Lab 1 – Device Characterization and Biasing Circuits

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ELECENG 3EJ4 – Electronic Devices and Circuits II

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Part 1: DC Characterization of an NPN-BJT 2N3904

A) SPICE Simulation

1.1

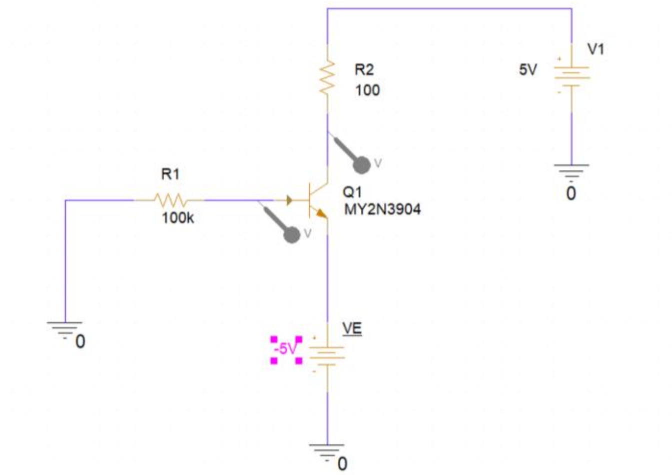


Figure 1: PSpice schematic diagram used to characterize a NPN-BJT 2N3904

1.2

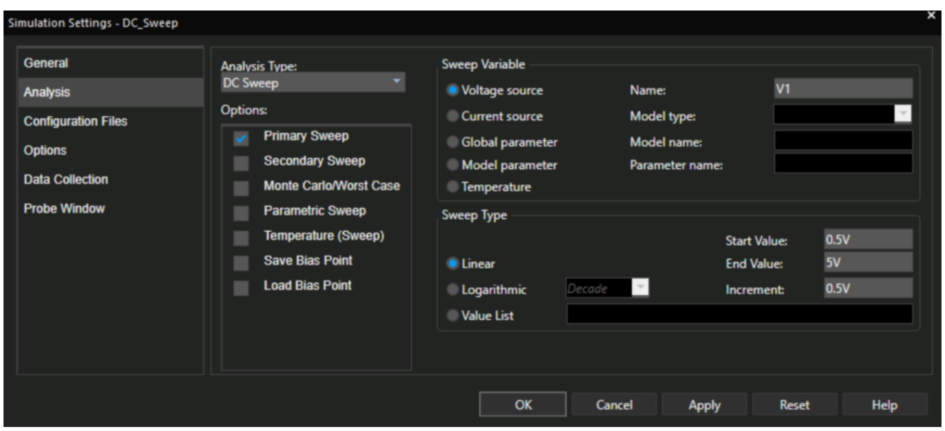


Figure 2: PSpice simulation settings used for DC sweep

1.3: The V_A represents the early voltage which is a measure of the output resistance of a BJT in the active region. By observing the definition of V_A in Fig. 6.18 of the textbook, I was able to calculate the V_A from the I_C vs. V_{CE} plot in excel using the equation of the trendline to solve for the intercept by setting $I_C = 0$:

$$I_C = mV_{CE} + b$$

$$0 = mV_{CE} + b$$

$$V_{CE} = -\frac{b}{m} \quad => \quad V_A = \frac{b}{m}$$

B) AD3 Measurement

1.5

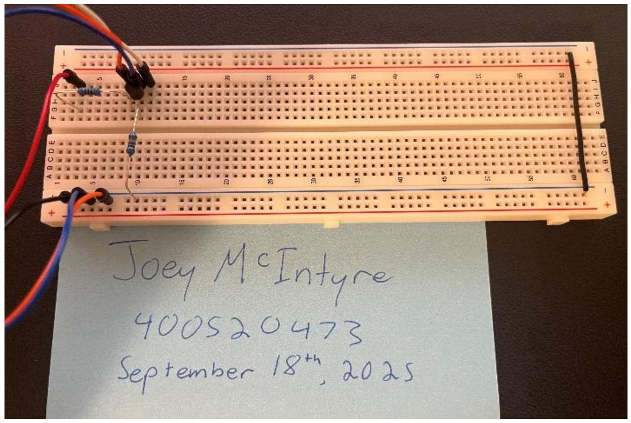


Figure 3: Experimental setup for the DC characterization of an NPN-BJT 2N3904

C) Questions for Part 1

For the NPN-BJT 2N3904 characterized, if we want to bias this device to conduct a collector current $I_C \approx$ 1.0 mA at the lowest V_{CE} value, answer the following questions.

Q1. (7 Points): Based on the simulated data in Steps 1.2-1.4, use the bias condition giving the closest I_C value to the desired collector current, find out:

V+ (VCC)	V- (VE)	V(Q1C) (Volt)	V(Q1B) (Volt)	VCE (Volt)	VBEon (Volt)	RC (ohm)	RB (ohm)	IC (A)	IB (A)	β = IC/IB	|VA| (V)	ro=VA/IC	gm = IC/25mV	rπ = 25mV/IB
0.5	-1.5	0.397558296	-0.878689331	1.898	0.621	100	1.00E+05	1.02E-03	8.79E-06	117	1000	9.76E+05	4.10E-02	2845

Figure 4: Closest I_C to 1.0 mA at the lowest V_{CE} Value

(1) What are the simulated V_{BEon} in volts and the base current I_B in μA?

$$V_{BEon} = 0.621\ V\ , I_B = 8.79 * 10^{-6}\ A = 8.79\ \mu\text{A}$$

(2) What is the $\beta = I_C/I_B$ value at this I_C?

$$\beta = \frac{I_C}{I_B} = 117$$

(3) What is the early voltage $|V_A|$ in volts?

$$|V_A| = 1000\ V$$

(4) What is the output resistance r_o in kΩ?

$$r_o = \frac{V_A}{I_C} = 9.76 * 10^5\ \Omega = 976\ \text{k}\Omega$$

(5) What is the transconductance g_m in mS?

$$g_m = \frac{I_C}{25mV} = 4.10 * 10^{-2}\frac{A}{mV} = 41\ mS$$

(6) What is the input resistance r_π in kΩ?

$$r_\pi = \frac{25mV}{I_B} = 2845\frac{mV}{A} = 2.845\ k\Omega$$

Q2. (8 Points): Based on the measured data in Step 1.8, use the same bias condition found in Q1 (or the first reliable data if that bias condition is an outlier), find out:

V+ (VCC)	V- (VE)	Channel 1 (VC)	Channel 2 (VB)	VCE (Volt)	VBEon (Volt)	RC (ohm)	RB (ohm)	IC (A)	IB (A)	β = IC/IB	|VA| (V)	ro=VA/IC	gm = IC/25mV	rπ = 25mV/IB
0.5	-1.5	0.37864	-0.82464	1.87864	0.67536	100	1.00E+05	1.21E-03	8.25E-06	147	55	4.53E+04	4.85E-02	3032

Figure 5: Same bias condition found in Q1

(1) How much is the measured collector current I_C in mA?

$$I_C = 1.21 * 10^{-3}\ A = 1.21\ mA$$

(2) What are the measured V_{BEon} in volts and the base current I_B in µA?

$$V_{BEon} = 0.67536\ V\ , I_B = 8.25 * 10^{-6}\ A = 8.25\ \mu\text{A}$$

(3) What is the $\beta = I_C/I_B$ value at this I_C?

$$\beta = \frac{I_C}{I_B} = 147$$

(4) What is the early voltage $|V_A|$ in volts?

$$|V_A| = 55\ V$$

(5) What is the output resistance r_o in kΩ?

$$r_o = \frac{V_A}{I_C} = 4.53 * 10^4\ \Omega = 45.3\ \text{k}\Omega$$

(6) What is the transconductance g_m in mS?

$$g_m = \frac{I_C}{25mV} = 4.85 * 10^{-2}\frac{A}{mV} = 48.5\ mS$$

(7) What is the input resistance r_π in kΩ?

$$r_\pi = \frac{25mV}{I_B} = 3032\frac{mV}{A} = 3.032\ k\Omega$$

Part 2: DC Characterization of a PNP-BJT 2N3906

A) SPICE Simulation

2.1

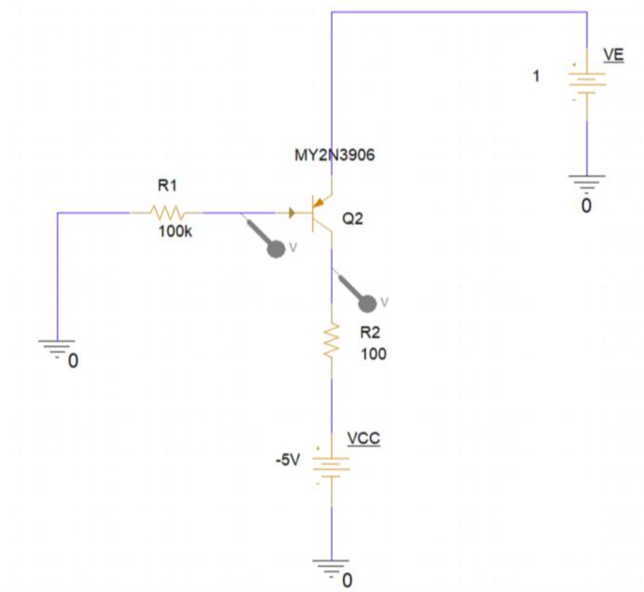


Figure 6: PSpice schematic diagram used to characterize a PNP-BJT 2N3906

2.2

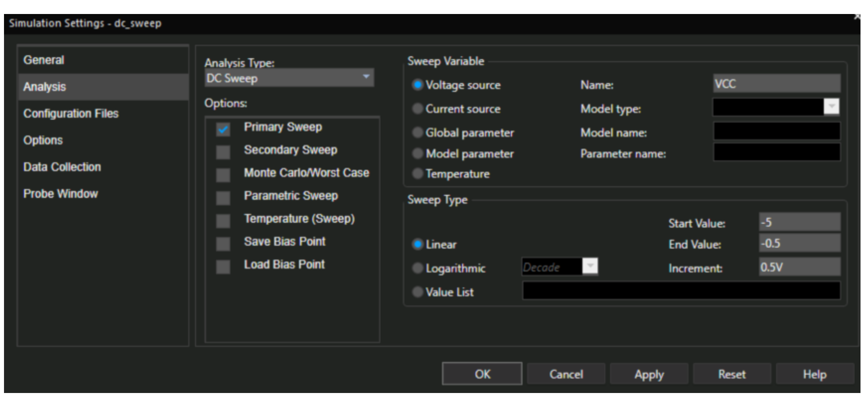


Figure 7: PSpice simulation settings used for DC sweep

2.3 The V_A represents the early voltage which is a measure of the output resistance of a BJT in the active region. By observing the definition of V_A in Fig. 6.18 of the textbook, I was able to calculate the V_A from the I_C vs. V_{CE} plot in excel using the equation of the trendline to solve for the intercept by setting $I_C = 0$:

$$I_C = mV_{CE} + b$$

$$0 = mV_{CE} + b$$

$$V_{CE} = -\frac{b}{m} \quad => \quad V_A = \frac{b}{m}$$

B) AD3 Measurement

2.5

Figure 8: Experimental setup for the DC characterization of an PNP-BJT 2N3906

C) Questions for Part 2

For the PNP-BJT 2N3906 characterized, if we want to bias this device to conduct a collector current $I_C \approx$ 1.0 mA at the lowest V_{EC} value, answer the following questions.

Q3. (7 Points): Based on the simulated data in Steps 2.2-2.4, use the bias condition giving the closest IC value to the desired collector current, find out:

V+ (VE)	V- (VCC)	V(Q1C) (Volt)	V(Q1B) (Volt)	VEC (Volt)	VEBon (Volt)	RC (ohm)	RB (ohm)	IC (A)	IB (A)	β = IC/IB	|VA| (V)	ro=VA/IC	gm = IC/25mV	rπ = 25mV/IB
1.5	-0.5	-0.397093315	0.839935339	1.90	0.660	100	1.00E+05	1.03E-03	8.40E-06	123	143	1.39E+05	4.12E-02	2976

Figure 9: Closest I_C to 1.0 mA at the lowest V_{CE} Value

(1) What are the simulated V_{EBon} in volts and the base current I_B in µA?

$$V_{BEon} = 0.660\ V\ , I_B = 8.40 * 10^{-6}\ A = 8.40\ \mu\text{A}$$

(2) What is the $\beta = I_C/I_B$ value at this I_C?

$$\beta = \frac{I_C}{I_B} = 123$$

(3) What is the early voltage $|V_A|$ in volts?

$$|V_A| = 143\ V$$

(4) What is the output resistance r_o in kΩ?

$$r_o = \frac{V_A}{I_C} = 1.39 * 10^5\ \Omega = 139\ \text{k}\Omega$$

(5) What is the transconductance g_m in mS?

$$g_m = \frac{I_C}{25mV} = 4.12 * 10^{-2}\frac{A}{mV} = 41.2\ mS$$

(6) What is the input resistance r_π in kΩ?

$$r_\pi = \frac{25mV}{I_B} = 2976\frac{mV}{A} = 2.976\ k\Omega$$

Q4. (8 Points): Based on the measured data in Step 2.8, use the same bias condition found in Q3 (or the first reliable data if that bias condition is an outlier), find out:

V+ (VE)	V- (VCC)	Channel 1 (VC)	Channel 2 (VB)	VEC (Volt)	VEBon (Volt)	RC (ohm)	RB (ohm)	IC (A)	IB (A)	β = IC/IB	|VA| (V)	ro=VA/IC	gm = IC/25mV	rπ = 25mV/IB
1.5	-0.5	-0.423	0.87924	1.92	0.621	100	1.00E+05	7.70E-04	8.79E-06	88	23	3.03E+04	3.08E-02	2843

Figure 10: Same bias condition found in Q3

(1) How much is the measured collector current I_C in mA?

$$I_C = 7.70 * 10^{-4}\ A = 0.77\ mA$$

(2) What are the measured V_{BEon} in volts and the base current I_B in µA?

$$V_{BEon} = 0.621\ V\ , I_B = 8.79 * 10^{-6}\ A = 8.79\ \mu\text{A}$$

(3) What is the $\beta = I_C/I_B$ value at this I_C?

$$\beta = \frac{I_C}{I_B} = 88$$

(4) What is the early voltage $|V_A|$ in volts?

$$|V_A| = 23\ V$$

(5) What is the output resistance r_o in kΩ?

$$r_o = \frac{V_A}{I_C} = 3.03 * 10^4\ \Omega = 30.3\ \text{k}\Omega$$

(6) What is the transconductance g_m in mS?

$$g_m = \frac{I_C}{25mV} = 3.08 * 10^{-2}\frac{A}{mV} = 30.8\ mS$$

(7) What is the input resistance r_π in kΩ?

$$r_\pi = \frac{25mV}{I_B} = 2843\frac{mV}{A} = 2.843\ k\Omega$$

Part 3: Design of a Current Source/Sink

Q5: (10 points) Express the base current I_B as a function of V_{BB}, R_{BB}, V_{Beon}, R_3, V_{EE}, and β.

Q5:

$i_B = i_e - i_c$, $i_c = \beta i_B$

$i_B = i_e - \beta i_B$

$i_e = i_B(\beta+1)$ ①

KVL around base-emitter loop:

$V_{BB} - i_B R_{BB} - V_{BEon} - i_e R_3 - V_{EE} = 0$

Sub in ①

$V_{BB} - i_B R_{BB} - V_{BEon} - i_B(\beta+1) R_3 - V_{EE} = 0$

$V_{BB} - i_B\left[R_{BB} + (\beta+1) R_3\right] - V_{BEon} - V_{EE} = 0$

$$\boxed{i_B = \frac{V_{BB} - V_{BEon} - V_{EE}}{R_{BB} + R_3(\beta+1)}}$$

Q6. (10 Points) Comparing the I_B expressions obtained in Q5 and in (3), what is the difference between these two equations? For a change ΔV_{EE} in the power supply V_{EE}, derive equations for the resulting change in the base current ΔI_B using the I_B expressions obtained in Q5 and in (3). Show that the emitter resistor R_3 reduces the change in the base current ΔI_B as a result of the change ΔV_{EE} in the power supply V_{EE}.

Q6:

Equation from Q5:

$$i_B = \frac{V_{BB} - V_{BEon} - V_{EE}}{R_{BB} + R_3(\beta+1)}$$

$$\Delta i_B + i_B = \frac{V_{BB} - V_{BEon} - (V_{EE} + \Delta V_{EE})}{R_{BB} + R_3(\beta+1)}$$

Equation (3):

$$i_B = \frac{V_{BB} - (V_{EE} + V_{BEon})}{R_{BB}}$$

$$\Delta i_B + i_B = \frac{V_{BB} - (V_{EE} + \Delta V_{EE}) - V_{BEon}}{R_{BB}}$$

The difference between the equation obtained in Q5, and the given equation (3) is that equation (3) does not include R_3 as it was set to zero. In the last question, I didn't set R_3 equal to zero, which is why $R_3(\beta + 1)$ is present in the denominator of the equation for I_B.

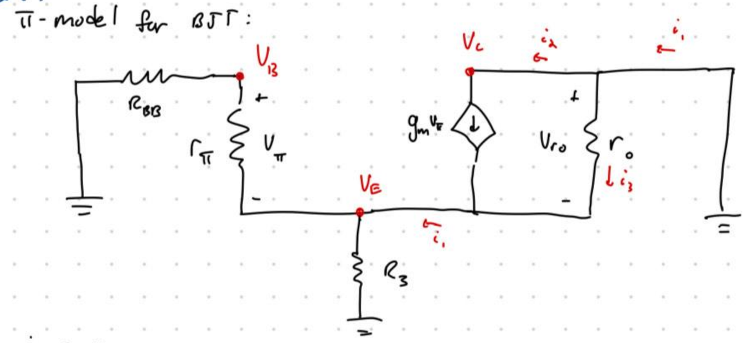
R_3 (β + 1) will always be a positive value since both β and R_3 are always positive, which means that the above equations will have the same numerator, but the equation derived from Q5 will have a slightly larger denominator than the one from equation (3). This proves that for any change ΔV_{EE} in the power supply V_{EE}, the change in the base current ΔI_B will always be less in the equation derived from Q5 as opposed to equation (3). This is proof that the emitter resistor R_3 reduces the change in the base current ΔI_B as a result of the change ΔV_{EE} in the power supply V_{EE}.

Q7. (15 points) Inserting the feedback R_3 at the emitter of the BJT not only stabilizes the I_B but also improves (or increases) the output resistance R_o of the current sink shown in Fig 6/ Fig 7 (i.e., I_o is more stable when there is a change in V_{CE}). Using a π-model for the BJT, prove that the output resistance of the current sink is $R_o = r_o + [R_3 \,||\, (R_{BB} + R_\pi)][1 + g_m r_o \left(\frac{r_\pi}{R_{BB}+r_\pi}\right)]$.

Below is the proof from a π-model for the BJT that the output resistance of the current sink is $R_o = r_o + [R_3 \,||\, (R_{BB} + R_\pi)][1 + g_m r_o \left(\frac{r_\pi}{R_{BB}+r_\pi}\right)]$.

Q7:

π-model for BJT:



$i_2 = g_m V_\pi$

$i_3 = i_1 - i_2$
$= i_1 - g_m V_\pi$

$V_{ro} = r_o i_3$

$V_{ro} = r_o(i_1 - g_m V_\pi)$

$V_E = i_1\left[(R_{BB} + r_\pi) // R_3\right]$

$V_\pi = -V_E \cdot \frac{r_\pi}{R_{BB} + r_\pi}$

$$V_c = V_E + V_{ro}$$
$$= i_1((R_{BB}+r_\pi)//R_3) + r_o(i_1 - g_m V_\pi)$$
$$= i_1((R_{BB}+r_\pi)//R_3) + r_o i_1 - r_o g_m V_\pi$$
$$= i_1((R_{BB}+r_\pi)//R_3) + r_o i_1 - r_o g_m\left(-V_E \cdot \frac{r_\pi}{R_{BB}+r_\pi}\right)$$
$$= i_1((R_{BB}+r_\pi)//R_3) + r_o i_1 + r_o \cdot \frac{g_m V_E r_\pi}{R_{BB}+R_\pi}$$

$$V_c = i_1((R_{BB}+r_\pi)//R_3) + r_o i_1 + r_o \cdot \frac{g_m r_\pi}{R_{BB}+R_\pi} \cdot i_1((R_{BB}+r_\pi)//R_3)$$

$$R_o = \frac{V_c}{i_1} = ((R_{BB}+r_\pi)//R_3) + i_1 + r_o \cdot \frac{g_m r_\pi}{R_{BB}+r_\pi} \cdot ((R_{BB}+r_\pi)//R_3)$$

$$\boxed{R_o = r_o + ((R_{BB}+r_\pi)//R_3)\left(1 + g_m r_o\left(\frac{r_\pi}{R_{BB}+r_\pi}\right)\right)}$$

Q8. (10 Points) Inserting the feedback R_3 at the emitter of the BJT improves the stabilization of the Q-point at the cost of increased $V_{o,min}$. What is the $V_{o,min}$ of the constant current sink when $R_3 \neq 0$? Express $V_{o,min}$ as a function of I_o, which is the I_C of Q1.

Because $R_3 \neq 0$, we must consider the voltage drop when calculating the $V_{o,min}$ of the constant current sink. Below us $V_{o,min}$ expressed as a function of I_o.

Q8:

$V_{o,min} = V_{EE} + 0.3V$ (when $R_3 = 0$)

Voltage drop across resistor R_3: $V_{R3} = I_e R_3$

$V_{o,min} = V_{EE} + 0.3V + V_{R3}$

$V_{o,min} = V_{EE} + 0.3V + I_e R_3$

$$\boxed{V_{o,min} = V_{EE} + 0.3V + \frac{\beta+1}{\beta} I_o R_3}$$

Q9. (15 Points) For V_{EE} = -5V, if we want to design a current sink with I_o = 1.0 mA and $V_{o,min}$ = -1 V using the NPN-BJT 2N3094 characterized in Q1, what is the resistance value for R_3? To reduce the DC power consumption of R_1 and R_2, we usually choose large resistance values (in tens or hundreds of kΩ) for R_1 and R_2. Suppose we choose R_2 = 100 kΩ, calculate R_1 in kΩ. Verify the I_o vs. V_{CC} characteristics of the design by sweeping V_{CC} from -5V to 5V with a 0.05V step and post the waveform of the simulated I_o vs. V_{CC} characteristics using the command "Window -> Copy to Clipboard" in the PSpice simulator window.

Q9:

1. Find R3:

$V_{o,min} = V_{EE} + 0.3V + \frac{\beta+1}{\beta} I_o R_3$

$-1V = -5V + 0.3V + \frac{118}{117}(1mA) R_3$

$R_3 = \frac{-1V + 5V - 0.3V}{\frac{118}{117}(1mA)}$

$$\boxed{R_3 = 3.669\,k\Omega}$$

2. Find base voltage:

$V_E = V_{EE} + I_E R_3 = -5 + \left(\frac{118}{117} mA\right)(3.669k\Omega) = -1.300$

$V_B = V_E + V_{BE_{on}} = -1.300 + 0.621$

$V_B = -0.679V$

(3) Solve for R_1

$$I_B R_{BB} + V_B = V_{BB}$$

$$I_B \frac{R_1 R_2}{R_1 + R_2} + V_B = \frac{R_1}{R_1 + R_2} V_{EE}$$

$$\frac{1}{117} \frac{100 R_1}{100 + R_1} - 0.679 = \frac{R_1}{100 + R_1} (-5)$$

$$\therefore \boxed{R_1 = 13.1 k\Omega}$$

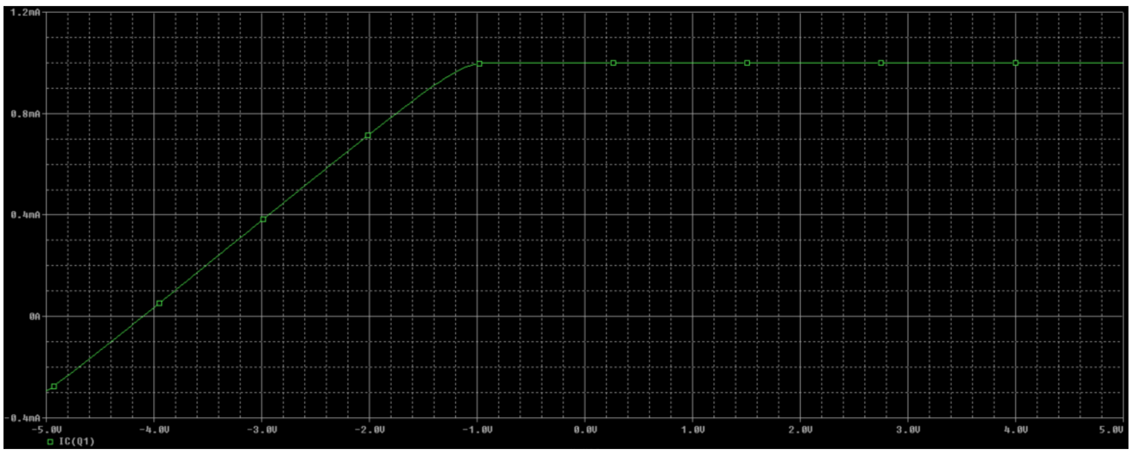


Figure 11: I_o vs. V_{CC} plot

Q10. (10 Points) When designing the constant current sink shown in Fig. 6, we assume that $|V_{CE}| \geq 0.3V$ and Q1 works in the active region. Based on the resistance values obtained in Q9, sweep V_{CC} in Fig. 6 from -5 V to +5 V with a 0.05 V step and measure V_E and I_C to determine the |VCE| required for Q1 to work in the active region.

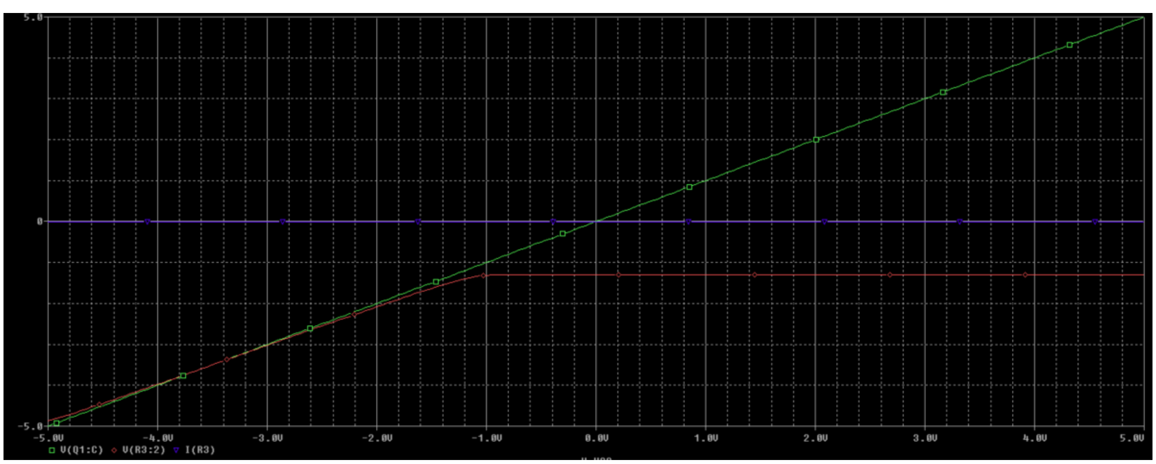


Figure 12: I_C, V_{CC}, and V_E plot

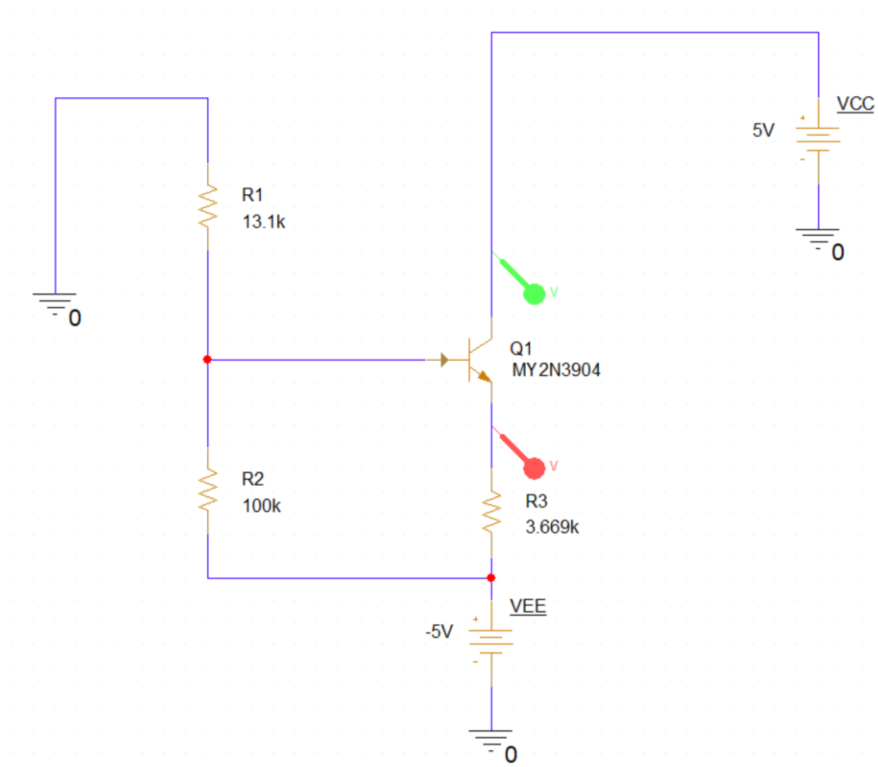


Figure 13: PSpice circuit used

From the graph that shows V_{CC} vs V_E, we can determine the $|V_{CE}|$ required for Q1 to operate in the active region. It can be observed that $|V_{CE}| = V_{cc} – V_E = (-1V) – (-1.3V) = 0.3V$. This verifies the operating condition is $|V_{CE}| >= 0.3V$ for Q1 to work in the active region.