APPLICATION OF GRAPHENE IN DEVELOPMENT OF HIGH-SENSITIVITY HALL-EFFECT SENSORS

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1. Introduction

Hall-effect sensors are one of the most commonly utilized magnetic field sensors with over 70% of share in market of industrial magnetic field measurement [1]. Because of this, Hall-effect sensors are intensively developed and new materials are under investigation for the possibility of application in this this type of sensors. Hall-effect is a physical phenomenon occurring in conductors and semiconductors. When a plate of conductor is subjected to the electric current flow and it is placed in the magnetic field with the direction perpendicular to the surface of the plate, electric potential difference, known as Hall voltage, can be observed as a result of Lorentz force acting on the charge carriers moving through the plate [2]. The Hall voltage is transverse to the direction of the current flow and, for simple case of conductor with electrons as a charge carriers, is given with the equation [3]:

$$V_H = -\frac{IB}{nte} \tag{1}$$

where V_H is Hall voltage, I is electric current flowing through the plate, B is magnetic flux density of the magnetic field, n is charge carrier (electrons) density, t is thickness of the conductor plate and e is electron elementary charge. As a result of the phenomenon, it is possible to measure magnetic flux density of the magnetic field by measuring Hall voltage.

Among many materials used so far in manufacturing of Hall-effect sensors, graphene is one of the most promising ones. Graphene is 2-dimensional crystalline allotrope of carbon. Its structure, with carbon atoms organized in sp^2-bonded hexagonal pattern, has a thickness of a single atomic layer, so graphene can be treated as a 2-dimensional material [4]. Graphene exhibits very interesting electric properties, like high charge carriers mobility of theoretical value reaching 200 000 $cm^2V^{-1}s^{-1}$ [5]. The real value of the charge carriers mobility in graphene grown on the SiC substrate is limited to about 15 000 $cm^2V^{-1}s^{-1}$ at carrier concentration of $2\cdot10^{11}$ cm^{-2} [4], which is still relatively high value. Because of these parameters, graphene is expected to be good material for Hall-effect sensors characterized by sensitivity significantly higher than for other materials used so far in Hall-effect sensors technology.

2. Preparation of graphene Hall-effect structure

For the investigation, several graphene Hall-effect structures were prepared. All of them were manufactured as Quasi-Free Standing Bilayer (QFS-bilayer) graphene structures, which contains two active layers of carbon atoms [6]. Structures were grown on semi-insulating on-axis 4H-SiC(0001) substrate using Chemical Vapour Deposition (CVD) method in standard hot-wall CVD Aixtron VP508 reactor [7]. Obtained QFS-bilayer graphene structures are characterized by domination of hole transport. Their charge carrier mobility reaches the value of 630 $cm^2V^{-1}s^{-1}$ at carrier concentration $1.8 \cdot 10^{13}$ cm^{-2}.

After the growth process was completed, the substrate with graphene layer was photolitographically shaped into Hall-effect structures. Structures were formed into the shape of symmetrical, equal-arm crosses, which is presented in Fig. 1. Each structure had four golden electrodes attached. Two opposite horizontal electrodes are used to power the structure with DC electric current. Between two vertical electrodes Hall voltage is measured.

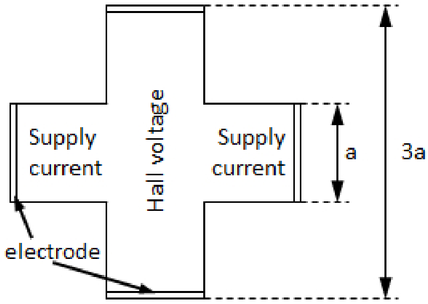

Fig.1: *Developed cross-shaped graphene Hall-effect structure, a =800 µm.*

Each of developed structures is characterized by the width of the cross bar, which was 800 µm in all investigated specimens. Prepared graphene Hall-effect structures were mounted on the developed PCB, which allowed to easily connect them to the measurement devices. Electrodes of the structure were bounded to the electric contacts of the PCB with golden wires.

3. Measurement setup

For all prepared graphene Hall-effect structures basic $V_H(B)$ characteristics and functional properties, like sensitivity and offset voltage, were measured. To perform investigation special digitally controlled measurement system was developed, utilizing precise Helmholtz coil as a source of reference magnetic field. Schematic diagram of the system is presented in Fig. 2.

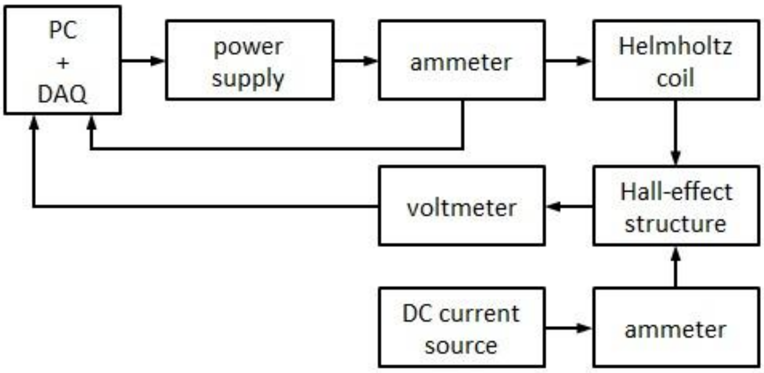

Fig.2: *Schematic block diagram of the developed measurement system.*

The graphene Hall-effect structure was powered by inmel 60 industrial calibrator working as a precise DC current source. The operational range of the current source was 0-20 mA. Supply current was measured with the APPA 207 control ammeter.

The Helmholtz coil was utilized as a source of reference magnetic field for investigation of $V_H(B)$ characteristics of the developed Hall-effect structures. Coil was controlled by PC with Data Acquisition Card (DAQ) NI USB-6009 installed. Special program for controlling measurement system and collecting measurement data was developed in National Instruments LabVIEW environment. DC voltage generated by DAQ was converted into current driving the Helmholtz coils by KEPCO BOP 36-6M bipolar power supply with current output. Current flowing through the coil was measured with precise FLUKE 8808A ammeter and results were transferred to the PC, where controlling program calculated value of magnetic flux density of the magnetic field according to the equation [8]:

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 n I_S}{R} \qquad (2)$$

where B is magnetic flux density, n is number of turns in the coil, I_S is supply current, R is radius of the coil and μ_0 is vacuum magnetic permeability (constant). Helmholtz coil utilized in developed measurement system allowed to obtain magnetic flux density within the range of ±6 mT. As a result of magnetic field acting on the graphene Hall-effect structure, Hall voltage was produced, which was measured with precise FLUKE 8846A voltmeter. Its indications were sent to the PC.

All measurements were performed in a standard laboratory conditions in room temperature (about 20°C) and normal atmospheric pressure.

4. Experimental results

For all developed graphene Hall-effect structures $V_H(B)$ characteristics were measured for several different values of supply current I within the range 0.1-10 mA. The exemplary results obtained for one of the structures are presented in Fig. 3. As it can be expected, slope of the characteristics is increasing with the supply current value. Hall voltage produced within the structure is decreasing with the increase of magnetic field flux density B, which is the effect of hole transport domination in QFS-bilayer graphene structure. All obtained $V_H(B)$ characteristics are characterized by high linearity, with coefficient of linear determination R^2 reaching the value over 0.9998.

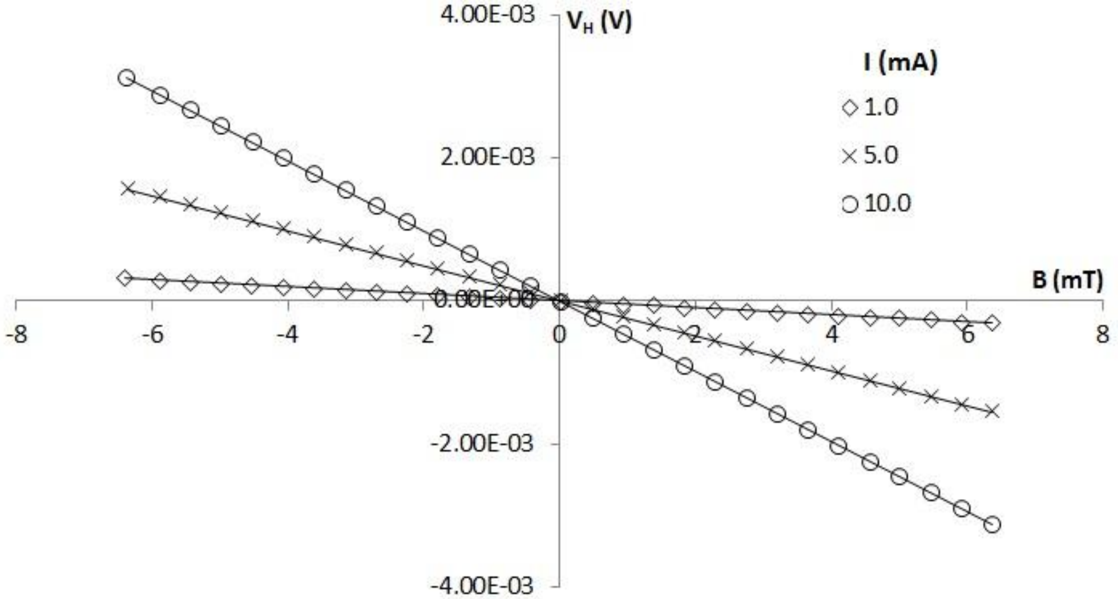

Fig.3: *Exemplary $V_H(B)$ characteristics obtained for one of the developed graphene Hall-effect structures for several values of supply current I.*

Obtained $V_H(B)$ characteristics allowed to perform analysis of basic functional properties of developed graphene Hall-effect structures. The main parameter is so called current related sensitivity, which can be determined according to the equation [9]:

$$S_i = \frac{1}{I} \frac{dV_H}{dB} \qquad (3)$$

The current related sensitivity as a function of supply current is presented in Fig. 4a. As it can be seen, current related sensitivity of developed graphene structure is almost constant with the average value 49.264 V/AT and standard deviation being only 0.039 V/AT. On the basis of presented results it can be stated that current related sensitivity of developed Hall-effect structure is constant. Deviations from the average value are probably the results of measurement equipment uncertainties.

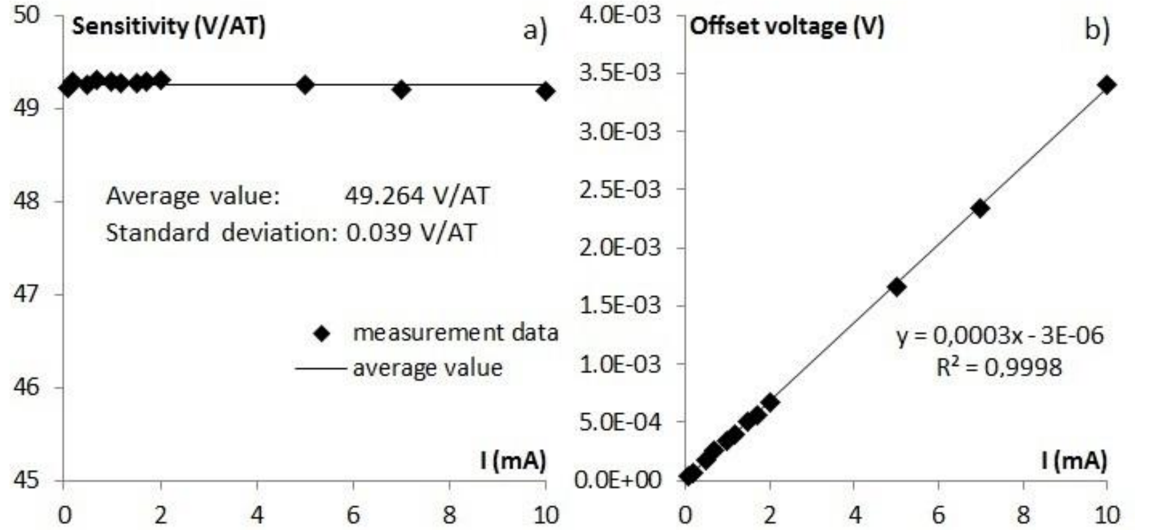

Fig.4: *Functional parameters of the developed graphene Hall-effect structure as a function of supply current I: a) current related sensitivity, b) offset voltage.*

Fig. 4b presents supply current dependence of the offset voltage for investigated Hall-effect structure. The offset voltage is growing with the increase of supply current in highly linear manner. Obtained values are relatively small and comparable to the traditional Hall-effect sensors commercially available. Offset voltage is mostly the result of imperfections in geometry of the developed Hall-effect structure.

Performed measurement procedure was repeated for five developed Hall-effect structures made of QFS-bilayer graphene. Investigated functional parameters of the structures for supply current I = 1.0 mA are presented in Tab. 1. All developed specimens are characterized by relatively high sensitivity and high linear determination of the $V_H(B)$ characteristics. Offset voltage values are significantly different for each specimen, which indicates that preparation process of the graphene structures requires further improvement to reduce geometrical imperfections in manufactured graphene and increase repeatability.

Tab. 1. *Basic functional parameters of developed graphene Hall-effect structures for supply current I = 1 mA.*

Specimen	Sensitivity	Offset voltage	R^2 coefficient
	V/AT	mV	-
1	49.295	0.336	0.9999
2	41.920	0.517	0.9998
3	43.868	1.283	0.9999
4	46.924	0.949	0.9999
5	50.030	1.851	0.9999

5. Conclusion

Experimental results presented in the paper are very promising and confirm that graphene can be successfully utilized in Hall-effect sensors. Developed graphene Hall-effect structures have satisfactory functional parameters. High sensitivity and linearity of characteristics of the developed structures are their great advantages. However manufacturing process still requires further improvement in order to reduce the offset voltage of the graphene structures.

Acknowledgement

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