BIPOLAR JUNTION TRANSISTOR | REPORT

Introduction:

Background:

The aim of this lab is to investigate the properties of a Bipolar Junction Transistor (BJT) and understand its behaviour in order to construct an audio amplifier. Understanding the characteristics of a BJT and knowing how it performs in different conditions is important to be able to apply it to certain circuits such as amplifiers and have it operate as intended.

Aims:

- To plot graphs of a BJT's key characteristics to understand is operational behaviour.
- To extract specific performance information from the characteristic graphs.
- To define the operating point of a BJT.
- To identify the difference between "small" and "large" signal models in the context of this experiment.
- To use the characteristic graphs to calculate the BJT's small signal model parameters and construct a working amplifier.

Theory:

Operation:

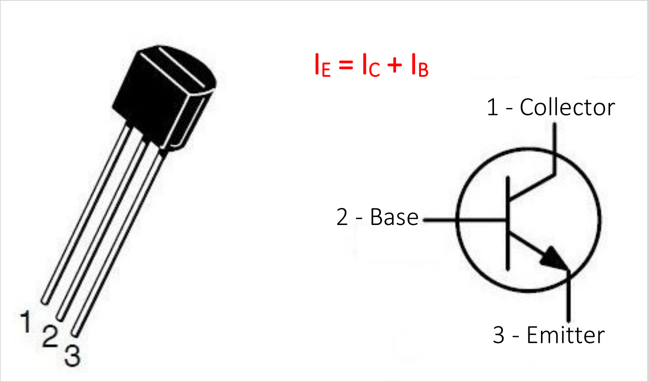

Figure 1: BJT pin layout. [7]

A BJT is a device that can regulate the current going through it, controlled by the bias voltage applied to its base terminal.

Bipolar junction transistors can operate in 3 different regions, which enable them to act as switches for digital electronics or amplifiers for analogue electronics.

These 3 regions are the **"Active Region"** where the transistor acts like an amplifier along with **"Saturation"** and **"Cut Off"**, where the transistor is fully ON and fully OFF. [1]

Configurations:

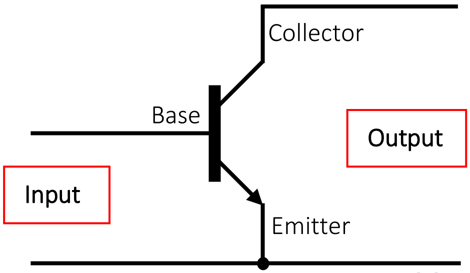

Figure 2: Basic common emitter circuit. [2]

The configuration used in the context of this laboratory experiments is **common emitter.** (see *figure 2)*

A **common emitter** configuration provides both **voltage** and **current gain**, where the input signal is between the base and emitter and the output signal is between the emitter and collector. In this configuration, the emitter is connected to both the input and output signal. [2]

Small changes in the **base-emitter** current cause **large changes** in the **collector-emitter** current, irrespective of V_{CE} above a certain point, which makes this configuration a **current amplifier**. However, to achieve **voltage amplification**, a **load resistance** is connected at the **collector**, so that there is a in **voltage across the load resistor** due to a change in the collector current. The voltage **gain** of the amplifier is determined by the **resistance** of the load resistor. [3]

The **quiescent point** or **operating point** of a BJT is in the active region and allows the **maximum change** in **output voltage** without **saturating**/entering switched-on mode. This can be found on the output characteristics graph shown in *figure 4* along the **DC load line**, represented by the resulting DC current and DC voltage across the BJT when **no input** AC signal is applied. Generally, it is at the point where the base current, I_B, is proportional to the collector current, I_C, making it suitable for **amplification** purposes. [3]

The **load line** is drawn on certain characteristics graphs and is used to analysis non-linear systems in order to represents its linear region. In the context of this experiment, the load line in *figure 6* intersects the operating point and the inverse of its gradient represents the **load resistance** at the operating point. A **DC load line** represents when there is no AC input signal.

To use a BTG as an **amplifier**, an **AC bias**, is applied to the **input** which sets the amplifier to operate between a certain **maximum** and **minimum** point about the **operating point**. If the bias is set correctly, an input signal can only be amplified between these two points and therefore prevents or reduces distortion of the output signal. However, the **input** wave form will be in **anti-phase** (180°) to the **output**. [4]

Input Characteristics:

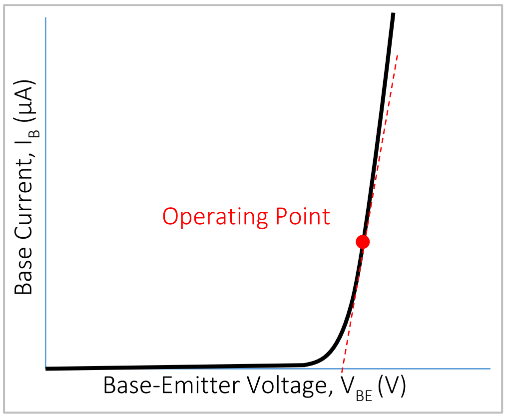

Figure 3: Input characteristics graph.

The input characteristic of a BJT is the relationship between the **input voltage** and **input current**, while keeping the **output voltage constant**. From *figure 3* it can be seen that almost no base current flows until the base-emitter voltage has surpassed the threshold voltage (the voltage where the BJT begins to conduct, which is **0.7V**). [5]

The inverse gradient of the curve around the operating point is the dynamic resistance, *r*be, in Ohms (Ω).

$$r_{be} = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{Base - Emitter\ Voltage\ (V)}{Base\ Current\ (A)}$$

Output Characteristics:

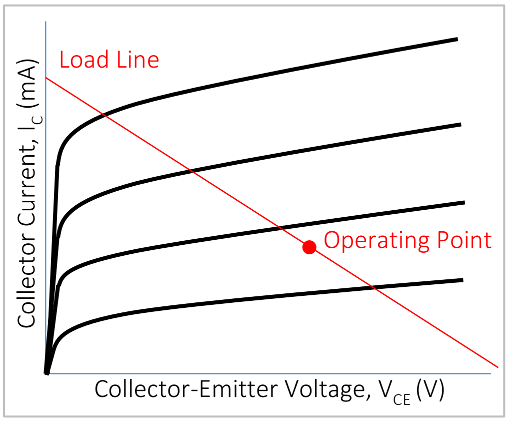

Figure 4: Output characteristics graph.

The output characteristic of a BJT is the relationship between the output current and output voltage with a constant input current. In *figure 4*, each of the lines represent different values of the base current, I_B.

The inverse gradient of the load line around the operating point is the output resistance, *r*out, in Ohms (Ω). [6]

$$r_{out} = \frac{V_{CE}}{I_C} = \frac{Collector - Emitter\ Voltage\ (V)}{Collector\ Current\ (A)}$$

The current gain, β (= *h*fe at low frequencies) can be calculated from the output characteristics graph by finding the change in the collector-current between a few of the lines representing different values of the base-current.

$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{Collector\ Current\ (A)}{Base\ Current\ (A)}$$

Transfer Characteristics:

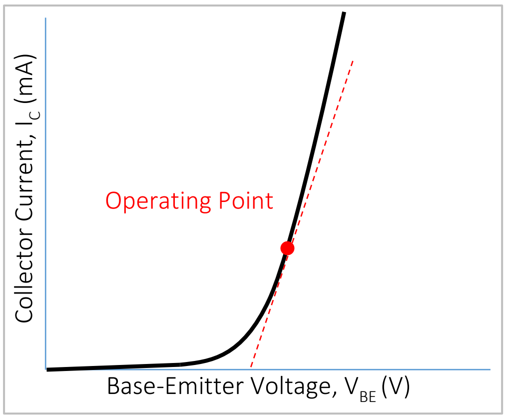

Figure 5: Transfer characteristics graph.

The transfer characteristic of a BJT is the relationship between the output current and the input voltage with a constant output voltage. From *figure 5*, the BJT only begins to conduct and allow current to flow when the base-emitter voltage is above the threshold (**0.7V**).

The **gradient** of the curve around the operating point is the **Transconductance**, g_m of the BJT, which is a measure of its gain (the greater the Transconductance, the greater the amplification is can provide).

$$g_m(Siemens, S) = \frac{I_C}{V_{BE}} = \frac{Collector\ Current\ (A)}{Base - Emitter\ Voltage\ (V)}$$

Alternatively, to calculate the Transconductance and current gain using technical data:

$$g_m = \frac{qI_C}{KT}$$

g_m = Transconductance, Siemens, S
q = Charge of an electron, Coulombs, C
I_C = Collector Current, Amps, A
K = Boltzmann Constant
T = Temperate, Kelvin, K

$$\beta = g_m \times r_{be}$$

β = Current gain
g_m = Transconductance, Siemens, S
r_{be} = Dynamic resistance, Ohms, Ω

Theoretical Data: *(The following data is taken from the manufacturers data sheet of the BJT (BC-549C)*

When the BJT is in its **active region,** at an ambient temperature of **298K** (25° C), the minimum and maximum **current gain, h_{fe} (=β at low frequencies)** is **450** and **900** respectively. Also, the potential barrier of the BJT is typically **0.62V**, so it should be expected to **start conducting** when V_{BE} between **0.62** and **0.7V**. [7]

Method:

Equipment:	Specification:	Equipment:	Specification:
NI Elvis Board (with software)	N/A	Oscilloscope (10:1 Probe)	N/A
Digital Multimeter (DMM)	+/- (0.05% reading + 0.015% range)	Function Generator	N/A
Handheld Multimeter x2	Precision: 0.01V	68kΩ + 7.32kΩ resistors.	Tolerance: +/-1%
15V DC Power Supply	Programming Accuracy: +/-0.25%	Electrical wire	N/A
Earphones (32Ω load)	32Ω impedance		

The first experiement yields the data needed to plot the output characterics:

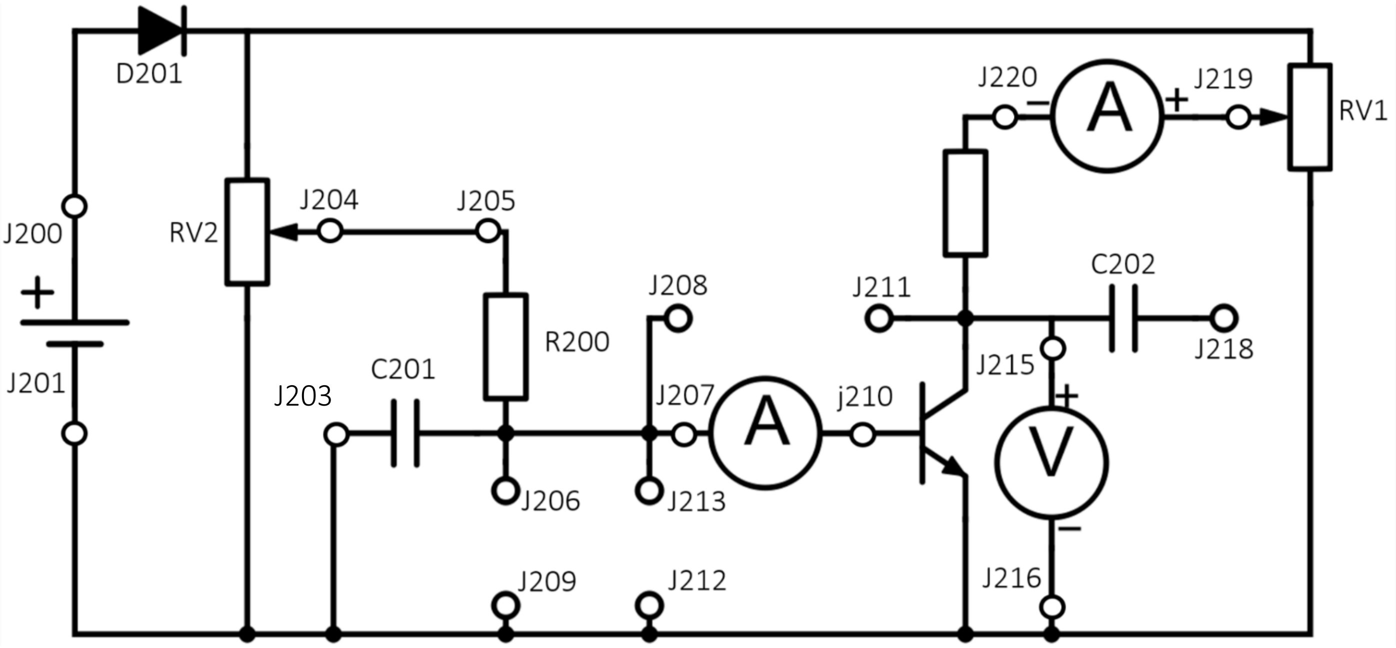

Figure 6: Output characteristics circuit.

To set up the NI Elvis board as in *figure 6*:

1) Connect a 15V DC power supply between the terminals J200 (+15V) and J201 and set the switch (SW200) to GND.
2) Connect together terminal J204 to J205 and terminal J203 to J201.
3) Connect a digital multimeter between terminals J207 and J210 to measure DC current (Base current, I_B) and set the range to 100μA.
4) Connect the NI Elvis digital multimeter between terminals J215 and J216 to measure DC voltage (collector – emitter voltage, V_{CE}) and set the range to 60V.
5) Connect a handheld multimeter between terminals J220 and J219 to measure DC current (collector current, I_C) and set the range to 20mA.

I_B (μA)	V_{CE} (V)	I_C (mA)
5	0	
5	0.05	

I_B (μA)	V_{CE} (V)	I_C (mA)
10	0	
10	0.05	

Figure 7: Example data tables.

6) Construct data tables such as in *figure 7* for different values of I_B ranging from 5μA to 30μA in steps of 5μA.
7) Use RV1 and RV2 to keep the current I_B constant and adjust V_{CE} to a range of values from 0V to 10-13V, starting with many small increments such as 0V to 0.05V to get an accurate graphical representation of the data.
8) Repeat step 7 for each of the different values of I_B record data into the different tables.

The second experiment yields the results needed to plot the input and transfer characteristics:

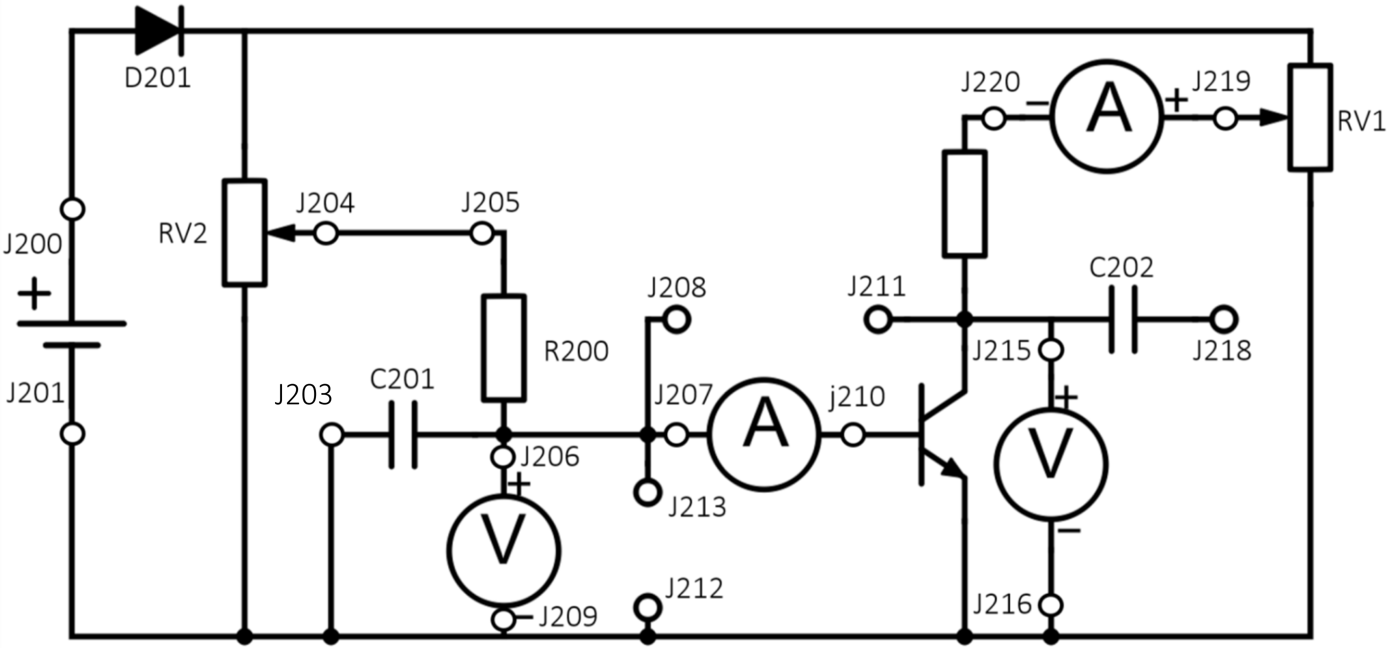

Figure 8: Input & Transfer characteristics

To set up the NI Elvis board as in *figure 8*:

1) Connect a 15V DC power supply between the terminals J200 (+15V) and J201 and set the switch (SW200) to GND.
2) Connect together terminal J204 to J205 and terminal J203 to J201.
3) Connect a digital multimeter between terminals J207 and J210 to measure DC current (Base current, I_B) and set the range to 100µA.
4) Connect the NI Elvis digital multimeter between terminals J206 and J209 to measure DC voltage (base – emitter voltage, V_{BE}) and set the range to 1V.
5) Connect a handheld multimeter between terminals J220 and J219 to measure DC current (collector current, I_C) and set the range to 20mA.
6) Connect a second handheld multimeter between terminals J215 and J216 to measure DC voltage (collector – emitter voltage, V_{CE}) and set the range to 20V.

I_C (mA)	V_{CE} (V)	I_B (µA)	V_{BE} (mV)
0	2.5		
0.1	2.5		

Figure 9: Example data tables.

7) Construct data tables such as in *figure 9* for different values of I_C ranging from 0mA to 13mA, with smaller increments in the 0mA to 1mA region to get a more accurate graphical representation at the point of interest.
8) Use RV1 to keep V_{CE} constant at 2.5V and use RV2 to adjust V_{BE} to achieve the I_C value stated in the table in *figure 9*.
9) Measure values of I_B and V_{BE} that for each set of I_C and V_{CE} values and record data in the table in *figure 9*, but allow some time for the readings to settle after making adjustments.

Before moving onto further experiments, small signal parameters need to be calculated.

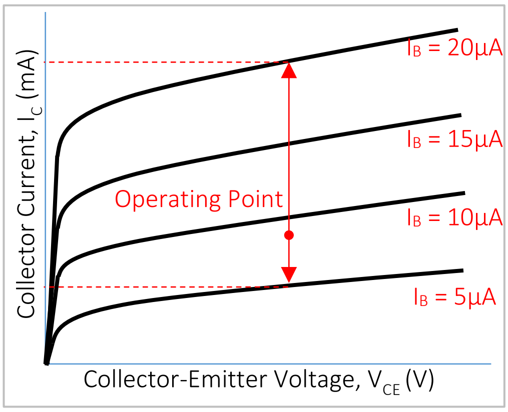

Figure 10: Current Gain calculation example.

1) Plot the **output** (I_C against V_{CE}), **input** (I_B against V_{BE}), and **transfer** (I_C against V_{BE}) characteristics graphs.
2) On the **output characteristics** graph mark the point V_{CE} = 14.3V, I_C = 0mA and the point V_{CE} = 7.5V, I_C = 5mA (this is the operating point). Draw a straight line through both these points, this is the load line.
3) Calculate the inverse gradient of this line to calculate the **output resistance, r_{out}** and then calculate the **current gain, β**, by measuring the change in the collector current, I_C, between several lines of I_B at the operating point (*figure 10 demonstrates this).*
4) Calculate the gradient of the tangent at the operating point on the **transfer characteristics** graph, which represents the **Transconductance, g_m**, of the BJT.
5) Calculate the gradient of the tangent at the operating point on the **input characteristics** graph, which represents the dynamic resistance, r_{be}.
6) To estimate the small signal circuit **voltage gain** of the BJT, find the change in I_C along the load line about the operating point for a small change in V_{CE} using the **output characteristics** graph. Then, using the **transfer characteristics** graph, find the change in V_{BE} that corresponds to the change in I_C about the operating point.
   Finally use the equation $\frac{V_{CE}}{V_{BE}}$ to calculate the voltage gain.

The third experiment investigates the use of the BJT as an audio amplifier.

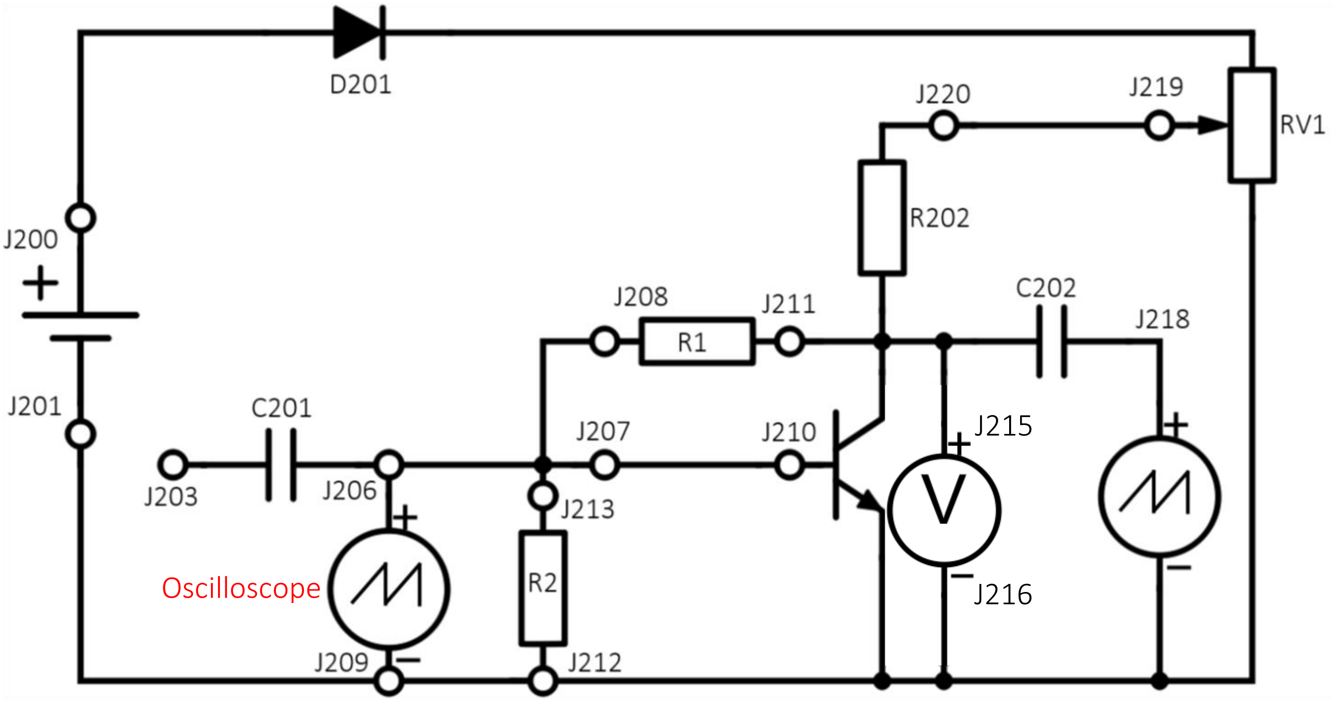

Figure 11: Audio amplifier circuit.

To set up the NI Elvis board as in *figure11*:

1) Connect a 15V DC power supply between the terminals J200 (+15V) and J201 and set the switch (SW200) to GND.
2) Connect together terminal J207 to J210.
3) Connect a 7.32kΩ (R2) resistor between terminal J212 and J213 then connect a 68kΩ (R1) resistor between terminal J208 and J211.
4) Connect the **sync out** terminal on the function generator to the **trig input** terminal and set the oscilloscope trigger to **external**.
5) Connect a calibrated 10:1 between J203 and ground, and another between J218 and ground to measure V_{in} and V_{out} respectively. Also connect a digital multimeter between J215 and J216 to measure V_{CE}.
6) Inject a 2V pk-pk, 10kHz sine wave between J203 and ground.
7) Set **V_{CE}** to **7.5V** using **RV1**. Measure and record V_{in} and V_{out}, then connect the **32Ω load** (earphones) at J218 and measure and record V_{in} and V_{out} again. Calculate the **gain** for both of these conditions.

Calculations:

Output resistance, r_{out}, from **output characteristics** = $\frac{\Delta V_{CE}}{\Delta I_C} = \frac{14.3}{10.5\times10^{-3}} = 1.362\ k\Omega$

Current gain, β, from the **output characteristics** = $\frac{\Delta I_C}{\Delta I_B} = \frac{10\times10^{-3}-3.18\times10^{-3}}{15\times10^{-6}-5\times10^{-6}} = 682$

Calculated Transconductance at **25°C** and I_C at **5mA** = $\frac{q\times I_C}{k\times T} = \frac{1.6\times10^{-19}\times5\times10^{-19}}{1.38\times10^{-23}\times(25+273)} = 0.1945\ S$

Measured Transconductance, g_m, from the **transfer characteristics** = $\frac{I_C}{V_{BE}} = \frac{12.6\times10^{-3}}{0.695-0.626} = 0.1826\ S$

Calculated **minimum** input resistance, r_{be} = $\frac{\beta}{g_m} = \frac{450}{0.1945} = 2.314\ k\Omega$

Calculated **maximum** input resistance, r_{be} = $\frac{\beta}{g_m} = \frac{900}{0.1945} = 4.267\ k\Omega$

Measured input Resistance, r_{be}, from the **input characteristics** = $\frac{\Delta V_{BE}}{\Delta I_B} = \frac{226.5\times10^{-6}}{0.695-0.6305} = 2.745\ k\Omega$

Predicted AC voltage gain with **no load** from the **output + transfer characteristics** = $\frac{V_{CE}}{V_{BE}} = \frac{2}{8.12\times10^{-3}} = 246.31$

Measured AC Voltage gain with **no load** = $\frac{V_{out}}{V_{in}} = \frac{2}{12.7\times10^{-3}} = 157.48$

Measured AC Voltage gain with **32Ω load** = $\frac{V_{out}}{V_{in}} = \frac{137\times10^{-3}}{42\times10^{-3}} = 3.26$

Results:

Output characteristics:

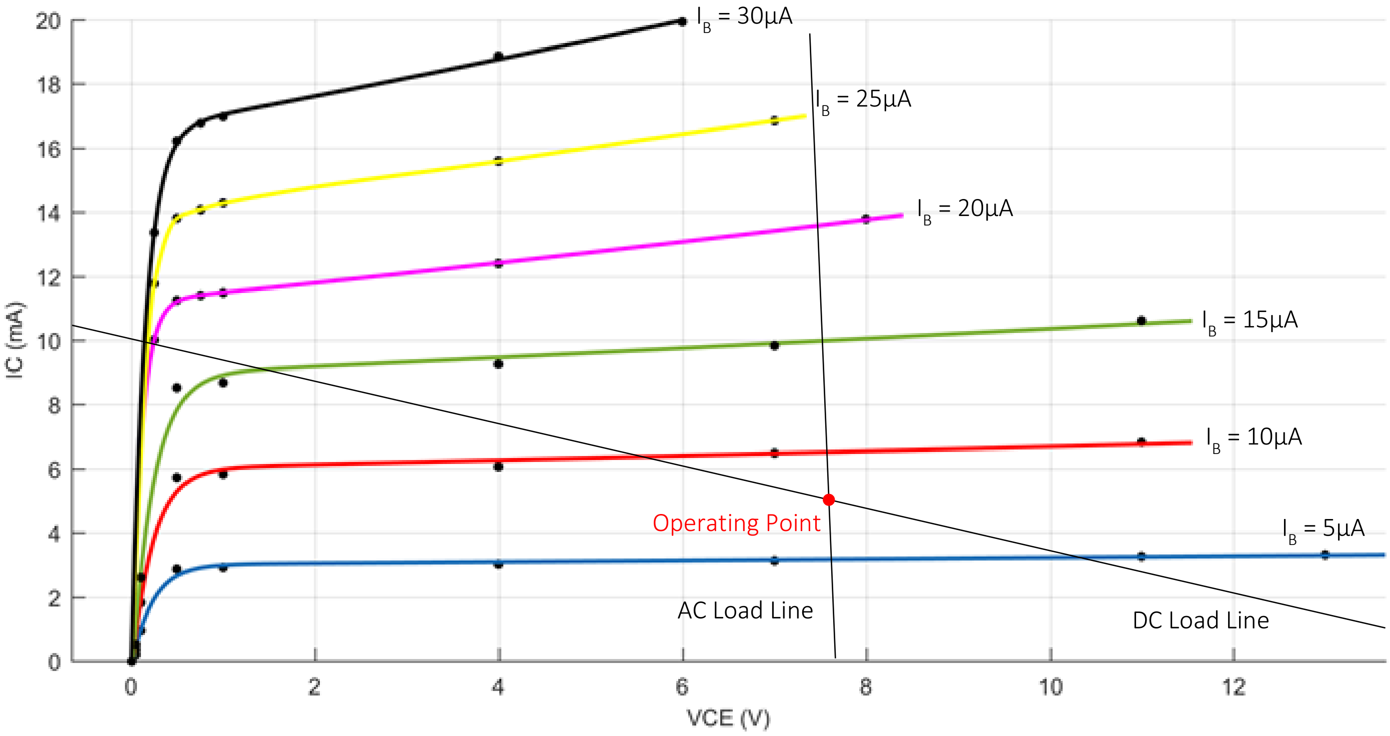

Figure 12: Output Characteristics Graph.

As seen in *figure 12*, as V_{CE} initially increases above 0V, I_C increases rapidly before levelling off. The region before I_C levels off is the **saturation region**, and after this region, it can be seen that I_C is essentially independent of V_{CE}, and is proportional to I_B, which is the **active region**. This is exactly how the BJT was expected to behave.

The operating point can also be seen at **V_{CE}=7.5V**, **I_C=5mA**, with the **DC load line** and **AC / dynamic load line** intersecting it. It can be observed that the **AC load line** has a much steeper gradient compared to the **DC load line**, which is due to a **32Ω load** being applied at the output. When the load is applied, the amplifier considers it to be in **parallel** with the **output resistance** of **1.362kΩ** at the collector, hence resulting is a big **reduction** in **output impedance** and therefore a much **lower voltage gain**. This is evident in the calculations of voltage gain before and after the 32Ω load is applied, **157.48** before and **3.26** after. This is what is expected to happen and is why impedance matching loads and amplifiers together in practice is very important to get the ideal behaviour.

Furthermore, the small signal **current gain, β**, calculated from the graph in *figure 12* was **682**, which is a suitable value since the lower and upper limit of the current gain from the manufactures data sheet is **450** to **900**.

Transfer Characteristics:

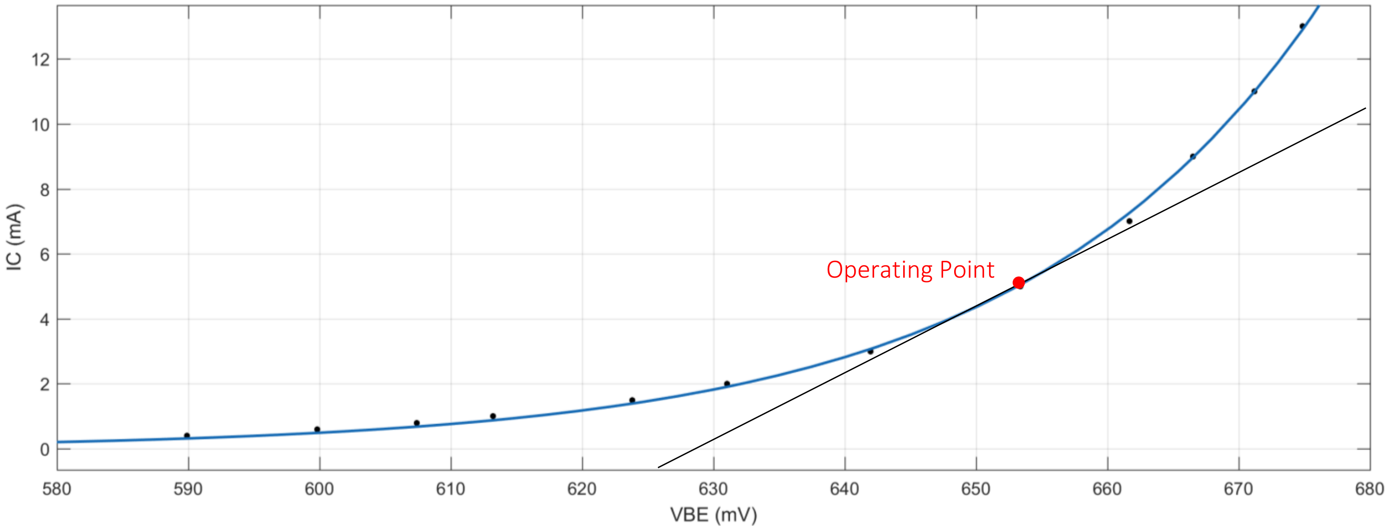

Figure 13a: Transfer Characteristics Graph.

As seen in *figure 13b,* the BJT does not appear to conduct initially and I_B remains zero as V_{CE} initially increases. However, upon closer inspection of the region where the base current I_B begins to increase in *figure 13a,* is can be seen that the BJT begins to **conduct** between **0.63V** and **0.66V**, which are in the correct region when comparing to the stated **0.62V** to **0.7V** conduction voltage in the data sheet.

Furthermore, the **transconductance** around the **operating point** by taking the gradient of the curve gave a result of **0.1826 S** compared to the theoretical value of **0.1945 S.**

Both these measured results are very similar to their theoretical counterparts, therefore the BJT worked exactly as predicted in this part of the experiment.

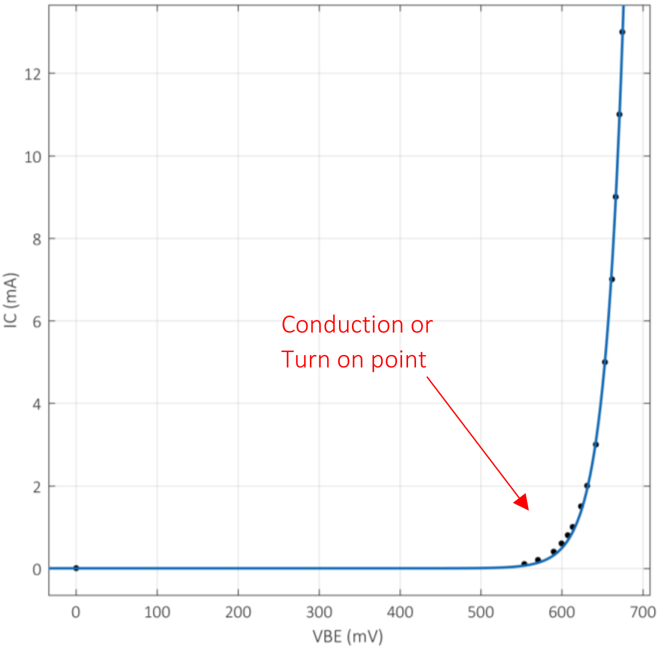

Figure 13b: Transfer Characteristics Graph.

Input Characteristics:

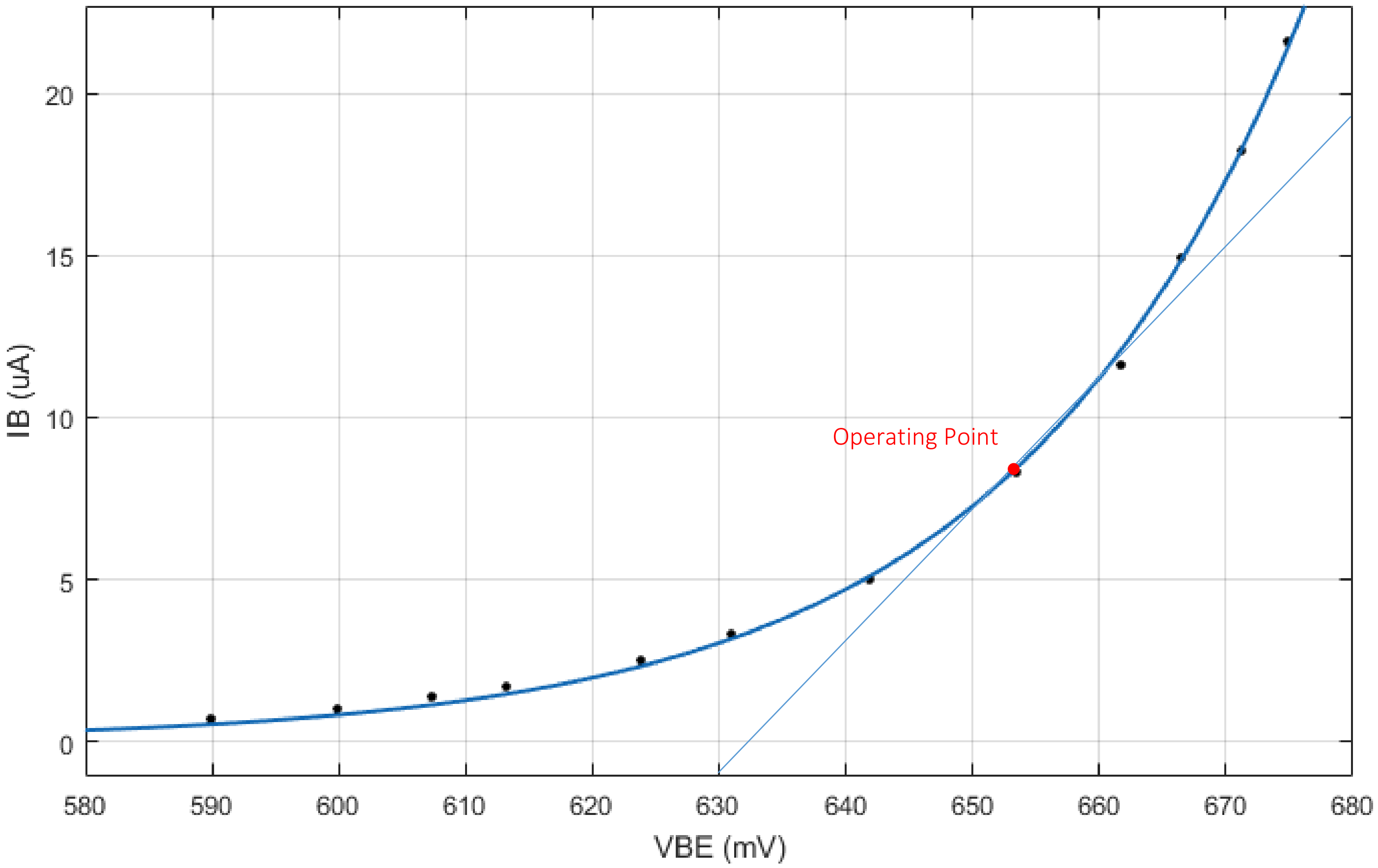

Figure 14a: Input Characteristics Graph.

As seen in *figure 14b,* similar to *figure 13b*, the BJT does not conduct until V_{BE} is between **0.63V** and **0.66V** and that it also follows the same shape as the transfer characteristics graph, indicating that I_B **is proportional** to I_C in the **active region** as predicted.

Furthermore, calculating the gradient of this curve in *figure 14b* about the operating point shows that the input resistance is **2.756kΩ**, which is between the calculated **minimum** and **maximum** input resistances, **2.314kΩ** and **4.267kΩ** respectively.

The **relative phase difference** between the input and output signal was **179.9°**, which is almost exact to the theoretical **180°** value.

Lastly, the **voltage gain** with no load, calculated from the output and transfer characteristics graph gave a gain of **157.48** compared to the calculated theoretical value of **246.31.** The reasons behind this value not being close to its theoretical value are expressed in the error analysis.

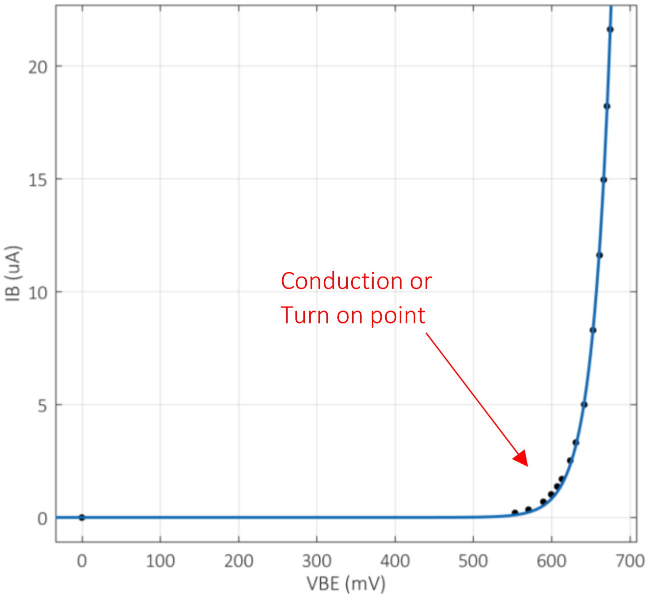

Figure 14b: Input Characteristics Graph.

Discussion:

Characteristics:

This experiment successfully obtained the data needed to construct the characteristic graphs needed, with all of them showing the predicted shape. Also, the accuracy of these graphs was evident through physical calculations which could be compared to their predicted theoretical values.

Amplifier:

The experiment also successfully showed the working principles of how to use a BJT as an audio amplifier through the use of biasing and the theory behind the significance of the active region. Physical testing also enabled comparisons between calculated and theoretical data, while using the amplifier in different operating conditions such as applying a load shows how its characteristics and behaviour changes.

Error Analysis:

Possibly the most dominant reasoning behind errors during this experiment were to do with uncertainty within the testing equipment's, the conditions in which the experiment was conducted and human error.

Firstly, all of the equipment used in this experiment has a tolerance or certain precision to the accuracy of the data it is measuring. For example, the tolerances and precision in the equipment such as the DMM, oscilloscope and function generator and the tolerance of the resistors used (1%) can add up to produce minor but significant fluctuations in results.

Secondly, the conditions in which the BJT operates in, especially **temperature** can have a large impact on its characteristics, since BJT's are very temperature **sensitive**. For example, the ambient temperature of the surroundings when the BJT was tested from the manufacturers data sheet was **25°C**, so the results from the experiments described in this report may have some uncertainty compared to the datasheet because of different testing temperatures. One of the theoretical calculations in this experiment that is partly defined by temperature is transconductance ($g_m = q \times I_C / k \times T$), where even a **slightly change** in **temperature** can have a **big effect** on the output **results**. Asides from ambient temperatures, the internal temperature also causes **fluctuation**s in readings. In the experiments to calculate the characteristics graphs, it is recommended to **wait** after making changes to allow the measurements on the bench equipment settle. This is because **high currents** of I_C cause the internal materials to **heat up** every time its value is adjusted. Allowing the BJT to **settle** allows this heat to **dissipate** and for the BJT to return to a steady state, hence providing more **accurate data**.

Lastly, **human error** could have also had an effect on the accuracy and reliability of the recorded data and measurements. The major human error that may have caused some **uncertainty** in these experiments is **not taking enough data points** when measuring the data needed to construct the characteristics graphs. This could cause the **trend line** to not be accurate which when calculating the gradient and other parameters will give **inaccurate data**.

In conclusion, the aims of the experiment were understood as well that the ability to apply the theory and techniques used in other applications. Furthermore, the results yielded have been proven to be accurate by comparing them to theory and the reasons behind uncertainty in the data have been addressed.

References:

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Appendix:

Data tables from output characteristics graph in *figure 12.*

Table 1

IB (µA)	VCE	IC (mA)
5	0.00	0.00
5	0.05	0.19
5	0.10	0.95
5	0.50	2.87
5	1.00	2.91
5	4.00	3.02
5	7.00	3.14
5	11.00	3.26
5	13.00	3.31

Table 2

IB (µA)	VCE	IC (mA)
10	0.00	0.00
10	0.05	0.35
10	0.10	1.82
10	0.50	5.73
10	1.00	5.83
10	4.00	6.07
10	7.00	6.47
10	11.00	6.82

Table 3

IB (µA)	VCE	IC (mA)
15	0.00	0.00
15	0.05	0.52
15	0.10	2.60
15	0.50	8.52
15	1.00	8.67
15	4.00	9.25
15	7.00	9.84
15	11.00	10.62

Table 4

IB (µA)	VCE	IC (mA)
20	0.00	0.00
20	0.25	10.01
20	0.50	11.25
20	0.75	11.39
20	1.00	11.48
20	4.00	12.40
20	8.00	13.77

Table 5

IB (µA)	VCE	IC (mA)
25	0.00	0.00
25	0.25	11.77
25	0.50	13.81
25	0.75	14.08
25	1.00	14.27
25	4.00	15.58
25	7.00	16.85

Table 6

IB (µA)	VCE	IC (mA)
30	0.00	0.00
30	0.25	13.36
30	0.50	16.23
30	0.75	16.77
30	1.00	16.97
30	4.00	18.86
30	6.00	19.93

Data table from the input and transfer characteristics graphs in *figure 13* and *figure 14.*

Table 7

IC (mA)	VCE (V)	IB (µA)	VBE (mV)
0.0	2.5	0.00	0.03
0.1	2.5	0.20	553.62
0.2	2.5	0.35	570.54
0.4	2.5	0.70	589.91
0.6	2.5	1.02	599.83
0.8	2.5	1.36	607.41
1.0	2.5	1.69	613.21
1.5	2.5	2.51	623.82
2.0	2.5	3.32	631.02
3.0	2.5	4.99	641.95
5.0	2.5	8.30	653.38
7.0	2.5	11.62	661.69
9.0	2.5	14.95	666.50
11.0	2.5	18.21	671.19
13.0	2.5	21.61	674.84