7. Bipolar Junction Transistor

7.1. Objectives
- To experimentally examine the principles of operation of bipolar junction transistor (BJT);
- To measure basic characteristics of n-p-n silicon transistor in common-emitter configuration.

7.2. Principles
A Bipolar Junction Transistor (BJT) is a three-terminal semiconductor device used as an amplifier of electric signals, or as an electronic switch. The three terminals are called the emitter (E), the base (B), and the collector (C). BJT is made as a three layer structure of p-type and n-type semiconductor material. Typical BJT consists of a thin base layer (either p- or n-type) sandwiched between two layers of the opposite type material (Fig. 1a). Thus, BJTs are either n-p-n or p-n-p. They are somewhat like two interconnected, back-to-back diodes, with two p-n junctions. The two types of BJTs are illustrated schematically in Fig. 1b below.

Three currents flowing inside BJT are collector current $I_C$, emitter current $I_E$ and base current $I_B$. Collector current $I_C$ is always less than emitter current $I_E$. In fact, $I_C = I_E + I_B$. The amplification function is achieved via control of a large current flowing from emitter into collector using a small base current. The amplification parameter $\beta$ known as the DC current gain is measured is the ratio of collector current ($I_C$) to base current ($I_B$):

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

The physical principle of operation of BJT transistor is the following. Applying forward bias to the EB junction, charge carriers are injected into the base from the emitter region. If no bias is applied to the CB junction, all the injected charge carriers drift to the base electrode and the EB junction works like a common bipolar diode. However, if negative bias is applied to the CB junction, the stream of the injected charge carriers splits into two streams: one flowing to the
base electrode and another flowing to the collector electrode. Since the base region is specifically made as a thin layer, the distance to the collector region is much shorter than the distance to the base electrode. Thus majority of the charge carriers injected into the base are captured by collector and only a minor portion of them reach the base electrode. In order to promote the drift of the charge carriers to collector, the voltage applied to the collector is much higher than the voltage applied to the base. Although the current flowing through the base electrode is small, it is sufficient to control bias on EB junction. Varying little base current one varies the bias of EB junction and the injection current from the emitter into base. Consequently the large current flowing between emitter and collector is controlled by the little base current.

In this lab work, the operation of the junctions and charge carrier flow between the terminals inBJP is studied experimentally. Three configurations for connecting BJT are common-base, common-emitter, and common-collector. A large number of transistor circuits use the common-emitter connection. This configuration is also used in the present lab work (Fig. 2a).

![Diagram of BJT configurations](image)

Fig. 2. (a) Three configurations for connecting BJT: common-base, common-emitter, and common-collector. (b) Currents (blue arrows) flowing in BJT connected in common-emitter configuration. Size of arrow represents the magnitude of current.

In this experiment, the input and output characteristics of an \textit{n-p-n} BJT are measured in the common-emitter configuration. The input characteristics (the base and emitter characteristics) are plots of $I_B$ versus $V_{BE}$ (Fig. 3a) and $I_E$ as a function of $V_{BE}$ at constant values of $V_{CE}$ (Fig. 3b).
Fig. 3. Input characteristics of BJT. (a) Base current versus forward base-emitter voltage. Base current drops down when the collector extracting voltage is applied (red arrow). (b) Emitter current versus forward base-emitter voltage. Emitter current increases when the extracting collector voltage is applied (red arrow).

The input characteristics are those typical of bipolar diode biased in forward direction. Reverse bias applied to the base-collector junction strongly influences the input characteristics. This voltage extracts the charge carriers from the base and reduces the base current. Simultaneously, the collector voltage extracting charge carriers from the base promotes injection from the emitter and thus increases the emitter current.

The output characteristic, often called the collector characteristic, is a plot of collector current $I_C$ versus collector-emitter voltage $V_{CE}$ (Fig. 4).
Fig. 4. Output characteristic of BJT: collector current versus emitter-collector voltage. Collector current exhibits a saturation-like behavior with the increase in collector voltage. Increase in base current drastically increase the saturation current in collector (red arrow).

The increasing collector voltage rapidly extracts with the charge carriers in the base resulting in rapid growth of the collector current. Once most charge carriers are extracted from the base, the collector current saturates and shows only minor increase at higher collector voltages. The base current strongly influences the collector current. The greater the base current the greater the efficiency of the injection from emitter and the greater the current flowing from emitter to collector.

Varying voltages on the junctions and measuring the resulting currents flowing through the emitter, base and collector terminals, one can evaluate the basic parameters of transistor as well as the voltage and current ranges of its operation.

The relationship between the base current $I_B$ and the collector current $I_C$ is nearly linear, that is $I_C = \beta \cdot I_B$. Usually commercial BJT have $\beta$ is in the range of 10 to 500. DC current gain is not a constant parameter being affected by temperature and current.

Another main parameters of BJT transistor is the transport factor, $\alpha$, which is defined as the ratio of the collector and emitter currents $\alpha = I_C / I_E$. It can be shown that $\beta$ and $\alpha$ relate to each other as:

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

The Q-point (the quiescent point), the maximum collector current $I_{C\text{max}}$, the maximum collector voltage (cut-off voltage) $V_{CC}$ and the maximum amplitude of symmetrical current swing allowed by the transistor without “clipping” are other main parameters of BJT. The meaning of these parameters can be understood from Fig. 5 below.
Fig. 5. BJT output characteristics. The load line connects the maximum cut-off voltage at zero base voltage with the maximum collector current.

The cut-off voltage is the maximum collector voltage at which the collector current remains negligibly small when the base current is zero. The maximum collector current is the collector current at the maximum base current when the transistor gain remains reasonably high. The straight line connecting the maximum collector voltage on the x-axis and the maximum current on the y-axis of the output characteristic is the load line. The center of the load line is the Q-point.
7.3. Materials
Global Specialties 1310 DC Power Supply
Wavetek 19 or similar Function Generator
BNC 2120 Accessory Board
LabView 2013 software
2N3055 or similar npn silicon transistor
10kΩ, 100Ω, 10Ω resistors
Connecting wires

7.4.1 Procedure A (NPN junction)

1) Open up the Characteristic Curve IV
2) Connect the breadboard for configuration (a) as seen below
3) Connect Vbb to the function generator with a 0-10V 1Hz triangle wave
4) Measure Ib and Vbe and graph the voltage characteristics
5) Repeat for Base-Collector junction (b)
7.4.3 Procedure B (Saturation Curves)

1) Connect the circuit as shown below

2) Connect VBB to the DC power supply, set to 1.3V
3) Connect VCC to the function generator, set to 0-10V, 1Hz, Triangle wave
4) Measure Ib, Ic, and Vce with LabView
5) Make an XY graph of Ic vs Vce
6) Set delay to 10ms
7) After a few seconds, Right Click on the XY graph and export data to Excel
8) Record the Base current for this curve
9) Raise the base current by slowly increasing the DC power supply, and restart the VI to clear any existing, unwanted data from the XY graph.
10) Take measurements of saturation curve at base currents of ~\((50, 100, 150, 250, 350, 450\mu A)\) or more if desired
11) Combine all data to 1 excel spreadsheet and graph with no connecting lines between points
12) Turn off power supplies and switch VBB and VCC
13) Set VCC to 5.0Vdc and set VBB to 0-10V, 1Hz, Triangle wave
14) Turn on LabView to obtain DC load line
15) Export this graph to excel and add it to the existing graph of saturation curves
7.4.4 Procedure C (Alpha & Beta values)

1) Set up circuit as seen below

![Circuit Diagram]

2) Measure Ib, Ic, and Ie with Labview
3) Connect VCC to the DC power supply, set to 1.3V
4) Connect Vbb to the function generator, set to 0-10V 1Hz triangle wave
5) Have LabView find Beta by dividing \( Ic/Ib \)
6) Have LabView find Alpha by dividing \( Ic/Ie \)
7) Make an XY graph of Beta vs Ib
8) Make an XY graph of Alpha vs Ie
9) Run the program and save waveforms of both graphs to Excel
10) Increase VCC in steps of 1V up to 10V and export all graphs
11) Combine all Beta graphs into 1 excel sheet, and similarly for all Alpha graphs

7.5. Calculations and Discussion

1. From Part A, what type of junctions are Base-Emitter and Base-Collector.
2. For Part B, determine Q-point and the working voltage and current ranges of the transistor.
3. Find Average Early Voltage of the transistor based on the saturation curves
4. From Part C, determine the maximum Beta on each curve, and discuss how this correlates to the operation of the transistor (how does it relate to the saturation curves).
5. Discuss how currents flowing through the transistor affect current gain and transport factor.
7.6. Questions

1. What is the maximum current gain and transport factor achievable with the transistor you have measured?

2. How current gain and transport factor change over the active region of the transistor?

3. List the main factors limiting the maximum collector voltage, the maximum collector current and the maximum power of BJT. Explain the reasons of these limitations.

4. Evaluate electric field developing in the base region at the Q-point.

5. Evaluate maximum electric field, which could develop in the base region of the transistor during your measurements. Compare this value with the breakdown electric field of silicon.