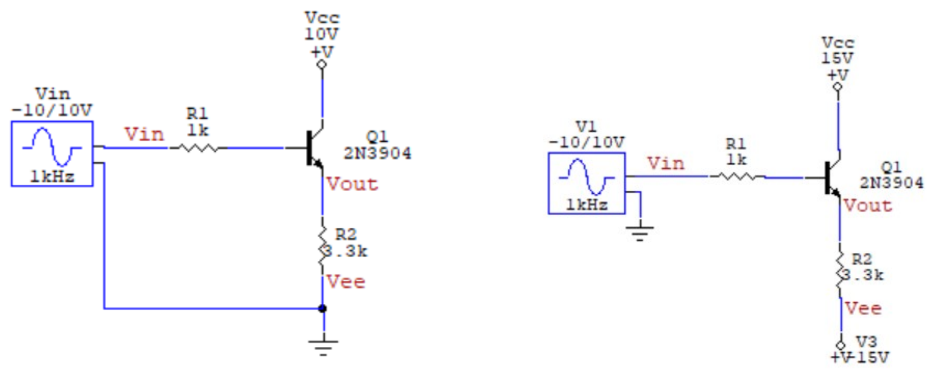
De Silva, CK
Geraldez, Lyle Kenneth
[AppPhysics 181]: Activity 5: Transistors

Objectives

1. To construct the different transistor configurations and compare the experimental gains from theoretical ones
2. To experimentally confirm the Ebers-Moll equation at room temperature conditions

Solution Proper

1. Application 1: **Emitter Follower Circuit**



(a) Circuit 1.1 (b) Circuit 1.2

Figure 1: Circuits 1

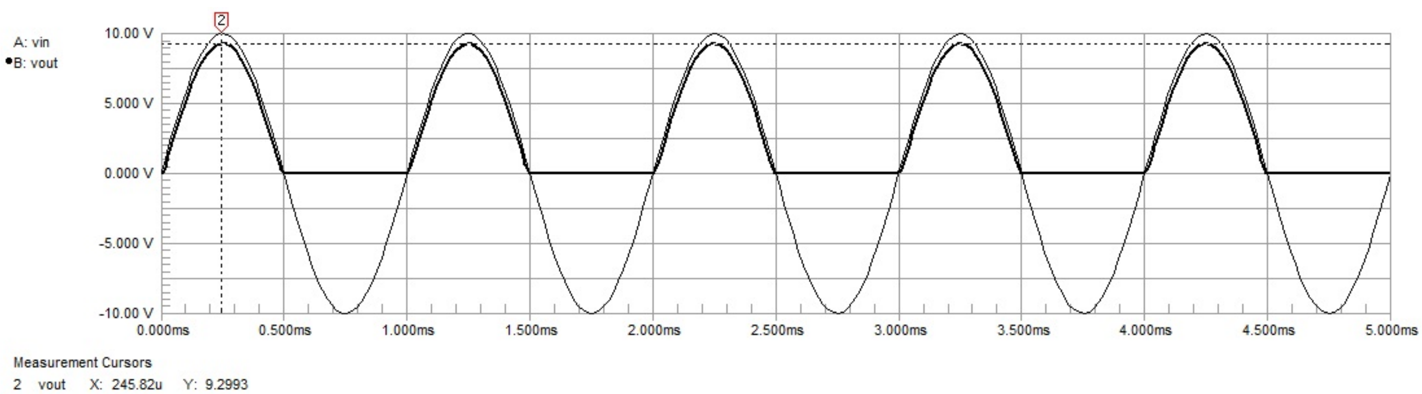


Figure 2: Input waveform (lighter curve) and output waveform (darker curve of Circuit 1.1

The circuit is an Emitter Follower Circuit. The input waveform is a 10 kHz sine wave with 10V amplitude. The resulting output waveform is truncated sine wave which behaves like a normal 10kHz sine wave in its positive half-cycle (albeit having a voltage drop to 9.3V), but is 0V in its negative half-cycle.

It can be observed the the positive half-cycle of the output waveform is similar to that of Circuit 1.1. However, for the negative half-cycle, it is no longer fixed at 0V but maintained the shape of the input sine waveform slightly shifted downwards. Since the peak-to-peak distance of the output waveform is approximately equal to the of the input waveform, the next effect of the circuit is a downward shift of the input waveform.

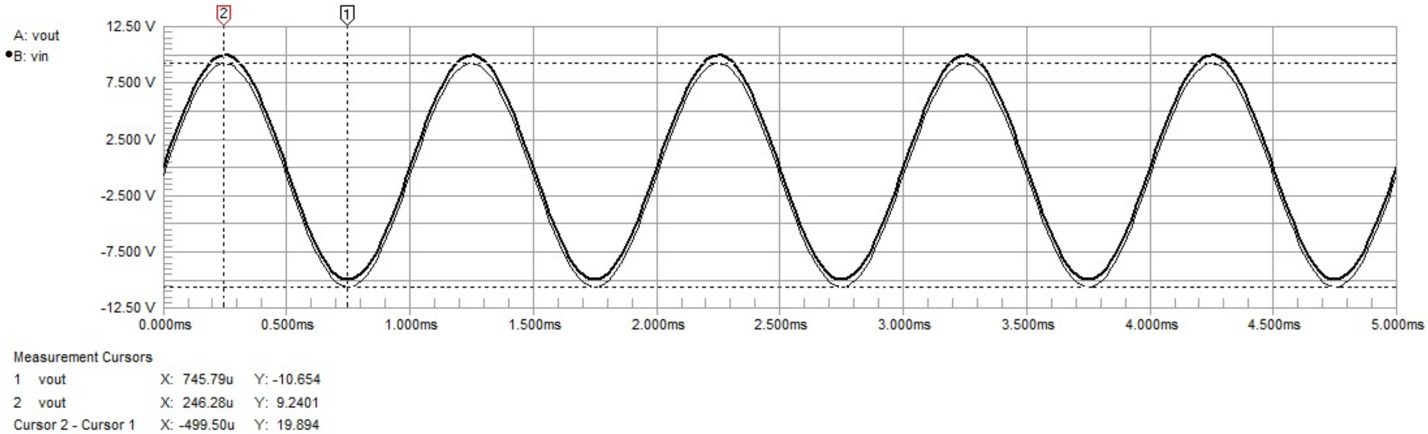


Figure 3: Input waveform (darker curve) and output waveform (lighter curve) of Circuit 2.1

2. Application 2: **Current Source**

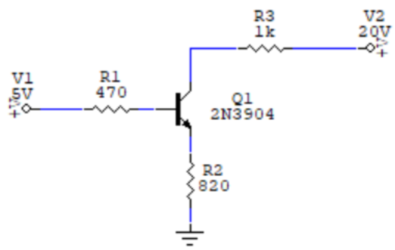


Figure 4: Circuit 2.1

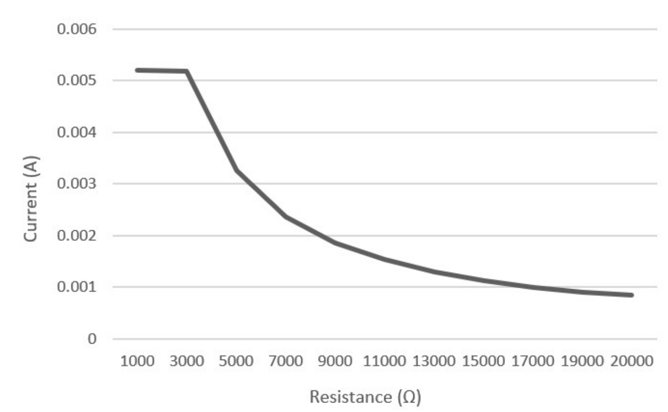


Figure 5: Resistance vs current plot of Circuit 2.1 from 1 kΩ to 20 kΩ with 2Ω increment

The plot in Figure 6 shows that the current remains constant as you increase the resistance up the the 3kΩ point. At this point, it exponentially decreases as you increase the resistance.

Upon tinkering, the value of the "produced" current I_{load} remains constant whatever the value of `V1` is and only depends in the value of the load resistance `R3`, following Ohm's Law from this point. This means that this is an ideal current source, only dependent on whatever the resistance is connected to this circuit. The transistor responds to the change in the voltage and attempts to generate an impedance to provide the same current.

3. Application 3: **Inverting Amplifier**

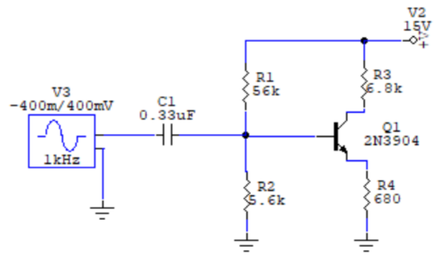


Figure 6: Circuit 3.1

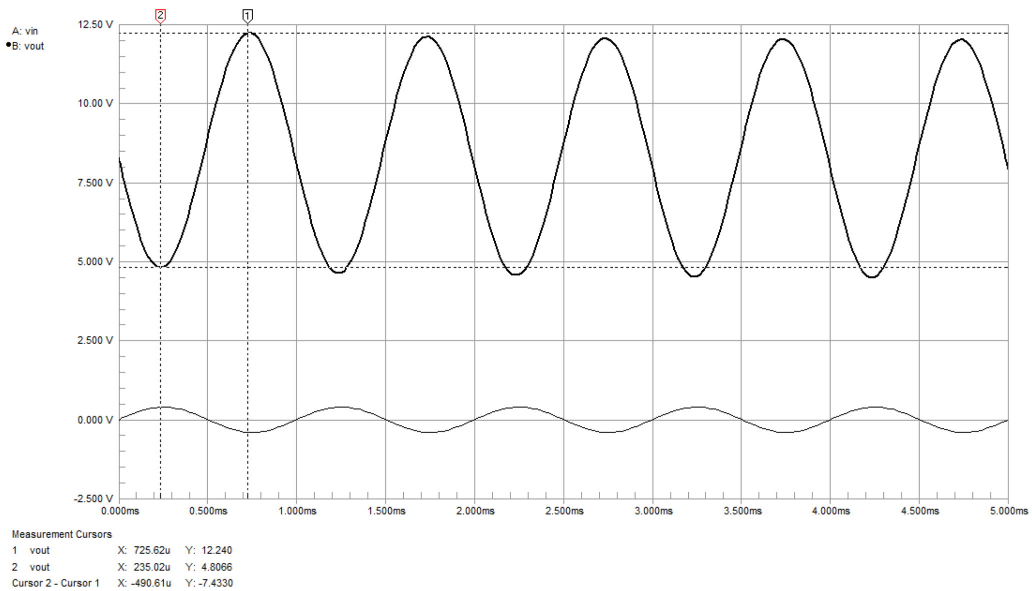


Figure 7: Input waveform (lighter curve) and output waveform (darker curve) of Circuit 3.1

From the plot of the input and output waveform in Figure 8, it can be observed the the troughs of the input waveform aligns with the crest of the output waveform. Hence, the is a 180° shifting of the output signal.

From the resistance value of the resistors in Circuit 3.1, $R_c = 6.8\ k\Omega$, $R_e = 0.68\ k\Omega$. Hence, the theoretical voltage gain is

$$A_{v,\text{th}} = \frac{R_c}{R_e} = \frac{6.8\ \text{k}\Omega}{0.68\ \text{k}\Omega} = 10$$

From the plot on Figure 8, the amplitude of the input waveform is 0.4 V while the output waveform is 3.72 V. Hence, the experimental voltage gain is

$$A_{v,\text{exp}} = \frac{3.72\ \text{V}}{0.4\text{V}} = 9.3$$

Comparing the experimental from the theoretical, the percent deviation is

$$\frac{10 - 9.3}{10} * 100\% = 7\%$$

4. Ground Emitter Amplifier

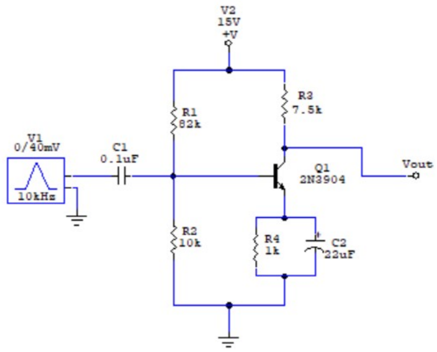


Figure 8: Circuit 4.1

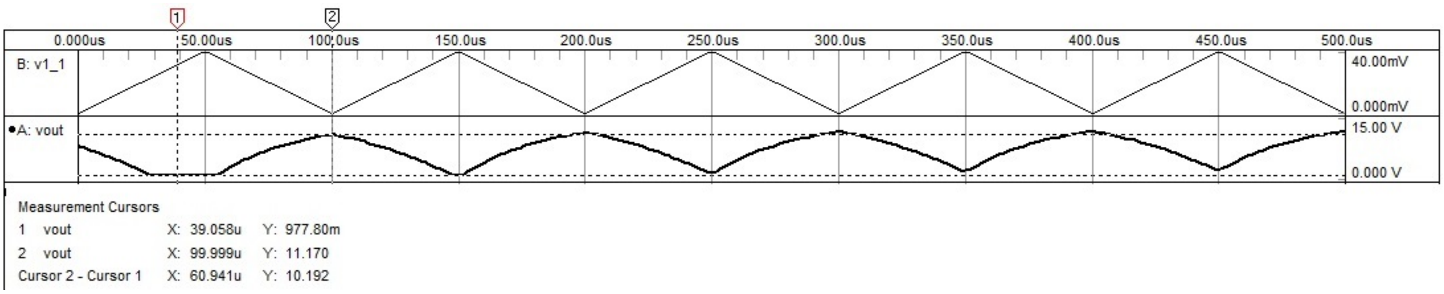


Figure 9: Input waveform (lighter curve) and distorted output waveform (darker curve) of Circuit 4.1

Figure 9 shows that the output waveform is a distorted barn-roof waveform with $V_{pp} = 10.1\text{V}$, 180° out-of-phase with the input triangle waveform. The distortion may be attributed to the inclusion of the capacitor. The capacitor introduces exponential, time-dependent modifications to the waveform which may explain the curviness of the output waveform. Moreover, since the triangle wave is a sum of different component harmonic waves, the capacitor also filters some of these harmonics introducing some distortions to the triangular shape.

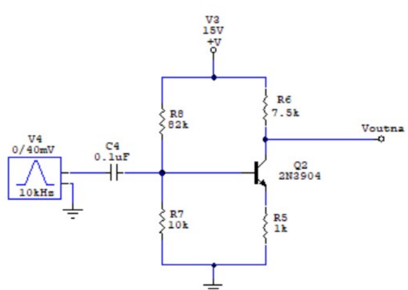


Figure 10: Circuit 4.2

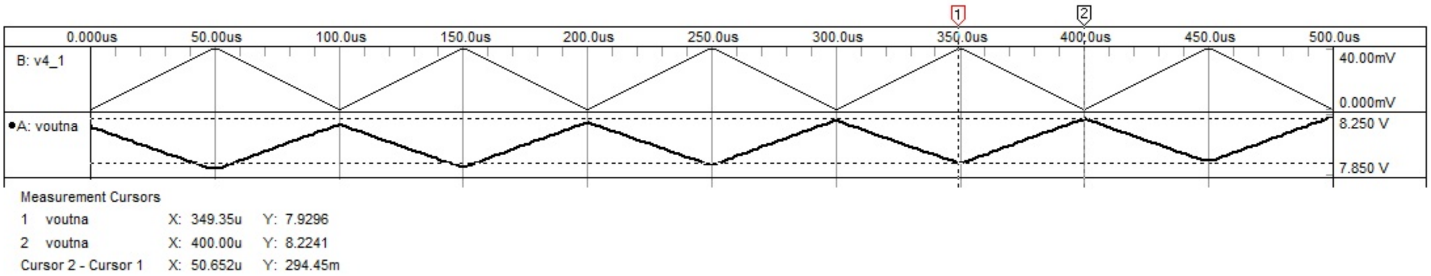


Figure 11: `Input waveform (lighter curve) and non-distorted output waveform (darker curve) of Circuit 4.2`

Figure 11 shows that the output waveform of Circuit 4.2 (circuit 4.1 with the capacitor removed) is a non-distorted version of the output waveform of circuit 4.1. The output waveform is an inverted triangular wave with $V_{pp} = 294.5\text{V}$. The removal of the capacitor also removed the barn-roof distortion associated with the reasons previously mentioned.

From the resistance value of the resistors in Circuit 4.2, $R_c = 7.5\ k\Omega$, $R_e = 1\ k\Omega$. Hence, the theoretical voltage gain is

$$A_{v,\text{th}} = \frac{R_c}{R_e} = \frac{7.5\ \text{k}\Omega}{1\ \text{k}\Omega} = 7.5$$

From the plot of the input and output waveform of Circuit 4.2 in Figure 10, the input amplitude is 40.000 mV while output amplitude is 294.45 mV. Hence, the experimental voltage gain is

$$A_{v,\text{exp}} = \frac{294.45\ \text{mV}}{40.000\ \text{mV}} = 7.44$$

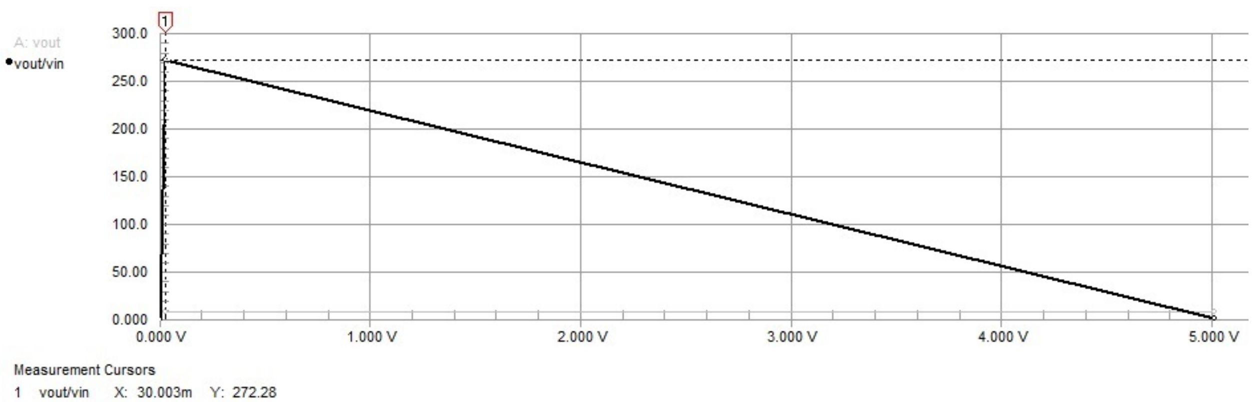


Figure 12: $\frac{V_{out}}{V_{in}}$ `DC sweep of Circuit 4.1`

From Figure 12, by plotting a $\frac{V_{out}}{V_{in}}$ vs V_{in} graph, we can find that the limit of the voltage gain $\frac{V_{out}}{V_{in}}$ as V_{in} approaches zero is $A'_{v,exp} = 272.28$. Meanwhile, the theoretical voltage gain at the quiescent point is calculated as follows. The base voltage V_b is found using the voltage divider equation

$$V_b = 15\text{V}\frac{10\text{k}\Omega}{10\text{k}\Omega + 82\text{k}\Omega} = \frac{75}{46}\text{V} \approx 1.63\text{V}$$

Since $V_{be} = V_b - V_e = 0.7\text{V}$, we get $V_e = V_b - 0.7\text{V} = 1.63\text{V} - 0.7\text{V} = 0.93\text{V}$. From Ohm's law,

$$I_e = \frac{V_e}{R_e} = \frac{0.93\text{V}}{1\text{k}\Omega} = 9.3 \times 10^{-4}\text{A}$$

For small base current I_b, $I_c \approx I_e = 9.3 \times 10^{-4}\text{A}$. Using the equation for transconductance: $g_m = \frac{I_c}{V_t}$, where the thermal voltage $V_t = 26\text{mV}$,

$$g_m = \frac{I_c}{V_t} = \frac{9.3 \times 10^{-4}\text{A}}{26\text{mV}} = 0.036\ \Omega^{-1}$$

Since $r_e = \frac{1}{g_m} = \frac{1}{0.036\ \Omega^{-1}} = 27.96\Omega$, the theoretical gain is, then, $A'_{v,th} = \frac{R_c}{r_e} = \frac{7.5\times10^3\Omega}{27.96\Omega} = 268.27$ with percent deviation

$$\frac{272.28 - 268.27}{268.27} * 100\% = 1.64\%$$

5. Ebers-Moll Equation

The Ebers-Moll equation is given by:

$$I_C = I_S\left(\exp\left[\frac{V_{BE}}{V_T}\right] - 1\right) \approx I_S \exp\left[\frac{V_{BE}}{V_T}\right] \tag{1}$$

By taking the logarithm of of the entire equation with the approximation, Equation 1 takes the form of a linear equation, having V_{BE} as the independent variable of $\ln I_C$ as seen in Equation 2.

$$\ln I_C \approx \ln I_S + \frac{V_{BE}}{V_T} \tag{2}$$

To test the Ebers-Moll equation. the circuit below was utilized, which allows the measurement of both V_{BE} and I_C by tinkering the resistance `Ro`. This experiment used the `Ro` values of 4.7 M-, 1 MΩ, 470 kΩ, 100 kΩ, 47 kΩ.

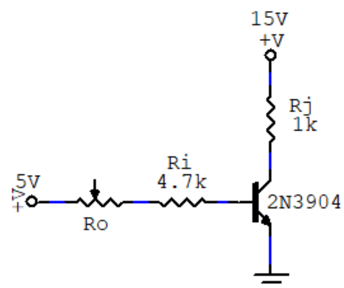


Figure 13: `Circuit 5.1`

Repeated measurements gave the data below:

Table 1: Raw Data of Experiment 5.5.1

Index	`Ro` [Ω]	V_{BE} [V]	I_C [A]
a	4.700E6	571.8E-3	63.77E-6
b	1.000E6	624.4E-3	478.7E-6
c	470.0E3	648.8E-3	1.194E-3
d	100.0E3	695.9E-3	6.009E-3
e	47.00E3	717.0E-3	11.06E-3

Plotting the values of V_{BE} and $\log I_C$:

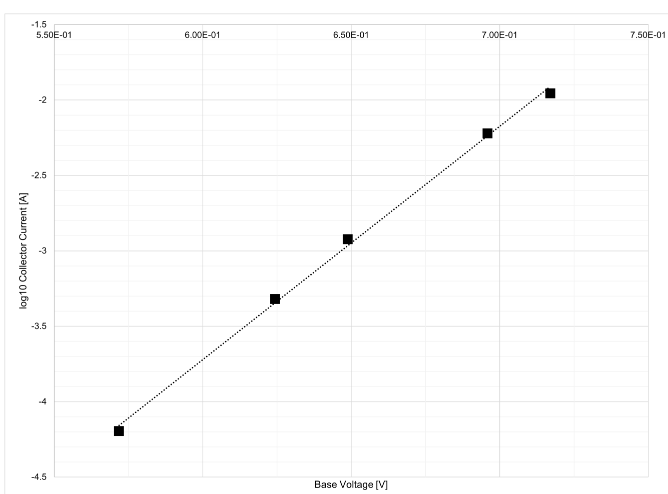


Figure 14: $V_{BE} \times \log I_C$, scaled

Quick statistical analysis found that the correlation coefficient (PPMCC) between V_{BE} and $\ln I_{\mathrm{C}}$ is $r = +0.9990$, indicating a definitive linear relationship between the variables of interest. The other essential statistical variables can be found in the table below.

Table 2: Essential Statistical Variables of Experiment 5.5.1

	V_{BE}	$\ln I_{\mathrm{C}}$
mean (μ)	0.65158	-2.9231517
st.dev (σ)	0.0577827136	0.8949385899
ppmcc	+0.9990358093	

Using the same correlation coefficient and the means and deviation for the data sets, the slope and the intercept were calculated as shown below. Dimensional analysis reveals that the value of m and b, while being essentially unitless in the calculations, has to have the units of volts and amperes, respectively to preserve the measured values.

$$\begin{aligned} m &= r\frac{\sigma_{V_{\mathrm{BE}}}}{\sigma_{\ln I_{\mathrm{C}}}} \quad [\mathrm{V}] \\ &= 0.9990358093 \cdot \frac{0.0577827136}{0.8949385899} \quad [\mathrm{V}] \\ &= 15.47306524 \quad [\mathrm{V}] \end{aligned} \qquad \begin{aligned} b &= \mu_{\ln I_{\mathrm{C}}} - m\mu_{V_{\mathrm{BE}}} \\ &= -2.9231517 - (15.47306524)(0.65158) \\ &= -13.00509155 \end{aligned} \tag{3}$$

Thus, the best fit line is:

$$y = (15.47306524\ [\mathrm{V}^{-1}])x - 13.00509155 \tag{4}$$

Comparing the coefficients of Equation 4 to Equation 2, the experimental values for the V_{T} and I_{S}, respectively.

$$\begin{aligned} \ln I_{\mathrm{C}} &\approx \ln I_{\mathrm{S}} + \frac{1}{V_{\mathrm{T}}} V_{\mathrm{BE}} \\ y &\equiv (b = \ln I_{\mathrm{S}}) + (m = \frac{1}{V_{\mathrm{T}}})x \end{aligned}$$

$$\begin{aligned} b &= \ln I_{\mathrm{S}} \\ \ln I_{\mathrm{S}} &= -13.00509155 \\ I_{\mathrm{S}} &= 2.24885008_E\text{-}6\ [\mathrm{A}] \\ I_{\mathrm{S}} &\approx 2.249\ [\mu\mathrm{A}] \end{aligned} \qquad \begin{aligned} m &= \frac{1}{V_{\mathrm{T}}} \\ \frac{1}{V_{\mathrm{T}}} &= 15.47306524 \\ V_{\mathrm{T}} &= 64.62843558_E\text{-}3\ [\mathrm{A}] \\ &\approx 64.63[\mathrm{mV}] \end{aligned} \tag{5}$$

Since it is known that the theoretical value of V_{T} is 60 [mV], the percent error is between 7-8%.

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To proceed with the analysis of the current gain β against the resistance `Ro`, the base voltages I_B for the same values of `Ro` were measured in `Circuit 5`.

The collected and calculated data were shown in Table 3.

Index	`Ro` [Ω]	I_B [A]	I_C [A]	β
a	4.700E6	941.2E-9	63.77E-6	67.76
b	1.000E6	4.355E-6	478.7E-6	109.9
c	470.0E3	9.166E-6	1.194E-3	130.2
d	100.0E3	41.11E-6	6.009E-3	146.2
e	47.00E3	82.84E-6	11.06E-3	133.5

Table 3: Measured and Collected Values for Experiment 5.5.2

Plotting these values:

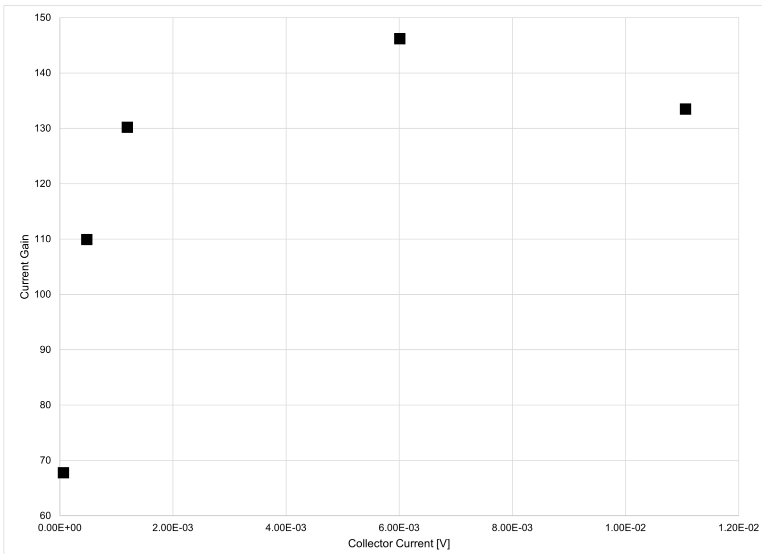

Figure 15: Collector Current $I_C \times$ Current gain β, scaled

The graph shows a graph a quick log-like increase and then a gradual die-down. In Figure 15, the plot peaked at the fourth point (index d); this is because when `Ro` is 100E3, the exponential increase of I_C intersected with the movement of the I_B.