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FUNCTIONAL PROPERTIES OF MINIATURE GRAPHENE HALL-EFFECT SENSOR

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In the paper, the process of manufacturing the graphene Hall-effect structure is presented. Moreover, the measurement system utilizing Helmholtz coils as a source of reference magnetic field is described. The basic functional properties of developed sensor, like sensitivity and offset voltage, were investigated. Also the influence of the supply current on sensitivity and offset voltage and time drift of this parameters were studied. Obtained results indicates that developed graphene Hall-effect sensor exhibits good functional properties and can be utilized in industrial measurements of magnetic field.

Keywords: graphene, Hall-effect sensor, magnetic field measurement

1 INTRODUCTION

Graphene, a 2-dimensional allotrope of carbon, is a newly developed and intensively studied material. Its structure has a thickness of single atomic layer and contains atoms of carbon organized in sp^2-bonded hexagonal pattern [1]. Because it exhibits many extraordinary properties, graphene has many possible technical applications. From the point of view of the magnetic field measurement, especially interesting are electrical properties of graphene, like high electron mobility and carrier concentration [2]. Due to these parameters, graphene is considered to be good material for high-sensitivity Hall-effect sensor [3].

Recent studies confirm this assumptions. Hall-effect graphene structures developed on the semi-insulating on-axis 4H-SiC(0001) substrate exhibit sensitivity significantly higher than materials so far used in Hall-effect sensors technology [4]. This results allow to take further works on utilizing graphene into industrial Hall-effect sensors of magnetic field.

This paper presents the newly developed miniature graphene Hall-effect sensor. Graphene Hall-effect structure is placed inside the standard QFN32 package for integrated circuits. Small dimensions of the package (5x5 mm) allows to easily apply developed sensor in electronic devices, for example current transformers.

2 THEORY OF HALL-EFFECT SENSOR

Hall-effect is a physical phenomenon involving generation of electric potential difference (Hall voltage) across an electric conductor. It occurs when electric current is flowing through the conductor, which is subjected to the magnetic field with direction perpendicular to the direction of the current flow [3]. Hall effect is the result of Lorentz force affecting charge carriers moving with the current flow, which occurs when charge carriers flows through magnetic field with direction not parallel to the flow direction. As a result of this phenomenon, electric potential difference is generated transverse to the direction of current flow. In simple case of metal with only one type of charge carriers – electrons, this electric potential difference known as Hall voltage is given with the equation [3]:

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

where V_H is Hall voltage, I is electric current, B is magnetic flux density of magnetic field perpendicular to the conductor, n is charge carrier density (electrons in this case), t is thickness of the conductor and e is electron elementary charge.

Discussed phenomenon is widely utilized in Hall-effect sensors of magnetic field. With known value of current flowing through the conductor and known parameters of material the conductor is made, it is possible to determine value of magnetizing field on the basis of measured Hall voltage value in the conductor.

3 PREPARATION PROCESS OF THE GRAPHENE HALL-EFFECT SENSOR

During the previous investigations, two types of graphene structures for Hall-effect sensor were tested. Monolayer graphene structure is composed of single layer of carbon atoms deposited on the buffer layer containing carbon atoms covalently bound to the substrate [5]. The buffer layer role is to separate active graphene layer from the substrate. Quasi-free standing bilayer (QFS-bilayer) graphene structure is obtained from the monolayer structure by decoupling buffer layer from the substrate through in-situ intercalation of hydrogen atoms [6]. Basic transport properties of both types of graphene structures are presented in Table 1. Both monolayer and QFS-bilayer structures were deposited on the Si face of

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semi-insulating on-axis 4H-SiC(0001) substrate. After comparing the results obtained for investigated types of graphene structure it was decided to focus further development on the QFS-bilayer graphene structure. Besides carrier mobility of monolayer structure higher than in QFS-bilayer, which should results in higher sensitivity, monolayer structure was also characterized by much higher value of the offset voltage (voltage measured in the graphene structure in absence of the external magnetic field). Moreover, offset voltage of monolayer structure was much more unstable in time, than in QFS-bilayer structure. This features decided that QFS-bilayer structure was chosen for further development.

Table 1. Basic transport properties of graphene Hall-effect structures

Structure type	Dominant charge carriers	Carrier mobility ($cm^2V^{-1}s^{-1}$)	Carrier concentration (cm^{-2})
Monolayer	electrons	1000	$4\cdot10^{12}$
QFS-bilayer	holes	630	$1.8\cdot10^{13}$

Miniature graphene Hall-effect sensor presented in the paper is composed of QFS-bilayer graphene Hall-effect structure mounted in standard package used in production of integrated circuits. QFS-bilayer graphene was grown with Chemical Vapour Deposition (CVD) method on the Si face of semi-insulating on-axis 4H-SiC(0001) substrate in a hot-wall CVD Aixtron VP508 reactor [7]. Next, graphene layer was formed into Hall-effect structures with electron-beam lithography process. As a result, QFS-bilayer graphene Hall-effect structure was obtained in the shape of symmetrical, equal-arm cross presented in Fig.1. Cross-shaped structure is characterized by the width of the bar (*a* dimension in Fig.1) which was 500 μm for prepared Hall-effect structures.

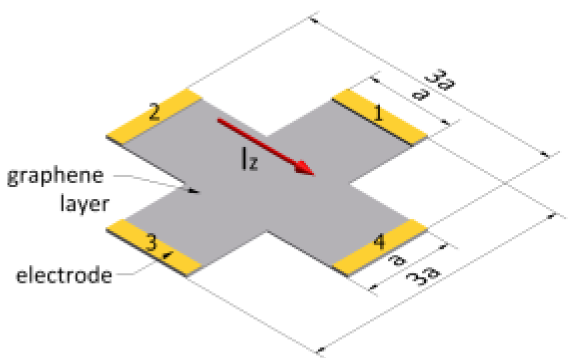

Fig. 1. Developed cross-shaped graphene Hall-effect structure, I_z – supply current flow direction, 1-4 – electrodes, a = 500 μm

After preparation of graphene structure was completed, four golden electrodes were attached to the structure, as presented in Fig. 1. Between two opposite electrodes (2 and 4 in Fig. 1) the electric current is flowing. Other two electrodes (1 and 3) are used to measure Hall voltage generated in the structure under the influence of external magnetic field.

Module containing Hall-effect structure and electrodes has a form of square with dimensions of 3.3x3.3 mm. The module is mounted inside standard QFN32 package for integrated circuits. Electrodes of the Hall-effect structure are bounded to the electrical contacts of the package with golden wires. Finished graphene Hall-effect sensor mounted in the package has dimensions of 5x5 mm, which is presented in Fig. 2. Developed sensor was covered with protective layer made of polymeric material protecting Hall-effect structure from the influence of the environmental conditions.

Fig. 2. Developed graphene Hall-effect sensors of magnetic field

4 MEASUREMENT SYSTEM

For investigating the functional properties of developed graphene Hall-effect sensor, special computer controlled measurement system was designed with Helmholtz coil as a source of reference magnetic field. The schematic block diagram of the system is presented in Fig. 3.

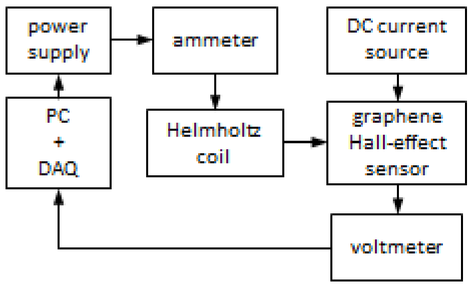

Fig. 3. Schematic block diagram of the measurement system

The graphene Hall effect sensor was powered by IMEL 60 calibrator working as precise DC current source within the range 0-20 mA.

As a source of the reference magnetic field, Helmholtz coil was used, powered with KEPCO BOP 36-6M bipolar power supply with current output. Power supply was controlled by PC with Data Acquisition Card (DAQ) NI USB-6009 installed. Value of the current I_s supplying Helmholtz coil was measured with precise multimeter FLUKE 8808A and transmitted to the PC, where actual value of magnetic flux density B generated by the Helmholtz coil was calculated according to the formula

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

where μ_0 is vacuum magnetic permeability, n is number of turns in Helmholtz coil and R is radius of the coil. Helmholtz coil utilized in the experiment allowed to obtain magnetic flux density B within the range about ±13 mT. High-precision measurement of the Hall voltage V_H was performed with FLUKE 8846A multimeter and transmitted to the PC, where $V_H(B)$ characteristics were determined and basic functional properties of the sensor were calculated: sensitivity and offset voltage.

All measurements were performed in a standard laboratory conditions in room temperature (about 22°C) and normal atmospheric pressure.

5 EXPERIMENTAL RESULTS

During the performed measurements $V_H(B)$ characteristics of developed graphene Hall-effect sensor were measured for several values of supply current I_z within the range 0.01-5 mA. The results of this investigation are presented in Fig. 4.

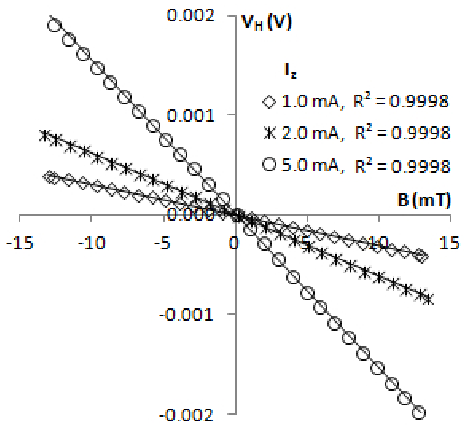

Fig. 4. $V_H(B)$ characteristics of developed graphene Hall-effect sensor for several values of supply current I_z

For all values of the supply current I_z Hall voltage generated in the active graphene layers is decreasing with the increase of the magnetic field B. This is characteristic feature of QFS-bilayer graphene structure, where dominant type of charge carriers are holes. As it can be seen, slope of the $V_H(B)$ characteristic is increasing with the value of supply current. All obtained $V_H(B)$ characteristics shows high linearity. Coefficient of linear determination R^2 reaches the value 0.9998 for all presented characteristics.

On the basis of the obtained characteristics of graphene Hall-effect sensor, basic functional properties were analysed. The dependence between current-related sensitivity of the sensor and value of the supply current I_z is presented in Fig. 5. As it is clearly visible, current-related sensitivity of the developed graphene sensor is almost constant for all investigated values of the supply current I_z. The calculated average value of the current-related sensitivity is 30.915 V/AT, while standard deviation is only 0.132 V/AT which indicates that current-related sensitivity of the sensor is constant and deviations from the average value may result from measurement equipment errors.

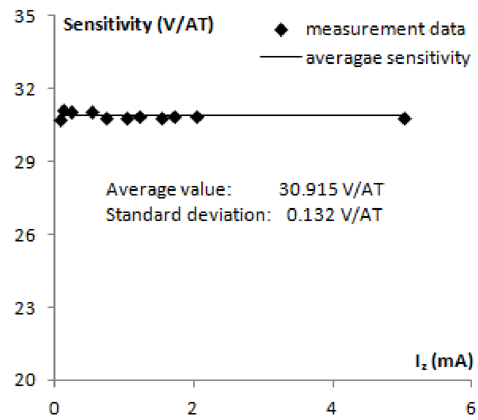

Fig. 5. Supply current I_z dependence of current-related sensitivity of developed graphene Hall-effect sensor

In the Fig. 6, the supply current I_z dependence of the offset voltage is presented. The dependence is highly linear. Obtained values of offset voltage are relatively low comparing to the previous reports [4, 8]. The offset voltage occurrence is result of imperfections of the geometry of developed Hall-effect structure and atomic structure of the graphene layer itself.

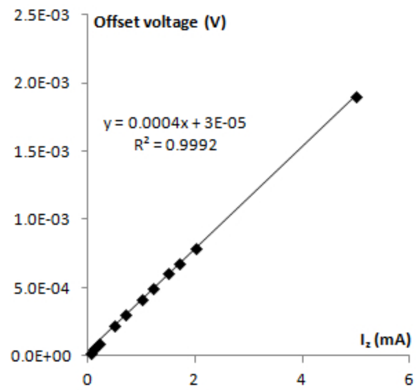

Fig. 6. Supply current I_z dependence of offset voltage of developed graphene Hall-effect sensor

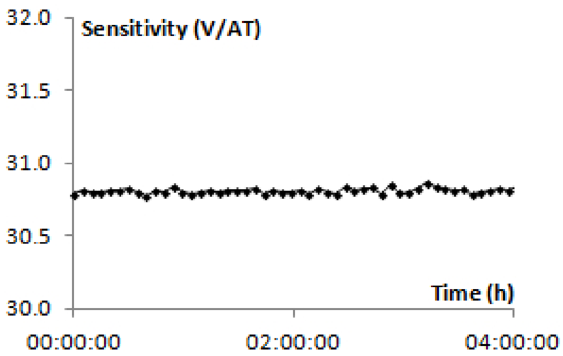

Fig. 7. Time drift of current-related sensitivity of developed graphene Hall-effect sensor

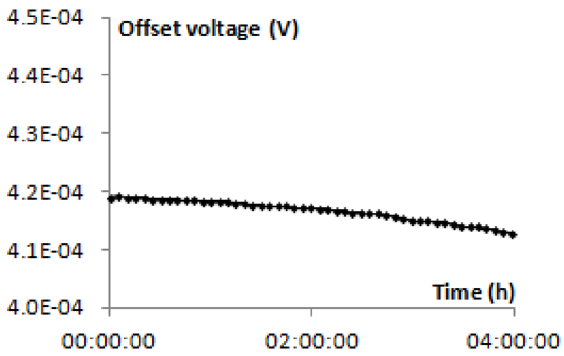

Fig. 8. Time drift of offset voltage of developed graphene Hall-effect sensor

During the investigation time drift of sensitivity and offset voltage was also measured. Measurement system was working constantly for about 4 hours performing measurement of sensitivity and offset voltage of the sensor in every 5 minutes. Hall-effect sensor was supplied with current I_z = 1.0 mA for all the time. The obtained results are presented in Fig. 7 and Fig. 8. Time drift of the current-related sensitivity is not observable. Values of the sensitivity are oscillating around the constant value 30.8 V/AT. Time drift occurs for the offset voltage. Its values are decreasing with the passage of time. Change of the offset value during all time of the experiment is 0.006 mV, which is relatively low, but noticeable value and cannot be omitted in the further investigations for improvement of developed Hall-effect sensor. Probably the drift of the offset voltage observed in time is connected with heating of the graphene Hall-effect structure under the influence of supply current flow. Especially temperature could increase near local inhomogeneity in the graphene structure.

For the investigated sensor value of the sheet resistance was also determined, utilizing Van der Pauw method [9]. The obtained result was 266.615 Ω/sq, which is typical value for QFS-bilayer graphene.

6 CONCLUSION

The experimental results presented in the paper indicates that developed graphene Hall-effect sensor of magnetic field is working properly. Graphene is good material for Hall-effect structures providing high sensitivity. By using QFS-bilayer graphene sensitivity is slightly lower than in monolayer structure, but offset voltage is lower. Mounting graphene Hall-effect structure in the standard QFN32 package used in electronic industry will allow to easily apply developed sensor in electronic devices, where Hall-effect sensors are utilized, such as current transformer.

Despite promising results obtained during the investigation of the developed Hall-effect sensor, further studies are still required. The major problem is to reduce the value of the offset voltage and its time drift, which is very undesirable phenomenon and is significant limitation for industrial application of the sensor. One of the possible ways to obtain this purpose is using so called spinning current method [10], which will be considered in further investigation.

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