# McMaster University

## Electrical and Computer Engineering Department

## EE3EJ4 Electronic Devices and Circuits II - Fall 2022

# Lab. 1 Device Characterization and Biasing Circuits

## Lab Report Due on Sep. 25, 2022

**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: $1 \times$ NPN-BJT 2N3904 $1 \times$ PNP-BJT 2N3906
- Resistors: $1 \times 100$ kΩ resistor $1 \times 100$ Ω resistor

**Information of Components:**

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 $r_\pi$ (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 LTspice, PartSim, or PSpice circuit simulator. It then verifies the results by measuring an NPN-BJT 2N3904 and a PNP-BJT 2N3906 using Analog Discovery 2 (AD2).

### A. SPICE Simulation

1.1 In Avenue to Learn, *Lab 1: Device Characterization and Biasing Circuits*, follow the link for the PartSim and Video 1.1 to Video 1.3 to prepare the PartSim circuit diagram as shown in Fig. 1 to characterize an NPN-BJT 2N3904. Because AD2 only measures voltages, we use $R_1$ and $R_2$ in Fig. 1 as the current sensors and obtain $I_B = -V(Q_{1B})/R_1$ and $I_C = [V_{CC} - V(Q_{1C})]/R_2$.

1.2 **DC Characteristics:** Set $V_E$ = -5 V, sweep $V_{CC}$ from 0.5 V to 5 V with 0.5 V step. Export and record the collector voltage $V(Q_{1C})$ and the base voltage $V(Q_{1B})$ 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 $I_C$ vs. $V_{CE}$ plot for $V_E$ = -5V in the Excel file, calculate the $V_A$ value for $V_E$ = -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 $V_E$ from -4.5V and -1 V with 0.5 V step, respectively.

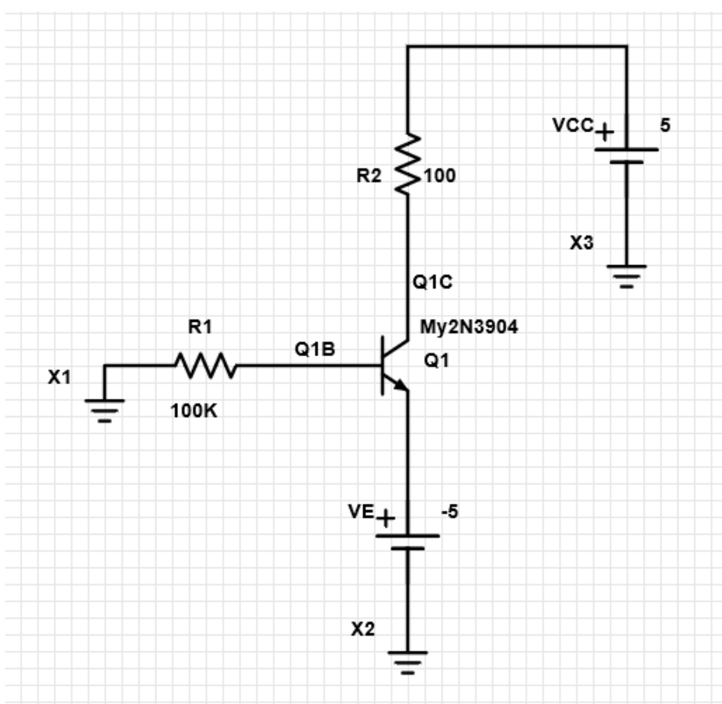


**Fig. 1** The schematic diagram for the DC characterization of an NPN-BJT 2N3904

**B. AD2 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 the 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 measurement progress 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 $V_C$ and the base voltage $V_B$ for each V- (or $V_E$) 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 $I_C$ vs. $V_{CE}$ plot for each $V_E$ 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”.

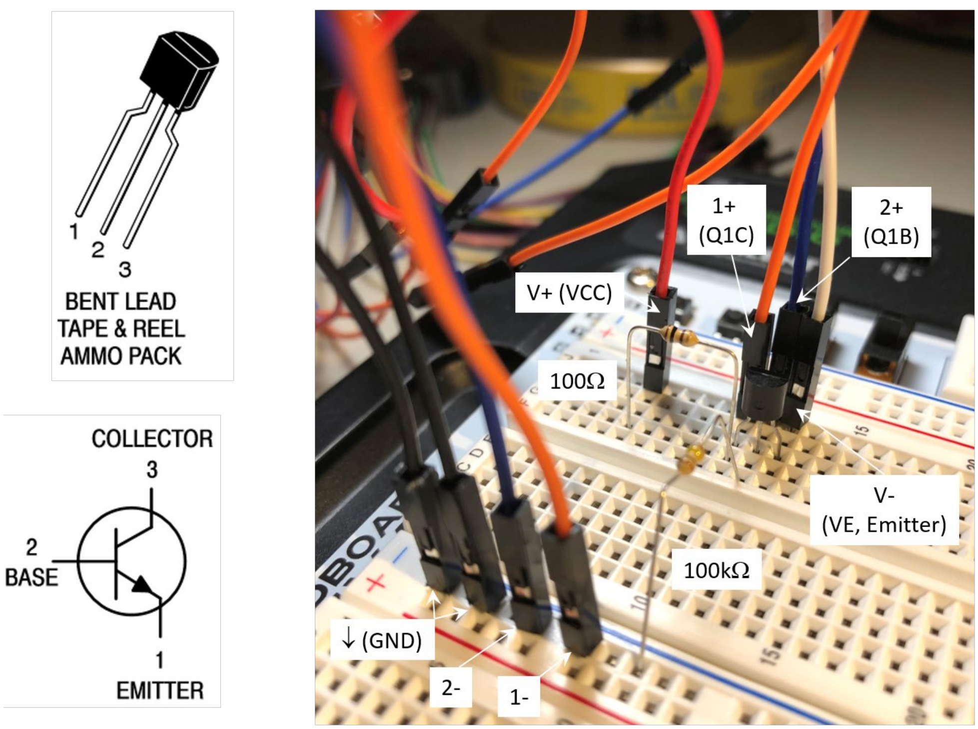


**Fig. 2** Experimental setup for the DC characterization of an NPN-BJT 2N3904

**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 $V_{CE}$ 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 $r_\pi$ 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 $r_\pi$ in kΩ?

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

**A. SPICE 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 shown in Fig. 3 to characterize a PNP-BJT 2N3906.

2.2 **DC Characteristics:** Set $V_E$ = 5 V, sweep $V_{CC}$ from -5 V to -0.5 V with a 0.5 V step, and record the collector voltage $V(Q_{1C})$ and the base voltage $V(Q_{1B})$ 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 $I_C$ vs. $V_{EC}$ plot for $V_E$ = 5V in the excel file, calculate the $|V_A|$ value for $V_E$ = 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 $V_E$ from 4.5V to 1 V with 0.5 V step, respectively.

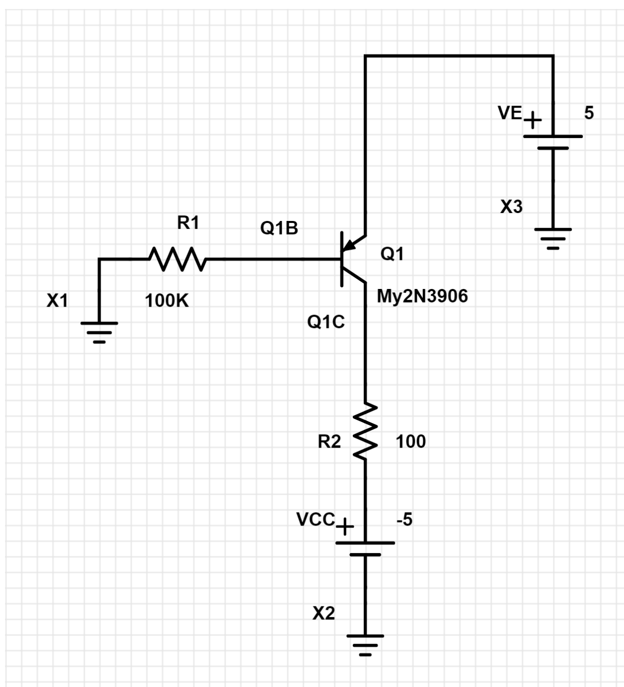


**Fig. 3** The schematic diagram for the DC characterization of a PNP-BJT 2N3906

**B. AD2 Measurement**

2.5 Prepare the circuit, as shown in Fig. 4, using the same settings for $V_E$ and $V_{CC}$ in Steps 2.2 to 2.4.

2.6 **DC Characteristics:** Start the 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 measurement progress 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 $V_C$ and the base voltage $V_B$ for each V+ (or $V_E$) 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 $I_C$ vs. $V_{CE}$ plot for each $V_E$ 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”.

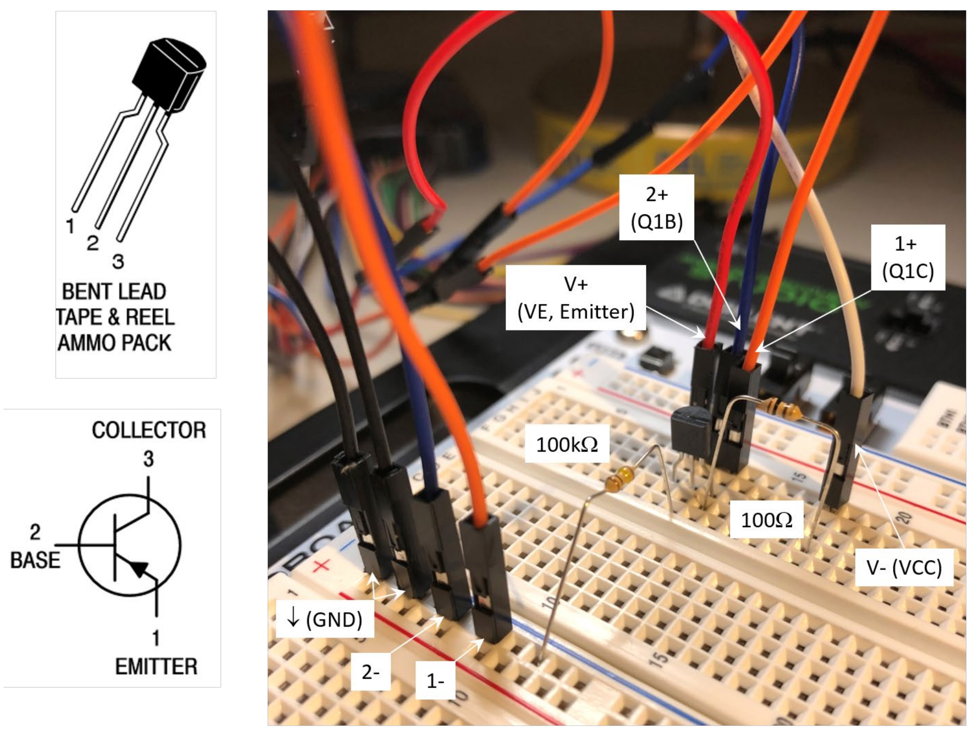


**Fig. 4** Experimental setup for the DC characterization of a PNP-BJT 2N3906

**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 $V_{EC}$ 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 $I_C$ value to the desired collector current, find out

(1) What are the simulated $V_{EBon}$ 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 $r_\pi$ 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 $V_{EBon}$ 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 $r_\pi$ 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, we need to consider the following to implement this function using a BJT.

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 $V_{o,max} = V_{CC} - 0.3\text{V}$.

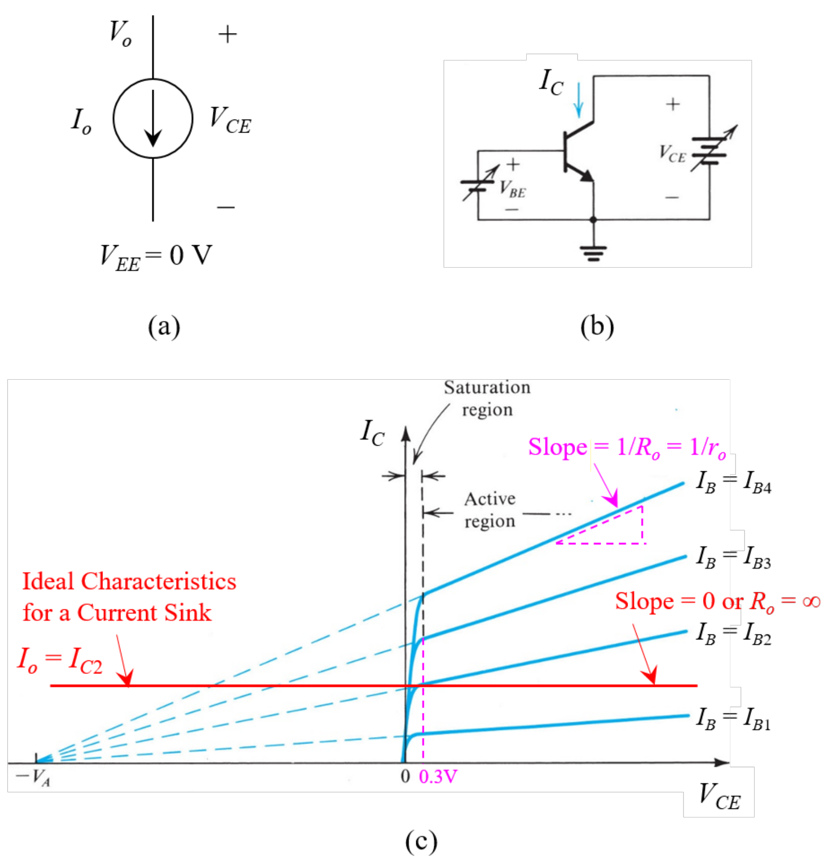


**Fig. 5** (a) Ideal current sink, (b) implementation of a current sink using an NPN-BJT, and (c) ideal and actual characteristics of a current sink.

## A. SPICE Simulation

3.1 In PartSim (LTspice or PSpice), construct a current sink as shown in Fig. 6 and load the SPICE 3 model parameters for Q1 following the same procedure as in Step 1.1.

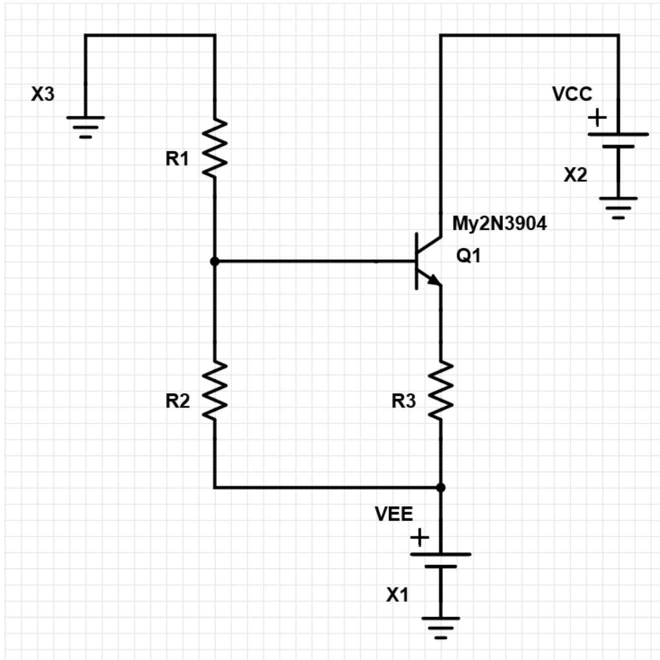


**Fig. 6** Constant current sink using an NPN-BJT 2N3904

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

$$V_{BB} = V_{EE} + \frac{R_2}{R_1 + R_2}\left(0 - V_{EE}\right) = V_{EE} - \frac{R_2}{R_1 + R_2}V_{EE} = \frac{R_1}{R_1 + R_2}V_{EE} < 0 \quad (1)$$

and

$$R_{BB} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}. \quad (2)$$

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

$$I_B = \frac{V_{BB} - \left(V_{EE} + V_{BEon}\right)}{R_{BB}} = \frac{R_2}{\left(R_1 + R_2\right)} \frac{\left(-V_{EE}\right)}{R_{BB}} - \frac{V_{BEon}}{R_{BB}} > 0. \quad (3)$$

Note that $-V_{EE} > 0$ and $V_{BB} < 0$ in (3). From (1) and (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 transistor's base current (or Q-point).

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 $I_B$ to be 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 the $V_{BE}$ of $Q_1$ and therefore increase $I_B$.

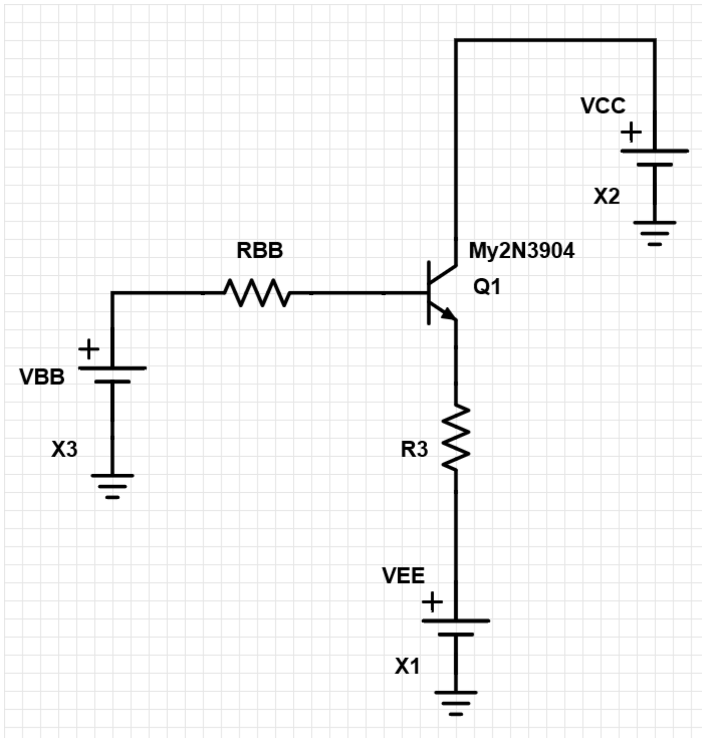


**Fig. 7** The equivalent circuit for the constant current sink in Fig. 6 with $R_1$, $R_2$, and power supply replaced by its Thevenin equivalent circuit $V_{BB}$ and $R_{BB}$.

## 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 $\beta$.

**Q6. (10 Points)** Comparing the $I_B$ expression obtained in Q5 with (3), what is the difference between these two equations? For a change $\Delta V_{EE}$ in the power supply $V_{EE}$, derive equations for the resulted change in the base current $\Delta I_B$ using (3) and the $I_B$ expression obtained in Q5. Show that the emitter resistor $R_3$ reduces the change in the base current $\Delta I_B$ as a result of the change $\Delta V_{EE}$ 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 $R_o = r_o + \left[R_3 \parallel \left(R_{BB} + r_\pi\right)\right]\left[1 + g_m r_o\left(\frac{r_\pi}{R_{BB} + r_\pi}\right)\right]$.

**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 $R_3 \neq 0$?

**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 screenshot of the simulated $I_o$ vs. $V_{CC}$ characteristics.

**Q10. (10 Points)** When designing the constant current sink shown in Fig. 6, we assume that $|V_{CE}| \geq$ 0.3V and $Q_1$ works in the active region. Based on the resistance values obtained in Q9, sweep $V_{CC}$ in Fig. 6 from -5 V to +5V with a 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.