Experiment VIII: The Transistor

I. References

Horowitz and Hill, *The Art of Electronics*.
Diefenderfer and Holton, *Principles of Electronic Instrumentation*
The American Radio Relay League, *The ARRL Handbook*

II. Equipment

Digital Oscilloscope
1 Digital multimeter
Bread Board
2 each 2N4124 transistors
100 mH inductor
2 each 10 kΩ resistor (1/4 Watt)
1 each 2.2 kΩ resistor (1/4 Watt)
2 each 1 kΩ resistors (1/4 Watt)
(one lead of the resistor should be bent over until it is parallel to the other, and then the other should be clipped so they end at the same place)
2 each 1000 pF ceramic capacitor
2 each 12000 pF ceramic capacitor
2 each 100 nf ceramic caps
short wires with ends stripped
2 BNC mini-grabber scope probes
Signal Generator
Variable Power Supply
2N2222 transistor
1 mH inductor
2 each 27 kΩ resistor (1/4 Watt)
2 each 470 Ω resistor (1/4 Watt)

III. Introduction

In this lab, you will learn what a transistor is and how to use it to build current and voltage amplifiers, and incorporate them into your radio circuit.

During the first lab, you learned that a diode is a device that allows current to flow in one direction, and blocks current flow in the other direction. A diode is constructed from crystalline Silicon or Germanium. These materials have 4 electrons in the outermost atomic shell. When these materials are "doped" with very small amounts of impurities (typically densities of 10^{13} to 10^{19} cm^{-3} or a part in $5x10^9$ to $5x10^{15}$) that have 5 valence electrons, such as P or As, they become "n-type" semi-conductors. When they are doped with impurities that have 3 valence electrons, such as B, Al, or In, they become "p-type" semi-conductors. A diode has a region of p-type doping adjacent to a region with n-type doping, as shown in Figure VIII-1. The diode conducts when the p-type region is more positive than the n-type region. The size of the current has a non-linear dependence on the voltage across the diode. Because the current is a strong function of the voltage difference, the voltage difference is typically less than 0.7 V for a Silicon diode when forward-biased. Currents producing larger voltage drops would destroy the diode. When reverse-biased, the current is small (μA) and only weakly dependent on the voltage.

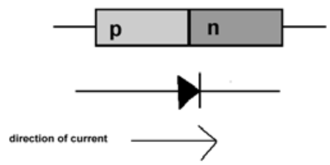

Figure VIII-1: Diode

A transistor is a 3 terminal device made from a crystal that either has a shallow region with p-type doping between 2 regions with n-type doping (a “pnp” transistor) or with n-type between p-type regions (“npn” transistors). The 3 terminals, which are connected to the 3 regions of the crystal, are called the “emitter”, the “base”, and the “collector”, as illustrated in Figure VIII-2, The relative voltages of the base, emitter, and collector controls the behavior of the transistor.

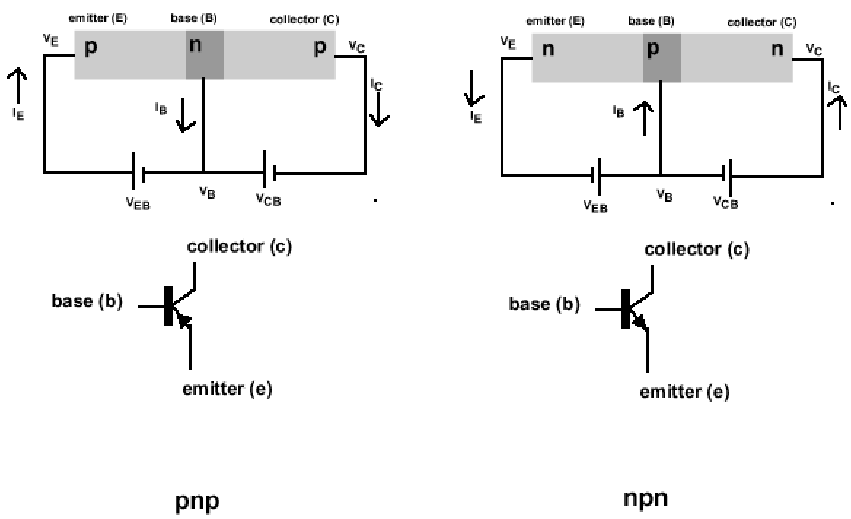

Figure VIII-2: pnp transistor and npn transistor

IV. Ebers-Moll Model of a Transistor Behavior

The basic operation of an npn transistor can be understood as follows (for a pnp transistor, just reverse all polarities):

- The collector should be more positive than the emitter
- The base-emitter junction acts like a forward-biased diode. The drop across this diode is typically less than 0.7 V for a silicon transistor. The emitter current is a strong, non-linear function of this voltage drop, as with a diode.

- The base-collector junction is biased like a reverse-biased diode, in that the collector is more positive than the base. However, it does not behave like one. The base current is due to recombination of the emitter current carriers in the base. Since this layer is thin, the base current must be small and the collector current must be approximately equal to the emitter current. The collector current is roughly proportional to the base current, with a constant of proportionality that is temperature dependent, varies from transistor to transistor, depends on the circuit, and is typically around between 50 and 250.

The transistor is thus a device which allows a small current (the base current) to control a larger current (the collector/emitter current). Since the collector current is roughly proportional to the base current, the transistor is a current amplifier.

The Ebers-Moll model describes the relation between the collector current, I_C, the base-emitter voltage, V_{BE}, and the base current, I_B.

$$I_C = I_S(e^{V_{BE}/V_T} - 1), \qquad \text{(VIII-1)}$$

$$I_B = I_C / h_{FE}, \qquad \text{(VIII-2)}$$

where V_T is approximately 25 mV at room temperature, I_S is the saturation current of the transistor, and h_{FE} is typically between 20 and 1000. All of these constants have a strong temperature dependence, and vary from transistor to transistor. (Note the similarities between VIII-1 and the ideal diode equation in Lab 2).

V. Transistor Basics

We'll be using a 2N4124 transistor, which is the one in the (short) black plastic can. See http://www.onsemi.com/pub_link/Collateral/2N4123-D.PDF for the specs and information on how to tell which pin is the emitter.

Set up the circuit shown in Figure VIII-3. Be careful. Some of the grabby things flip the polarity if the banana to bnc is put in upside down. Check the voltage polarity from the power supply as it arrives at your board by hand. DO NOT TURN ON THE POWERSUPPLY UNTIL YOUR INSTRUCTOR HAS CHECKED YOUR CIRCUIT! First, before you set up the circuit, check to see if the power bus is at the correct voltage. Then, spread the leads on the transistor a bit so they will not end up in adjacent holes and insert it into the breadboard. Now add the resistors, etc. You will use the multi-meters to measure current and voltage. Start with V_{var}= 12 V, and use R1 = 1 kΩ, R2 = 1 kΩ, R3 = R4 = 10 kΩ. Vary V_{var} and measure V_{BE} (the voltage between the base and the emitter) and I_C (the collector current).

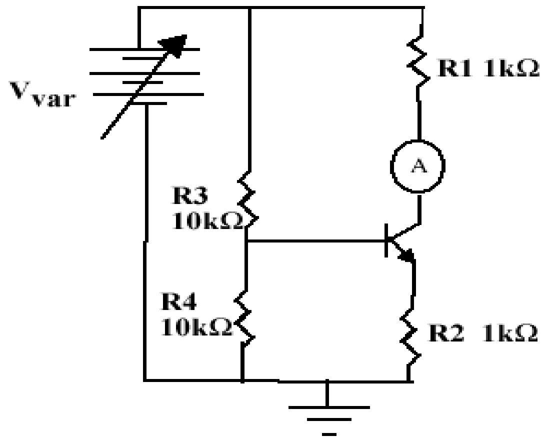

Figure VIII-3: Circuit for part V.

Plot both the raw data (I_C vs. V_{BE}), and then $\ln(I_C)$ versus V_{BE}. Do your measurements agree with the predictions of the Ebers-Moll model?

VI. Common Emitter Amplifier (see the applet http://www.falstad.com/circuit/e-ceamp.html)

Take another look at the circuit schematic in Figure VIII-3. Notice that the voltage at the collector is V_{var} - $I_C R_1$.

If you put a small voltage, ΔV, wiggle on the base, because the voltage drop from the base to the emitter is approximately constant (1 diode drop, or about 0.7 V), the voltage at the emitter will change by the same amount, causing a current wiggle in the emitter current of $\Delta I_E=\Delta V/R_2$. Since the emitter and collector current are about the same, this gives a voltage wiggle at the collector of $-I_C R_1$ (figure out for yourself why the negative sign) or $(R_1/R_2)\Delta V$.

The voltage at the collector should therefore be 180 degrees out-of-phase with that at the base, and have a gain of (R_1/R_2)

Now modify the circuit show in Figure VIII-3 by adding the function generator to the circuit as shown in Figure VIII-4. Use V_{var} of about 12 V and C1= 0.1 μF. On the function generator, set up a sine wave with an amplitude of about 0.25 V and a frequency of 10 kHz. You may wish to use a 3-way BNC T connector on the function generator so you can send the signal to both the circuit and your scope. Remember to be careful with your grounds! Display both V_{IN} and V_{OUT} simultaneously on the oscilloscope (**try looking at V_{OUT} using both AC and DC coupling**). Capture the wave form with V_{OUT} on AC couplings and with the same V/division setting as V_{IN} and paste into your spreadsheet. Compare the gain to its theoretical value. Finally replace R1 with a (roughly) 500 Ω resistor and measure V_{OUT} again. Does the circuit behave as expected? Capture the wave form and paste into your spreadsheet.

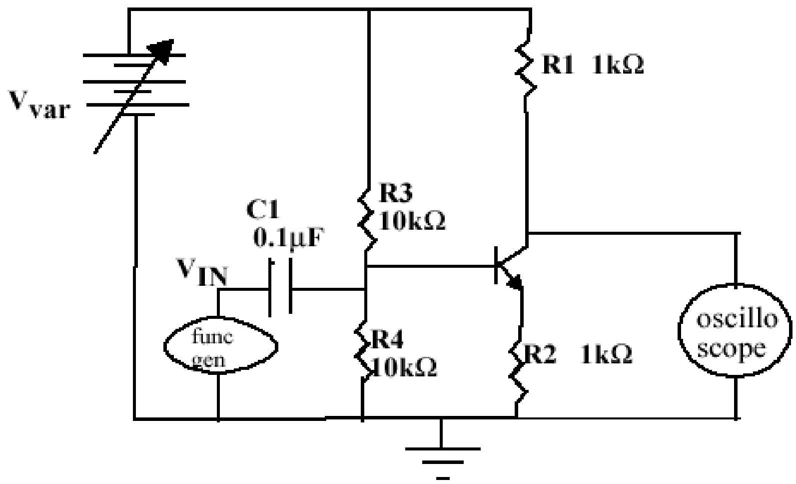

Figure VIII-4: Circuit for part VI.