**Tomsk Polytechnic University**

# PHYSICS II
# Laboratory Guide

Tomsk

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The Methodical Instructions have been discussed and approved by the Methodical Council of the Theoretical and Experimental Physics Department.

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# Experiment 1. Electric Field Research

## 1. Devices and Instruments

Galvanometer, measuring circuit, electric bath, electrodes of the plane and cylindrical forms, plotting paper.

## 2. Introduction

An *electric field* is a special form of matter which manifests in the force influence on charged bodies and particles, independently of the velocity of their motion. Basic characteristics of an electric field are *the field strength* and *potential*. The field strength **E** is a physical quantity numerically equal to the force, influencing a point charge located on a given point of the field. Vector **E** coincides with the vector of force. The electric field is graphically represented in the form of field lines. The *field line* is called a curve a tangent to every point of this one coincides in the direction of a field vector. A *potential* of some point of electric field $\varphi$ is a physical quantity numerically equal to a displacement work of a point charge from infinity to a given point. An *equipotential surface* is a locus, where potentials are equal. Consequently, a displacement work of a point charge on the *equipotential surface* equals zero. It follows from the equation:

$$A = q(\varphi_1 - \varphi_2).$$

Let's compare the above equation with another one:

$$A = qEl\cos\alpha,$$

where $l -$ displacement of charge, $\alpha -$ corner between the force direction $qE$ and $l$. Obviously, that the equipotential surfaces are mutually perpendicular with the field lines on every point of the field. Therefore, one can imagine a picture of the field lines knowing a certain form of the equipotential surfaces and vice versa., a disposition of the equipotential surfaces can be constructed knowing a form of the field lines.

A purpose of this work is determining of the equipotential surfaces and construction of the field lines of the field strength and **E**. It is well-known that

$$\mathbf{E} = -\mathbf{grad}\varphi; \qquad grad\varphi = \frac{d\varphi}{dl},$$

where $dl -$ magnitude of a normal displacement relatively equipotential surfaces. In that way, by finding small finite quantities $\Delta l$ it's possible to find the magnitude of vector **E**.

## 3. Description of the Laboratory Plant and its Application for the Electric Field Research

To find the equipotential surfaces of the electric field, an electrolytic bath is used, which looks like a plain vessel. It's filled with an electrolyte. Metallic electrodes of a given form are put down in the bath. An electric field appears when a certain potential difference is applied to the electrodes. An electroconductivity of liquid is small. Therefore, the vector of field strength **E** is practically perpendicular to the surface of electrodes. Thus, their boundaries are the equipotential surfaces, the same way as in the case of a non-conducting medium.

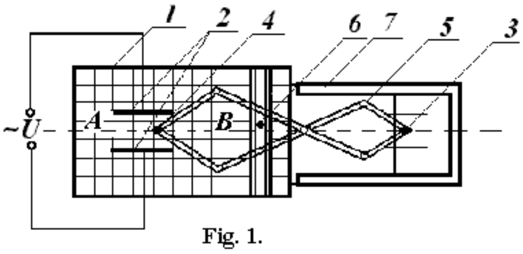

Fig. 1.

The scheme of electrode's allocation in the bath is shown in Figure 1., where (1) - an

electrolytic bath, (2) - electrodes, (3) - a fixing device, (4) - a pickup probe, (5) - a pantograph, (6) - a reference electrode, (7) - a plotting paper frame.
The electric field is measured between the electrodes (2). The pickup probe (4) looks like a thin isolated conductor attached on the one side of the pantograph (5). The fixing device (3) is attached to the other side of the same. The reference electrode is situated at some distance from the pickup probe. The bath is filled with a weak liquid of electrolyte. Usually, an aqueous solution of sulfuric acid, sodium chloride or copper sulfate and another salts is used.
To exclude the polarization phenomenon in the electrolytic liquid, a source of alternating current is usually used. The measuring scheme is shown in Figure 2. The method of electrolytic bath is used for the determination of the equipotential surfaces. If the pickup probe (4) and the preference electrode (6) are put to the points of the field, which have different potentials, then the current begins to flow through the galvanometer and the pointer of galvanometer deviates. The pointer is at zero position in case the potentials are equal. This condition allows finding the equipotential surfaces.

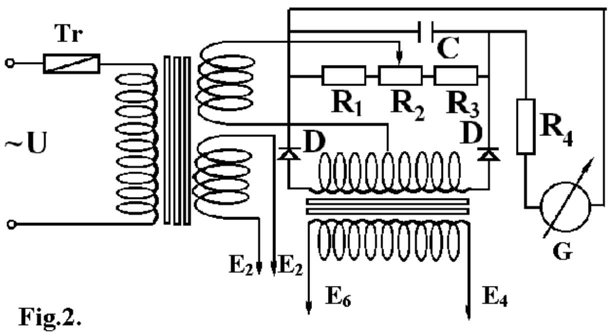

Fig.2.

The preference electrode (6) is placed on some line of coordinate scale of the electrolytic bath. This line is parallel of the electrodes (2) (for example line ***AB*** in Figure 1.). The pickup probe is moved until the current through the galvanometer is equal zero. This position of the pickup probe is marked on the plotting paper placed under frame (7). This operation is repeated 7-8 times fixing another points. Connecting the points you get an intersection line of the potential surface with the plane where the plotting paper is lying (some equipotential line). After that, the preference electrode (6) is moved on the other horizontal line (with respect to the electrodes (2)). The procedure is repeated to find 7-8 points of the next potential line.

## 4. Work Tasks

1. Find and plot equipotential lines of the electric field produced by plane electrodes.
2. Determine potentials of the equipotential lines. To do that you have to calculate the potential gradient. In case of the plane electrode, the potential gradient near the center of plates is equal $\frac{U}{l}$, where $U$ - applied voltage, $l$ - distance between the electrodes. Knowing the potential gradient and coordinates of points it's possible to calculate the potential of every potential surface using the formula:

$$\varphi = \frac{U}{l} x , \qquad (1)$$

where $x$ - coordinate of point where the potential is calculated. The point of origin coincides with the center between the electrodes (2).

3. Plot the field lines.
4. Find and plot equipotential lines of the electric field produced by cylindrical electrodes.

5. Determine the potentials of equipotential lines. The distance between the electrodes $d > a$, where $a$ - the electrode radius (see Figure 3.). Such electric field corresponds to the field produced by two long parallel wires. The formula for the field strength looks like:

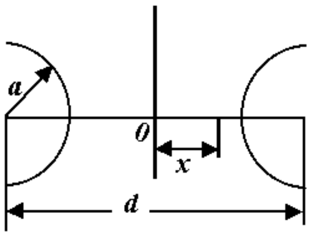


**Fig. 3**

$= \frac{\tau}{2\pi\varepsilon_0 x}$, where $\tau$ - the line density of the ırge, $\varepsilon_0$ - the permittivity, $x$ - coordinate of ld point. The potential in this point is equal $\varphi = -\int E dx$. The potential between wires is equal $\varphi = \varphi_1 + \varphi_2$, where $\varphi_1$ - potential of the first conductor, $\varphi_1$ - potential of the second conductor. The potential of the point located between wires (see Fig.3.) is:

$$\varphi = -\int_{-(d/2-a)}^{x} \frac{\tau dx}{2\pi\varepsilon_0 (d/2 + x)} + \int_{x}^{(d/2+a)} \frac{\tau dx}{2\pi\varepsilon_0 (d/2 - x)} = \frac{\tau}{2\pi\varepsilon_0}\left[ -\ln\frac{d/2 + x}{a} - \ln\frac{a}{d/2 - x} \right] =$$

$$= \frac{\tau}{2\pi\varepsilon_0} \ln \frac{d/2 - x}{d/2 + x}.$$

It suits to set the point of origin at the center between the electrodes because the electric field is symmetric. Substituting the coordinates of electrodes into the above formula we get that a circuit voltage is:

$$U = \varphi_{1`} - \varphi_2 = \frac{\tau}{2\pi\varepsilon_0}\left( \ln\frac{d-a}{a} - \ln\frac{a}{d-a} \right) = \frac{\tau}{2\pi\varepsilon_0} 2\ln\frac{d-a}{a} = \frac{\tau}{\pi\varepsilon_0}\ln\frac{d-a}{a}.$$

Finally, the equation for the potential in some point of field $x$ is

$$\varphi = \frac{U}{2\ln\left(\frac{d-a}{a}\right)} \ln\left( \frac{d/2 - x}{d/2 + x} \right). \qquad (2)$$

6. Plot the electric field lines.

## 5. Procedures.

1. Fasten list of plotting paper with the help of frame (7).
2. Mark electrode contours on the plotting paper (don't switch on the voltage).
3. Reset pointer of galvanometer on zero. For that the preference electrode and pickup probe have to be on the equipotential line passing through the electrode symmetric line. Switch on the current source. Get zero position rotating of the vernier "Zero reset". Find the equipotential surface with zero potential moving the pickup probe along symmetric line.
4. Change position of the reference electrode. Set it on some line which is parallel to line ***AB*** (see Fig.1.). Set the pickup probe within 1-2 cm from the reference electrode. Find a point which conforms to the zero current of galvanometer. Mark it on the plotting paper. Do this operation about 7-8 times. Plot the equipotential line.
5. Repeat item 4 to get no less than 4 equipotential lines.
6. Measure the shortest distance between the electrode contours on the plotting paper and the distance along the x-axis from the point of origin to the corresponding

equipotential lines $(X_1, X_2, ...)$. Find the potentials using formulas (1) and (2). Write down data in Table 1.

| Order of the equipotential line | Distance (cm) | Potential (Volt) |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |

7. Replace the electrodes of the one form to the other form electrodes. Repeat items 1-6.
8. Plot the electric field lines using the table data.

## 6. Test Questions

1. Give a definition of the terms: field strength and potential of electric field.
2. How are the field strength and potential at a given point of field related?
3. Prove that field lines and equipotential surfaces are mutually perpendicular.
4. What field is called potential?
5. How electrode forms influence an electric field?

# Experiment 2. Determination of the Charge of Hydrogen Ion

## 1. Purpose of Work

Determine the charge of hydrogen ion and compare it with the elementary charge.

## 2. Devices and Instruments

Hoffman's voltmeter, rheostat, source of direct current, milliammeter, switch, connecting wires.

## 3. Introduction

An atom of hydrogen consists of one proton and an electron. If the electron is removed, the atom changes into a positive ion of hydrogen. The ions of hydrogen are received as a result of electrolysis of aqueous solution of sulphuric acid $H_2SO_4$. Sulphuric acid is dissociated into ions when direct current flows through a given solution:

$$H_2SO_4 \rightarrow 2H^+ + SO_4^-$$

In the electric field the hydrogen ions move to a cathode. Getting from it a negative charge, the ions change into neutral atoms, i.e. there occurs the following reaction

$$H^+ + e^- \rightarrow H$$

The combination of two atoms is a molecule $H_2$, which educing near the cathode. Negative ions $SO_4^-$ move to anode, give it its own surplus negative charge and react with water, forming the sulphuric acid and evolving an atom of oxygen O. The combination of two oxygen atoms is a molecule $O_2$, which are educing near the anode. When a current flows through the electrolyte the following takes places: one molecule of acid $H_2SO_4$ produces one molecule $H_2$ and one atom of O. Consequently, to find one oxygen molecule $O_2$ near the anode it is necessary to dissociate two molecules of the acid $H_2SO_4$, but it would also evolve two hydrogen molecules $2H_2$ near the cathode. Thus, having the same thermodynamic conditions, the volume of hydrogen near the cathode would be twice as large the volume of oxygen that is evolved near the anode. If to take these gases separately, it is possible to determine the number of molecules of any gases that are formed by the electrodes on condition that the parameters of volume, pressure and temperature are known. When the number of molecules of any gas is known, it becomes easy to find the number of ions. Next, measuring the charge $Q$ that was transferred by the ions, it's possible to calculate the charge of one ion:

$$q^+ = \frac{Q^+}{n^+}; \qquad q^- = \frac{Q^-}{n^-}. \tag{1}$$

Values of charges $Q^+$, $Q^-$ are equal and depend on the current strength and passing time of this current through the electrolyte.

## 4. Description of an Experimental Assembly and Formula Construction of Calculations

The Hoffman's voltmeter is used to divide gases that are educed during the electrolysis. It consists of three communicating vessels, two of which end in stopcocks $K_1$, $K_2$. To every one the electrodes are soldered in. The third (middle) vessel has a funnel for filling of the vessels with electrolyte.

The experimental assembly with Hoffman's voltmeter and the electric scheme is shown in Figure 1. To the point **ε** a rectifier is connected. Here,

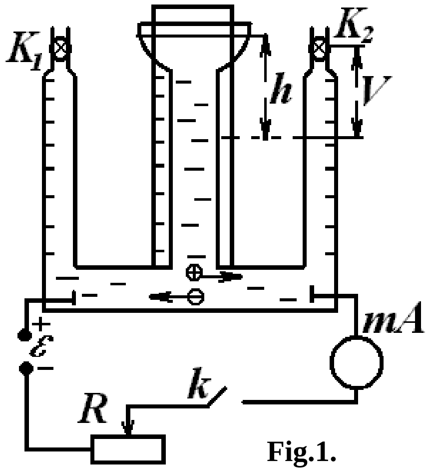


**Fig.1.**

⊕→ - the direction of moving of hydrogen ions,

⊖→ - the direction of moving of ions of acid residuum.

The vessels with $K_1$, $K_2$ have scale divisions that allow determining the volume in millimeters, the middle vessel is used for determining of a height of electrolyte column $h$. Hoffman's voltmeter is filled with the aqueous solution of sulphuric acid. It's connected to an electric circuit by means of the electrodes. The electric circuit involves rheostat *R*, milliammeter, switch *k* and the direct current source **ε**.

When the current flows through the electrolyte, hydrogen accumulates in the vessel with the positive electrode and oxygen - in the vessel with the negative electrode. These gases force out the electrolyte from the vessels with $K_1$, $K_2$. A pressure is created in the volume above the level of electrolyte. This pressure is balanced by the atmosphere pressure and the pressure of surplus liquid column in the middle vessel with respect to the liquid level in the vessels with $K_1$, $K_2$. The condition of the balance for the middle vessel and vessel with $K_2$ (in that vessel hydrogen is evolved) is pressure's equality:

$$P_{H2} + P_{H2O} = P_{at} + P_h \qquad (2)$$

where $P_{H2}$ - the partial pressure of hydrogen, $P_{H2O}$ - the partial pressure of saturated water steam at temperature of electrolyte, $P_{at}$ - the atmospheric pressure, $P_h$ - the pressure of surplus liquid column of electrolyte (height $h$).

Current $I$ flows through the electrolyte towards cathode during $t$ seconds. At the same time ions of hydrogen transfer the following charge:

$$Q^+ = It \qquad (3)$$

The same negative charge would be transferred towards the anode by acid residual.

According to the Faraday law, the mass of evolved hydrogen is proportionate to the transferred charge. If the evolved mass of hydrogen is known (every hydrogen molecule consists of two atoms), it is possible to define the number of hydrogen ions:

$$n^+ = \frac{2M}{m}, \qquad (4)$$

where $M -$ evolved mass of hydrogen, $m -$ mass of one molecule $H_2$.

The evolved hydrogen mass is calculated from the ideal gas law:

$$M = \mu \frac{P_{H_2} V}{RT}, \qquad (5)$$

where $\mu -$ mass of one kilomole ($kmole$) $H_2$,

$R = 8.31$ $Joule \cdot kmole^{-1}$ - the absolute gas constant,

$P_{H_2} -$ the partial pressure of hydrogen,

$V -$ the volume of evolved hydrogen,

$T$ – temperature.

By substituting the equation (5) into the formula (4) it is possible to get the number of hydrogen ions:

$$n^{+} = 2\frac{\mu}{m}\frac{P_{H_2}V}{RT} \quad (6)$$

Using Equations (3) and (6), we can get the formula from Equation (1) to calculate the ion charge of hydrogen:

$$q^{+} = \frac{m}{2\mu}\frac{RTIt}{P_{H_2}V} \quad (7)$$

The mass of one hydrogen molecule is defined as: $m = \frac{\mu}{N_A}$,

where $N_A = 6.023 \cdot 10^{26} kmole^{-1}$ - the Avogadro constant.

Using partial hydrogen pressure from (2), we get the calculation formula:

$$q^{+} = \frac{It}{2N_A}\frac{RT}{P_{H_2}V} \quad (8)$$

Thus, in order to define the ion charge of hydrogen using Hoffman's voltmeter, it is necessary to measure the volume, the temperature and to calculate the partial hydrogen pressure. Also it necessary to measure the value of the current and the time of its flowing through the electrolyte.

## 5. Procedures

1. Open vessels $K_1$, $K_2$. Fill in the voltmeter's tubes by electrolyte through the funnel of the middle vessel. The air should be completely forced out from vessels.
2. Assembly electric circuit according to Figure 1.
3. Close the contact by switch *k*. Set the necessary value current using the rheostat (current value is given by the teacher). Some minutes later the electrolyte should become saturated with evolved gases, that is gas bubbles would pass to air. At that moment, close the vessels $K_1$, $K_2$ and note the time from the beginning of process.
4. Keep the current in steady statement using the rheostat (time of experiment is given by the teacher). Note the time and break a circuit using switch *k*.
5. The voltmeter has to get cold at room temperature.
6. Define the partial pressure of hydrogen $P_{H2}$ using Formula (2). The atmospheric pressure $P_{at}$ is measured by barometer ($1\,\text{millimeter of mercury} = 133{,}3\ Pa$). Measuring the difference of the electrolyte levels $h$ calculate the pressure $P_h = \rho gh$, where $g = 9.8\ m \cdot s^{-2}$ - the gravitational acceleration, ρ – density of electrolyte (in a given case for 10% electrolytic solution, $\rho = 1{,}1 \cdot 10^3\ kg \cdot m^{-3}$. The pressure of saturated water steams is equal $P_{H2O} = aP_T$, where $a$ – an empirical coefficient, $P_T$ - the pressure of saturated water steams at the room temperature (use Table 1). It depends on the concentration of electrolyte. In this case, $a = 0{,}9$. Thus, the partial pressure of hydrogen is defined in the following way:

$$P_{H2} = P_{at} + \rho gh - aP_T \quad (9)$$

7. Define the volume of evolved hydrogen $V$ using scale divisions on the vessels $K_1$, $K_2$.
8. Enter the measured and calculated data in Table 2.

9. Repeat experiment no less than 3 times. Calculate averages out of all values. Define the ion charge of hydrogen using Formula (8).
10. Calculate precision of measurements using formula:

$$\frac{\Delta \bar{q}}{\bar{q}} = \sqrt{\left(\frac{\Delta \bar{T}}{\bar{T}}\right)^2 + \left(\frac{\Delta \bar{I}}{\bar{I}}\right)^2 + \left(\frac{\Delta \bar{t}}{\bar{t}}\right)^2 + \left(\frac{\Delta \bar{P}_{H_2}}{\bar{P}_{H_2}}\right)^2 + \left(\frac{\Delta \bar{V}}{\bar{V}}\right)^2}; \qquad (10)$$

11. Write down the final result $q = \bar{q} + \overline{\Delta q}$. Compare it with the value of elementary charge and draw a conclusion.

**Table 1.**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *T* *[$^0$C]* | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| $P_T$ *[kPa]* | 1,23 | 1,31 | 1,40 | 1,50 | 1,60 | 1,70 | 1,82 |
| *T* *[$^0$C]* | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
| $P_T$ *[kPa]* | 1,.94 | 2,05 | 2,20 | 2,34 | 2,49 | 2,64 | 2,81 |

**Table 2.**

| № exp. | *I* *[A]* | *t* *[sec]* | *T* *[$^0$K]* | *V* *[m$^3$]* | $P_{at}$ *[kPa]* | *h* *[m]* | $P_h$ *[kPa]* | $P_t$ *[kPa]* | $P_{H2}$ *[kPa]* | $q^+$ *[C]* |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | | | | | | | | | | |
| 2. | | | | | | | | | | |
| 3. | | | | | | | | | | |
| 4. | | | | | | | | | | |
| Average value | | | | | | | | | | |

**Choice set for experiment.**

| | | | | | | |
|---|---|---|---|---|---|---|
| *I* *[mA]* | 75 | 100 | 125 | 150 | 175 | 200 |
| *t* *[sec]* | At the teacher's option (within $300 \div 900$) | | | | | |

## 6. Test Questions

1. What is the value of elementary charge?
2. What is the effect of electrolytic dissociation?
3. Formulate the first Faraday law.
4. What charge type has the ion of hydrogen?
5. Where would the volume of evolved gases be lager, near cathode or anode? Why?
6. You mix the acid and water. The order of mixture: the first component is acid and water is the second. Why is such order used?
7. What influences the value of the electrolyte conductivity?

# Experiment 3. Measurements of Capacitance and Permittivity by the Bridge Method

## 1. Devices and Instruments

Sound-frequency generator, oscillograph, two standard capacitors, two capacitors to be investigated, plane air capacitor, dielectric plates, variable resistor, caliper.

## 2. Theoretical Contents

In laboratory practice the bridge methods are being widely used for measurement of capacitance. The electric scheme of a capacity bridge is shown in Figure 1. The capacitors $C_1$, $C_2$ and resistors $R_1$, $R_2$ are called the arms of a bridge. The current source is linked across the bridge diagonal *MN*. The sound-frequency generator is used as a current supply energy source/ An electric oscillograph is used as a voltage indicator. The bridge voltage distribution can be expressed as follows:

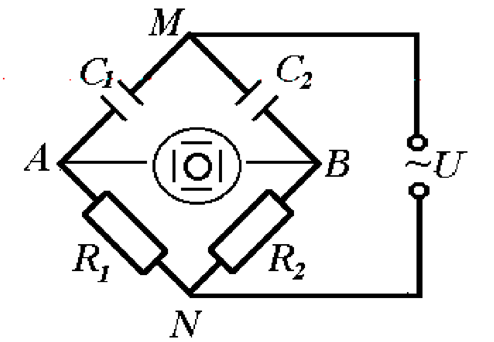

Fig.1.

$$U_{C1} = \varphi_M - \varphi_A \; ; \qquad U_{C1} = \varphi_M - \varphi_B \; ;$$

$$U_{R1} = \varphi_A - \varphi_N \; ; \; U_{R1} = \varphi_A - \varphi_N \, ,$$

where $\varphi_M$, $\varphi_N$, $\varphi_A$, $\varphi_B$ are the electric potentials of bridge points $M, N, A, B$. When $R_1$ and $R_2$ are chosen in such a way that $\varphi_A = \varphi_B$, on the indicator the current strength equals zero, then the following expressions are true: $U_{C1} = U_{C2}$ ; $U_{R1} = U_{R2}$.

Obviously, $I_1 = U_{C1} C_1 \omega$; $I_2 = U_{C2} C_2 \omega$; $I_1 = U_{C1} / R_1$; $I_2 = U_{C2} / R_2$. In this formulas $I_1$, $I_2$ are the current strengths in the arms of the bridge. Thus, it's easy to see that $I_1 / I_2 = C_1 / C_2$; $I_1 / I_2 = R_2 / R_1$. Or,

$$R_2 / R_1 = C_1 / C_2 \qquad C_1 = C_2 R_2 / R_1 . \qquad (1)$$

If $C_2$ is known, the last relation gives the magnitude of the capacitance under investigation - $C_2$ (of course, on condition that the ratio $R_2 / R_1$ is known).

Using the capacity bridge method, we can measure the permittivity ε of a substance. For this purpose, a plane air capacitor can be used. A dielectric plate is inserted between capacitor's plates (see Figure 2.).

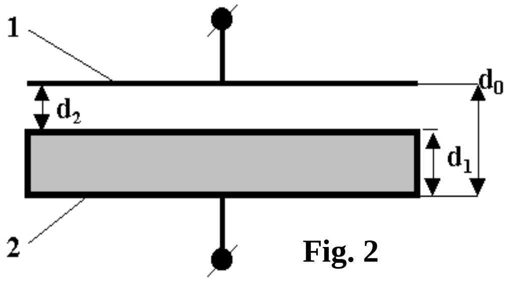

**Fig. 2**

It's cleared that $d_2 = d_0 - d_1$. The total capacitance is the inverse sum of two capacitors connected in series $1/C = 1/C_1 + 1/C_2$, where $C_1 = \varepsilon_0 \varepsilon S / d_1$, $C_2 = \varepsilon_0 S / d_2$ ($S$ - the area of capacitor plate).

1 – the capacitor plate, 2 – the dielectric plate, $d_0$ – the distance between the plates, $d_1$ – the thickness of the dielectric plate, $d_2$ – the thickness of the air layer. Using these equations we easily get:

$$C=\frac{C_1C_2}{C_1+C_2}=\frac{\frac{\varepsilon\varepsilon_0 S}{d_1}\cdot\frac{\varepsilon_0 S}{d_2}}{\frac{\varepsilon\varepsilon_0 S}{d_1}+\frac{\varepsilon_0 S}{d_2}}$$

From the last expression it follows

$$\varepsilon=\frac{C\ d_1}{\varepsilon_0 S-Cd_2}$$

## 3. Devices

In this work capacitance of two capacitors and capacitance of their series and parallel connection are measured. Besides, the permittivity of a substance is also measured. There are two standard capacitors: one of which has a big capacitance and the other - small. The "small" capacitor is used in order to measure capacitance of a plane capacitor, the permittivity of which can be changed. A capacitive reactance is in inverse proportion to frequency and capacitance, i.e. $X_c=\frac{1}{\omega C}$. In order to raise sensitivity of the device, it's necessary to use high frequency oscillations. In that way, the higher volumes of current strength are being produced. The electric scheme is shown in Figure 3.

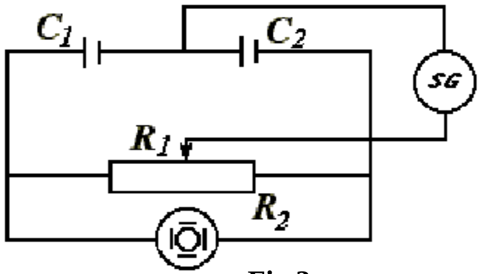

**Fig.3.**

## 4. Procedures

1. Connect the electric scheme: $C_1$ - standard capacitor, $C_2$ - capacitor under investigation.
2. Switch on the oscillograph and generator (frequency $10^3$ Hertz, voltage output - in minimal position).
3. After the devices have been "heated" about two minutes, djust the output vernier of generator and amplifying verniers of oscillograph in such position as to have the oscillograph picture with dimensions ~ (5-6) cm horizontally and ~ (2-3) cm vertically.
4. Equalize the bridge tuning variable resistor. Here, the signal upon oscillograph screen transforms in a narrow strip.
5. Find the values of $R_1$ and $R_2$. Do it not less than three times (disbalance and balance the bridge again).
6. Measure the other capacitances in analogous way.
7. Record the experimental results in Table 1.

**Table 1.**

| Investigated capacitance | $R_1$ | $\overline{R_1}$ | $\overline{R_2}$ | Value of capacitance |
|---|---|---|---|---|
| $C_{x1}$ | | | | |
| | | | | |
| | | | | |
| $C_{x2}$ | | | | |
| | | | | |
| | | | | |

| | | | | |
|---|---|---|---|---|
| $C_{xP}$ (in parallel) | | | | |
| | | | | |
| | | | | |
| $C_{xS}$ (in series) | | | | |
| | | | | |
| | | | | |

8. Change the standard capacitor. Use a plane capacitor. Put the frequency value up to $10^4$ Hertz.
9. Repeat items 3,4,5, and using (1), calculate capacitance of the plane capacitor.
10. Measure $d_1$, $d_2$ and calculate ε.
11. Record the data in Table 2.
12. Evaluate the experimental error.

**Table 2.**

| Dielectric | $d_0$ | $d_1$ | $d_2$ | $S$ | $C$ | $\varepsilon$ |
|---|---|---|---|---|---|---|
| | | | | | | |

## 6. Additional task (on the instructions of tutor)

Find the electric field strength, polarization, surface charge density and energy density of the plane capacitor. Compare their values with those one of the air capacitor (without dielectric).

# Experiment 4. Determination of High Value Resistance and Capacitance by Means of Relaxed Oscillations

## 1. Theoretical Contents

Electric oscillations are called relaxed if the electric energy of the circuit is being liberated by an inevitable process and transforms in some other forms of energy. Relaxed oscillations can be generated in the electric circuit, which consists of a gas-discharge tube (G.D.T.), resistor, capacitor and direct current source. The electric scheme is shown in Fig. 1. Gas-discharge tube is a balloon filled with an inert gas. There are two electrodes inside the tube. When the voltage applied to the gas-discharge tube is increased to the value of $U_{ig}$ (ignition potential), the electric current begins to flow through the tube. The potential decreases and the current does not flow through the tube. This critical potential is called the quenching voltage $U_q$. At that $U_q << U_{ig}$. The capacitor voltage-time dependence is given in Fig. 2. Under the action of applied voltage $U_0$, the capacitor $C$ begins to get charged and the voltage across it is changed in accordance with Formula (1):

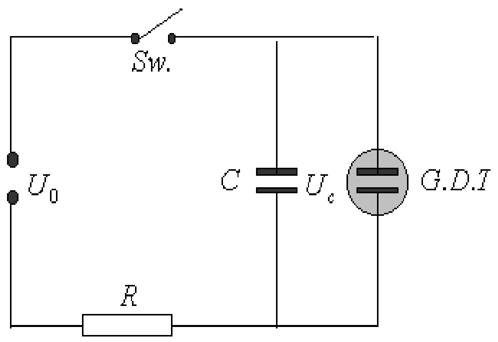

Fig. 1.

$$U = U_0(1 - e^{-t/RC}) \qquad (1)$$

When $U = U_{ig}$ the lamp flashes. The resistance of the lamp decreases and becomes much smaller in comparison $R$. The capacitor begins to discharge and the voltage across it decreases in accordance with Formula (2):

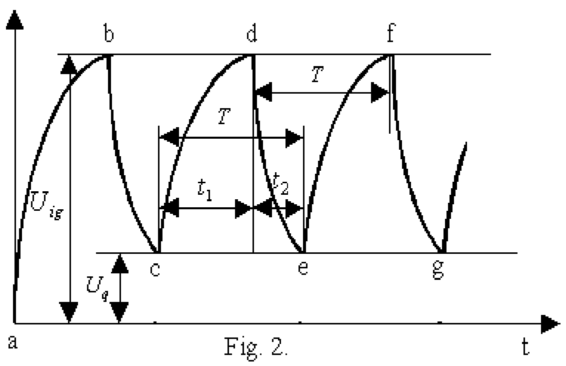

Fig. 2.

$$U = U_{ig}e^{-t/RC}) \qquad (2).$$

In this formula, time must be counted from the moment of ignition. When $U = U_q$, the capacitor begins to get charged again, i.e. the process of charging and discharging is being periodically repeated. The steady-state process is established after several oscillations. In Fig. 2., the unsteady-state process is shown symbolically as one cycle (curve $abc$). From point "$c$", the process is considered to be steady.

In time interval $cd$, the voltage varieties in accordance with Formula (3), the time must be counted from the moment "$c$": $U = U_q + (U_0 - U_q)(1 - e^{-t/RC})$ (3).

In time interval $de$ the voltage varieties in accordance with Formula (4), the time must be counted from the moment "$d$": $U = U_{ig}e^{-t/RC}$ (4).

Using (3) and (4) we have:

$$U_{ig} = U_q + (U_0 - U_q)(1 - e^{-t/RC}) \qquad (5)$$

$$U_q = U_{ig}e^{-t/RC}) \qquad (6).$$

Using (5) and (6) it's easy to obtain: $t_1 = RC \ln\left(1 - \frac{U_{ig} - U_q}{U_0 - U_q}\right)$ (7)

$$t_2 = RC \ln\left(U_{ig} / U_q\right) \quad (8).$$

Hence, the period of relaxed oscillations $T = t_1 + t_2$ can be expressed in the form:

$$T = RCf\left(U_0, U_{ig}, U_q\right) \quad (9)$$

where $f\left(U_0, U_{ig}, U_q\right) = \ln\left(1 - \frac{U_{ig} - U_q}{U_0 - U_q}\right) + \ln\left(U_{ig} / U_q\right)$ (10).

The function $f$ is dependent only on voltages acting in the electric circuit. From (9) it follows that for different resistors, but the same capacitor we have:

$$\frac{T_1}{T_2} = \frac{R_1}{R_2} \quad (11).$$

And in the analogous way, for different capacitors, but the same resistor we have:

$$\frac{T_1}{T_2} = \frac{C_1}{C_2} \quad (12).$$

Let's assume that the values of $R_1$ and $C_1$ are known. Then, after having measured $T_1$ and $T_2$ it's possible to calculate the values of $R_2$ and $C_2$:

$$R_2 = R_1 \frac{T_2}{T_1}; \quad C_2 = C_1 \frac{T_2}{T_1} \quad (13).$$

## 2. Experimental Procedures

1. Assemble the electric circuit, using $R_1$ and $C_1$ whose values are known.
2. Find the period of oscillations. It's necessary to switch on the timer and count the time $t$ between $n+1$ flashes (recommended $n = 10$). Obviously, $T = t/n$. Do these procedures not less than five times. Write down the data in Table 1.

**Table 1.**

| Electric circuit parameters | Number of The experiment | $t$ [sec] | The numbers of flashes, $n$ | $T_1$ [sec] | $\overline{T_1}$ [sec] |
|---|---|---|---|---|---|
| $C_1 =$ <br> $R_1 =$ | 1. | | | | |
| | 2. | | | | |
| | 3. | | | | |
| | 4. | | | | |
| | 5. | | | | |

3. Do the analogous measurements using $C_1$ and $R_2$.
4. Calculate $R_2 = R_1 \frac{\overline{T_2}}{\overline{T_1}}$. (15)
5. Do the analogous measurements using $C_2$ and $R_1$.
6. Calculate $C_2 = C_1 \frac{\overline{T_2}}{\overline{T_1}}$. (16).

**Note**: obviously, the values of $\overline{T_2}$ in (15) and (16) can be quite different, the value of $\overline{T_1}$ is the same.

7. Calculate the experimental errors.

## Additional Task (on instruction of tutor)

Measure the other unknown resistance $R_3$ and capacitance $C_3$. Connect them in series and in parallel, and check the well-known formulas:

$$R_S = R_2 + R_3; \qquad 1/R_P = 1/R_2 + 1/R_3;$$

$$C_P = C_2 + C_3; \qquad 1/C_S = 1/C_2 + 1/C_3.$$

## 3. Test Questions

1. Can you propose another method of measurement of big values $R$ and $C$?
2. What oscillations are called relaxed?
3. Explain the physical process which occurs in electric circuit of relaxed oscillation generator?
4. What's the physical sense of $U_{ig}$?
5. What's the physical sense of $U_q$?
6. Get Formulas (7) and (8).
7. What do you think happens during the unsteady-state process?
8. Can you get the Formulas (1) and (2)?
9. What is the main part of the gas-discharge tube?
10. Get the formulas for estimating of experimental errors.

# Experiment 5. Study of Semiconductor Resistance-Temperature Dependence. Determination of Activation Energy

## 1. Devices and Instruments

Semiconductor resistor (theristor), vessel with water, potentiometer, direct current sources, voltmeter, microammeter, switch and wires.

## 2. Model Conception on a Semiconductor Conductivity Mechanism

It is well known that an isolated atom can be considered as a potential well in which an electron is in one of the possible discrete energy states. In solids, atoms are located at a distance of an order $10^{-10}$, therefore they interact in a very strong way. On one hand, this interaction reduces the height of a potential barrier between atoms, and on the other hand – splits the electron energy levels into energy zones. Thus, instead of discrete energy levels, which are typical for an isolated atom, in a crystalline solid the system of energy bands is produced.

The next simplified scheme is being usually used for graphical interpretation of energy bands in a crystalline solid. Here: a - intrinsic activation, b - impurity activation. Because a lot of processes in crystalline solid are caused by configuration of valence electron states, only two allowed energy bands are shown: a valence band (V-zone) which represents excited states of valence electrons. There is a forbidden band between the full-filled valence band and conductive band and that is a very typical and interesting feature of semiconductors. Having acquired energy increment $\Delta E = E_c - E_v$, an electron transits through the forbidden band from the valence band into the conductive band. Quantum mechanical analysis of this phenomenon shows that in this process the empty places behave as the free positive electric charges, which are conventionally called "holes". An electron concentration ($n$) equals a hole concentration ($p$), i.e. $n = p = n_i$. This quantity determines the intrinsic conductivity of a semiconductor at a given temperature:

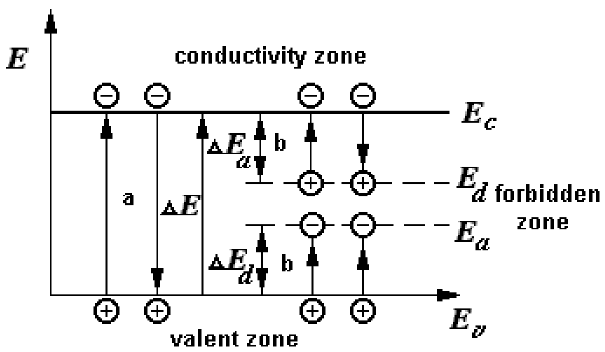


Fig.1.

$$\sigma = en_i(\mu_n + \mu_p) \quad (1)$$

where $e$ – elementary charge, $\mu_n, \mu_p$ – mobility of electrons and holes. These quantities represent drift velocity of electrons and holes in an electric field with unit field strength. Very often a free charge concentration is much greater than the intrinsic charge concentration. It's caused by an electric activity of impurities - its ability to transfer electrons and holes in bands. That can be easily explained with the help of model conceptions. Two-dimensional model of a silicon lattice is shown in Figure 2. The $As$ impurity atoms are inserted into the silicon lattice (see Figure 2a). Four valence electrons of the $As$ impurity atom are covalently linked to four silicon-neighboring atoms.

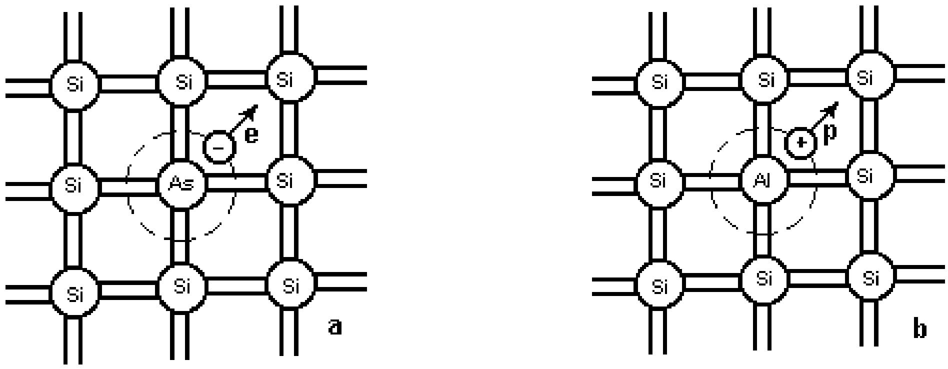


**Fig.2. Scheme of a crystalline lattice of donor (a) and acceptor (b) type.**

The fifth electron of an arsenic atom is weakly tied. Therefore, when the temperature is increased the fifth electron can easily leave the atom and move freely in crystal.

Thus, such a semiconductor is called an electron type semiconductor or $n-$type and the impurity is called the donor impurity. If an impurity of the third valence band (example, Al) is inserted into the silicon lattice (the fourth valence band), then the Si valence electron can engage the free tie of aluminum atom (see Fig.1b). In such a way, the free hole is generated. It can move freely in crystal and make a contribution to the conductivity of crystal. The impurities capturing electrons are called the acceptor impurities, and the semiconductor is called the hole type ($p-$type) semiconductor. In Figure 1, $E_a$ is an energy level of an acceptor impurity. It is above the highest level of a valence band. $E_d$ is an energy level of a donor impurity. It is below the lowest level of a conductive band. Besides the processes which produce free electrons and holes, an inverse process (recombination) occurs and the number of free charges diminishes.

## 3. Temperature-Resistance Dependence of Semiconductor

It is known that the conductivity of semiconductor is proportional to the concentration and mobility of free charges (1). The last investigations show that the concentration of free charges in a semiconductor depends on temperature in the exponential way. As a result, the resistance of a semiconductor is being decreased with increasing of the temperature in accordance with an exponential law:

$$R = R_0 e^{\Delta E/kT} \tag{2}$$

where $R_0-$constant quantity for given semiconductor, $k-$Boltzmann constant, $T-$absolute temperature, $\Delta E-$activation energy (it's the necessary energy to produce free charges in semiconductor).

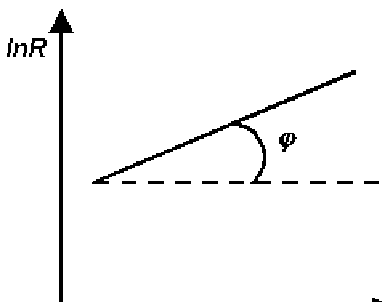


Fig.3

In order to study this law, it is very convenient to use a logarithmic scale. From (2) we easily get the following formula:

$$\ln R = \ln R_0 + \Delta E/kT \tag{3}$$

This dependence (in coordinates $\ln R$ and $T^{-1}$) is given in Figure 3. You see that the dependence is linear. And that is the reason of using such a kind of calculation. It's easy to get that $\Delta E = ktg\varphi$. Of course, $tg\varphi$ is a tangent in geometric sense. It can be found in a very simple way, with the help of relation:

$$tg\varphi = (\ln R_1 - \ln R_2) \Big/ (T_1^{-1} - T_2^{-1})$$

## 4. Thermoresistors (thermistors)

Thermoresistors (thermistors) are the electric devices by constructing of which the temperature-resistance dependence of semiconductor is being used. Thermistors (TR) are non-linear resistances. The standard volt-ampere characteristic of a thermistor is shown in Fig.4. In the first stage (when currents are small) the power liberated in a semiconductor is not sufficient to produce a notable temperature increment and therefore Ohm's law is true. In the next stage, the semiconductor's temperature is higher than the temperature of the external medium. The semiconductor's resistance is decreased, therefore, the applied voltage is being also decreased. In Figure 4., $I'$ is a value of the current strength corresponding to the maximal value of applied voltage $U_m$.

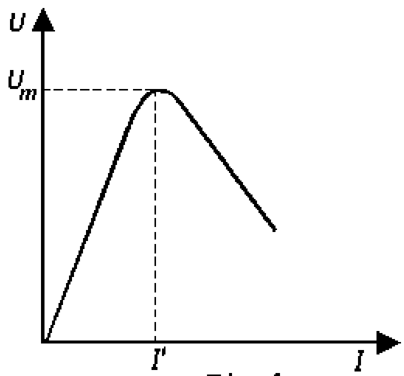

Fig.4

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## 5. Experimental Plant

An electric circuit used in this laboratory work is mounted upon a panel and consists of a current source, voltmeter, microammeter, potentiometer, switch, hot plate, vessel with water, thermometer and thermistor. The electric scheme is shown in Figure 5. Using the potentiometer it is possible to change the voltage in intervals of (0÷12) volts. Measuring the current strength in the electrical circuit it can get a voltage-current characteristic of thermistor. The heating of the thermistor is being made by an electric hot plate. The temperature is measured by a mercury thermometer. This is a method to get a temperature-resistance dependence of the thermistor.

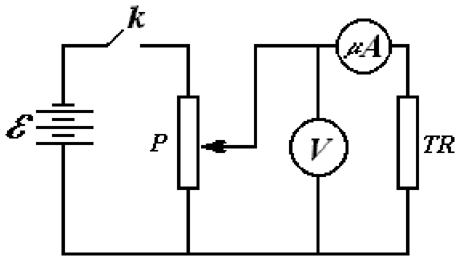

Fig.5.

## 6. Procedures

1. Assemble the electric circuit in accordance with the scheme shown in Figure 1.
2. In series, increase the applied voltage and determine the voltage-current characteristic. The step of the voltage increment can be chosen ad arbitrium, or with the help of the leading teacher. Insert the date in Table 1. Plot the voltage-current characteristic of the thermistor at a room temperature.

**Table 1**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *U* (volt) | | | | | | | | | | |
| *I* (ampere) | | | | | | | | | | |

3.In order to study the temperature-resistance dependence the thermistor is immersed into the vessel with water. The applied voltage should be constant (about 1-2 volts). Write down the values of temperature and current in Table 2. The resistance of semiconductor can be calculated using Ohm's law.

**Table 2.**

| $t^0C$ | $T^0K$ | $1/T$ | $I$ $(Ampere)$ | $U$ $(Volt)$ | $R$ $(Ohm)$ | $\ln R$ |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
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4.Using the date of Table 2 plot the graph of the temperature-resistance dependence of the thermistor. Plot the graph of the ($\ln R - T^{-1}$) dependence. Using this graph find out the conductivity activation energy.

Give the result in terms of the electron volt, 1eV=$1.6 \cdot 10^{-19}$ Joules.

## 7. Additional Task (on the instruction of tutor)

Using the resulting graph at the temperature-resistance dependence find out the temperature range in which the sensibility of a given thermistor is maximum.

# Experiment 6. Measurement of the Magnetic Field Strength of the Solenoid

## 1. Devices and Instruments

Solenoid, millivoltmeter, measuring coil, rheostat, connecting wires.

## 2. Introduction

A dielectric cylinder with wire turns on is called the solenoid. If the solenoid wire turns are in closed mechanical contact, then the resulting magnetic field inside the solenoid equals the sum of fields generated by single turn. If $L >> d$ ($L -$ solenoid length, $d -$ solenoid's diameter), a magnetic field inside the solenoid is uniform except for the edges of the solenoid. Near the edges of a solenoid the magnetic induction decreases and practically falls to zero at a distance (2-3) order unit of the solenoid diameter.

The basic characteristic of a solenoid is the magnetic induction **B**,

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{j}) \qquad (1)$$

Here: **H** - a magnetizing force; **j** - a magnetization vector, $\mu_0$ - a magnetic constant;

The magnetizing force is produced by external electric currents, i.e. by currents passing through the wire turns of solenoid. (Earth's magnetic field usually is too small in comparison with the basic field of a solenoid). The magnetization vector **j** determines the magnetization of the solenoid's core made of special magnetic steel or ferrite. The magnetization is numerically equal to a magnetic moment per unit of volume. The air permeability is practically 1, thus for the solenoid without magnetic core **j** $\approx 1$ and

$$\mathbf{B} = \mu_0\mathbf{H} \qquad (2)$$

a magnetic induction can be evaluated by the sum of inductions produced by the single turns of a solenoid.

Let $dl$ is an elementary length, $n -$ number of turns per unit of length. Thus, a quantity $Indl$ is an elementary circular current. Using the expression for the magnetic induction of a circular current we can write (see Figure 1):

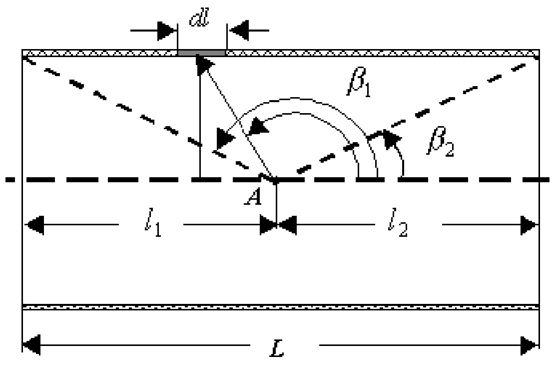


Fig.1

$$dB = \frac{\mu_0 I R^3 n dl}{2(R^2 + l^2)^{3/2}} \qquad (3)$$

Here: $dB -$ elementary introduction (at the point ***A***) produced by an elementary current $Indl$, $l -$ distance from $dl$ to a given point

$$l = R\,\text{ctg}(\beta) \qquad (4)$$

β is an angle between the axis of solenoid and radius-vector from an element $dl$ to the point ***A*** ; $R$ is a radius of the solenoid's turn. Derivation of (4) gives $dl = -R\dfrac{d\beta}{\sin^2\beta}$. As $R^2 + l^2 = \dfrac{R^2}{\sin^2\beta}$< we can rewrite the expression (3) in the form:

$$dB = -R\frac{\mu_0 I R^2 n \sin^3\beta d\beta R}{2R^3\sin^2\beta} = -\frac{\mu_0 In}{2}\sin\beta d\beta$$

The total magnetic induction at the point ***A*** can be received by integrating the last expression from $\beta = \beta_1$ up to $\beta = \beta_2$ :

$$B = \frac{\mu_0 In}{2}\int_{\beta_1}^{\beta_2} \sin\beta d\beta = \frac{\mu_0 In}{2}(\cos\beta_2 - \cos\beta_1) \qquad (5)$$

where $\cos\beta_1 = \frac{l_1}{\sqrt{l_1^2 + R^2}}$ ; $\cos\beta_2 = \frac{l_2}{\sqrt{l_2^2 + R^2}}$

Because $L = l_1 + l_2$ - total length of the solenoid, it can be rewritten (5) in the form:

$$B = \frac{\mu_0 In}{2}\left(\frac{l_1}{\sqrt{l_1^2 + R^2}} + \frac{L - l_1}{\sqrt{(L - l_1)^2 + R^2}}\right) \qquad (6)$$

If $l_1 = L/2$ (center of the solenoid) then

$$B = \frac{\mu_0 nIL}{\sqrt{L^2 + 4R^2}} \qquad (7)$$

If $L \to \infty$ ("long" solenoid)

$$B = \mu_0 In \qquad (8)$$

Putting $\beta_1 = \pi/2$ or $\beta_2 = \pi/2$ we can get the value of $B$ at the end of the solenoid:

$$B = \frac{\mu_0 nIL}{2\sqrt{L^2 + R^2}} \qquad (9)$$

Using the analogous calculations, a formula for magnetic induction at any external point (on the axis of solenoid) can be got:

$$B = \frac{\mu_0 In}{2}\left(\frac{(L + a)}{\sqrt{(L + a)^2 + R^2}} - \frac{a}{\sqrt{a^2 + R^2}}\right) \qquad (10)$$

Here, $a -$ distance from the end side of the solenoid up to a given external point.
atom are covalently linked to four silicon-neighboring atoms.

## 3. Experimental Plant

In this work, a measurement of the magnetic field of a solenoid is being made using the phenomenon of the electromagnetic induction. The experimental plant is shown in Figure 2. The solenoid is fed by an alternating current. The variable resistor $R$ and ammeter $A$ are in series with the solenoid. There is a measuring coil $b$ inside the solenoid. It can be moved along the solenoid's axis. The position of the coil is controlled with the aid of special scale $S$. e.m.f, produced in the coil, is measured by a millivoltmeter. The total magnetic flux through the coil:

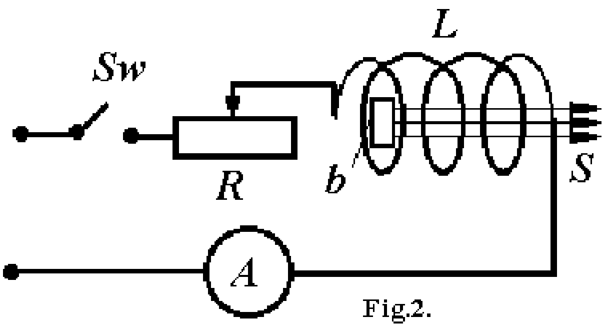

Fig.2.

$$\psi = B_m SN\cos(\omega t) \qquad (11)$$

Here: $B_m -$ maximal magnetic induction, $S -$ coil cross-section, $N -$ number of coil turns and $\omega -$ cycle frequency of alternating current.

E-e.m.f generated in the coil:

$$\varepsilon = \frac{d\psi}{dt} = B_m SN\sin(\omega t) \qquad (12)$$

Its maximal magnitude $\varepsilon_m = B_m SN\omega$ (13)

$\varepsilon_m = \sqrt{2}\varepsilon,$ where $\varepsilon -$ effective e.mf measured by the millivoltmeter.

So, $B_m = \sqrt{2}\dfrac{\varepsilon}{SN\omega}$ and $H_m = \dfrac{B_m}{\mu_0}$ (14)

Changing the current, it is possible to measure the magnetic induction at a given point and establish $B - I -$ dependence. Changing the position of the coil it is possible to find $B - I -$ dependence.

## 4. Procedures

1. Assemble the electric circuit in accordance with the scheme shown in Fig.2.
2. Put the measuring coil inside the solenoid, and changing the current (using a rheostat) measure emf. The current step is chosen to be 0.5 *A*.
3. Choose some value of a current strength (with the help of the teacher) and measure emf at the points along the solenoid's axis (recommended step - 1 cm).
4. Using the data, calculate $B_m$ and $H_m$.
5. Record results in Table 1 and Table 2.
6. Plot the graphs $B(I)$ and $B(x)$.
7. Compare the experimental results with calculations made in accordance with formulas (6)-(10).

**Table 1.**

| | |
|---|---|
| $I$ $(Ampere)$ | |
| $\varepsilon$ $(Volt)$ | |
| $B$ $(Tesla)$ | |
| $H$ $(Ampere/m)$ | |

**Table 2.**

| $I$ $(Ampere)$ | $x$ $(cm)$ | |
|---|---|---|
| | $\varepsilon$ $(Volt)$ | |
| | $B$ $(Tesla)$ | |
| | $H$ $(Ampere/m)$ | |

## 5. Additional Task (on instructions of tutor)

1. Determine the solenoid magnetic field energy corresponding to the given current (the current strength is given by the teacher).

2. Calculate the magnetic flux inside the solenoid (in its central point).
3. Calculate the solenoid's inductance.

## 6. Test Questions

1. What is the difference between the magnetic induction and magnetic field strength?
2. How does an induction depend on the magnetic strength?
3. What magnetic field is called uniform?
4. How does an induction in the central point change if the length of a solenoid is decreased?
5. What phenomenon is called an electromagnetic induction?