The University Of Sheffield.

student reg. number:

Department of Electronic and Electrical Engineering

EEE160: 1st Year Laboratory Experiment

THE BIPOLAR JUNCTION TRANSISTOR (BJT)

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1. AIMS

The aims of this experiment are for you to:

- understand the basic operation of bipolar junction transistors (BJTs),
- become familiar with some of the characteristics of BJTs,
- measure some of their characteristics,
- observe effects of the external circuit on transistor performance.

2. INTRODUCTION

Sections 2.1-2.3 contain background information. **Please read sections 2.1-2.3 before attending the Laboratory** session. The remaining sections describe the experiments, and will become clearer when the equipment is in front of you.

You are requested to **fill in the open boxes in this handout**, describing briefly what you have done during the laboratory experiment, plotting and describing the curves you measured and answering the questions that test your understanding of the subject. **Keep your answers within the boxes provided.** The marks contribute 10% towards the EEE160 module.

You will have two sessions on consecutive days. If you are well prepared and quick you may have time to perform all measurements on the first day, but usually both days will be needed.

2.1. Basic information about Bipolar Junction Transistors (BJTs)

The bipolar junction transistor is a three-terminal device that can act as amplifier or switch. Figure 1 shows the conventional circuit symbols used to represent the two different kinds of bipolar transistors, 'NPN' and 'PNP'. These letters refer to the type of doping in the semiconductors used to make the emitter, base and collector regions of the transistor.

BJTs basically consist of two diodes with a shared electrode in their middle, where one diode is forward and one reverse biased. The central electrode is called 'base' and is made very thin. For a PNP transistor the base is usually negatively biased compared to the emitter, and the applied electric field allows current to flow from the heavily doped emitter to base. Some carriers (holes in the case of a PNP transistor, electrons for an NPN transistor) can diffuse through the base region into the reverse-biased diode area where they will move towards the emitter under influence of the applied voltage. So, finally, both an emitter-base and an emitter-collector current flow and the biasing controls the currents. This gives rise to five distinct operation modes:

1. **active amplification** in forward-biased mode as explained above, with collector-emitter current ~100 times larger than the base-emitter current
2. inverse-active or **inverted operation** by reversing the biasing (emitter and collector change role, but since the device is not built symmetrically the current gain is much smaller). This operation is only rarely used, e.g. in bipolar logic circuits or for failsafe operation.
3. **saturation mode** with both junctions forward-biased, yielding high current flow ('on')
4. **cutoff mode** when both junctions are reverse-biased, with only small leakage currents ('off')
5. **avalanche breakdown** by impact ionisation when the base is connected to a high impedance, e.g. a current source, or the reverse bias exceeds a critical value (~5.6V for Si)

However, when designing a circuit using transistors it is often not necessary to consider the internal operation in detail; instead the known electrical behaviour of the transistor as measured at its terminal points is important. Plots of the output current (vertical axis) vs. input voltage (horizontal axis) are called characteristic curves of the transistor.

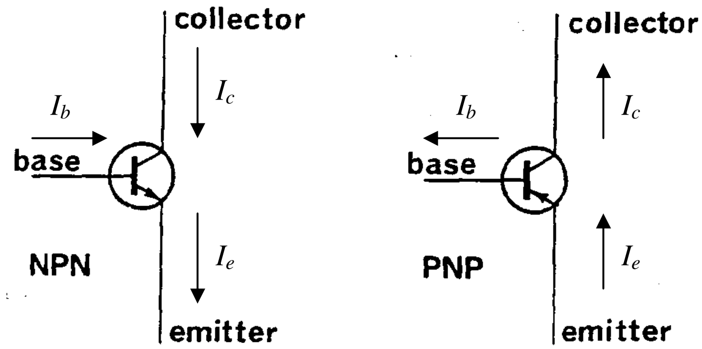


Figure 1: NPN and PNP transistors

A diode requires a small 'turn-on' voltage to start to conduct, beyond which the current increases rapidly with voltage. Hence, the usual working currents for a transistor are produced by an *approximately constant* base-emitter voltage. The DC bias conditions **for a PNP** transistor are:

(i) The base is held negative with respect to the emitter by a value given by $|V_{be}|$; typically 0.6V to 0.7V for a Si transistor (and 0.1V to 0.2V for a Ge transistor), so that the base-emitter junction *is forward biased* and a DC current, I_b, flows through the base;

(ii) The collector is held negative with respect to the emitter by a value given by $|V_{ce}|$ of anything between a few volts and a few hundred volts, depending on the particular transistor's application and capabilities, and a DC current I_c flows out of the collector;

(iii) When a current flows into the emitter this then splits into a small current through the base and a larger through the collector, according to Kirchhoff's Law: $I_e = I_b + I_c$

For NPN transistors, all of these DC bias polarities are reversed, so that the collector and base are connected to *positive* voltages with respect to the emitter for correct operation. The arrow on the transistor symbol on a circuit diagram indicates the direction of conventional current flow through the emitter of the device. Thus, for an NPN transistor, the conventional current flow is such that I_b and I_c flow *into* the device, and I_e flows *out* of it, as shown in Figure 1.

Questions:

1. ***Tabulate clearly the values and signs that V_{be} will take for silicon and germanium NPN and PNP transistor. (2 points)***

2. ***The speed of operation is important for high-frequency applications. Below are listed electron and hole mobilities [in $m^2V^{-1}s^{-1}$ at 300K] for some semiconductors. What can you say about the optimum choice of semiconductor material and the role of BJT type? (4 points)***

material	electron mobility	hole mobility
Si	0.15	0.045
Ge	0.39	0.19
AlAs	0.03	0.02
GaAs	0.85	0.04
InAs	2.3	0.02
InP	0.46	0.015
GaP	0.008	0.0017
InSb	4.5	0.075

2.2. Amplification, Current Gain, Input Resistance, and Mutual Conductance

Consider what is required in an amplifier. We wish to take some small input signal (for example from the pick-up head of a tape recorder) and make the signal larger, so in the case of an audio signal we can hear it when the signal drives the speaker. These varying signals can be both positive and negative, like for example a sine wave.

These (smaller) signal currents and voltages are represented by lowercase letters: in the simple transistor amplifier circuit of Figure 2, i_b and v_{be} represent the input signal and i_c and v_{ce} the output. The upper case letters represent DC currents and voltages used to set the circuit at the "quiescent" and "operating" point. These DC signals merely "set the scene" and are designed to allow the signal to be amplified without catastrophic signal distortion. From the above it should be clear that the *instantaneous* value of collector current, for example, is given by $I_c + i_c$, and the *instantaneous* value of base-emitter voltage is given by $V_{be} + v_{be}$. In other words, the signal can be regarded as a variation of the DC values (see Figure 2). Because the changes in base current and collector current are proportional, we can write

$$\beta = i_c / i_b ,$$

where β is the '**small signal current gain**' and is typically between 10 and 1000 for commercial devices. Correspondingly, the fraction of collector to emitter current is often defined as

$$\alpha = I_c / I_e$$

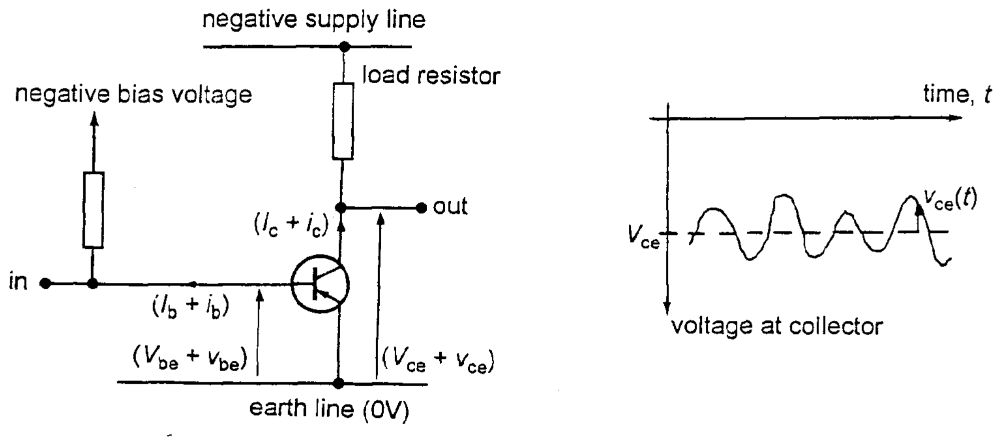


Figure 2: PNP transistor biased in a simple circuit

Usually a 'load' resistor connected between one power-supply terminal and either the emitter or collector establishes the DC collector-emitter bias voltage, V_{ce}. Therefore, small changes in collector or emitter current are proportional to small voltage changes across this load resistor. In addition, under the usual DC bias conditions, the base-emitter part of the transistor appears to obey Ohm's Law for small signals, so that a small change in the base current, i_b, is proportional to the corresponding small change in base-emitter voltage:

$$v_{be} = r_{be}\, i_b$$

where r_{be} is the '**small-signal input resistance**' of the transistor. Then, the expression for the small-signal collector current is often written as:

$$i_c = g_m\, v_{be}$$

where g_m is called the '**mutual conductance**'.

Questions:

3. ***Deduce how α and β are related for small signals. What value has α for β=100?***
   (2 points)

4. ***Deduce how β and g_m are related. (2 points)***

2.3. Objectives

The objectives of this experiment are to measure the relationships between voltage and current, which determine the transistor's performance both as an amplifier and as a switch. In particular the following will be measured:

(i) INPUT CHARACTERISTIC for common-emitter configuration, *i.e.* the input current I_b versus V_{be} for fixed values of V_{ce}

(ii) OUTPUT CHARACTERISTIC for common-emitter configuration, *i.e.*, the output current I_c versus V_{ce} for fixed values of I_b

(iii) small signal current gain, β.

(iv) frequency dependence of small signal voltage gain

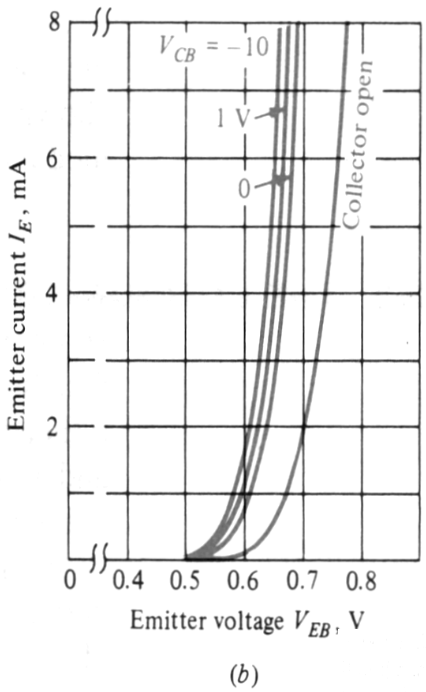
Typical input and output characteristics for two types of transistors are shown in Figures 3-6. However, there are large *quantitative* manufacturing differences between individual transistors having the same type number.

Questions:

5. ***Using the information from the characteristic curves given, what material do you think the transistors 2N2907A and ACY21 are made of? What type of BJT are they? Give reasons for your decision. (4 points)***

We shall also see how the transistor operates as an AUDIO AMPLIFIER, hearing and seeing the effects of distortion (clipping at large signal levels).

6. ***Determine whether the BJT type BC212 , which you use in this experiment, is a PNP or an NPN transistor. (1 point)***



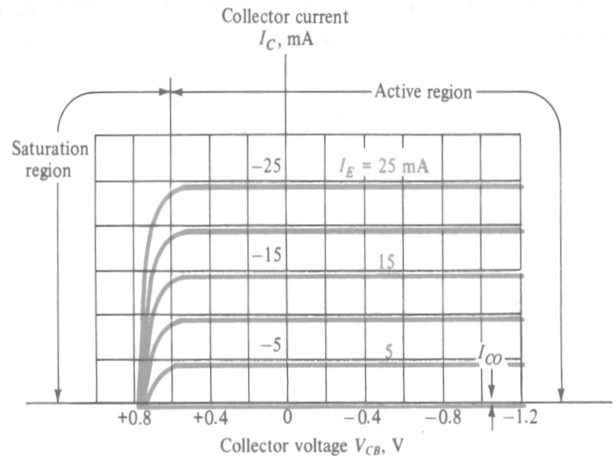


Figure 3: Common-base input characteristic for 2N2907A (*J Millman & A Grabel – Microelectronics, McGraw Hill ed)*

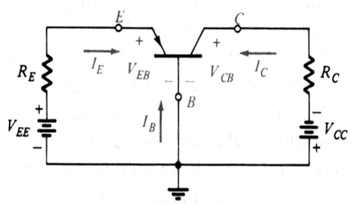
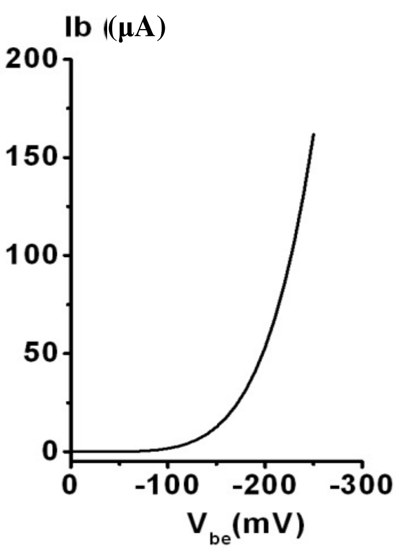


Figure 4: Common-base output characteristic for 2N2907A *(J Millman & A Grabel – Microelectronics, McGrawHill ed)*



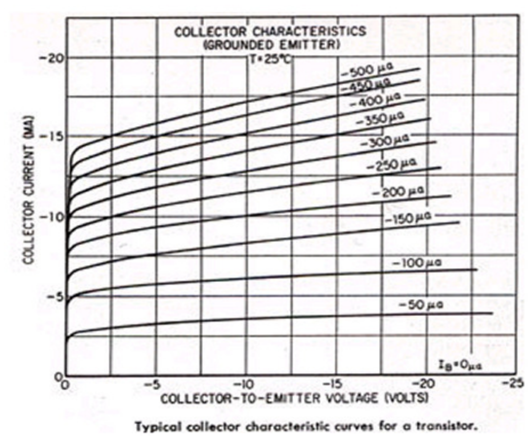


Figure 5: Common-emitter input characteristic for ACY21

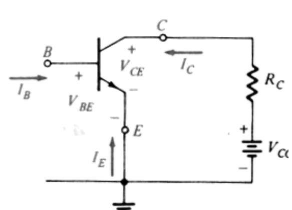


Figure 6: Common-emitter output characteristic for a typical transistor (above) and set-up for npn-type BJTs (left)

DAY 1

Spend some time familiarising yourself with the test-rig and the various pieces of equipment at your disposal. Also start writing everything down in your lab book, in a professional, ordered and clear manner. You will need these notes when you prepare the assessment.

3.1 COMMON-EMITTER INPUT CHARACTERISTICS

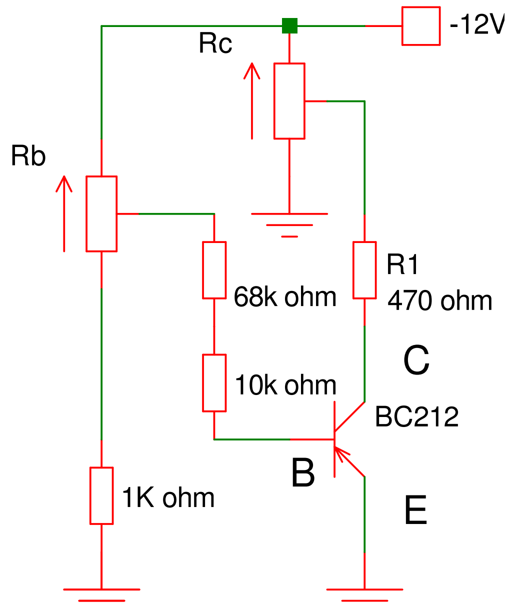


Figure 7: Common-emitter mode.

1. Connect the circuit according to Figure 7. The 470Ω resistor R1 is external. Rc and Rb are the two 5kΩ potentiometers in the test-rig. You also need two voltmeters to monitor V_{be} and V_{ce} as well as an ammeter to monitor I_b.
2. Adjust the potentiometers R_b and R_c to measure I_b versus V_{be} for V_{ce} = -3V over the range allowed by the equipment. Plot your data points in a graph, which should be similar to Fig. 5 (but covering a different range of V_{be}). Repeat for V_{ce} = -2V and -4V.
3.

Question:

7. ***Explain what happens to I_B and I_C if you change Rb or Rc in Figure 7 but keep V_{CE} constant (4 points)***

Task 1: Plot the common emitter input characteristics (I_B on the vertical axis, V_{BE} on the horizontal axis) for 3 values of V_{ce} in the following space provided. (12 points)

3.2 COMMON-EMITTER OUTPUT CHARACTERISTICS

1. Still using the circuit as depicted in Figure 7, now use one voltmeter and two ammeters to monitor I_b, I_c and V_{ce}. Set I_b = 25μA, then measure how I_c varies with V_{ce}. Cover as wide a range of V_{ce} values as you can. Plot a graph of I_c against V_{ce} again <u>as you make the measurements</u>. Take at least 10 <u>equally spaced</u> data points for this value of I_b. [Hint: just like for the input characteristics, you should find the maximum range of your data before you start taking the data]

2. Repeat the experiment with two different I_b values (one higher and one lower).

3. Open-circuit the base branch in the circuit to give I_b = 0. The very small current I_c which flows in this case is the collector **'leakage' current.** Try to measure it at two large values of V_{ce}.

Questions:

8. ***Is the slope of the characteristic curves I_c vs. V_{ce} at high V_{ce} always the same constant value for different $|I_b|$? How is this different from the common base output in Figure 4? (3 points)***

9. ***Which region of the output characteristics corresponds to analogue operation (i.e. the transistor acting as an amplifier)? Label your graph appropriately. What is the reason for the slight slope of the curve? How is the slope affected if we measure I_c vs. V_{ce} with a larger or smaller constant value of $|I_b|$? (4 points)***

Task 2: Plot the common emitter output characteristics (I_C on the vertical axis vs. V_{CE}) for 3 values of I_b in the following space provided and also indicate the leakage current measured as described above. (12 points)

This completes the task for DAY 1. Switch off all equipment but leave your circuit connected as you will need the same set-up configuration on DAY 2.

DAY 2

4.1 CURRENT GAIN for common-emitter mode

Current amplification, in which a small change in the base current produces a proportional, larger, change in the collector current, is the most useful property of the bipolar transistor. The aim of this exercise is to measure the current gain.

Task 3: Measure 6 pairs of I_c and I_b, while keeping V_{ce} = -6V, to build up a table of results that you write down. Also plot your data in the box provided below. (12 points)

Question:

10. ***Use your above data to calculate the "large-signal current gain", $h_{FE} = I_c / I_b$. How would you calculate β (see section 2.2) from your results? What is the principle difference between β and h_{FE}? What applies in the special case here? (4 points)***

4.2 SIMPLE AUDIO AMPLIFIER DESIGN

So far, you have used variable resistors to set up the correct bias conditions for the quiescent points. This is acceptable when making measurements, but is best avoided when designing circuits because adjusting variable components takes far too long in production and such components can go out of adjustment over a long time. A simpler way to establish the correct bias conditions is to connect a fixed resistor, R_b, directly between the collector and base terminals, as shown in Figure 8.

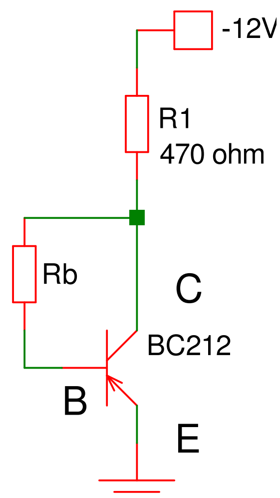


Figure 8: Simple amplifier

Question:

11. ***Using your graph of common-emitter output characteristics obtained in Day 1, what ideal value of V_{ce} would allow the largest possible undistorted output amplitude when amplifying sine-wave signals? Give reasons (3 points).***

Check if the voltage between the negative supply rail and ground is indeed 12V.

Questions:

12. ***Calculate the value of R_b (connected directly between collector and base) needed to achieve the ideal value of V_{ce}. [Hints: as you have already decided the ideal value of V_{ce}, you can calculate I_c, which flows through the collector load resistor R1. You can then calculate $I_b = I_c / h_{FE}$, which flows through R_b. Finally, by calculating the voltage across R_b, you can now find its resistance. The base-emitter diode turn-on voltage, V_{to}, is the value of V_{be} for which the transistor starts conducting for fixed V_{ce}] (3 points)***

13. ***Unfortunately, there are large variations in the large-signal current gain, h_{FE}, between individual transistors, and so it is good design practice to arrange that such variations affect the bias conditions as little as possible. Why is the method described in this section preferable to simply connecting R_b between the base terminal and the negative supply rail? (5 points)***

Find a resistor having the *nearest value* to that you just calculated. Measure the resistor value with an ohmmeter. Then connect the circuit according to Figure 8 using your chosen R_b.

Measure V_{ce}. Is it close to the ideal value you have chosen? If V_{ce} is significantly different from the value you expected, check your calculations and/or the resistor you used.

Questions:

14. ***Can you calculate how much error in V_{ce} will be produced for a given deviation ΔRb from the ideal value Rb? Show that the relationship is linear. Compare ideal and measured V_{ce} (5 points)***

15. ***What will be the amplitude of the largest alternating output voltage that your amplifier could produce without significant distortion? (2 points)***

Following Figure 9, test your deduction by connecting the signal generator between earth (0V) and input terminal, which is at the end of a 0.22μF capacitor (provided in the test-rig). Display the input signal on channel 1 of your oscilloscope (make sure the oscilloscope is AC coupled). Use channel 2 to display the signal from the collector (output), and connect the high-impedance earphone to the collector, via the second 0.22μF capacitor, using the 'jack' plug and socket. Look at the difference between the undistorted low-level waveform and the distorted high-level waveform, by varying the input signal level from the signal generator. Record appropriate signal levels.

Substitute the cassette player, which supplies an audio signal, for the signal generator, and repeat your observations. This is one of the simplest methods of designing an amplifier. This design still has some shortcomings (principally concerned with the stability of the bias point) that can be overcome with a more complex circuit. You can easily hear the distortions, because your ears are very sensitive to these. This is the reason good audio amplifiers are more complicated and expensive.

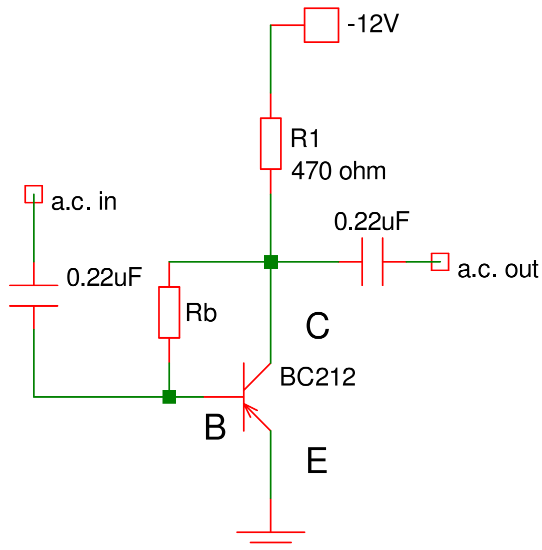


Figure 9: Audio amplifier

Question:

16. ***What is the role of the capacitors in Figure 9? Do they influence the bias?(2 points)***

Task 4: Use the oscilloscope to measure the output voltage u_C for three different input voltages u_B and tabulate the results below for three significantly different frequencies in the range between 50Hz and 50kHz. (9 points)

Question:

17. ***Calculate the small signal voltage gain of the circuit from the above data for the three frequencies. How does this compare to the current gain measured before, and why are the values so different? (5 points)***

Notes for the assessment:

Please hand in a completed version of this report **within one week after the last laboratory session**. See the course timetable for possible changes. Try to answer all questions and tackle the set tasks in the boxes provided in your lab sheets. You may write and also draw curves by hand or paste in a computer print-out. In any case, the answers should be legible and all graphs be appropriately labelled. You may make annotations in the margins of the lab sheets for yourself or enter the data for the graphs you need to plot, but **only answers within the framed boxes will be marked and assessed!**

suggested Literature: B. Streetman – Solid State Electronic Devices, PHIE ed – Chapter 7
J Millman & A Grabel – Microelectronics, McGraw Hill – Chapter 3

These notes will also be accessible as teaching resources via the following link:
http://www.shef.ac.uk/eee/staff/t_walther.html