

NORTHWESTERN UNIVERSITY TECHNOLOGICAL INSTITUTE

ECE 270

Experiment #5
BIPOLAR JUNCTION TRANSISTORS
Prelab

1. Perform parts 1) through 13) of the PROCEDURE and record your results.

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INTRODUCTION

This write-up is concerned only with how a transistor is used to amplify. If you wish to know how a transistor works internally, there are many books on the subject.

Transistors can be made from materials such as, silicon and germanium. The characteristics of a given device depend strongly on the material, but all devices of a given material will have certain traits in common.

Two common transistors that we will be using this term are the Bipolar Junction Transistor (BJT) and the Field Effect Transistor (FET). This lab is concerned with the BJT and next lab will look at the FET.

The BJT can either be an NPN or a PNP structure (these names come from the internal device structure - think of Negative Positive Negative (NPN) or Positive Negative Positive (PNP)). Their symbols are shown below along with the names given to the three leads.

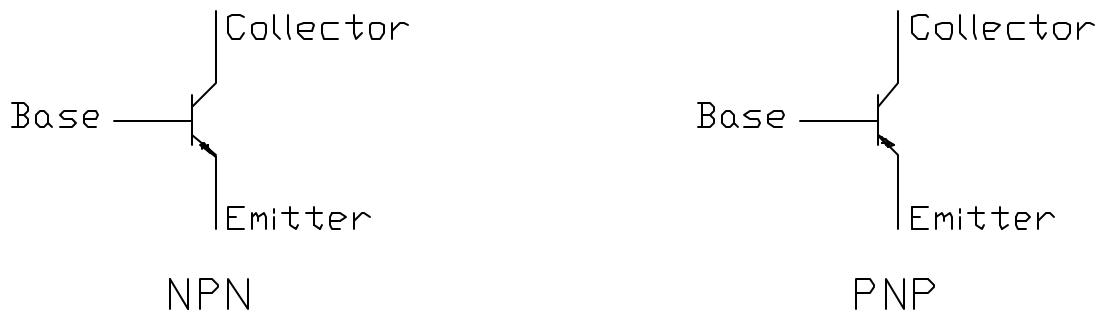


Figure 1

Note that the only difference in symbols is the direction of the arrow in the emitter lead. This arrow shows the direction current must flow through the device. In the NPN transistor, for instance, current must flow from base to emitter and from collector to emitter.

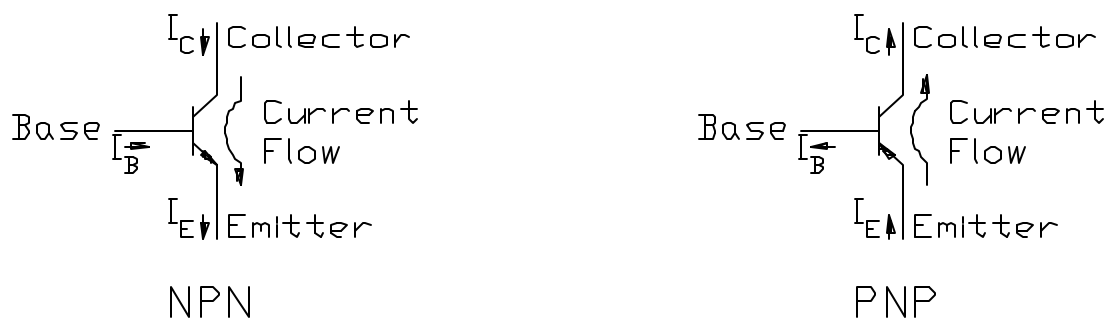


Figure 2

The whole point of the transistor is that a small change in the base current causes a large change in the collector current. We can control a large current with a small one and thus have amplification. The base current we call I_B and the collector current we call I_C . Obviously the emitter current, I_E , must be the sum of I_B and I_C .

Besides worrying about these currents (note that we need only worry about two of them because the third can always be found from $I_E = I_C + I_B$) we also have three voltages to consider.



Figure 3

Again we need only concern ourselves with two of the voltages because $V_{CE} = V_{CB} + V_{BE}$. From the voltage and current equations there are six variables, but only four independent variables. If we know these, we can always find the other two.

The four variables of most interest are: i_B , i_C , v_{CE} and v_{BE} . These are often plotted on two graphs as shown below. These graphs are representative of both silicon and germanium transistors and, as long as current directions and voltage polarities are correct, for either NPN or PNP type.

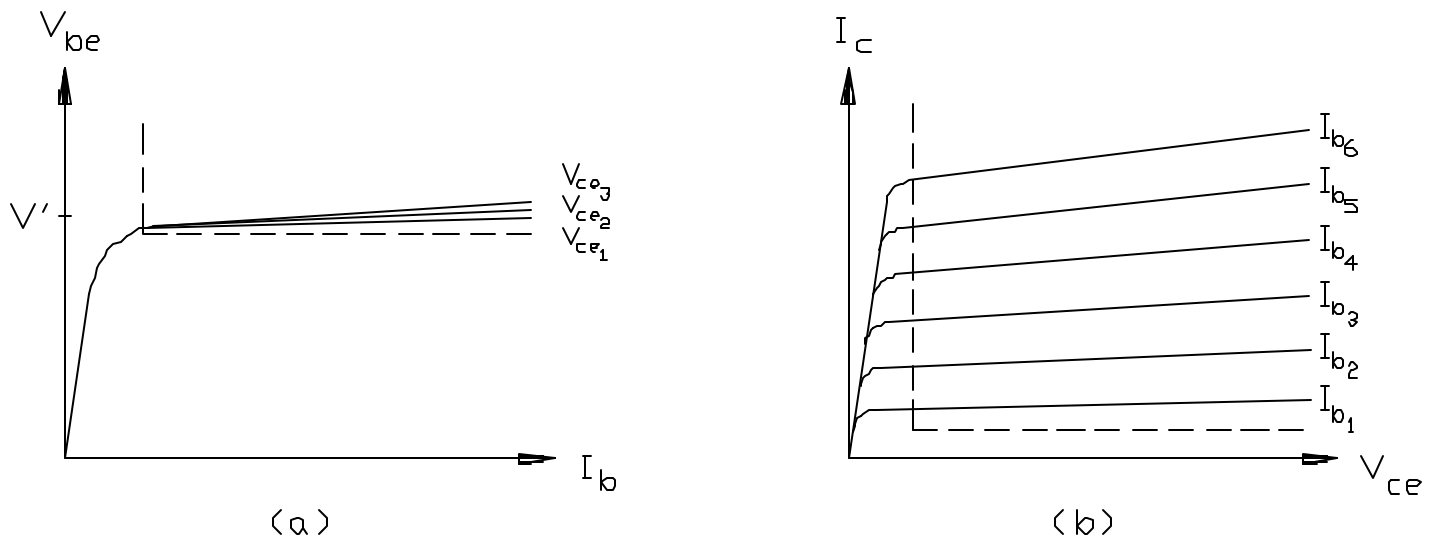


Figure 4

There should be nothing mysterious about these graphs, although it seems at first as if there is. They are simply plots of experimental data. For example, in Figure 4(a): if you set $v_{CE} = v_{CE2}$ and vary i_B , the middle line will be traced out. If you use $v_{CE} = v_{CE1}$ and vary i_B , the bottom line will be traced out, etc. If you pick a v_{CE} between these two values, an intermediate line will be traced, but you have a very good idea what it will look like.

For reasons that may become clear later, the transistor is almost always used in the area above and to the right of the dashed line on both graphs. This is called the active region.

Note that in the active region of Figure 4(a) $v_{BE} \gg v'$ for all values of i_B and v_{CE} (the three v_{CE} lines shown represent a large variation in v_{CE}). The value of v' is about 0.7V for silicon transistors and about 0.2V for germanium. In other words, the voltage from the transistor base to the emitter is almost constant regardless of how large or small the base current or collector-emitter voltage is (within reason of course). The base-emitter junction acts like a forward biased diode - and that's what it is. Thus this graph conveys little information for our purposes other than $v_{BE} \approx 0.7V$ for silicon (and $v_{BE} \approx 0.2V$ for germanium).

The right-hand graph is the useful one. Take a good look at it. What it shows is that in the active region, regardless of what v_{CE} is, a given value of i_B will give you a certain value of i_C . The graph is duplicated below with values that are typical for NPN silicon transistors.

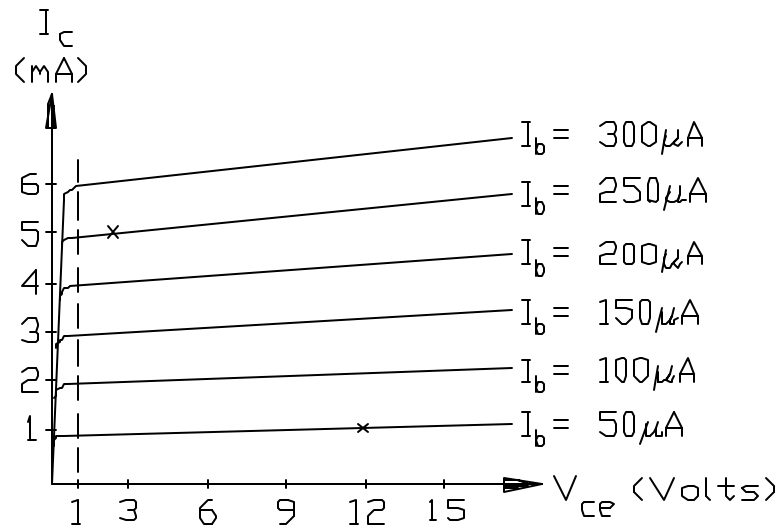


Figure 5

If we go from $i_B = 50A$ to $i_B = 100A$, we see that i_C goes from 1.0mA to 2.0mA. Thus $i_B = 50A$ and $i_C = 1.0mA$. If we take the ratio, i_C/i_B , we get $1 \times 10^{-3} / 50 \times 10^{-6} = 20$. Similarly, if we moved from one x to the other x on the graph we get $i_C = 5.0mA - 1.0mA = 4.0mA$ and $i_B = 250A - 50A = 200A$. The ratio is still 20. If the graph were ideal, that is the active region included the whole graph, then instead of taking the ratio of the differences we could have just taken i_C/i_B . We will pretend that this is true and use i_C/i_B which is called the β of the transistor. Often it is also called the h_{fe} . Now knowing β , if we know the collector current we can always get the base current, or vice-versa.

We now move on to actually using the transistor. Basically we wish to accomplish this: We feed into the device a low-level signal and some raw power and want to get out a more powerful version of what we put in.

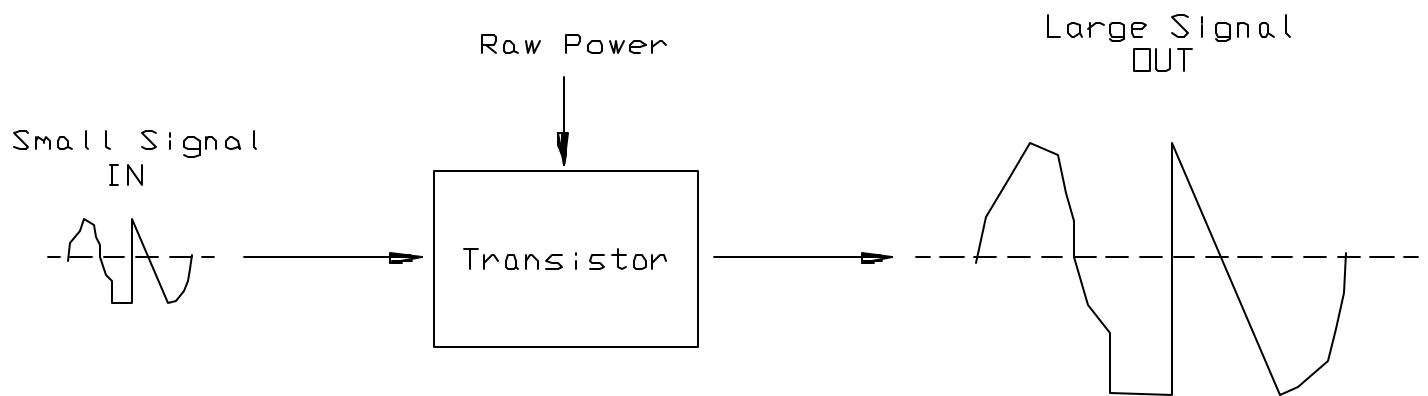


Figure 6

Suppose we set up the following circuit:

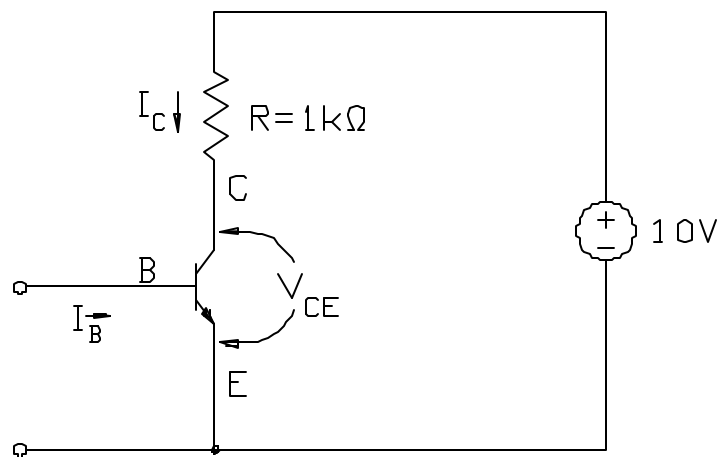


Figure 7

If $\beta = 20$ for the transistor and $i_B = 0.1\text{mA}$, you immediately know that $i_C = \beta i_B = 2.0\text{mA}$. Since this flows through R , the voltage across R is $v_R = i_C R = 2.0\text{V}$. Thus $v_{CE} = 8\text{V}$ to make the sum around the loop = 0. If I say $i_B = 0.2\text{mA}$, you can find $i_C = 4.0\text{mA}$, $v_R = 4.0\text{V}$, $v_{CE} = 6.0\text{V}$. If I say $i_B = 0.5\text{mA}$, you say $i_C = 10\text{mA}$, $v_R = 10\text{V}$ and $v_{CE} = 0\text{V}$.

What if I say $i_B = 1.0\text{mA}$? You might say $i_C = 20\text{mA}$, $v_R = 20\text{V}$ and $v_{CE} = -10\text{V}$. WRONG! We cannot make the device work with v_{CE} less than 0V . Look at Figure 4 and Figure 5 - we are outside the active region. In the above circuit v_{CE} can only range from 0V to 10V . This means we can only let i_B range from 0mA to 0.5mA (in this circuit) and still expect proper results.

In this example our input was i_B and our output was either v_{CE} or i_C . In order to use i_C as our output, we would need an R that would respond to the current. This resistance (R) might be in the form of a speaker or a light bulb for instance. Note that as i_B increased, i_C increased and v_{CE} decreased. Increasing i_B decreases v_{CE} , and vice-versa.

Suppose now we wish to amplify the following current waveform:

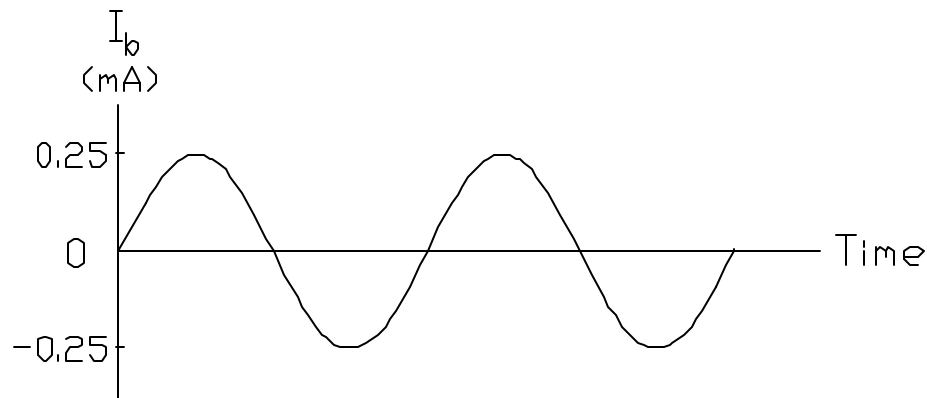


Figure 8

If we apply it directly to the base we see that it should work fine as long as i_B is greater than zero. But, our waveform swings just as much below zero as above. What shall we do?

If we apply a steady $+0.25\text{mA}$ to the base even with no input signal and then apply the input signal on top of that, we find that now the total input signal (the waveform plus the steady 0.25mA) ranges from 0.5mA maximum to 0mA minimum. This always falls within our limits. We will find that v_{CE} will swing from 0V to 10V . This steady current is called the bias current.

There are two popular ways of supplying this bias current. Both are shown below.

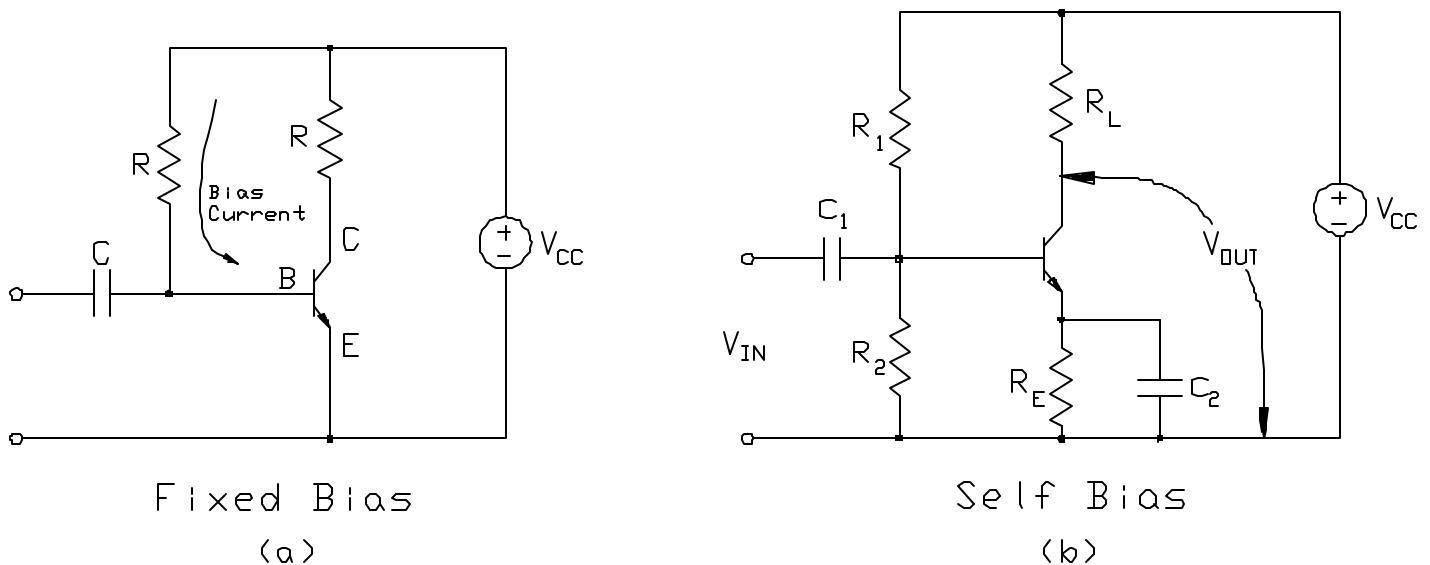


Figure 9

Despite the simplicity of the fixed-bias circuit, it exhibits certain instabilities that limit its use. The self-bias circuit is much more popular and is the one that we will use. The steps for its complete design follow:

PROCEDURE

- 1) Pick a value for V_{CC} . Often as not, this will be obvious. If you are making something to go in your car, you will probably want to use 12V so you can run it directly off the car battery. If you want to build a pocket radio, you might want to use a little 9V battery, etc. For this lab, we will use a value of $V_{CC} = 12.0V$
- 2) Decide on the maximum value you want i_C to be (i_C^{max}). This will depend on what your application is and on what the transistor is rated at. To drive a small speaker you would want i_C to be as high as perhaps several hundred milliamps. For a small signal amplifier or audio preamp 1.0mA to 10mA is quite sufficient. For this lab, use a value of $i_C^{max} = 2.32mA$.
- 3) In Figure 9(b), consider the loop that includes V_{CC} and V_{out} . The current through R_L is i_C and the current through R_E is $i_E = i_B + i_C$ (recall that V_{CC} is a DC source and a capacitor like C_2 acts like an open circuit for DC). Now $i_B = i_C / \beta$, so for a large β , $i_C \gg i_B$ and $i_E \approx i_C$. Therefore, the current through R_E is approximately i_C and the loop equation is $V_{CC} - i_C R_L - V_{CE} - i_C R_E = 0$. i_C is a maximum when $V_{CE} = 0$ (recall V_{CE} must be greater than zero). Therefore, pick $R_L + R_E = V_{CC} / i_C^{max}$.
- 4) Let R_L be twice to ten times the value of R_E (use $R_L = 10R_E$). From this and Step 3 you should now have values for both R_L and R_E .
- 5) We want the bias current into the base to cause the output current and voltage to be about half of their maximum value. This way the output signal can swing an equal amount above and below this value. So, find half of i_C^{max} . This is called the quiescent collector current (I_{CQ}).
- 6) Find the quiescent base current -- the base current that causes I_{CQ} to flow. This is what we have been calling the bias current $I_{BQ} = I_{CQ} / \beta$. Use $\beta = 80$.
- 7) Find the voltage across R_E . Since you know its resistance and the current through it, $V_{R_E} = (I_{CQ} + I_{BQ}) * R_E$.
- 8) Now V_{BE} is about 0.7V (assuming a silicon transistor). Therefore, $V_{R_2} = 0.7 + V_{R_E}$
- 9) Find $V_{R_1} = V_{CC} - V_{R_2}$
- 10) Let the current through R_1 be about ten times the value of I_{BQ} and find $R_1 = V_{R_1} / (10I_{BQ})$.
- 11) Since part of the current flowing through R_1 is diverted into the base, the rest must be the current through R_2 . You already found the voltage across R_2 , so find the value of $R_2 = V_{R_2} / (I_{R_1} - I_{BQ})$.
- 12) Since you went to all this trouble to bias the transistor, it would be a shame to screw things up by trying to apply your input signal directly across R_2 and suddenly finding that all of your bias current is flowing back into your signal source instead of into the base. For this reason the input is run through C_1 . The capacitor will pass your AC input signal but not your DC bias current. To the incoming signal it appears (by Thevenin's theorem) that R_2 is in parallel

with the base-emitter junction and with R_1 . This always bothers people at first, but remember that when doing Thevenin equivalent circuits you replace voltage sources with shorts and current sources with opens. If we call this combination of R_1 , R_2 and the base-emitter junction R_{BE} ($R_{BE} \approx 1.1\text{k}\Omega$), R_{eq} we see that C_1 and R_{eq} form a high-pass filter. If we know that the base-emitter junction appears to have a resistance of about 1.1k , we can find R_{eq} and the half-power frequency of this filter ($f_{1/2} = 1/(2\pi R_{eq} C_1)$). Decide the lowest frequency you want to amplify (choose a value between 100Hz and 10kHz) and use this in the formula as $f_{1/2}$ to find C_1 .

- 13) Make C_2 at least as large as C_1 .
- 14) Before applying an input signal, verify that the circuit is biased properly. That is measure the quiescent voltages and currents that you just calculated. Remember, these are DC signals so it is easier and more accurate to use a meter for these measurements. Tabulate the Base to ground voltage (V_B), the Collector to ground voltage (V_C) and the Emitter to ground voltage (V_E). Using these measured voltages calculate I_{CQ} , I_{BQ} for your transistor. Compare these measured values to the values you obtained in parts 5) & 6) of this procedure.
- 15) Apply a small AC voltage across the input terminals, this will cause the base current to vary up and down around the bias current and will cause an amplified version to appear at the output. The ratio of output voltage to input voltage (the AC components) can be shown to be: $A_V = -\beta R_L / R_{BE}$. If C_2 is removed, it can be shown that (for a large β) $A_V = -R_L / R_E$. Measure to see if you can obtain either of these results from your circuit.
- 16) Increase the input signal until the output becomes distorted or clipped. What are the magnitudes of the input and output just as the output begins to clip or distort? What is the peak-to-peak voltage of v_{CE} at this point? Keeping in mind the discussion on page 4, explain why the output is distorted.