Lab 4: Bipolar transistors and transistor circuits

Objectives:
- investigate the current-amplifying properties of a transistor
- build a follower and investigate its properties (especially impedances)
- build a transistor voltage amplifier and investigate its properties
- use a transistor to switch large currents on and off

Special notes:
The transistors we’ll use are in a TO-92 package; the leads are arranged like this:

(top view, leads pointing away from you)

Use frequencies in the kHz range for your signals in this lab.
Power your breadboard down before changing components in your circuits.
Use care in bending the transistor leads and inserting them in the breadboard.

4-1: Basic transistor properties
A semiconductor diode is formed from a pn junction. A bipolar semiconductor transistor is either npn or pnp. For an npn transistor such as the 2N3904, the junctions act in some sense like back-to-back diodes as shown below (but don’t take this too seriously: a working transistor does not behave in a circuit like two back-to-back diodes). There’s just enough truth in this picture to make it possible to use the diode test function of a meter to spot check a transistor that’s suspected to be bad.

Get a 2N3904 transistor and use the BK meter’s diode test function to measure the voltage drop across the BC junction and the BE junction in the forward and the reverse direction. (The meter applies a small current and reads the junction voltage that corresponds to that current.) Are the results similar to what you got for a Si diode (such as the 1N914)?

The BC junction may be distinguished from the BE junction by looking at the forward voltage drops: since the BC junction is physically larger than the BE junction, the BC junction has a slightly lower current density and therefore a slightly lower voltage drop. Is this true for your transistor?

The BK meter also has a transistor test function. Put the transistor in the appropriate place on the meter and record the reading. This reading is the current gain (hFE or β) of the transistor, defined as the ratio of the collector current to the base current, that is, \( h_{FE} = \beta = \frac{I_C}{I_B} \). (The BK meter uses a base current of 10 μA and a collector-emitter voltage of \( V_{CE}=3.45 \) V as the conditions for the measurement of \( \beta \).)
Finally, the oscilloscope-based curve tracer can be used to look at $I_C$ vs. $V_{CE}$ for different values of $I_B$. Have me show you how it works. Sketch and label the resulting curves in your lab book. Show where the saturation region, active region, and cutoff regions are.

**4-2 Direct measurement of transistor current gain**

In order to measure the current gain for different $I_B$ and $V_{CE}$ values, set up the circuit below. Include another meter to measure $V_{CE}$. The goal is to measure $I_C$ (the collector current) and $V_{CE}$ (the collector-emitter voltage) for a number of different values of $I_B$. Then you can calculate $\beta$ ($h_{FE}$) for each of those values.

To vary $I_B$, use different values for $R$ (e.g. 0, 4.7k, 10 k, ... 1 M). For each value of $R$ you use, estimate the base current $I_B$, assuming that $V_{BE}=0.6$ V; then measure $I_C$ and $V_{CE}$. Calculate $\beta$ ($h_{FE}$) for each of these measurements. Make a rough plot of $\beta$ vs. $V_{CE}$.

Does the maximum value for $\beta$ agree fairly well with what the BK meter says $\beta$ is for your particular transistor? Why is $\beta$ sometimes considerably below this value? (Hint: look at what $V_{CE}$ is doing.)

*Summarize:* Under what conditions is $\beta$ large?

**4-3 Emitter follower (common collector)**

Build the circuit shown on the next page (use a 2N3904). Drive it with a sine wave and look at the output with the scope. Try varying $V_{in}$ from about 1 $V_{pp}$ to about 10 $V_{pp}$ and see how $V_{out}$ changes.

For $V_{in}$ of about 10 $V_{pp}$, sketch $V_{in}$ and $V_{out}$. Describe the major differences between $V_{in}$ and $V_{out}$, and explain what causes $V_{out}$ to differ from $V_{in}$ (be quantitative).
Now try connecting the emitter return (the point marked $V_{EE}$) to $-15$ V instead of ground and look at the output again. Why is there an improvement? (Hint: think about what’s going on with $V_B$ and $V_{EE}$.)

Is there any voltage gain (that is, is $V_{out}/V_{in} > 1$? Remember that $V_{out}$ and $V_{in}$ refer to amplitude, $V_{pp}$, or $V_{rms}$.) Is there any current gain? Explain your reasoning.

What causes the offset between $V_{out}$ and $V_{in}$?

What is the range of $V_{in}$ values for which $V_{out}$ will “follow” $V_{in}$—that is, for which the output signal looks like the input signal with no distortion other than an offset?

**Impedances:** Using the values of the resistances in the circuit and the measured value of your transistor’s $\beta$, predict the input and output impedances for the follower (don’t include the 270 ohm resistor in making your predictions).

Try to measure the input impedance ($R_{in}$) for the follower. (Hint: think of a voltage divider with the 270 ohm resistor being one resistor and the follower (transistor with 3.3k resistor) being the other “resistor.”) Use a fairly small signal voltage.

Now determine the output impedance ($R_{out}$) by measuring $V_{out}$ with no load, and then measuring the voltage across a 1k resistor between $V_{out}$ and ground.

When you have determined $R_{in}$ and $R_{out}$, compare them to your predictions.

**Summarize:** What does the follower do (in terms of $V_{out}$ and $V_{in}$, and also in terms of the current)? What good is the follower, given that it doesn’t produce any voltage gain?
Optional: Have me show you how to build a single-supply follower (one that will operate from a single +15 V supply over a range of several V without clipping.) Sketch the circuit, sketch $V_{in}$ and $V_{out}$, and describe why this works better than the original follower circuit operating from a single supply.

4-4 Common emitter amplifier (single supply)
Build the common emitter amplifier shown below with a 2N3904. Predict the quiescent operating voltages (the voltages with no input signal) at the base, collector, and emitter. Measure them and compare to your predictions.

Predict this amplifier’s voltage gain for a fairly small signal (about 1 Volts peak to peak), and then measure the gain and compare to your prediction.

Is the output inverted with respect to the input signal? Should it be, and why?

Is there any DC offset (that is, is the signal centered around a voltage other than 0V)? Should there be, and why?

Increase the amplitude of the input signal till you see distortion or clipping on the output signal. At what input amplitude does this distortion first occur? Why does it occur there?

Summarize: What does the common-emitter amplifier do (in terms of $V_{out}$ and $V_{in}$, and also in terms of the current)?
What is the purpose of the 56k and the 5.6k resistors? (Could you accomplish a similar thing by using a −15V power supply? Hint: think about what we did with the emitter follower.)
Optional: Measure the output impedance of the amplifier and compare with what you expect. (Again, use an appropriate resistive load, and this time you’ll also need a 4.7 microfarad blocking capacitor in series with the load. The blocking capacitor keeps the load from changing the DC biasing scheme while still having a very low impedance at frequencies in the kHz range—for example, a 4.7 µF capacitor has $X_C=34 \, \Omega$ at 1 kHz.)

4-5 Transistor switch
The following circuit illustrates the use of a transistor for switching rather than amplification. We provide enough base current to saturate the transistor—that is, to produce so much collector current that $V_{CE}$ will be driven as low as it will go, close to 0 V, so that the transistor becomes essentially a short circuit. In this way, switching a relatively small current on and off can control a much larger current (in this case, through the lamp). We use a 2N4400, which is similar to the 2N3904, but can dissipate more power.

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+5V
1k
#47 lamp (0.15 A at 6.3
2N4400
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Turn the base current on and off by pulling one end of the resistor out of the breadboard. What happens?

Measure $V_{CE}$ with the switch open and with it closed, and use the value with the switch closed to estimate the voltage across and the current through the lamp. (The lamp is a non-ohmic device, so a calculation of current using Ohm’s law will be only an estimate; if you wish, you may measure the current directly, but an estimate should be good enough for our purposes.) Calculate $I_B$. Use your results to estimate the current gain $\beta$ for the transistor. Now measure $\beta$ with the BK meter. Why is the current gain of the transistor lower in this circuit than the BK meter indicates? (Hint: the answer is in section 4-2 of the lab.)

Summarize: Explain how the transistor is being used to let a small current switch a larger one on and off. Why do we use the transistor in the saturation region in this case?