McMaster University

Electrical and Computer Engineering Department

EE3EJ4 Electronic Devices and Circuits II - Fall 2021

Lab. 1 Device Characterization and Biasing Circuits

Lab Report Due on Sep. 26, 2021

Objective: These are the objectives of this lab.

- Review all available functions on the Analog Discovery 2 (AD2)
- Simulate and characterize the bipolar junction transistors
- Analyze, simulate, and construct the constant current sources

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

- **Competence in specialized engineering knowledge to simulate circuit performance using SPICE-based circuit simulator and conduct analog circuit debugging;**
- **Ability to obtain substantiated conclusions as a result of a problem solution, including recognizing the limitations of the approaches and solutions; and**
- **Ability to assess the accuracy and precision of results.**

Test Equipment:

- Analog Discovery 2 (AD2)
- WaveForms from Digilent Link
- Analog Discovery 2 Quick Start Series Videos
- WaveForms Reference Manual

Components:

- Transistors: 1 × NPN-BJT 2N3904 1 × PNP-BJT 2N3906
- Resistors: 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 develops the characterization procedure to obtain its I_C vs. V_{CE} characteristics and these parameters using the PartSim circuit simulator. It then verifies the results by measuring an NPN-BJT 2N3904 and a PNP-BJT 2N3906 using Analog Discovery 2 (AD2).

A. Pre-lab Simulation

1.1 In Avenue to Learn, *Lab 1: Device Characterization and Biasing Circuits*, follow the link for the 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 **DC Characteristics:** Set VE = -5 V, sweep VCC from 0.5 V to 5 V with 0.5 V step. Export and record the collector voltage V(Q1C) and the base voltage V(Q1B) in columns C and D in the sheet "Steps 1.2-1.4" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

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 in the sheet "Step 1.2" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

1.4 Repeat steps 1.2 and 1.3 above with VE from -4.5V and -1 V with 0.5 V step, respectively.

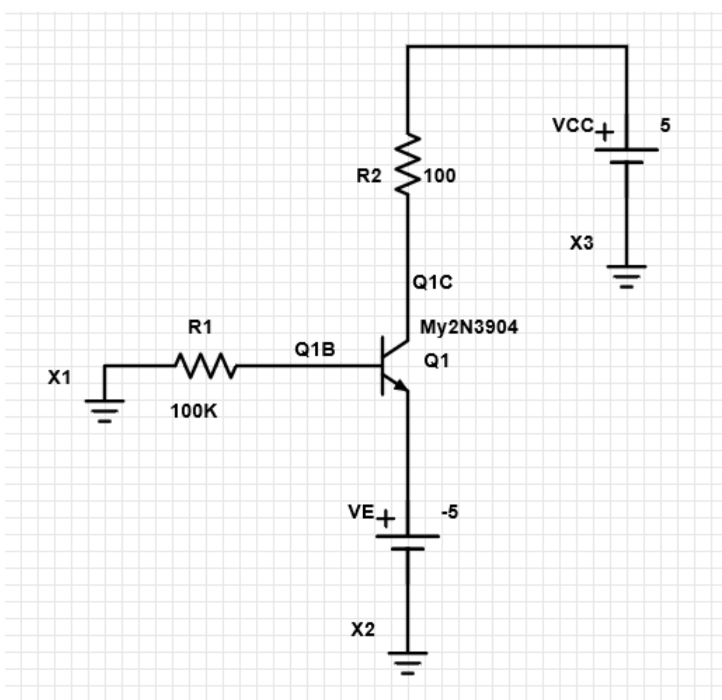

Fig. 1 The schematic diagram for the DC characterization of an NPN-BJT 2N3904

B. In-lab Measurement

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.

1.6 **DC Characteristics:** Start WaveForms program, click Workspace, open the provided script function workspace file “Lab1_Step1.6.dwf3work”, and press Run. This script function takes about 10 minutes to complete the whole sweep measurements automatically. Monitor the progress of the measurement by clicking the Supplies tag at the bottom of the Output window. The last measurement is done at V+ = 5V and V- = -1V. Click on the Script tag, select all data in the Output window, and right-click to save them into a text file “Lab1_Step1.6.txt”.

1.7 Run Excel and open the text file “Lab1_Step1.6.txt”. Choose Delimited as the file type, Comma in Delimiters, and General in Column data format to import the data. Select and copy the whole data. Go to a new sheet, right-click the destination cell A1, choose Paste Special from the context menu, and select Transpose.

1.8 Copy the measured collector voltage VC and the base voltage VB for each V- (or VE) to the corresponding cells in columns C and D in sheet “Step 1.8” of the Excel file “Lab 1 – DC Characterization and Current Sink.xlsx”.

1.9 Based on the definition of V_A in Fig. 6.18 in the textbook, use the IC vs. VCE plot for each VE value in the excel file, remove the outliers (right-click the data cell and choose Clear Contents) to have $R^2 \geq 0.9$, calculate their V_A values using the linear fitted dashed line, and record it in column L in the sheet “Step 1.8” of the Excel file “Lab 1 – DC Characterization and Current Sink.xlsx”.

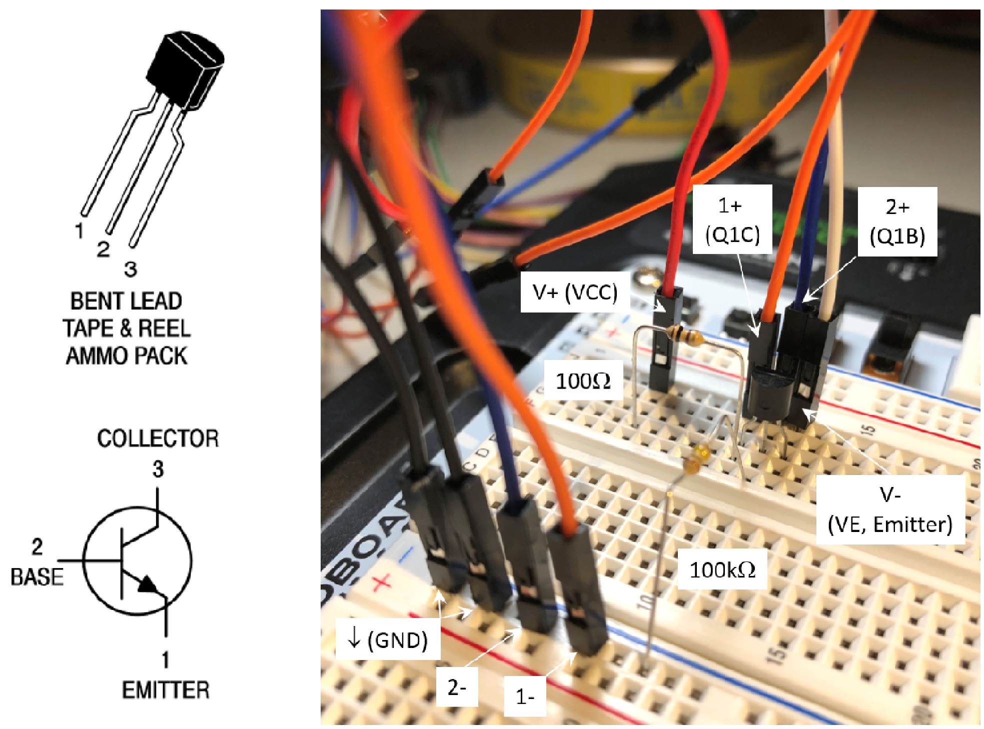

Fig. 2 Experimental setup for the DC Characterization of an NPN-BJT 2N3904

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 <u>at the lowest *VCE* value</u>, 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

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

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

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

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

(5) What is the transconductance g_m in mS?

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

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

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

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

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

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

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

(6) What is the transconductance g_m in mS?

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

<u>Part 2</u>: DC Characterization of a PNP-BJT 2N3906

A. Pre-lab Simulation

2.1 In Avenue to Learn, *Lab 1: Device 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 **DC Characteristics:** 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 in the sheet "Steps 2.2-2.4" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

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 in the sheet "Step 2.2" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

2.4 Repeat steps 2.2 and 2.3 above with VE from 4.5V to 1 V with 0.5 V step, respectively.

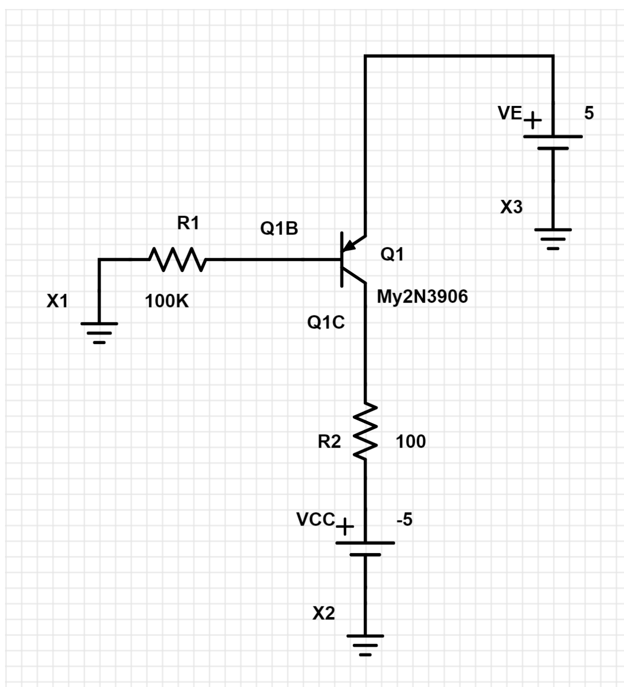

Fig. 3 The schematic diagram for the DC characterization of a PNP-BJT 2N3906

B. In-lab Measurement

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.

2.6 **DC Characteristics:** Start WaveForms program, click Workspace, open the provided script function workspace file "Lab1_Step2.6.dwf3work", and press Run. This script function takes about 10 minutes to complete the whole sweep measurements automatically. Monitor the progress of the measurement by clicking the Supplies tag at the bottom of the Output window. The last measurement is done at V+ = 1V and V- = -0.5V. Click on the Script tag, select all data in the Output window, and right-click to save them into a text file "Lab1_Step2.6.txt".

2.7 Run Excel and open the text file "Lab1_Step2.6.txt". Choose Delimited as the file type, Comma in Delimiters, and General in Column data format to import the data. Select and copy the whole data. Go to a new sheet, right-click the destination cell A1, choose Paste Special from the context menu, and select Transpose.

2.8 Copy the measured collector voltage VC and the base voltage VB for each V+ (or VE) to the corresponding cells in columns C and D in sheet "Step 2.8" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

2.9 Based on the definition of V_A in Fig. 6.18 in the textbook, use the IC vs. VCE plot for each VE value in the excel file, remove the outliers (right-click the data cell and choose Clear Contents) to have $R^2 \geq 0.9$, calculate their V_A values using the linear fitted dashed line, and record it in column L in the sheet "Step 2.8" of the Excel file "Lab 1 – DC Characterization and Current Sink.xlsx".

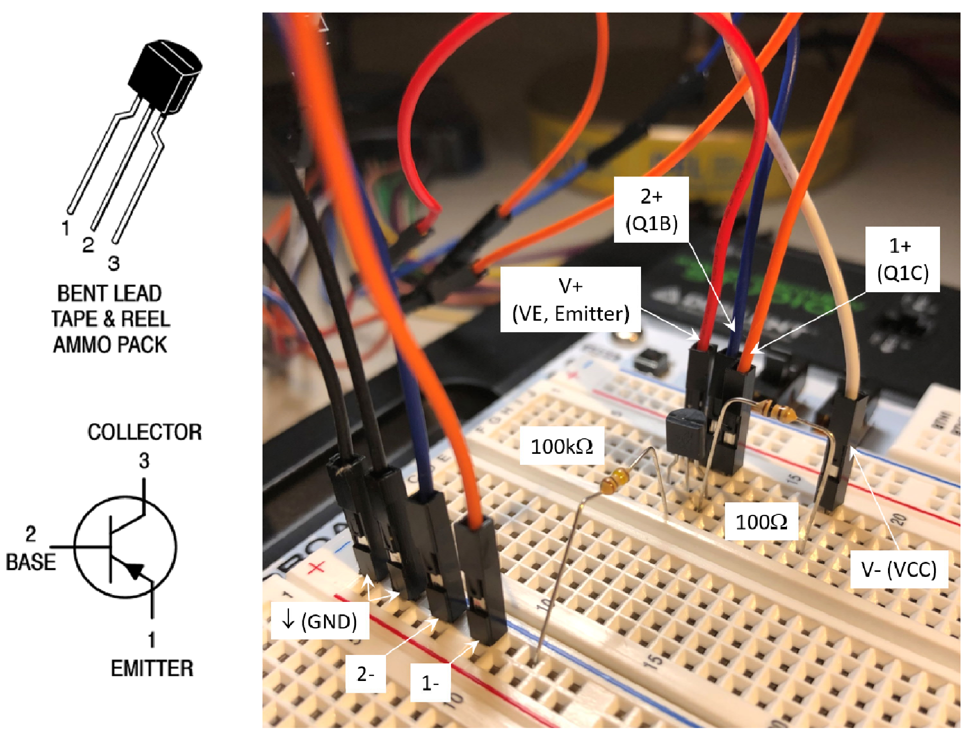

Fig. 4 Experimental setup for the DC Characterization of a PNP-BJT 2N3906

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 *VCE* 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 I_C value to the desired collector current, find out

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

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

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

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

(5) What is the transconductance g_m in mS?

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

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

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

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

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

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

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

(6) What is the transconductance g_m in mS?

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

Part 3: 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 $|V_{BE}| = V_{BEon} \approx 0.7$V and $|V_{CE}| \geq 0.3$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 $|V_{CE}| \geq 0.3$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 $V_{o,max} = V_{CC} - 0.3$V.

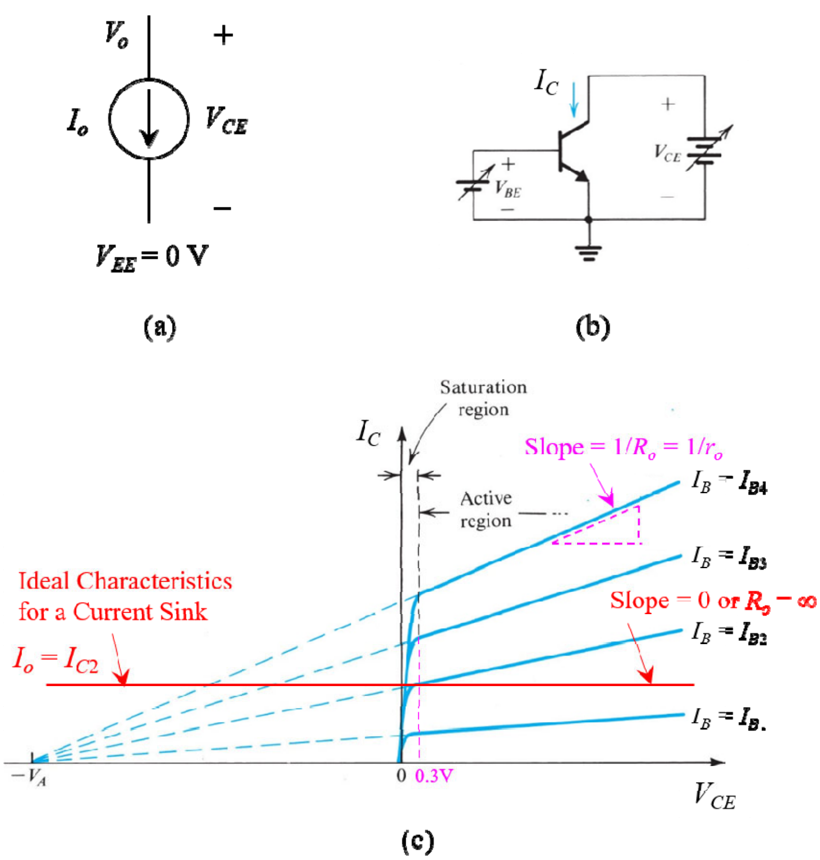

Fig. 5 (a) Ideal current sink, (b) implementation of a current sink using an NPN-BJT, and (c) ideal and actual characteristics of a current sink.

A. Pre-lab Simulation

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 Step 1.1.

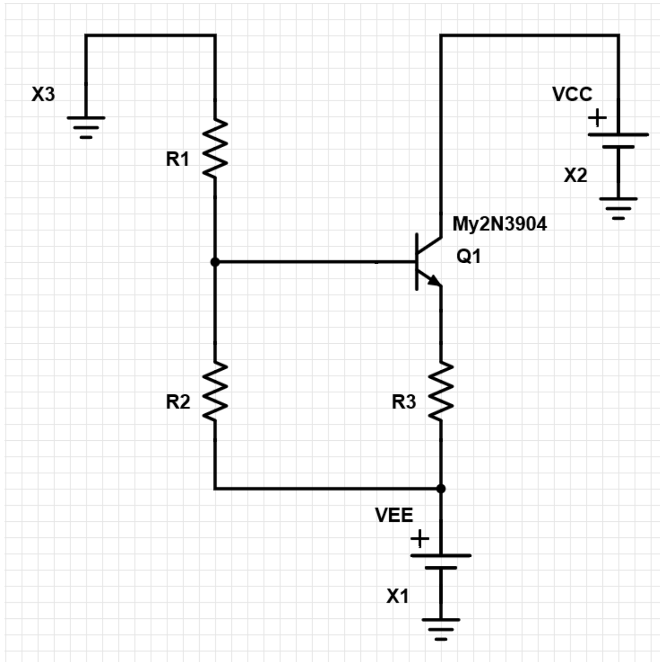

Fig. 6 Constant current sink using an NPN-BJT 2N3904

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

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

Fig. 7 shows the equivalent circuit of the constant current sink using V_{BB} and R_{BB}. 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, which 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.

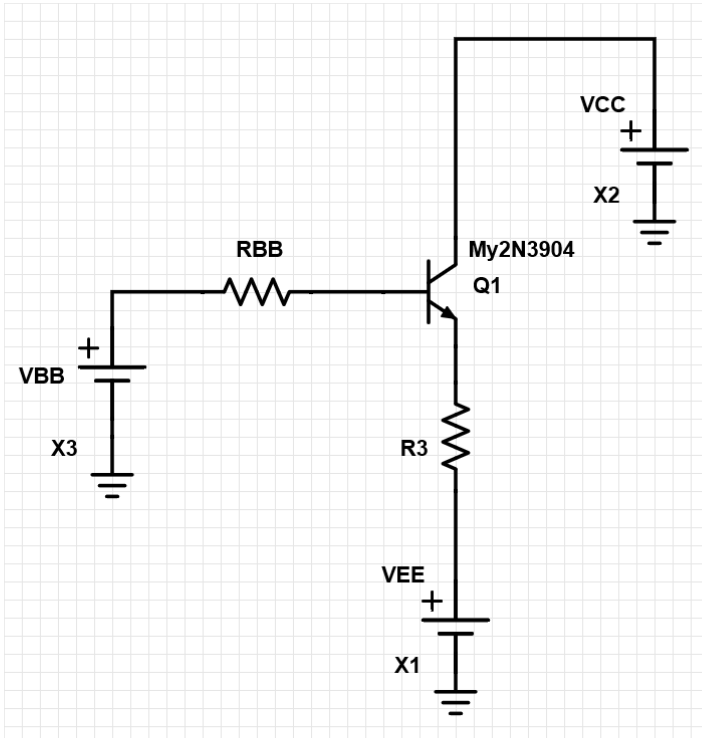

Fig. 7 The equivalent circuit for the constant current sink in Fig. 6 with R_1, R_2, and power supply replaced by its Thevenin equivalent circuit V_{BB} and R_{BB}.

B. Questions for Part 3:

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

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.

Q6. (10 Points) Compare the I_B expression obtained in Q5 with (1.3), what is the difference between these two equations? For a change ΔV_{EE} in the power supply V_{EE}, derive equations for the resulted change in the base current ΔI_B using (1.3) and the I_B expression obtained in Q5. 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}.

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

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 $R_3 \neq 0$?

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 0.05V step and post the screenshot of the simulated I_o vs. V_{CC} characteristics.

Q10. (10 Points) When designing the constant current sink shown in Fig. 6, we assumed that $|V_{CE}| \geq$ 0.3V 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 measure V_E and I_C to determine the $|V_{CE}|$ required for Q_1 to work in the active region.