Technobius Physics, 2024, 2(4), 0022, DOI: https://doi.org/10.54355/tbusphys/2.4.2024.0022

Technobius Physics

https://technobiusphysics.kz/

e-ISSN

3007-0147

Article

Investigation of the electrical properties and carrier concentration in n- and p-doped germanium

Galina Troshina, Natalya Voronena*

Interdisciplinary Center for Particle Physics and Astrophysics, Novosibirsk State University, Novosibirsk, Russian Federation

*Correspondence: voronena93@mail.ru

Abstract. This work investigates the Hall effect in n- and p-doped germanium samples through experimental measurements of Hall voltage, electrical conductivity, charge carrier mobility, and carrier concentration under varying magnetic fields and temperatures. The experimental setup involved measuring Hall voltage as a function of control current, magnetic field induction, and temperature using a TSE Co, LTD company Hall-effect unit. The linear dependence of the Hall voltage on the magnetic field was confirmed, yielding regression line slopes of b = 0.144 VT^{-1} ± 0.004 VT^{-1} for n-germanium and b = 0.125VT^{-1} ± 0.003VT^{-1} for p-germanium. Corresponding Hall constants were calculated as R_H = 4.8×10 m^{-3}/C and R_H = 4.17×10 m^{-3}/C. Electrical conductivities were determined as σ = 53.6 S/m for n-germanium and σ = 57.14 S/m for p-germanium. The Hall mobilities were found to be μ_H =0.257±0.005 m^2/Vs for n-germanium and μ_H = 0.238±0.005 m^2/Vs for p-germanium. Carrier concentrations were n = 13.0×10^{20} m^{-3} for electrons and p =14.9×10^{20} m^{-3} for holes. From temperature-dependent measurements, the energy bandgaps were calculated as $E_g = 0.50 \pm 0.04$ eV for n-germanium and $E_g = 0.72 \pm 0.03$ eV for p-germanium. The experimental findings provide comprehensive insights into the electronic properties of doped germanium, highlighting its behavior under magnetic fields and varying temperatures, with precise parameter evaluation crucial for semiconductor applications.

Keywords: hall effect, germanium, charge carrier mobility, electrical conductivity, semiconductor properties.

1. Introduction

The Hall effect is a crucial phenomenon in semiconductor physics, offering deep insights into the electrical properties of materials, particularly the behavior of charge carriers in the presence of a magnetic field [1]. When a current flows through a conducting material placed in a perpendicular magnetic field, a transverse voltage is generated across the material, which is proportional to the magnetic field and the current [2]. This effect is widely used to determine key material properties such as charge carrier concentration, carrier mobility, and the type of charge carriers, making it an indispensable tool for the characterization of semiconductors.

In semiconductor materials, the Hall effect allows for the differentiation between n-type and p-type conduction [3]. N-type semiconductors are characterized by an excess of electrons as the majority charge carriers, while p-type semiconductors feature holes (missing electrons) as the majority carriers. Germanium (Ge), a Group IV semiconductor, is of particular interest due to its relatively narrow bandgap of 0.66 eV and high charge carrier mobility, which makes it ideal for high-speed electronic devices, infrared detectors, and optoelectronic applications [4].

The Hall effect is instrumental in deriving several critical parameters of doped germanium, such as carrier concentration and mobility [5]. Through precise measurements of Hall voltage as a function of both the magnetic field and temperature, one can also estimate the energy bandgap and other electronic properties of the material [6]. Temperature-dependent Hall measurements provide valuable data on both intrinsic and extrinsic conduction mechanisms in germanium, which are essential for understanding how charge carriers behave under different environmental conditions [7].

The purpose of this experiment is to study the Hall effect in n- and p-Germanium, including determining the concentration and mobility of charge carriers, as well as determining their type. To achieve this goal, the Hall voltage is measured, which occurs when an electric current passes through semiconductor wafers in a magnetic field of various inductions. The experimental data obtained are used to calculate the key parameters of semiconductors and analyze differences in their behavior under conditions of an external magnetic field. By conducting temperature- and magnetic-field-dependent measurements, this research will offer critical insights into the electronic properties of germanium, contributing to its continued optimization for use in modern semiconductor technologies.

2. Methods

The object of research was germanium, which has a diamond-type crystal structure with a cubic lattice in which the atoms are connected by covalent bonds that determine its semiconductor properties. Its bandgap width is about 0.66 eV at room temperature, which is much smaller than that of silicon, making its charge carriers - electrons and holes - highly mobile [4]. Due to its semiconductor properties, germanium has found a wide range of applications in research and technological development [8]. In semiconductor physics it serves as a model material for studying the zone structure, mobility of charge carriers and other parameters important for describing transport phenomena [5]. In the electronics industry, germanium is used to produce transistors, diodes, photovoltaic cells, and infrared sensors [9]. Its high electron mobility makes it ideal for creating high-frequency devices [10]. In optoelectronics, germanium is used in photodetectors and infrared systems due to its ability to effectively absorb infrared radiation [11].

In the pure state, germanium is an intrinsic semiconductor in which the concentrations of electrons and holes are equal. However, due to the doping process, its electrical properties can be significantly changed by introducing impurity atoms into the crystal lattice. The addition of Group V elements (e.g., phosphorus or arsenic) produces an n-type semiconductor in which the main charge carriers are electrons and the non-main charge carriers are holes. This is due to the presence of an extra valence electron in the impurities, which becomes a free charge carrier, increasing the electrical conductivity of the material. In the case of doping with Group III elements (such as boron or indium), a p-type semiconductor is formed, where the main charge carriers are holes, resulting from the lack of one electron in the valence shell of the impurity atoms. In this work, we used $1 \cdot 10^{-3}$ m thick samples.

In addition, research in the field of quantum electronics shows that germanium can be used to create quantum dots and develop new technologies in the field of quantum computing. However, all its properties are not fully understood. In connection with this, it was decided to study the semiconductor properties of germanium through the Hall effect.

The experimental technique for studying the Hall effect in p-Ge and n-Ge semiconductors involves the use of specialized TSE Co, LTD company equipment, including the installation of the Hall effect HU 2 11801-01, a digital teslameter with a tangential Hall sensor, a digital multimeter, a voltage-controlled power supply, a coil with a number of turns 600, a U-shaped iron core with pole tips, and there are also circuit boards with p-Ge and n-Ge semiconductor wafers. The equipment wiring diagram is presented in Figure 1. Additionally, a tripod, angle clamps, support rods and connecting wires are used.

Before starting the experiment, the coil is mounted on an iron core with pole tips, which are fixed on a tripod. The coil is connected to a power source to create a magnetic field. A digital multimeter measures the current flowing through the coil, and the magnetic field induction is determined using a digital teslameter. The semiconductor wafer is fixed on the Hall effect installation and connected to a power source that creates an electric current, as well as to a multimeter for measuring the Hall voltage.

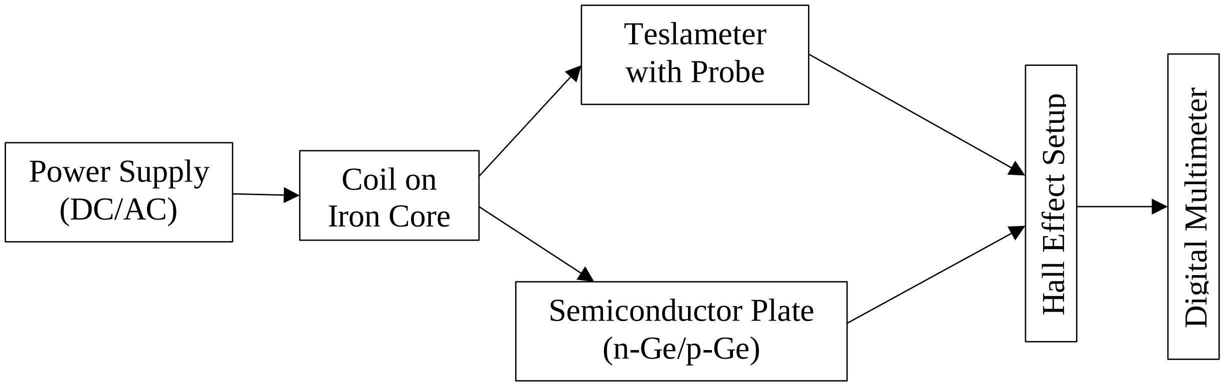


Figure 1 – Equipment wiring diagram

During the experiment, an electric current is supplied through the coil, creating a magnetic field, the magnitude of which is controlled by a teslameter. Then an electric current is passed through the semiconductor wafer, and the Hall voltage value is recorded by a multimeter. Measurements are carried out at different values of magnetic field induction and currents through a semiconductor. Similar operations are performed for both p-Ge and n-Ge semiconductors, which makes it possible to determine the type of main charge carriers and compare the results obtained.

The processing of experimental data includes the calculation of the Hall voltage according to the Equation (1):

$$U_H = \frac{BI}{ned} \tag{1}$$

Where: B – the induction of a magnetic field, I – the current through the plate, n – the concentration of charge carriers, e – the electron charge, d – the thickness of the semiconductor plate. The mobility of charge carriers is defined as:

$$\mu = \frac{U_H}{BI} \tag{2}$$

The analysis of experimental data allows us to draw conclusions about the concentration and mobility of charge carriers in the studied samples, as well as to establish differences in the behavior of p-Ge and n-Ge in the magnetic field. Moreover, the following statistical methods are used to confirm the reliability of the experimental data in the study of the Hall effect:

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3}$$

Where: N – the number of measurements, x_i – values of individual measurements.
An estimate of the scatter of the data relative to the mean was defined as:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{4}$$

Graphical representations were constructed considering the statistical processing methods to confirm the results' reliability.

In order to study the dependence of the electrical characteristics of a semiconductor sample (n- or p-germanium) on temperature, the voltage changes at constant control current during heating and subsequent cooling of the sample was investigated. In this case, the current was set at 30 mA with the magnetic field off. The sample was heated to a maximum temperature of about 140 °C, after which heating was automatically stopped. After the heating was turned off, cooling curve measurements were made, recording the voltage changes as a function of sample temperature from 140 °C to room temperature.

3. Results and Discussion

During the experiment, the multimeter was connected to the Hall voltage measurement connectors on the front side of the experimental module. The module display was set to the current display mode. The current was set to zero before starting the measurements, after which the Hall voltage was calibrated to eliminate possible initial offsets. The magnetic field was set at 250 mTl by adjusting the voltage and current of the power supply. To investigate the dependence of Hall voltage on current in n-type and p-type semiconductors, measurements were carried out at varying the current in the range from -30 mA to 30 mA with a step of 5 mA. As a result, typical dependencies were obtained as shown in Figures 2 and Figure 3 for n-germanium and p-germanium, respectively. The measured values reflect the linear dependence of Hall voltage on current.

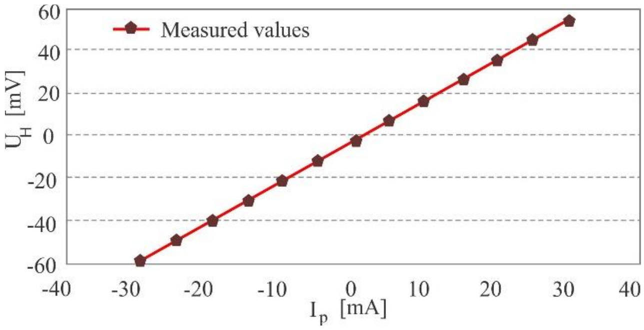


Figure 2 – Hall voltage as a function of the current I_P with B = 250 mT and T = 300 K, a case for n-Germanium

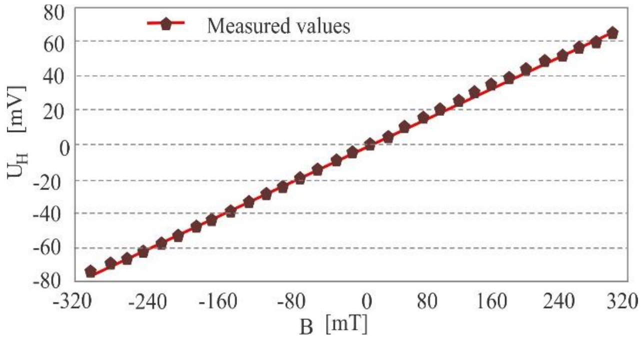


Figure 3 – Hall voltage as a function of the current I_P with B = 250 mT and T = 300 K, a case for p-Germanium

Figures 2 and 3 show the linear relationship between Hall voltage and control current for both n-germanium and p-germanium. This dependence can be described by Equation (5):

$$U_H = \alpha * I_P \tag{5}$$

Where: α – is the proportionality coefficient. Since electrons are the main charge carriers in n-germanium and holes are the main charge carriers in p-germanium, the sign of the proportionality coefficient is as follows α is reversed. This leads to different directions of Hall voltage variation with increasing control current, which is clearly demonstrated by the plots in Figures 2 and 3. Thus, the sign of the Hall voltage makes it possible to determine the type of conductivity of the material.

To investigate the dependence of the sample voltage on magnetic induction, measurements were carried out when the magnetic induction varies B in the range from 0 to 300 mTl with positive field direction.

Based on the obtained data, the change in resistance of the samples was calculated using Ohm's law and the relationship between the measured voltage and the applied current. The results of the calculations were presented as plots of resistance versus magnetic induction, as shown in Figures 4 and 5.

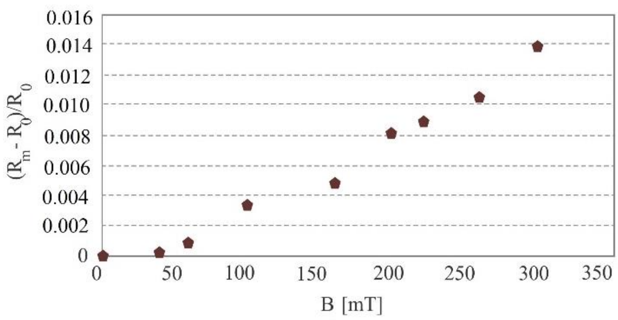


Figure 4 – Change of resistance as a function of the magnetic flux B with I_P = 30 mA and T = 300 K for n-Germanium

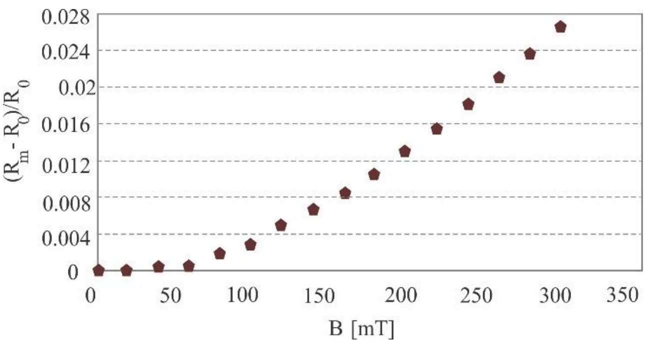


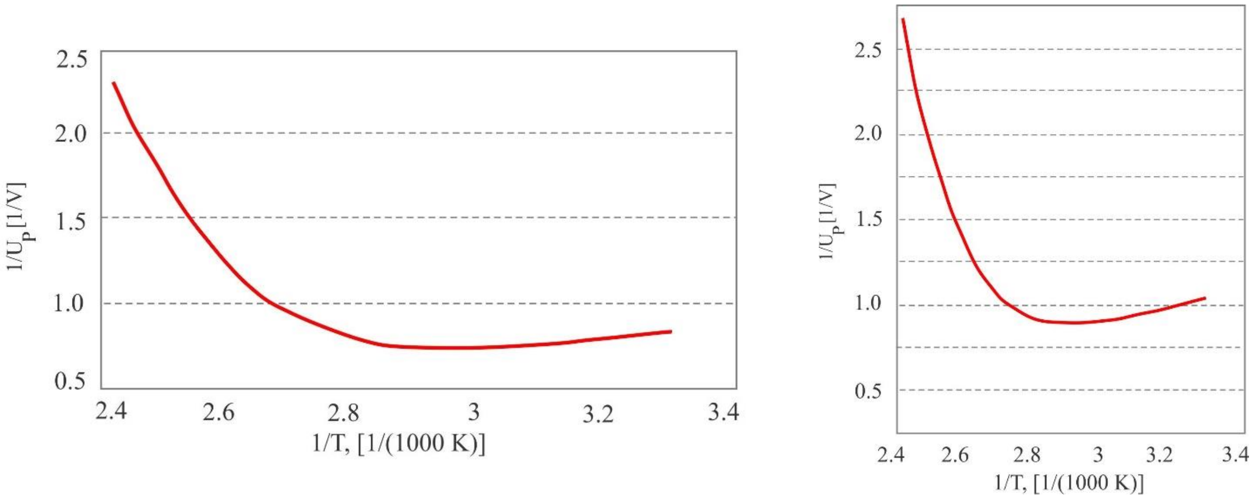
Figure 5 – Change of resistance as a function of the magnetic flux B with I_P = 30 mA and T = 300 K for p-Germanium

The obtained dependences demonstrate the influence of the magnetic field on the resistance of semiconductors, which corresponds to theoretical ideas about the behavior of charge carriers in a magnetic field.

Figures 4 and 5 show the variation of resistance for n-germanium and p-germanium samples, respectively. The graphs show a nonlinear increase in resistance with increasing magnetic induction. For n-germanium, this is due to negatively charged electrons as the main charge carriers, while for p-germanium it is due to positively charged holes. The difference in behavior is due to differences in the effective masses and mobility of charge carriers in these materials. Change of sample resistance under the action of magnetic field B is caused by a decrease in the average free path of charge carriers. When a magnetic field is applied to a semiconductor, the charge carriers begin to move along curvilinear trajectories due to the Lorentz force, which increases the probability of collisions and reduces their mobility. This leads to an increase in the effective resistance of the sample.

To study the effect of temperature on the electrical properties of a semiconductor sample, voltage changes at a constant reference current of 30 mA were investigated during heating to 140°C and cooling to 23°C of the sample. The results are presented in Figure 6a and Figure 6b.

In the intrinsic conductivity region, the electrical conductivity of a semiconductor depends on temperature and is described by an exponential dependence. The conductivity is determined by the pre-exponential coefficient, which depends on the material properties, and the forbidden zone energy, which characterizes the difference between the valence and conducting zones.



a) n-Germanium b) p-Germanium

Figure 6 – Plotting of reciprocal sample voltage with no magnetic flux and reciprocal absolute temperature $\frac{1}{T}$ with I_P = 30 mA

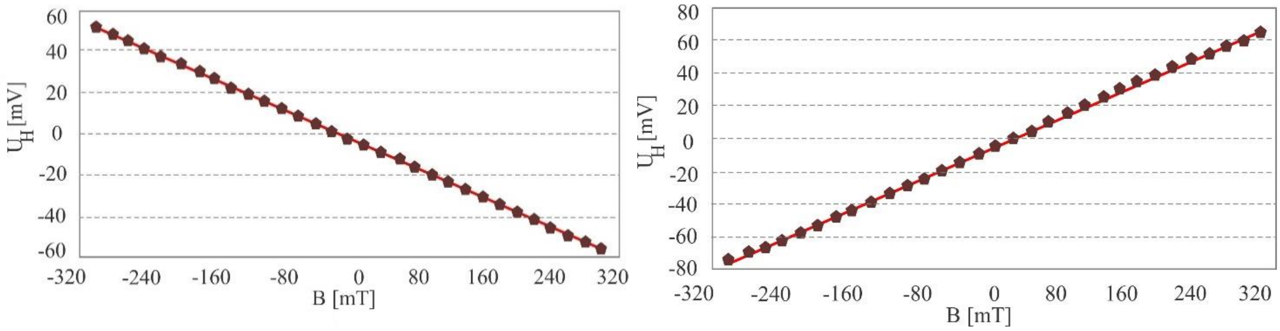
If we take into account that the conductivity decreases with increasing temperature, we can plot the dependence of the logarithm of the conductivity on the inverse temperature. This dependence will be linear, and the slope of the resulting straight line will be related to the width of the forbidden zone. Having measured the slope, we calculated the energy value of the forbidden zone using the known value of the Boltzmann constant. From the measured values presented in Figure 6a and Figure 6b, it follows that the slopes of the regression lines for n-germanium and p-germanium semiconductors are as follows $b = -2.87\times10^3$K $\pm$ 0.3×10^3K for n-germanium and $b = -4.18\times10^3$K $\pm$ 0.07×10^3K for p-germanium. These values confirm the temperature dependence of the conductivity in the intrinsic conduction region and allow us to estimate the bandgap width for both types of germanium with high accuracy. Thus, the bandgap width amounted to $E_g = b * 2k =$ (0.5$\pm$0.04) eV for n-germanium and $E_g = b * 2k =$ (0.72$\pm$0.03) eV for p-germanium.

The conductivity of a semiconductor sample at room temperature is calculated from its geometric dimensions and electrical resistance. The length of the sample l, its cross-sectional area A and the measured resistance R are related as follows:

$$\sigma_0 = \frac{l}{R \cdot A} \tag{5}$$

In our case, under the conditions that l = 0.02 m, R = 37.3 Ω for n-Ge, and R = 35.5 Ω for p-Ge, A = $1{\cdot}10^{-5}m^2$, the conductivity σ_0 =53.6 $\Omega^{-1}m^{-1}$ for n-Ge and σ_0 =57.14 $\Omega^{-1}m^{-1}$ for p-Ge. The Hall mobility of charge carriers has been established as $\mu_H = 0.257 \pm 0.005\ \frac{m^2}{Vs}$ and $\mu_H = 0.238 \pm 0.005\ \frac{m^2}{Vs}$ for n-Ge and p-Ge, respectively.

Next, we studied the Hall voltage relationships as a function of changes in magnetic induction and analyzed the properties of semiconductors in the presence of an external magnetic field. The results presented in Figure 7a and Figure 7b, illustrate the dependence of Hall voltage on magnetic induction for a semiconductor material at a fixed value of current 30 mA.



a) n-Germanium b) p-Germanium

Figure 7 – U_H as a function of magnetic flux B with T = 300 K and I_P = 30 mA

U_H measurements were performed as a function of magnetic induction starting from -300 mTL to 300 mTL. The polarity of the power supply coil was varied to change the direction of the magnetic field, and the magnetic induction was increased in steps of about 20 mTl. At the zero point of magnetic induction, the polarity of the field was also changed.

At a certain direction of the control current and the external magnetic field, the charge carriers in the sample are deflected towards its leading edge as a result of the Lorentz force. This deflection results in a potential difference known as the Hall voltage. In the case of an n-doped sample, the main charge carriers are electrons, so the leading edge of the sample becomes negatively charged. In a p-doped sample, the main carriers are holes, resulting in a positive charge at the leading edge.

The conductivity of the material, the mobility of charge carriers and their concentration are related to each other through the Hall constant, which is determined experimentally. Figure 7 shows the linear dependence of the Hall voltage on the magnetic induction B, which confirms the theoretical model. For the conditions used in the experiment, a regression line with the corresponding Equation 5 describing this dependence was constructed. The obtained results demonstrate the correct behavior of Hall voltage in semiconductor samples and confirm the effectiveness of the measurement method.

The experimental data presented in Figure 7, demonstrate the linear dependence of Hall voltage on magnetic induction described by Equation (6):

$$U_H = U_0 + b * B \tag{6}$$

The slope of the regression line calculated by us was b = 0.144 VT^{-1} with a standard deviation of $\pm$0.004 VT^{-1} for n-doped germanium and b = 0.125 VT^{-1} with a standard deviation of $\pm$0.003 VT^{-1} for p-doped germanium. Based on these values, the Hall constant was calculated using the Equation (7):

$$R_H = \frac{U_H}{B} \cdot \frac{d}{I} = b \cdot \frac{d}{I} \tag{7}$$

Thus, the Hall constant evaluated $R_H = 4.8{\cdot}10^{-3}\ \frac{m^3}{As}$ with standard deviation $\pm 0.2{\cdot}10^{-3}\ \frac{m^3}{As}$ for n-doped germanium and $R_H = 4.17{\cdot}10^{-3}\ \frac{m^3}{As}$ with standard deviation $\pm 0.08{\cdot}10^{-3}\ \frac{m^3}{As}$ for p-doped germanium.

The experimental results allowed us to determine the concentration of charge carriers in the studied semiconductor samples on the basis of experimentally obtained values of Hall constant. For p-doped germanium the concentration of holes p, calculated by Equation (8):

$$p = \frac{1}{e} \cdot R_H \tag{8}$$

And amounted to p = 14.9·10^{20} m^{-3}. Similarly, for n-doped germanium, the electron concentration calculated by the same Equation is n = 13.0·10^{20} m^{-3}. The obtained results demonstrate the effectiveness of the method of measuring the parameters of charge carriers using the Hall effect.

4. Conclusions

During the experiment, a linear increase in the Hall voltage was obtained with an increase in the magnetic field. The slopes of the regression lines were b = 0.144 VT^{-1} with a standard deviation of $\pm$0.004 VT^{-1} for n-doped germanium and b = 0.125 VT^{-1} with a standard deviation of $\pm$0.003 VT^{-1} for p-doped germanium. These values made it possible to calculate the Hall constants $R_H = 4.8 \cdot 10^{-3}\,\frac{m^3}{As}$ with standard deviation $\pm 0.2 \cdot 10^{-3}\,\frac{m^3}{As}$ for n-doped germanium and $R_H = 4.17 \cdot 10^{-3}\,\frac{m^3}{As}$ with standard deviation $\pm 0.08 \cdot 10^{-3}\,\frac{m^3}{As}$ for p-doped germanium.

The calculated conductivity of the samples at room temperature was σ_0 =53.6 $\Omega^{-1}m^{-1}$ for n-Ge and σ_0 =57.14 $\Omega^{-1}m^{-1}$ for p-Ge. Based on these values, the Hall mobility of charge carriers was determined as $\mu_H = 0.257 \pm 0.005\,\frac{m^2}{Vs}$ and $\mu_H = 0.238 \pm 0.005\,\frac{m^2}{Vs}$ for n-Ge and p-Ge, respectively. The electron concentration was n = 13.0·10^{20} m^{-3} for n-Ge and the concentration of holes p = 14.9·10^{20} m^{-3} was for p-germanium. As a result, of temperature measurements, the values of the forbidden band width were determined as Eg = 0.50 ± 0.04 eV for n-germanium and Eg=0.72±0.03eV for p-germanium. The nonlinear increase in resistance with increasing magnetic field recorded in Figures 4 and 5, confirmed the decrease in the mean free path of charge carriers. Thus, the experimental results fully reflect the electrical characteristics of the studied samples.

References

[1] R. A. Masut, “Poisson’s equation in semiconductors: impact of charge depletion on Hall effect measurements,” *Can. J. Phys.*, vol. 101, no. 3, pp. 141–149, Mar. 2023, doi: 10.1139/cjp-2022-0158.

[2] N. Saleh and A. H. Qureshi, “Conductivity tensor and hall effect in magnetic semiconductors,” *J. Appl. Phys.*, vol. 42, no. 11, pp. 4313–4314, Jan. 1971, doi: 10.1063/1.1659772.

[3] T. Bauer, J. Kolb, A. B. Hummel, H. G. Roskos, Y. Kosevich, and K. Köhler, “Coherent hall effect in a semiconductor superlattice,” *Phys. Rev. Lett.*, vol. 88, no. 8, pp. 86801/1-86801/4, Feb. 2002, doi: 10.1103/PhysRevLett.88.086801.

[4] C. A. Stephenson *et al.*, “Band structure of germanium carbides for direct bandgap photonics,” *2016 IEEE Photonics Soc. Summer Top. Meet. Ser. SUM 2016*, pp. 53–54, Aug. 2016, doi: 10.1109/PHOSST.2016.7548543.

[5] M. M. Dettling *et al.*, “Carrier mobilities in heavily doped pseudomorphic Ge1-x Snx-epilayers,” *2020 43rd Int. Conv. Information, Commun. Electron. Technol. MIPRO 2020 - Proc.*, pp. 17–21, Sep. 2020, doi: 10.23919/MIPRO48935.2020.9245273.

[6] X. Li *et al.*, “Optical bandgap anomaly with tuning dimensionality in germanium perovskites: Interplay between quantum confinement and lone pair expression,” *Chem*, vol. 10, no. 3, pp. 891–909, Mar. 2024, doi: 10.1016/j.chempr.2023.11.011.

[7] M. A. Razali, A. J. Smith, C. Jeynes, and R. M. Gwilliam, “Temperature-dependant study of phosphorus ion implantation in germanium,” *AIP Conf. Proc.*, vol. 1496, pp. 193–196, Jan. 2012, doi: 10.1063/1.4766522.

[8] J. Satgé, “Some applications of germanium and its derivatives,” *Main Gr. Met. Chem.*, vol. 27, no. 6, pp. 301–307, Jan. 2004, doi: 10.1515/MGMC.2004.27.6.301.

[9] K. Li, K. H. Kong, H. Gamble, and M. Armstrong, “Ultra-shallow emitter formation for germanium bipolar transistor by diffusion from polycrystalline germanium,” *2011 Int. Semicond. Device Res. Symp. ISDRS 2011*, p. 2011, doi: 10.1109/ISDRS.2011.6135275.

[10] M. Mederos, S. N. M. Mestanza, R. Lang, I. Doi, and J. A. Diniz, “Germanium nanoparticles grown at different deposition times for memory device applications,” *Thin Solid Films*, vol. 611, pp. 39–45, Jul. 2016, doi: 10.1016/j.tsf.2016.05.026.

[11] K. L. Guo, H. H. Chen, X. M. Huang, T. H. Hu, and H. Y. Liu, "Solar broadband metamaterial perfect absorber based on dielectric resonant structure of Ge cone array and InAs film," *Chinese Phys. B*, vol. 30, no. 11, p. 114201, Jan. 2022, doi: 10.1088/1674-1056/abf91e.

Information about authors:
Galina Troshina – Candidate of Physical and Mathematical Sciences, Researcher at Interdisciplinary Center for Particle Physics and Astrophysics, Novosibirsk State University, Novosibirsk, Russian Federation, g.n.troshina@mail.ru
Natalya Voronena – MS, Research Assistant at Interdisciplinary Center for Particle Physics and Astrophysics, Novosibirsk State University, Novosibirsk, Russian Federation, voronena93@mail.ru

Author Contributions:
Galina Troshina – concept, interpretation, methodology, resources, data collection, editing.
Natalya Voronena – testing, modeling, analysis, visualization, drafting, funding acquisition.

Conflict of Interest: The authors declare no conflict of interest.

Use of Artificial Intelligence (AI): The authors declare that AI was not used.

Received: *04.11.2024*
Revised: 30.11.2024
Accepted: 23.12.2024
Published: 25.12.2024