Laboratory 6
DC Behavior of Bipolar Junction Transistors

OBJECTIVE

To examine the DC behavior of transistors in the active and saturation regions. To learn to use the curve tracer to obtain $V_{CE}$-$I_C$ characteristics of transistors. To learn to measure the DC current gain $\beta_{DC}$ of a transistor.

BACKGROUND

A Bipolar Junction Transistor (BJT) is a three-terminal device. The terminals of the device are labeled the emitter (E), base (B), and collector (C). Each terminal connects to one of three semiconductor regions of the BJT. The three regions could be an $n$ type emitter, a $p$ type base, and an $n$ type collector, in which case the transistor is a NPN transistor. A PNP transistor has an $n$ type base sandwiched between a $p$ type emitter and a $p$ type collector.

The circuit symbols for NPN and PNP transistors are depicted in Fig. 6-1. The arrowhead on the emitter of the symbol points in the direction of normal current flow in the emitter (the forward direction of the base-emitter junction).

BJTs have three possible modes of operation: cutoff, active, and saturation. The biases on the emitter-base junction (EBJ) and the collector-base junction (CBJ) determine the mode of operation. Table 6-1 indicates the biases on the EBJ and CBJ for each mode of operation.

<table>
<thead>
<tr>
<th>MODE</th>
<th>EBJ</th>
<th>CBJ</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutoff</td>
<td>Reverse-biased</td>
<td>Reverse-biased</td>
<td>$I_C = 0, I_E = 0$</td>
</tr>
<tr>
<td>Active</td>
<td>Forward-biased</td>
<td>Reverse-biased</td>
<td>$I_C = \beta I_B, I_C = \alpha I_E$</td>
</tr>
<tr>
<td>Saturation</td>
<td>Forward-biased</td>
<td>Forward-biased</td>
<td>$V_{CESat} \approx 0.2V$</td>
</tr>
</tbody>
</table>

Table 6-1: Modes of operation of BJTs
Active Mode
The EBJ is forward-biased, and the CBJ is reverse-biased in the active mode. The voltage and current polarities of NPN and PNP transistors biased in the active mode are depicted in Fig. 6-2. The base-emitter voltage $V_{BE}$ is about 0.7V (voltage drop across a conducting diode) for a NPN transistor. For a PNP transistor, the emitter is at a higher potential than the base, and $V_{EB}$ is about 0.7V. The CBJ is reverse-biased — we thus have $V_{CB} > 0V$ for an NPN transistor ($V_{CB} = 0V$ is the boundary of the active region). If $V_{CB}$ becomes less than zero, the transistor starts coming out of the active region and begins to go into saturation). For a PNP transistor, we need $V_{BC} > 0V$ for operation in the active region.

![Fig. 6-2: Voltage and current polarities for transistors in the active mode](image)

The collector and base currents are related as follows in the active mode:

$$I_c = \beta_{DC} I_B \quad \text{Eq. 6-1}$$

In the above equation, $\beta_{DC}$ is a parameter called the common-emitter current gain. Transistors of the same type can have widely differing values of $\beta_{DC}$. For example, the small-signal current gain $\beta_{ac}$ (or $h_{fe}$) of a 2N2222A transistor is specified to lie in the range of 100 to 175 at a collector current of 1mA. The values of $\beta_{DC}$ and $\beta_{ac}$ are close to each other. We will henceforth use the symbol $\beta$ to denote $\beta_{DC}$.

Kirchhoff's current law applied to the transistor yields $I_E = I_B + I_C$. Applying Eq. 6-1 yields the following relationship between the collector and emitter currents:

$$I_c = \alpha I_E \quad \text{where} \quad \alpha = \frac{\beta}{\beta + 1} \quad \text{Eq. 6-2}$$

The parameter $\alpha$ is called the common-base current gain and has a value close to unity since $\beta$ is relatively large. The collector and emitter currents thus are very similar in magnitude.

Saturation mode
In the saturation mode both the EBJ and CBJ are forward-biased. Assume that the NPN transistor of Fig. 6-4 is saturated. We have $V_{BE} \approx 0.7V$. The CBJ is also forward-biased and we have $V_{CB} \approx -0.5V$. The collector-emitter voltage $V_{CE} = V_{CB} + V_{BE}$ is about 0.2V. The transistor
thus behaves as a closed switch with about 0.2V appearing across the switch (collector/emitter
terminals). The transistor is "ON", and almost all of the supply voltage \( V_2 \) appears across the
collector resistor \( R_2 \). Let the collector current under saturation be denoted \( I_{\text{Sat}} \). We have

\[
I_{\text{Sat}} \approx \frac{(V_{CC} - 0.2)}{R_C} \quad \text{Eq. 6-3}
\]

where \( V_{CC} \) is the supply voltage and \( R_C \) is the collector resistor. To force a transistor into
saturation we need to supply a minimum base current \( I_{B_{\text{min}}} = \frac{I_{\text{Sat}}}{\beta} \). To ensure hard saturation
of the transistor we design for a base current \( I_B \) that is 2 to 10 times larger than \( I_{B_{\text{min}}} \).

**PRELAB**

1. Perform DC analysis of the transistor circuit depicted in
   Fig. 6-3 and determine the potentials at the base, collector,
   and emitter. Also determine all the circuit currents. Use
   \( \beta_{DC} = 100 \) for your analysis. Simulate the circuit using
   PSpice and compare your results. Use a Qbreakn part for
   the transistor. Edit the instance model and insert the
   statement \( (bf = 100) \) before the termination characters *$.
   This sets the value of \( \beta_{DC} \) to 100.

   ![Fig. 6-3: Circuit for prelab question 1](image)

2. Use the PSpice schematic depicted in Fig. 6-4 to
   obtain the \( V_{CE}-I_C \) characteristics of a 2N2222
   transistor. Sweep both voltage sources across
   appropriate ranges. Your output plot should contain
   \( V_{CE}-I_C \) curves for about 8 values of base current \( I_B \).
   Use your curves to calculate \( \beta_{DC} \) of the transistor near
   \( V_{CE} = 5V, I_C = 5mA \).

   ![Fig. 6-4: Circuit for prelab question 2](image)

3. It is desired to turn an LED on (using a circuit similar to Fig. 6-4) by supplying appropriate
   base drive to a transistor and saturating it. A 5V supply provides power to both the base and
   collector circuits. A LED and a current limiting resistor \( R_C \) are used in place of the resistor
   \( R_2 \) of Fig. 6-4. Assume that the transistor is in hard saturation and that the voltage drop
   across the LED is 2V. The LED current desired is 20mA for optimum brightness. Choose a
   resistor \( R_C \) that accomplishes this. Assume a \( \beta_{DC} \) value of half the minimum for a 2N2222A
   transistor to calculate the required base current. Choose a base resistor \( R_B \) to set up the
   required base current. Simulate the circuit using PSpice (use 3 regular diodes to model the
   drop in the LED). What collector and base currents result? What is the value of \( V_{CE} \)?
IN LAB

1. Use the curve tracer to obtain $V_{CE}$-$I_C$ curves for the 2N2222A transistor in your lab kit. From the curves obtain the value of $\beta_{DC}$ in the vicinity of $V_{CE} = 5V$, $I_C = 5mA$. Ask two of your neighbors for the $\beta_{DC}$ of their transistor. Record these values. Comment on the variations in $\beta_{DC}$ for the 2N2222A transistor.

2. Measure the small signal $\beta$ in the vicinity of the same operating point (use the two nearest curves to make this measurement).

3. Construct the circuit of Fig. 6-3. Measure the potentials at the collector, base, and emitter. Also measure all the circuit currents. Redo your theoretical calculations with the $\beta_{DC}$ value measured above. Compare your experimental results with the theoretical values.

4. Construct the LED driver circuit designed in part 3 of the prelab. With the power supply to the base disconnected, verify that the transistor is in cutoff and that the LED is off. Measure $V_{BE}$ and $V_{CB}$ and use these values to justify the fact that the transistor is in cutoff.

5. Connect the 5V supply to the base circuit and verify that the LED turns on. Measure $V_{BE}$, $V_{CB}$, and $V_{CE}$. What conclusions can you make about the bias of the emitter-base and collector-base junctions? Is the transistor in hard saturation? Explain. Also measure $I_B$ and $I_C$ and compare with the values calculated in the prelab. Finally, measure and record the voltage drop across the conducting LED.

6. Use the Wavetek function generator to produce a 1Hz square wave that varies between the voltage levels 0V and 5V. Use this signal to provide the base drive to the LED driver circuit. Comment on the behavior of the circuit.