Serie 06

Preamble

In Lecture 6, we introduced the Bipolar Junction Transistor (BJT) and its equations. Many approximations and assumptions are made during the demonstrations, and we recall them here. In order to understand them and the BJT in general, it is important to get familiar with the notation that indicates different positions along the device length. We report below the minority carrier profiles of a BJT with short base, emitter, and collector in forward operation, as an example. The focus is on understanding the meaning of the different positions along the x-axis.
Back to the assumptions and approximations:

1. **Short base approximation.** A well-designed BJT has a very short base (compared to the electron diffusion length): $W_B{}^{'} = W_B – X_{pE} - X_{pC} << L_{nB}$. In forward operation, this ensures minimal recombination of electrons injected into the base from the emitter, which are then accelerated by the electric field in the depleted region of the base-collector junction (reversely biased) and easily collected by the collector. This ensures a high gain of the BJT. This is always the case for a good BJT. This entails that the minority carrier profile in the QNR of the base is always approximately linear with x (see Preamble and Solutions of Serie 05) and depends on $W_B{}^{'}$, and not on L_{nB}.

2. **Influence of the base depleted regions.** As we saw in Serie 05, in the short neutral side case, the minority carrier profiles depend on the side length W minus the depleted region on that side X_p (or X_n). We also know that the extension of the depleted region depends on the bias applied to the junction. This is what causes in a BJT the Early effect, for example, where the collector current I_C changes as a function of V_{CE} because this modulates the width X_{dC}, therefore $W_B{}^{'}$, and therefore the common base current amplification in forward operation β_F. In some cases, the width of the base depleted regions will be neglected so that $W_B{}^{'} \sim W_B$. This approximation has to be verified by calculating the widths of the depleted regions at the specific operation point.

3. **Emitter and Collector neutral sides lengths.** Once again, depending on the length of the emitter and collector neutral sides compared to the diffusion length of holes (for an NPN transistor), the holes minority carrier profile can be exponential or linear in the QNRs. The formulas for the diffusion currents have to be adjusted accordingly. In particular, the common base current amplification in forward operation α_F has to be adjusted to consider $W_E{}^{'}$ or L_{pE}.

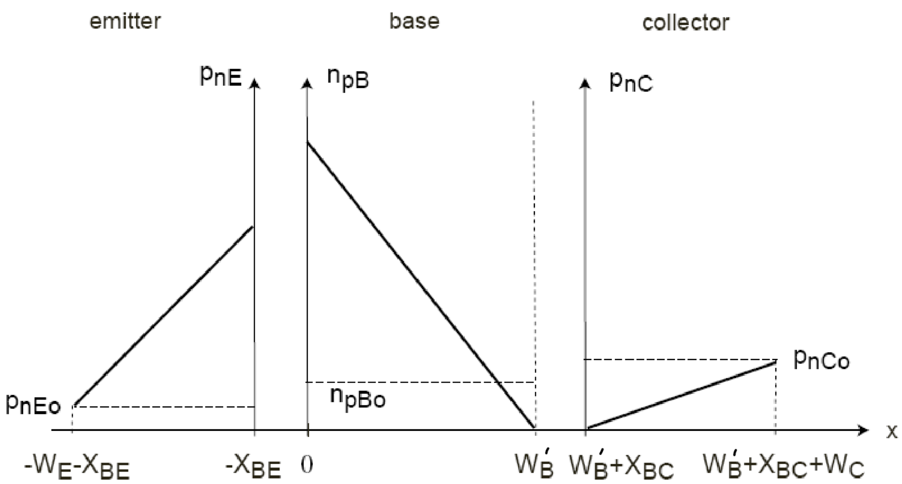


Figure 1: Minority carriers profiles in a NPN BJT in forward bias.

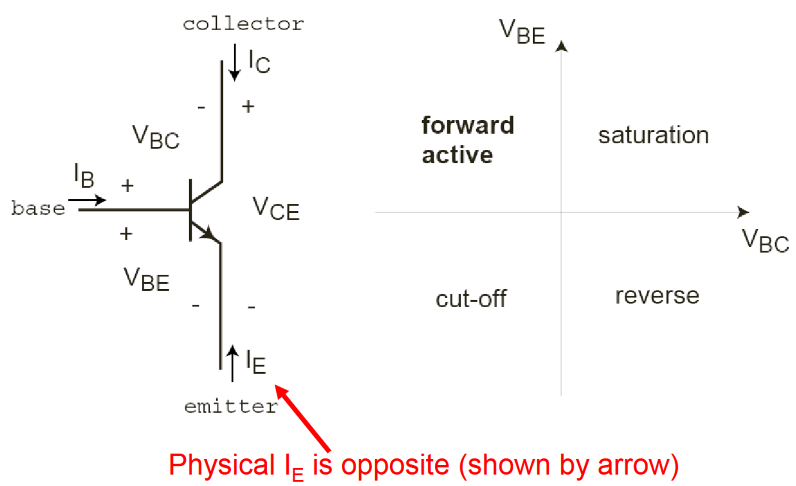


Figure 2: NPN BJT: circuit symbols and operating regions.

Exercise 01

Consider the properties associated to the polarization of a bipolar junction transistor (BJT) in different regions: **forward active, reverse, saturation, cut-off**.
Among the following sentences, select the correct ones.

Q1. The BJT can be used in analogical amplification applications both in forward active region and in reverse region.

Q2. The amplification factor β is independent on the polarization region.

Q3. From a circuital point of view, a BJT is equivalent to two junction diodes.

Q4. The saturation region is interesting for an application as an electronic switch, due to the low resistance.

Q5. The large difference in the values of β in the forward and reverse regions is due to the difference in doping between the emitter and the collector (the transistor is optimized only for the forward active region).

Q6. In saturation, we can approximate V_{CE} $\sim$0 V.

Q7. The values of the factor β=I_C/I_B in the saturation and forward active regions are identical.

Q8. The values of the factor β in the forward active and reverse regions for the same transistor can be equal, if the BJT has perfectly symmetric doping of the emitter and collector.

Q9. The slope of the characteristics I_C and I_B as a function of V_{BE} is limited to 60 mV/dec at T=300 K, as in the junction diode.

Exercise 02

Calculate the relationship between the current amplification factor $\beta = I_C/I_B$ and the factor $\alpha = I_C/I_E$ of a BJT in forward active region. Find the values of β for $\alpha = 0.95$ and 0.99.

Exercise 03

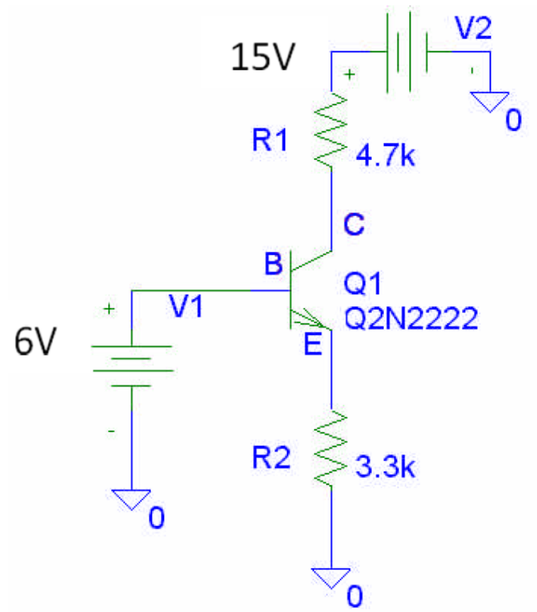
Determine the ratio between the doping concentration of the emitter N_{DE} and that of the base N_{AB} in an NPN BJT, so that the common base current amplification in forward operation is $\alpha_F = 0.9967$. What is the physical meaning of α_F? How can the common emitter current amplification in forward operation β_F be improved technologically?
For this exercise, we suppose $D_p \approx D_n$ and $W_B \approx W_E$, with W_B and W_E much smaller than the minority electrons and holes diffusion lengths. We also neglect the width of the depletion region of the B-E junction.

Exercise 04

Calculate the change in the neutral base width W'_B of a bipolar transistor with the voltage V_{BC}. Assume uniform doping concentrations $N_{AB} = 5 \cdot 10^{16} \left[cm^{-3}\right]$ and $N_{DC} = 2 \cdot 10^{15} \left[cm^{-3}\right]$, the transistor at room temperature $T = 300\,[K]$ and in forward operation region. The metallurgical dimension of the base is $W_B = 0.70\,[um]$. The voltage V_{BC} changes from $-2\,[V]$ to $-10\,[V]$. By how much, in %, does the neutral base width change when V_{BC} has the proposed variation? Discuss the impact of this observation on the collector current and the definition of the Early voltage of the bipolar transistor.

Exercise 05

Consider the following circuit containing a NPN BJT:



Suppose that $\beta = 100$, $V_1 = 6$ V, and $V_2 = 15$ V. Determine in which region the transistor is working and calculate the tensions V_{BE}, V_{CE}, V_{BC}, and the currents through the transistor.