BEE 332 Devices and circuits II
Spring 2017
Lab 1: Bipolar junction transistor characterization*

1 Objectives

The objectives of this experiment are to observe the operating characteristics of bipolar junction transistors (BJTs). Methods for extracting device parameters for circuit design and simulation purposes are also presented.

Figure 1. The 2N3904.

1.1 No special precautions

Bipolar junction transistors can usually be handled freely, and are rarely damaged by ESD. This makes them very pleasant to work with.

BJTs do not employ a fragile, thin gate oxide like MOSFETs do, and they are thus much more robust against electrostatic discharge (ESD) damage. Since all three leads of the BJT are interconnected by internal pn-junctions, small charges can bleed off through the leakage currents of these junctions, and static charges are soon dissipated internally.

2 BJT base lead and sex identification

As represented in their schematic representations in figure 2, a BJT has two pn (diode) junctions, one between the base and emitter and the other between the base and collector.

The objective of this procedure will be to determine which lead of the BJT is the base, and whether the BJT is an NPN or PNP device using a multimeter.

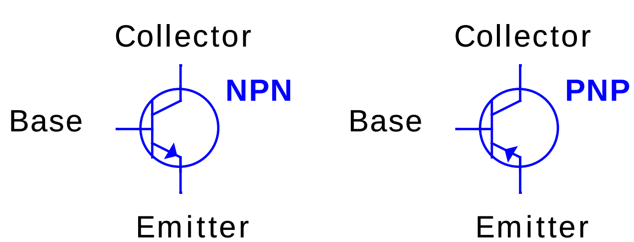

Figure 2. NPN and PNP BJTs.

* This lab was originally created by R. B. Darling at UW Seattle and has been updated by R. Yotter, T. Chen and N. Hamilton.

2.1 Setup

The parts you will need for this step are:

1. 2N3904 BJT.
2. 1N4148 diode that you'll use as reference.

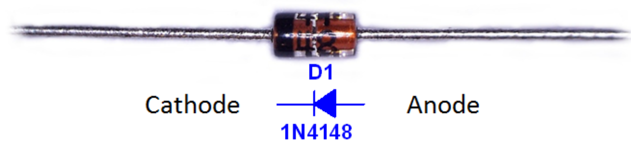

Figure 3. The 1N4148

The 2N3904 is a three lead device in a small plastic TO-92 package as shown in figure 1. The 1N4148 is shown in figure 3.

Turn on the multimeter and plug a black test lead into the negative (−) jack and a red test lead into the positive (+) jack of the meter. Determine how to use it for (two wire) resistance and "diode test" measurements.

2.2 Diode test mode

In diode test mode, the multimeter measures the diode drop, i.e., the voltage drop across the diode when it's on. The multimeter outputs a constant current of about 1 mA and it measures the voltage between the two leads without computing a resistance. The measured voltage is the turn-on voltage of the pn-junction for a 1 mA current, if the diode is forward biased. If the diode is reverse biased, then the multimeter cannot force 1 mA of current into the diode and the voltage across the diode rises up to the upper range limit of the multimeter, usually about 1.5 to 2.0 volts. Some meters give an over-range indication in this case.

2.3 Diode measurement

Measure the resistance and turn-on voltage of the 1N4148 diode with the multimeter in both the forward and reverse bias directions as shown in figure 4.

Note that the red lead from the (+) input of the multimeter is the one which will have the more positive voltage for this type of test.

Record these readings in your lab notebook, and note these readings as being "typical" for a forward and reverse biased pn-junction.

You can then refer to these readings to determine the polarity of pn-junctions that exist within the BJT.

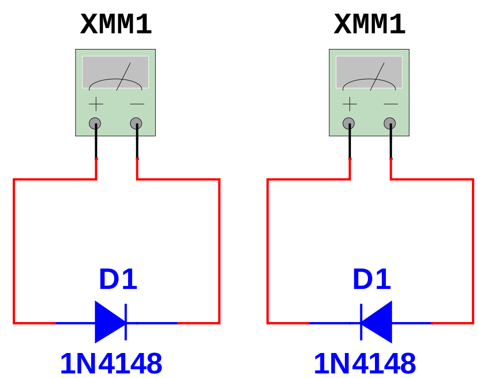

Figure 4. Forward and reverse diode measurements.

2.4 Identify the base

Use the multimeter in its ohmmeter and diode test modes to test pairs of leads on the BJT and therefore identify the base lead on the device.

From the polarity which causes the base terminal to conduct, deduce whether the BJT is an NPN or PNP device as shown in figure 5.

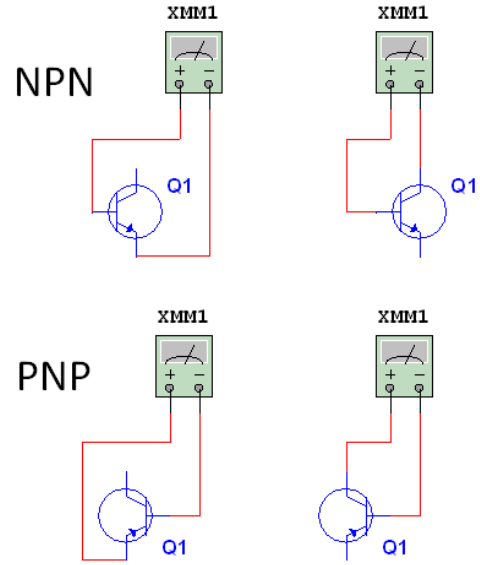

Figure 5. These will be on, all others will be off.

2.5 Identify the collector and emitter

With the base lead identified, it stands to reason that the remaining leads must be the emitter and collector. A few measurements will next be made to examine if these two remaining leads can be distinguished by multimeter measurements.

1. Measure the resistance and diode drops between emitter and collector with the base terminal open circuited as shown in the first row of figure 6. Try this with both polarities of the multimeter leads.
2. Measure the resistance and diode drops between emitter and collector with the base connected to the (–) lead of the multimeter as shown in the second row. Again, try this in both polarity directions.
3. Measure the resistance and diode drops between the emitter and collector with the base connected to the (+) lead of the multimeter as shown in the third row. Again, try both polarity directions.

You should end up with a total of six resistance measurements: 3 different base conditions (open, voltage low, voltage high) times 2 emitter/collector test voltage polarities.

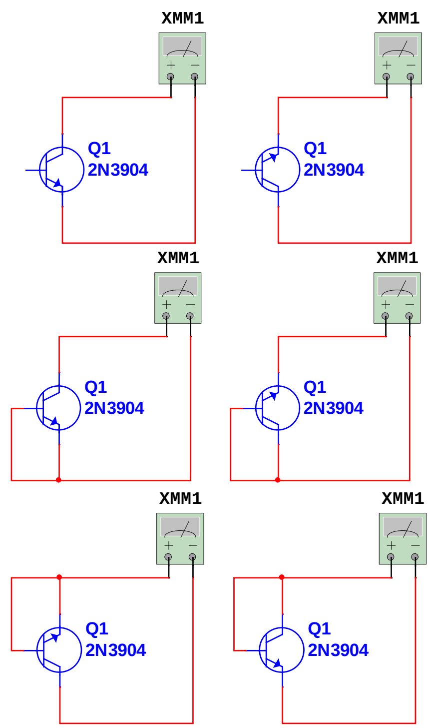

Figure 6. Six measurements, shown here for an NPN.

2.6 Questions

1. From your measurements above, summarize your findings about the given 2N3904 BJT in your notebook. Draw a picture of the device package and label the leads appropriately as E, B, C. (It is conventional to do this with a view of the device looking down on it with the leads pointing away from you, as if it were soldered into a printed circuit board. This is usually termed a component-side view, in reference to the component side of the circuit board.)
2. Is it possible to distinguish the emitter lead from the collector lead using only an multimeter? Explain why or why not.
3. Look up the data sheet for the 2N3904 and compare your deductions with the manufacturer's specifications.
4. The base terminal is normally thought of as the “control” terminal for the BJT, as it controls current flow from emitter to collector. With the base lead open circuited, is the BJT a “normally-on” or a “normally-off” device? Explain your answer in reference to the internal pn-junctions of the BJT and how they must be biased in order for conduction to occur.

3 Measurement of BJT & dependence of β_F on collector current

3.1 Setup

For this step you will need the following additional parts:

1. RB = 100 KΩ 5% 1/4W
2. RC = 1.0 KΩ 5% 1/4W

The measurements will be made with the emitter at a ground potential reference.

Power supplies PPS1 and PPS2 are used for the collector and base voltage excitations, respectively.

The current sensing resistors RC and RB and the BJT under test are then connected as shown in Figure 7, where the left multimeter measures VRB, and the right one measures VCE.

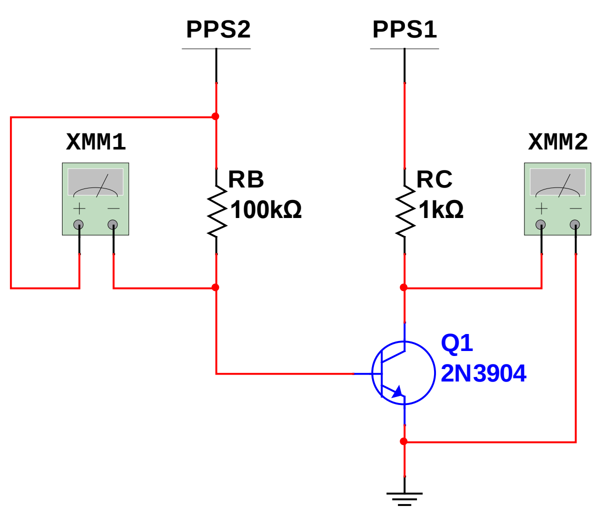

Figure 7. Test configuration for β_F

In place of a second multimeter, the oscilloscope can be used with the input set for DC coupling.

The excitation voltage VCC is from PPS1 power supply. This voltage is applied across the series connection of a current limiting resistor RC = 1.0 KΩ and the collector-emitter leads of the device under test (DUT). Thus, VCC = VCE + VRC.

3.2 Measurements

1. Vary PPS2 from 1.0 V to 1.75 V in 0.25 V increments.
2. For each setting of PPS2, vary PPS1 from 0.0 V to 10.0 V in 1.0 V increments.
3. For each combination of PPS1 and PPS2, measure and record VRB and VCE and calculate IB = VRB/100 KΩ, IC = (PPS1 – VCE)/1.0 KΩ and β_F = IC/IB.

3.3 Analysis

1. Create a graph with individual curves for IC versus VCE for the various values of PPS2 and comment on your result.
2. Use interpolation with each set of measurements corresponding a given value of PP2 to find estimated values PPS1, VRB, IB, IC and β_F corresponding to VCE = 3.0 V.
3. Create a plot of β_F versus IC at VCE = 3.0 V from your interpolated results. Comment on the dependence of β_F on IC and estimate the value of IC which yields the maximum value of β_F.

3.4 Comment

At low values of collector current, generation-recombination processes in the base-emitter junction produce additional base current which is not associated with a proportional collector current. Hence, at low current levels, the current gain falls. At high values of collector current, series resistance and high-level injection phenomenon become important both of which cause the current gain to fall off in this region.

All BJTs have a designed “sweet spot” where they deliver maximum current gain. Usually, other operational parameters such as frequency response, power efficiency, and minimum noise production are also optimized around this region.

It is certainly possible to use a BJT outside of this region of optimal current gain, but one must suffer degradation in all of these parameters when doing so. The manufacturer’s data sheets provide very detailed information about how all of these parameters vary with collector current level. A little effort expended in matching these performance curves to a given design will lead to much better circuit performance.

4 Measurement of BJT output conductance

4.1 Early voltage

As shown in figure 8, the characteristic output curves for a BJT are not exactly horizontal in the forward-active region of operation.

If the BJT behaved like an ideal current source, the output current would not be a function of VCE, and the curves would be truly horizontal. This tilting is due to a conductance through the transistor in the active region that behaves as if there was a resistor (whose value depends on VBE) in parallel with the transistor.

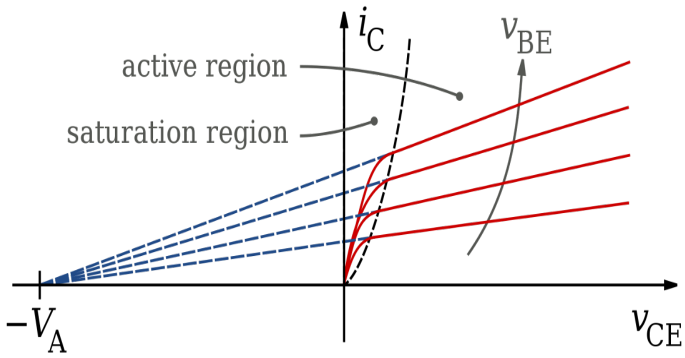

Figure 8. Early voltage, V_A.
(Image source: Wikipedia.)

Extending the straight parts of the curves, the point where they converge at IC = 0 is VA, the Early voltage, named after James M. Early, who discovered it, not because it happens "early".

The points where they cross the Y-axis are referred to as IC_{sat}, the saturated value of forward-active collector current, i.e., the current that would result in the absence of any output conductance

4.2 Measurements

Insert a 10 KΩ resistor in parallel with the emitter and collector terminals of the 2N3904 BJT under test as shown in figure 8. This resistor simulates the effect of increasing the output conductance of the BJT.

Repeat the previous procedure:

1. Vary PPS2 from 1.0 V to 1.75 V in 0.25 V increments.
2. For each setting of PPS2, vary PPS1 from 0.0 V to 10.0 V in 1.0 V increments.

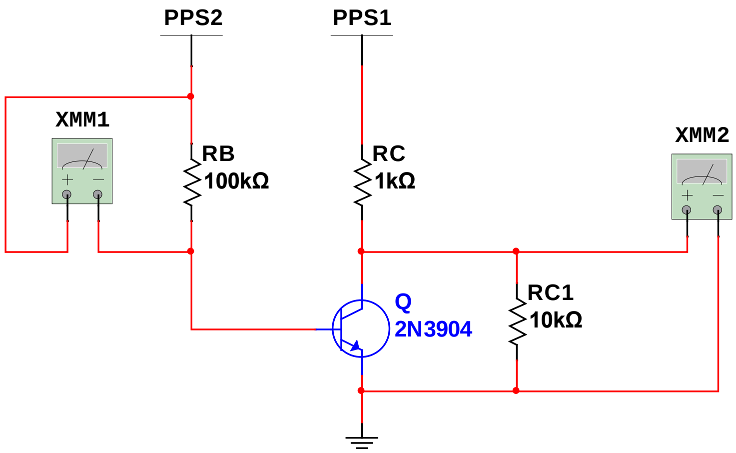

Figure 8. Test configuration for output conductance measurements

3. For each combination of PPS1 and PPS2, measure and record VRB and VCE and calculate IB = VRB/100 KΩ, IC = (PPS1 – VCE)/1.0 KΩ and β_F = IC/IB.

4.3 Analysis

1. As you did before, create a graph with individual curves for IC versus VCE for the various values of PPS2 for this new circuit with the resistor added. Comment on how this graph compares to the one you produced for the circuit without the bypass resistor.
2. Using measurements taken on the ***without*** the bypass resistor connected, compute the slopes of the straight parts of output curves in units of Ω^{-1} (or Mhos, Siemens, or S).
3. The value of the BJT output conductance will tend to increase in proportion to the collector current IC. The output conductance is usually expressed as λI_{Csat}, where λ is a constant with units of V^{-1}. Calculate IC_{sat} at VCE = 0 and VA at IC = 0 on each fitted line (as if the straight part was extended.)
4. Find the best fit value of λ which allows the forward-active output curves to be well approximated by the relationship IC = IC_{sat} (1 + λ VCE).

5 Reverse active

In this step, you'll measure the behavior of the transistor in reverse active mode.

5.1 Setup

Remove the bypass resistor and flip the transistor as shown in figure 9, reversing the collector and emitter.

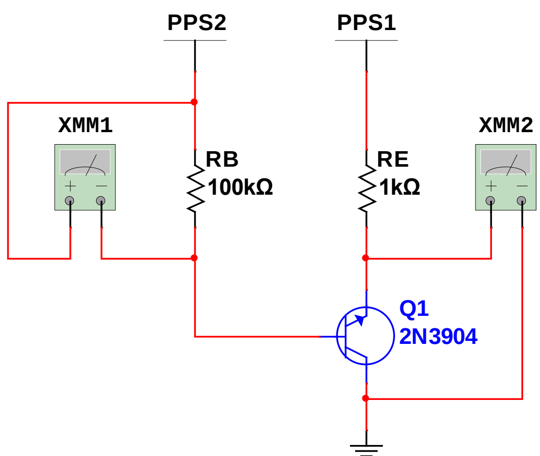

Figure 9. Test configuration for β_R

5.2 Measurements

As before:

1. Vary PPS2 from 1.0 V to 1.75 V in 0.25 V increments.
2. For each setting of PPS2, vary PPS1 from 0.0 V to 10.0 V in 1.0 V increments.
3. For each combination of PPS1 and PPS2, measure and record VRB and VEC and calculate IB = VRB/100 KΩ, IE = (PPS1 – VEC)/1.0 KΩ and β_R = IE/IB.

5.3 Analysis

1. Create a graph with individual curves for IE versus VCE for the various values of PPS2 and comment on your result.
2. Use interpolation with each set of measurements corresponding a given value of PP2 to find estimated values PPS1, VRB, IB, IE and β_R corresponding to VEC = 3.0 V.
3. Create a plot of β_R versus IC at VEC = 3.0 V from your interpolated results.
4. Compare these results with those from your measurements in forward active.
5. If the base-emitter and base-collector junctions seemed fairly symmetric when measured with a multimeter, do they behave symmetrically in a circuit?