Jacobs University Bremen

CH-210-B
Electrical Engineering I Lab

Fall Semester 2020

Course Electrical Engineering I Lab – CH-210-B

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3. Week

   (a) Experiment 4 : Single PN - Junction

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2. Grading of the course

1. All grades are collected in percent according to the Jacobs grading scheme.
2. The lab is a part of the module CH210 and counts 30%. The grade is collected by writing lab reports.
3. Attendance to the course is mandatory. Missing an experiment without valid excuse will subtract 1/6 or 5% from the lab grade.

2.1 About the Lab reports

1. For the experiment(s) of a week every student has to deliver the data for all experiments and has to write one report. In total 3 reports for the whole course. Grading is done individually. Reports are no group work.
2. The reports have to follow the '**Report Writing Guidelines**'. Objective of the lab is not only to consolidate the EE lecture. You should learn to conduct and to document an experiment and to interpret the results.
3. Submission of the notes and the requested number of reports is mandatory. A missing report count 0% for the grade!!!
4. The deadline for submission of the notes and the report is the second weekend after execution, Sunday evening 24:00! (In other words you should submit after nine or ten days after the experiment). In general:

   a. Only those reports are treated as delivered which include a sufficient amount of gradable content!!!!
   Rule of thumb: Reports without *Experimental Set-up and Results* and -SOLVED- *Evaluation* section definitely do not have enough content!

   b. Reports submitted after the deadline will be downgraded by one full mark per day (15.01%). After 7 days the report counts as not submitted!!!!

   Exams, other homework, a broken computer, missing data, etc. is noexcuse for no or late submission!

5. Return of the handed in report is usually about 2-3 days after delivery. After returning you are encouraged to correct and redeliver the report. You have one week (7 days) to do this. The grade will be adjusted dependant on your corrections.
6. In case of cheating or plagiarism (marked citations are allowed but no complete copies from a source) we will follow **'The Code of Academic Integrity'** and the report will be counted as 0%.
   Note that there there can be more consequences of a disciplinary nature depending on the circumstances.

3. Report Writing Guidelines

3.1 Report Structure

The main purpose for a lab report is to enable others to duplicate the work in a straightforward manner and to communicate the results. When preparing the report you can use word processors, spreadsheets, graphic and CAD tools. In case of computer problems a hand written report is fine too! Submitting is possible on paper or by Email. Preferred format is PDF. Try to avoid special formats. Convertors to PDF are available for all systems.
A report should be as short as possible but contain all necessary information. It should be presented in the following (or a similar!!) format:

1. *Cover Sheet*
   - Title (name of the experiment)
   - Location, Date of the experiment, Semester
   - Names of the students in the group
   - **and important** - Name of the author of the report
   - **also important** - IRC mailbox number
2. *Introduction*
   Objective of the experiment and a short summary of the theory.
3. *Experimental Set-up and Results*
   This section is the documentation of the conducted experiment:
   - Show the experimental set-up (circuit) and describe the procedure.
   - Show the results of the experiment.
4. *Evaluation*
   Here you should answer all the questions from the Evaluation section(s). Answer as short as possible. For any calculation show the used formulas together with the numbers and units. The result should have a reasonable number of digits.

   Depending on the experiment item 3 and 4 may have several subsections. In this case it is sufficient to specify the used instruments only once in the beginning of the section!
5. *Conclusion*
   This is the final part of the report! Here you should summarize the results and compare them to theory. Draw your conclusions related to the topic of the experiment. Address directly what has been learned in lab. Discuss the possible errors and deviations so far not already done during evaluation.

6. *References*
   List **-ALL-** sources you used to write the report.

7. *Appendix*
   The data of the other experiment of the week.

You can find a skeleton lab report on the course web page under 'GeneralEELab I & II Files' *'Other Important Documents'*

3.2 An advice to save your time

It is a good idea to prepare an experiment the day/ morning before the lab. At least read the manual better also a second source. Prepare the needed tables and graphs! During the experiment plot the graphs simultaneously, i.e., in Excel using the "XY (Scatter)" option. In this way you will see odd results straight away. In this manner a big part of the lab report is already done when leaving the lab.

3.3 My data 'disappeared' or 'I'm lost' because of the topic– what to do?

In case of 'lost' data ask your group mates or someone from other groups. Of course you can also get a full set from the instructor. In the last two cases don't forget to mention it in the report.
If you lose track among the evaluation questions ask the instructor! He should be more or less always available!!! Either personal in his office (9:00 to 16:00 for sure) or by mail. Contact info is on the cover page.

4. Manual Guideline

The manual and the course web-site contains all necessary information around the course. Beside this the manual includes a description of all experiments. Every experiment is divided in the Objective section and one (or more) sub section(s) with Preparation, Execution, and Evaluation.

The Objective Section should give an introduction to the problem. In some cases it also contains theory not completely covered in the lecture.

The Preparation Section describes the electrical setup.

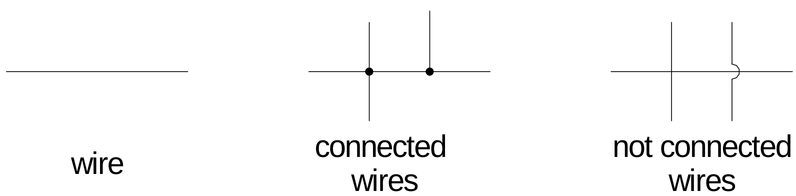
The Execution Section is a detailed description on what to do and how and what to measure.

The Evaluation Section should deepen the understanding of the topic. There are questions about the experiment. You should solve these with help of the taken data and compare the results to theory.
Before you start working on a (sub)section read **-the whole-** section carefully. Try to understand the problem. If something is not clear read again and/or ask the TA or instructor. Follow the preparation carefully to have the right setup and not to destroy any components. Take care that you record **-ALL-** requested data. You may have problems to write a report otherwise!!

4.1 Circuit Diagrams

Next is an overview about the used symbols in circuit diagrams.

Connections

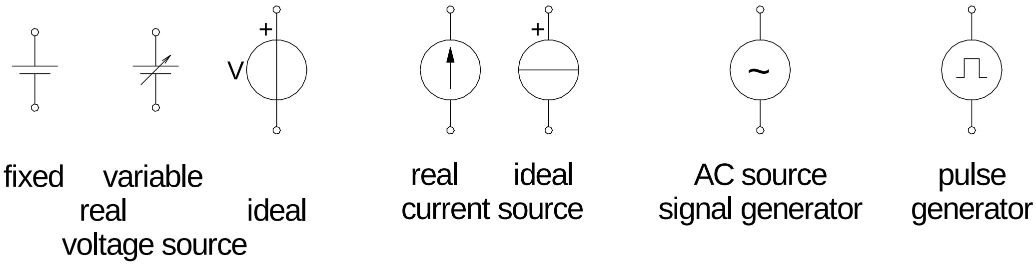


Connection are usually made using 1 or 0.5m flexible lab wires to connect the setup to an instrument or voltage source and short solid copper wires one the breadboard. In most of our experiments we consider these connections as ideal, i.e. a wire is a real short with no 'Impedance'. In the following semesters you will see that this is not true.

Instruments

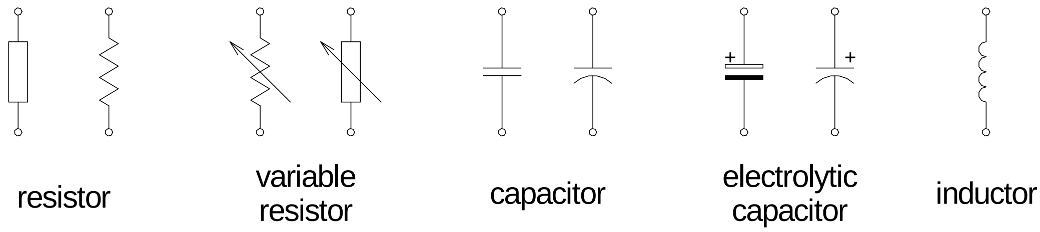
Since we have 'Multimeters' this symbol tells you how to connect and configure the instrument. Take care of the polarity. Be careful, in worst case you blow it!!!

Voltage/Current Sources



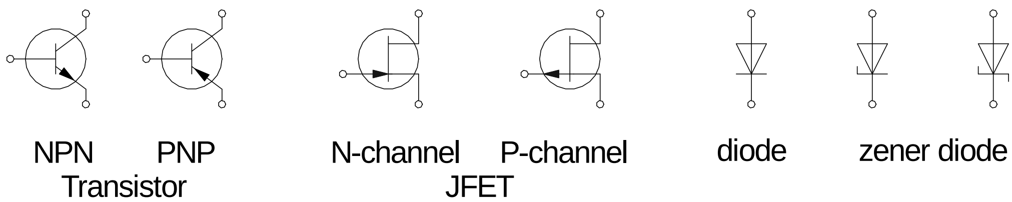
These are the symbols used in the manual. If you check the web and look into different books there are also other symbols in use!

Lumped Circuit Elements



There is a different symbol for every lumped circuit element. Depending which standard is used (DIN or IEC).

Semiconductors



Same as with the symbols before you may find different representations for every component!

4.2 Values in Circuit Diagrams

As you will see in the lab, we use resistors with colored rings. These rings represent numbers or a multiplier. Most of the resistors have five rings. Three digits for the value, one multiplier for the dimension, and one for the tolerance. In the circuit diagrams we have a similar scheme. There are three digits and a dimension. The letter of the dimension also acts as the comma i.e.:

1R00, 10R0, 100R	for	$1\,\Omega$, $10\,\Omega$, $100\,\Omega$	$(= Value * 10^0)$
1K20, 10K0, 100K	for	$1.2\,\mathrm{K}\Omega$, $10\,\mathrm{K}\Omega$, $100\,\mathrm{K}\Omega$	$(= Value * 10^3)$
1M00, 10M0	for	$1\,\mathrm{M}\Omega$, $10\,\mathrm{M}\Omega$	$(= Value * 10^6)$

The numbering for capacitors in the circuit diagram is similar. Only the dimension differs. Instead R, K, M (Ω, KΩ, MΩ) we have μ, n, or p (μF, nF, pF) (i.e. 1n5 means 1.5nF). The value is printed as number on the component.

4.3 Reading before the first Lab Session

As preparation for the first lab session read the description of the workbench, especially the parts about the power supply and the multimeter. You will find the document on the course Web page in 'GeneralEELab I & II Files'
'Instruments used for the Experiments'.

Part II

Experiments

5. Experiment 1 : Usage of Multimeter

5.1 Objective

This experiment is a two days experiment. It includes safety instructions and an overview about errors and error calculation. A short 'How To start' to write a report follows. Main purpose is to introduce and to demonstrate the usage of multimeters. The multimeter is one of the most important instrument in electrical engineering. It is used to measure basic electrical properties and a basic tool to troubleshoot circuit problems. In this experiment you should become familiar with the usage and learn how to get accurate results from the measurements.

5.2 Theory

To analyze the measurements we need Ohm's Law and Kirchhoff's Laws. Both topics should have been covered by the lecture. To apply these laws we also need some basic knowledge about the multimeter and it's usage.

5.2.1 Measuring Voltage and Current

There are several methods to measure these quantities. For nearly every method it is true that it takes power from the circuit under test.

!! Always keep in mind that a connected volt-, or ammeter changes the circuit under test !!

You are responsible to keep this influence negligible or at least acceptable.

5.2.2 Voltmeter

The voltmeter has to be connected in parallel to the circuit under test. It needs current to operate and determines the voltage by using Ohm's Law $U = I * R_i$. For general purpose instruments like the ones in the lab $R_i \approx 10\,\mathrm{M\Omega}$, for single range even $R_i \approx 2.5\,\mathrm{G\Omega}$. The actual resistance of the voltmeter is given in the manual. Under all circumstances the current has to be negligible compared to the current used by the circuit. If you do not take care the measured value might be accurate but it is wrong because of the internal resistance. You changed the circuit and the device under test doesn't work properly anymore!!

5.2.3 Ammeter

An ammeter has to be connected in series to the load. It determines the current also by using Ohm's Law $I = U/R_i$. For the TENMA the resistance varies dependant on the range between $0.05\,\Omega$ and $500\,\Omega$. For the Elabo the actual resistances are given in the manual. From the formula you can see that you include two errors into your circuit. First you add an additional load, i.e. the overall current is lowered. Second you get a voltage drop lowering the voltage at the load. Under all circumstances the voltage drop has to be negligible compared to voltage at the load. If you do not take care the measured value might be accurate but it is wrong because of the internal resistance. You changed the circuit and the device under test doesn't work properly anymore!!

5.2.4 Multimeter

A multimeter is a combination of several functions. In almost all cases it is able to measure voltage, current, and resistance. Better instruments can test semiconductors, measure capacitance and frequency. Before first use always check the manual. Figure out how to connect the instrument in any mode and find the properties to keep the influence of the instrument small!

5.2.5 Errors

For a short introduction into errors and the used terms read the chapter 1, 3, and 4 of the 'Errorbooklet' available under 'GeneralEELab I & II Files' and *'Other Important Documents'*. In the Electrical Engineering Lab we only take care about systematical errors! Especially instrument and methodical errors. It is also important to be able to estimate the error propagation when using measured values in calculations.

Absolute Error

The absolute error is the deviation of the measured value from the true value. That is mostly an instrument error. The absolute error of a multimeter is the error/ the accuracy given as a set of formulas documented in the manual. The accuracy of an instrument may be defined in different ways and is dependant on the properties of the hardware and the used range. The absolute error ($E_{abs}, {}_{\triangle}E$) of the most DC voltage ranges of the instruments in lab is:

- Tenma Multimeter ${}_{\triangle}E = \pm(0.05\%\,\mathrm{rdg} + 5\,\mathrm{dig})$ – ${}_{\triangle}$E in [V] Range 4V to 1000V
- Elabo Multimeter ${}_{\triangle}E = \pm(0.03\%\,\mathrm{f.Value} + 0.01\%\,\mathrm{f.Range})$ – ${}_{\triangle}$E in [V]

For the current and resistor ranges these formulas are different!

Example: You measure with the Tenma and the Elabo. The Tenma is in range 1 (4 V) and the Elabo is in the 2 V range! Tenma reading is 1.5000 V. Elabo reading is 1.5000 V. **Mind the digits after the decimal point!!! More digits mean better resolution, so better accuracy.**

Calculation for the Tenma, $rdg = 1.5000\,\mathrm{V}$ and $1\,\mathrm{dig} = 1\,\mathrm{mV}$:

$$_{\triangle}E = \pm(0.05\%\,\mathrm{rdg} + 5\,\mathrm{dig}) = \pm\frac{0.05 * 1.500\,\mathrm{V}}{100} + 5 * 0.1\,\mathrm{mV} = 0.00125\,\mathrm{V}$$

$$E_{\%} = \pm\left(\frac{_{\triangle}E}{\mathrm{rdg}} * 100\%\right) = \pm 0.083\%$$

Calculation for the Elabo, $rdg = 1.5000V$ and $Range = 2V$:

$$_{\triangle}E = \pm(0.03\%\,\mathrm{f.Value} + 0.01\%\,\mathrm{f.Range})$$

$$= \pm\frac{0.03 * 1.5000\,\mathrm{V}}{100} + \frac{0.01 * 2\,\mathrm{V}}{100} = 0.00065\,\mathrm{V}$$

$$E_{\%} = \pm 0.043\%$$

Relative Error

To compare error values the 'Relative Error' ($E_{rel}, E_{rel\%}, E_{\%}$) is used. It is the absolute error divided by the true value. The general formula is:

$$E_{rel} = \frac{|Val_{meas} - Val_{true}|}{Val_{true}} \quad \text{– or in \% –} \quad E_{\%} = \frac{|Val_{meas} - Val_{true}|}{Val_{true}} * 100\%$$

Val_{meas} is a measured value.
Val_{true} is the known true value.

To get the relative error from the measurements with the multimeter we take

$$Val_{meas} - Val_{true} \equiv {}_{\triangle}E \equiv \text{Absolute Error from formula}$$
$$Val_{true} \equiv \text{reading from multimeter}$$

$$E_{rel} = \frac{E_{max}}{rdg} \quad \text{– or in \% –} \quad E_{\%} = \frac{E_{max}}{rdg} * 100\%$$

Error Propagation

When using measured values in a formula the error of the result will depend on the individual errors of the values. The general method of getting formulas for propagating errors involves the total differential of a function. Given is a function $x = f(a, b, c, ...)$ where the variables a, b, c, etc. must be independent variables! The maximal absolute error is calculated

$$_{\triangle}E_{max} = \left|\left(\frac{\partial f}{\partial a}\right)_{b,c}\right| * {}_{\triangle}a + \left|\left(\frac{\partial f}{\partial b}\right)_{a,c}\right| * {}_{\triangle}b + \left|\left(\frac{\partial f}{\partial c}\right)_{a,b}\right| * {}_{\triangle}c + ...$$

$_{\triangle}$a, $_{\triangle}$b, and $_{\triangle}$c are the absolute errors in each component.

Simple cases are

- sums and difference.
  For sums and difference the absolute error $_{\triangle}E$ adds up.
- products and ratios.
  For products and ratios the relative error $E_{\%}$ adds up.

Example 1: Two resistors with tolerance in series :

$R = R_1 + R_2 \qquad$ with $R_1 = 100\,\Omega \pm 5\%$ and $R_2 = 100\,\Omega \pm 10\%$

General solution:

$$_\Delta R = \left| \left(\frac{\partial R}{\partial R_1} \right)_{R_2} * {_\Delta R_1} \right| + \left| \left(\frac{\partial R}{\partial R_2} \right)_{R_1} * {_\Delta R_2} \right|$$

Equation solved:

$$_\Delta R =_\Delta R_1 +_\Delta R_2$$

So absolute errors add up

$$_\Delta R = 100\,\Omega * \frac{5}{100} + 100\,\Omega * \frac{10}{100} = 5\,\Omega + 10\,\Omega = 15\,\Omega$$

and the relative error becomes

$$E\% = \frac{_\Delta R}{R} * 100\% = \frac{15\,\Omega}{200\,\Omega} * 100\% = 7.5\%$$

Example 2: Ohm's law:

$U = R * I \qquad$ with $R = 100\,\Omega \pm 5\%$ and $I = 1\,\mathrm{A} \pm 10\%$

$$_\Delta U = \left| \left(\frac{\partial U}{\partial R} \right)_I * {_\Delta R} \right| + \left| \left(\frac{\partial U}{\partial I} \right)_R * {_\Delta I} \right|$$

The solution is :

$$_\Delta U = I *_\Delta R + R *_\Delta I$$

If this equation is divided by $R * I = U$ we get the relative error

$$\frac{_\Delta U}{U} = \frac{I * {_\Delta R}}{R * I} + \frac{R * {_\Delta I}}{R * I} = \frac{_\Delta R}{R} + \frac{_\Delta I}{I}$$

Here the relative errors add up $E\% = R\% + I\% = 5\% + 10\% = 15\%$

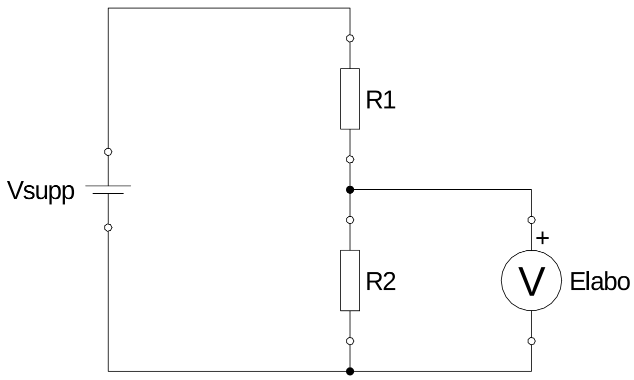
5.3 Part 1A : Voltage Measurement

5.3.1 Objective

In this part we use the ELABO multimeter as a voltmeter. We measure a single value and determine the change of the value in the different ranges. The goal is to show the influence of the multimeter range on the accuracy of the result.

5.3.2 Preparation

Before you start using the ELABO multimeter set the measure mode and the range. In our case 'V' and 'DC', and since we always start in the highest range set the turn-wheel to the 2000 V. Assemble the following circuit on the breadboard:



Settings : $V_{SUPP} = 9.0\,\mathrm{V} \quad R_1 = 8K20\,\Omega \quad R_2 = 1K80\,\Omega$

5.3.3 Execution

Measure and record the voltage value for the range 2000 V, 200 V, 20 V, 2 V, 0.2 V. Take care that you record all digits from the display!
Hint: Use tabular form for the recordings. First column is the variable parameter, here the range. The other column show the readings.

5.4 Part 1B : Voltage Measurement Pitfall

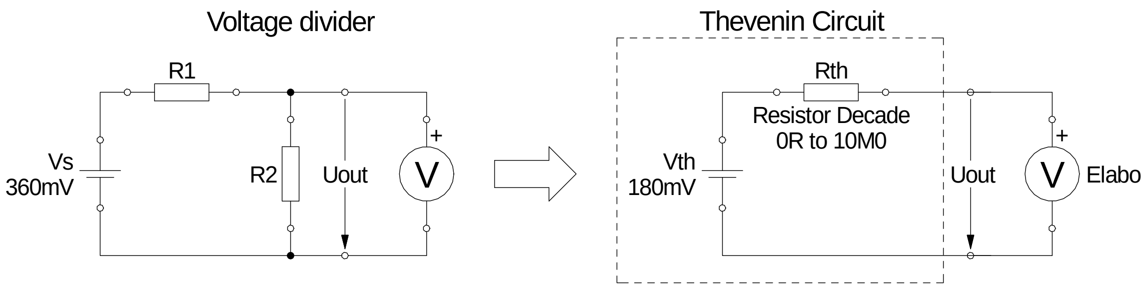
5.4.1 Objective

In the experiment before we can neglect methodical errors. We only have the instrument error. But is this true for any circuit?

5.4.2 Preparation

Turn off the power when changing the setup!! We don't have to change the mode of the multimeter. Only set the range turn-wheel back to 2000 V.

In general you can reduce every resistive DC circuit to an ideal voltage source and a resistor to a so called Thévenin circuit.



The voltage divider converts to $\Rightarrow V_{th} = V_S \dfrac{R_2}{R_1 + R_2}$ and $R_{th} = \dfrac{R_1 + R_2}{R_1\, R_2}$

The task is to measure the voltage $V_{out} = V_{th}$. The value should be independent from the resistors in the circuit and the connected voltmeter. Assemble the Thévenin circuit from the schematic above.

5.4.3 Execution

Switch on the power and adjust the supply to V_{th}. Select 0 R at the resistor decade. Set the range of the voltmeter to the best resolution and record the used range. Now record the values at the voltmeter for 0 R, 10 R, 100 R, 1 K00, 10 K0, 100 K, 1 M00, 10 M0. **Hint:** Use tabular form for the recordings. The first column is the independent parameter, that is varied, here the resistance. The other column show the readings.

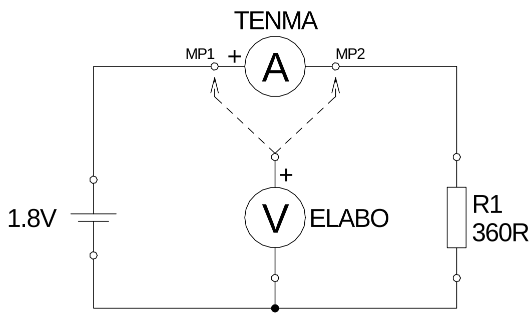
5.5 Part 2 : Current Measurement and Pitfalls

5.5.1 Objective

Like for the voltmeter there are similar instrumental and methodical errors. The following experiment will demonstrate this.

5.5.2 Preparation

Disconnect all wires from the DC supply. Set the voltage to $1.8V$. Now wire up the following circuit:



Connect the voltmeter in a way that 'MP1' and 'MP2' are the plugs at the ammeter!. This is to reduce/eliminate the influence of the connecting wires to the ammeter. Initially use the 'A' plug of the ammeter. Put the turning knob to 'A'. Before you connect the circuit set the voltmeter to the highest range.

5.5.3 Execution

- Connect the circuit to the power supply and choose the best range for the voltmeter. Record the range of the voltmeter. The ammeter is already set to highest range.
- Record the current and the voltages at MP1 and MP2.
- Change the input terminal at the ammeter from 'A' to '$mA\mu A$'. Switch the turning knob of the ammeter to 'mA'.Here you change to a medium range!
- Record the current and the voltages.
- Switch the turning knob of the ammeter to 'μA'. This is the best range (range with highest resolution) of the ammeter.
- Record the current and the voltages.

Hint: Use tabular form for the recordings. The first columns show the variable parameters, here 'Plug' and current range. The other rows show the readings. Example:

Plug	Switch	V_{MP1}	V_{MP2}	Current
A	A			
$mA\mu A$	mA			
$mA\mu A$	μA			

5.6 Evaluation

5.6.1 Part 1A : Voltage Measurement

1. Calculate all absolute and relative errors of the values measured with the multimeter from Part 1A. The necessary formulas can be found in the data sheet of the ELABO multimeter!
2. What is your conclusion regarding the usage of the voltmeter ranges? What is the influence of the range to the accuracy?
3. Draw a diagram of the relative error $E_{\%} = f(U)$ for the 2 V range.

5.6.2 Part 1B : Voltage Measurement Pitfall

1. Calculate the relative error of the measured U_{th} value for all R_{th} settings.
2. It should be clearly visible that the accuracy of the displayed values is very good. But some of them are far away from the real values (the $R_{th} = 0\,\Omega$ case). Here we can see a methodical error. What is the course of this error? Calculate the relative methodical error for all cases.
3. What is the internal resistance of the used voltmeter (data sheet!!). What should it be to reduce the methodical error to zero?

5.6.3 Part 2 : Current Measurement and Pitfalls

1. Calculate the relative error of the measured current for all settings. The necessary formulas can be found in the Tenma 72-7732A Multimeter data sheet!
2. Calculate the relative methodical error for all settings.
   Hint: To get a 'true value' use the measured voltage V_{MP1} and the nominal resistor value $R_1 = 360\,\Omega$!
3. How to interpret the results of the systematical and methodical error calculation?
   - Which range has the best accuracy?
   - In which range we get the smallest methodical error?
   - The 'A'mper range should have the smallest methodical error. Why isn't it true in our calculation?
4. If look at instrument and methodical error which range is best/ most acceptable in our case? What is your conclusion on using an ammeter?

5. Calculate the resistance of the ammeter in all three ranges. There are two ways to calculate the resistance:

$$R_i = \frac{V_{MP1} - V_{MP2}}{I} \quad (1) \quad \text{and} \quad R_i = \frac{V_{MP1}}{I} - R_1 \quad (2)$$

   Calculate the resistance using both formulas. Compile a table with the calculated values.

   The resistance for A-Range is $\approx 50m\Omega$, for the mA-Range it is $\approx 5\Omega$, and for μA-Range $\approx 500\Omega$. These values are measured and all approximate values. they may be be different for each instrument. Therefore they are not indicated in the data sheet!!

6. Why are the results so different? Determine the error propagation in the μA range in both formulas for R_i. What is the conclusion for using measured values in calculations?
   (**Hint :** For the given formulas it is simpler to use partial differentiation instead of the 'simple' rules!!)

6. Experiment 2 : Ohm's Law

6.1 Objective

This experiment should demonstrate Ohm's Law and show the behavior of different resistive components.

6.2 Theory

Ohm's law states that the current through a conductor between two points is directly proportional to the potential difference across the two points. The constant of proportionality is called resistance. With this definition this relation is described by the following formula :

$$I = \frac{V}{R}$$

For a strict fulfillment of the rule the temperature need to be constant and the resistance R must be constant, i.e. independent from I. Only in this strict case the behavior is called 'ohmic'. In general the formula yields the instantaneous current.

6.3 Part 1 : Resistance of a copper wire

6.3.1 Objective

The resistance of a copper wire is described by the following formula:

$$R = \rho \frac{\mathrm{l}}{\mathrm{A}}$$

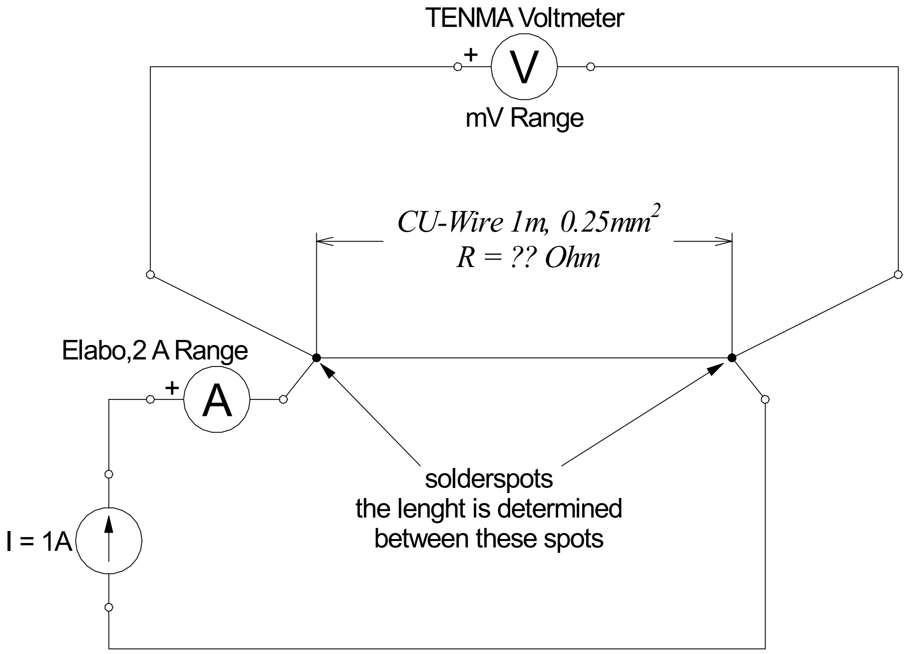
The resistance is dependant on a material constant called resistivity ($\rho =$ Greek letter Rho). It is proportional to the length (l) and inversely proportional to the cross sectional area (A).
ρ is different for every material. For copper you will find a lot of different values. This is due to the different purity of the used copper. For the wires we use in our experiment the value is given in the data sheet from the manufacturer:

$$\rho = 0.0195 \frac{\Omega\,\mathrm{mm}^2}{\mathrm{m}}$$

The task is to measure the resistance of a 1 m long wire with $0.25\,\mathrm{mm}^2$ cross sectional area. Since the resistance is very low we use the so called Kelvin (4-wire) resistance measurement method. Using this method the influence of connecting wires/contacts is eliminated. The only important thing is that the voltmeter (see diagram!) is connected to ends of the piece of wire to be measured. In our case the limiting points are the solder spots, i.e. the resistance between the solder spots is measured.

6.3.2 Preparation

Before you connect the power select one of the variable supplies from the workbench. Set the voltage to 10 V. In this experiment we use the supply as a constant current source. Use a lab wire to shorten the output terminals. Switch the internal instrument to current. Set the current to ≈ 1 A. As test item use the prepared wire at your workbench. Wire up the following circuit (**Hint**: use the plugs from the breadboard to connect to supply and instruments):



6.3.3 Execution

- Switch on and record voltage and current.
- As second step measure and record the resistance of the wire using one of the multimeters in resistance mode.

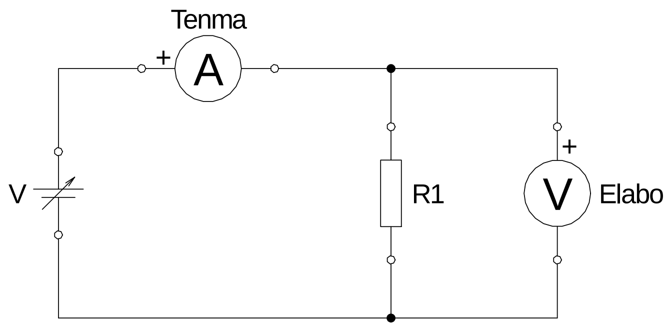
6.4 Part 2 : Resistance of a metal film resistor

6.4.1 Objective

Metal film resistors are frequently used components in electronic circuits. In this experiment it is used as an example for an ohmic resistance. In fact it is not really true, but in the narrow limits of our experiment (and mostly in any circuit design) we can take it as constant. To see the behavior of a metal film resistor we measure the resistance at different voltage values.

6.4.2 Preparation

Wire up the following circuit:



$$R_1 = 1k50\,\Omega$$

6.4.3 Execution

Vary the voltage at the supply from $V = 0$ to $24\,\mathrm{V}$ in $2\,\mathrm{V}$ steps and record voltage and current. Collect the values directly into a spreadsheet program and draw the diagram.

6.5 Part 3 : Resistance of a PTC resistor

6.5.1 Objective

In the experiment before you should have seen a linear (real ohmic) resistance. The following component is different. The PTC (Positive Temperature Coefficient) resistor changes the resistance dependant on temperature. With higher temperature the resistance increases. Most of the used conductors show this behavior! So one has to take care if components has to operate in harsh environments.
For lower temperature ranges (up to $\approx 150°\,\mathrm{C}$) following formula applies:

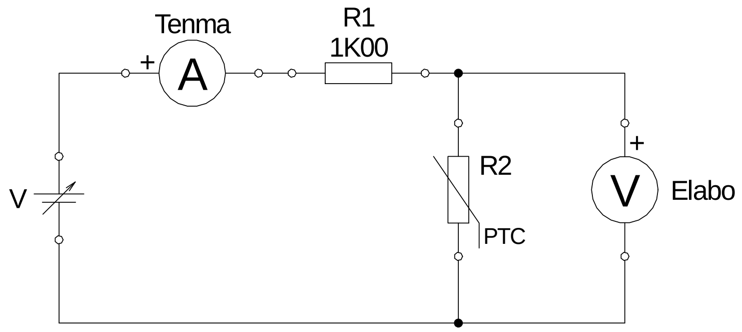
$$R_T = R_{25}(1 + \alpha\Delta T)) \quad \text{with} \quad \Delta T = T - T_{REF}$$

- R_T is the resistance at temperature T.
- R_{25} is the resistance at the reference temperature (in our case $25°C$).
- T is the actual temperature.
- T_{REF} is the reference temperature of the element. Here $25°\,\mathrm{C}$
- ΔT is the difference between T and T_{25}.
- α is the (linear) temperature coefficient. It has the dimension of an inverse temperature ($1/\,\mathrm{K}$ or K^{-1}). For higher temperatures quadratic and cubic components are added!

We use a nickel thin film thermistor as PTC element. At $25°\,\mathrm{C}$ $R_{25} = 1500\,\Omega$. The temperature coefficient is $\alpha = 3.8724 * 10^{-3}\,°\,\mathrm{K}^{-1}$. The component is heated by the supplied power, so by self heating.

6.5.2 Preparation

Wire up the following circuit:



$$R_2 = 1k50\,\Omega$$

Before you connect the power supply take care that the voltage is set to 0 V!!!

6.5.3 Execution

Vary the voltage at the supply from 0 V to 24 V in 2 V Steps. After you set the voltage wait about 2 minutes (in the lab report, do not forget to mention why!!) until you record voltage and current. During measurement do not touch the component!! Draw the diagram while collecting the data!

6.6 Part 4 : Resistance of a NTC resistor

6.6.1 Objective

The NTC (Negative Temperature Coefficient) resistor also changes the resistance dependant on temperature. For the NTC the resistance decreases with rising temperature. The behavior is dependant by the material and is described by the following formula:

$$R_T = R_{25} * e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

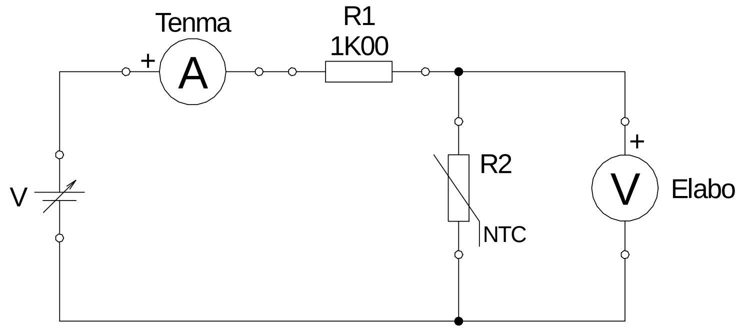
It is important that all temperatures in this formula are in K (Kelvin)!

- R_T is the resistance at temperature T.
- R_{25} is the resistance at the reference temperature (in our case $25°C$).
- T is the actual temperature.
- T_0 is the reference temperature (here $273.15\,° + 25\,° = 298.15\,°$ K).
- B is a constant dependant on the material. In our case $B = 3560$ K.

Again the change of temperature is done by the supplied power.

6.6.2 Preparation

Wire up the following circuit:



$$R_2 = 1k50\,\Omega$$

Before you connect the power supply take care that the voltage is set to 0 V!!!

6.6.3 Execution

Vary the voltage at the supply from 0 V to 24 V in 2 V Steps. After you set the voltage wait about 2 minutes (in the lab report, do not forget to mention why!!) until you record voltage and current. During measurement do not touch the component!! Draw the diagram while collecting the data!

6.7 Evaluation

6.7.1 Part 1 : Resistance of a wire

- Calculate the resistance of the wire using the values from the 4-wire measurement.
- Calculate the relative error of R using the values from the 4-wire measurement (error propagation!).
- Calculate the theoretical resistance of the wire ($l = 1\,\mathrm{m} - A = 0.25\,\mathrm{mm}^2$). Use the ρ given in the experiment section.
- The experimental taken R value should be very accurate. Why there are differences to the theoretical value?
- Compare the calculated R value from U and I to the value gotten with the multimeter in resistance range. Using the ohm range of the multimeter includes methodical error. Name these errors. How they are avoided using the 4-wire method?

6.7.2 Part 2, 3, 4 : Resistance of different components

- Draw the graph $R = f(I)$ for all resistors. Put all three graphs in one diagram.
- Do the graphs show the expected behavior?

- Draw the temperature at the PTC as a function of the resistance of the PTC resistor.
- Draw the temperature at the NTC as a function of the resistance of the NTC resistor.
- Why might it be dangerous to connect a NTC resistor to higher voltages?
- What kind of 'resistor' is the copper wire? What are the consequences when using it with high currents or with hight temperatures.

7. Experiment 3 : Thévenin's and Norton's Theorem

7.1 Objective

There are a lot of ways to analyze simple linear electrical networks. E.g.

- Ohm's Law as a basic tool
- Kirchhoff's laws
- Superposition theorem
- Mesh-current - node analysis

Depending on the complexity of a circuit the named techniques are hard to use. In this case sometimes it is usefull to simplify and convert a circuit into an equivalent one. Methods are

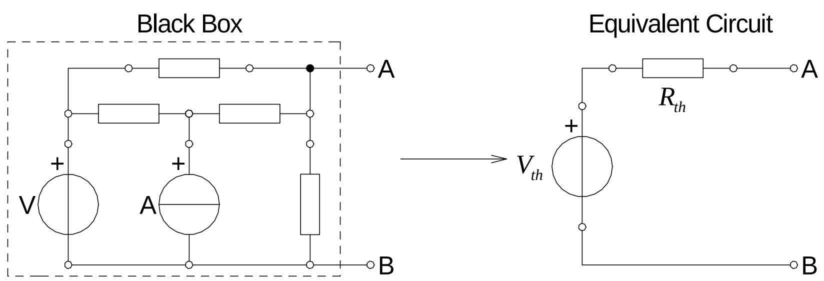
- Star-Delta and delta-star transformation
- Thévenin's theorem
- Norton's theorem

Today's experiment should introduce Thévenin's and Norton's theorem.

7.2 Theory

7.2.1 Thévenin's Theorem

Thévenin's theorem states that any linear electrical network can be replaced by an equivalent voltage source in series with an equivalent resistance.

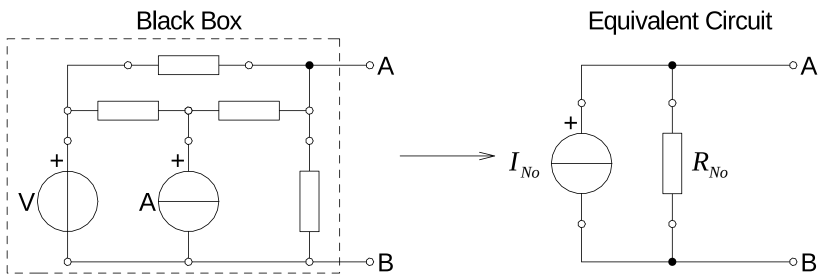


- The equivalent voltage V_{th} is the voltage obtained at terminals $A-B$ of the network with terminals $A-B$ open circuited.
- The equivalent resistance R_{th} is the resistance obtained at terminals $A-B$ of the network with all its independent current sources open circuited and all its independent voltage sources short circuited.

For AC systems, the theorem can be applied to reactive impedances as well as resistances.

7.2.2 Norton's Theorem

Norton's theorem states that any linear electrical network can be replaced by an equivalent current source in parallel with an equivalent resistance.



- This equivalent current I_{No} is the current obtained at terminals $A - B$ of the network with terminals $A - B$ short circuited.
- The equivalent resistance R_{No} is the resistance obtained at terminals $A - B$ of the network with all its voltage sources short circuited and all its current sources open circuited.

For AC systems the theorem can be applied to reactive impedances as well as resistances.

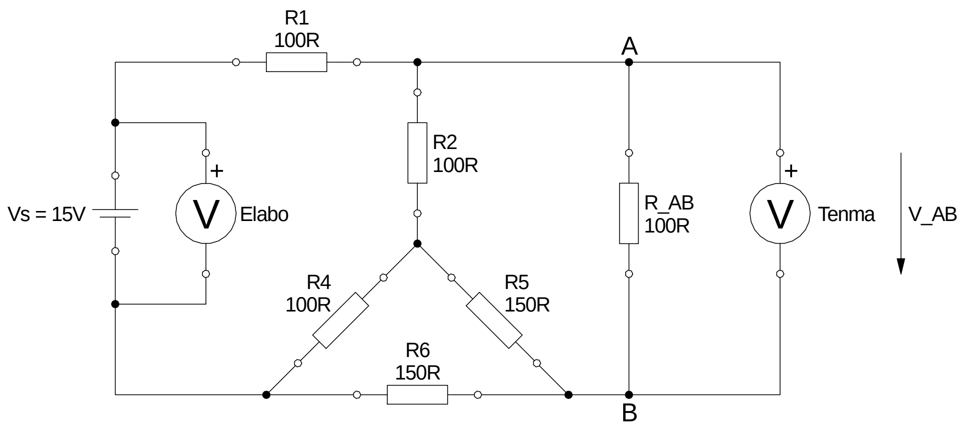
7.3 Part 1 : A Linear Network

7.3.1 Objective

Setup a circuit and determine current and voltage between the terminals $A - B$.

7.3.2 Preparation

Wire up the following circuit. Take care of the polarity of the multimeter!!



7.3.3 Execution

Set the power supply to the requested voltage. Measure and record the value of V_S and V_{AB}.

7.4 Part 2 : Determine Thévenin's and Norton's parameters

7.4.1 Preparation

To get the parameter for the two equivalent circuits vary the circuit from above.

7.4.2 Execution

- Determine V_{th}
  Like described in the theory section you get V_{th} when you remove the load between point $A - B$. Record the voltage at the ELABO voltmeter.
- Determine I_{No}
  To get I_{No} you have to replace the load resistor by a short. So switch the Tenma from voltmeter to ammeter (assume it is a short!!) and record the current in the best range.
- Determine R_{th} and R_{No}
  From theory section you know that both resistors are determined in the same way! So replace the power supply by a short and switch the Tenma multimeter at the terminals $A - B$ to Ohm. Record the resistance.

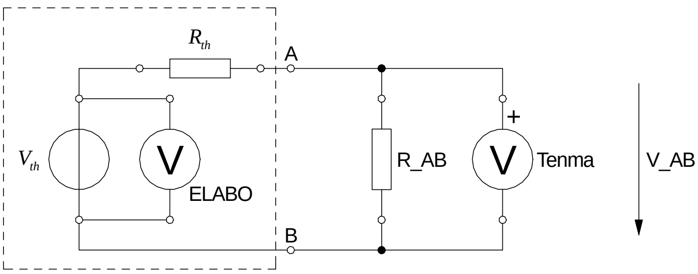
7.5 Part 3 : Determine V_{AB} using Thévenin's Circuit

7.5.1 Objective

Check the parameters for the Thévenin's equivalent circuit found in the step above.

7.5.2 Preparation

Wire up the following circuit. Use the R-decade for R_{th}. **Take care of the polarity of the power supply!!!**)



$R_{AB} = 100\,\Omega$

7.5.3 Execution

Set V_{th} as accurate as possible at the ELABO voltmeter. **Take care of the polarity of the voltmeter!!!**). Record the voltage V_{th} and V_{AB}. Compare V_{AB} to part one of the experiment. Is it similar? If not check for errors!

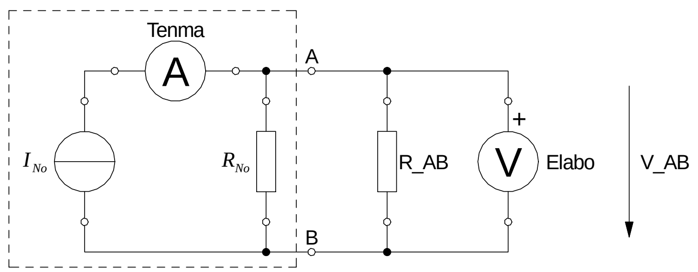
7.6 Part 4 : Determine V_{AB} using Norton's Circuit

7.6.1 Objective

Check the parameters for the Norton's equivalent circuit found in the step above.

7.6.2 Preparation

For this experiment we use the power supply in constant current mode. To get the required current the voltage in voltage mode needs to be higher than the voltage drop over R_AB. Set the voltage of the supply to about $V = 10\,\mathrm{V}$. Shorten the output terminals and set the short circuit current to about the needed current ($\approx 50\,\mathrm{mA}$). Wire up the following circuit. Use the R-decade for R_{No}. **Take care of the polarity of the power supply and the ammeter!!!**)



$R_{AB} = 100\,\Omega$

7.6.3 Execution

Switch on and adjust the current supply to the found I_{No} as accurate as possible at the tenma ammeter. Record I_{No} and V_{AB}. Compare V_{AB} to part one of the experiment. Is it similar? If not check for errors!

7.7 Evaluation

7.7.1 Part 1

Calculate V_{AB} for the given network in 'Part 1'. Choose any convenient method of analysis!

7.7.2 Part 2, 3, 4

- Calculate the components for Thévenin's and Norton's equivalent circuit of the given circuit.
- Calculate V_{AB} using the found values for Thévenin's and Norton's circuit.
- Create a table with all measured and calculated values.
- Discuss the errors! Name the methodical and systematical errors and the influence on the result.

8. Experiment 4 : Single PN - Junction

8.1 Objective

This experiment should demonstrate the behavior of a single pn-junction of two semiconductors, also called diode. Topics covered in this experiment are:

- the forward bias and V-I-Diagram of a general purpose silicon diode
- the Characteristic of a Zener-Diode
- a simple application

8.2 Theory

As preparation to this experiment read the relevant chapters (semiconductor, single pn-Junction, Diode) of the lecture or/and read the relevant chapter from **Sarma** or **Floyd**. You **need** the additional information related to the Zener-Diode from the course web page under 'GeneralEELab I & II Files'/ 'GenEELab1 Information'/ *'Z-Diode Theory'*

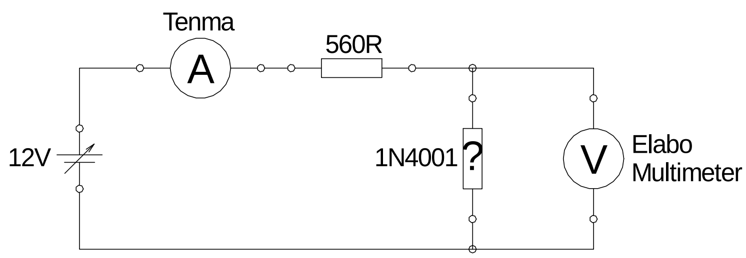
8.3 Part 1 : Determine Anode and Cathode

8.3.1 Objective

Determine anode (p type silicon) and cathode (n type silicon) of the diode.

8.3.2 Preparation

Wire up the following circuit. Ignore the polarity of the diode for now.



8.3.3 Execution

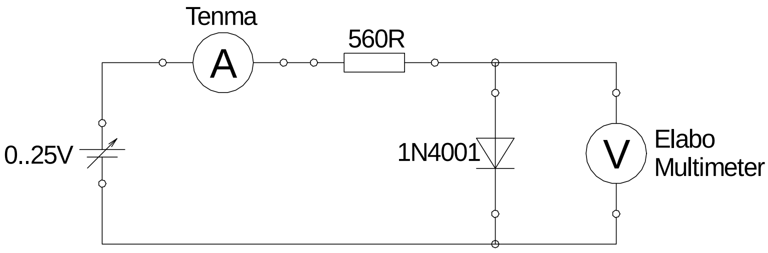
- Record the voltage drop over and the current through the diode. Record the orientation of the diode in the circuit. Use the ring as reference.
- Reverse the diode in the circuit and record the orientation. Measure and record voltage drop and current again.

- There is a second easier way to determine the polarity of a diode. You can use the Tenma multimeter. Connect lab wires with crocodile clips to the 'COM' and the 'V Ω ..' plug. The 'V Ω ..' has positive polarity relative to the 'COM'. Clamp the diode in both directions to the multimeter. Record the values shown at the multimeter for the two orientations of the diode. Use 'COM' of the multimeter and the ring of the diode as reference.

8.4 Part 2 : Forward V-I-Curve of a general purpose diode

8.4.1 Preparation

Wire the following circuit:



8.4.2 Execution

Record the forward V-I-curve of the 1N4001 diode from $0 - 40$ mA. Execute in the following way:

- Set the current at the Tenma ammeter by adjusting the supply voltage. Use the following approximate current values:

  $0\,\mu\,\mathrm{A}, 50\,\mu\,\mathrm{A}, 100\,\mu\,\mathrm{A}, 200\,\mu\,\mathrm{A}, 500\,\mu\,\mathrm{A}, 1000\,\mu\,\mathrm{A}$

  $2\,\mathrm{mA}, 3\,\mathrm{mA}, 4\,\mathrm{mA}, 5\,\mathrm{mA}, 10\,\mathrm{mA}, 20\,\mathrm{mA}, 40\,\mathrm{mA}$

- Use the lowest possible range with the Tenma multimeter. Set the values as close as possible.

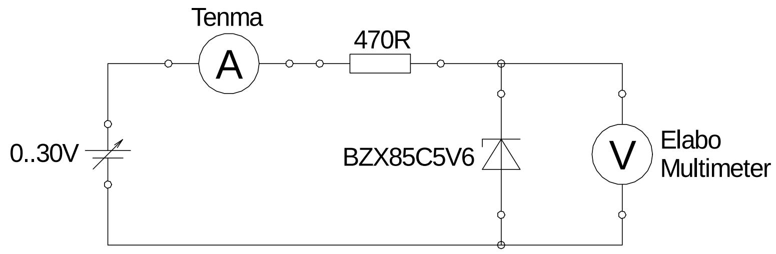
- Record the set I_F from the ammeter and the resulting U_F from the voltmeter! (F denotes forward bias)

Hint : Generate the diagram $I_F = f(U_F)$ together with the table! You can check your data for errors and you may see if you need more data points in regions where the current changes rapidly. Anyway it is needed for the evaluation.

8.5 Part 3 : Reverse and Forward Characteristic of a Z-Diode

8.5.1 Preparation

Wire up the following circuit on the breadboard:



8.5.2 Execution

- Record the reverse V-I-curve of the BZX85C5V6 from 0-45mA. Set the current at the Tenma ammeter by adjusting the supply voltage. Use the following approximate current values:

  $$0\,\mu\text{A}, 100\,\mu\text{A}, 200\,\mu\text{A}, 500\,\mu\text{A}, 700\,\mu\text{A}, 1000\,\mu\text{A}, 1100\,\mu\text{A},$$

  $$1.5\,\text{mA}, 2\,\text{mA}, 5\,\text{mA}, 10\,\text{mA}, 20\,\text{mA}, 40\,\text{mA}, 45\,\text{mA}$$

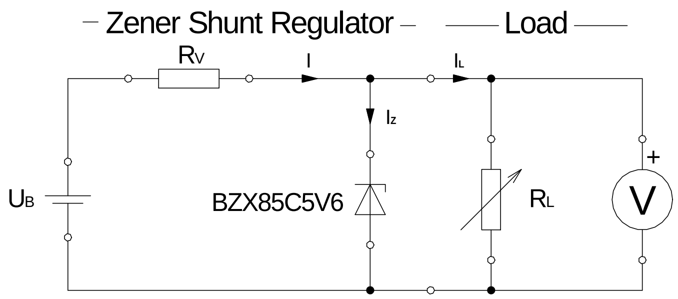
  Simultaneously with the recording of the data draw the diagram $I_R = f(U_R)$ to get a 'smooth' curve!!

- Reverse the polarity of the diode. Record the forward V-I-curve of the BZX85C5V6 from $0 - 30\,\text{mA}$. Proceed like in 8.4!

8.6 Part 4 : A Zener Shunt Regulator

8.6.1 Objective

Unlike the normal diode a Zener-Diode is used in reverse direction. It can be used to limit or stabilize voltages. Here we want to take a closer look at Zener Shunt Regulator:

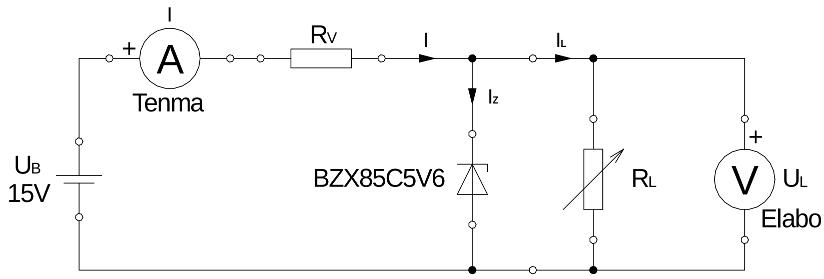


The Zener-Diode supplies a nearly constant voltage to a load. For a detailed description of the theory use a book of your choice or have a look at the course web page under 'GeneralEELab I & II Files'/ 'GenEELab1 Information'/ *'Z-Diode Theory'*

The circuit behaves like a current divider. The current through R_V is supplied to R_L and the diode. In the experiment we try to understand how the Z-Diode stabilizes the load voltage. Based on the schematic above the task is to design a circuit which supplies an output voltage of 5.6 V and a load current of 10 mA.

8.6.2 Preparation

- The load current should be 10 mA at 5.6 V. Calculate R_V for two cases. $I_Z = 1\,\text{mA}$ and $I_Z = 10\,\text{mA}$
- Assemble the following circuit:



  Use the R-Decade-Box from the shelf for R_L. For the first part insert the R_V you found for $I_Z = 1\,\text{mA}$.

8.6.3 Execution

- Record I and U_L for load resistors 56R, 560R, 5K60, and without R_L (means open circuit!).
- Insert R_V for $I_Z = 10\,\text{mA}$.
- Repeat the measurements from before.

8.7 Evaluation

8.7.1 Exp Part 1 : Determine Anode and Cathode

- Use the measurements to explain which terminal of the diode is the anode, and which one is the cathode? In general the lead with the ring has the same polarity for every diode!

8.7.2 Exp Part 2 : Forward I-V-Curve of a general purpose diode

- Plot the diagram $I_F = f(U_F)$.

8.7.3 Exp Part 3 : Reverse and Forward Characteristic of a Z-Diode

- Plot $I = f(U)$ for both directions.
- Determine the differential resistance of the diode at $Z_{ZT}@I_{ZT} = 45\,\mathrm{mA}$ and $Z_{ZK}@I_{ZK} = 1\,\mathrm{mA}$ in reverse direction from your experimental data? Compare with the data sheet. What information do you get from the differential resistance?

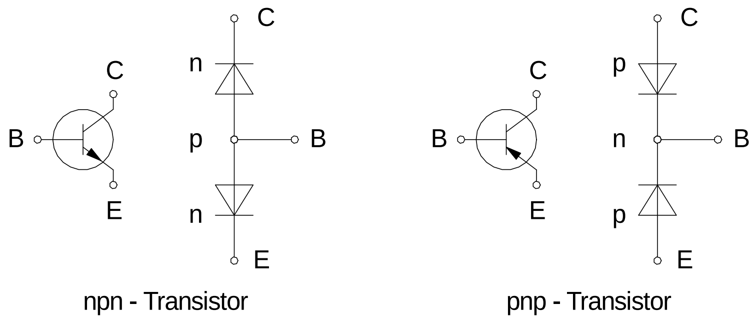
8.7.4 Exp Part 4 : A Zener Shunt Regulator

- Show the full calculation for R_V.
- Compile a table with the measured values.
- Describe the function of the circuit.
- Why is it not advisable to use loads with a too low resistance?

9. Experiment 5 : Transistor Characteristics

9.1 Objective

A bipolar transistor is an active 3 terminal semiconductor device. The three terminals are Emitter, Base, and Collector.
A transistor is build of consists of 2 junctions forming diodes 'back to back', i.e. NPN or PNP.



In this experiment you will explore the transistor parameters, i.e. how the two diodes work together to perform the transistor action like e.g. current amplification.

9.2 Theory

As preparation to this experiment read the relevant chapters of the lecture or/and read the relevant chapter from **Sarma** or **Floyd**.

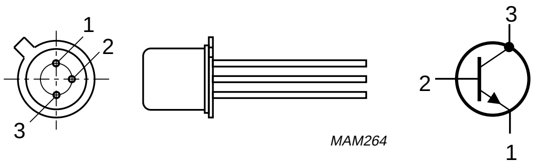
9.3 Part 1 : Input Characteristic

9.3.1 Objective

The input characteristic shows the behavior of the base emitter diode. We will record both, the forward and the reverse characteristic.

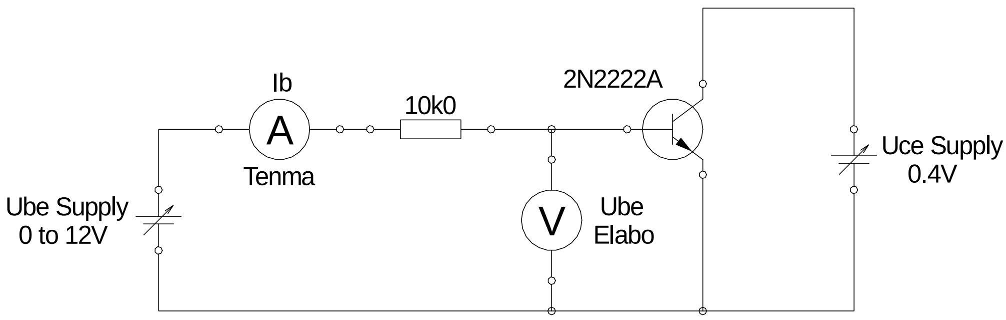
9.3.2 Preparation

Below is the circuit symbol for an 2N2222 NPN-Transistor together with its pin out.



Pin	Description
1	emitter
2	base
3	collector

Wire the following circuit on the breadboard:



9.3.3 Execution

- Record the forward characteristic of the base-emitter diode. The procedure is similar to the normal diode.

  - Set the U_{CE} supply to 0.4 V.
  - Set the current at the Tenma ammeter. Use the following current values:

    $0\,\mu\text{A}, 5\,\mu\text{A}, 10\,\mu\text{A}, 20\,\mu\text{A}, 40\,\mu\text{A}, 60\,\mu\text{A}, 80\,\mu\text{A}, 100\,\mu\text{A}$

    $200\,\mu\text{A}, 400\,\mu\text{A}, 600\,\mu\text{A}, 800\,\mu\text{A}, 1000\,\mu\text{A}$

    Use the lowest possible range with the Tenma multimeter. Set the values as close as possible to the given ones.
  - Record the set I_{BE} from the ammeter and the resulting U_{BE} from the voltmeter!
    Important : Take the values as quickly as possible, because the transistor heats up and the characteristics change with temperature.

- As second step we evaluate the reverse characteristic of the base-emitter diode. Disconnect U$_{CE}$ and reverse the U_{BE} supply. Record the reverse current I_{Br} as a function of U_{BE}. Change I_{Br} in similar steps as before. Make sure that you record the values with values close enough to each other to get enough points for the graph when the current starts to change rapidly with increasing reverse bias voltage. Record U_{BE} and I_{Br}

For both problems immediately create a graph beside the table!

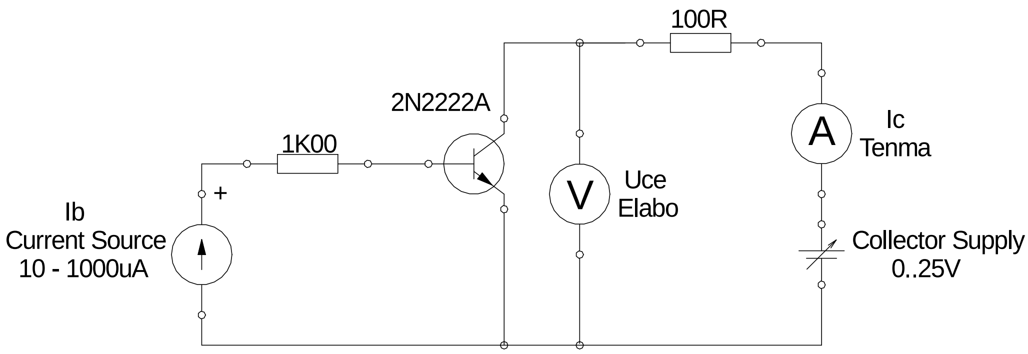
9.4 Part 2 : Output Characteristic

9.4.1 Objective

The output characteristic is a series of curves. It shows the the function $I_C = f(U_{CE})$ for various I_B. I_B is a parameter which represents the input to the transistor from which the current amplification of the transistor can be evaluated.

9.4.2 Preparation

Wire the following circuit on the breadboard.



The constant current source is the small black box in the shelf of the workbench labeled *"Current μA"* . Plug it into one of the outputs of the DC-supply. Set the voltage to 20V. The output of the source is the BNC-plug at the bottom. Use the BNC to Cleps cable to connect it to the circuit. The red wire of the BNC-cable is the positive terminal and the black wire is the ground.

9.4.3 Execution

- Set I_B to 20μA. Vary the collector supply in a way that U_{CE} (**read at the Elabo**) changes from 0 V to 20 V. Use the following steps:

  - from 0 V to 1 V every 0.2 V
  - then 2.5 V, 5 V, 10 V, 15 V, and 20 V

  Use a spread sheet to record the values of U_{CE} and I_{CE}. Take the values quickly because the transistor heats up and changes characteristic. In worst case it might be destroyed! Check the power dissipated between the collector and the emitter. Do not exceed $P_{CE} = U_{CE} * I_{CE} = 700\,\text{mW}$. Calculate the power for every step and if you exceeded it or will exceed skip the remaining steps.

- Repeat the first step for $I_B = 40\,\mu\text{A}, 60\,\mu\text{A}, 80\,\mu\text{A},$ and $100\,\mu\text{A}$.

- Record I_{CE} for $I_B = 100\,\mu\text{A}, 200\,\mu\text{A}, 300\,\mu\text{A}, 400\,\mu\text{A}$, and $500\,\mu\text{A}$ with U_{CE} set to 1 V. Be careful, adjust U_{CE} every time after you have changed I_B!

9.5 Evaluation

9.5.1 Part 1 : Input Characteristic

- Draw the diagrams of the input characteristic $I_B = f(U_{BE})$ with $U_{CE} = const. = 0.4\,\mathrm{V}$
- Draw the diagram of the reversed base-emitter-diode $I_{Br} = f(U_{BE})$.
- Compare to the diode curves from the diode experiment.

9.5.2 Part 2 : Output Characteristic

- Plot the output characteristic $I_{CE} = f(U_{CE})$ for every I_B into one diagram.
- The max. power dissipation for the 2N2222 is 700 mW. Insert the curve for P_{tot} into the $I_{CE} = f(U_{CE})$ plot. Did you exceed the limit during the measurement?
- Plot the current amplification $I_C = f(I_B)$ with $U_{CE} const. = 1\,\mathrm{V}$ and determine the current amplification β by fitting a straight line through the data points.
- Indicate in your diagram the area in which linear operation is possible (i.e. the linear region).

Part III

Additional Information

A. Appendix

A.1 Books and other Tools

A.1.1 Book

- Sarma
- Floyd

A.1.2 Programs

- LTSpice
- Matlab
- Octave