PRACTICAL 5.12

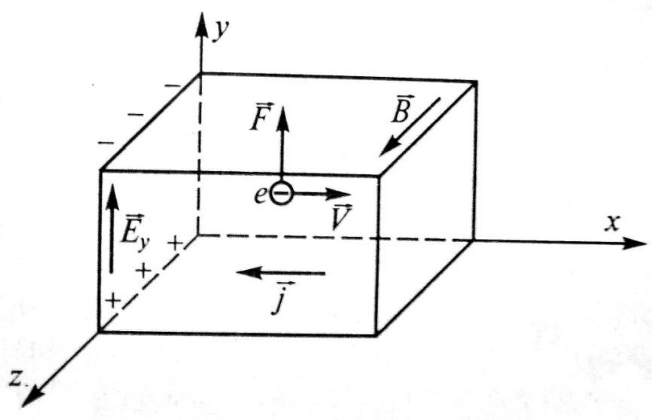
THE HALL EFFECT

Objective: to investigate the dependence of the Hall voltage in semiconductors on the magnetic field induction. Determination of the concentration and mobility of the main charge carriers in a semiconductor.

Instruments and accessories: a sample of a semiconductor material - germanium (Ge), a tunable DC voltage regulator P36-2, a digital voltmeter, a milliammeter, an electromagnet, a power supply VS-24M.

INTRODUCTION

The Hall effect in semiconductors is the appearance of a transverse potential difference in a semiconductor sample with a current placed in a magnetic field. Consider a semiconductor sample in the form of a rectangular plate with an electronic conductivity type (Fig. 1).



1Fig. 1. The Hall effect

The direction of the average ordered electron velocity is opposite to the vector of current density. The magnetic field is perpendicular to the plane of the figure. Under the action of the Lorentz force, the electrons will deflect to the upper face of the sample, on which a negative charge accumulates, on the opposite face there remains an uncompensated positive charge of the ions of the crystal lattice. The resulting transverse potential difference is known as the *Hall voltage*.

The separation of charges in the sample will continue until the electrical and magnetic components of the Lorentz force balance each other. Under this condition (notations from Fig. 1)

$$ev_xB_z - eE_y = 0. \qquad (1)$$

From here:

$$E_y = v_xB_z = \frac{j_xB}{en_e} = R_Hj_xB. \qquad (2)$$

$R_H = \frac{1}{en_e}$ here is the Hall constant, n_e is the electron concentration. For a negatively charged electron, the Hall constant is negative:

$$R_H = -\frac{1}{|e|n_e} \qquad (3)$$

Obviously, the Hall constant in the p-type material, where the main charge carriers are holes, is:

$$R_H = \frac{1}{en_p} \qquad (4)$$

where n_p is the concentration of holes.

Comparison of expressions (3) and (4) shows that the sign of the Hall constant R_H and, therefore, the sign of the Hall voltage U_H will depend on the sign of charge carriers in the semiconductor. If we go from the Hall field strength E_y to the Hall voltage U_H and from the current density to the total current I through the sample, then expression (2) is converted to:

$$U_H = \frac{R_H IB}{d} \qquad (5)$$

where *d* is the sample size in the direction of the magnetic field *B*.

From the analysis of expressions (3), (4) and (5), it can be seen that the Hall voltage value allows us to find the concentration and the sign of charge carriers.

If, in addition to the Hall voltage, measure the electrical conductivity σ :

$$\sigma = en\mu_n \qquad (6)$$

then we can find the mobility of the main carriers, equal to the product of RH by σ :

$$R_H\sigma = \frac{1}{en}(en\mu) = \mu\,. \qquad (7)$$

Thus, by measuring the Hall voltage and conductivity, one can determine such important semiconductor parameters as the sign and concentration of the main charge carriers and their mobility.

DESCRIPTION OF EXPERIMENTAL INSTALLATION

The measurement of the Hall voltage and the specific resistance of semiconductor samples is carried out using the circuit shown in Fig. 2.

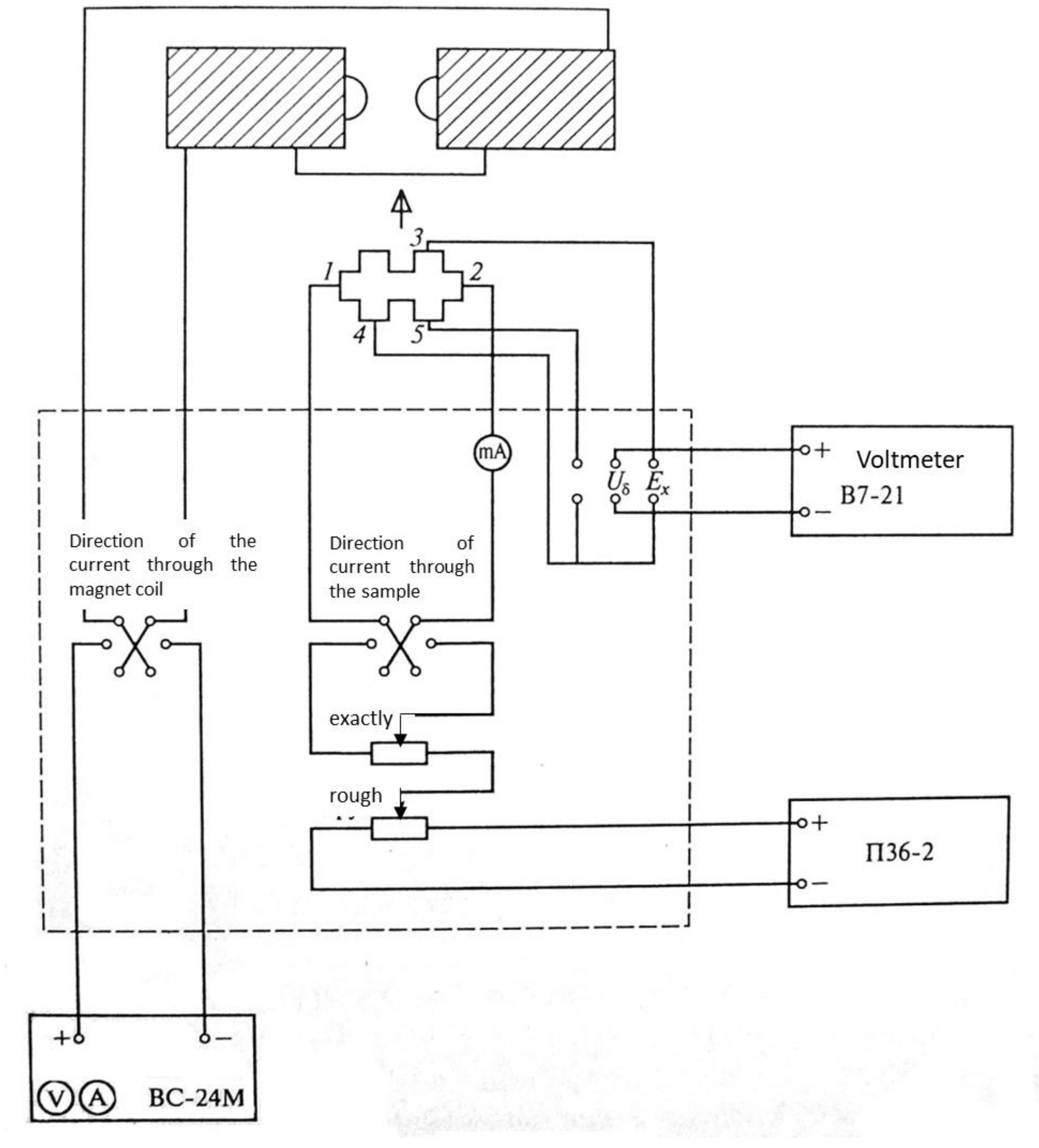


Fig. 2. Experimental setup diagram

The main element of the circuit is a semiconductor sample, which is a single crystal of germanium with a small addition of impurity (sample size: d = 0.106 cm (in the direction of the magnetic field), l = 0.29 cm (in the direction of the current), cross-sectional area S = 0.165 × 0.106 cm^2), made in the form of a dumbbell to ensure the best equipotentiality of the side probes for measuring the Hall voltage. Contacts 1, 2 are used to create an electric current in the sample, 3–5 - to measure the Hall voltage, 4–5 - to measure the resistivity.

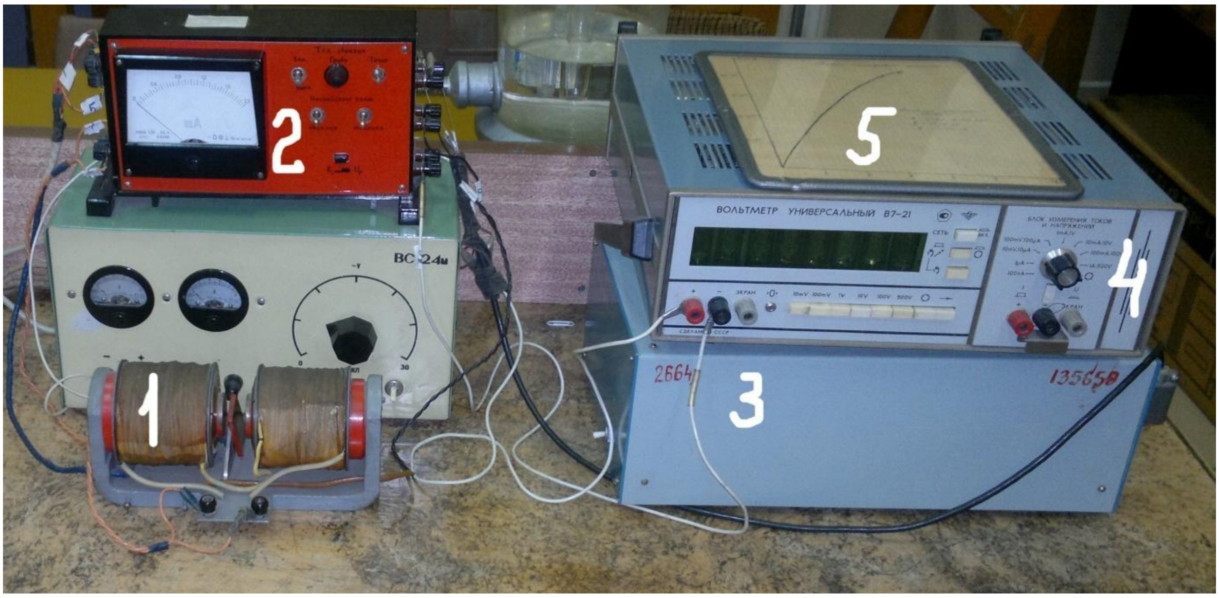


Fig. 3. Experimental setup

<u>Attention:</u>

The current through the sample should not exceed *1 mA !*

Also, a special care MUST be taken during operation of the electromagnet with high current of up to *4.5 A !*

A semiconductor sample is placed between the poles of an electromagnet *1* (photo above). The current in the electromagnet is created using a power supply VS-24M and is measured by an ammeter on the power supply panel. To change the direction of the current in the magnet winding, there is a special switch located on the control panel *2*. The induction of the magnetic field depending on the current through the electromagnet is determined using a calibration graph *5* attached to the installation.

The current in the semiconductor sample is created using a DC regulator *3*, which is equipped with additional potentiometers for coarse and fine adjustment of the current and a switch to change the direction of the current in the sample. The current through the sample is measured by a milliammeter. “Rough” and ”fine” potentiometers, current direction switch and milliammeter are located on the control panel *2*.

The Hall voltage and the voltage value on the sample to calculate the resistance of the sample are measured using a digital voltmeter *4*. The selection of the measured parameter is performed using the “E_x / U_σ” type of operation switch on the control panel *2*.

MEASUREMENT AND PROCESSING OF RESULTS

Get started:

Turn on stabilizer 3.

Turn on the control unit 2. Using the “rough” and “fine” tuning knobs, set the value of the current through the sample I = 0.5 mA.

Turn on the digital voltmeter 4 and set the measurement limit to “100 mV”.

Turn on the power supply VS-24M.

Task 1. Measurement of the dependence of the Hall voltage on the induction of the magnetic field at a constant current in the sample.

1) Set the “E_x / U_σ” switch on the control panel 2 to the “pressed” position, which corresponds to the measurement of the Hall voltage U_H.

2) Set the dial “sample current and magnet direction” on control panel 2 to the up position. Using a digital voltmeter, determine the value of U_H Hall voltage and put it in a table (in column↑↑).

Turn both toggle switches “sample current and magnet direction” to the lower position, remeasure the U_H value and put it in the table (in the ↓↓ column).

Measure the U_H values in opposite directions of the toggle switches (↑ ↓ and ↓ ↑) and enter in the corresponding columns of the table.

The value of the Hall voltage is taken to be the arithmetic mean of the four values obtained.

3) Next, change the values of the current of the electromagnet with a step of ***0.5 A*** to a maximum value of ***4.5 A*** and measure the Hall voltage dependence on the magnetic field induction *B*. For each value of the magnetic field induction, 4 measurements should be made corresponding to different directions of current through the sample and electromagnet. The results are listed in the table.

I_{magn}, A	B, T	U_H, mV				$U_{H\,avg}$, mV
		↑↑	↓↓	↑↓	↓↑	
0.5 1.5 … 4.5						

At the end of the measurements, set the electromagnet current to zero and turn off the power supply VS-24M.

4) Based on the measurement results, make a plot of $U_{avg}(B)$.

Task 2. Determination of carrier concentration by the value of the Hall constant.

From the $U_{avg}(B)$ plot determine the Hall constant:

$$R_H = \frac{U_H d}{IB} \text{ [m}^3\text{ / C].}$$

(d = 0.106 cm, I = 0.5 mA)

Estimate the accuracy of the result also using the graph.

Calculate the concentration of main charge carriers:

$$n = \frac{1}{eR_H} \text{ [m}^{-3}\text{].}$$

Task 3. Determination of the mobility of the main charge carriers.

Set the measurement limit of the digital voltmeter to "1 V".

Set the "E_x / U_σ" switch on the control panel 2 to the "pressed" position, which corresponds to the measurement of the voltage U_σ on the sample between probes 4 and 5.

Write down the U_σ reading of the digital voltmeter.

Calculate the conductivity of a semiconductor sample:

$$\sigma = \frac{I}{U_\sigma} \cdot \frac{l}{S}, \qquad (8)$$

(S = 0.165×0.106 cm^2 - the cross-sectional area of the sample, l = 0.29 cm - the length of the sample in the direction of the current).

Knowing the Hall constant R_H and conductivity, find the mobility of free charge carriers:

$$\mu = R_H \sigma.$$

QUESTIONS AND EXERCISES

1. What is the carrier mobility? From the definition of mobility and Ohm’s law in differential form, we obtain formulas (6) and (7).

2. What are the conditions for the Hall voltage appearance? What determines the value of this voltage and its sign?

3. What are the features of the band structure of semiconductors, dielectrics and metals?

4. How do donor and acceptor impurities affect the structure of semiconductor energy levels?

5. Do the classical Boltzmann statistics apply to electrons in the conduction band and to holes in the valence band? Justify the answer.

6. What is a degenerate electron gas? Is electron gas degenerate at room temperature in a metal? in semiconductor?