Physics 3150, Laboratory 5
Transistor Circuits
February 22 and 24, 2016

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Last revised Feb. 15, 2016

Purpose:

1. To investigate transistor characteristics.
2. To study small-signal or “dynamic” impedances and gain.
3. To explore circuits using the transistor as an amplifier and a switch.

References:

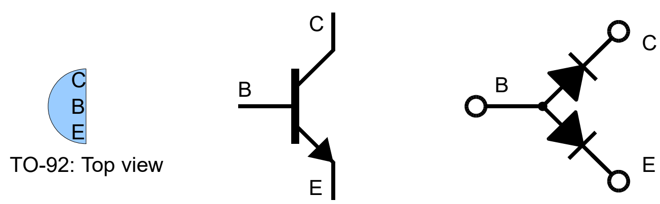
Chapter 4 of Eggleston, Chapter 2 of Horowitz and Hill (highly recommended!), or Chapter 5 of Meyer. We will focus on bipolar transistors this week, looking in turn at a simple emitter follower, a common-emitter amplifier, and a saturated switching application.

Equipment:

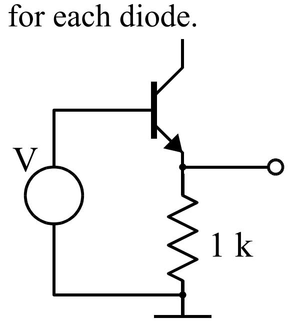
The usual stuff, plus:

1. 2N4400 or 2N4401 npn transistors. They are identical except that the guaranteed range for the small-signal gain, h_{FE}, is 20–250 for the 2N4400 and 40–500 for the 2N4401.
2. Light-emitting diodes (LEDs).

I. Transistor Basics



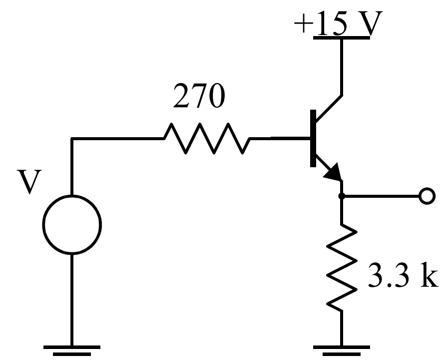
1) Use the diode setting on your DMM to verify that the B-E junction and B-C junction act like diodes in the correct direction. Record the diode voltage drops for each diode.
2) Now, connect the emitter to ground through a 1 kΩ resistor and apply a +2 V dc signal to the base. Measure V_B, V_E, and the current into the base, I_B. Calculate the current through the resistor, I_E.
3) Now, connect the collector to +12 V. Again, measure V_B, V_E, I_B, and I_C (the current into the collector). Calculate I_E.



Questions:

1) Which voltage drop is bigger, V_{BC} or V_{CE}?
2) Explain the voltages and currents you measured in step 2) – the unpowered transistor. Are I_B and I_E the same or different and why or why not?
3) Again, explain the voltages and currents you measured in step 3) – the powered transistor. How did the current flow change and why is this significant? What is your estimate for the value of β for this transistor?

II. Emitter follower
The circuit in part I is close to a circuit called an emitter follower. Build this version, using either a +12V or +15V supply depending on availability:

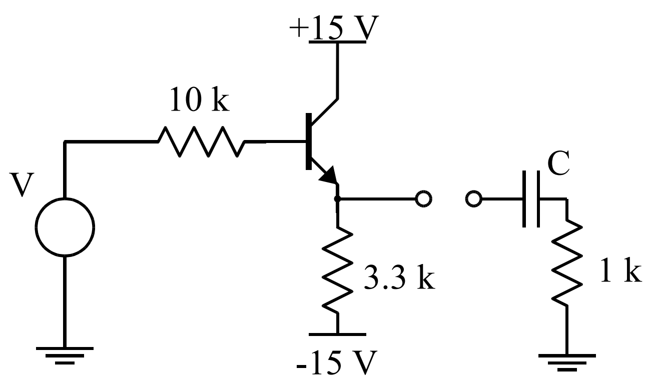


1) Apply a 4 $V_{p\text{-}p}$ 1 kHz sine wave to the circuit and observe the output signal. Make sure you have no dc offset.
2) Now, connect the 3.3 kΩ resistor to –12 V or –15 V instead of ground.

Questions:
1) Explain as much as you can about the output waveform that you observed in step 1). Why do you think this is called an "emitter follower"?
2) Why does the output from step 2) look the same, or different, from step 1)?

III. Input and output impedance of an emitter follower
It may not be clear why an emitter follower is so useful. One of the most significant features of the circuit is its input and output impedance, which we will measure in this part.

1) Make minor changes to the previous circuit by adding a high-pass filter at the output, and by increasing the base resistor to 10 kΩ. Choose a value for *C* such that your high pass filter has a cutoff frequency well below your signal frequency.



2) Measure the ac output impedance Z_{out} of this circuit. The output impedance can be characterized by measuring how a load impedance (R_{load}) loads down a circuit:

$$V_{out} = V_{oc}\left|\frac{Z_{load}}{Z_{load}+Z_{out}}\right|, \text{ where } V_{oc} = \text{open-circuit output voltage.}$$

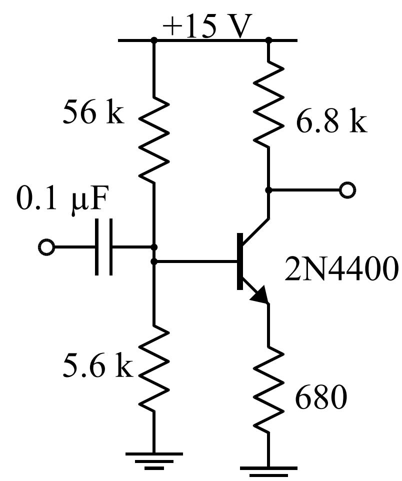
Find Z_{out} by looking at the output with and without the load and solving the voltage-divider formula above for Z_{out}. The capacitor blocks the dc bias level so only the ac signal is seen. The signal reduction will be small, so you must measure it carefully.
3) Measure the input impedance Z_{in} for small signals Here, Z_{in} can be obtained from $Z_{in} = v_{in}(ac)/i_{in}(ac)$, where $i_{in}(ac)$ is the signal current to the transistor base.
4) Repeat steps 2 and 3 without connecting the collector, so the transistor effectively is reduced to a simple diode junction..

Questions:

1) What are the input and output impedances of this circuit?
2) What was the impedance of the capacitor at your driving frequency? How much error is introduced by ignoring it?
3) What value of β can you deduce from these impedances?
4) How does this value for β compare to the value from Part I?
5) How much worse were the input and output impedances without powering the transistor?

IV. The common-emitter amplifier

Build the circuit shown at the right, again using either a 12 V or 15 V supply depending on availability.



1) Measure the quiescent dc voltages V_B, V_E, and V_C.
2) Apply a small ac signal to the input and measure the magnitude and phase (or sign) of the gain.

Questions:

1) What should the gain of this circuit be (amplitude and sign)? Does this agree with your measurement?
2) Calculate the quiescent voltages. Do those agree with your measurement?

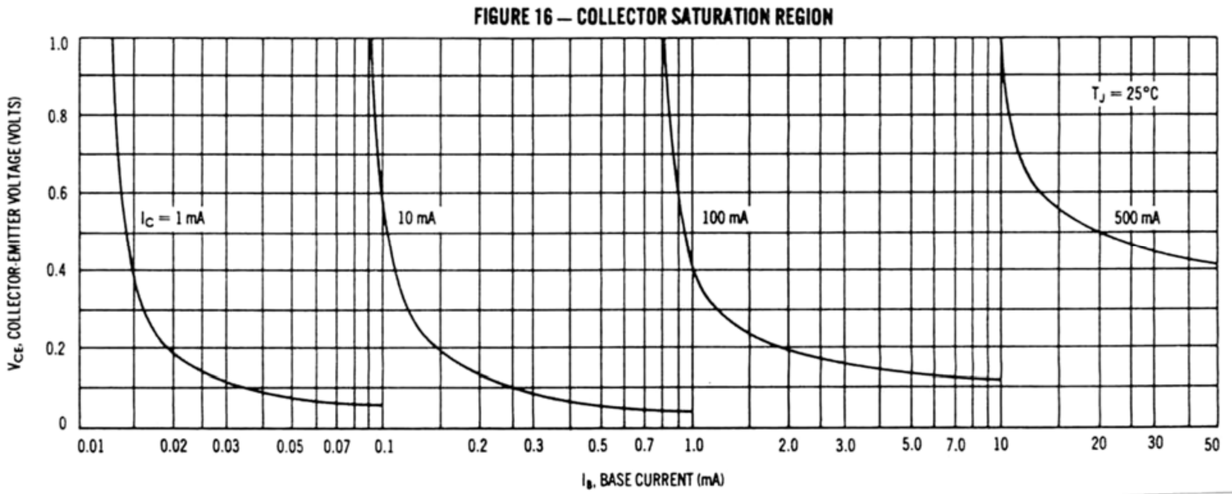
V. Transistors as saturated switches

A. Discussion

The use of transistors as for logic and power control usually depends not so much on their linear gain characteristics as on their ability to turn on and off rapidly. For this purpose the base-emitter junction is switched between two states: completely cut off or strongly forward-biased. The result is that the collector-emitter voltage V_{CE} is either equal to the full supply voltage or to a very low saturation voltage, with a voltage drop that may be less than 0.1 V. In this laboratory we will look at a saturated switch at low speeds.

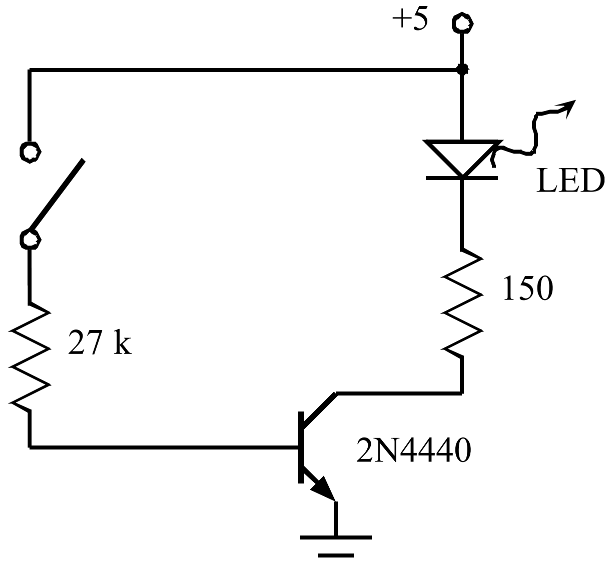
The saturation voltage can never actually reach zero, because for very low values of V_{CE} the base-collector junction becomes forward-biased, and more and more base current is needed to further reduce the collector-emitter drop. The effective current gain becomes very low, and can be orders of magnitude less than the small-signal h_{FE}. Often it's worth supplying this excess base current even though the external voltages are hardly affected, because if the transistor is switching a high-current load, the power $I \cdot V_{CE}$ dissipated in the device can get very large. The figure on the next page shows the saturation curves for the 2N4400, showing the dramatic dependence on collector current.

In this experiment we also will meet the light-emitting diode (LED). Typically made from gallium arsenide phosphide, these devices behave electrically like ordinary diodes but with a much higher forward voltage drop, about 2 V for a red LED. However, they are optimized to emit light whose photon energy is about equal to the bandgap energy (can you see why a 0.6 V bandgap would be a bad idea?) In effect, a hole and an electron annihilate one another at the junction to produce a photon. A forward current of 2-10 mA ordinarily produces good illumination. LED's are almost always used with series resistors to limit the current, as they would otherwise self-destruct by conducting excessively.



B. Procedure

Take a look at the LED. The negative terminal is usually marked with a flat spot on the case, which can sometimes be quite subtle. Don't worry too much about finding it—if you connect the diode backwards it simply refuses to conduct, and nothing happens. Connect your LED, in series with a 500 Ω resistor, to a 5V supply and measure the voltage drop across the LED.



1) Now try a 150 Ω resistor instead, noting the change in brightness. How much did the forward voltage drop change? How much current flows through the LED? (This is easily determined by measuring the voltage drop across the resistor with a DMM.)
2) Next add a transistor switch to the circuit as shown below. To switch the base resistor on and off you can pull it in and out of the breadboard rather than using a real mechanical switch if you like. Measure the transistor voltage drop V_{CE}, and find the base current by measuring the voltage drop across the 27K base resistor. Now place a 1K resistor in parallel with the 27K resistor. Is their any noticeable change in brightness? What is the effect on V_{CE} and on the base current?

Question

1) Consider your results for the effects of replacing the 27 KΩ base resistor with a ~1 K resistor. Do the numbers for V_{CE} and the base current make sense based on the typical saturation curves for the 2N4400 shown above?