Experiment 6: The Transistor

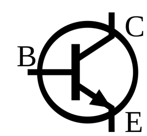
Goal: To generate the collector characteristic curves for an NPN bipolar junction transistor and measure its current gain for application to constructing a transistor amplifier circuit (Expt. 7).

Background notes:

The transistor was invented in 1949 by Shockley, Bardeen and Brattain, who won the Nobel Prize in Physics for their work. The transistor is a semiconductor device that can be used to amplify and switch electronic signals and power, and as such is a fundamental building block in modern electronic devices.

The bipolar junction transistor that we will study in this laboratory consists of 3 layers of alternately doped semiconductor. Each layer has one external connection which is labeled according to its functionality in the device: the three connections are labeled "emitter", "base" and "collector", or E, B, C for short.

The circuit symbol for an NPN transistor[1], as we will use in this experiment, is shown in the figure to the right. The majority charge carriers in the emitter and collector regions are electrons (N for 'negative'), in contrast to the base region where the predominant charge carriers are holes (P for 'positive').



When a transistor is connected in a circuit with appropriate bias voltage, charges travel from the emitter to the collector. To get there, they have to cross through the narrow base region, which is doped with the opposite carrier type. Notice the direction of the arrow indicating the emitter current for the NPN transistor: electrons travelling through the device from E to C correspond to a positive current flowing out of the emitter contact in the direction shown.

The polarity is extremely important here – the transistor is <u>not</u> symmetric, having a much more heavily doped emitter section compared to the collector. It will not work backwards!

The emitter-base combination acts as a diode which only conducts current when it is forward biased, as studied in experiment 5. Thus, the main flow of current through the transistor can be switched on or off by controlling the biasing of the emitter-base junction. This is the basis for applications of transistors as circuit switches.

When current flows through the transistor, a small fraction of the charge starting out at the emitter is lost due to recombination with the opposite carrier type as it traverses the base region. This loss is compensated by a flow of charge into the base via the external biasing circuit, which provides the "base current", I_b. The design of the transistor is such that the recombination losses are small (less than 1%) under normal operating conditions; thus, $I_b \ll I_e$ and $I_c \approx I_e$.

Furthermore, as the base current increases, both the emitter and the collector current increase; the collector current $I_c = \beta I_b$, where $\beta >> 1$; β is referred to as the dc current gain. This feature

[1] The other type of bipolar junction transistor is PNP; the circuit symbol in that case indicates positive current flowing into the emitter junction. To avoid confusion, only the NPN case is shown here.

can be exploited to configure the transistor as a current amplifier, which we will do in experiment 7.

The processes involved in current flow through an appropriately biased NPN transistor are illustrated in the figure below. Note the explicit labels of the two bias voltages V_{BE} and V_{CB}.

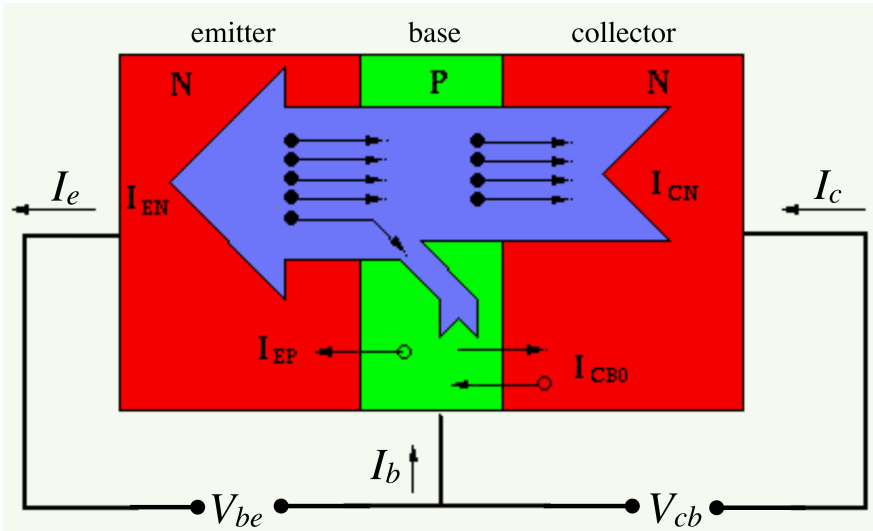


Fig. 1: Charge transport in an NPN transistor

The following relations hold:

1) $I_e = I_c + I_b$; 2) $V_{cb} + V_{be} = V_{ce}$; 3) $I_c = \alpha I_e, \alpha \cong 1$; 4) $I_c = \beta I_b$, $\beta = \frac{\alpha}{1-\alpha} \gg 1$

Notice that while the emitter-base junction is forward biased, the base-collector junction is reverse biased. Two back-to-back individual diodes would not normally conduct current, but the integration of the two junctions in one element, with the very narrow base region allows for minority-carrier injection of charges from the heavily doped emitter to the base, and these can move freely to the collector. If the base region is too thick, all of these injected charges will recombine along the way and the transistor will not conduct any current. Note that the strong electric field across the base-collector junction accelerates electrons to the collector, enhancing the charge transport.

The operating conditions for a transistor are summarized by a set of **characteristic curves**, which plot I_c versus V_{ce} for for a series of constant values of I_b. A set of curves that are similar to what you should obtain with the 2N4400 in this lab are shown in **Figure 2.**

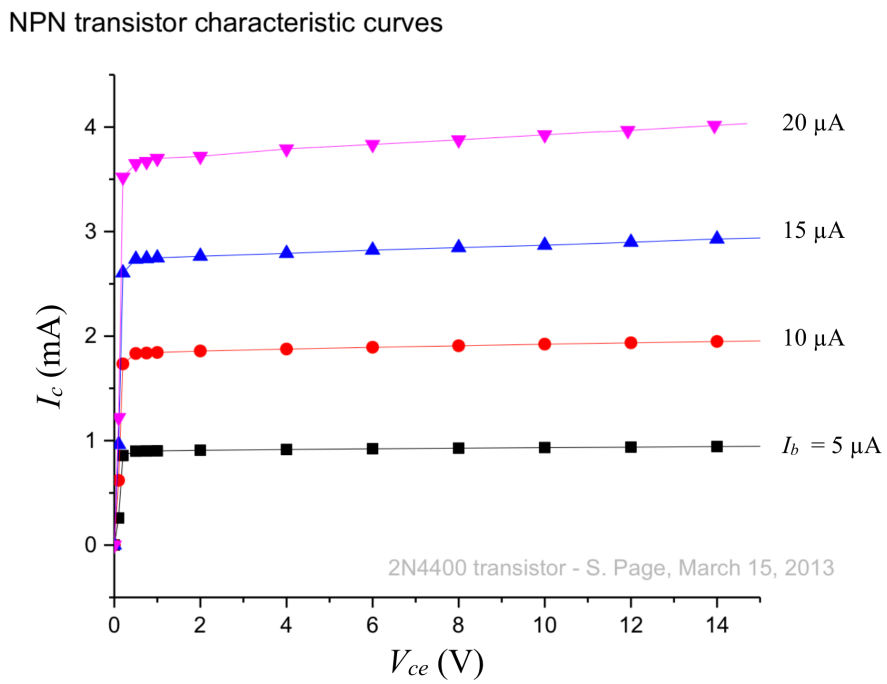
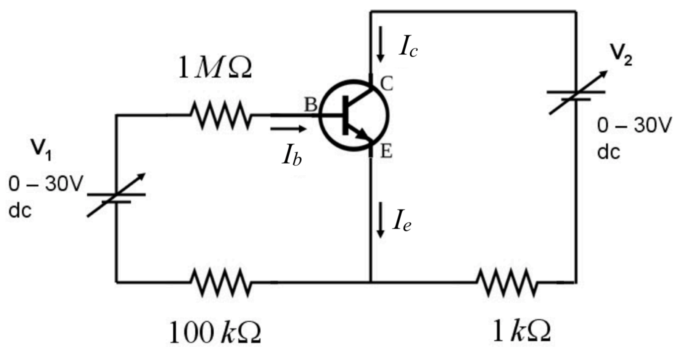


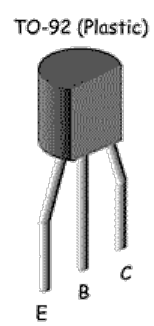
Fig 2: Characteristic curves for a typical 2N4400 transistor.

Equipment list:

- NPN bipolar junction transistor 2N4400
- 2 dc power supplies
- 3 DMM's
- assorted resistors as shown in the circuit diagram

Circuit:





Note that the voltage across the 1 MΩ resistor reads directly the value of I_b in µA, and similarly the value of I_c is read directly in mA via the voltage across the 1 kΩ resistor. The power supplies provide floating output , so they do not have to have a common ground.

Setup:

Construct the circuit as shown, and set up one DMM to measure the control variable V_{ce}. A second DMM should be set to measure the voltage across the 1 MΩ resistor, and hence I_b. A third DMM should be set to measure the voltage across the 1 kΩ resistor, and hence I_c. Indicate these meter placements on your circuit diagram. **Take care to minimize the number of alligator clip connections so that your construction is mechanically stable**!

Measure and note the component values for the 1 MΩ and 1 kΩ resistors.

Verify that you have the transistor connected properly by setting V_1 = 6 V, V_2 = 10 V; you should have about 5 μA of base current and about 1 mA of collector current. Now scan up and down with V_2 and watch what happens to I_c as a function of V_{ce}. You should see the behavior plotted in Fig. 2. If not, the transistor is likely connected backwards; reconfigure the circuit and try again!

Measurements:

1. Characteristic curves:

Record data for characteristic curves for I_b = 5, 10, 15, and 20 μA.

Set the dc supply V_1 to produce these base currents, and then for each base current, adjust V_2 to give 4 or 5 values of V_{ce} up to about 15 V in the linear region, recording the collector current for each one. You may have to adjust V_1 to keep the base current constant as you vary V_2. Tabulation and plotting in Origin will be easier if you use the same values of V_{ce} for each curve. The detailed behavior at low V_{ce} is not important, so a reasonable set of values of V_{ce} is 0, 0.5, 1, 4, 8, 12, 16 V.

Plot the characteristic curves for the transistor by selecting all columns from your data table and choosing a scatter plot (Fig. 2).

2. Current gain:

Evaluate the current gain at V_{ce} = 5 and 9 V using your characteristic curves to determine I_c at the 4 values of I_b. Plot the data and determine the slope. The slope represents the ac current gain $\beta_{ac} = \frac{\Delta I_c}{\Delta I_b} = i_c/i_b$. Is there any difference between the ac value of β and the dc value (I_c/I_b)? Is there any difference in the values of β at the two voltages?

3. V_{be} diode curve:

Rearrange the DMM's in the circuit to measure I_b versus V_{be} at V_{ce} = 9V. Plot the data and evaluate the slope of the graph to estimate the device resistance r_{be} near I_b = 12 μA for use in experiment 7.

The report should include plots of the characteristic curves and the diode curve, and calculations of the current gain and the base-emitter resistance. Both students should keep a record of these values. They will be needed for the prelab exercises for experiment 7.

Keep the transistor and all the data for the next experiment