

Laboratory exercise: the Bipolar Transistor

Semiconductor Physics 2017

Lab meeting point – k-space at Solid State Physics

This exercise consists of two experimental parts and one simulation part.

In the first experimental part you will be measuring the IV -characteristics of a Si nnp -transistor in the common emitter mode and analyse the gain of the transistor in a so called Gummel plot.

In the second experimental part you will be using a transistor to amplify a small current.

In the simulation part you will use commercial software which is used for industrial design of semiconductor devices. We will use the software to study physical parameters such as electric field and carrier concentration inside the device.

As a preparation for this lab you need to study the handout and the chapter about the bipolar transistor in the text book (chapter 4 in Sze 3rd edition, chapter 5 in the 2nd edition) and complete the following tasks.

1. Make a sketch indicating the currents in a bipolar transistor in active mode.
2. Make a sketch of the *minority* carrier concentrations in active mode
3. Make a sketch of the *majority* carrier concentrations in active mode (assuming low-level injection)

Device layout

In the simulation software, it may take some effort to identify the emitter, collector and base regions of the device. Look at the screenshot below:

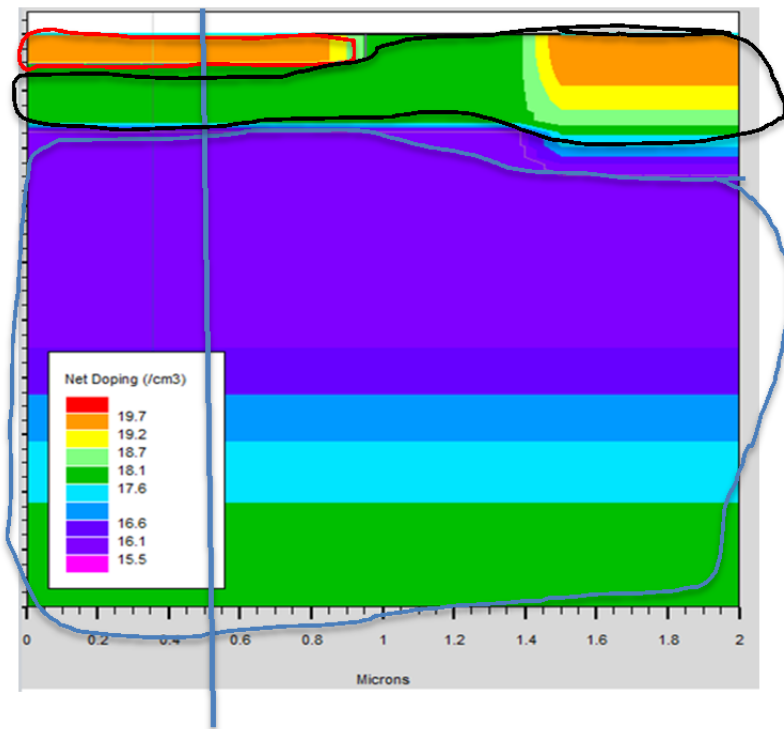


Figure 1: Screenshot from ATLAS.

The emitter is the highly doped region on the top left (orange, outlined in red).

The base is below it (green, outlined in black). The region of base doping extends out to the right hand side where there is a heavily doped area (orange) under the top base metal contact. The purpose of a high level of doping under the metal contact is to reduce the resistance at the semiconductor/metal interface.

Below the base is the lighter doped collector region (purple/blue/green, outlined in blue), taking up the majority of the structure above. The collector contact is at the bottom of the entire structure.

The emitter-base-collector sequence is thus arranged vertically in the image along a vertical line such as the one inserted in the figure. This is the direction of current in the device.

Simulation Part

The simulation program numerically finds the solution to a set of coupled differential equations (the Poisson equation and the continuity equations). The solutions to these equations, with proper boundary conditions, determine all intrinsic parameters like potential, electric field and carrier concentrations. The program uses a finite element method, where the device geometry is divided into a fine mesh. Numerical iteration is then performed for each mesh point in order to determine the solution to the differential equations.

About the software:

We are using a commercial software tool, ATLAS by Silvaco, for the simulations. The program basically consists of a numerical solver, which finds a solution for for instance carrier concentrations, electric fields and band structure by iterations as described above.

The program is controlled via a set of tools for graphical interaction. In this exercise, we will be using a module called **Deckbuild**, into which we will load a code defining the device geometry. The software then deduces solutions for various boundary conditions (biases or current levels) and saves the solutions to output files.

The second module we will use is a graphical interface called **Tonyplot**, which displays the calculated values graphically. We can for instance obtain 2D plots of the device geometry and of physical parameters, like the electrical field and the carrier concentration. In addition to the 2D plots we can also make cuts through the device geometry and study 1D cross-sections of the device. Finally, Tonyplot may also be used to plot the calculated IV-characteristics.

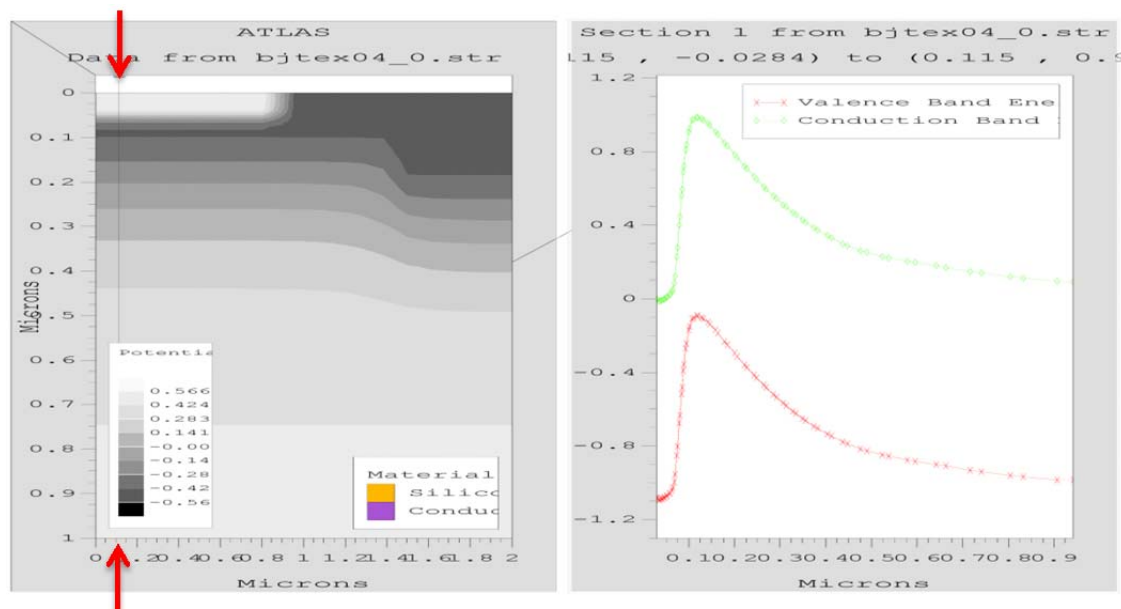


Figure 2. Example of output from the Silvaco modelling tool on a bipolar transistor. Left: 2D plot of potential. Right: valence and conduction band edge energies along the vertical cut in the left image.

Running the simulations

Start the simulation tool `Silvaco Deckbuild`. A shortcut is located on the desktop. The computer must be connected to the licence server via LU Web-logon.

Load and run `bipolar_lab_2015.in`

The doping profiles are graded instead of constant, in contrast to doping profiles depicted in the textbook. In a commercial device, doping profiles would typically be graded.

Three bias setups (with the emitter always at 0 V) are included:

1. no applied biases (thermal equilibrium),
2. reverse biases of 1 and 2 V on the BC junction
3. reverse bias of 2 V on the BC junction and biases of 0, 0.5 and 1 V on the EB junction

Study the `.in` file. The first part sets the geometry and doping levels of the device. The second part solves for carrier concentrations, band structure etc. and creates output files. There is no need for you to understand each command but the overall structure of the program should be clear.

In the `.in` file, there is a `quit` command after each of the setups above. In order to proceed from setup 1 to set up 2 and so on, you need to remove the `quit` command and run the code again. Take screenshots related to the tasks/questions below for your report!

Setup 1 (output `Vb0_Vc0.str`)

- Familiarize yourself with the structure (by looking at the plot similar to that in Fig 1 on the previous page). In what direction will current run? How will electrons and holes flow? How do we need to bias the transistor to put it in active mode?
- Define a cut-line and check that bands, fields and carrier concentrations match what you would expect from the doping profile.
- Notice the degenerate doping in the emitter – Fermi level (QFL) in the conduction band.

Setup 2 (`Vb0_Vc0`, `Vb0_Vc1`, `Vb0_Vc2`)

- How can we see that there is now a bias applied to the structure?
- Across which junction (EB or BC) is it applied?
- How large are the biases?

Setup 3 (`Vb0_Vc2`, `Vb05_Vc2`, `Vb1_Vc2`).

- How can we tell that the EB junction is forward biased? Estimate the applied forward biases from the plots.
- Compare the electron concentration in the collector to the collector doping. Do we have high or low injection?

Gummel and IV plot

- Does it look as you would expect?
- What happens at high base voltages?
- What happens at low base voltages?
- At what base does the transistor work in active mode?

Experimental Part 1:

A. IV-characteristics

We will start the experimental part by measuring the IV -characteristics of a Si npn bipolar transistor in the common emitter mode. These measurements will be performed by the measurement set-up shown below where we vary the base current as well as the emitter-collector bias V_{CE} and measure the current I_C through the collector. These measurements are performed for a set of different base currents I_B and hence we get the IV -characteristics for a bi-polar transistor in common-emitter mode (fig 10 p. 137 in Sze 3rd edition and fig 10, page 145 in the 2nd edition).

Connect the instruments as shown below:

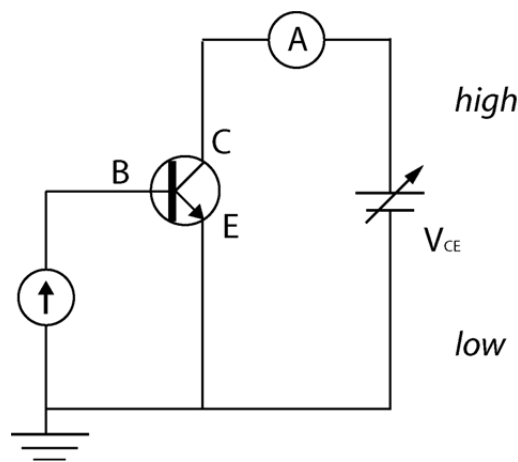


Figure 3 Experimental set up for IV characterisation in common emitter mode.

- Measure the IV characteristics. Use input parameters:
 - $V_{\text{start}} = 0\text{V}$, step = 0.1V , $V_{\text{stop}} = 6\text{V}$,
 - Start base current = 0A , Stop base current = $100\text{ }\mu\text{A}$, step = $20\text{ }\mu\text{A}$
- Estimate I_{CE0}
- The IV curves have a certain slope. Explain why!

B. Gummel plot

The gain of a transistor is a key parameter and we will be measuring it in a so-called Gummel plot, where I_C and I_B are plotted as a function of V_{BE} (left part of figure 4).

We will thus measure the base- and collector current as a function of the base-emitter bias at a fixed collector voltage (2V). I_C/I_B will give the common emitter gain, β , of the device. The measurement set-up is pictured in figure 4.

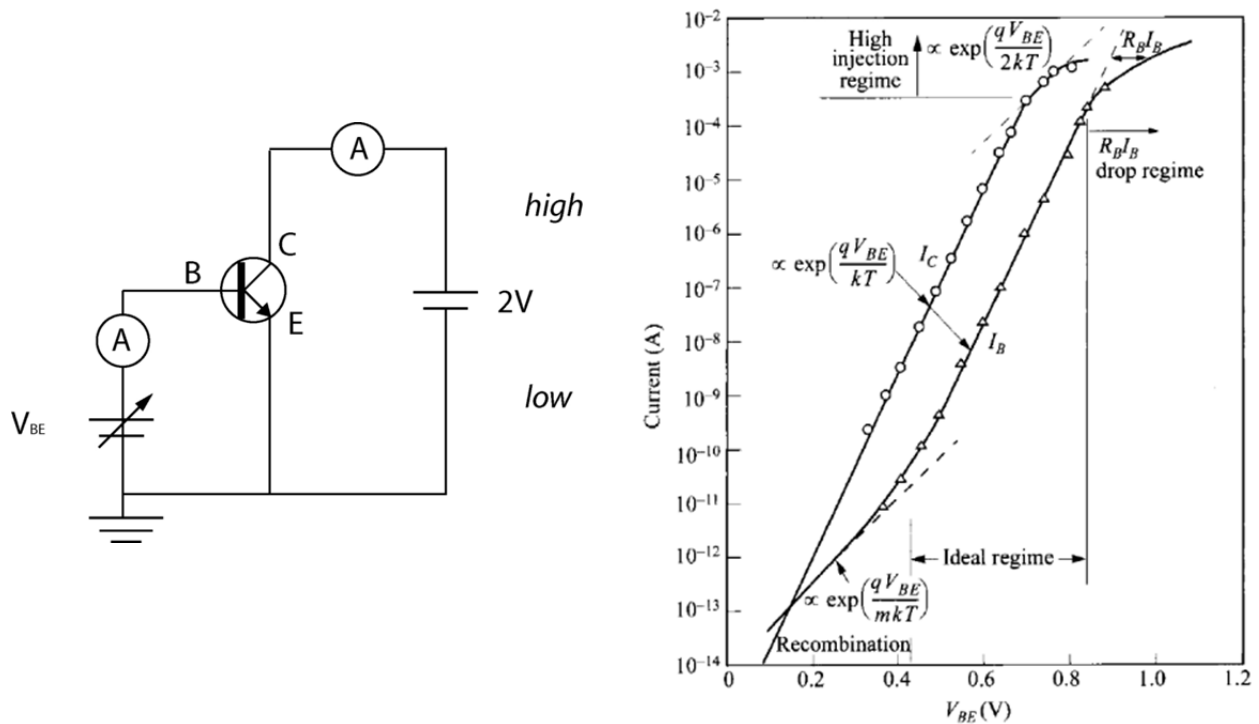


Figure 4 Left: Experimental set-up to obtain a Gummel plot. The base and collector currents are measured for varying base-emitter voltages. Right: example of a Gummel plot.

Measurements

- Connect the instruments as in fig 4
- Measure the Gummel plot (base and collector current while sweeping the base voltage). Use input parameters:
 - $V_{\text{start}} = 0.1\text{V}$, $V_{\text{stop}} = 1.1\text{V}$ and $V_{\text{step}} = 0.05\text{V}$.
- Plot I_C and I_B vs V_{BE} .

Data Analysis and Discussion

- Calculate the common emitter gain β for each value of collector current and plot it as a function of collector current. What does β describe and why is it (for application purposes) important to have a region of nearly constant value of β ?
- From β , find the common base gain, α , and include that in your plot of β . What does α describe and what is the theoretical maximum value for α ?
- Why is the common emitter gain lower for very small and very large collector currents?

- Discuss the problems of obtaining a high gain in the device. Is it, for instance, possible to combine a high gain and a high current level?
- Is the transistor symmetric? What would happen to α and β if we used it “backwards” (using the lower doped collector as emitter)?
- If you, in common emitter mode, want to amplify a small sine wave (symmetric around 0V), which we apply on the base, what do you need to do?

Experimental Part Two:

This part aims at giving a brief practical experience of using a BJT in a circuit. Your task is to design a set-up in which a photo resistor is used to switch on or off a small fan.

The transistor should be used in common-emitter mode. The idea is to control the base current using a photo resistor. When the photo resistor is in darkness (put your hand over it) it has a high resistance and then base current is very low. If so, the collector current is also low (not large enough to run the fan). When you allow light to reach the photo resistor, the resistance is small allowing a higher base current to flow. The collector current is increased accordingly, and ideally it is large enough to make the fan start spinning.

Make a sketch of how you would like to realize the circuit and show it to the supervisor. You will use a single 9 V battery to provide both V_{BE} and V_{CE} .

Next, examine the parts and do some calculations:

- Measure the resistance of the photo resistor in darkness and in bright light. Assume that the maximum allowed current (a higher current causes it to break) in the photo resistor is approximately 5 mA. Do you need to put an additional resistor in series with the photo resistor in order to limit the current? Assume that the voltage drop over the base-emitter junction, V_{BE} , is 0.6 V.
- How much current does the fan draw?
- What is the common emitter current gain of the transistor BC548B? (Datasheet will be available.)
- Given the current level of the fan and the gain, what is a suitable base current in order to make the fan go at full speed? Even if your circuit cannot supply enough base current, it may still be enough to make the fan spin, although at a lower speed.

Now connect the components on the prototype board and connect the supply (battery).

Don't close the circuit until you are sure that your setup is ok – check with the lab supervisor. Be alert for smoke and smell of hot components.

If your setup is working as intended, proceed to measure the following:

- What is the voltage drop over the fan at high and low illumination?
- What is the base-emitter voltage at high illumination?

For the lab report:

Your report should show that you have understood the relevant physics. You need to include plots (output from simulation and your measurements) and analysis, and discuss your results. Specifically:

- a) Experimental part one: plot the measured data of the transistor (IV characteristics and Gummel plot) and answer the questions in the text.
- b) Simulation part: show some results of the simulation and explain what you see. Answer the questions in the text.
- c) Experimental part two: show a sketch of the circuit. Answer the questions in the text.