The 2N3393 Bipolar Junction Transistor

Common-Emitter Amplifier

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Abstract

The bipolar junction transistor (BJT) is a non-linear electronic device which can be used for amplification and switching. Several experiments are presented that describe the various characteristics of the BJT. The gain, small-signal gain, input resistance, output resistance, saturation and cutoff are experimentally found for this device. Finally, two practical applications of the BJT are presented.

Introduction

Overview

This experiment investigates the various properties and characteristics of the BJT. First, the output characteristics of the transistor are discussed when operating with a constant base-to-emitter voltage. Second, the BJT's ability to amplify an AC signal is investigated. Third, the BJT's limitations are discussed and the saturation and cutoff are found. Finally, two practical applications of the BJT are presented.

Theory

The bipolar junction transistor (transistor) is a three terminal device consisting of a *base*, a *collector*, and an *emitter.* The primary characteristic of this device is that the current flowing across one junction affects the current flowing in the other junctions.

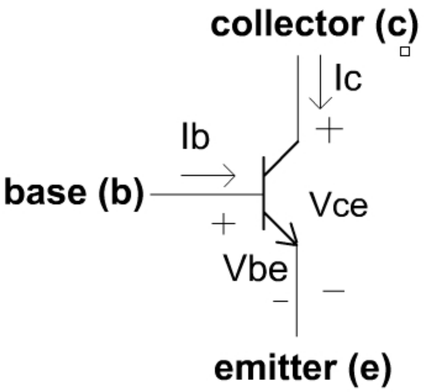

Figure 1: Bipolar Junction Transistor

This experiment is concerned with the use of the BJT in the *common-emitter* configuration, where the base and the collector are both connected to the emitter. An example of this configuration is shown below.

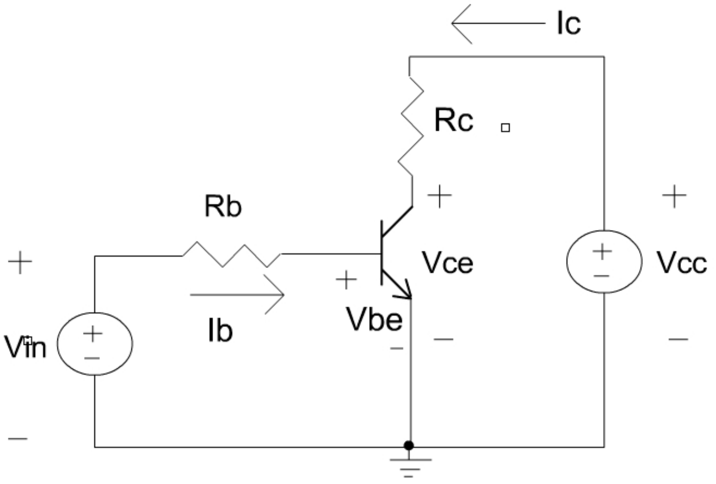

Figure 2: BJT in common-emitter configuration

When voltages Vbe and Vce are within certain ranges, the current flowing in Ic is a multiple of the current flowing in Ib. This multiple (called the *gain,* or *Beta*) stays consistent throughout large ranges of Ib. Because of this, small changes in Ib result in amplified changes in Ic. Since changes in Ic and Ib relate to changes in voltage, the BJT can be used to amplify AC signals.

The Characteristics of the 22N3393 BJT

In this experiment, the device was examined first under DC conditions. The current gain Beta was calculated for the device, as well as the device's output resistance. Second, an AC signal was applied and the small-signal current gain was calculated, as well as the device's small-signal input and output resistance. Third, the device's limitations were tested for signal amplification and the saturation and cutoff for the device were investigated. Finally, two practical applications for the BJT were tested.

BJT output under DC bias

The first part of this experiment considers the output characteristics of the BJT. The following circuit (previously shown in the introduction) was used:

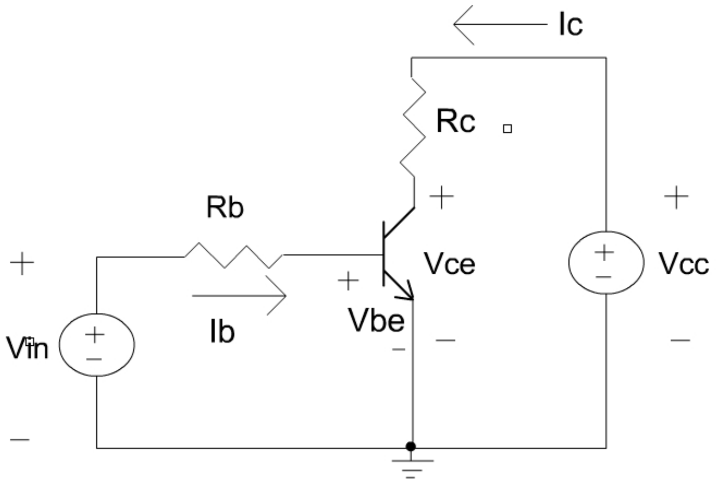

Figure 3: Common-emitter circuit

For the data collected, Rb was set at 2 Kohm and Rc was set at 100 ohm. Vin was then adjusted until Ib was equal to a fixed value, and Vbe was at least 0.6V (in order to forward bias the transistor). Then Vcc was set at 0 and slowly brought up, while the data was collected via an ammeter in series with Rc (to measure Ic) and a voltmeter in parallel with Vce (to measure Vce). The process was repeated for three values of Ib: 10, 20 and 30 microamps. The data collected is presented in the Appendix under *Table 1* and is graphed below in Figure 3.

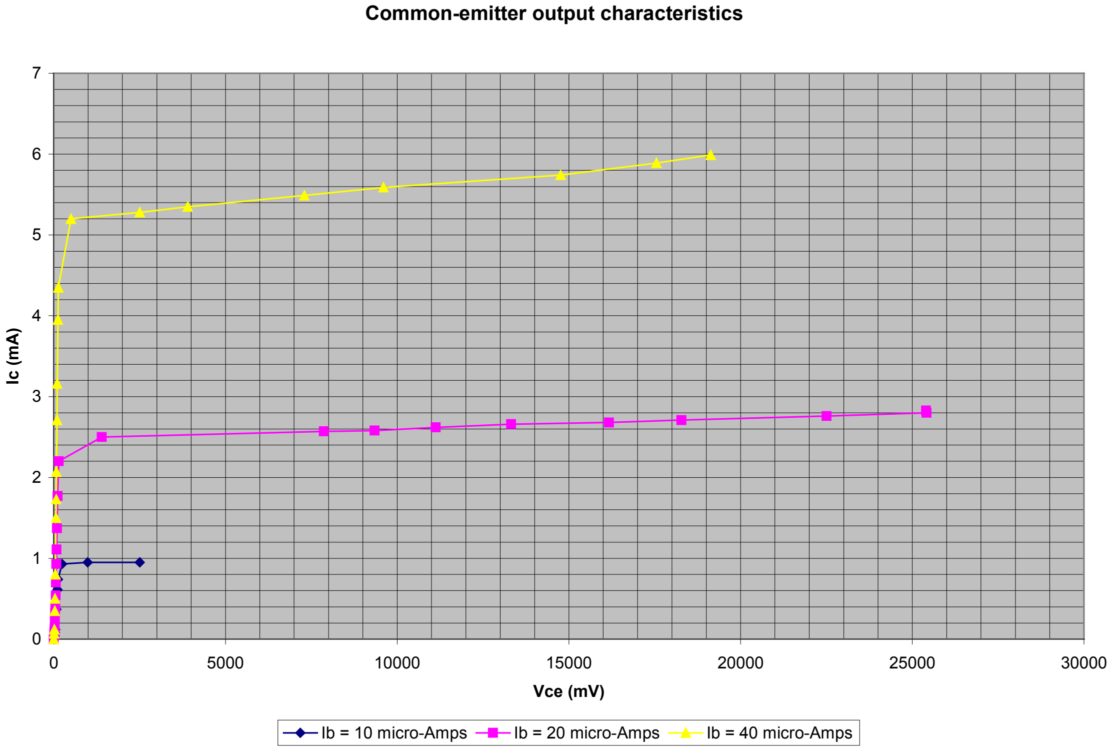

Figure 4: Common-emitter output characteristics for fixed values of Ib

As can be seen from the three lines in Figure 3, the output characteristics follow a similar pattern regardless of Ib. Ic rises sharply from 0 as Vce increases but levels off to nearly a horizontal line when Vce is anywhere above 0.2 volts (called the active region). As long as Vce is above 0.2 volts, Ic remains relatively constant.

From this data, we can determine the output resistance Ro by looking at the slope of the line where Vce is greater than 0.2 volts (R=V/I). The values for the delta Vce and delta Ic were obtained by subtracting the values of Vce and Ic from Table 1 at the boundaries of the active region.

delta Vce (V)	delta Ic (mA)	Ic (milliamps)	Ro (ohms)
2.257	0.02	1	112
24	0.63	2.6	38
16.63	0.71	5.6	23

Table 2: Output Resistance - Ro for the BJT

We can also determine the gain by dividing Ic by Ib (where Ic is an approximation of the average Ic when Vce is greater than 0.2).

Ic (milliamps)	Ib (microamps)	Beta
1	10	100
2.5	20	125
5.5	30	137.5

Table 3: Beta for the Bipolar Junction Transistor

From this data, it appears Beta is increasing with Ic or Ib (or both).

However, from theory we know that in order for the BJT to be a useful amplifier Beta should be a constant regardless of Ib. The next part of the experiment shows that Beta does in fact stay nearly constant regardless of Vce or Ib.

The circuit from Figure 3 was once again used, but in this case, Vin was brought to zero and Vcc was adjusted until Vce was at 2 volts. Ic and Ib were measured via ammeters in series with Rb and Rc. Then Vin was raised by a small amount so that Ib would increase, while Vcc was changed so that Vce remained at 2 volts. These steps were repeated for each data point. When all points were collected, the entire process was repeated for Vce equal to 4 volts. The data is graphed below in Figure 5.

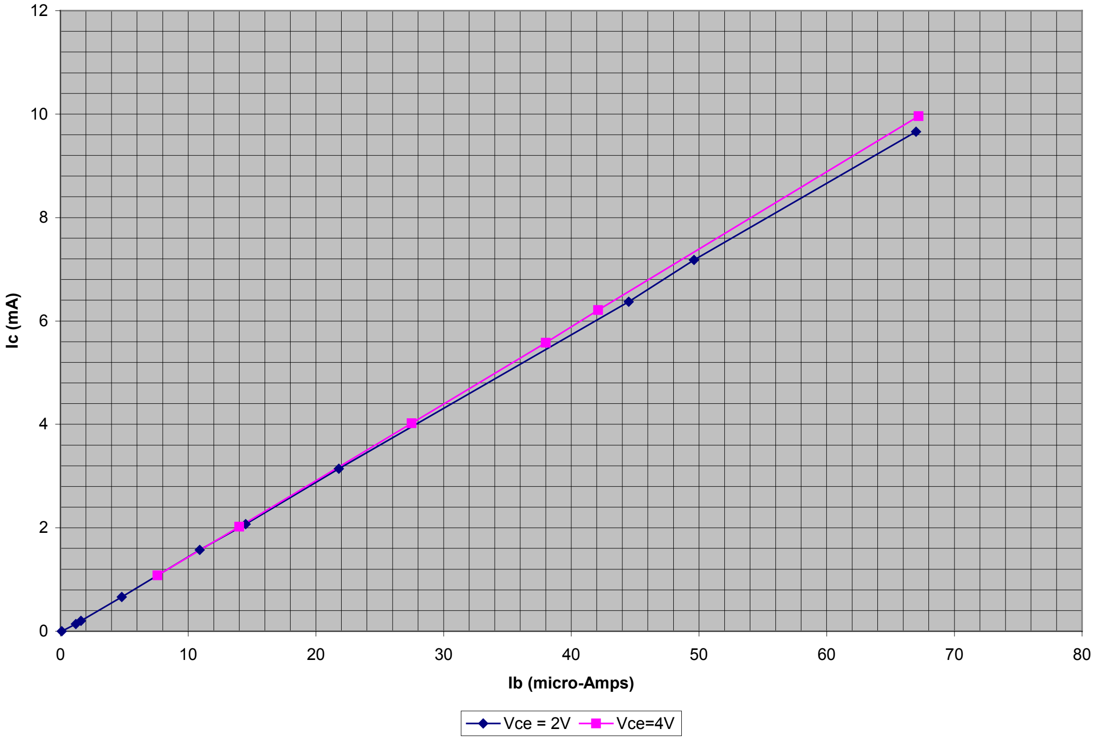

Figure 5: Ic vs. Ib for fixed values of Vce

From the graph we can see that slope of the line is almost identical for the two values of Vce. We can also see that it is fairly linear. The points are show below in Table 4 along with the value of Beta for each point:

Ib (micro-Amps) Vce=2V	Ic (milli-Amps) Vce=2V	Beta	
67	9.66		144.17
49.6	7.18		144.76
44.5	6.37		143.15
21.8	3.14		144.04
14.5	2.07		142.76
10.9	1.57		144.04
4.8	0.66		137.5
1.6	0.2		125
1.2	0.14		116.7
0.1	0		
		Average 143.57	

Ib (micro-amps) Vce=4V	Ic (milli-Amps) Vce=4V	Beta	
67.2	9.96		148.21
42.1	6.21		147.51
38	5.58		146.84
27.5	4.02		146.18
14	2.02		144.29
7.6	1.08		142.11
		Average 145.86	

Table 4: Beta values for various levels of Ib and fixed values of Vce

Once again we see that Beta is in fact increasing as Ib increases, but slowly compared to the increases in Ib. Beta vs. Ib is graphed below to illustrate.

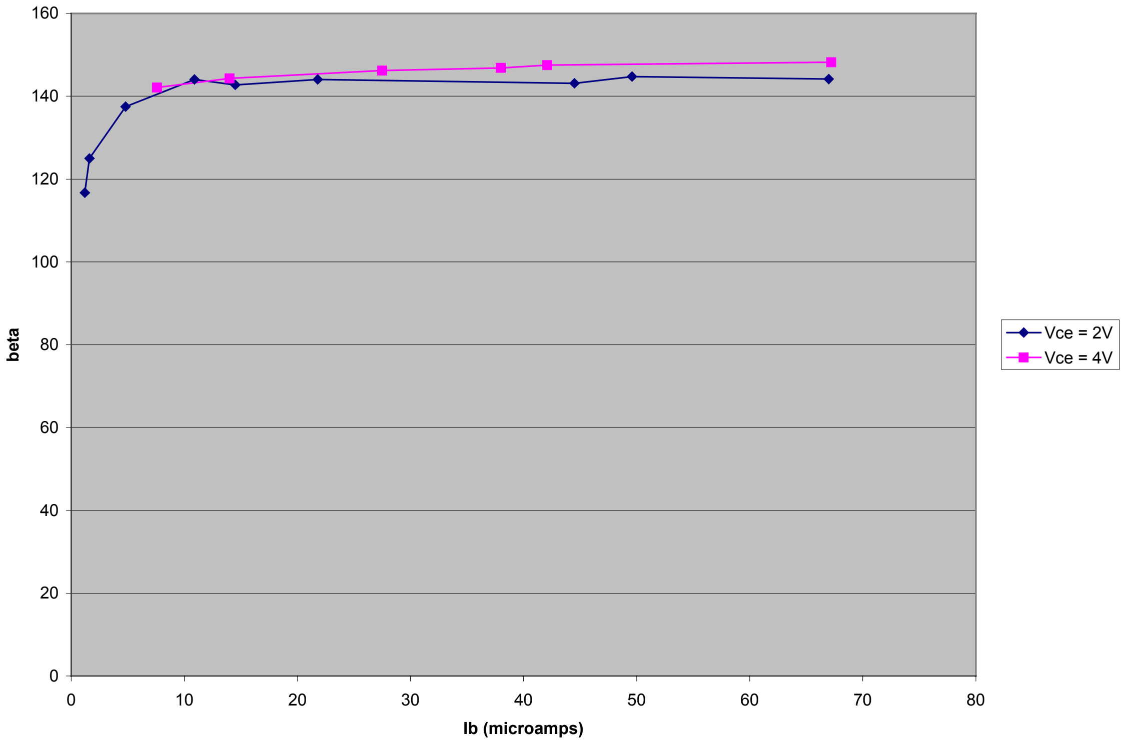

Figure 6: Beta vs. Ib

It would appear that the device is in saturation when Ib is less than 10 micro-amps in this circuit. The exact values for Vbe for each point was not taken down in this experiment and cannot be verified. Only the value of Ib was measured and that Vbe was at least 0.6 volts was verified. The values for Beta from Table 1 were taken when Vbe was 0.6 V and those values for Beta also increase as Ib increase. It was assumed that setting Vbe > 0.6 volts and Vce > 0.2 volts was all that was necessary to put the device into the active region. Amplifiers built to operate too close to the saturation region would distort the output, amplifying the top part of the signal more than the bottom. Further study into the boundaries of the saturation region is recommended.

For now ignoring the boundaries of the data, we can see that the gain remains constant for the two different fixed values of Vce. This falls in line with the expectation that the gain of the transistor is fairly linear for both Vce as well as Ib.

BJT Characteristics with an AC signal

We now look at the BJT's response with an AC signal applied to the DC bias. Once again the circuit from Figure 3 was used with Rb = 22 Kohm, Rc = 1 Kohm, Vcc = 18 V. Vin was a sin wave with a minimum of 800 mV and maximum of 3.6 mV (Peak-to-peak of 2.8 V centered about 2.2 V). Vout was taken at Vce and was measured as a sin wave with minimum of 900 mV and maximum of 16.4 V (Peak-to-peak 15.5 centered about 8.65 V) The graphs of Vin and Vout are shown below in Figure .

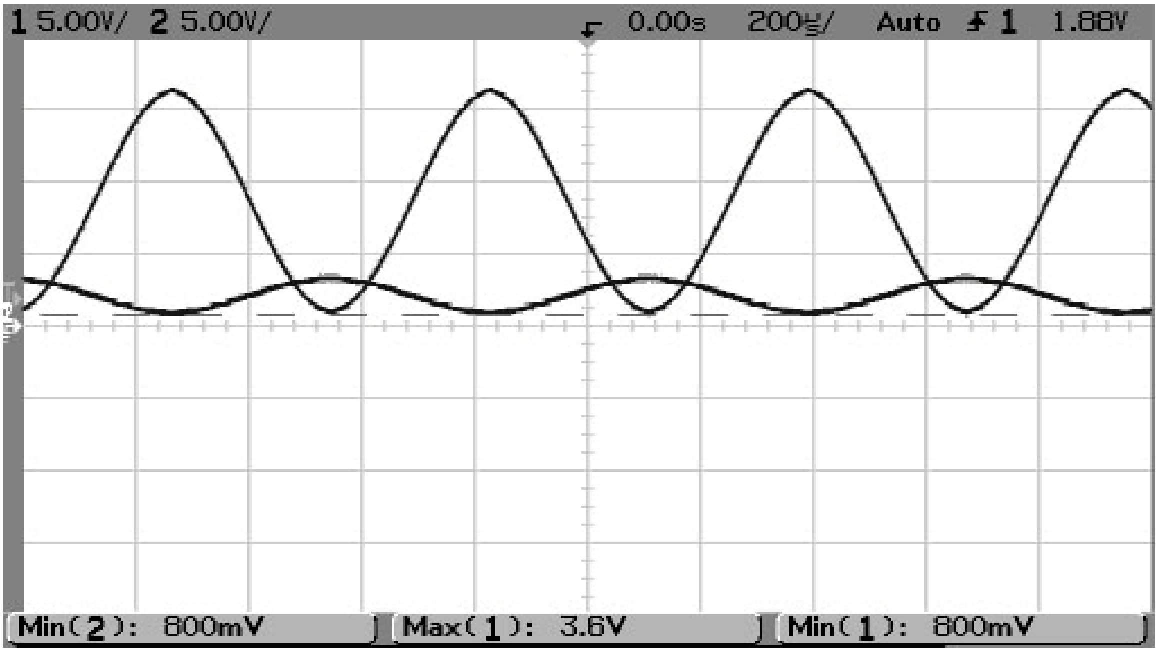

Figure 7: Input and Output for a BJT with applied AC signal

Since the peak-to-peak of the input is 2.8 and the peak-to-peak of the output is 15.5, the small-signal voltage gain can be calculated by dividing 15.5 by 2.8 = 5.54. In order to calculate the small-signal current gain, we first need to calculate the value of the currents ib and ic. We can calculate ib by dividing the peak-to-peak voltage (Vrb) over the resistor Rb by 22 Kohm (the value of Rb). ic would then be the peak-to-peak voltage over the resistor Rc (Vrc) divided by 1 Kohm (the value of Rc). Because the oscilloscope has a positive lead and a negative lead that goes directly to ground, we need to read the peak-to-peak voltages on each side of each resistor and subtract them in order to calculate the peak-to-voltage over each resistor.

We will first look at the input signal shown below in Figure 8.

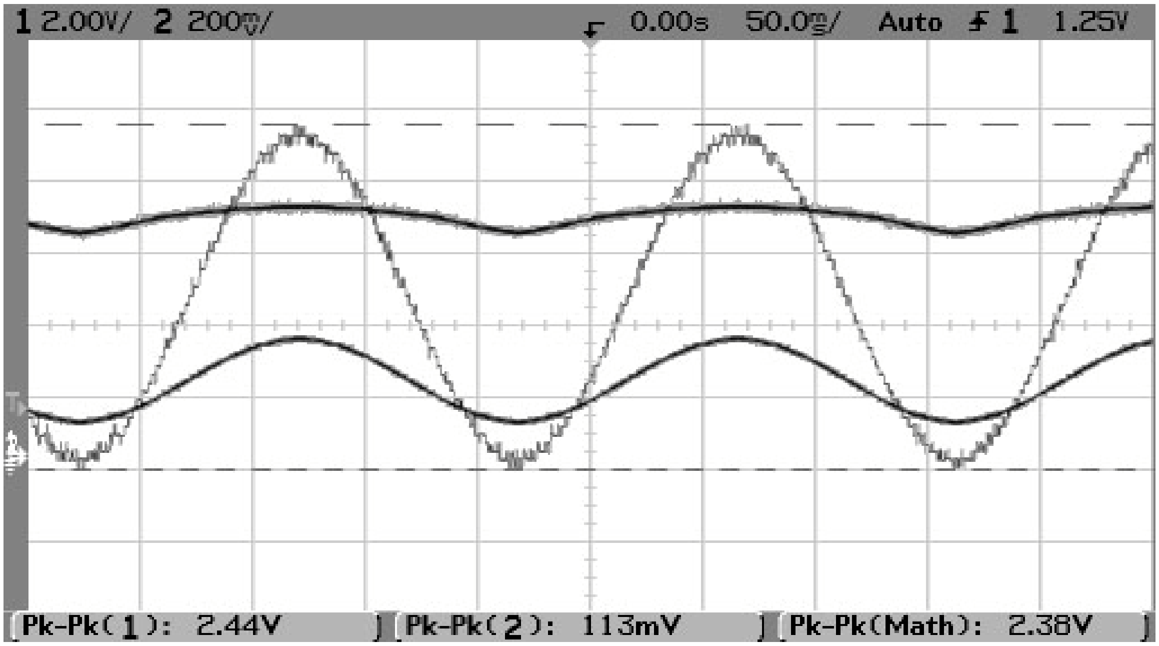

Figure 8: Vin, Vbe, and Vrb

The large sin wave is the voltage over the resistor Rb (Vrb). The peak-to-peak of this signal is 2.38 V. 2.38 V / 22 Kohm = 108 microamps, our value for ib. Another characteristic we can calculate from this data is the input resistance. The input resistance is equal to the peak-to-peak of Vbe divided by ib. The peak-to-peak of Vbe is shown below in Figure 8.

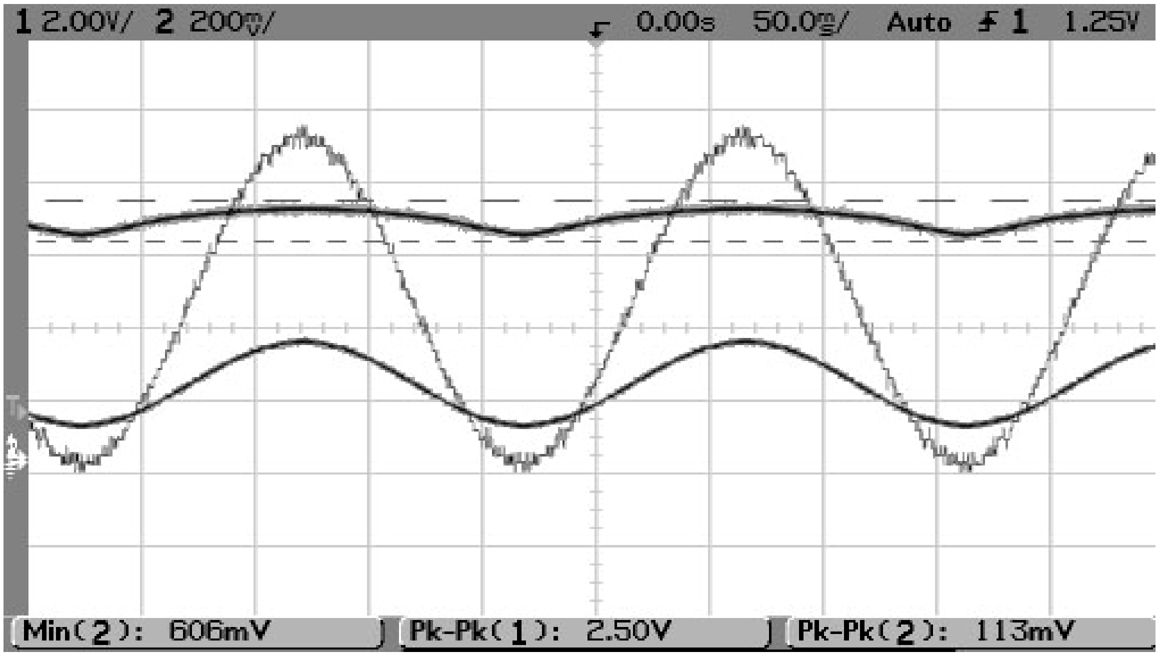

Figure 9: Peak-to-peak of Vbe

The input resistance is then 113 mV / 108 microamps = 1 Kohm. Applying the same principle to the output signals (shown below in Figure 10),

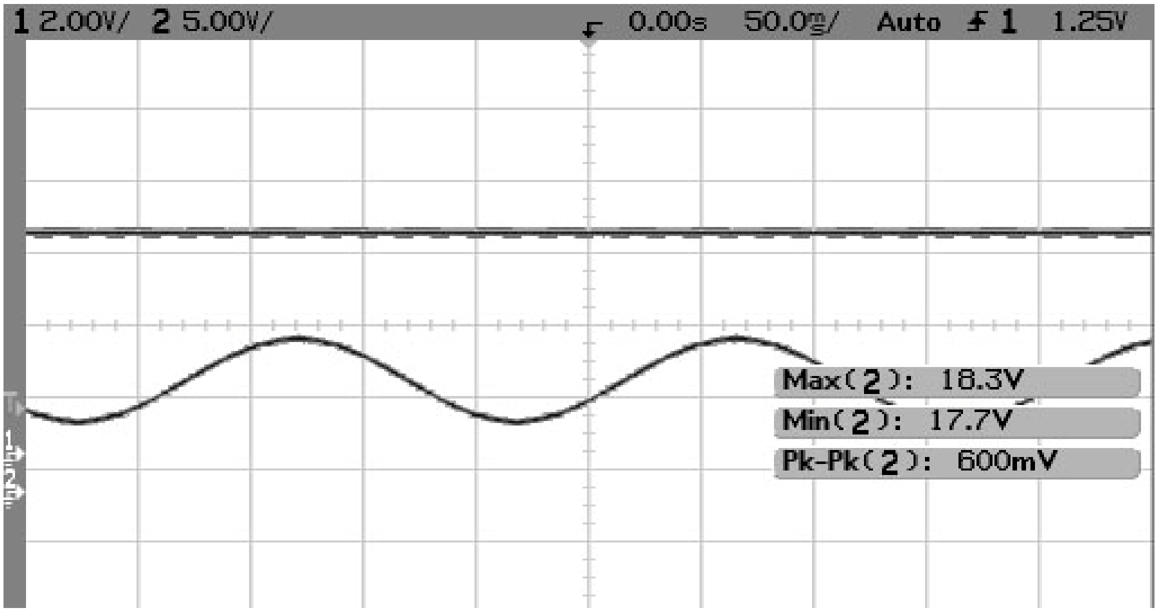

Figure 10: Peak-to-peak of Vcc

We already know the peak-to-peak of Vce is 15.5 V and the peak-to-peak of Vcc is .6 V, so the peak-to-peak of Vrc = 15.5 - .6 = 14.9 V. Following the same steps to calculate current ic = 14.9 V / 1 Kohm = 14.9 mA. The output resistance Ro = Vce (peak-to-peak) / ic = 15.5 / 14.9 mA = 1 Kohm. This is not what is expected – as seen above in Table 3, Ro should be at least less than 100 ohms.

Now that we have ic and ib, we can calculate the small-signal current gain ic/ib. 14.9 milliamps / 108 microamps = 137.96 which is close to 140 - our calculated value for Beta from above.

Saturation and Cutoff

The AC input signal applied above was properly biased and was purposefully adjusted so that the output signal was neither in cutoff or saturation. However, there are limits to what Vce can range between. We already know that Vce must be at a minimum of 0.2 V, but there is also an upper limit to Vce. Once again the same circuit from Figure 3 was used, with Rb = 22 Kohm, Rc = 2 Kohm, and Vcc = 18 V, with Vin supplied as a triangle wave ranging from –800 mV to 4.81 V. The input signal Vin and output Vout (Vce) are shown below.

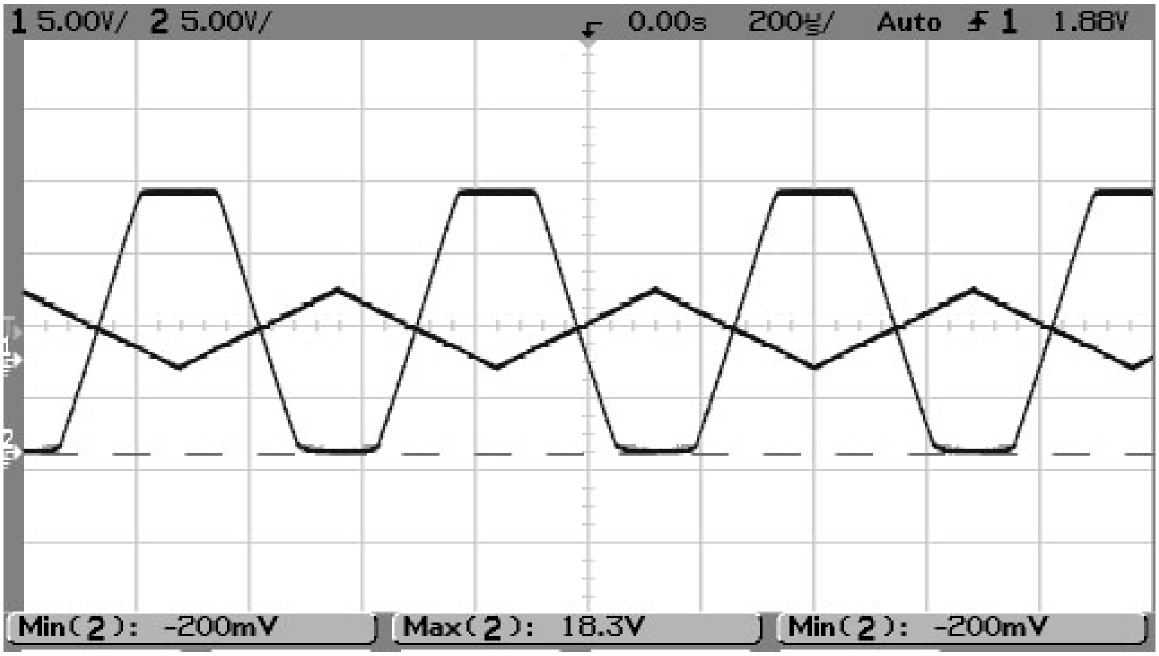

Figure 11: Output signal in both saturation and cutoff

The maximum and minimum of the output signal were recorded as 18 V and negative 0.2 V. The clipping at 16.6 is occurring because when Ib is reduced to a certain amount Vbe will no longer be forward biased. When Vbe is not forward biased, no current flows in Ic. If no current is flowing, the Vcc = Vce. The clipping at the bottom end of the output waveform occurs because when Ib is large enough, Ic becomes so large that the drop across the resistor Rc increases to a point where Vce is driven less than 0.2 volts. This is the saturation region, and as seen in the output waveform the bottom is clipping at negative 0.2 V. I don't understand why it's not clipping at positive .2 instead.

Practical Applications of the BJT

Now that the characteristics of the transistor have been established we can look at a few practical applications of the BJT. The first example uses the transistor to switch and LED on and off with a specific frequency. The second uses two transistors to create what is called a current-mirror; a configuration in which the current in one loop can be controlled with the current in another loop.

BJT as a switch

The first example uses the transistor as a switch. The same circuit that has been used throughout this paper is used again, with an LED inserted in series with Rc. The circuit is shown below in Figure 12. The values for the circuit were Rb=10 Kohm, Rc=220 ohm, and Vcc=18V.

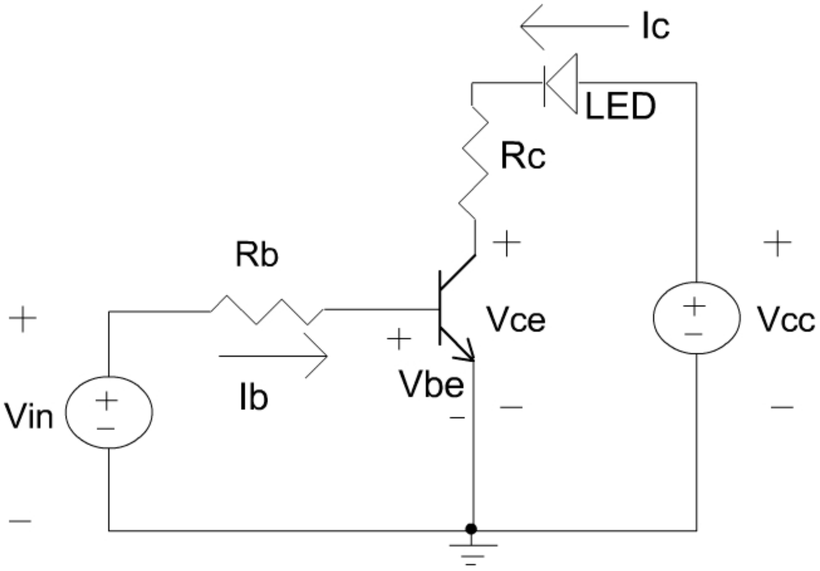

Figure 12: BJT used as a switch

In order to use the circuit for switching, we use an input waveform that drives the device into cutoff. The input and output signals are shown in Figure 13.

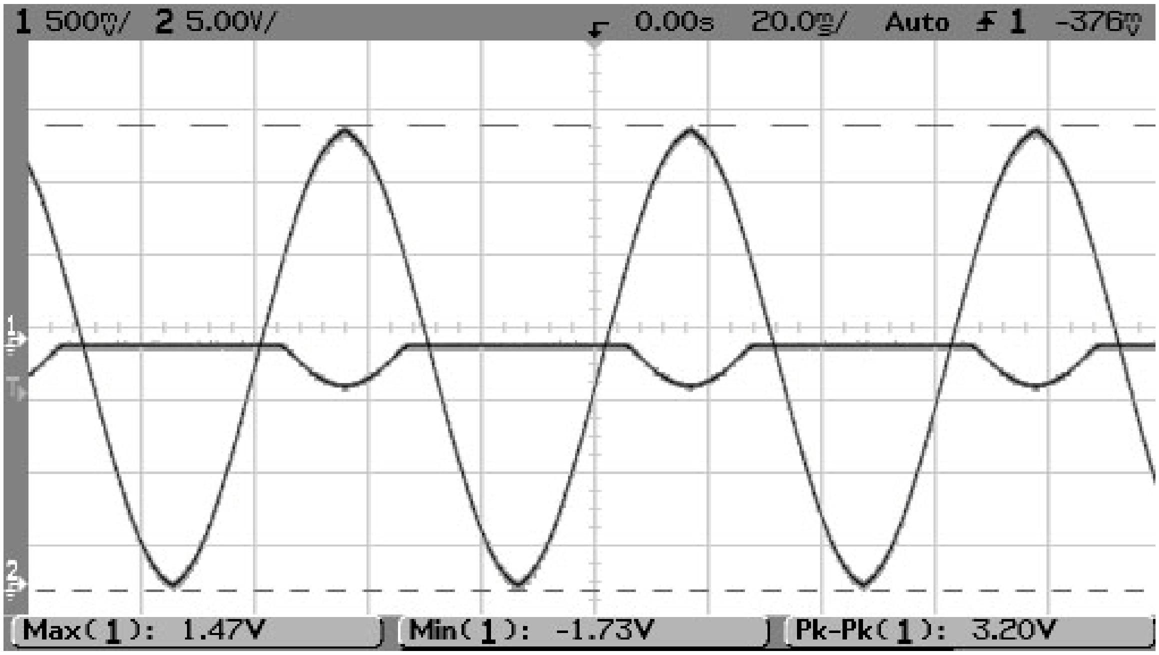

Figure 14: Input and Output for BJT used as a switch

The output waveform is the large sin wave, with a maximum of 1.47 volts and a minimum of negative 1.73 volts. Vce is the smaller waveform, with a maximum of 16.7 volts and a minimum of 13.3 volts. As seen above, when the sin wave swings into the negative side of its cycle, Ic becomes zero (Vce is in cutoff at 16.7 V, and the LED and the resistor Rc make up the remaining 1.3 V potential). When the input swings into the positive side of the cycle, Vce drops down to 13.3 volts so that current in Ic begins to flow. In this circuit the LED flashed with the frequency of the input waveform (5Hz) but any device could be similarly switched.

An example of how this circuit could be useful in application would be used to control a motor using pulse width modulation. A variable power supply could be placed in series with a signal to adjust the bias up and down, controlling how much of the output signal was in cutoff. This would translate to controlling what percent of the time the motor is being given it’s full power, which would in turn control what speed the motor is running at.

Current-mirror

The second application covered is called a current-mirror. The current-mirror is shown below in Figure 15.

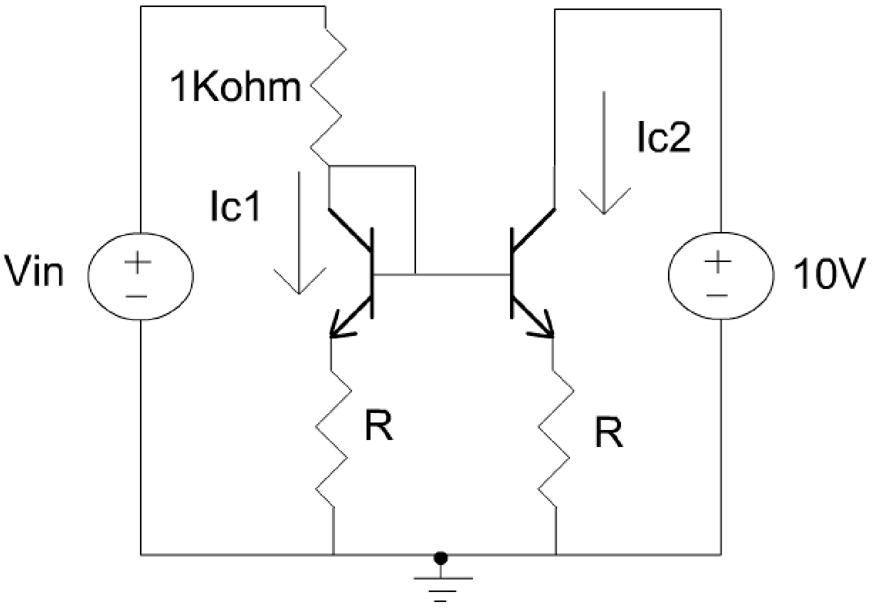

Figure 15: Current-mirror Circuit

Because the transistors share the same base and assuming the devices share the same values for Beta, the currents Ic1 and Ic2 should be the same. The circuit does in fact function as a current-mirror, however the value for R affects how the circuit behaves.

The above circuit was constructed and the currents Ic1 and Ic2 were measured for values of Ic1 ranging from 0 to 10 milliamps. This process was repeated for different values of R. The data is graphed below in Figure 16.

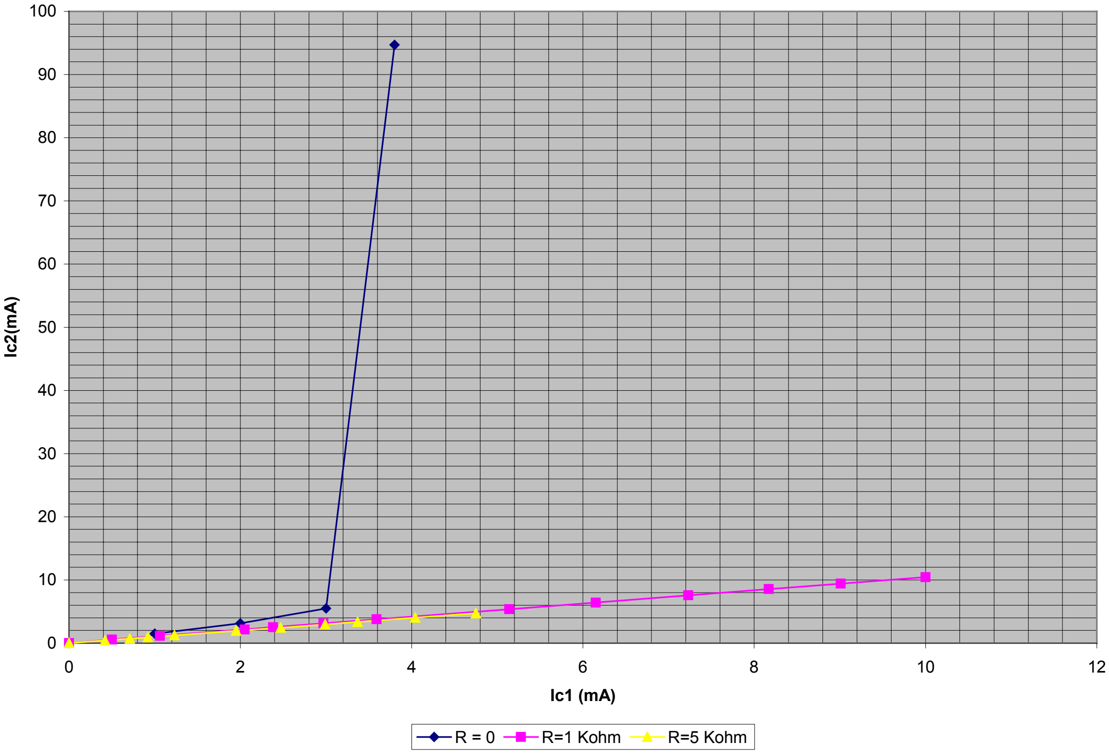

Figure 16: Ic1 vs. Ic2 for different values of R

When R is equal to zero, the current-mirror initially increases linearly but suddenly rapidly increases when Ic1 is anywhere above 3 milliamps. An explanation for this could be that without any resistance in Ic2 and the small resistance of Ro, once current begins to flow, the 10V potential is enough to flow across Vce regardless of Ib. In other words, once current begins flowing, the circuit becomes a short for the battery. With the value for R set, the current-mirror functions as expected as seen below in Table 5 and 6.

R = 1K	R = 1K
Ic1 (mA)	Ic2 (mA)
10	10.45
9.01	9.42
8.17	8.55
7.23	7.56
6.15	6.43
5.14	5.37
3.59	3.78
2.97	3.13
2.38	2.52
2.05	2.17
1.06	1.15
0.5	0.58
0	0

Table 5: Ic1 and Ic2 for R = 1

R = 5K	R = 5K
Ic1	Ic2
4.75	4.72
4.04	4.01
3.37	3.34
2.99	2.97
2.47	2.44
1.95	1.95
1.23	1.24
0.92	0.92
0.71	0.71
0.42	0.42
0	0

Table 6: Ic1 and Ic2 for R = 5

When R is 1 Kohm, the current in Ic2 is close to Ic1 and increases linearly as Ic1 increases. Similiarly, when R is 5 Kohm the current is even closer and stays close throughout the range of Ic1. This proves that the as long as R is somewhere between 1 and 5 Kohm for currents ranging between 0 and 10 mA that the current-mirror circuit operates correctly.

Conclusion

In this experiment, several characteristics of the BJT were found were experimentally. The gain *Beta* of the BJT was found to be 140 when the device was not operating near saturation. It was also found that when Ib was small enough, the gain would begin to drop, even when the device was properly biased. Further study into the properties of the device when operating at extremely low input currents (less than 10 microamps) is recommended.

The output resistance of the device was found to be relatively small (less than 100 ohms) and decreased as the output current Ic increased. However, the small-signal output resistance did not agree with this value. For now it is assumed that the method used for calculating the small-signal output resistance is incorrect.

Saturation occurred when Vce was less than 0.2 volts and cutoff occurred when Vbe was less than 0.6 volts under DC conditions. Under AC conditions the output waveform went to negative 0.2 volts. This is not understood and requires further study.

The input resistance of the device was found to 1 Kohm, under both DC and AC conditions.

Finally, the BJT's practical applications presented were proved to be effective. The BJT can be used to effectively amplify AC signals. The use of the device as a switch was also shown to be functional, illustrating how the device could be used to switch high power devices with small signals. Finally, the use of the BJT in the current-mirror configuration was presented, showing how the transistor can be used to successfully model current sources.

Properties of the BJT

Beta = 140
Output Resistance = less than 100 ohms for Ic greater than 1 milliamp
Input Resistance = 1 Kohm
Saturation = Vce less than 0.2 volts
Cutoff = Vbe less than 0.6 volts

Appendix

Table 1: Vce vs. Ic for fixed values of Ib

Voltage (mV) Ib=10microA	Current (mA) Ib=10microA
Measured Voltage	Measured Current
2500	0.95
988	0.95
243.1	0.93
120.7	0.74
103.3	0.61
75.9	0.37
42.3	0.12
33.4	0.08
23.8	0.04
10.5	0

Voltage (mV) Ib=20microA	Current (mA) Ib=20microA
Measured Voltage	Measured Current
25400	2.83
25420	2.8
22500	2.76
18280	2.71
16170	2.68
13320	2.66
11120	2.62
9340	2.58
7870	2.57
1400	2.5
144	2.2
114.1	1.77
95.1	1.37
83.9	1.11
75.6	0.93
64.9	0.7
56.5	0.54
48	0.4
43	0.33
37	0.25
27.1	0.14
23.7	0.11
19.5	0.08
15.3	0.05
0	0

Voltage (mV) Ib=20microA	Current (mA) Ib=20microA
Measured Voltage	Measured Current
19130	5.99
17550	5.89

14760	5.74
9600	5.59
7300	5.49
3900	5.35
2500	5.28
500	5.2
137.3	4.35
123.2	3.95
102.3	3.16
92.2	2.71
78.3	2.07
70.8	1.73
65.7	1.5
48.6	0.8
36.2	0.5
28.6	0.35
15.3	0.12
11.3	0.07
0	0