Lab 11: Bipolar Junction Transistor

1. Objectives

Characterize single Bipolar Junction Transistor (BJT), i.e. measure its input and output IV-characteristics.

Determine the BJT small-signal parameters: input resistance r_π, output resistance r_0 and transconductance g_m.

Observe the effect of bias on BJT small signal parameters.

2. Introduction

<u>BJT operation</u>

A bipolar junction transistor has three terminals: emitter (E), base (B) and collector (C). In BJT the current flowing from E to C (I_C) is controlled by changing voltage drop between B and E, or equivalently by changing current flowing into B terminal (I_B). In the most common circuits the signal current I_B is usually quite small as compared to I_C. Hence, BJT-based circuits can be used to amplify the signal since small input variations (low input power) can produce large output variation (high output power). Of course the energy is not generated from nothing inside BJT. The extra power that becomes available at the output comes from power supply that has to be present in BJT-based amplifier circuits (actually, power supply has to be present in any amplifier circuit). Hence, one can say that V_{BE} or I_B controls the amount of energy taken from DC power supply to change I_C.

One can recognize common emitter (CE), common base (CB) and common collector (CC) BJT configurations in circuits depending on which BJT terminal is grounded (i.e. used as a reference point for the input and output signals). A BJT gain stage can amplify voltage (CB), current (CC) or both (CE). *In this lab we will use only the CE configuration when the input voltage is applied between the base and emitter terminals, and the output voltage is taken at the collector with respect to the ground (emitter).*

Internally BJT is three layers of semiconductors of different conductivity types. For instance, in n-p-n Si-based BJT the emitter is n-type Si, base is p-type Si and collector is again n-type Si. Hence, inside the BJT there are two pn-junctions. By applying voltages between terminals, one can bias Base-Emitter or Base-Collector junctions either in forward or reverse direction. In n-p-n BJT the positive $V_{BE} = V_B - V_E$ means forward bias to B-E junction. Forward bias of the B-E junction lowers the energy barrier for electron injection from Emitter to Base (Figure 1). Electrons from the Emitter are injected to Base and can diffuse across the B provided that they are rapidly removed at the B-C junction. For this purpose the B-C junction is reverse biased, i.e. $V_{BC} = V_B - V_C$ is negative. In other words, the positive Collector accepts electrons coming from Emitter through the Base.

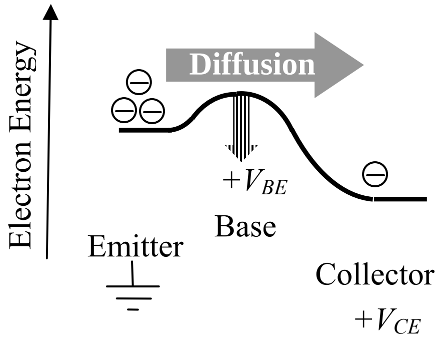

Figure 1

The hole current in n-p-n BJT is unwanted current component and it is minimized by design of BJT transistor. One manifestation of the hole current is recombination current in Base, i.e. electrons that came from Emitter recombine inside the Base with holes that came from Base terminal. The flux of hole from Base terminal is essentially the base current I_B. To make the base current small as compared to the emitter current, the Base width is made very small and the acceptor concentration (doping) in the Base is made much smaller than the donor concentration in the Emitter. Thus, with increase of the B-E forward bias we get small flux of holes coming from Base (small I_B) and large flux of electrons from Emitter into Collector (large I_C). Since $I_B << I_C$, in many cases one can use approximation $I_C=I_E$. The ratio of collector and base currents is the BJT current gain β. Usually the current gain is being introduced for variations of current i_B and i_C around some preset value I_{B0} and I_{C0} – bias currents.

$$\beta = \left.\frac{\partial I_C}{\partial I_B}\right|_{I_{B0}}, \text{ or } i_C = \beta\, i_B\,, \tag{1}$$

where lowercase letters denote amplitudes of AC signals, while capital letters denote DC values.

BJT operation regimes

The mode of operation described above is called *forward-active-mode* (B-E forward biased and B-C reverse biased). Forward active mode of operation is used for signal amplification. For amplification of AC signals it is necessary to apply positive DC voltage to the base to keep the B-E junction forward biased for both half-waves of the AC signal. If the amplitude of AC signal is larger than DC bias - for the negative half-wave the B-E junction will be under reverse bias. When B-E is reverse biased (more precisely, not forward biased) The BJT is switched off and cannot conduct the current; this is the BJT *cutoff-mode*. Besides keeping B-E junction forward biased the C-B junction has to be reverse biased for BJT to stay in *forward–active-mode*. When both B-E and C-B junctions are forward biased, the collector is not extracting electrons from base but actually is trying to inject them there. The BJT is than enters *saturation-mode*.

In CE configuration, the input AC signal with amplitude v_{BE} controls the output AC current with amplitude i_C, i.e. BJT is characterized by *transconductance:*

$$g_m = \frac{\partial I_C}{\partial V_{BE}}, \text{ or } i_C = \beta i_B = g_m\, v_{BE} \tag{2}$$

The BJT *input characteristic* is highly nonlinear because base current I_B depends exponentially on the base-emitter voltage:

$$I_B \propto \exp\left(\frac{V_{BE}}{V_T}\right) \tag{3}$$

BJT *input impedance* for AC signals, r_π, is obtained by differentiation of equation (3)

$$\frac{1}{r_\pi} = \frac{\partial I_B}{\partial V_{BE}} = \frac{I_B}{V_T} \tag{4}$$

One can see that r_π decreases bias current I_B.

In *forward-active-mode*, the collector current I_C should be ideally independent of collector voltage V_{CE}, i.e. the BJT *output characteristic* I_C (V_{CE}) is a horizontal line that shifts up and down in accordance with changes in base current I_B. In the real BJT, I_C increases with V_{CE}. This dependence can be described by BJT *output impedance* r_0.

$$r_0 = \frac{\partial V_{CE}}{\partial I_C} = \frac{V_A}{I_C} \tag{5}$$

Here V_A is the Early voltage parameter (typically in the range of 100 - 200 V). Again r_0 is bias dependent.

Figure 2 shows the circuit to be used to characterize the n-p-n BJT. VBB and VCC are two power supplies that serve to bias the transistor into *forward-active-mode* as well as to give energy for signal amplification. Resistor R_{load} converts AC current i_C into AC output voltage v_{out}. This resistor also limits the current in the collector path. If input current amplitude becomes too large, than for positive half-waves output current I_C saturates at the maximum value of $I_{Cmax} = V_{CC}/R_{load}$. BJT enters the *saturation-mode* where it cannot control the output current because the output voltage is near zero. In modern BJTs the typical C-E *saturation voltage* V_{CE}^{SAT} is 0.2-0.3 V. In this mode the C-B junction is not reverse-biased. In the *saturation-mode* the BJT transconductance is small.

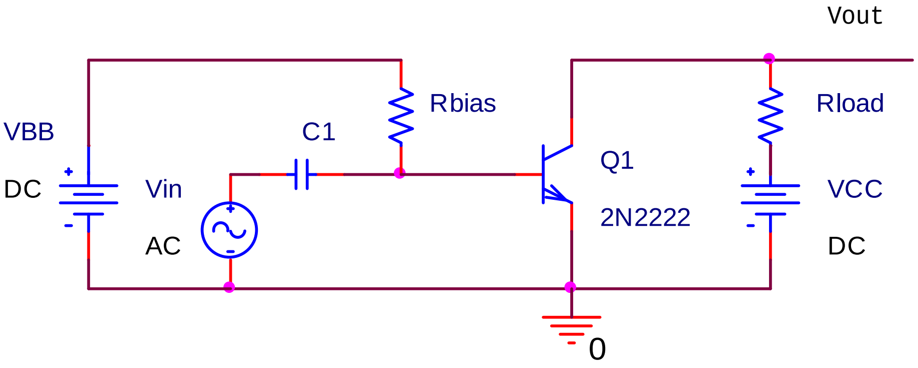

Figure 2

3. Preliminary lab

Simulate using PSPICE the circuit in Figure 2.

*For **A.** and **B.** use R_{bias} = 100 kΩ, R_{load} = 0 Ω, remove AC source and C1 from circuit.*

A. Obtain BJT input characteristics, i.e. simulate dependence of I_B on V_{BE} for fixed value of V_{CE} To perform the simulation DC-scan the value of VBB at fixed V_{CC}. Plot two dependences $I_B(V_{BE})$ for $V_{CC} = V_{CE} = 0$ V and 10 V on the same graph. Obtain dependence of r_π on I_B using simulated data.

B. Obtain the BJT output characteristics I_C (V_{CE}) for $I_{B1} \cong 10$ and $I_{B2} \cong 20$ μA, i.e. perform DC-scan of VCC at fixed V_{BB}. The values of V_{BB} required to produce I_{B1} and I_{B2} can be estimated assuming 0.7 V of voltage drop across forward biased B-E junction. Present both output characteristics on the same plot. Find the values of I_C corresponding to the given I_B currents at $V_{CE} = 5$ V. Calculate r_0 for these collector current values.

*For **C.** use R_{bias} = 100 kΩ, R_{load} = 1 kΩ, V_{CC} = +10V.*

C. Obtain dependence of i_C on I_B in the range of I_B values from 0 to 100 μA with 20 μA steps (adjust V_{BB} to obtain the required I_B). Plot the BJT transconductance as a function of I_B.

4. Experiment

The experiments will be performed with n-p-n BJT 2N2222A. Assemble the circuit in Figure 3 with the following parameters: R_{bias} = 100 kΩ, R_{load} = 1 kΩ, C_1 = 10 μF.

1. <u>Input characteristics</u>.

Set V_{CC} = 10 V and vary V_{BB}.

Perform point-by-point measurement of the dependence of I_B on V_{BE} using DMM. I_B is the DC bias current that can be calculated from the voltage drop across R_{bias}.

Present the result in Table 1.

Plot I_B versus V_{BE}.

Estimate the differential input resistance r_π from the slope of the curve.

Table 1

V_{BB}(V)	V_{BE} (V)	V_{Rbias} (V)	I_B (μA)
0.5			
0.7			
1.0			
1.2			
1.5			
1.7			
2.0			
2.7			

2. Output characteristics.

Set V_{BB} to get I_{B1}= 10 μA and vary V_{CC}.

Measure the dependence of I_C on V_{CE} in point-by-point manner using DMM. I_C can be calculated from the voltage drop across R_{load}.

Repeat for I_{B2}= 20 μA.

Present the result in Table 2.

Plot obtained dependences of I_C on V_{CE} in one figure. Estimate the differential output resistance r_0 from the slope of linear parts of the curves.

Table 2

V_{CC} (V)	V_{CE1} (V)	V_{Rload1} (V)	I_{C1} (μA)	V_{CE2} (V)	V_{Rload2} (V)	I_{C2} (μA)
0.2						
0.5						
0.7						
1.0						
1.2						
1.5						
2.0						
2.5						
3.0						
5.0						
10.0						

3. Transconductance

Measure the dependence of i_C on I_B using oscilloscope. Set V_{CC}= 10 V, apply an AC input v_{in} = v_{BE} with amplitude of 10 mV and frequency of 1 kHz.

Change I_B by varying V_{BB} like you did in previous experiments.

The i_C (amplitude of the collector current) can be calculated from the amplitude of the AC voltage across R_{load}.

Present result in Table 3. Calculate the transconductance g_m using equation (2) and plot dependence of g_m on I_B.

Table 3

I_B (μA)	i_C (mA)	g_m (1/Ω)
5		
10		
20		
30		
40		
50		

Report

The report should include the lab goals, short description of the work, the experimental and simulated data presented in plots, the data analysis and comparison followed by conclusions. Please follow the steps in the experimental part and clearly present all the results of measurements.