Chapter 2

Bipolar Junction Transistor

2.0 History

The name bipolar is used because both types of carriers namely hole and electron are used in the transistor, as opposed to field effect transistor, which is considered a unipolar device.

Transistor was invented by J. Bardeen (1908 - 1987), W. Shockley (1910-1989), and W. Brattain (1902 - 1987) in 1948. Fig. 2.1 shows the picture of three transistor inventors. In 1950 the junction transistor was made using molten germanium. The bipolar transistors produced in 1950s were typically made with alloyed junction.

The planar technology developed around 1960 started to use silicon as the semiconductor material. Today bipolar junction transistor enjoys a large market but they have been challenged by MOSFETs because of cost, yield, power, miniaturization, and etc.

Figure 2.1: Inventors of transistor John Bardeen, William Shockley, and Walter Brattain (left to right)

Figure 2.2 shows the picture of first transistor made by three mentioned inventors.
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In 1999, a vertical replacement gate transistor of 50 nm thick was invented by scientist in Lucent laboratory. Figure 2.3 shows the picture of the Lucent Transistor. There was other smaller transistor reported during that time by research laboratory of a university in Ohio State.

Transistors both bipolar and field effect type, are a three terminal semiconductor device used primarily for signal amplification and switching. It is also formed the fundamental element for integrated circuit design such as the VLSI microprocessor.

Bipolar junction transistor can be divided into two types namely $npn$ and $pnp$. 

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**Figure 2.2:** First transistor built in 1948

**Figure 2.3:** 50nm transistor built by Lucent Laboratory
Field effect transistor FET may be broadly divided into JFET, MESFET, MODFET, and MOSFET, where MOSFET can further be divided into depletion-enhancement type and enhancement type. In today's VLSI design, complimentary MOSFETs are used to reduce power consumption and fast switching application.

2.1 Bipolar Junction Transistor

Bipolar junction transistor BJT can be viewed as two $pn$ junctions connected back to back to form $np$-$pn$ or $pn$-$np$ structures namely as $nnp$ or $pnp$ transistors. Figure 2.4 illustrates the structure showing two $pn$ junctions.

![Figure 2.4: The structure of a transistor showing two pn junctions](image)

Bipolar junction transistor is manufactured in miniature formed by the fabrication process, which involved oxidation, photolithography, etching, deposition, ion implantation, diffusion, chemical/mechanical polishing processes, metallization, and etc.

Like $pn$ junction, the current components of BJT come from two carrier types, which are the hole and electron. This is also the reason why the transistor is called bipolar junction transistor.

The current components are diffusion hole, diffusion electron, drift hole, and drift electron, which are illustrated in Fig. 2.5.
2.1.1 Design Concept of Bipolar Junction Transistor

Bipolar junction transistor has three terminals. One terminal is used to inject carrier name as emitter E, one is used to control the passage of the carrier named as base B, and one is used to collect the carrier named as collector C.

Traditional way of designing a bipolar junction transistor is designed in such that the doping concentration of its emitter is higher than the doping concentration of the base and collector. The order of doping concentration is highest for emitter $\sim 10^{18}\text{ cm}^{-3}$, followed by collector $\sim 10^{17}\text{ cm}^{-3}$ and then base $\sim 10^{16}\text{ cm}^{-3}$. To ensure almost 100% of the injected carrier from emitter is collected by collector, the diffusion carriers have to outnumber the diffusion carriers of base and to outnumber recombination of carrier in the base.

The base is also designed to be much shorter than the diffusion length $L_n$ or $L_p$ of the minority carriers. This is used to minimize the chance of recombination of minority carrier with majority carrier in the base.

Bipolar junction transistor that meets the design concept would have high emitter efficiency and high current gain beta $\beta$ value.

2.1.2 Type of Bipolar Junction Transistor

Bipolar junction transistor can be divided into two types namely $npn$ and $pnp$ types which have their structures shown in Fig. 2.6.
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2.1.3 Symbol of Bipolar Junction Transistor

The symbols of \textit{npn} and \textit{pnp} bipolar junction transistors are shown in Fig. 2.7. The terminal with arrow sign signifies the emitter side. The tail of the arrow shows the \textit{p}-type, whilst the head of arrow shows the \textit{n}-type.

2.1.4 Power the Bipolar Junction Transistor

In normal operation of BJT, the emitter-to-base junction of the bipolar junction transistor is always forward biased. The collector-to-base is always reverse-biased.
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The corresponding energy band diagram of a \textit{pnp} bipolar junction transistor is shown in Fig. 2.9.

![Energy Band Diagram of pnp Transistor](image)

\textbf{Figure 2.9}: Energy band diagram of \textit{pnp} transistor under voltage bias

### 2.1.5 dc Operation Mode of Bipolar Junction Transistor

Figure 2.10 shows the current components of a bipolar junction transistor under normal bias.

![Biasing Configuration of pnp Transistor](image)

\textbf{Figure 2.10}: Biasing configuration of \textit{pnp} transistor

There are three current types flowing in bipolar junction transistor. There are collector current $I_C$, emitter current $I_E$, and base current $I_B$.

By Kirchhoff's Current Law KCL,

$$I_E = I_B + I_C$$  \hspace{1cm} (2.1)

There is a small portion of the injected carrier recombines with majority carrier in the base to form part of the base current. Thus, the emitter current $I_E$ is equal to $(I_C + I_B)$. 

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The ratio of collector current to emitter current is called $\alpha$, which is also named as $h$-parameter $h_{FB}$. This parameter is commonly known as *common base gain*.

$$\alpha = \frac{I_C}{I_E}$$

(2.2)

The typical value of $\alpha$ ranges from from 0.95 to 0.99. For a good transistor, its $\alpha$ value is closed to one.

The ratio of collector current to base current is $\beta$, which also denoted as $h$-parameter-$h_{FE}$. This parameter is commonly known as *common emitter gain*.

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

(2.3)

The typical range value of $\beta$ is between 20 to 500.

Substitute equation (2.1) into equation (2.3), it yields

$$I_E = I_B(\beta + 1)$$

(2.4)

The relationship of $\alpha$ and $\beta$ parameters shall be

$$\beta = \frac{\alpha}{(1 - \alpha)}$$

or

$$\alpha = \frac{\beta}{(\beta + 1)}$$

(2.5)

**Example 2.1**

A transistor has $I_B = 0.08mA$ and $I_E = 9.60mA$. Determine its collector current $I_C$, $\alpha$, and $\beta$.

**Solution**

$$I_C = I_E - I_B$$

$$= 9.60mA - 0.08mA$$

$$= 9.52mA$$

$$\alpha = \frac{9.52mA}{9.60mA} = 0.9917$$

$$\beta = \frac{9.52mA}{0.08mA} = 119$$
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or

\[ \beta = \frac{\alpha}{1-\alpha} = \frac{0.9917}{0.0083} = 119 \]

2.1.6 Characteristics of Beta $\beta$

The beta $\beta$ of transistor increases as the junction temperature of BJT increases. Thus, it will affect the quiescent Q-point of the transistor. However, if the BJT is properly biased, the effect is insignificant.

The basic reason for the increase is due to increase of electron-hole pair EHP at higher temperature as compared to lower temperature.

2.1.7 Reversed Bias Mode of Bipolar Junction Transistor

When the transistor is in reverse-biased mode, there are leakage currents, which can be measured. They are minority currents, which are drift currents in the collector-to-emitter and collector-to-base junctions. In engineering sense, they are referred as leakage currents.

Two types of leakage current namely $I_{CEO}$ at open emitter mode and $I_{CBO}$ at open base mode are of interest because it affects the operating Q-point of the transistor as the operating temperature increases. In the industrial analogue circuit design, $I_{CEO}$ and $I_{CBO}$ values are normally considered as very small in nanoampere range, which can be ignored.

Figure 2.11 shows the set up to measure $I_{CBO}$ with emitter left open i.e. $I_C = I_{CBO}$.

![Figure 2.11: $I_{CBO}$ measurement](image)
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Figure 2.12 shows the set up to measure $I_{CEO}$ current with base open i.e. $I_C = I_{CEO}$.

![Figure 2.12: $I_{CEO}$ measurement](image)

Taking into account $I_{CEO}$ and $I_{CBO}$, the real $\alpha_{(\text{real})}$ and $\beta_{(\text{real})}$ parameters shall be re-calculated.

![Figure 2.13: It illustrates the $I_{CBO}$ and $I_{CEO}$ leakage current components](image)

$$I_C = I_{C(\text{real})} + I_{CBO} \quad (2.6)$$

$$\alpha_{(\text{real})} = (I_C - I_{CBO})/I_E \quad (2.7)$$

$$I_C = \alpha_{(\text{real})} I_E + I_{CBO} \quad (2.8)$$

$$I_B = I_E - (\alpha_{(\text{real})} I_E + I_{CBO}) \quad (2.9)$$

Since $\alpha = \frac{\beta}{\beta+1}$,
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\[ I_B = \frac{I_E}{\beta+1} - I_{CBO} \]  \hspace{1cm} (2.10)

\[ \beta_{(real)} = \frac{I_C - I_{CBO}}{I_B + I_{CBO}} \]  \hspace{1cm} (2.11)

\[ I_C = \beta_{(real)} I_B + I_{CBO}(\beta+1) \]  \hspace{1cm} (2.12)

In open base condition, the collector current \( I_C \) is

\[ I_C = I_E + I_{CEO} \]  \hspace{1cm} (2.13)

Thus, the open base collector-to-emitter current \( I_{CEO} \) is

\[ I_{CEO} = I_{CBO}(\beta+1) \]  \hspace{1cm} (2.14)

Note that \( I_{CEO} \) value in equation (2.14) is indeed the cutoff base current of a bipolar junction transistor.

**Example 2.2**
A silicon bipolar junction transistor has \( \beta = 100 \) and \( I_{CBO} \) of 0.01\( \mu \)A. Calculate the value of \( \alpha \), \( I_C \) and \( I_B \) assuming \( I_E = 1 \)mA.

**Solution**

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

\[ I_C = \alpha I_E + I_{CBO} \]
\[ = 0.99(1 \text{mA}) + 0.01 \mu \text{A} \]
\[ = 0.99001 \text{ mA} \]

\[ I_B = \frac{I_E}{\beta+1} - I_{CBO} \]
\[ = 1 \text{mA/101} - 0.01 \mu \text{A} = 9.89 \mu \text{A} \]

**2.1.8 Collector Characteristic Curves**

By fixing the base current \( I_B \) and varying the \( V_{CC} \) voltage and knowing \( \beta \) value, the characteristic curve of collector current \( I_C \) versus collector-to-emitter voltage \( V_{CE} \) can be plotted as shown in Fig. 2.14. By changing the value of base current
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$I_B$, a new collector characteristic curve can be obtained by varying the collector-to-emitter voltage $V_{CE}$ and measuring the collector current $I_C$.

When base current is zero i.e. $I_B = 0$, the transistor is said to be at cutoff. When base current is increased, the collector current $I_C$ is also increased, and collector-to-emitter voltage $V_{CE}$ is decreased. $V_{CE}$ will decrease until it is equal to $V_{CE(sat)}$, which is approximately equal to $0.1 \sim 0.2V$. At this condition, the transistor is saturated because $I_C$ will not increase any further and base-to-collector junction becomes forward bias (equation (2.19); $V_{CB} = V_{CE} - V_{BE}$). In this condition, the current gain $\beta$ formula will not follow.

Note also that at cutoff, $V_{CE}$ is almost equal to $V_{CC}$ and likewise at saturation, collector-to-emitter voltage is almost zero. i.e.$V_{CE} \approx 0V$.

![Collector characteristic curves](image)

Figure 2.14: Collector characteristic curves

2.2 dc Configuration of Bipolar Junction Transistor

There are three biasing configurations for the bipolar junction transistor. They are common-base, common-emitter, and common-collector configurations. We shall study each of the configurations in details.
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2.2.1 Common-Base CB Configuration

The transistor is connected with base as common ground terminal as shown in Fig. 2.15 is called *common-base configuration*. The current gain is $\alpha$, which is the ratio of collector current and emitter current $I_C/I_E$. The input is at emitter terminal, whilst the output is at collector terminal.

![Common-base CB configuration](image)

**Figure 2.15:** Common-base CB configuration

2.2.2 Common-Emitter CE Configuration

The transistor is connected with emitter as the common or ground is called *common-emitter configuration* as shown in Fig. 2.16.

![Common-emitter configuration](image)

**Figure 2.16:** Common-emitter configuration

The current gain of this configuration is $\beta$, which is the ratio of collector current $I_C$ and base current $I_B$. $\beta$ is also called as *static forward transfer current ratio* $h_{fe}$. The input is at base terminal, whilst the output is at collector terminal.
2.2.2.1 dc Analysis

Reference to common-emitter configuration shown Fig. 2.17, there are three currents and three voltages, which are base current $I_B$, emitter current $I_E$, collector current $I_C$, base-to-emitter voltage $V_{BE}$, collector-to-base voltage $V_{CB}$, and collector-to-emitter voltage $V_{CE}$. For any other dc biasing configuration, there always have these currents and voltages.

![Figure 2.17: Common-emitter current and voltage](image)

At room temperature $25^0C$, the base-to-emitter voltage $V_{BE}$ is approximately equal to 0.7V, which is the forward voltage drop of a diode.

The voltage across base resistor $R_B$, $V_{r_B}$ is

$$V_{r_B} = V_{BB} - V_{BE} \quad (2.15)$$

Therefore, the base current $I_B$ is

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} \quad (2.16)$$

Knowing the beta value, using equation (2.2) and (2.3), collector current $I_C$ and emitter current $I_E$ can be determined.

The voltage drop across collector resistor $R_C$ is $V_{r_c}$, which is
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\[ V_{Rc} = I_C R_C \] (2.17)

The voltage drop across collector and emitter \( V_{CE} \) shall then equal to

\[ V_{CE} = V_{CC} - I_C R_C \] (2.18)

The voltage drops across collector and base shall follow equation (2.19), which is

\[ V_{CB} = V_{CE} - V_{BE} \] (2.19)

**Example 2.3**

Determine if the transistor shown in circuit is in saturation. Assume that \( V_{CE(Sat)} \) is small enough to be neglected.

![Circuit Diagram]

**Solution**

The collector saturation current is

\[ I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{10V}{1k\Omega} = 10mA. \]

If \( I_B \) is large enough to produce \( I_{C(sat)} \) then the base current \( I_B \) is

\[ I_B = \frac{V_{BB} - 0.7V}{R_B} = \frac{2.3V}{10k\Omega} = 0.23mA. \]

The collector current is

\[ I_C = \beta I_B = (50)(0.23mA) = 11.5mA. \]

This shows that with the specified \( \beta \), this base current is capable of producing the collector current \( I_C \) greater than \( I_{C(sat)} \). Since the transistor is saturated, the collector current value of 11.5mA is never attained.
2.2.3 Common-Collector CC Configuration

The transistor is connected with collector as the common is called common-collector configuration as shown in Fig. 2.18.

![Figure 2.18: Common-collector configuration](image)

The current gain is $\beta+1$ since $I_E = I_C + I_B$. This shall mean that emitter current is $I_E = I_B(\beta + 1)$. The input is at base terminal, whilst the output is at emitter terminal.

2.2.3.1 dc Analysis

The current and voltage shown in Fig. 2.19 depend on the transistor characteristics and external circuit values.

![Figure 2.19: Currents and voltage of common collector configuration](image)

The voltage at base is $V_{BB}$. The voltage at emitter $V_E$ is $(V_{BB}-V_{BE})$, where $V_{BE} = 0.7V$ for silicon at room temperature. Thus, the emitter current $I_E$ is
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\[ I_E = \frac{V_E}{R_E} \]  
\[ I_E = \frac{V_{BB} - V_{BE}}{R_E} \]

(2.20)  
(2.21)

Since emitter current is \( I_E = I_C + I_B \) and beta is \( \beta = I_C/I_B \)

\[ I_B = \frac{I_E}{\beta + 1} \]

(2.22)

The collector-to-emitter voltage \( V_{CE} \) is

\[ V_{CE} = V_{CC} - V_E \]  
\[ V_{CE} = V_{CC} - I_E R_E \]

(2.23)

The collector-to-base voltage \( V_{CB} \) is

\[ V_{CB} = V_{CC} - V_E - V_{BE} \]

(2.24)

**Example 2.4**

Determine current \( I_B, I_C, I_E \) and voltage at each transistor terminal with respect to ground and \( V_{CE} \) voltage in the figure. \( \beta = 200 \).

**Solution**

Emitter current is \( I_E = \frac{V_{BB} - V_{BE}}{R_E} = \frac{10V - 0.7V}{10k\Omega} = 0.93mA \)
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\[ I_C = I_E \frac{\beta}{\beta + 1} = 0.925 \text{mA} \]

\[ I_B = \frac{I_E}{\beta + 1} = \frac{0.93 \text{mA}}{201} = 4.43 \mu\text{A} \]

\[ V_C = V_{CC} = 20 \text{V} \text{ and } V_B = V_{BB} = 10 \text{V} \]

\[ V_E = I_ER_E = (0.93 \text{mA})(10k\Omega) = 9.3 \text{V} \]

\[ V_B = 9.2\text{V} + 0.7\text{V} = 10\text{V} \]

\[ V_{CE} = 20\text{V} - 9.3\text{V} = 10.7\text{V} \]

2.3 dc Operating Point

The dc operating point is referred to Q-point (quiescent point). It is a point on the transistor characteristic curve. If one chooses collector current \( I_C \) versus collector-to-emitter voltage \( V_{CE} \) characteristics curve then Q-point is the point on the curve determined by collector current \( I_C \) and collector-to-emitter voltage \( V_{CE} \) for a fixed value of base current \( I_B \) derived from the biasing of circuit. Using the transistor biasing circuit shown in Fig. 2.20, the Q-point on the characteristics curve can be determined by finding the values of \( I_C \) and \( V_{CE} \) for a given base current \( I_B \) determined by the circuit. The line joining the Q-point is known as dc load line.

![ Bias circuit and characteristic curve ]

Figure 2.20: (a) Biasing circuit for determining Q-point and (b) showing Q-point and dc load line

If there is a sine wave of amplitude 1.0V superimposed on base voltage \( V_{BB} \) as shown in Fig. 2.21 The base current \( I_B \) varies 100.0\( \mu \text{A} \) above and 100.0\( \mu \text{A} \)
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below the Q-point. The collector current $I_C$ will vary between 20.0mA to 40.0mA, which is ±10.0mA above and below Q-point of 30.0mA. The collector-to-emitter voltage $V_{CE}$ will vary from 2.0V to 6.0V as shown in Fig. 2.22, which is 2.0V above and below Q-point of 4.0V.

Figure 2.21: It shows the transistor with ac signal superimposed on dc

Figure 2.22: It shows the transistor dc load line
2.3.1 Distortion of Output

The location of Q-point can cause distortion of the output and it determines the maximum input voltage. The output signal is clipped if the input is driven into either saturation or cutoff area. Fig. 2.23 illustrates the conditions of output distortion.

Example 2.5
Determine the Q-point for circuit shown in the figure and the peak value of base current for linear operation. Given that the beta value $\beta$ of the $nnpn$ transistor is 200.
Solution

Q-point is defined by collector current $I_C$ and collector-to-emitter voltage $V_{CE}$ on the output characteristic curve. The base current is

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10V - 0.7V}{50k\Omega} = 186\mu A$$

and the collector current $I_C$ is

$$I_C = \beta I_B = 200 \times 186\mu A = 37.2mA.$$ The collector-to-emitter voltage $V_{CE}$ is

$$V_{CE} = V_{CC} - I_C R_C = 20V - 37.2 mA(300\Omega)$$
$$= 20V - 11.6V$$
$$= 8.84V$$

Thus, first Q-point is at $I_C = 37.2mA$ and $V_{CE} = 8.8V$ for $I_B = 186.0\mu A$

The next Q-point shall be determined at saturation. $I_C$ at this point is

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = \frac{20V}{300\Omega}$$
$$= 66.7 mA$$

Now a dc load line can be drawn as shown in the figure. From the graph, $V_{CE}$ at cutoff is found to be 20.0V.
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From the graph, the operating $I_C$ range is $37.2\text{mA} \pm 29.5\text{mA}$. Thus, the peak base current $I_B$ value is $I_{b(\text{peak})} = 29.5\text{mA}/200 = 147.5\mu\text{A}$.

![Graph showing $I_C$ and $V_{CE}$ relationship]

2.4 dc Biasing a Transistor Amplifier

The purpose of dc bias is to make transistor to work as amplifier or alternative one can say to keep the transistor alive. All three terminals of the bipolar junction transistor must be biased. Showing here is the most common type of dc biasing for transistor, which are base bias, emitter bias, voltage-divider bias, and collector feedback bias. The constant current bias shall also be discussed briefly.

dc analysis and the effect of temperature for each biasing type shall be discussed detail. The advantage and disadvantage of each bised type shall also be discussed.

2.4.1 Base Bias

Circuit in Fig. 2.24 illustrates the base biasing of a bipolar junction transistor. The base of the bipolar junction transistor is biased using $V_{CC}$ voltage instead of a separated voltage.
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2.4.1.1 dc Analysis

The voltage drop across base resistor $R_B$ is $(V_{CC} - V_{BE})$.

Therefore, base current $I_B$ is

$$I_B = \frac{(V_{CC} - V_{BE})}{R_B} \quad (2.25)$$

Also collector-to-emitter voltage is

$$V_{CE} = V_{CC} - R_C \beta I_B \quad (2.26)$$

From the above dc analysis, it shows that collector-to-emitter voltage $V_{CE}$ is dependent on $\beta$ parameter. Since beta $\beta$ increases with temperature, it shall mean that collector current $I_C$ will also increase. Increase of collector current reduces collector-to-emitter voltage $V_{CE}$. Thus, it affects the Q-point.

Based on the analysis, the bipolar junction transistor biased with base bias technique is not a good biasing technique unless the operating temperature can be kept constant.

2.4.2 Emitter Bias

Emitter bias of bipolar junction transistor is shown in Fig. 2.25. The emitter is normally biased.
2.4.2.1 dcAnalysis

At base-emitter loop,

\[ I_B R_B + V_{BE} + I_E R_E = V_{EE} \]  \hspace{1cm} (2.27)

\[ (I_C/\beta)R_B + V_{BE} + \frac{\beta+1}{\beta} I_C R_E = V_{EE} \]

Thus, the collector current \( I_C \) is

\[ I_C = \frac{V_{EE} - V_{BE}}{R_E (\beta + 1)/\beta + R_B /\beta} \]  \hspace{1cm} (2.28)

Since \( R_B/\beta \) is small as compared to \( R_E \) and \( (\beta + 1)/\beta \equiv 1 \), the effect of collector current \( I_C \) with temperature is minimum. Thus, emitter bias is a good biasing technique for linear circuit design. The collector voltage \( V_C \) is

\[ V_C = V_{CC} - I_C R_C \]  \hspace{1cm} (2.29)

and collector-to-emitter voltage \( V_{CE} \) is
Example 2.6
Determine how much the Q-point of the circuit shown in the figure will change over temperature where $\beta$ increases from 50 to 100 and $V_{BE}$ decreases from 0.7V to 0.6V.

Solution
For $\beta = 50$ and $V_{BE} = 0.7V$

\[
I_C = \frac{V_{EE} - V_{BE}}{R_E(\beta + 1)/\beta + R_B/\beta} = \frac{20V - 0.7V}{10k\Omega(51/50) + 10k\Omega/50} = 1.86mA
\]

\[
V_C = V_{CC} - I_CR_C = 20V - (1.86mA)(5k\Omega) = 10.72V
\]

Therefore, the emitter voltage $V_E$ is

\[
V_E = -1.86mA/50x10k\Omega - 0.7V = -1.072V
\]

and the collector-to-emitter voltage is
\[ V_{CE} = V_C - V_E \]
\[ = 10.72V - (-1.072V) \]
\[ = 11.79V \]

For \( \beta = 100 \) and \( V_{BE} = 0.6V \)

\[ I_C = \frac{V_{EE} - V_{BE}}{R_E(\beta + 1)/\beta + R_B/\beta} \]
\[ = \frac{20V - 0.6V}{10k\Omega(101/100) + 10k\Omega/100} \]
\[ = 1.90mA \]

\[ V_C = V_{CC} - I_C R_C \]
\[ = 20V - (1.90mA)(5k\Omega) \]
\[ = 10.49V \]

Therefore, the emitter voltage and collector-to-emitter voltage are

\[ V_E = -1.90mA/100\times10k\Omega - 0.6V = -0.79V \]
\[ V_{CE} = V_C - V_E \]
\[ = 10.49V - (-0.79V) \]
\[ = 11.28V \]

The % change in collector current \( I_C \) as \( \beta \) changes from 50 to 100 is

\[ \Delta I_C = \frac{1.90mA - 1.86mA}{1.86mA} \times 100\% = 2.15\% \]

The % change in collector-to-emitter voltage \( V_{CE} \) is

\[ \Delta V_{CE} = \frac{11.79V - 11.28V}{11.79V} \times 100\% = 4.32\% \]

From the results, one can conclude that the emitter bias circuit is a good way to stabilize Q-point due to change of \( \beta \) caused by temperature.

### 2.4.3 Voltage-Divider Bias

Voltage-divider bias is the most widely used technique for linear circuit design. The base voltage \( V_B \) is biased based on device circuit shown in Fig. 2.26.
If the base current $I_B$ is very small as compared to current $I_2$ flows in $R_2$, then the divider circuit can be simplified and depends on $R_1$ and $R_2$. Otherwise, the input resistance $R_{IN(base)}$ at the base needs to take into consideration.

**Figure 2.26**: Voltage-Divider bias circuit

**Figure 2.27**: (a) Divider circuit without input resistance and (b) with input resistance
The input resistance of base $R_{IN(base)}$ is defined as $R_{IN(base)} = (\beta+1)R_E$ as shown in Fig. 2.27. In most cases, $R_{IN(base)}$ is very large as compared to $R_2$. Thus, it can be ignored in the calculation. Since $(\beta+1) \cong \beta$, then $(\beta+1)R_E \cong \beta R_E$

From Thévenin's theorem, an equivalent base-emitter circuit is shown in Fig. 2.28 and its dc model circuit is shown in Fig. 2.29. The dc model can be used for the case where $R_{IN(base)}$ is considered as part of input and also the base current is not assumed to be zero.

**Figure 2.28:** Thévenin's equivalent circuit of base-to-emitter circuit

**Figure 2.29:** dc model circuit of voltage divider amplifier


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2.4.3.1 dc Analysis

Consider circuit shown in Fig. 2.30, the base voltage $V_B$ at point A is equal to

$$V_B = \frac{R_2 \parallel (\beta + 1)R_E}{R_1 + [R_2 \parallel (\beta + 1)R_E]} V_{CC} \quad (2.31)$$

If term $(\beta+1)R_E >> R_2$ then the base voltage is approximately equal to

$$V_B \approx \frac{R_2}{R_1 + R_2} V_{CC} \quad (2.32)$$

Knowing base voltage is $V_B$ and emitter voltage is $V_E = V_B - V_{BE}$, the emitter current is equal to

$$I_E = \frac{V_B - V_{BE}}{R_E} \quad (2.33)$$

Since collector current is $I_C = \alpha I_E$ and emitter voltage is $V_E = I_E R_E$, the collector-to-emitter voltage $V_{CE}$ is equal to

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E$$
$$= V_{CC} - I_E (\alpha R_C + R_E) \quad (2.34)$$

Usually the value of input base resistance $R_{IN(base)} = (\beta + 1)R_E$ is much larger as compared to $R_2$. Therefore, Q-point is only slightly effected by $\beta$, which is temperature dependent.

**Example 2.7**

Using the circuit shown in the figure, determine the values of base voltage $V_B$ and emitter current $I_E$.

If the transistor is replaced with one that has $\beta = 250$, what is the change of base voltage $V_B$?
**Solution**

In this example, $R_{IN(base)}$ cannot be ignored since it involves $\beta$ parameter.

\[
R_{IN(base)} = 51(1\,\text{k}\Omega) = 51\,\text{k}\Omega
\]

\[
V_B = \frac{R_2 \parallel R_{IN(base)}}{R_1 + R_2 \parallel R_{IN(base)}} V_{CC}
\]

\[
= \frac{50\,\text{k}\Omega \parallel 51\,\text{k}\Omega}{100\,\text{k}\Omega + 50\,\text{k}\Omega \parallel 51\,\text{k}\Omega} 10\text{V}
\]

\[
= 2.01\text{V}
\]

\[
I_E = \frac{(V_B - V_{BE})}{R_E}
\]

\[
= \frac{(2.01\text{V} - 0.7\text{V})}{1\,\text{k}\Omega}
\]

\[
= 1.31\text{mA}
\]

If beta $\beta$ increases to 250, input base resistance $R_{IN(base)}$ is 251kΩ and base voltage $V_B$ is

\[
V_B = \frac{50\,\text{k}\Omega \parallel 251\,\text{k}\Omega}{100\,\text{k}\Omega + 50\,\text{k}\Omega \parallel 251\,\text{k}\Omega} 10\text{V}
\]

\[
= 2.94\text{V}
\]

Base voltage $V_B$ increases from 2.01V to 2.94V.
2 Bipolar Junction Transistor

2.4.4 Collector Feedback Bias

The circuit of collector feedback bias or voltage feedback bias is shown in Fig. 2.30. It provides base-to-emitter bias. This circuit is good to stabilize the effect $\beta$ on Q-point caused by temperature.

![Collector feedback bias circuit diagram]

**Figure 2.30:** Collector feedback bias

2.4.4.1 dc Analysis

The base current $I_B$ is

$$I_B = \frac{V_C - V_{BE}}{R_B} \quad (2.35)$$

The collector-to-emitter voltage $V_{CE}$ is

$$V_{CE} = V_C = V_{CC} - (I_C + I_B)R_C \equiv V_{CC} - I_C R_C \quad (2.36)$$

Also the base current $I_B$ is equal to

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

But $I_B = I_C/\beta$, thus,
2 Bipolar Junction Transistor

\[
\begin{align*}
I_C &= \frac{V_{CC} - I_C R_C - V_{BE}}{\beta} \\
I_C &= \frac{V_{CC} - V_{BE}}{R_C + R_B / \beta} 
\end{align*}
\] (2.37)

Normally the value of \( R_B / \beta \) is small as compared to \( R_C \). Thus, collector current \( I_C \) is fairly independent of \( \beta \).

2.4.5 Biasing Using Current Source

Current source biasing has advantage because emitter current is independent of \( R_B \) resistance and \( \beta \) value of the transistor as shown in Fig. 2.31(a). Thus, \( R_B \) can be made as large as possible to increase the input impedance without disturbing the stability of the bias. Current source also leads to significant design simplification. It keeps the collector voltage at point \( V \) greater than voltage at base \((-V_{EE} + V_{BE})\). The circuit in Fig. 2.31(b) has the current ratio \( I/I_{REF} \) which is depending on the design aspect ratio \((A/\omega_b)\) of the transistor \( Q_1 \) and \( Q_2 \). Thus, the relationship \( I/I_{REF} = \frac{(A/\omega_b)_{Q2}}{(A/\omega_b)_{Q1}} = \frac{\beta_2}{\beta_1} \) is established. If transistor \( Q_1 \) and \( Q_2 \) have same design geometry then \( I \) is a replica or mirror of current reference \( I_{REF} \). Thus it is also called the current mirror, a name that is used irrespective of the ratio of device dimension.

\[
I_{REF} = \frac{V_{CC} - (-V_{EE}) - V_{BE}}{R} 
\] (2.38)

\( I_{REF} \) is also equal to the sum of collector current \( I_C \) flows in transistor \( Q_1 \) and the base current flows in both transistors. Thus,

\[
I_{REF} = I_C + 2I_B
\]

also

\[
I_{REF} = I_C + 2I_C/\beta
\]

and \( I_C = I \), therefore, current \( I = \frac{\beta}{\beta + 2} \times I_{REF} \) for transistor \( Q_1 \) and \( Q_2 \) that have same \( \beta \) value.
2 Bipolar Junction Transistor

![Bipolar Transistor Diagram]

(a) Basic current source  
(b) Current mirror

**Figure 2.31:** Bipolar transistor biased using current source

### 2.5 Output Impedance $r_o$

With reference to Fig. 2.14, we assume that the output impedance $r_o$ of the bipolar junction transistor is infinite at amplification region. Thus, we ignore $r_o$ at the gain calculation. In reality the output impedance of the transistor for a specified $I_B$ current is depending on the Early voltage $V_A$ and the collector current $I_C$. This is illustrated in Fig. 2.32. Thus, the output impedance of the transistor is $r_o = \left| \frac{V_A + V_{CE}}{I_C} \right| \approx \frac{V_A}{I_C}$.

At saturation and upon further increase $V_{CE}$ voltage, the depletion thickness at collector-to-base region increases in such that the effective width $W$ of the base is reduced. This causes an increase of minority carrier, which is the source of reversed saturation current $I_S$. Knowing that $I_S$ is inversely proportional to $W$ and $I_C = I_S e^{V_{sw}/V_T}$, thus there is an increase of $I_C$ current.
2.5 Transistor As a Switch

In digital electronic, transistor is configured as a switch that operates between cutoff and saturation regions. Consider an npn bipolar junction transistor circuit shown in Fig. 2.33. If the input voltage $V_{\text{in}}$ is equal to $V_{\text{CC}}$ and the ratio of the base resistance to collector resistance $R_B/R_C$ or the ratio of collector current to base current $I_C/I_B$ is less than $\beta$ value, then the transistor is be driven into saturation. Likewise, if the input voltage $V_{\text{in}}$ is less than the base-to-emitter voltage $V_{\text{BE}}$ of 0.7V, the transistor will be at cutoff. Under these conditions, the transistor acts like an inverter switch.

From circuit shown in Fig. 2.33, base current $I_B$ is equal to $I_B = \frac{(V_{\text{in}} - V_{\text{BE}})}{R_B}$. However, at saturation collector current $I_C$ is equal to $I_C = \frac{V_{\text{CC}}}{R_C}$.

Knowing that $I_C = \beta I_B$, thus, the result of $R_B/R_C$ at saturation is equal to $\frac{R_B}{R_C} = \left(\frac{V_{\text{in}} - V_{\text{BE}}}{V_{\text{CC}}}\right) \beta$. If $V_{\text{in}} = V_{\text{CC}}$, then $\left(\frac{V_{\text{CC}} - V_{\text{BE}}}{V_{\text{CC}}}\right)$ is less than one. This shall mean that ratio of $R_B/R_C$ is less than $\beta$ for a transistor to operate as a switch. This result infers that the ratio of $I_C/I_B$ current is less than $\beta$ for a bipolar junction transistor to work as switch.
2 Bipolar Junction Transistor

![Bipolar Junction Transistor Diagram]

**Figure 2.33:** An *npn* bipolar junction transistor used as an inverter switch

**Tutorials**

2.1. The majority carrier in base region of an *npn* transistor is ________________.

2.2. Explain the purpose of a thin, lightly doped base and a heavily doped emitter.

2.3. Why collector current $I_C$ is less than emitter current $I_E$?

2.4. Discuss how the base-emitter terminal and collector-emitter terminal of a bipolar junction transistor should be biased for normal functioning.

2.5. A base current of 50µA is applied to a transistor in figure below and a voltage of 5V is dropped across resistor $R_C$. Determine $\alpha$ and $\beta$ for the transistor.
2.6. Find $V_{CE}$, $V_{BE}$, and $V_{CB}$ of the transistor shown in figure below. Deduce whether or not the transistor is saturated.

2.7. Calculate the $V_{CE(max)}$ and $I_{C(sat)}$ for the amplifier shown in figure below and draw its dc load line. What is the ac range can be applied at the base without distortion given that $\beta = 100$?
2.8. Refers to circuit of Q2.7, if you need $I_B$ to be 10.0µA, what will be the values of $V_{BB}$ and the Q-point of this amplifier? You may take and $\beta = 100$.

2.9. Among the dc biasing circuits for transistor that you have learnt, name the one that its Q-point will be greatly affected by temp.variation. State the reason.

References