BJT Characteristics and Amplifiers

Matthew Beckler
beck0778@umn.edu
EE2002 Lab Section 003

April 2, 2006

Abstract

As a basic component in amplifier design, the properties of the Bipolar Junction Transistor (BJT) are very important. Starting with the basic relationships of voltage and current, the operation of the BJT is reasoned out. Using these relationships, useful circuits can be constructed, such as flashing an LED or constructing a current mirror.

Introduction:

The BJT is the first device we have looked at that can perform amplification of a signal. The three connections, the Base, Collector, and Emitter, are used in a variety of configurations, depending on the application.

A BJT is constructed from three pieces of silicon, with one piece of p-type silicon sandwiched between two pieces of n-type silicon. The p-type silicon is known as the Base connection, while the other two are the Collector and Emitter. The base and the emitter form a PN junction that is very similar to the PN junction found in a simple silicon diode. The voltage that this pseudo-diode activates is known as the *threshold voltage*, V_t.

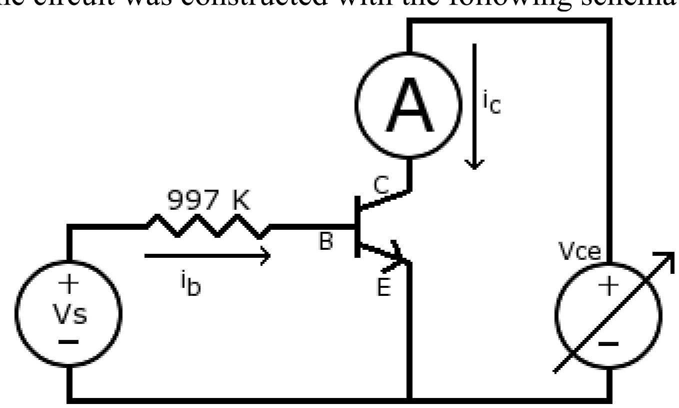
There are three basic mode of operation of a BJT. When the voltage across the base and emitter is less than the threshold voltage, usually 0.6 volts, the transistor is said to be in the *cutoff* region. While in cutoff, the transistor acts as an open circuit, allowing no current to pass through any ports. When the base-emitter voltage is greater than the threshold voltage, provided that the collector-emitter voltage is great enough, the transistor operates in the *active* region. If V_{ce} is not large enough, the device operates in the *saturation* region.

Principles of basic amplifier design will also be utilized to operate the BJT as a digital switch, by driving it between cutoff and saturation. We will use this to blink an LED with a continuously variable input signal and a digital output.

Experiments:

1) Measure Collector Current versus Collector-Emitter Voltage:

The first step in creating the data charts for measuring the BJT's characteristics is to construct a test circuit. Here, we are using a simple circuit with only one resistor, two voltage supplies, an ammeter, and the BJT. The circuit was constructed with the following schematic:



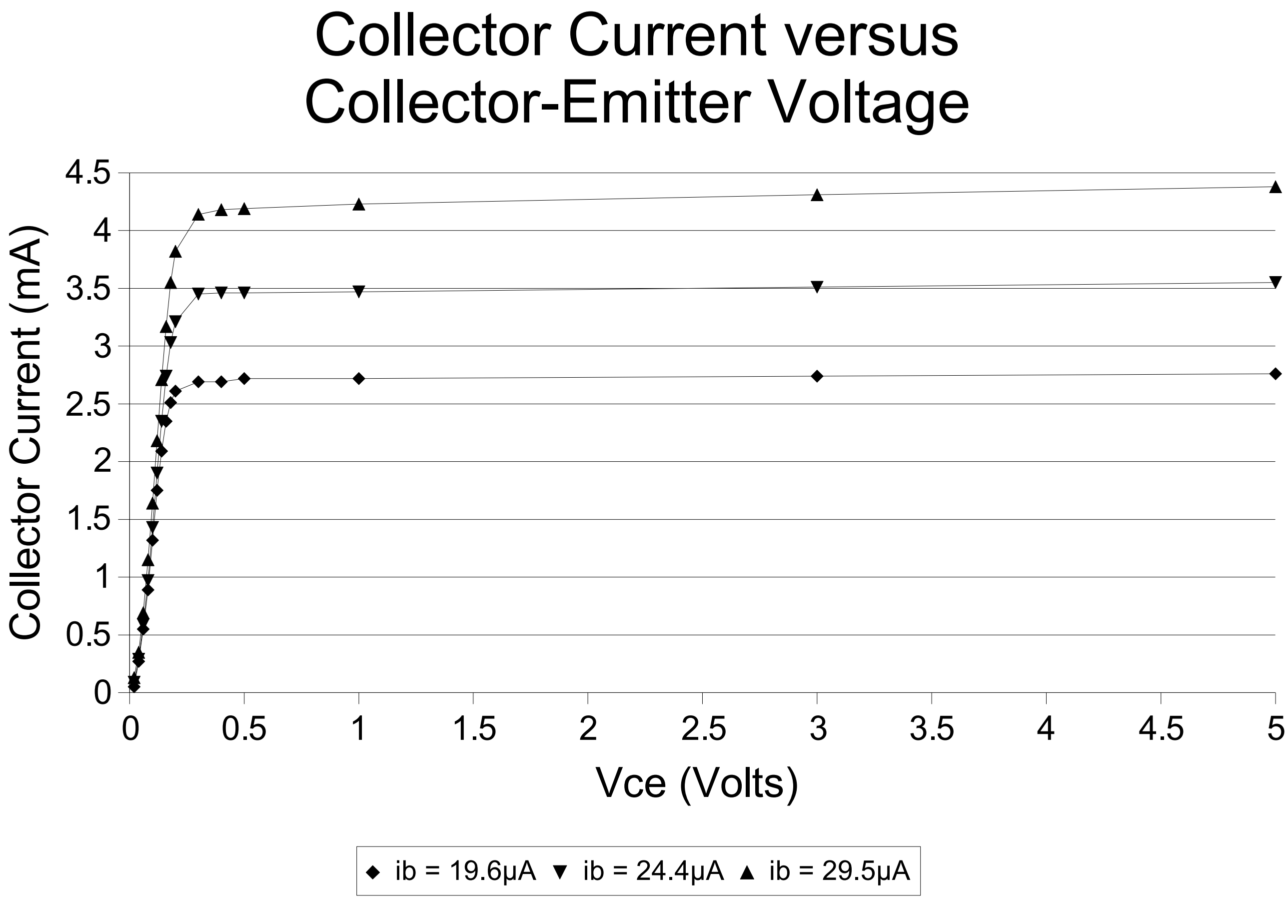
Circuit Schematic - Experiment 1

We used three experimental trials, with a different V_s for each trial. Since the voltage drop across the Base-Emitter junction is a constant 0.7 volts, the remainder of Vs must drop across the resistor. This allows us to find the value of the base current. The resistor used was labeled 1 MΩ , but the real value was 997 KΩ. The value of V_s and i_b are summarized in the following table:

Base Voltage (V_s)	**Base Current (i_b)**
20	19.6µA
25	24.4µA
30	29.5µA

For each of the three trials, we varied V_{ce} between 0.02 volts and 20 volts and measured the resulting collector current, i_c. Since the chart of these values is very linear between V_{ce} = 1 and V_{ce} = 20, and the interesting parts are with V_{ce} < 1. Therefore, more values were measured in the interesting region. The following table summarizes the data collected:

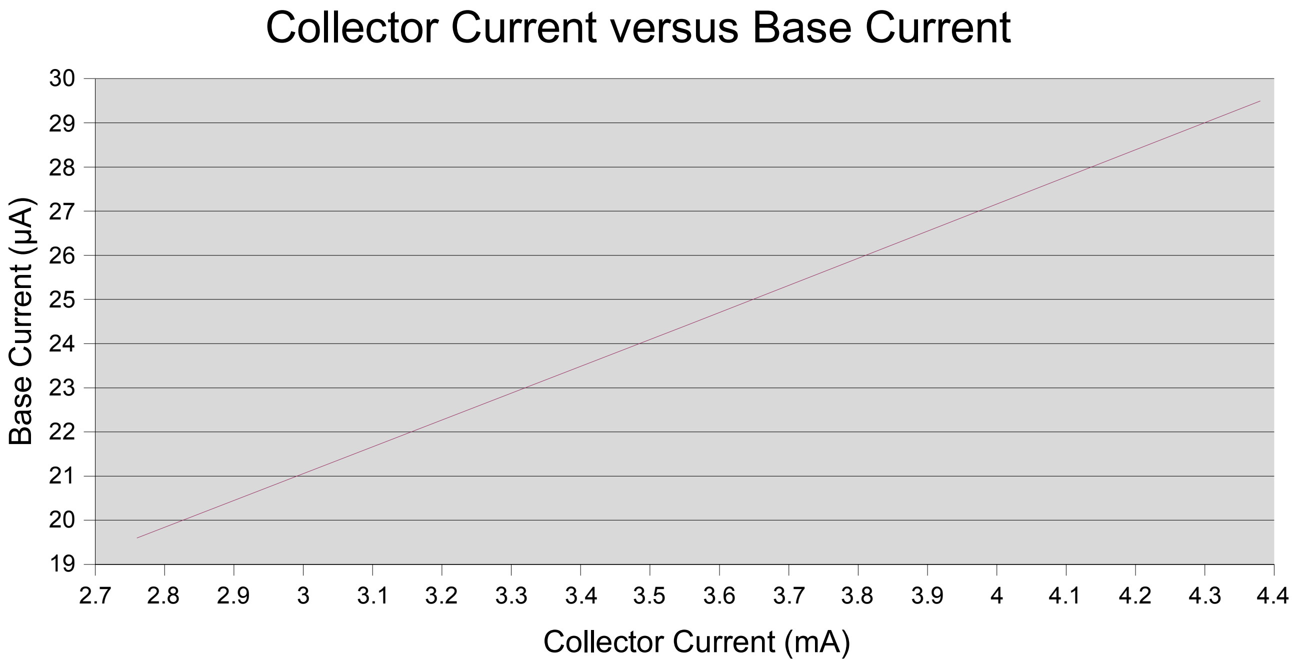
	Collector Current - i_c (mA)		
V_{ce} (Volts)	**i_b = 19.6µA**	**i_b = 24.4µA**	**i_b = 29.5µA**
0.02	0.05	0.09	0.13
0.04	0.27	0.29	0.35
0.06	0.55	0.59	0.69
0.08	0.89	0.97	1.15
0.10	1.32	1.43	1.64
0.12	1.75	1.90	2.18
0.14	2.09	2.35	2.71
0.16	2.35	2.74	3.17
0.18	2.51	3.03	3.55
0.2	2.61	3.21	3.82
0.3	2.69	3.45	4.14
0.4	2.69	3.46	4.18
0.5	2.72	3.46	4.19
1.0	2.72	3.47	4.23
3.0	2.74	3.51	4.31
5.0	2.76	3.55	4.38
7.0	2.79	3.59	4.41
9.0	2.82	3.63	4.48
11.0	2.85	3.66	4.53
13.0	2.87	3.70	4.57
15.0	2.90	3.73	4.58
17.0	2.92	3.77	4.65
19.0	2.95	3.81	4.70
20.0	2.96	3.84	4.71



In this chart, you can see the cutoff region of operation in the area of the chart with a steep slope. After this region is the nearly horizontal region of active mode operation. Ideally, the behavior of the chart in this region would be perfectly horizontal, but since we are working with real components, nothing can be perfect.

One of the basic equations used when working with BJT's is the equation relating i_b and i_c. This equation is $\mathbf{i_c = ß * i_b}$, where **ß** is the value of the transistor's gain.:

Collector Current (i_c) (mA)	Base Current (i_b) (μA)
2.76	19.6
3.55	24.4
4.38	29.5



Based on the relationship $\mathbf{i_c = ß * i_b}$, we expect the previous chart to be linear. The slope of the line can be used to calculate a value for beta, which we will do in the next section.

All of the results in the sub-section match the theory behind the BJT's operation. For a specific value of I_b, the value of I_c should be the same, regardless of V_{ce}, once V_{ce} is greater than a certain value. A graph of I_c vs I_b should have a linear slope, because the relationship between those two variables is linearly related by $\mathbf{i_c = ß * i_b}$.

2) Calculate Beta and Output Resistance:

The common-emitter current gain, also known as beta, is the inverse of the slope of the graph from the previous section. We can also calculate beta using any combination of collector current and base current. This is the method we will use.

V_{ce} (V)	i_c (mA)	ß
V_s = 20V, i_b = 19.6µA		
2	2.71	140.93
5	2.76	143.05
10	2.83	119.17
V_s = 20V, i_b = 19.6µA		
3	3.51	143.85
5	3.55	145.49
11	3.66	150.00
V_s = 20V, i_b = 19.6µA		
3	4.31	146.10
5	4.38	148.50
11	4.53	153.60

The small-signal output resistance of the BJT circuit is calculated from the slowly-increasing region of the first chart of I_c vs V_{ce}. The slope of that linear region is the inverse of the small-signal output resistance. For each value of V_s, we calculated the value of R_{out}:

$V_s = 20V$: $R = \frac{1}{m} = \frac{\Delta x}{\Delta y} = \frac{(20-1)}{(2.96\text{m}-2.72\text{m})} = \frac{19}{0.24\text{m}} = \mathbf{79.16}\, \boldsymbol{k\Omega}$

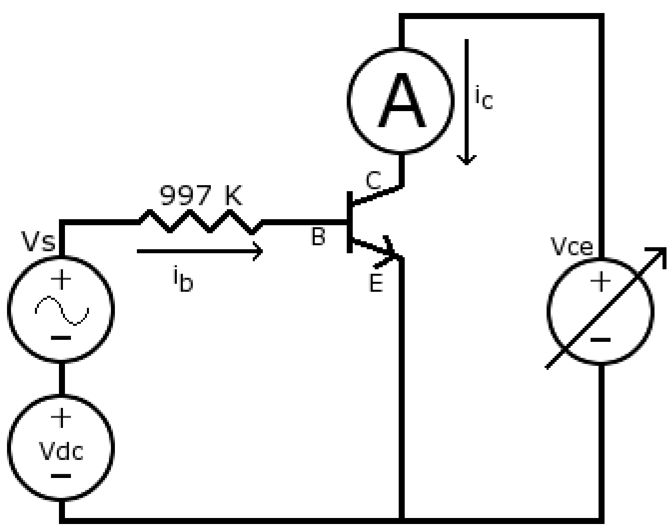
$V_s = 25V$: $R = \frac{1}{m} = \frac{\Delta x}{\Delta y} = \frac{(20-1)}{(3.84\text{m}-3.47\text{m})} = \frac{19}{0.37\text{m}} = \mathbf{51.35}\, \boldsymbol{k\Omega}$

$V_s = 30V$: $R = \frac{1}{m} = \frac{\Delta x}{\Delta y} = \frac{(20-1)}{(4.71\text{m}-4.23\text{m})} = \frac{19}{0.48\text{m}} = \mathbf{40.00}\, \boldsymbol{k\Omega}$

All results in this section match the theory of the BJT. All the values calculated for beta were relatively close in magnitude. The average seems to be approximately 146.4. The values calculated for the small-signal output resistance were somewhat close to one another, but they are all in a reasonable order of magnitude, and make sense in the scope of this experiment.

<u>3) AC Signals and Gain</u>

For this section of the experiment, a new circuit has been constructed that provides both an AC signal as well as a DC signal. This allows us to bias our transistor into the active region with the DC component of the signal, and then measure the 'small-signal' parameters with the AC signal. The new circuit looks something like this:



Circuit Schematic - Experiment 3

For a couple values of V_{ce} we have measured both I_b and I_c, and used them to calculate the value of the current gain. The current gain, A_i is defined as:

$$A_i = \frac{I_c}{I_b} = \beta$$

So really, we are simply finding beta again, but this time using the small signal values. We used values of V_{ce} of 5, 10, and 15. We used a source with a DC component that created a base current of 1.6µA. The results are summarized in the following table:

V_{ce} (V)	I_b (μA)	I_c (mA)	A_i = ß
5.0	1.6	0.268	167.5
10.0	1.6	0.263	164.4
15.0	1.6	0.271	169.4

The values of beta for this section are much closer than the previously calculated values of beta. The next value to calculate is the value of the small-signal input resistance. This value is also known as $\mathbf{R_\pi}$, named after the resistance used in the small-signal model of the BJT. This value is calculated using the following formula:

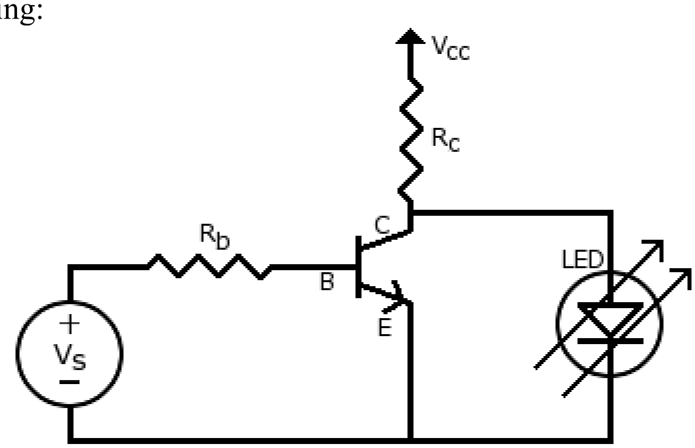
$$R_\pi = \frac{V_T}{I_{BQ}} = \frac{0.026\,V}{1.6\mu A} = \mathbf{16.25}\ \boldsymbol{k\Omega}$$

Here, $\mathbf{V_T}$ is the thermal voltage, which is a constant 0.026 V at room temperature. The other value, $\mathbf{I_{BQ}}$, is the Quiescent base current, or the base current from the DC component of the input signal.

The results in this section all match the theory of the BJT. The small-signal calculated values of beta are fairly close to the DC values calculated, and the calculation of R_π is very straightforward. The results we have received make sense and are of the right order of magnitude.

<u>4) LED Switch</u>

Many times in building a circuit, the situation arises where you need to provide more current than an integrated circuit or other circuit component can provide. In this situation, you could use a BJT as a current amplifier, to provide the necessary current. In this experiment section, we will do just that, by using a function generator that cannot provide enough current to drive an LED. We will be driving the BJT between cutoff and saturation, to turn on and off the LED, respectively. Here is the circuit schematic we will be using:

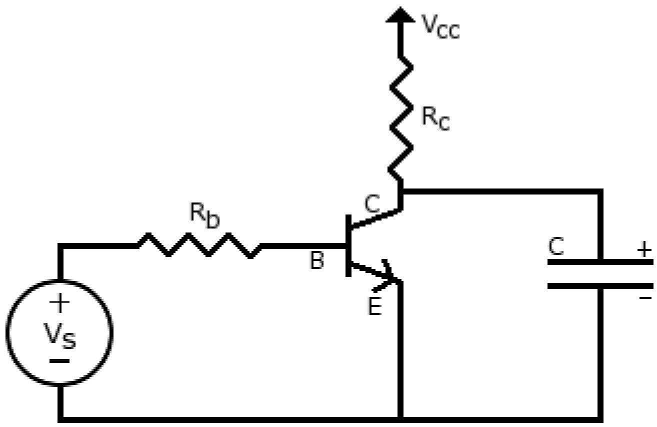


Circuit Schematic - Experiment 4

A bit of explanation is necessary at this point. When the voltage of V_s is not enough to forward-bias the junction between base and emitter, the BJT is acting like an open-circuit, which allows the LED to light. When the BJT enters into the active mode, there is a virtual short circuit between collector and emitter, effectively grounding the LED's terminals, turning the LED off. The resistor Rc is very important because it limits the amount of current through the LED. In the scope of this problem ,we have chosen to use a value of 10 volts for V_{cc}. To allow no more than 20 mA of current through the LED, we need a resistor of at least 500 ohms. However, many combinations of voltage and resistance will exceed the recommended power dissipation rating for the ¼ watt resistors we are using. For the best operation, a value of 10KΩ has been used, which allowed a maximum of 1 mA through the LED. The resistor R_b was 100 KΩ, which was driven by a signal of approximately 6.86 volts from trough to peak. The theory of this problem, including BJT theory as well as generic diode theory matches the results of the experimentation.

5) Triangular Wave and Capacitor Circuit

After removing the LED from the previous circuit, we have replaced it with a capacitor. Here is the circuit schematic:



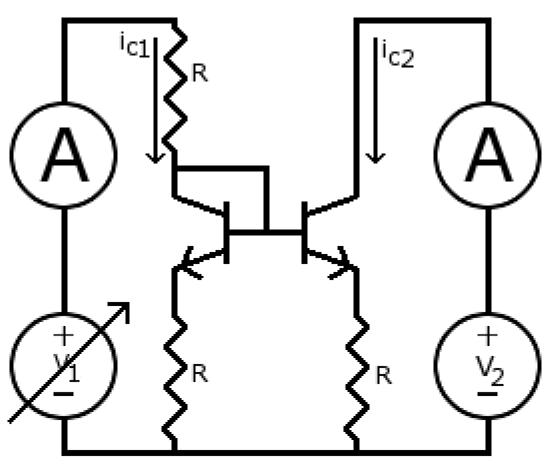
Circuit Schematic - Experiment 5

This will allow us to observe the capacitor charging and discharging, when the BJT is in the cutoff and active modes respectively. This is best illustrated by a trace made from the oscilloscope:

When the transistor is in cutoff mode, the capacitor is charging through the Rc resistor to Vcc. When the transistor enters the active region, the capacitor discharges through the transistor to ground. This happens quite quickly.

6) Current Mirror

When designing a circuit, it is often handy to have a controlled source of current. This can be accomplished through the use of a simple current mirror. Here is a circuit schematic:



Circuit Schematic - Experiment 6

The current through the left branch, Ic1, will be mirrored in the right branch, Ic2. If we change the value of the V1 voltage source, we can change the value of Ic1. This will become the value of Ic2. We set up two Ammeters to measure the branch currents. Here is the data we have collected:

V_2 (Volts)	I_{C1} (mA)	I_{C2} (mA)	Ratio I_{c1}/I_{C2}
2.7	1.00	0.99	1.01
4.6	2.00	1.979	1.01
6.6	3.00	2.965	1.01
8.6	4.00	3.93	1.02
10.6	5.00	4.92	1.02
12.6	6.00	5.90	1.02
14.6	7.00	6.88	1.02
16.5	8.00	7.87	1.02
18.5	9.00	8.85	1.02
20.5	10.00	9.81	1.02

As you can see, the current mirror is very effective at its job. This circuit works on the assumption that the transistors have nearly the same value of beta. Since the bases of both transistors are tied together, they should both have the same collector current. For this experiment, we have used resistances of 1 KΩ for all resistors. We also used a value of 10 Volts for V2.

The results obtained for this problem match the theory of BJT transistor operation. The results are also very dependent on the values of beta. Since the beta-value for a transistor can vary from transistor to transistor, some sort of biasing network of resistors is often used to reduce the effect of beta on the transistor circuit operation.

Results and Conclusion:

For the fundamental analysis of the BJT, the data collection and graphing was a success. We successfully obtained data for three different values of Ib. This produced three functions on the chart. The charts were all very well behaved, and looked very close to the expected values. The calculated values of beta were all very close together, around 146. Using the slight slope of the Vce vs. Ic graph between 1 and 20 volts, we calculated the small signal output resistance at a few values of the collector current. The numbers received were of the right order of magnitude, and made sense in the scope of the problem.

Using an AC signal, we can measure and calculate the small-signal current gain (beta) and the small-signal input resistance. Beta is calculated in much the same fashion as the previous section, and the small-signal input resistance is calculated from a simple equation involving the Thermal Voltage (Vt) and the quiescent base current. Again, the values measured and calculated were very close to each other, indicative of good precision if not good accuracy.

To use a BJT as a digital switch to drive an LED, we design the circuit to drive the BJT between cutoff and saturation with a sine wave. Using a current-limiting resistor, we can safely drive an LED with more current than the signal generator can provide. This concept will extend to many applications, such as driving LED's from a digital logic chip, or driving larger lamps and motors from a small circuit.

Using a common capacitor, we can create an interesting effect by replacing the LED of the previous circuit with the aforementioned capacitor. This produces a series of charging-discharging cycles, depending on the current mode of the transistor. When the transistor is in cutoff, the capacitor is charging through the collector resistor. When the transistor enters into the active region, the capacitor is shorted to ground, and discharges.

For the current mirror used, the results were very spectacular. The ratios of Ic1 to Ic2 were within 2% for all values of Ic1 used. The correct operation of this current mirror relies on the transistors having very similar values of beta. By the relationship $\mathbf{i_c = \beta * i_b}$, with both transistor's bases tied together to the same voltage, they should have the same collector current, assuming the same value of beta. As seen in our results, this is a valid assumption, as the collector currents were very similar.