0.048m = 0.53m$$
$$R_1 = \frac{V_{CC} - V_B}{I_1} = \frac{12 - 1.9}{0.53m} = 19K\Omega$$

We can check the circuit reaction by using the Thevenin transform of R_1, R_2, and V_{CC}.

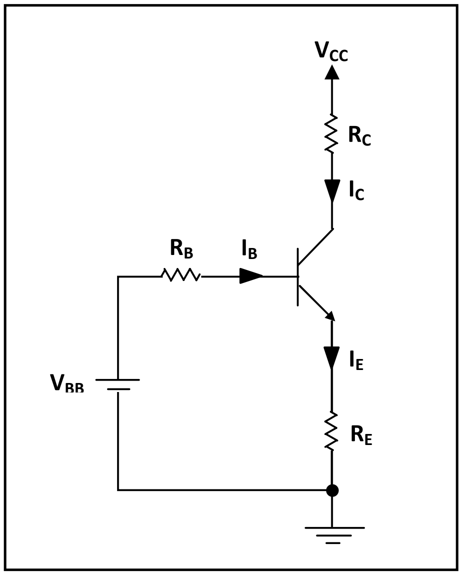

Figure 2-17

$$V_{BB} = \frac{V_{CC} \cdot R_2}{R_1 + R_2} = \frac{12 \cdot 4K}{23K} = 2.1V$$
$$R_B = \frac{R_1 \cdot R_2}{R_1 + R_2} = \frac{19K \cdot 4K}{23K} = 3.3K$$
$$R_B << (\beta + 1)R_E$$

Let's check the new operating point:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{2.1 - 0.7}{3.3K + 51 \cdot 0.5K} = 0.048mA$$
$$I_C = \beta I_B = 2.4mA$$
$$V_{CE} = V_{CC} - I_C(R_C + R_E) = 12 - 2.4m \cdot 2.5K = 6V$$

The same as before. Let's double now β to 100.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{2.1 - 0.7}{3.3K + 101 \cdot 0.5K} = 0.026mA$$
$$I_C = \beta I_B = 100 \cdot 0.026m = 2.6mA$$
$$V_{CE} = V_{CC} - I_C(R_C + R_E) = 12 - 2.6m \cdot 2.5K = 5.5V$$

The operating point changes very little although β is doubled.

The bipolar transistor circuit is the following one:

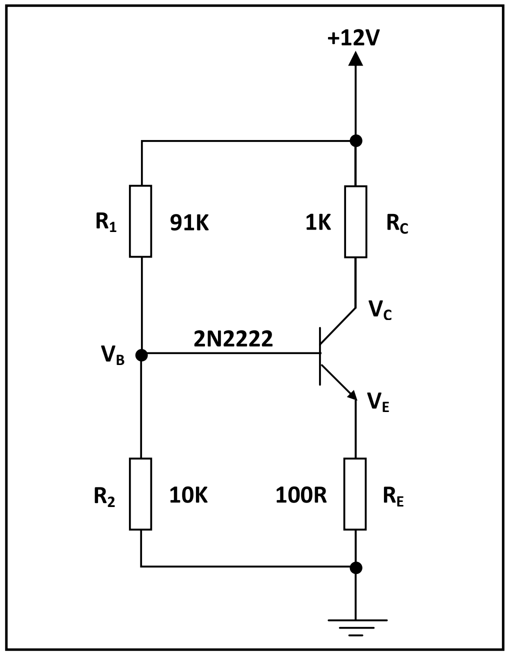

Figure 2-18

The Thevenin equivalent to this circuit is the following:

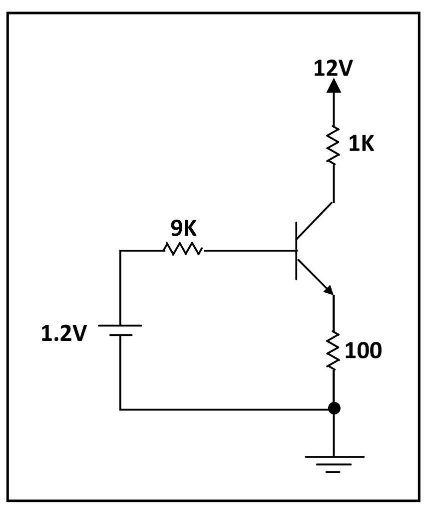

Figure 2-19

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{1.2 - 0.7}{9K + 101 \cdot 100} = \frac{0.5}{19K} = 26\mu A$$

Calculate I_C, V_{RC}, V_{RE} and V_{CE} assuming that β = 100.

2.2.1 Linear amplifier

One of the major applications of the transistor is as an amplifier. We supply a small AC signal to its input and get an amplified signal (voltage or current) in its output.

To distinguish between DC parameter and AC parameter (Voltage or Current) we use capital letter for DC and small letter for AC.

We describe an amplifier as follows:

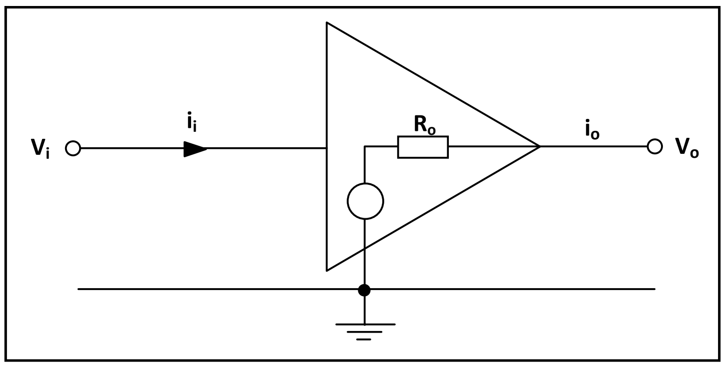

Figure 2-20

Amplifier parameters are A_V, A_i, R_i, R_o.

A_V is the voltage gain:

$$A_V = \frac{V_o}{V_i}$$

A_i is the current gain:

$$A_i = \frac{i_o}{i_i}$$

A_V and A_i do not have measurement units.

R_i is the input impedance:

$$R_i = \frac{V_i}{i_i}$$

R_o is the output impedance of the amplifier. It acts as a serial as a serial resistance located in the amplifier's output.

2.2.2 Bipolar transistor h parameters

In order to understand the behavior of the internal parts of the transistor to AC signals, an h parameter model was developed.

This model is shown in the following figure:

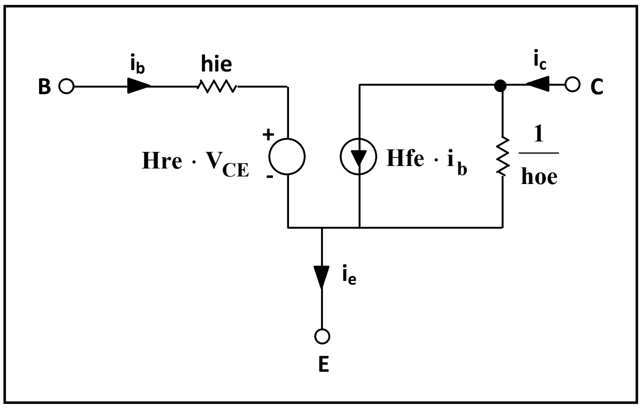

Figure 2-21

hie is an input resistance. Its typical value is 1-2KΩ. hie depends on the operating point according to the following formula:

$$hie = \frac{\beta \cdot 26}{I_E(mA)}$$

hoe represents the output resistance but the parameter value shows it continuance. We prefer to use resistance and that's why we use $\frac{1}{\mathbf{hoe}}$. The typical value of $\frac{1}{\mathbf{hoe}}$ is 40KΩ.

Usually, we find in the transistor data sheet the hfe parameter and h_{FE} which is β.

The signal in the input of the transistor affects the output. We can see a current source with the value $\text{hfe} \cdot i_b$ in the output branch. This is the AC current gain of the transistor. The typical value of hfe is 50-200.

The output also affects the input. We can see it as a voltage source in the input branch with the value $\text{hre} \cdot V_{CE}$. The typical value of hre is $2.5 \cdot 10^{-4}$. It is so small that we usually neglect it.

Usually we use the following h parameters model.

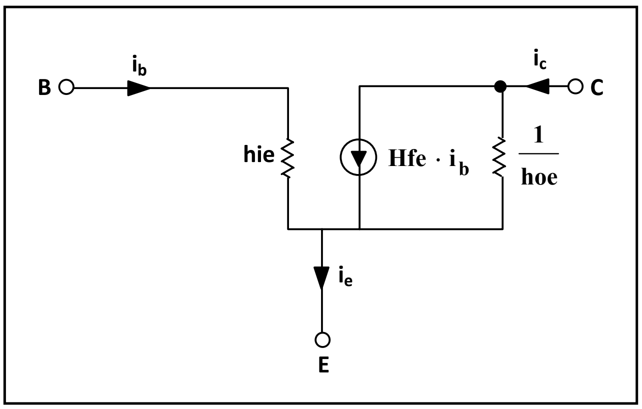

Figure 2-22

If R_C is less than 4KΩ we may neglect also the resistance $\frac{1}{\mathbf{hoe}}$. We will get the following model, which is easy for calculation and quit accurate.

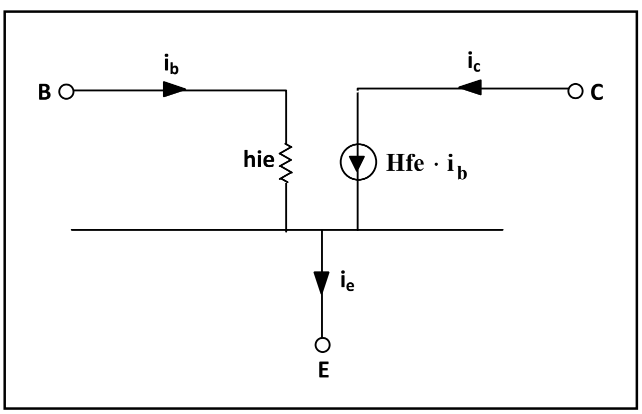

Figure 2-23

We will use this model for the following example.

In AC as in DC:

$$I_e = i_b + i_C$$

2.2.3 Common emitter amplifier

In the Common Emitter (C_E) amplifier, the input signal is supplied to the base and the output signal is received on the collector.

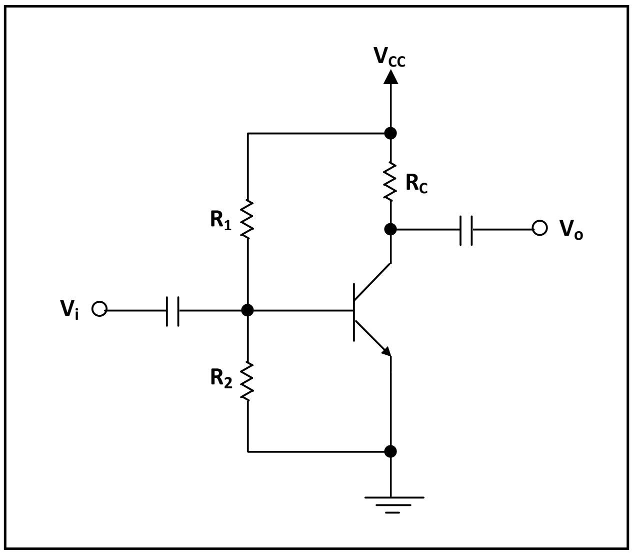

Figure 2-24

In h parameter model, we refer to a capacitor and a voltage source as a short circuit. In this way R_1 and R_2 are connected in parallel in AC analyze.

The h parameter model of the above circuit is the following one.

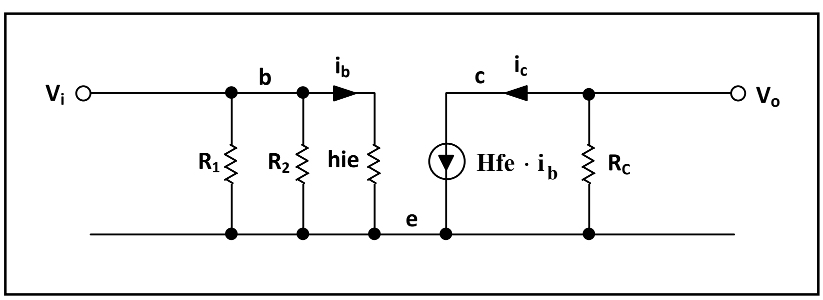

Figure 2-25

We will replace R_1 in parallel to R_2 with the equivalent resistor R_B.

$$R_B = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

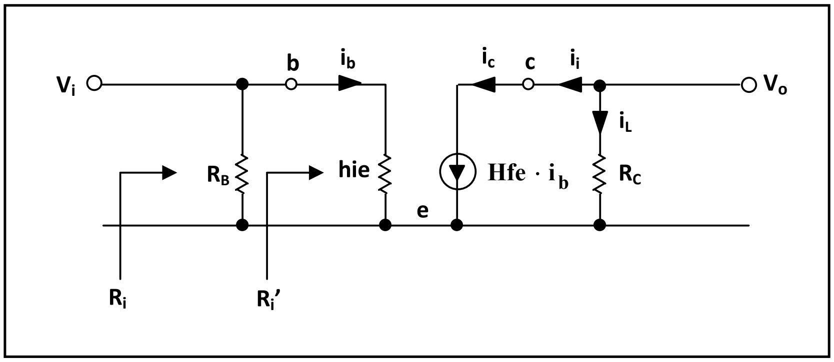

Figure 2-26

If we use R_E resistor for self bias but we do not want it to affect the AC analyze we by pass it with a capacitor.

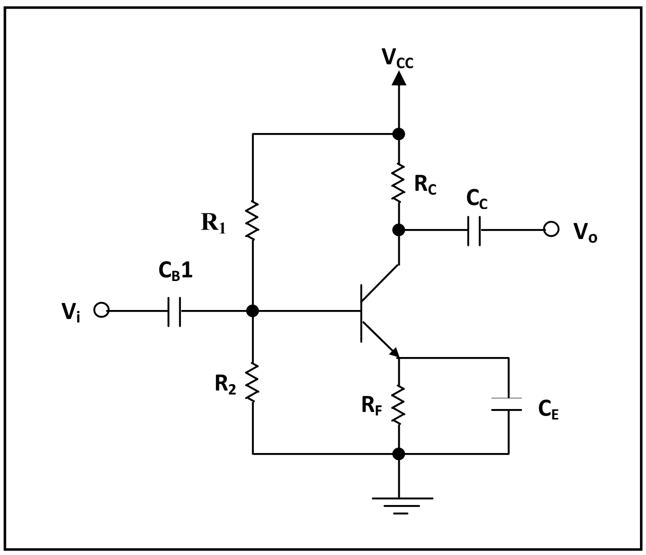

Figure 2-27

As we said, we refer to a capacitor as a short circuit in AC analyze.

Voltage gain A_V:

$$A_V = \frac{V_O}{V_i}$$

$$V_i = i_b \cdot hie$$

$$V_o = I_L \cdot R_C$$

$$I_L = -i_C = -hfe \cdot i_b$$

$$\Uparrow \quad V_o = -hfe \cdot i_b \cdot R_C$$

Although we are dealing with AC voltage and current, we use polarity. It is important because in this way, we can see the output signal is in the same phase of the input signal or inverted. It is in the opposite direction of i_c.

$$A_V = \frac{V_o}{V_i} = -\frac{hfe \cdot i_b \cdot R_C}{i_b \cdot hie} = -\frac{hfe \cdot R_C}{hie}$$

The goal is to have a formula without variables (like i_b, V_i, V_o) and only with h parameters and resistors.

The negative sign indicates that this amplifier is inverted. The output voltage is shifted by 180° from the input voltage.

R_i input resistance:

In order to calculate the input resistance, first we calculate the input resistance without the R_B influence. Afterwards we calculate the general input resistance R_i.

$$R_i' = \frac{V_i}{i_b}$$

$$V_i = i_b \cdot hie$$

$$R_i' = \frac{i_b \cdot hie}{i_b} = hie$$

$$R_i = R_B | R_i'$$

Current Gain A_I:

$$A_i = \frac{i_o}{i_i}$$

The simple way for calculation is to use A_V and R_i for calculating A_I.

$$V_o = -i_o \cdot R_2 \qquad V_i = i_i \cdot R_i$$

$$i_o = -\frac{V_o}{R_L} \qquad i_i = \frac{V_i}{R_i}$$

$$A_I = \frac{i_o}{i_i} = \frac{-\frac{V_o}{R_L}}{\frac{V_i}{R_i}} = -\frac{V_o}{V_i} \cdot \frac{R_i}{R_L}$$

$$\boxed{A_I = -A_V \frac{R_i}{R_L}}$$

Source Voltage gain A_{VS}:

If a voltage V_S source is connected to the amplifier through resistor R_S.

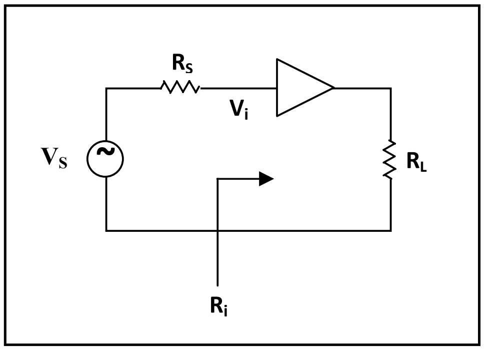

Figure 2-28

$$A_{VS} = \frac{V_o}{V_S}$$

$$V_i = -\frac{V_S \cdot R_i}{R_i + R_S}$$

$$V_S = -\frac{V_i (R_i + R_S)}{R_i}$$

$$A_{VS} = \frac{V_o}{V_S} = \frac{V_o}{V_S} = \frac{V_o}{V_i \frac{R_i + R_S}{R_i}}$$

$$A_{VS} = \frac{V_o}{V_i} \cdot \frac{R_i}{R_i + R_S}$$

$$\boxed{A_{VS} = A_V \cdot \frac{R_i}{R_i + R_S}}$$

Output Impedance R_O:

Output impedance is an imaginary resistance, which is in series with the output line.

Our output is composed of a current source $hfe \cdot i_b$ and a parallel resistor R_C.

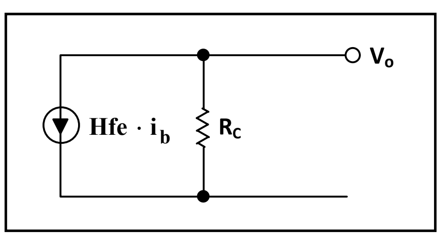

Figure 2-29

With Norton transform, we may transform it to a voltage source and a resistor in series as follows:

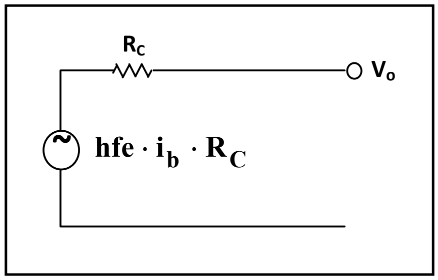

Figure 2-30

Here it is easy to see that:

$R_o = R_C$

2.2.4 Common Emitter with R_E (C_E+R_E) Amplifier

Two problems we have in C_E amplifier:

1) $A_V = \dfrac{hfe \cdot R_C}{hie}$

Like β we can't know exactly the hfe values and it is different in every transistor, even in the same kind.

2) ***$R_i = R_B \,||\, hie$***

Usually hie is very small so $R_i \cong$ hie. In voltage amplifier, we prefer high input impedance.

The C_E+R_E amplifier solves these two problems.

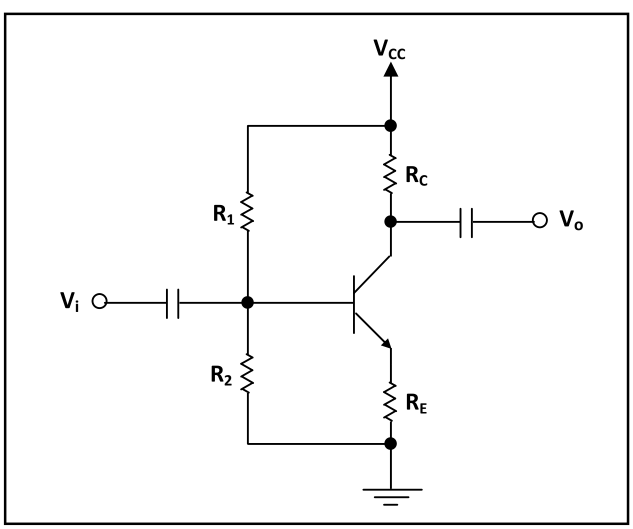

Figure 2-31

The h parameters model is as follows:

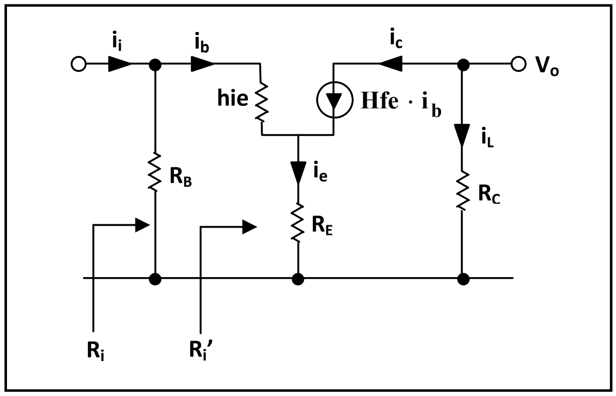

Figure 2-32

$\underline{A_V}$

$$V_i = i_b \cdot hie + i_e \cdot R_E$$
$$V_i = i_b \cdot hie + (i_b + hfe \cdot i_b)R_E$$
$$V_i = i_b \cdot hie + i_b(hfe+1)R_E$$
$$V_i = i_b\left[hie + (hfe+1)R_E\right]$$
$$V_o = i_L \cdot R_C$$
$$V_o = -i_b \cdot hie \cdot R_E$$
$$A_V = \frac{V_o}{V_i} = \frac{-i_b \cdot hie \cdot R_C}{i_b\left[hie+(hfe+1)R_E\right]} = -\frac{hfe \cdot R_C}{hie+(hfe+1)R_E}$$
$$hie << (hfe+1)R_E$$
$$A_V \cong \frac{hfe \cdot R_C}{(hfe+1)R_E}$$
$$\boxed{A_V \cong -\frac{R_C}{R_E}}$$

The gain depends no more on hfe or hie. With R_C and R_E we can determine the amplifier gain.

$$\frac{R_i}{R_{i'}} = \frac{V_i}{i_b} = \frac{i_b\left[hie+(hfe+1)R_E\right]}{i_b}$$
$$R_{i'} = hie + (hfe+1)R_E$$
$$R_i = R_2 \| R_{i'}$$

Now we have to select R_1 and R_2 with high resistance for having high input impedance. It conflicts the requirement for low R_B resistance for DC operating point stability. As everything in life, we have to compromise.

$\underline{A_I}$

$$\boxed{A_I = -A_V \frac{R_i}{R_I}}$$

$\underline{A_{VS}}$

$$\boxed{A_{VS} = A_V \frac{R_i}{R_i + R_S}}$$

$\underline{R_o}$

$$\boxed{R_o = R_C}$$

2.2.5 Emitter follower amplifier

This circuit is also called Common Collector (CC) amplifier.

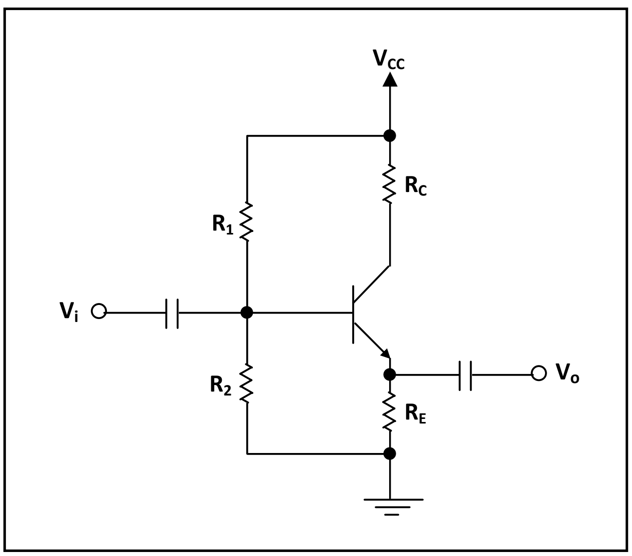

Figure 2-33

The h parameter model is as follows:

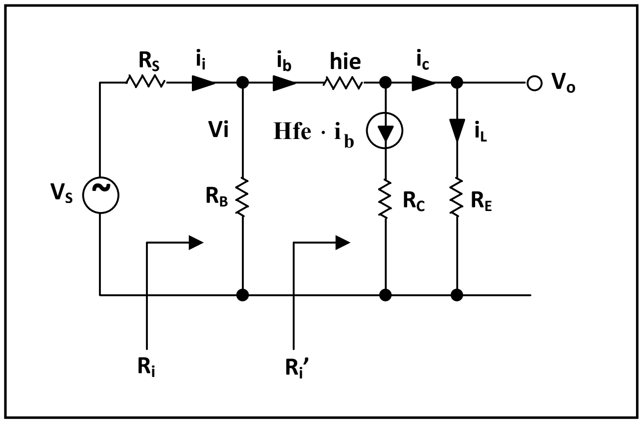

Figure 2-34

$\underline{A_V}$

$$V_i = i_b \cdot hie + i_e \cdot R_E$$

$$V_i = i_b \cdot hie + i_b (hfe \cdot 1) R_E$$

$$V_i = i_b \left[hie + (hfe+1) R_E \right]$$

$$V_o = i_L \cdot R_L = i_e \cdot R_L = i_b (hfe \cdot 1) R_E$$

$$A_V = \frac{V_o}{V_i} = \frac{i_b \cdot (hfe+1) R_E}{i_b \left[hie + (hfe+1) R_E \right]}$$

$$\boxed{A_V = \frac{(hfe+1) R_E}{hie + (hfe+1) R_E} \cong 1}$$

The output and the input signals are almost the same and with the same phase. That's why it is called emitter follower. The emitter follows the base.

We use this circuit as a buffer. It has high input impedance and very low output impedance.

$\underline{R_i}$

$$V_i = i_b \left[hie + (hfe+1) R_E \right]$$

$$R_{i'} = \frac{V_i}{i_b} = hie + (hfe+1) R_E$$

$$\boxed{R_i = R_B \| R_{i'}}$$

$\underline{A_I}$

$$\boxed{A_I = -AV \frac{R_i}{R_E}}$$

$\underline{A_{VS}}$

$$\boxed{A_{VS} = AV \frac{R_i}{R_i + R_S}}$$

In order to calculate R_o we have to short circuit V_S. The input branch is then composed of R_S || R_B+hie. The current through this branch is i_b.

This branch is in parallel with R_E which has the current $i_b(hfe+1)$.

If we convert the current source into a voltage source, its R_o will be:

$$\frac{R_S \| R_B + hie}{hfe+1} \| R_E$$

This is a very low impedance.

2.2.6 Common base amplifier

In Common Base (CB) amplifier, the input signal is supplied to the emitter and the output signal is received on the collector.

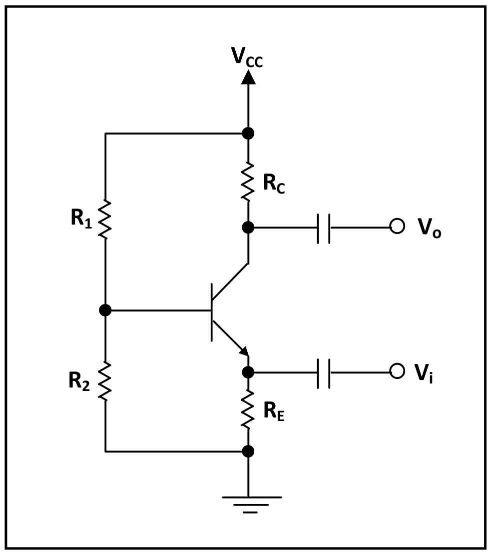

Figure 2-35

This circuit was common, in the past, in high frequency amplifiers. Today, the transistors' frequency response is much better, so this circuit is less popular. Its R_i is low and its R_o is high (the opposite of a good amplifier characteristics).

The h parameter model is as follows:

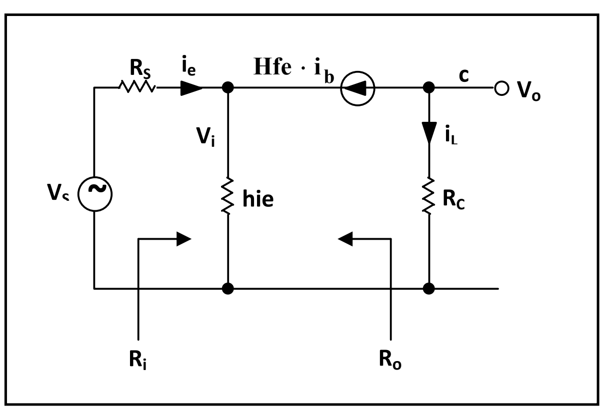

Figure 2-36

Analyze the circuit and prove that:

$$A_i = \frac{hfe}{1+hfe}$$

$$R_i = \frac{hie}{1+hfe}$$

$$A_V = \frac{hfe \cdot R_C}{hie}$$

$$R_o \approx R_C$$

2.2.7 How to measure amplifier parameters

In order to measure the amplifier's parameters, we connect it to an alternate voltage source V_S through a series resistance R_S and its output to a load resistance R_L as follows:

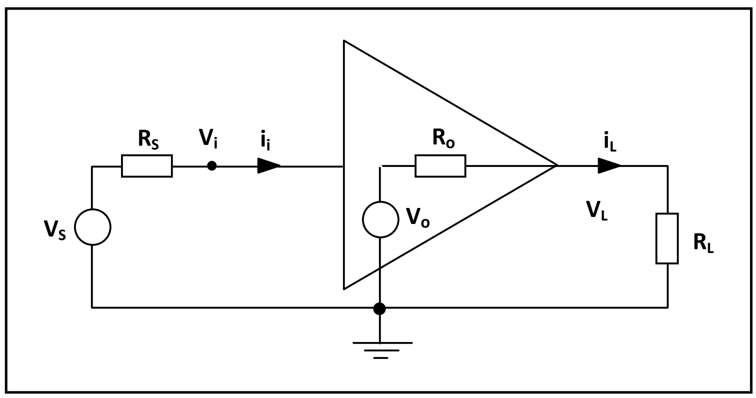

Figure 2-37

The absolute value of i_o is equal to i_L which equals:

$$i_L = \frac{V_L}{R_L}$$

i_i equal to the current through R_S:

$$i_i = \frac{V_{RS}}{R_S}$$

To calculate the R_o we measure V_L without R_L (V_o) and with R_L (V_L).

R_o is determined according to the following formula:

$$V_o - I_L \cdot R_o = V_L$$
$$V_o - \frac{V_L}{R_L} \cdot R_o = V_L$$
$$R_o = \frac{V_o - V_L}{V_L} \cdot R_L$$

2.2.8 Series and parallel feedback

Usually the amplifier is an open loop system. The input signal is amplified according to the amplifier gain. The problem is that the gain is not accurate and may change dramatically when replacing component or at temperature change.

Let's look at the following diagram, which describes a system with negative feedback.

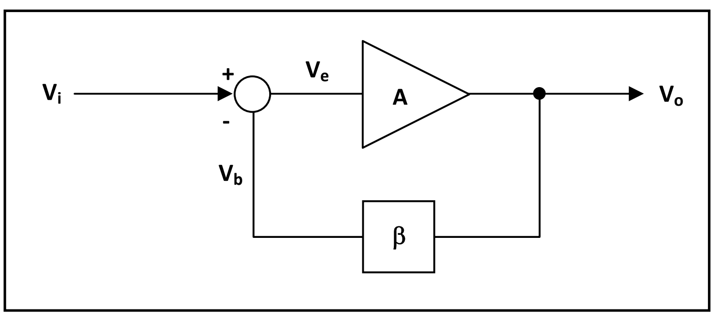

Figure 2-38

Vo is the voltage at the output. A part of it is fed back to the input negatively, i.e. it is subtracted from the input voltage. This parameter is called Vb (Vback) and its value is:

Vb = βVo

The voltage, which is fed into the amplifier that drives Vo, is called Ve (Verror) and is the difference between the input voltage Vi and the feedback voltage Vb.

Ve = Vi - Vb = Vi - βVo

Vo is the product of the amplification of Ve.

Vo = AVe = A(Vi - βVo)

In this equation, Vo (the output value) appears in both sides of the equation. We will isolate Vo to see the system equation. First, we open the parentheses:

Vo = AVi - βAVo

Now let's collect all the elements with Vo on the left:

$$\mathbf{V_o + \beta A V_o = V_i \cdot A}$$
$$\mathbf{V_o(1+\beta A) = V_i \cdot A}$$

Thus the final system equation is:

$$V_o = V_i \frac{A}{1+\beta A}$$

This is the formula for the amplification of a negative feedback control system.

In an open circuit system, A indicates the ratio between Vo and Vi. It is difficult to control exact amplification especially in a system in which there is an interference of the controlled variable, which affects the amplification of the amplifier.

To achieve accurate and stable amplification in the system, we see to it that the amplification A is as large as possible (even approaching infinity). β is obtained from an accurate attenuator such as a resistor voltage divider for example. The feedback system b does not have to contend with interferences to its output variable as it is connected directly into the amplifier's internal summation system (which presents a fixed load on b).

In cases where $\beta A >> 1$ and $A \rightarrow \infty$, we will have:

$$V_o = V_i \frac{A}{1+\beta A} \approx V_i \frac{A}{\beta A} = V_i \frac{1}{\beta}$$

As β is smaller than 1 the result is that Vo is greater than Vi. The system amplification is equal to $\frac{1}{\beta}$ and does not depend on the accuracy of the amplifier A. In other words, fluctuations in A (assuming that this value is still very high) will not affect Vo.

2.3.1 FIELD EFFECT TRANSISTOR

In the bipolar transistor, the current of the input circuit affects the operating point of the output circuit.

The Field Effect Transistor (FET) works differently. An electrical field in the input circuit affects the output circuit. There is no current in its control terminal.

There are two types of FETs. One is called JFET (Junction FET) and the other one is called MOSFET (Metal Oxide Silicon FET).

The two types are 3-leg transistors. The legs are D (Drain), S (Source) and G (Gate).

The electrical field of the JFET is one that exists in a reverse PN junction. The gate is the reverse PN junction.

The gate of the MOSFET is a metal gate isolated by oxide silicon from the drain and the source.

2.3.2 JFET – Junction Field Effect Transistor

There are two kinds of JFET – N channel and p channel. They are built as follows:

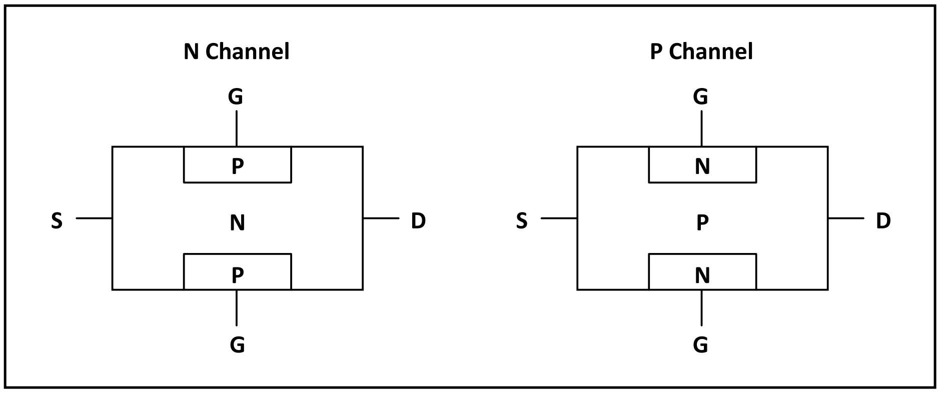

Figure 2-39

Their symbols are as follows:

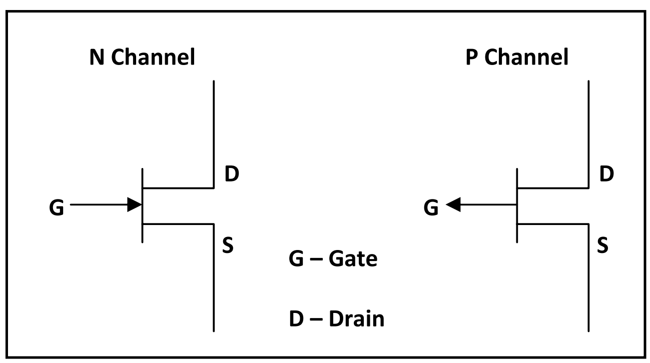

Figure 2-40

We will describe the N channel, which is more common. The P channel works the same with the opposite voltages.

When there is no voltage on the gate, the JFET conducts. The N material includes free electrons, so current can flow from D to S and from S to D. Usually, D is positive refer to S and current flows from D to S.

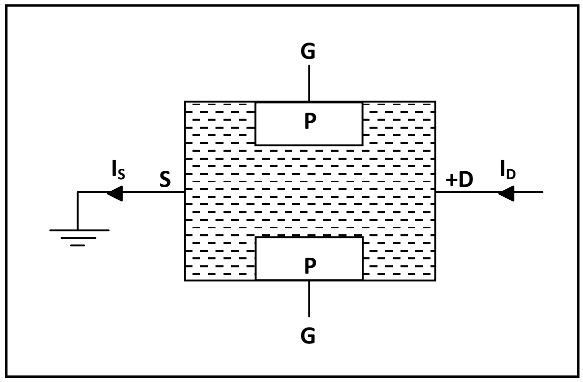

Figure 2-41a

When the gate of the N channel has negative voltage refer to the voltages of the S and D, depletion areas are surrounding the P material (the free electrons get a free way to the gate) as follows:

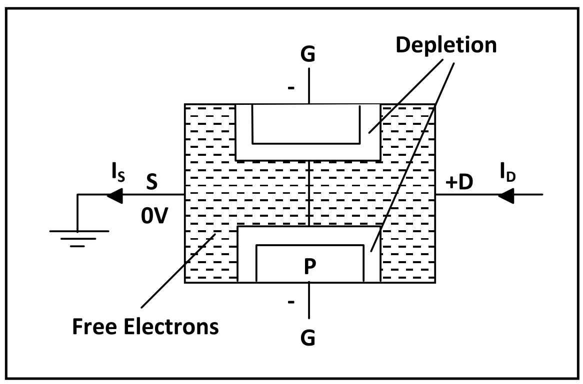

Figure 2-41b

D is positive refer to S, so it is more positive refer to G. This is why the depletion area is wider in the D side then in the S side. I_D is equal to I_S.
When the voltage V_{DS} increase, I_D increase, but the depletion areas near the D side expand, until they touch each other. This voltage is called V_p (Punch Voltage).

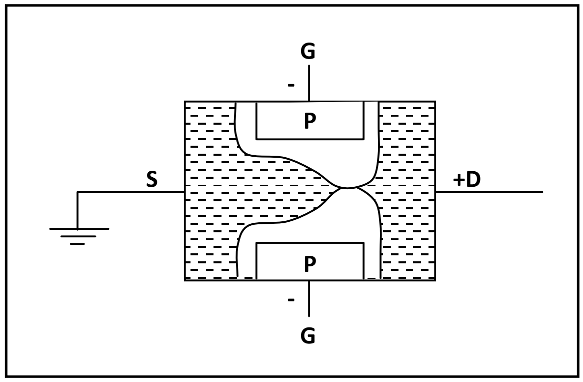

Figure 2-42

At this point, increasing V_{DS} does not affect I_D and I_D becomes constant. If V_{DS} is too high (over the maximum rating), the transistor beaks and the current goes high at once.

The output characteristic of the transistor is as follows:

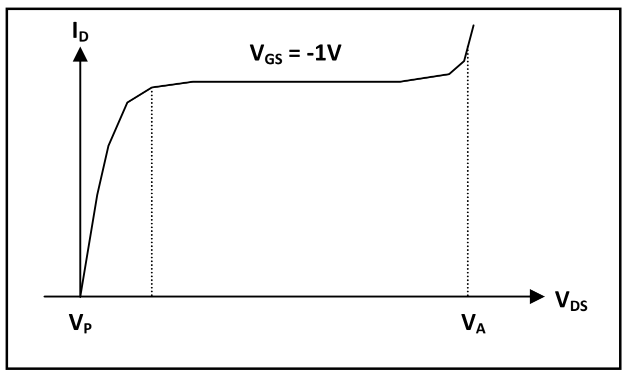

Figure 2-43

From now on, we disregard the V_A, because this is the breaking area and usually damages the transistor.

The area between V_P and V_A is called the linear area and all the FET calculations relate to this area.

The JFET characteristics depend on the V_{GS} voltage. As higher the voltage is (more negative) it creates a faster punching.

For different values of V_{GS} we get the following output characteristics.

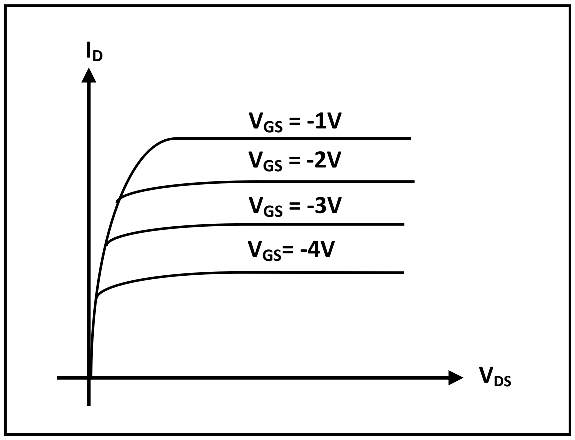

Figure 2-44

On a certain voltage of V_{GS}, I_D is so small, thus we call this area the cutoff area.

2.3.3 MOSFET

The second type of the FET is the MOSFET (Metal Oxide Semiconductor Field Effect Transistor). This transistor can be made by silicon only, because it is based on the characteristics of the silicon oxide. The MOSFET has 3 terminals- Drain, Source and Gate. The gate is insulated from the semiconductor material by silicon oxide, as shown in the following figure:

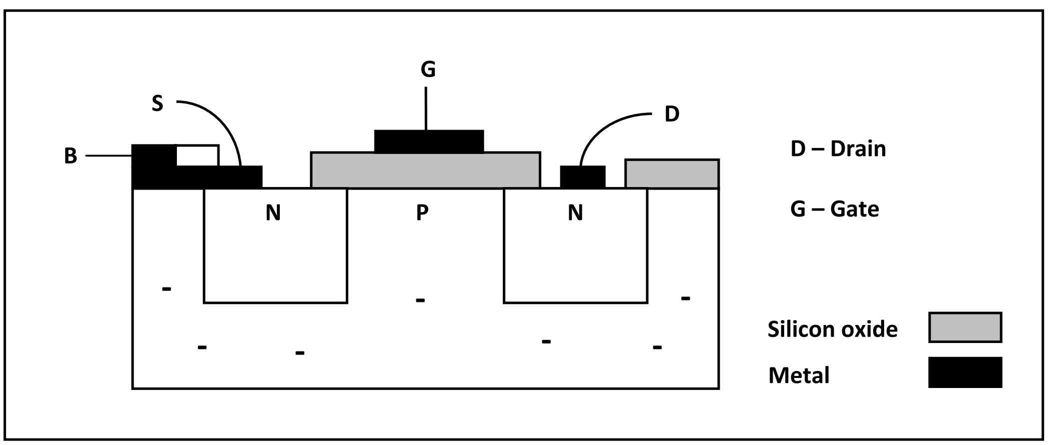

Figure 2-45

When there is no voltage on the gate, there is no current between D (Drain) and S (Source). The P substrate has holes as charge carrier, but also a few free electrons as minor charge carrier.

When we apply a positive voltage on the gate (between the gate and S and B (Bulk-Substrate) electrodes, the minor charge carriers (the free electrons) of the P-substrate are attracted to the gate. They are accumulated near the gate and create an n-type channel and the FET conducts.

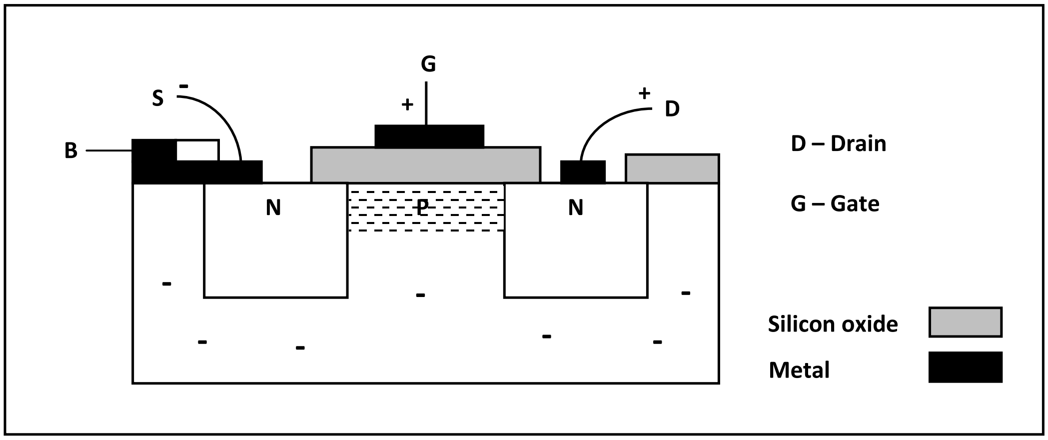

Figure 2-45

The voltage between the gate and the source is called V_{GS}. The higher the V_{GS} is, the wider is the n-type channel and the greater is ID.

There is another kind of MOSFET called P-channel MOSFET.

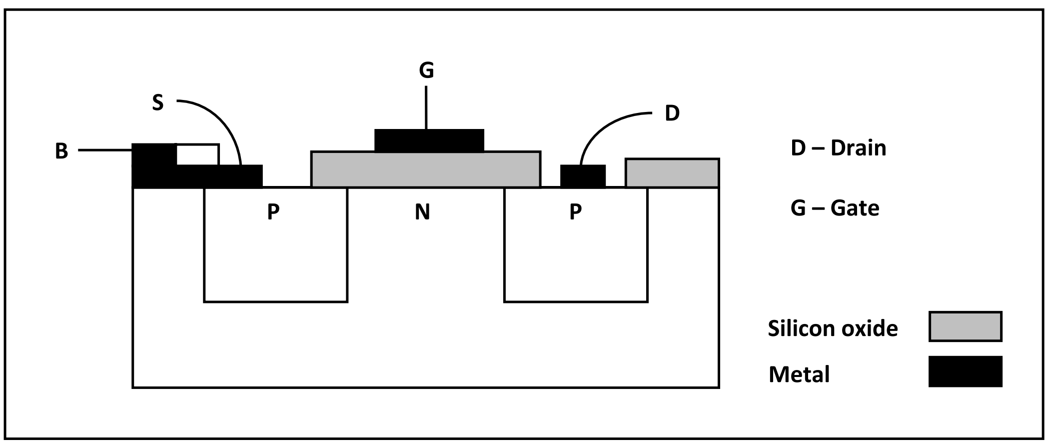

Figure 2-46

In this transistor, the holes are the charge carriers.

The MOSFET is called an enhancement MOSFET and its symbols are:

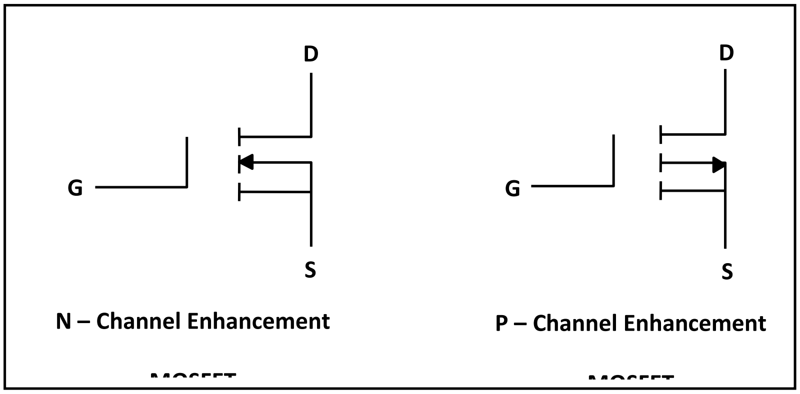

Figure 2-48

The MOSFET output characteristics is as follows:

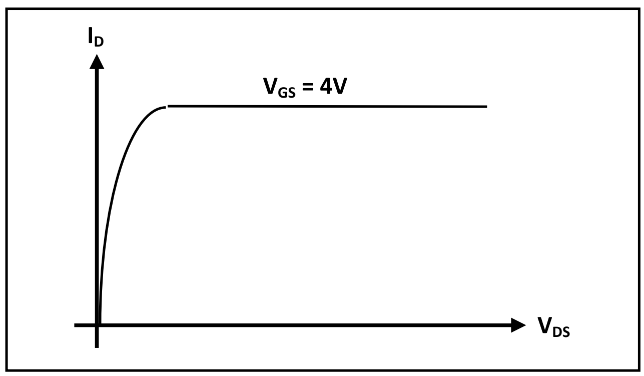

Figure 2-49

Up to a certain value of V_{DS} I_D increases and vice versa. After it reaches this value, I_D stays constant and does not depend on V_{DS}. It depends only on the width of the channel, which depends on V_{GS}.

For different values of V_{GS} we get the following output characteristics.

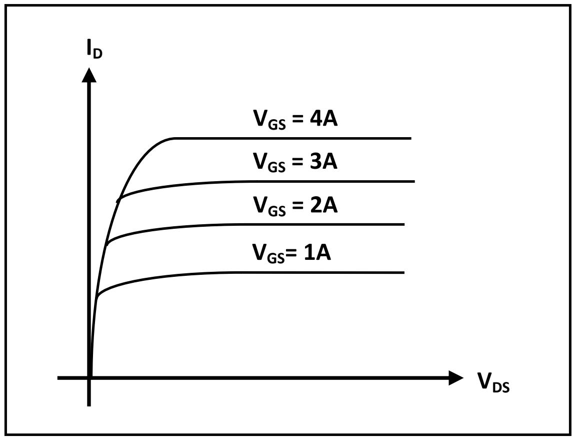

Figure 2-50

The above MOSFET is enhancement type FET. The channel is enhanced depend on V_{GS}.

Another kind of MOSFET is depletion/enhancement MOSFET. In this type of MOSFET, an n-type channel is injected between D and S.

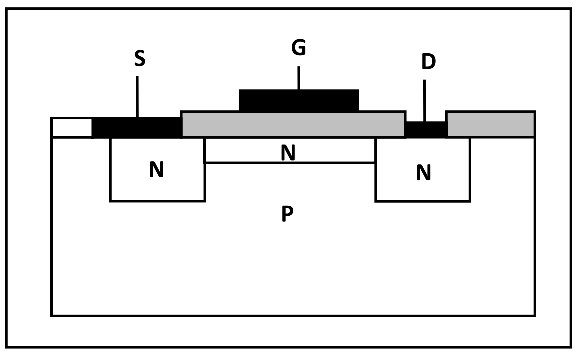

Figure 2-51

When V_{GS}=0V, the FET conducts. When V_{GS} increases, the conductance increases, because of the accumulation of electrons in the P-type material near the n-channel.

If we supply a negative V_{GS}, the free electrons in the n-channel are rejected under the gate and we get a depletion area, which decrease the current and the conductance.

The symbols of this type of MOSFET are:

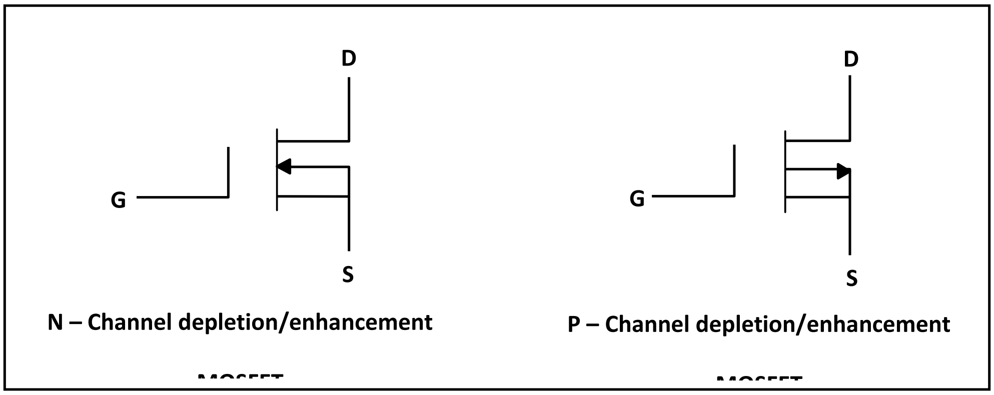

Figure 2-52

The MOSFET depletion/enhancement is called in short MOSFET depletion.

The output characteristics are as follows:

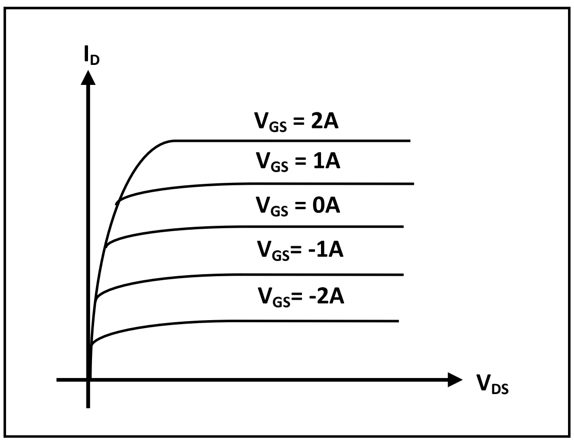

Figure 2-53

The V_{DS} value where I_D becomes constant and does not depend on V_{DS}, is called V_P (V punch). For every V_{GS} V_P is a slightly different.

In the output characteristics, we can see how I_D depends on V_{GS} and V_{DS}. We can find 3 regions:

1) The **SATURATION** region - In this range $V_{DS} < V_P$ and I_B depend on V_{DS}.

2) The **LINEAR** region - In this range $V_{DS} > V_P$ and I_D depend only on V_{GS} and not on V_{DS}.

3) The **CUTOFF** region - In this range $V_{GS} < V_{PO}$ (V_{GS} OFF). In this region, I_D is very small.

The MOSFET major advantage is its isolated gate. It creates a very high input impedance.

This isolated gate creates two problems. One is that it acts as a capacitor and decreases the speed of the transistors of the component.

The other problem is that the gate accumulates electrical static charges when it is open. It means that before putting the component in a circuit, its gate can have a very high voltage that breaks it and damages the component.

This is why MOSFET are packed in anti-static material packages.

Most of the MOSFET components are gate protected today by diodes.

2.3.4 The transition characteristic

The relationship between I_D (the Drain current) and V_{GS} is described in the following transition characteristic.

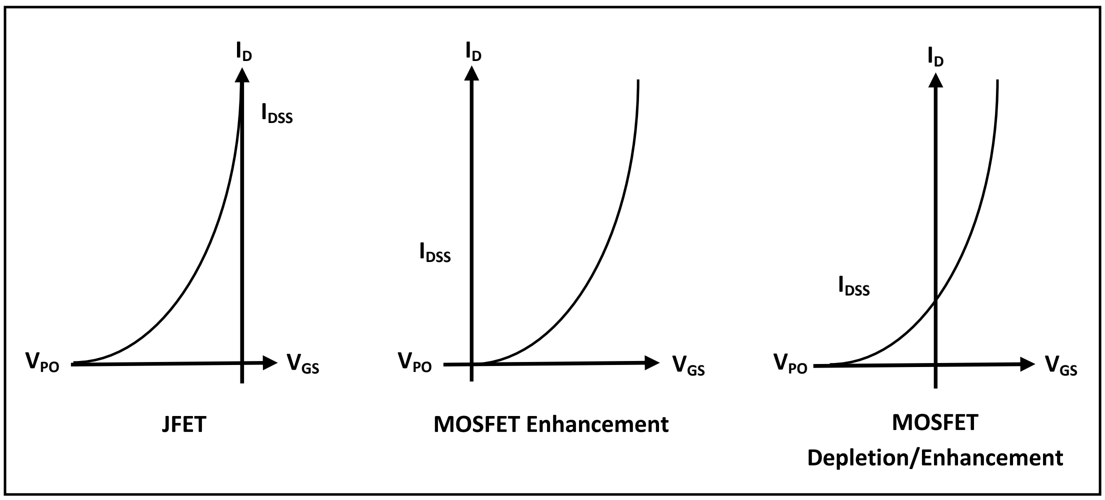

Figure 2-54

The FET does not have I_G current. (I_G=0) so I_D=I_S always.

In the bipolar transistor, we need only one parameter (β) for the relationship between I_C and I_B. Here we need two parameters (I_{DSS} and V_{PO}) for the relationship between I_D and V_{GS}.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{PO}}\right)^2$$

As we can see it is a parabola formula.

I_{DSS} is the value of I_D when V_{GS}=0

V_{PO} is the value of V_{GS} for I_D=0. It is called V_{GS} OFF.

Usually V_{PO} is negative.

There is no connection between V_P (V Punch), which relates to V_{DS} and V_{PO} (which is V_{GS} OFF).

2.3.5 The MOSFET DC bias

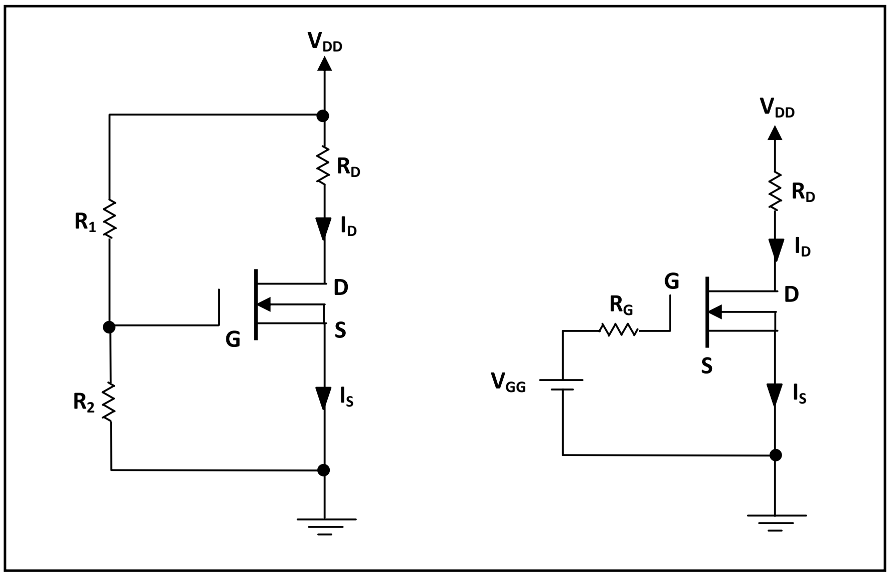

Figure 2-55

If we use a voltage divider as in the left circuit, then

$$V_{GS} = V_{R1} = \frac{V_{DD} \cdot R_2}{R_1 + R_2}$$

$$I_D = I_S$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{PO}}\right)^2$$

$$V_{DS} = V_{DD} - I_D \cdot R_D$$

The load line and the operating point are similar to the bipolar transistor.

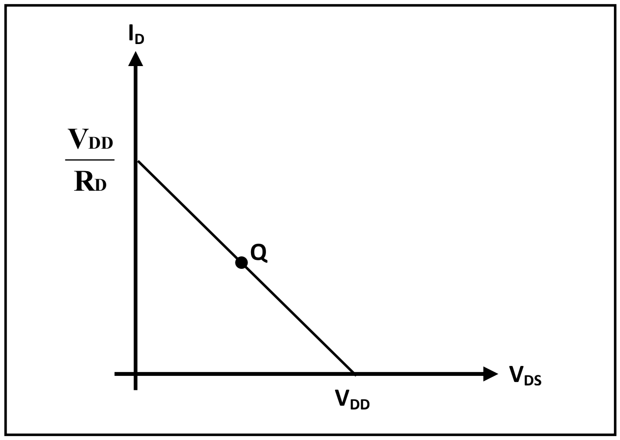

Figure 2-56

When we use a depletion/enhancement MOSFET bias we may give up on R_1, V_{GS}=0V and I_D=I_{DSS} which is not small in this type of transistor.

We use a very high resistance resistors for biasing the MOSFET in order not to spoil its high input impedance (described in the following chapter).

We may add a R_S resistor for the stability of the operating point.

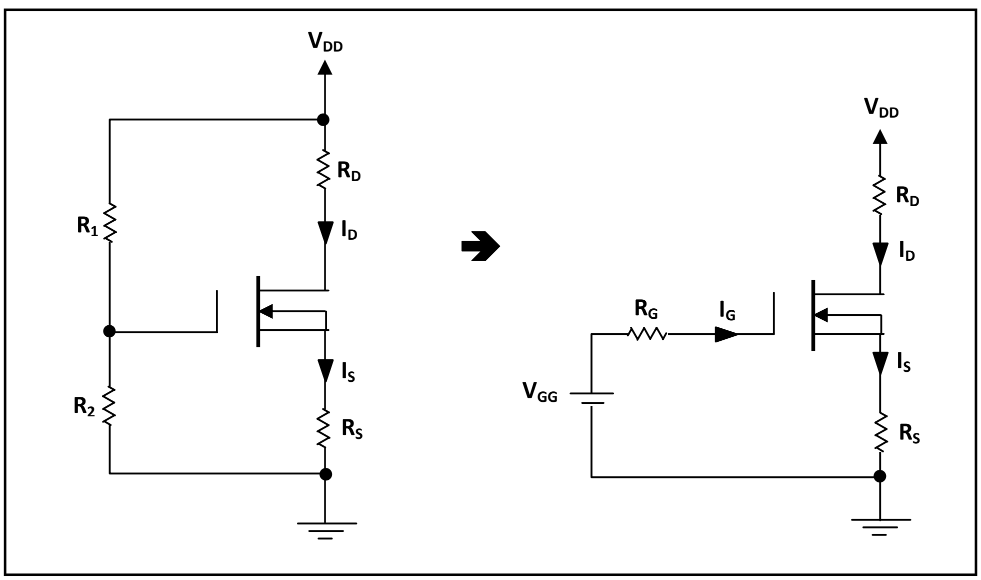

Figure 2-57

$$I_G = 0$$

$$V_{GG} = V_{R1} = \frac{V_{DD} \cdot R_2}{R_1 + R_2}$$

$$R_G = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

$$V_{GG} = I_G \cdot R_G + V_{GS} + I_S \cdot R_S = V_{GS} + I_S \cdot R_S$$

$$I_D = I_S$$

$$V_{GS} = V_{GG} - I_S \cdot R_S = V_{GG} - I_D \cdot R_S$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{PO}}\right)^2$$

$$\Rightarrow I_D = I_{DSS}\left(1 - \frac{V_{GG} - I_D \cdot R_S}{V_{PO}}\right)^2$$

We have a second degree equation which we have to solve in order to calculate I_D.

$$V_{DD} = I_D \cdot R_D + V_{DS} + I_S \cdot R_S$$

$$V_{DS} = V_{DD} - I_D(R_D + R_S)$$

As in the bipolar transistor, we try to get:

$$V_{DS} = \frac{V_{DD}}{2}$$

Adding RS enables to create negative V_{GS}, which is required for JFET. A JFET (and also in some MOSFET depletion), the common circuit is the following one:

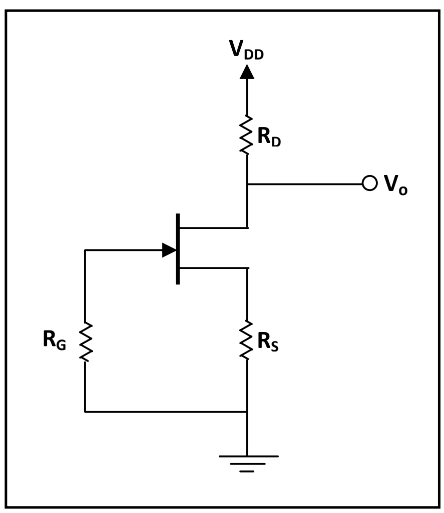

Figure 2-58

$$I_D = I_S$$
$$I_G \cdot R_G = 0V$$
$$V_{GS} = -I_D \cdot R_S$$
$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{PO}}\right)^2$$
$$I_D = I_{DSS}\left(1 + \frac{I_D \cdot R_S}{V_{PO}}\right)^2$$

We should remember that in JFET and in MOSFET depletion V_{PO} is negative.

3.0 OSCILLATORS

Oscillators are good examples of feedback amplifiers. Example of oscillators are wein bridge, triangle wave and rectangle wave oscillators.

3. 1 Wein bridge oscillator

A Wein Bridge Oscillator is a special circuit, which includes an amplifier with positive feedback.

An amplifier with positive feedback looks like this:

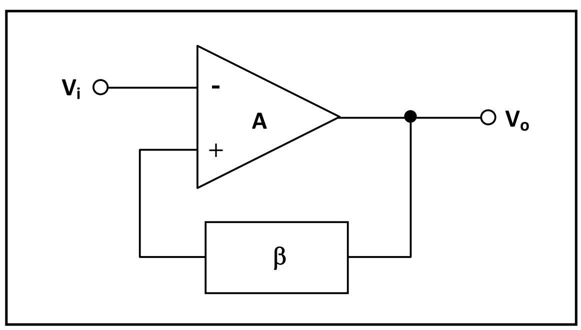

Figure 3-1

β is the feedback factor, which indicates what part of the output is returned and added to the input. Positive feedback drives the amplifier to one of its extreme points (+V or –V). There is a special case where the feedback voltage is the amplifier input signal.

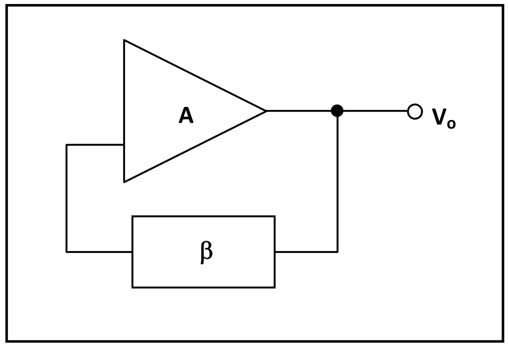

Figure 3-2

In this amplifier:

$\mathbf{V_o = A\beta V_o}$

There are three cases:

1) **$A\beta < 1$**. In this case, the output voltage will bound to 0.
2) **$A\beta > 1$**. In this case, the output will be bounded to one of the extreme voltages.
3) **$A\beta = 1$**. In this case, the amplifier acts as an oscillator.

A Wein bridge oscillator is the following amplifier:

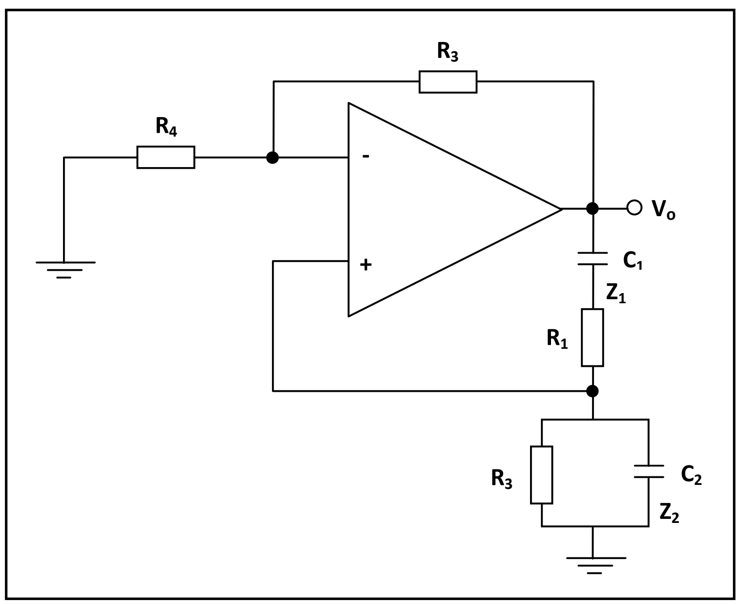

Figure 3-3

If we consider the V+ input as the amplifier input, we can treat the amplifier as a non inverting amplifier:

$$A_V = 1 + \frac{R_3}{R_4} = \frac{R_4 + R_3}{R_4}$$

The feedback signal is equal to:

$$V + \frac{V_o \cdot Z_2}{Z_1 + Z_2}$$

Hence:

$$\beta = \frac{Z_2}{Z_1 + Z_2}$$

For the amplifier to oscillate we must have:

$$A\beta = \frac{R_3 + R_4}{R_4} \cdot \frac{Z_2 + R_4}{Z_1 + Z_2} = 1$$

Aβ May be described as follows:

$$A\beta = \left(1 + \frac{R_3}{R_4}\right) \cdot \frac{1}{1 + \frac{Z_1}{Z_2}}$$

The oscillating condition only applies to a specific frequency. To calculate this frequency, it is enough to find the condition in which the phase shift of $\frac{Z_1}{Z_2}$ is equal to zero.

$$\frac{Z_1}{Z_2} = \frac{R_1 + \frac{1}{jwc1}}{R_2 \left\| \frac{1}{jwc2} \right.}$$

In our circuit:

$R_3 = R_1 = R$
$C_1 = C_2 = C$

We will get:

$$f = \frac{1}{2\Pi R_C}$$

Prove this.

Calculate the oscillator frequency according to the component values in the following values:

R_1 = 4.7KΩ, R_2=4.7KΩ, R_3=1KΩ, R_4=1KΩ , C_1=0.1μF, C_2=0.1μF

3.2 A square wave oscillator

The following circuit is a square wave generator.

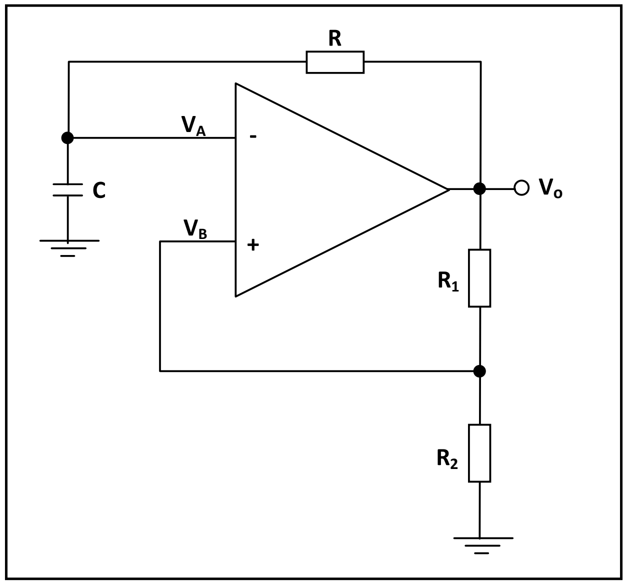

Figure 3-4

V_o has only two states because of the positive feedback, +V and –V of the operational amplifier.

When V_o = +V then:

$$V_B = +V \frac{R_2}{R_1 + R_2}$$

The capacitor C is charged and V_A increases.

When V_A goes a little over V_B, V_o changes to –V and:

$$V_B = -V \frac{R_2}{R_1 + R_2}$$

Now, the capacitor C is discharged and charged to a negative value.

When V_A lower then V_B, V_o changes to +V and vice versa.

The following is the output wave of the above application.

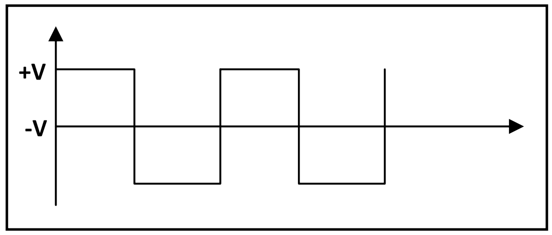

Figure 3-5

The capacitor C is charged exponentially according to RC values.

3.3 A triangle wave oscillator

To get a triangle wave we need to charge the capacitor with a current source. We use an integrator circuit for that.

The following circuit is a triangle wave generator.

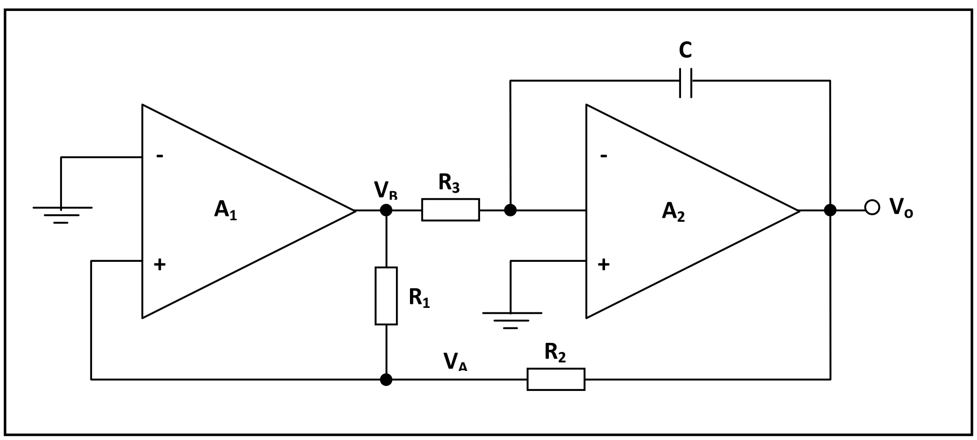

Figure 3-6

V_B has only two states because of the positive feedback - +V and –V of the operational amplifier.

When V_B is equal to +V then the capacitor is charged at the negative direction of V_o (V_o will be negative). The process stops when $V_A = 0$.

$$V_A = \frac{(V - V_o)R_2}{R_1 + R_2} + V_o = 0$$

After extracting V_o, we will get:

$$V_o = \frac{V \cdot R_2}{R_1}$$

Now the capacitor is charged to the other direction, until:

$$V_o = \frac{V \cdot R_2}{R_1}$$

V_o is the capacitor voltage. At one period of charging its voltage the change is:

$$\Delta V = 2\frac{V \cdot R_2}{R_1}$$

$$V_o = \frac{V \cdot R_2}{R_1}$$

$$t = \frac{\Delta V \cdot C}{I} = \frac{\Delta V \cdot C}{\frac{V}{R_3}} = \frac{R_3 \cdot \Delta V \cdot C}{V} = \frac{R_3 \cdot 2V \cdot \frac{R_2}{R_1} \cdot C}{V}$$

$$t = \frac{2 \cdot R_2 \cdot R_3 \cdot C}{R_1}$$

$$T = 2t = \frac{4 \cdot R_2 \cdot R_3 \cdot C}{R_1}$$

$$f = \frac{1}{t} = \frac{R_1}{4 \cdot R_2 \cdot R_3 \cdot C}$$

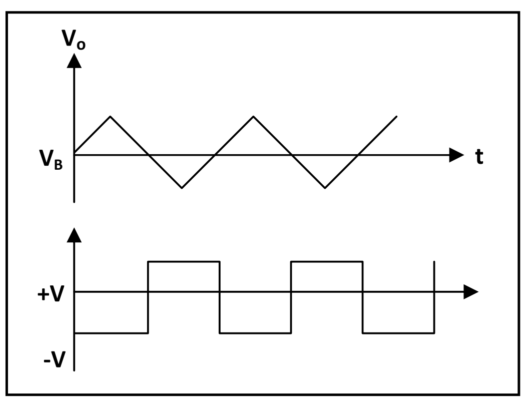

Figure 3-7