McMaster University

Electrical and Computer Engineering Department

EE3EJ4 Electronic Devices and Circuits II - Fall 2020

Lab. 1 DC Characterization and Current Source/Sink

Lab Report Due on Sept. 27, 2020

Objective: These are the objectives of this lab.

- Review all available functions on the Analog Discovery 2 (AD2)
- Analyze, simulate, and construct the constant current sources
- Analyze, simulate, and construct the current mirrors

Attributes Evaluated: These are the attributes you need to demonstrate in your solutions.

- **Competence in specialized engineering knowledge;**
- **Ability to obtain substantiated conclusions as a result of a problem solution, including recognizing the limitations of the solutions; and**
- **Ability to assess the accuracy and precision of results and recognize the limitations of the approach.**

Test Equipment:

- Analog Discovery 2 (AD2)
- WaveForms from Digilent Link: https://store.digilentinc.com/waveforms-download-only/

Components:

- 1 × NPN-BJT 2N3904
- 1 × PNP-BJT 2N3906
- 1 × 100 kΩ resistor
- 1 × 100 Ω resistor

Transistors in the circuit:

For the detailed description of these transistors, please check the following websites:

https://www.onsemi.com/products/discretes-drivers/general-purpose-and-low-vcesat-transistors/2n3904 or https://www.onsemi.com/pub/Collateral/2N3903-D.PDF

https://www.onsemi.com/products/discretes-drivers/general-purpose-and-low-vcesat-transistors/2n3906 or https://www.onsemi.com/pub/Collateral/2N3906-D.PDF

Reminder: Switch off the DC power suppliers first whenever you need to change the circuit configurations. Switch on the DC power suppliers only when you do not have to change the circuit connection anymore.

<u>Part 1</u>: DC Characterization of an NPN-BJT 2N3904

Description of DC Characterization

To use a bipolar junction transistor in circuit design, we need to know its I_C vs. V_{CE} characteristics and DC/AC parameters. These parameters include the common-emitter current gain $\beta = I_C/I_B$ (6.2), the turn-on base-emitter voltage V_{BEon}, the Early voltage V_A (as defined in Figure 6.18), the transconductance g_m (7.63), the input base-emitter resistance r_π (7.67), and the output resistance r_o (6.19). This section is to develop the characterization procedure to obtain its I_C vs. V_{CE} characteristics and these parameters using PartSim online circuit simulator first and verify the results by measuring an NPN-BJT 2N3904 and a PNP-BJT 2N3906 using Analog Discovery 2 (AD2).

A. Pre-lab Preparation

1.1 In Avenue to Learn, Lab 1: DC Characterization and Biasing Circuits, follow the link for PartSim circuit simulator and Video 1.1 to Video 1.3 to prepare the circuit diagram as shown in Fig. 1 to characterize an NPN-BJT 2N3904. Because AD2 only measures voltages, we use R1 and R2 in Fig. 1 as the current sensors, and obtain IB = -V(Q1B)/R1 and IC = [VCC-V(Q1C)]/R2.

1.2 Set VE = -5 V, sweep VCC from 0.5 V to 5 V with 0.5 V step, and record the collector voltage V(Q1C) and the base voltage V(Q1B) in columns C and D of the excel file "Lab1 Part1 – DC Parameters of NPN-BJT 2N3904" under the "Simulation" sheet.

1.3 Based on the definition of V_A in Fig. 6.18 in the textbook, use the IC vs. VCE plot for VE = -5V in the excel file, calculate the V_A value for VE = -5 V, and record it in column L.

1.4 Set VE from -4.5V to -1 V with 0.5 V step, repeat steps 1.2 and 1.3 above.

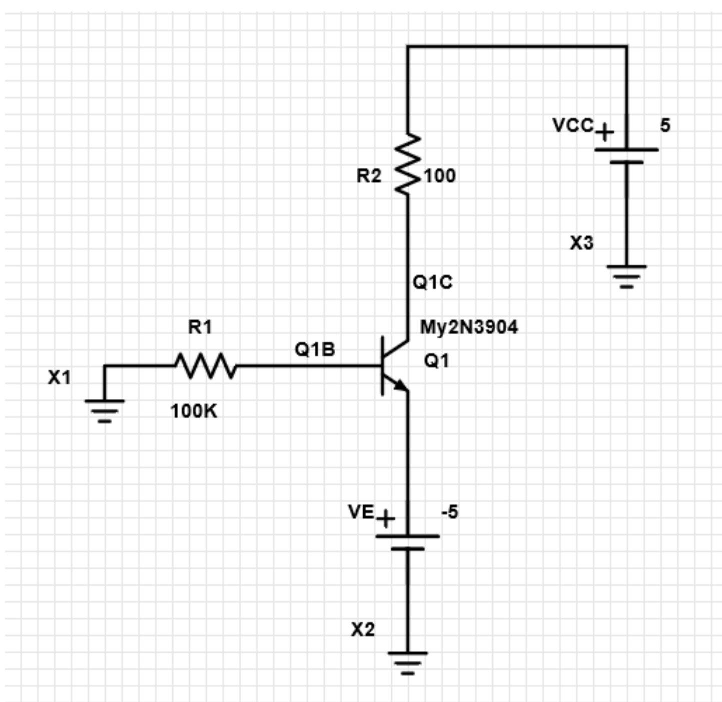

Fig. 1 The schematic diagram for the DC characterization of an NPN-BJT 2N3904

B. In-lab Requirement

1.5 Prepare the circuit as shown in Fig. 2, using the same settings for VE and VCC in steps 1.2 to 1.4, measure the collector voltage VC and the base voltage VB, and record the measured data in the columns C and D of the "Measurement" sheet in the excel file "Lab1 Part1 – DC Parameters of NPN-BJT 2N3904".

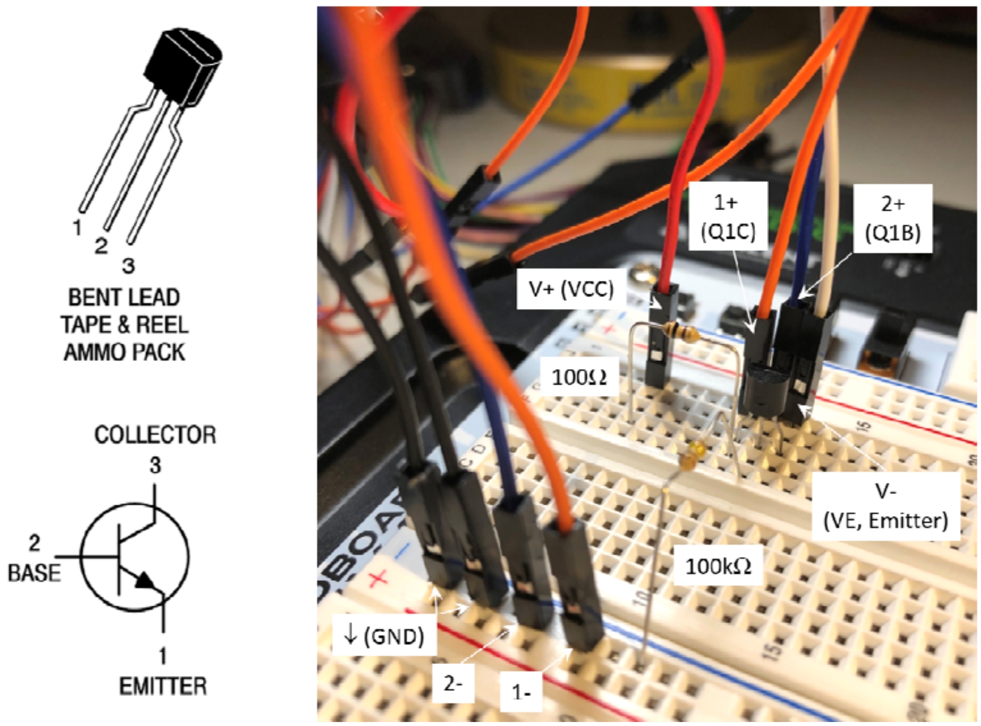

Fig. 2 Experimental setup for the DC Characterization of an NPN-BJT 2N3904

C. Questions for Part 1:

For the NPN-BJT 2N3904 characterized, answer the following questions with simulated and measured data, and discuss any discrepancy between the simulation and measurement results.

Q1. Plot the simulated and measured I_C vs. V_{CE} characteristics. What do you learn from these data?

Q2. Plot the simulated and measured common-emitter current gain β, the turn-on base-emitter voltage V_{BEon}, the early voltage $|V_A|$, the transconductance g_m, the input base-emitter resistance r_π, and the output resistance r_o vs. V_{CE} characteristics. What do you learn from these data?

Q3. Did you observe any discrepancy between the simulated and measured data? If yes, what could be the reason causing the discrepancies?

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

A. Pre-lab Preparation

2.1 In Avenue to Learn, *Lab 1: DC Characterization and Biasing Circuits*, follow Video 2.1 to Video 2.3 to prepare the circuit diagram as shown in Fig. 3 to characterize a PNP-BJT 2N3906.

2.2 Set VE = 5 V, sweep VCC from -5 V to -0.5 V with 0.5 V step, and record the collector voltage V(Q1C) and the base voltage V(Q1B) in columns C and D of the excel file "Lab1 Part2 – DC Parameters of PNP-BJT 2N3906" under the "Simulation" sheet.

2.3 Based on the definition of V_A in Fig. 6.18 in the textbook, use the IC vs. VEC plot for VE = 5V in the excel file, calculate the $|V_A|$ value for VE = 5 V and record it in column L.

2.4 Set VE from 4.5V down to 1 V with 0.5 V step, repeat steps 1.2 and 1.3 above.

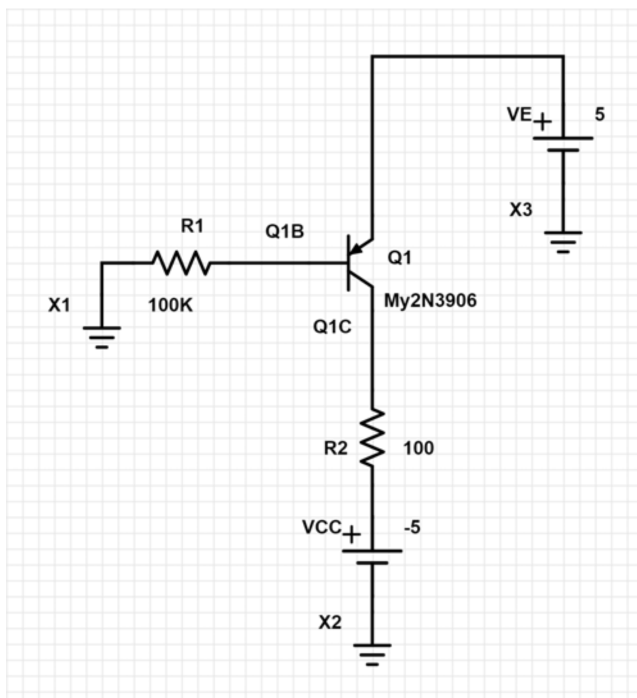

Fig. 3 The schematic diagram for the DC characterization of a PNP-BJT 2N3906

B. In-lab Requirement:

2.5 Prepare the circuit, as shown in Fig. 4, using the same settings for VE and VCC in steps 2.2 to 2.4, measure the collector voltage VC and the base voltage VB, and record the measured data in the columns C and D of the "Measurement" sheet in the excel file "Lab1 Part2 – DC Parameters of PNP-BJT 2N3906".

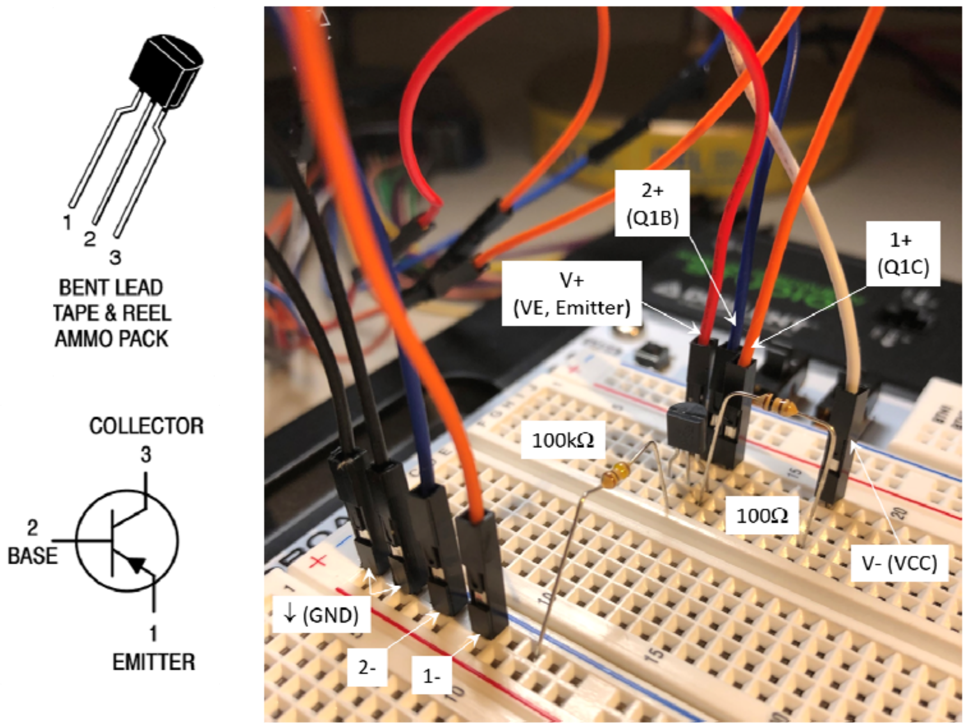

Fig. 4 Experimental setup for the DC Characterization of a PNP-BJT 2N3906

C. Questions for Part 2:

For the PNP-BJT 2N3906 characterized, answer the following questions with simulated and measured data, and discuss any discrepancy between the simulation and measurement results.

Q4. Plot the simulated and measured I_C vs. $|V_{CE}|$ characteristics. What do you learn from these data?

Q5. Plot the simulated and measured common-emitter current gain β, the Early voltage $|V_A|$, the turn-on emitter-base voltage V_{EBon}, the transconductance g_m, the input base-emitter resistance r_π, and the output resistance r_o vs. $|V_{CE}|$ characteristics. What do you learn from these data?

Q6. Did you observe any discrepancy between the simulated and measured data? If yes, what could be the reason causing the discrepancies?

<u>Part 3</u>: Design of a Current Source/Sink

The function of a current source/sink is to deliver a constant current, regardless of the voltage drop across its terminals, as shown in Fig. 5. The current source locates between the V_{CC} (the highest voltage used in the system) and the supporting circuit, while the current sink sits between the supporting circuit and ground (or $V_{EE} < 0$, the lowest voltage used in the system). In this section, to implement this function using a BJT, we need to consider the following.

1. **Biasing:** to deliver a constant current, we need to bias the BJT to work in the active region, assuming its $|V_A|$ is infinite. According to Fig. 6.14 in the textbook, it requires that we set its $|V_{BE}| = V_{BEon} \approx 0.7\text{V}$ and $|V_{CE}| \geq 0.3\text{V}$.
2. **Current:** since the BJT works as a current amplifier, we need to control I_B to deliver a constant current $I_C = \beta \cdot I_B$.
3. **Output Resistance:** To provide constant current, we need to reduce the current change due to the Early effect $|V_A|$. To evaluate the Early effect, we calculate the output resistance R_o of the current source. If the BJT has no Early effect, the output resistance R_o of the current source is infinite.
4. **Maximum/Minimum Output Voltage:** Since $|V_{CE}| \geq 0.3\text{V}$ is required for a BJT to work in the active region, the minimum output voltage $V_{o,min}$ of a current sink is $V_{o,min} = V_{EE} + 0.3$ V, and the maximum output voltage of a current source is $V_{o,max} = V_{CC} - 0.3\text{V}$.

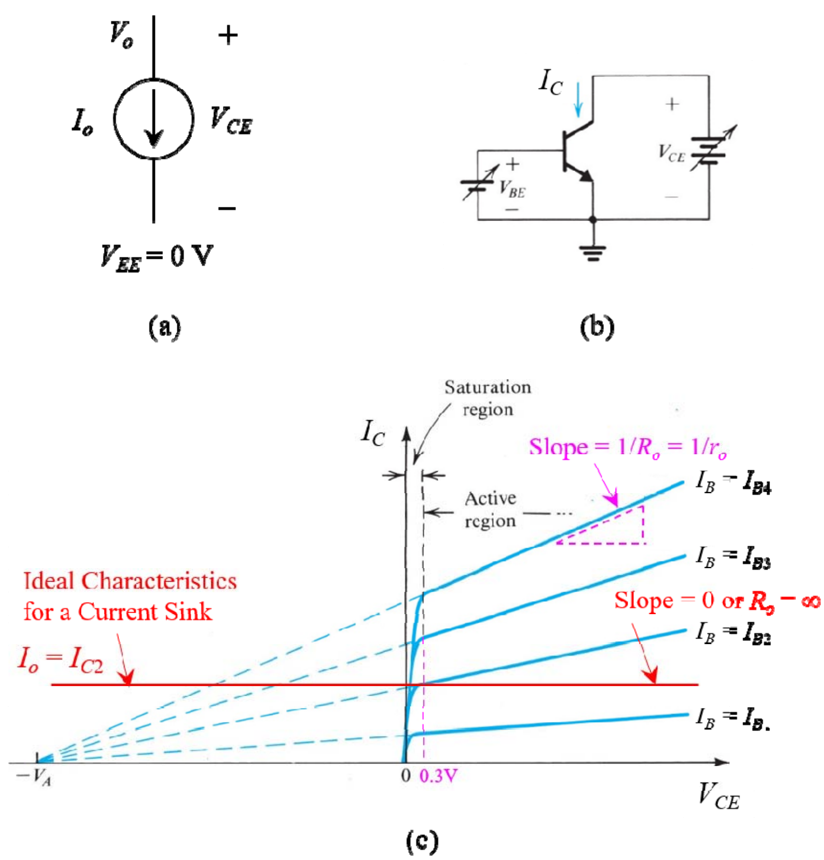

Fig. 5 (a) Ideal current sink, (b) implementation of a current sink using an NPN-BJT, and (c) ideal and actual characteristics of a current sink.

A. Pre-lab Preparation

3.1 In PartSim, construct a current sink as shown in Fig. 6 and load the SPICE 3 model parameters for Q1 following the same procedure as shown in Video 1.2, *Lab 1: DC Characterization and Biasing Circuits*.

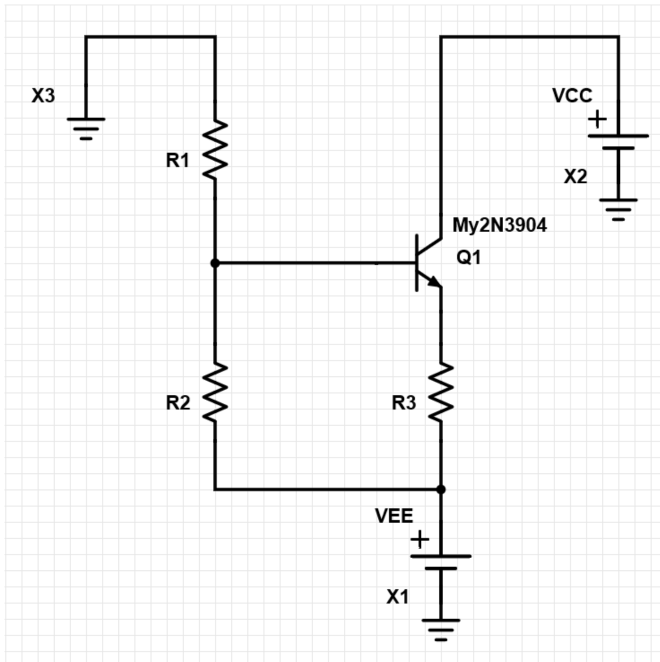

Fig. 6 Constant current sink using an NPN-BJT 2N3904

3.2 Simplify the base circuit using Thevenin's theorem and calculate the equivalent based voltage V_{BB} and resistance R_{BB} by

$$V_{BB} = V_{EE} + \frac{R_2}{R_1 + R_2}\left(0 - V_{EE}\right) = V_{EE} - \frac{R_2}{R_1 + R_2} V_{EE} = \frac{R_1}{R_1 + R_2} V_{EE} < 0 \tag{1.1}$$

and

$$R_{BB} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}. \tag{1.2}$$

We show the equivalent circuit of the constant current sink using V_{BB} and R_{BB} in Fig. 7. If $R_3 = 0$, based on the V_{BEon} obtained in Part 1, we could obtain the base current I_B by

$$I_B = \frac{V_{BB} - \left(V_{EE} + V_{BEon}\right)}{R_{BB}} = \frac{R_2}{\left(R_1 + R_2\right)} \frac{\left(-V_{EE}\right)}{R_{BB}} - \frac{V_{BEon}}{R_{BB}} > 0. \tag{1.3}$$

Note that $-V_{EE} > 0$ and $V_{BB} < 0$ in (1.3). From (1.1) and (1.3), we notice that if there is a change in the supply voltage V_{EE}, then the base current I_B will also change by a proportional amount. Here we apply a feedback technique to stabilize the base current (or Q-point) of the transistor.

To avoid the change in I_B, we connect R_3 to the emitter of the BJT, as shown in Fig. 6, to work as a feedback resistor. For example, if $|V_{EE}|$ reduces that causes I_B smaller than the designed value, the resulting I_E will produce a smaller voltage drop across R_3 and results in the reduction of V_E at the emitter terminal of Q_1. This reduced V_E will increase V_{BE} of Q_1 and therefore increase I_B.

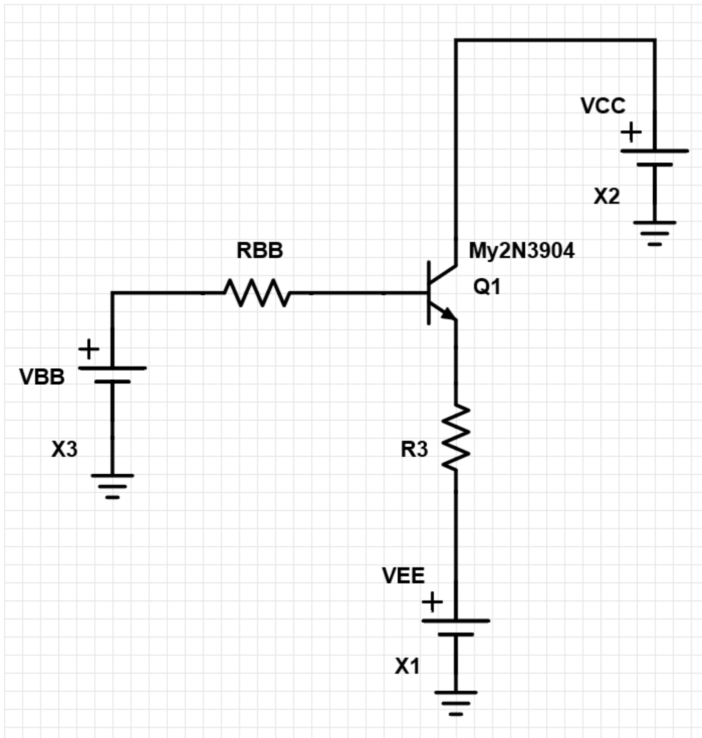

Fig. 7 The equivalent circuit for the constant current sink in Fig. 6 with R_1, R_2, and power supply replaced by its Thevenin's equivalent circuit V_{BB} and R_{BB}.

B. Questions for Part 3:

Based on the equivalent circuit in Fig. 7 to answer the following questions.

Q7. Express the base current I_B as a function of V_{BB}, V_{BEon}, V_{EE}, R_{BB}, R_3, and β.

Q8. Compare the I_B expression obtained in Q7 with (1.3), what is the difference between these two equations? Explain how 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}.

Q9. 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 (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

$$R_o = r_o + \left[R_3 \,||\, \left(R_{BB} + r_\pi\right)\right]\left[1 + g_m r_o \left(\frac{r_\pi}{R_{BB} + r_\pi}\right)\right].$$

Q10. 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 $R_3 \neq 0$?

Q11. For V_{EE} = -5V, if we want to design a current sink with I_o = 1 mA and $V_{o,min}$ = -1V using the NPN-BJT 2N3094 characterized in Part 1, 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. Complete and verify the design using the PartSim online circuit simulator.

Q12. When designing the constant current sink shown in Fig. 6, we assumed that $|V_{CE}| \geq 0.3$V for Q_1 to work in the active region. Sweep V_{CC} in Fig. 6 from -5 V to +5V with 0.05 V step and measured V_E and I_C to determine the $|V_{CE}|$ required for Q_1 to work in the active region.