BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LXII No. 2/2010	28 - 35	Seria Matematică - Informatică - Fizică

The Hall Effect Experiment Using New Data Acquisition and Processing Methods

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Abstract

The Hall Effect, in all its variants (classic, quantum or fractional quantum), is one of the effects that revolutionized certain areas of physics, not only theoretically but also in technological terms, for example the development of sensitive magnetometers. The observation and study of all characteristic properties for this effect, in laboratory and under optimum conditions, involve the development of a complex experimental assembly. Also, when introducing teaching criteria for an optimal presentation of the Hall effect for both students and specialists attending training courses, etc (to better know, understand and retain), we must consider additional issues such as those related to laboratory work implementation. The experimental data collection can be done in several ways. The classic version of the experimental setup includes analog measurements devices and the reading of the studied quantities values is done visually. Automatic data acquisition in electronic form can be achieved only if we have an interface between the experimental setup and the computer. In this article, we propose such a complex experimental assembly, which is able to acquire and to process experimental data in real time by using COBRA 3 dedicated software. After data set acquisition, we can also send (live or after being processed) this database or processed information for direct or later presentations. There are also presented the advantages and disadvantages of the two variants of the experiment, both in terms of experiment performing and in terms of teaching methods quality.

Keywords: *Hall Effect, Physics Laboratory, experimental setup, data acquisition, teaching physics.*

Introduction

In Physics Laboratory, experimental study of physical phenomena is a necessary way to teach students or specialists attending training courses, to better know, understand and retain the studied phenomena. When performing experimental assembly, it is very important to keep in mind the requirements regarding the methodology of teaching Physics. We present the classical Hall effect using two variants of the experimental arrangement.

In the former version, this study is performed using classical apparatus for measuring the Hall effect characteristic physical measures. In the latter version, it is used a modern variant of the arrangement which allows the experimentation of the phenomenon from more points of view. Other implementation of this phenomenon was performed for educational proposes in [9, 10].

The structure of the paper is organized as follows:

- *Theoretical aspects*, section in which there are presented several theoretical elements of the Hall effect phenomenon;

- *The assembly and the working stages of the experiment (version I)*, section where there are presented the components of the classical experimental setup and some experimental results using analog multimeters;
- *The assembly and the working stages of the experiment (version II)* presents the automatic data acquisition method and compares the same experimental results with the results from version I experimental setup. Additional results (temperature dependencies) are also presented;
- *Conclusions* highlight the advantages and disadvantages of these two versions, both in terms of experiment performing and in terms of teaching methods quality.

Theoretical Aspects

The Hall effect was discovered by the American physicist Edwin Herbert Hall (1855-1938) [1, 6]. It consists in the appearance of a voltage (Hall voltage) between the surfaces of a conductor, or semiconductor (located in external magnetic field) crossed by a driving electric current. The three characteristic directions, normal vector on surfaces, magnetic field lines and the driving current direction, are mutually perpendicular [1, 4].

The Hall effect demonstrates experimentally the magnetic field action on the moving electrons, i.e. the existence of the Lorentz force $\vec{F}_L = q_e(\vec{\upsilon} \times \vec{B})$. Using this theoretical start point, it is demonstrated [1, 2] that the Hall voltage (U_H), depends on both the external magnetic field (B) and the driving current (I),

$$U_H = bB\frac{I}{nq_e bc} = \frac{BI}{nq_e c}, \tag{1}$$

where q_e - represents the electron charge, n - the electrons concentration and c - the probe dimension along the magnetic field lines [1].

From a practical perspective, the effect allows the construction of sensitive devices for measuring the magnetic field induction, namely Hall probes.

The aims of this laboratory work are to study experimentally the classical Hall effect, linear dependence of Hall voltage on the current intensity through the plate, and to determine, within the first version, the carrier charges concentration in the material. In the second version, in addition, we determine the dependence of drop voltage (or current intensity – these two measures are linearly correlated) on temperature, at constant driving current and the dependence Hall voltage (current intensity) on temperature, with constant magnetic induction.

The Assembly and the Working Stages of the Experiment (Version I)

The experimental montage for this variant is presented in Figure 1. This montage is composed of: electromagnet (ELM), semiconductor plate(P), two voltage sources (E_1, E_2), two rheostats used to the fine adjustment of the intensity from the electromagnet circuit (R_s) an the driving current (R_{si}), an ammeter that can measure currents of the order of amperes (A), an ammeter that can measure currents of the order of milliamperes (mA) and a voltmeter for measuring the Hall voltage (U_H). These components are used to create and to measure the Hall effect's three characteristic physical measures along the three directions using three separated circuits (1), (2) and (3), as presented in Figure 1.

In this version, the Hall voltage is measured in two cases. In the former, the magnetic field induction is modified when the driving current is constant and in the latter case, the driving current is modified when the magnetic field induction is constant.

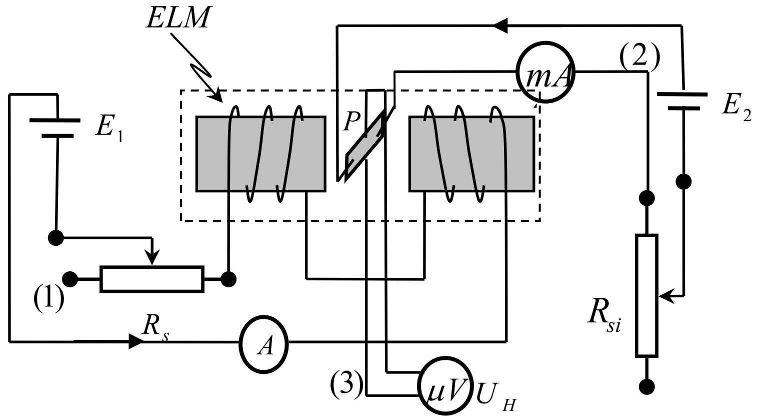


Figure 1: The experimental assembly for version I

After the measurement, two graphics can be realized to verify the linear dependency. The former graph presents dependency of the Hall voltage, as function of the induction magnetic field, and the latter - the Hall voltage, as function of the driving current intensity through plate. The experimental data is represented in Tabel 1. and Tabel 2.

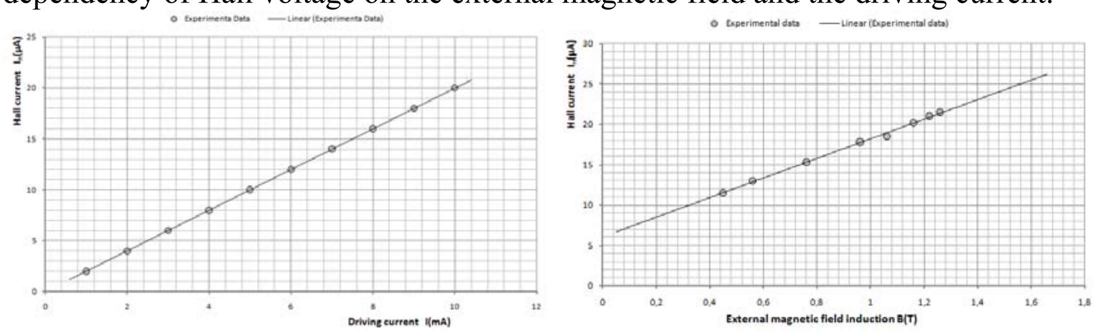
Table 1. Dependency the Hall voltage as function of the induction magnetic field

I_B(A) [1]	1	1,5	2	2,5	3	3,5	4	4,5
B(T)	0,45	0,56	0,76	0,96	1,06	1,16	1,22	1,26
I_H(μA)	11,5	13	15,3	17,8	18,5	20,2	21	21,5
U_H(10^{-2} V)	1,97	2,23	2,63	3,06	3,18	3,47	3,60	3,69

Table 2. Dependency the Hall voltage as function of the driving current intensity through plate

I(mA)	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
I_H(μA)	2	4	6	8	10	12	14	16	18	20
U_H(mV)	3,44	6,87	10,31	13,75	17,20	20,63	24,10	27,50	30,94	34,38

After the representation of these dependencies, we can verify the equation (1), the linear dependency of Hall voltage on the external magnetic field and the driving current.



a) b)

Figure 2: The linear dependency of Hall voltage on the external magnetic field and the driving current

[1] I_B represents the current intensity through electromagnet, using this values the magnetic field inductions are calculated, see row 2 in Table 1.

The main disadvantage of this experiment consists in the fact that all measurements are handmade and for few observations one must spend longer time than using the second version. These measurements also involve increased errors for the obtained results.

The Assembly and the Work Stages of the Experiment (version II)

In this version, the method allows the study of more properties of the Hall effect, which means that, by using a new experimental assembly we can realize measurements and graphical representations of the following dependencies: the Hall voltage as function of the current, resistance depending on magnetic field, drop voltage on the crystal as function of the temperature, the Hall voltage as function of the magnetic field and the Hall voltage as function of the temperature.

Explicitly, in order to achieve these goals, one must pass through the next steps:

- at constant room temperature and with an uniform magnetic field, one measures the Hall voltage as a function of the control current and plot the values on a graph (measurement without compensation for error voltage);
- at room temperature and with a constant control current, one measures the voltage across the specimen as a function of the magnetic flux density (magnetic field induction) B;
- at a constant control current, one measure the voltage across the specimen as a function of temperature. From the readings taken, one calculates the energy gap of germanium;
- at room temperature, one measures the Hall Voltage U_H as a function of the magnetic flux density B. From the taken data, one determines the Hall coefficient R_H and the sign of the charge carriers. Also the Hall mobility μ_H and the carrier density n are calculated;
- one measures the Hall voltage U_H as a function of temperature at uniform magnetic flux density B, and plot the readings on a graph.

The experimental montage [3, 5] (Figure 3) consists of: **1** - Power supply 0...12 V DC / 6 V, 12 V AC, **2** - „Hall effect” module, **3** - PCB, containing plate o germanium and necessary contacts, **4** - Cobra3 BASIC-UNIT, **5** - Measuring module, Tesla, 6 - sonda Hall, 7 - Coil, 600 turns, **8** - Iron core, U-shaped, laminated, **9** - Pole pieces, plane, 30x30x48mm, **10** - Power supply 12V/2A.

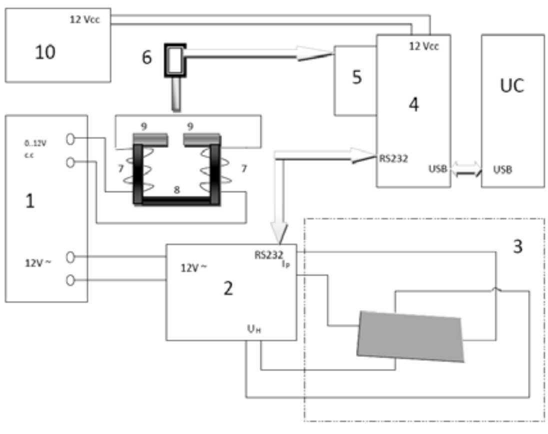


Figure 3: Experimental installation in case II

All measurements will be performed by COBRA 3 software [5]. The Hall probe must be inserted in the manner presented in Figure 1, so one measures the magnetic flux that crosses the germanium crystal. After processing data with the above-mentioned software, there are drawn the dependences, as presented in Figures 4-8.

The main advantage of this experimental arrangement is the data acquisition directly in an electronic form. Furthermore, all controls for this can be made using a simple interface in COBRA 3 software. All databases and graphics can be saved in order to use these measurements for later presentations. They can also be transmitted online in real time for other participants in the Hall effect experimental study.

Some graphical results are represented in Figures 4-8. These plots are realized based on other database files where the number of observations is larger than in case of version I.

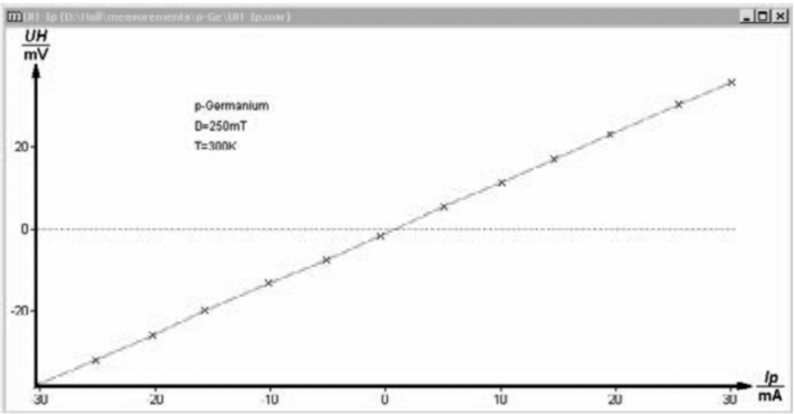


Figure 4: The Hall voltage as function of the current

In Figure 4, one observes a same linear dependency of Hall voltage by driving current (notated by I_p in COBRA 3) as in Figure 2.a.

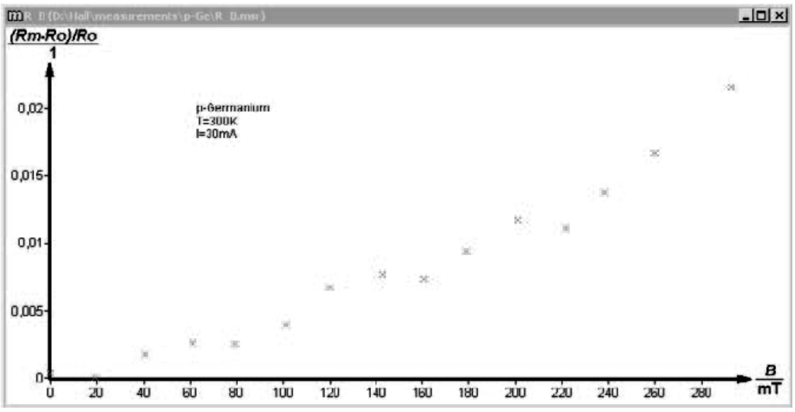


Figure 5: The resistance depending on magnetic field

In semiconductors the external magnetic field decreases the charge carriers' mobility that leads to the increase of the electrical resistance. In Figure 5, the relative variation of these values is represented, where R_m is the actual value of resistance and R_0 represents the plate resistance in absence of the magnetic field. For example, at approximately $\approx 280\,\mathrm{mT}$, the resistance increases with 2%.

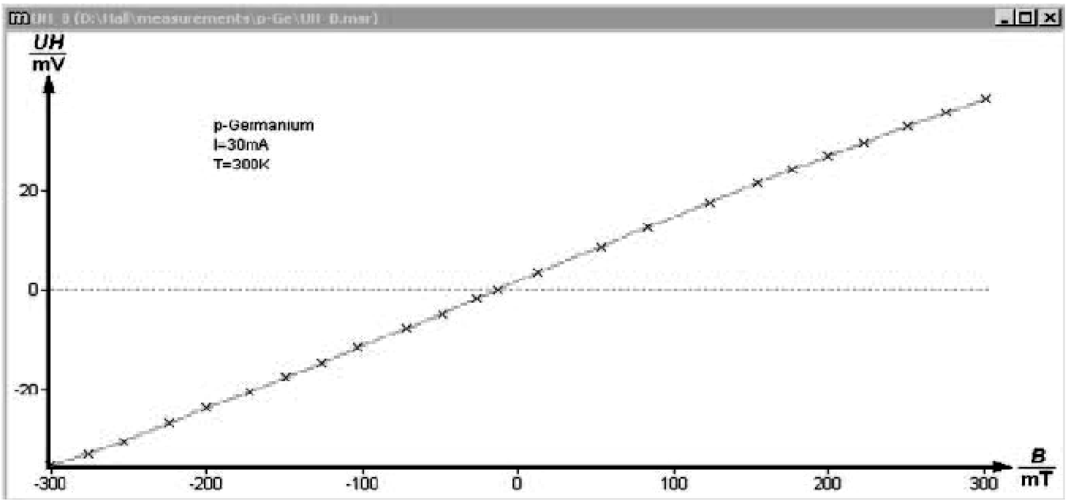
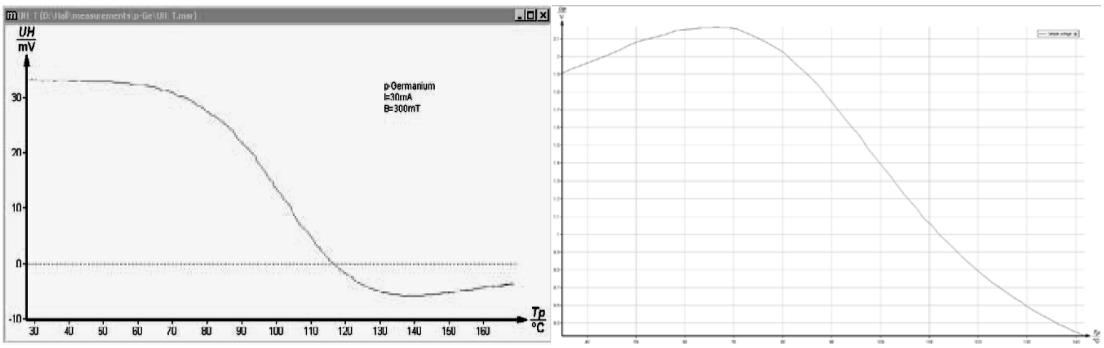


Figure 6: The Hall voltage as function of the magnetic field

In Figure 6, one observes the same linear dependence of the Hall voltage on the external magnetic field (notated by B in COBRA 3), as in Figure 2.b. Also, there is an essential difference between the two experimental setups, i.e. in the first version the external magnetic field must be 10 times higher to observe a significant Hall voltage for measurements.



a) b)

Figure 7: The Hall voltage (a) and the drop voltage (b) as function of the temperature

In Figure 7 there are represented the temperature dependences of the two significant measures of Hall effect, the Hall voltage (U_H) and the drop voltage (U_p - notation used by COBRA 3). The Hall voltage depends on temperature by means of electron concentration, see equation (1). These dependences cannot be studied in the first experimental setup.

Conclusions

The paper presents a parallel between two methods, emphasizing the advantages and disadvantages of each method.

The former method facilitates the understanding of the Hall Effect phenomenon, and highlights the causal relationship between the measures characterizing it. This method requires a longer duration for carrying out the work and for processing the experimental data that are to be represented in plotting graphs.

The latter method allows carrying out the work in less time and obtaining direct dependence graphs. The method requires computer knowledge and modern methods of data acquisition and processing and it highlights the interdisciplinary nature of the training and learning process. It is also suitable for online presentations of the physical phenomenon or interactive manipulation of data acquisition and processing.

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Studiul experimental al efectului Hall utilizând metode noi de achiziție și prelucrare a datelor

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Rezumat

Efectul Hall în toate variantele lui (cel clasic, cuantic sau cuantic fracționar) reprezintă unul din efectele care a revoluționat anumite domenii ale fizicii nu numai din punct de vedere teoretic dar și din punct de vedere al implicaților în evoluția tehnologiilor de realizarea a magnetometrelor. Studiul tuturor proprietăților caracteristice, în laborator, ale acestui efect în condiții optime, implică realizarea unui montaj experimental complex. De asemenea, la introducerea unor criterii didactice de prezentare a acestui efect studenților, specialiștilor în cadrul unor cursuri de perfecționare etc., trebuie să ținem cont de aspecte suplimentare în realizarea lucrării de laborator aferente. Culegerea datelor experimentele se poate realiza prin mai multe metode. Varianta clasică a lucrării de laborator include aparate de măsură analogice, iar citirea valorilor mărimilor studiate se realizează vizual. Achiziționarea automată în format electronic a datelor se poate realiza numai dacă dispunem de o interfață între dispozitivul experimental și calculator. În prezentul articol propunem un asemenea montaj cu posibilitatea de a achiziționa și prelucra datele experimentale în timp real prin utilizarea unui software dedicat, COBRA 3. După achiziționare, datele pot fi transmise la distanță (în timp real sau prelucrat) în vederea prezentării directe sau ulterioare. Vor fi prezentate, de asemenea, avantajele și dezavantajele celor două variante ale experimentului, atât din punct de vedere al desfășurării acestuia cât și din punct de vedere al calităților didactice ale metodelor.