1.0 Objective

In this lab, you will determine the $I_C - V_{CE}$ characteristics of a BJT in several regions of operation. The large signal parameters will be determined experimentally. You will then derive the large signal model for the BJT in each region of operation. The key concepts introduced in this laboratory are:

- The 4 regions of operations of the BJT
- Determination of the region of operation based on the voltages $V_{BE}$ and $V_{CE}$
- Determination of large signal parameters such as $\beta$ and $V_A$.

2.0 Prelab

- H & S Chapters 7.1 - 7.4
- Write down the complete Ebers-Moll Equations
- Write down the simplified equations appropriate for the forward active and reverse active regions. From these equations, derive the Ebers-Moll large-signal model for each region of operation.

3.0 Procedure

Shown below is the complete Ebers-Moll model for the bipolar junction transistor. You will find all the parameters for this model in this experiment. You might find it useful to tabulate your data into a table such as Table1.
FIGURE 1. Ebers-Moll Model for the npn Bipolar Junction Transistor

![Ebers-Moll Model for the npn Bipolar Junction Transistor](image_url)

Table 1: Regions of Operations and Measurements

<table>
<thead>
<tr>
<th></th>
<th>Forward Active</th>
<th>Saturation</th>
<th>Cutoff</th>
<th>Reverse Active</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{BE}$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$V_{BC}$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$I_B$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$I_C$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$\beta$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$I_{ES}$ or $I_{CS}$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

3.1 Circuit Measurements

1. Connect the M3500 (NPN1) on Lab Chip 2 as shown in Fig. 2. Let $R_C = 5k\Omega$, $R_B = 1$ M$\Omega$, and $R_E = 100$ $\Omega$. Let $V_{CC} = 5V$. 
2. Increase $V_{BB}$ until $I_C = 0.5\, \text{mA}$. Measure $V_{BE}$ and $V_{BC}$. What region of operation is the transistor operating in? Measure $I_B$, the base current and compare that to the collector current. What is $\beta$? Once $\beta$ is found, you can calculate $\alpha$.

**Lab Tip**

It is often more convenient and sometimes, more accurate to measure the current by measuring the voltage across the resistor through which the current flows, using Ohm’s Law.

3. Draw the simplified Ebers-Moll model for the BJT in this region of operation and find its parameters.

4. While keeping the voltage $V_{BB}$ constant at 4V, vary $V_{CC}$ from 0V to 6V. This should take the transistor through 2 regions of operation. Note the base current $I_B$. Make a careful plot of $I_C$ vs. $V_{CE}$ and the noise in the $I_C$ measurement. You will need to take many points at low $V_{CE}$ due to the steep slope of the curve. Note $V_{BE}$, $V_{BC}$, and $I_B$ at saturation. Draw the simplified Ebers-Moll model for the BJT in the saturation region. From this plot, find the early voltage $V_A$. Does the Ebers-Moll model predict the correct behavior?

5. Change $V_{BB}$ to -3V ($V_{CC}$ remains at 5 V) How much collector current flows? Does it agree with the Ebers-Moll model? What region of operation is this? What is $V_{BE}$ and $V_{BC}$? Draw the simplified Ebers-Moll model for the BJT in this region of operation.
6. Interchange the collector and the emitter and let $V_{BB}$ be 4V. Measure $V_{BE}$ and $V_{BC}$. What region of operation is the transistor operating in? Measure $I_B$, the base current and compare that to the collector current. What is $\beta$? Draw the simplified Ebers-Moll model for the BJT in this region and find its parameters.

3.2 HP-4155 Measurements

1. Load the program PBJT6 into the HP-4155
2. Place the Lab Chip 2 into the test fixture and connect with the SMUs.
3. At the Source Setup Screen, change the start value of the base current to be the base current you found in procedure 3.1.4. Strictly speaking, the base current is not a constant in procedure 3.14.
4. Run the test program and note the curves traced out by the 4155.
5. Using the marker and cursor, find the Early voltage, $V_A$ for the curve corresponding to the base current you observed in procedure 3.1.4.

6. You can find $\beta$ by comparing the collector current with its corresponding base current. Find the value of $\beta$ for the base current you found in procedure 3.1.4. How do they compare?
7. Get a hardcopy of the $I_C - V_{CE}$ curve.
8. Interchange the connection for the collector and emitter and repeat the experiment. Find $\beta_R$ and $V_{AR}$. Note: you will need to change the scaling manually to see the curves.
9. Get a hardcopy of the $I_C - V_{CE}$ curve.
3.3 Diode Characteristics of BJT

1. Load the default diode program for HP-4155.
2. Connect the base and the emitter of Lab Chip 2 to the appropriate SMUs as described by the *SOURCE SETUP SCREEN*.
3. The program will plot the current as a function of the base-emitter voltage on a log scale. Using the equation for a forward biased diode, determine $I_{ES}$.
4. Interchange the connections and repeat the experiment to find $I_{CS}$.
5. Get a hardcopy

4.0 Optional Experiment

4.1 Circuit Simulation

Perform a SPICE analysis using the parameters you found. The circuit is shown above. You will need to perform a nested sweep. $V_{CC}$ will vary from 0 to 5 V and $I_{B}$ will vary with the initial base current from procedure 3.1.4 in steps of 10 µA. Plot $I_{C}$ vs. $V_{CE}$. Fill in the parameters for the M3500 in the data sheet in the Appendix.

Using the program PBJT and PDIODE, modify them to find the parameters for the pnp transistor M3511 (PNP) on Lab Chip 1 (collector = pin 27, base = pin 26, emitter = pin 25).
FIGURE 5. Data Sheet for M3500 and M3511

<table>
<thead>
<tr>
<th></th>
<th>M3500</th>
<th>M3511</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_S$</td>
<td></td>
<td>$I_S$</td>
</tr>
<tr>
<td>$V_{An}$</td>
<td></td>
<td>$V_{Ap}$</td>
</tr>
<tr>
<td>$\beta_n$</td>
<td></td>
<td>$\beta_p$</td>
</tr>
</tbody>
</table>