Department of Physics and Biophysics; Institute of Biology

First name .... Date ....

Last name .... Degree program name ....

Exercise 241

Determination of the electron charge by means of the p-n junction characteristics (semiconductor diode)

Resistance of the resistor *R* ………………………….. **Ω**

Room temperature *T* ..……………………………………… K

Knob position	Voltage across the diode - U [V]	Voltage across the resistor - U_I [V]	Current through the diode - I[mA]	Natural logarithm of the current - ln I
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Calculated charge of the electron q_e = ………………………………………$\cdot 10^{-19}$ C

Estimated measurement uncertainty Δq_e = ………………………………………$\cdot 10^{-19}$ C

The value of the electron charge

in the physics data tables $q_{e,tabl}$ = ………………………………………$\cdot 10^{-19}$ C

Exercise 241. Determination of the electron charge by means of the p-n junction characteristics (semiconductor diode)

PURPOSE

The purpose of the exercise is the measurement of the current-voltage characteristic I(U) of the semiconductor diode in the selected voltage range and on this basis determining the absolute value of the electron charge q_e, i.e. ***the elementary charge.***

THEORY

A ***crystal*** is a system of many atomic nuclei arranged in an ordered structure, with electrons between them, forming ***chemical bonds*** (***covalent, ionic, or metallic***).

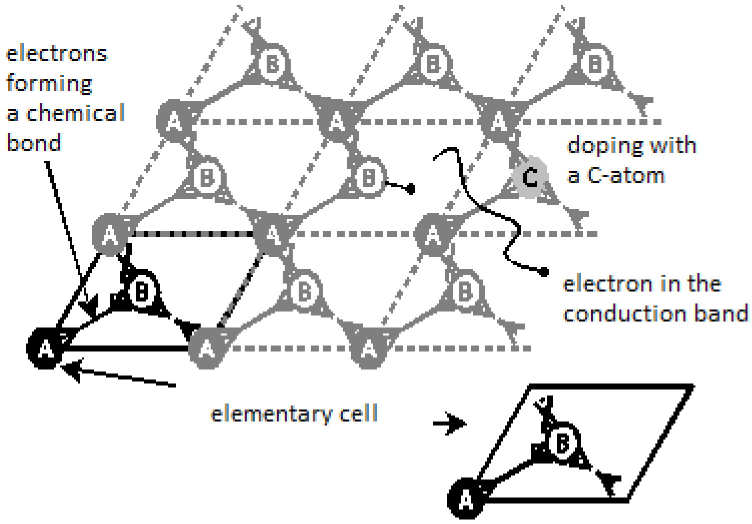


Fig.1. Crystal

Energy the electronic band structure - electrons cannot assume any total energy, but only energies from certain ranges called ***bands***.

The electronic band structure (or simply band structure) of a solid describes the range of energy levels that electrons may have within it, as well as the ranges of energy that they may not have (called ***band gaps*** or ***forbidden bands***). The energy of certain ranges is called ***bands.***

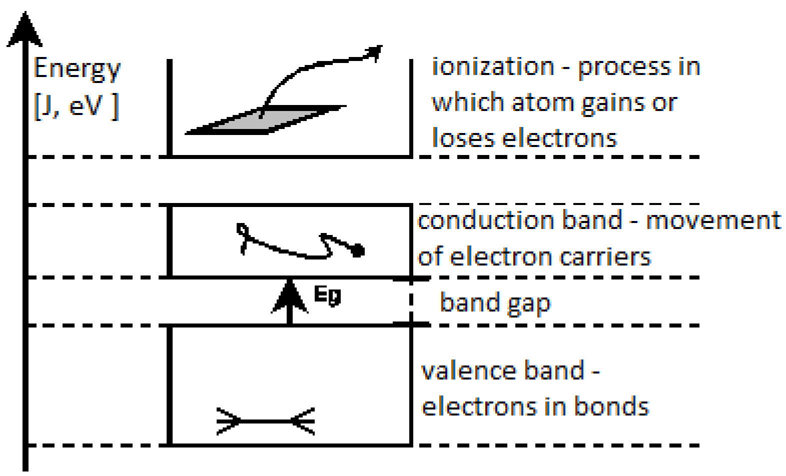


Fig. 2 Energy bands in the crystal

The energy bands can be divided into:

- ***valence band*** - energy ranges corresponding to electrons, that are very strongly bound to only one atom or creating bonds between atoms.
- ***conduction bands*** - energy ranges corresponding to the electrons that can move freely in the crystal.

The valence and conduction bands cover ever higher energy ranges. There are usually so-called ***band gaps*** - these are energy ranges that do not correspond to any electronic states allowed for a given crystal. For the passage of an electron from the valence band to the conduction band (Figure 2), sufficient energy greater than the band gap width E_g is required.

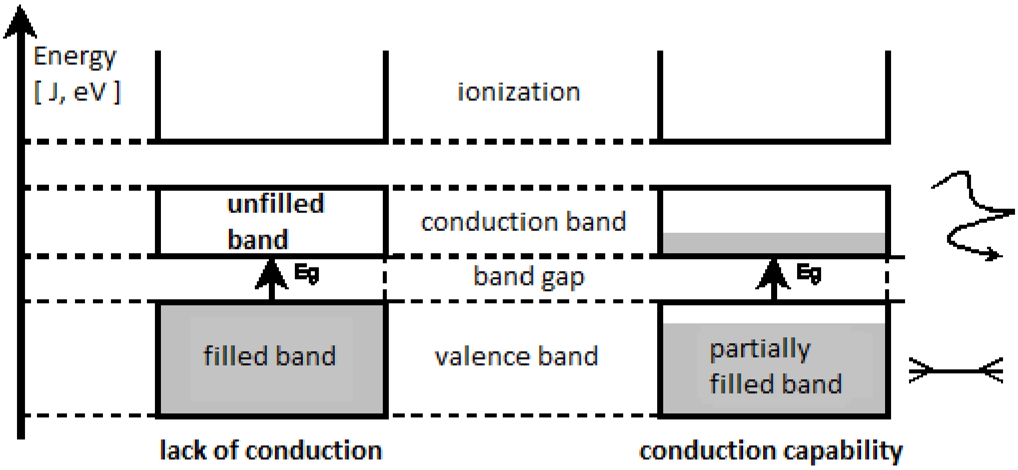


Fig. 3. Energy bands. The figure shows a simplified model - one valence and conduction band separated by a band gap with energy equals E_g.

The electrons in a totally filled band do not conduct current. This effect can be explained by the fact that a slight change in energy caused by an external electric field cannot transfer the electron to a state corresponding to a movement in a given direction in a given band because this state is already occupied. To obtain conductivity, the band must be partially empty - it can be got in two ways:

1. the application of a sufficiently large electric field (that is, a correspondingly very high voltage) - the so-called ***breakdown of the insulator (electrical breakdown or dielectric breakdown)***
2. appropriate heating of the material - such that the electron receives a portion of energy greater than E_g and will be moved to the conduction band.

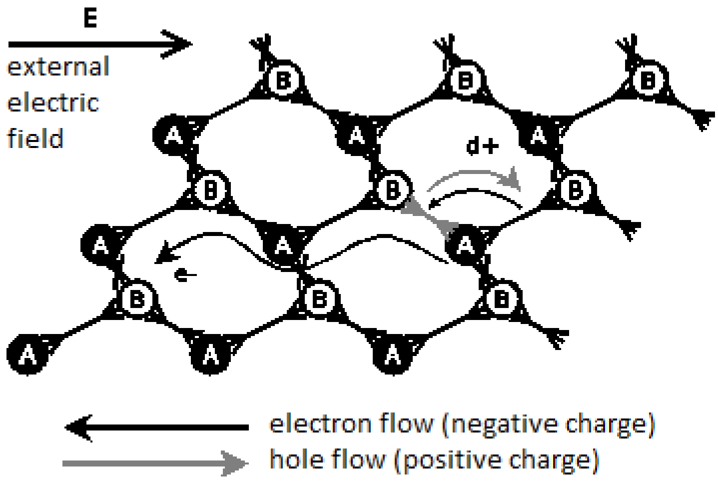


Fig. 4. Electrons and holes current

In the conduction band, electrons move in the opposite direction to the external electric field $\vec{E}$ and create an ***electron current*** - see Fig.4.

Empty places after chemical bonds in the valence band can be filled with electrons from adjacent bonds. Under the influence of an external electric field, the electrons begin to jump to adjacent empty places. The positively charged area of the missing bond, called the ***hole***, moves in the direction of the field (fig. 4), resulting in a hole current. Both phenomena result in electric currents (understood conventionally as the movement of positive charges) flowing along the field. In conductors, a current is produced by the only motion of electrons but in semiconductors, a current is produced by both electrons in the conduction band and holes in the valence band.

A current caused by an electron motion is called an ***electron current,*** and a current caused by a hole motion is called a ***hole current***. The electron carries a negative charge, while the hole carries a positive charge.

An electronvolt is the measure of an amount of kinetic energy gained by a single electron accelerating from rest through an electric potential difference of one volt in a vacuum, hence:

$$1eV = 1q_e \cdot 1V \approx 1.6 \cdot 10^{-19} J\ .$$

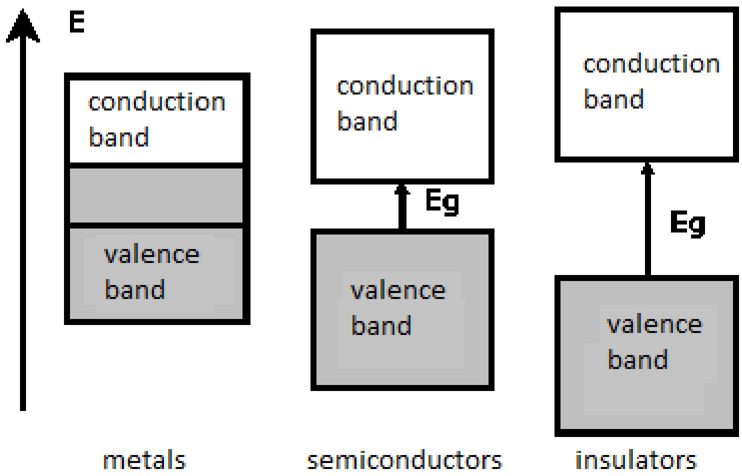


Fig. 5. Classification of crystals according to energy gap width.

Due to the width of the energy band gap E_g, crystals can be divided into:

metallic $E_g = 0eV$,

semiconductors: $0.1eV \le E_g \le 4eV$,

insulators: $4eV \le E_g$

(see Fig.5). In the case of metallic crystals, the valence and conduction bands coincide. The electron in the metal can be transferred to the conduction band without any energy input. The above division results from the comparison of the band gap energy with the ***average thermal energy***:

$E_T = k_B T$,

where T – temperature of a crystal in Kelvin, $k_B = 1.38 \cdot 10^{-23} J/K$ – **the Boltzmann constant**.

For T=300 K (i.e. approx. 27°C) the thermal energy is approx. $E_T = 0.0256eV$.

This energy is proportional to the average vibration energy of atoms. The higher the temperature - the higher the probability of an electron transfer from the valence band to the conduction band.

An example of the so-called an ***intrinsic semiconductor*** is pure silicon (Si) - Figure 6. The silicon atom has 4 electrons on the last shell that participate in the formation of bonds.

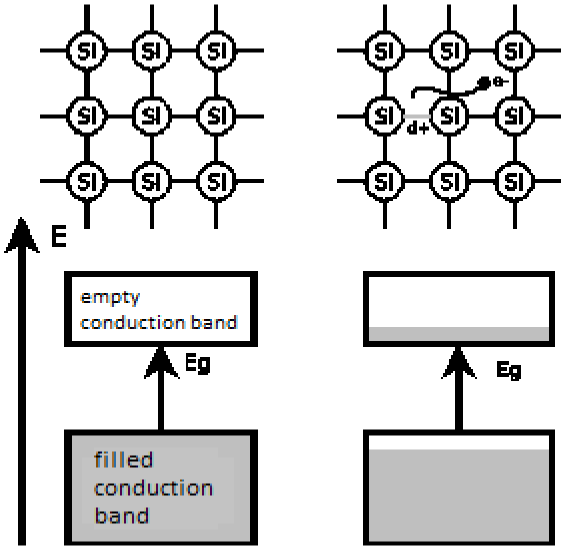


Figure 6. An intrinsic (pure) semiconductor

If we transfer an electron to the conduction band in an intrinsic semiconductor, a hole will form in the valence band. Free electrons and holes are formed in intrinsic semiconductors in similar proportions. The electron and hole currents are generally not the same - holes are less mobile than electrons. In practice, the energy gap for intrinsic semiconductors is large compared to the thermal energy at room temperature. Pure silicon has an energy gap $E_g \approx 1.1eV >> E_T$, therefore it conducts electricity very poorly under normal conditions.

The conductivity of a semiconductor changes rapidly with the addition of ***impurities***, i.e. foreign atoms in place of silicon in the crystal lattice - see Figure 1, atom C. The inserted atom gives us additional energy levels between the valence and conduction bands, additionally located very close to one of these bands.

If we replace the silicon atom with a 5-electron atom (phosphorus P, arsenic As) - we obtain a donor energy level filled with electrons ("***donor level***") just below the conduction band - see Figure 7.

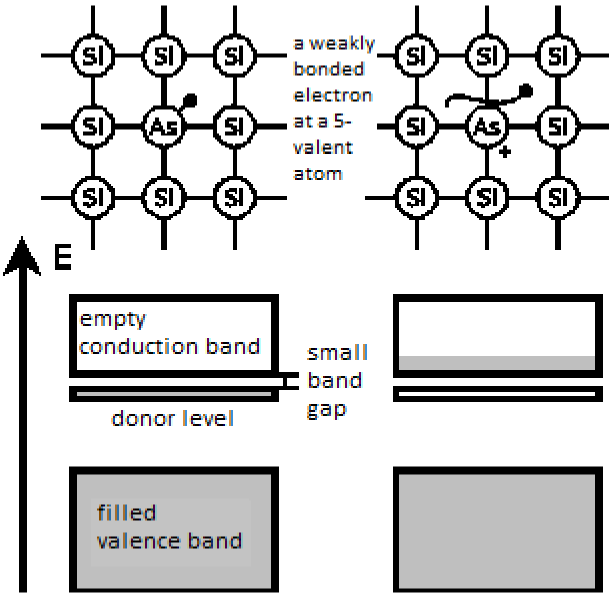


Figure 7. n-type semiconductor

From this level, we can easily transfer an electron to the conduction band - enough thermal energy E_T at room temperature, because the energy gap is small. This electron will be the carrier of the electron current.

This kind of semiconductor is called the ***n-doped semiconductor*** (n-type semiconductor). The dominant charge carriers inside the structure are electrons.

Similarly, if we doped with a 3-electron atom (aluminum Al, gallium Ga) - we get an empty ***acceptor level*** ("electron receiver") lying just above the valence level Figure 8.

Up to this level, at low energy, it is possible to transfer electrons from the valence level and form holes. This kind of semiconductor is called the ***p-doped semiconductor (p-type).*** The dominant charge carriers inside the structure are holes**.**

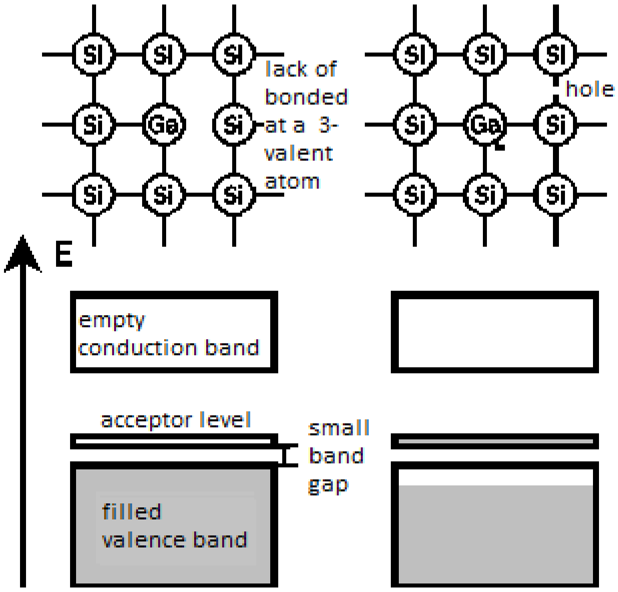


Figure 8. p-type semiconductor

A p-n junction - diode.

One of the basic elements of electronic circuits is a ***semiconductor diode***.

It consists of two electrodes: an ***anode*** and a ***cathode*** - see Figure 9a, below.

Usually the diode has a cylindrical shape on which the cathode is marked with a line. A semiconductor diode is a junction of semiconductors of two different types – a ***p***-type (anode) and a ***n***-type (cathode). If we connect a ***p***-type semiconductor with a ***n***-type semiconductor, electrons will flow from the ***n***-type material to the ***p***-type material and the holes in the opposite direction. Therefore, when the electric field in the ***p-n*** junction is presence we can observe a potential difference between ***p*** and ***n*** regions, called the *contact (junction) voltage* U_k or the *potential barrier*. For most silicon metals, the potential barrier equals U_k=0,7÷0,8 V.

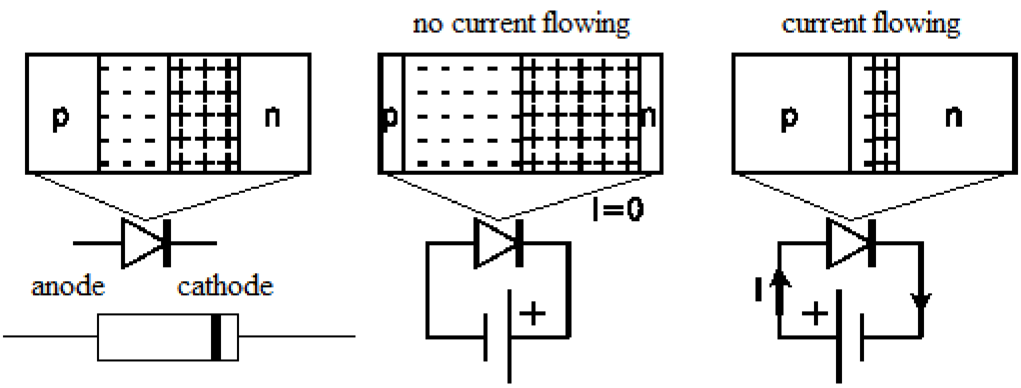


Figure 9. Working principle of the semiconductor p-n diode

If the constant voltage is applied to the p-n junction so that the positive pole of the battery is connected to the n-type semiconductor and the negative pole to the p-type semiconductor (Figure 9 – the middle side), holes and electrons will be pulled from the junction boundary, as a result, the potential barrier increases. This direction of the junction polarization called the *reverse direction* allows for movements of electrons from the semiconductor p to n and holes in the opposite direction. Since electrons in the p-type material and holes in the n-type material are minority carriers, hence a current of very low intensity can flow through the junction.

If we polarize the p-n junction in the opposite direction (Figure 9 – the right side), the potential barrier , as well as, the junction resistance decreases. This direction of a junction polarization, called the *conduction direction*, allows for the flow of majority carriers, i.e. electrons from ***n*** to ***p*** type material and holes from ***p*** to ***n*** material, as a result, we can observe a rapid increase in the current intensity along with increasing voltage.

A semiconductor diode passes current in one direction, in the opposite direction there is practically no current.

The current-voltage characteristic of a diode, i.e. a graph of the dependence of the current density (current per unit cross-section of a conductor) on the voltage, for a real diode, is shown in Figure 10.

The Shockley diode equation shows the current-voltage relationship for an ideal diode.
The equation looks like this:

$$I(U) = I_S \cdot \left[\exp\left(\frac{q_e}{k_B T} U \right) - 1 \right]$$

where:
I – the current flowing through the diode,
I_S – reverse saturation current,
U – voltage applied to the diode,
q_e – electron charge, (sometimes denoted by e^-)
$k_B T$ – predefined thermal energy.

We assume that in the tested voltage range our diode is an ideal diode.

We will test the silicon diode for the voltage range from 0.3 V to up, while $\frac{k_B T}{q_e}$ at room temperature approx. equals 0.0256 V, which is over 10 times less. Therefore, we can assume that $\exp\left(\frac{q_e}{k_B T} U \right) >> 1$, as a result, we can use the approximate form of Shockley's formula:

$$I(U) = I_S \cdot \exp\left(\frac{q_e}{k_B T} U \right).$$

The above equation, after logarithmising both sides, reduces to the form:

$$\ln I(U) = \frac{q_e}{k_B T} U + \ln I_S,$$

Hence, to a linear relationship *y=ax+b*, where *y=ln I(U), x = U,* $a = \frac{q_e}{k_B T}$.

Using the straight-line fitting method, we will determine the coefficient *a*, from which we will calculate the electron charge q_e, knowing the temperature and the constant k_B.

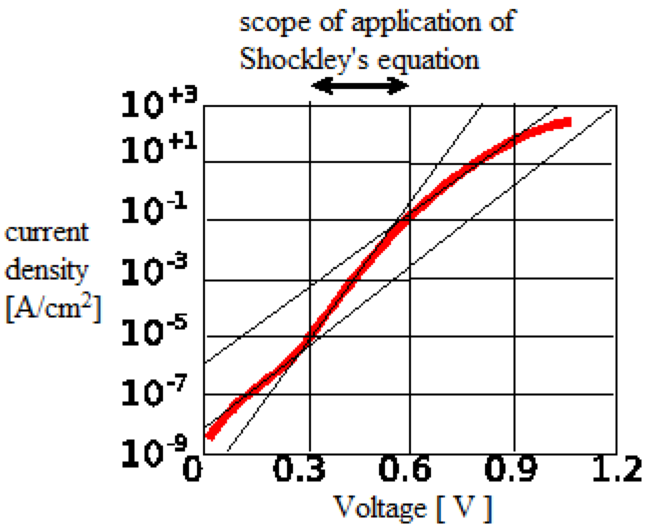


Figure 30. Current-voltage characteristics for a real diode; in our case we will measure the diode for the the marked range in which the Shockley's equation is satisfied (for voltages of 0.3-0.6 V)

Performance of the task

The measuring set is a box with a voltage regulator and four outputs (in the photo at the bottom right).

1. The setup consists of a regulated DC voltage source U, a diode D and a resistor R.

<u>**WARNING: UNDER ANY CIRCUMSTANCES DO NOT CONNECT TO THE SYSTEM ANY POWER SUPPLY THAT USED FOR OTHER EXERCISES !!!**</u>

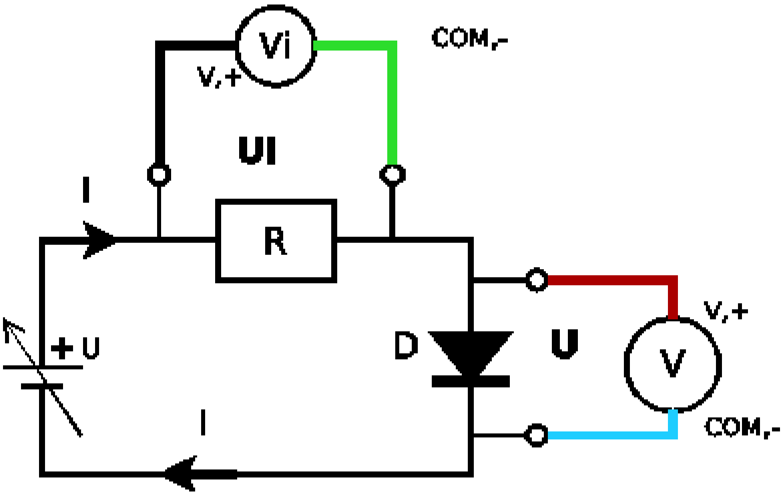
3. Two universal multimeters connect to the system as DC voltmeters - position V. **Setting the multimeter as an ammeter, in that case, may damage the multimeter and /or the setup !!!** 4.

4. Connect the multimeter slots to:

V+ - from the anode side of the diode (black triangle),

COM - from the cathode side of the diode (black line).

If the connection is reversed, the meters will show a negative voltage - in this exercise, the sign is not important, so we omit it. The circuit diagram is shown in the figure.



5. **Once the layout has been approved by the teacher,** we switch on the mains plug.
6. Read the voltages Ui and U for next positions of the supply voltage knob.
7. Read the resistance of the resistor R from the device housing and write it down on the table.
8. Read the temperature T from the thermometer indicated by the teacher and write it on the table.

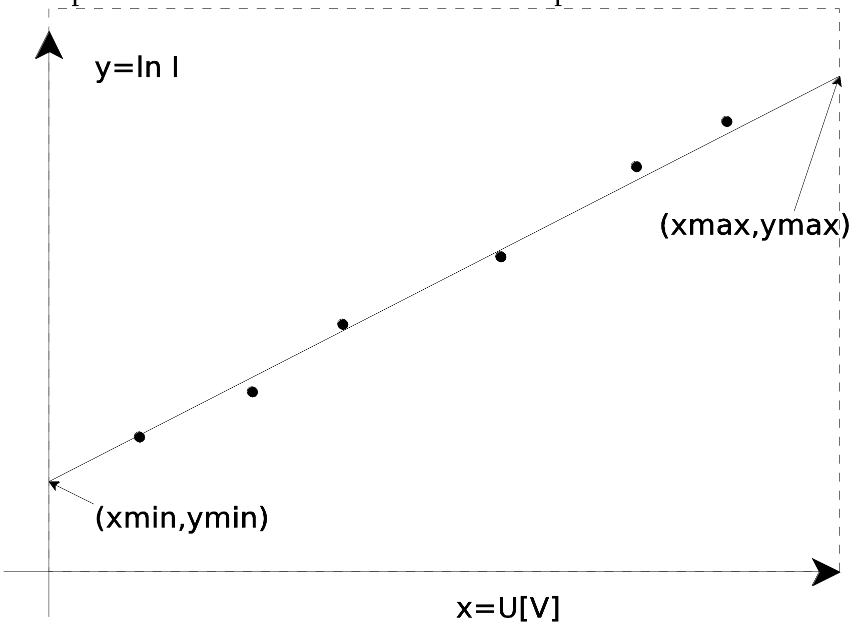
Data and error analysis

Perform the following calculations for all 10 measurements:

a. The current flowing through the diode: $I = \frac{U_I}{R}$

b. **Natural <u>logarithm</u>** of the current I: *ln I*
- perform calculations using the function [ln] from a scientific calculator, do not use the decimal logarithm [log].

2. To draw the dependence of *ln I on U* - measurement points should lie on a single line:



3. Fit the linear function $y = ax + b$ (i.e. a straight line) to the measuring points to find the coefficient *a*.

   Here $y = \ln I$, $x = U$, $a = \frac{q_e}{kT}$.

   Do it graphically - fitting the straight line "by eye" with the use of a transparent ruler.

4. Let choose two points on the straight line: one for the smallest possible value of U, the other for the largest possible value of U. For both points, let read from the graph the values of x_{min} and y_{min} as well as x_{max} and y_{max}. respectively. The slope of the line, i.e. the value of the coefficient, is calculated from the formula:

   $$a = (y_{\max} - y_{\min})/(x_{\max} - x_{\min})$$

5. Calculate the electron charge from the determined value of the coefficient *a*, temperature *T*, and the Boltzmann constant k_B:

   $$q_e = a \cdot k_B \cdot T$$

6. Calculate the influence of the inaccuracies of the meters on the accuracy of the electron charge measurement (relative error): $\frac{\Delta q_e}{q_e} = \frac{\Delta a}{a} + \frac{\Delta T}{T} = 2\frac{\Delta U}{U} + \frac{\Delta R}{R} + \frac{\Delta T}{T}$.

   Assume that the relative accuracy for the voltage ΔU / U is 1%, for the temperature ΔT / T is 1%, and for the resistance of the resistor ΔR / R is known to an accuracy of 5%.

7. Compare the calculated electron charge (taking into account its error $\frac{\Delta q_e}{q_e}$) with the value in the physical table data (give the source of the table value!).

Questions for discussion

- Does the found elementary charge correspond to the value in the physical data table (in the range of the value Δq_e)?

- What approximations used in this measurement method affect the result obtained?