Bipolar Transistor Circuits

Introduction and Objective

Transistors are awesomely cool electronic devices. Their invention in the late 1940’s earned William Shockley, John Bardeen, and Walter Brattain the Nobel Prize in Physics. Bardeen later won a second Nobel prize for his theory of superconductivity—the only person to win two Nobel prizes in physics (he was also a good golfer). Transistors underlie all modern electronics. Their two most paramount uses (among the countless functions that they serve) are for amplification and digital gates.

Transistors are three-terminal active devices. As an active device, the transistor must be powered independently from the input signal. We will study bipolar transistors, but be aware that there are also Field Effect Transistors (FETs). The three terminals are labeled “base”, “collector”, and “emitter”. Transistors are very complex devices and to fully understand their workings one needs sophisticated models and a good deal of solid state physics and quantum mechanics. Do not worry. We will use a very simple model of the transistor that is remarkably powerful. This simple model allows one to understand lots of interesting circuits (though not all). We will just look at three main circuits: the emitter follower, the current source, and the common emitter amplifier.

Here is the model: a transistor is a valve, but not a pump. It does not force current to flow; it controls current flow while the remainder of the circuit is trying to force current through the device.

Here are the rules in this simple model for a NPN transistor:

1. If $V_{BE} = V_B - V_E < 0.6$ V, then current cannot flow out the emitter terminal, otherwise $V_{BE} = 0.6$ V and current flows. (Note how this is the same as our rule about diodes).
2. $V_C > V_E$ by 0.2 V or more or the transistor will become “saturated” and no longer work as a valve.
3. $I_C = \beta I_B$ and $\beta \approx 100$ when (1) and (2) are satisfied.
4. $I_E = I_C + I_B = (1 + \beta)I_B = I_C$ when (1) and (2) are satisfied.

That’s it. If we carefully use these rules, we will be able to analyze all the circuits in this lab and many others as well. The main objective of this lab is to see how
this model explains the three most important bipolar transistor circuits. Here is a simple diagram to help you remember the three circuits:

- **Follower**
  - In
  - Fixed
  - Out

- **Current Source**
  - Fixed
  - Out

- **Amplifier**
  - Fixed
  - Fixed

“In” and “out” are connected to the input and output signals; “fixed” means that the terminal is held at some fixed voltage. If there are two “fixed” terminals, they are not at the same voltage (this would break the rules given above).

**Laboratory Exercises**

1. **Emitter Follower**

   First you must learn how to test a NPN bipolar transistor. The transistor consists of two abrupt diode junctions, but it **does not act like two diodes wired together** because the material in the middle is the same piece of material for one side of both junctions, unlike simply wiring the terminals of two diodes together. Use a 2N3904 NPN transistor, identify its leads, and use your multi-meter’s transistor $h_{FE}$ function to test the transistor. $h_{FE}$ is another name for $\beta$ and should have a value between 50-250.

   ![2N3904 Transistor](image)

   Now construct the emitter follower circuit shown on the next page. Use the +15 V from the dual-output voltage supply. Make sure that the voltage supply, the breadboard, the function generator (which provides input), and the oscilloscope (which measures output) all share a common ground.
The purpose of the follower is for the emitter AC voltage signal to vary the same as the base AC voltage signal (i.e. the emitter follows the base), while at the same time creating a high input impedance and a low output impedance. Wow, what a great device to put between a voltage source and a load, if you need to stiffen the source! (Explain this statement in your lab notebook). Here’s a diagram showing how the follower accomplishes this neat trick:

Remember that high input impedance draws little current in and low output impedance allows lots of current to flow out, which is exactly what the follower does. The follower is a current (and power) amplifier.

Now let’s try some experiments. Drive the follower with a small amplitude (< 5 V) sine wave at about 10 kHz with no dc offset. Using our simple model explain the shape of the output.

If you turn up the amplitude, you will see small bumps start to appear below ground on the output. Our simple model does not explain these bumps. Instead refer to the data sheet attached to the lab. In particular find the emitter-base breakdown voltage. What does this parameter mean, and how does it explain the funny bumps?

Now connect $V_{EE}$ to −12 V instead of ground (use the negative voltage output of the dual-voltage supply). Explain why the output looks so much better. “Biasing” the transistor means setting the voltages of the transistor terminals in the absence of an input signal (These are sometimes referred to as the quiescent voltages). Properly biasing a transistor circuit is crucial for it to operate correctly.

In the voltage follower, $Z_{in} = \beta Z_{load}$ and $Z_{out} = Z_{source} / \beta$ with $\beta \approx 100$. This means that a transistor should have $Z_{in} \gg Z_{load}$ and $Z_{out} \ll Z_{source}$. Test these
predictions. Replace the 270 Ω base resistor with a 47 k resistor, in order to simulate a signal source of moderately high impedance, i.e. low current capability. Also, reconnect $V_{EE}$ to ground.

a) Measure $Z_{in}$ of the follower. Treat the follower as a black box with some unknown input impedance. Assume the black box is the second resistor of a voltage divider and that the 47 k resistor is the first resistor. Why are we ignoring the output impedance of the function generator? Measure the signal on each side of the 47 k resistor. You will want to use a small amplitude signal. You can then use the voltage divider equation to determine $Z_{in}$ of the follower circuit. Does your value agree approximately with the prediction above?

b) Measure $Z_{out}$ of the follower. Again the follower is a black box, only this time it is the first resistor of a voltage divider. Replace the 3.3 k $R_e$ with a smaller value ~ 300 ohms (leave the 47 k resistor at the input). Once again use the voltage divider equation to determine $Z_{out}$. In this case, the voltage divider formed by the follower and the 300 ohm resistor is supplied by a voltage equal to $V_{in}$. You will need to solve the voltage divider equation using your measured $V_{in}$ and $V_{out}$. Does your value agree approximately with our simple model?

Now you will build a properly-biased emitter follower circuit that is operated from a single positive supply voltage (shown below). Not properly biasing was the mistake we made in the very first emitter follower circuit that we built. See how large an amplitude signal you can drive the emitter with before the onset of clipping. Sketch the voltage at the input, the base, and at E. Do your results make sense? Here’s a design trick: if you aren’t likely to have signals large enough to be clipped just use equal-valued resistors to bias the base. Explain how this will alter your circuit.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{f2.png}
\caption{Emitter follower circuit diagram}
\end{figure}

2. Current Source

Build the current source shown below. Slowly vary the 10 k variable load and measure (or at least look at) the current with the ammeter. Over what range of $R_{load}$ is the current reasonably constant? Explain this with our model.
3. Common Emitter Amplifier

All right, here is the big one—the common emitter amplifier, a voltage (and power) amplifier. Wire it up and check the voltage gain. Does it agree with the model? Is the signal inverted, i.e. out of phase? What is the function of the capacitor? Hint: it is called a blocking cap. What does it block?

Now you know some of the basics about bipolar transistors and their uses. Check out the miscellaneous transistor circuits on pages 868-871 of Simpson for some other ideas of transistor uses and for ideas for your final project. Transistors are ubiquitous in circuits, so there is no shortage of fun projects that incorporate them into a circuit design.

References

Significant parts of this lab, including diagrams, are taken from Hayes and Horowitz, Student Manual for the Art of Electronics, Cambridge University Press (1989).