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Temperature Dependence of the Graphene Hall Sensor for Special Applications

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This study investigates the effect of temperature on the parameters of Hall sensors based on quasi-free-standing (QFS) graphene. The graphene layers were obtained using chemical vapor deposition (CVD) on silicon carbide (4H-SiC (0001)) substrates. This approach ensures high material uniformity and reduces the influence of impurities, allowing the fabrication of sensors with improved metrological characteristics. The experimental study was conducted in a temperature range from 30 to 120°C. The dependence of the Hall signal on temperature was measured, and sensor stability was evaluated in long-term tests. To enhance measurement accuracy, the current-spinning technique was employed, effectively reducing parasitic signal components arising from thermoelectric effects and material inhomogeneities. The experimental results indicate that the dependence of the Hall signal on temperature is close to linear for most samples, simplifying temperature correction in practical applications. Some samples exhibit a lower level of temperature-induced variations, which may be attributed to structural variations in the graphene layer or an uneven distribution of residual stresses in the material. The overall signal variation does not exceed 10%, which is acceptable for most technological applications. The obtained results confirm the potential of QFS graphene for Hall sensors capable of operating under varying temperature conditions. Further research may focus on optimizing sensor structures, improving fabrication methods, and developing algorithms for compensating temperature effects.

Keywords: Hall sensor; QFS graphene; temperature dependence; off-set signal; spinning current method

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Introduction

Graphene, a two-dimensional material composed of carbon atoms, is attracting considerable attention in the field of sensor technology due to its exceptional electronic, thermal, and mechanical properties. One of the most promising applications of graphene is the creation of Hall sensors, due to their high sensitivity to magnetic fields and low power consumption [1, 2].

A key challenge in the development of such sensors lies in the temperature dependence of both the sensitivity and electrical resistance of the active layer. This issue is particularly critical for devices intended for use in extreme environments, such as the high-temperature conditions found in nuclear fusion reactors [3]. Therefore, studying the influence of temperature on the performance and stability of graphene-based Hall sensors is of great importance.

Scientific studies have demonstrated that temperature fluctuations significantly impact the mobility of charge carriers in graphene, which in turn affects the accuracy and reliability of sensor measurements [4]. Although the high thermal conductivity of graphene may help sensors adapt rapidly to thermal changes, concerns remain regarding their stability and functionality under sustained exposure to elevated temperatures [5].

The study by Bolshakova et al. [6] showed that the sensitivity of graphene Hall sensors exhibits a nonlinear dependence on temperature. Specifically, the authors observed a peak in sensitivity within the 200–250 K range, suggesting the existence of an optimal operating temperature. This behavior is attributed to a trade-off between charge carrier mobility and impurity scattering, which becomes increasingly pronounced at lower temperatures.

Beyond direct investigations of Hall sensors, other graphene-based sensing devices — such as temperature sensors — have also been the focus of recent research. For instance, Tang et al. [7] provide a comprehensive review of the development of graphene temperature sensors, highlighting the material's thermoelectric properties, mechanisms of temperature sensitivity, and long-term thermal stability. Although Hall sensors are not directly discussed in that work, the findings support the potential of graphene to maintain functional performance at elevated temperatures —

an important consideration for magnetic sensors intended for harsh environments.

Furthermore, several studies have demonstrated graphene's capacity for partial self-repair under thermal annealing conditions. This so-called "self-healing" effect helps reduce the density of structural defects, including those induced by radiation exposure [8–11]. Such properties open promising avenues for the application of graphene-based devices in settings characterized by high radiation and thermal loads [3].

The purpose of this study is to investigate the temperature dependence of the characteristics of Hall sensors based on graphene, in particular, sensors based on Quasi Free Standing (QFS) graphene, and to determine the optimal conditions for their operation.

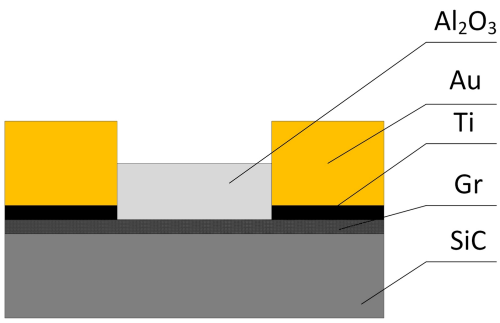

Fig. 2. Structure of the Hall sensing element

1 Hall sensors based on QFS graphene

Hall sensors based on QFS graphene were fabricated according to the traditional symmetrical structure (Fig. 1), which is formed for the effective implementation of the spinning current method [12] and the elimination of parasitic effects.

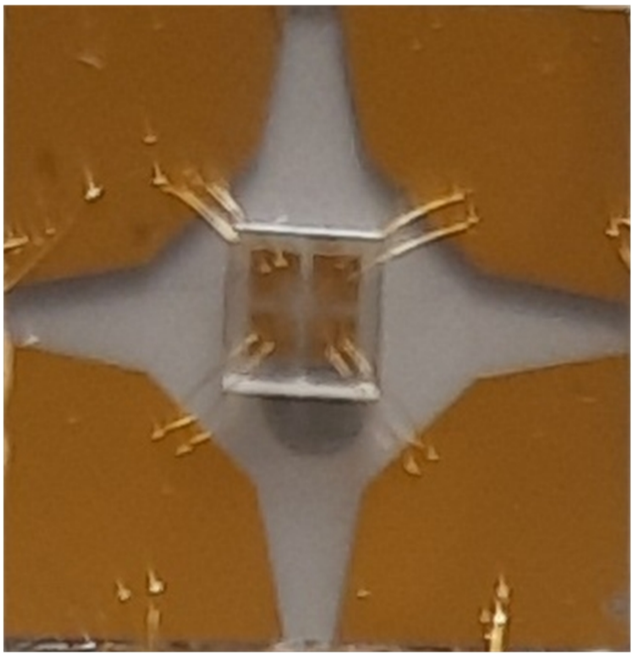

Fig. 1. Appearance of the Hall sensor

The overall dimensions of the sensing element are 1.4×1.4×0.5 mm. The sensing element is glued to a 6.6×6.6×0.364 mm transition board using cyanoacrylate. The contact pads of the sensing element are connected to the contact pads of the transition board using 20 μm thick gold wires by ultrasonic welding. Each pair of contact pads is connected twice, which increases the reliability of the contact. The structure of the sensitive element (Fig. 2) was made by the Lukasiewicz Research Network – Institute of Microelectronics and Photonics, Warsaw, Poland.

Quasi-free-standing graphen is obtained on 4H-SiC(0001) substrates of a large area (the thickness of the substrate of the order 500 μm). The Hall sensor element had in-situ hydrogen-intercalated [13]. QFS graphene grown in a hot-wall Aixtron VP508 reactor using the epitaxial Chemical Vapor Deposition (CVD) method in argon flow at 1600°C and thermally decomposed propane as a source of carbon [12]. The flow of argon was adjusted to create optimum conditions to form a boundary layer that simultaneously inhibits the sublimation of the topmost silicon atoms from the SiC(0001) surface and enables mass transport of propane [14]. The deposition was preceded with in-situ etching of the SiC(0001) surface in a purely hydrogen atmosphere at 1600°C and chamber pressure of 100 mbar, and followed by in-situ hydrogen intercalation at 1000°C under 900 mbar argon atmosphere.

The graphene layer used in the sensors is almost a single atomic layer, i.e., close-to-single-layer graphene [12, 14]. This type of graphene is compatible with modern planar technology, enabling the fabrication of sensors with high reliability and consistent parameters suitable for mass production.

The concept of defect-engineering is achieved by pre-epitaxial modification of the SiC(0001) substrate by implantation of protons (H^+) at energy of 5 keV [15]. This modification of the substrate significantly improves thermall stability of the basic properties of graphene, in particular the concentration of charge carriers [16].

To create reliable contacts, a thin (about 10 nm) layer of titanium is applied to the graphene contact area, and then gold contact pads with a thickness of about 110 nm are formed. The sensitive area of the sensor is passivated by a protective layer of amorphous atomic-layer-deposited Al_2O_3 with a thickness of 100 nm [17].

2 Temperature stability of graphene Hall sensors: research methodology

2.1 Laboratory equipment and measuring systems

The temperature dependence of the signals of Hall sensors based on QFS graphene was studied in the temperature range (30÷120)°C. The measurements were carried out using hardware and software based on high-precision industrial measuring instruments developed in the laboratory specifically for the study. The hardware of the measuring system is shown in Fig. 3.

The core of the measuring system is built on a Keithley 2182 nanovoltmeter and a Keithley 220 current source and signal switcher. The combination of these devices makes it possible to implement measurement algorithms that allow determining the following: Hall signal (by two methods), parasitic residual (off-set) signal, and surface resistance. Additionally, a Tectronix PWS 2323 current source and a magnetic field switch based on the BTS 7960 H-bridge circuit (Lake Shore) are used to solve magnetic field control problems.

The temperature control and monitoring system is represented by a separate unit using a copper rod, 25 cm long and 20 mm in diameter, which is placed vertically. A bifilar furnace with a Pt100 temperature sensor inside the winding, is placed on the bottom of the rod. The temperature is regulated using a RT-0102 controller. The test sample is placed on the upper part of the copper rod, where, in addition to the test sample, another temperature sensor is placed. Such spatial separation of the test sample and the heating element, as well as the use of bifilar winding of the heating element, allows us to avoid electromagnetic interference arising from the operation of the temperature control system as efficiently as possible.

The above-mentioned hardware of the measuring system is controlled by a personal computer, and special software has been implemented for convenient and efficient system management (Fig. 4).

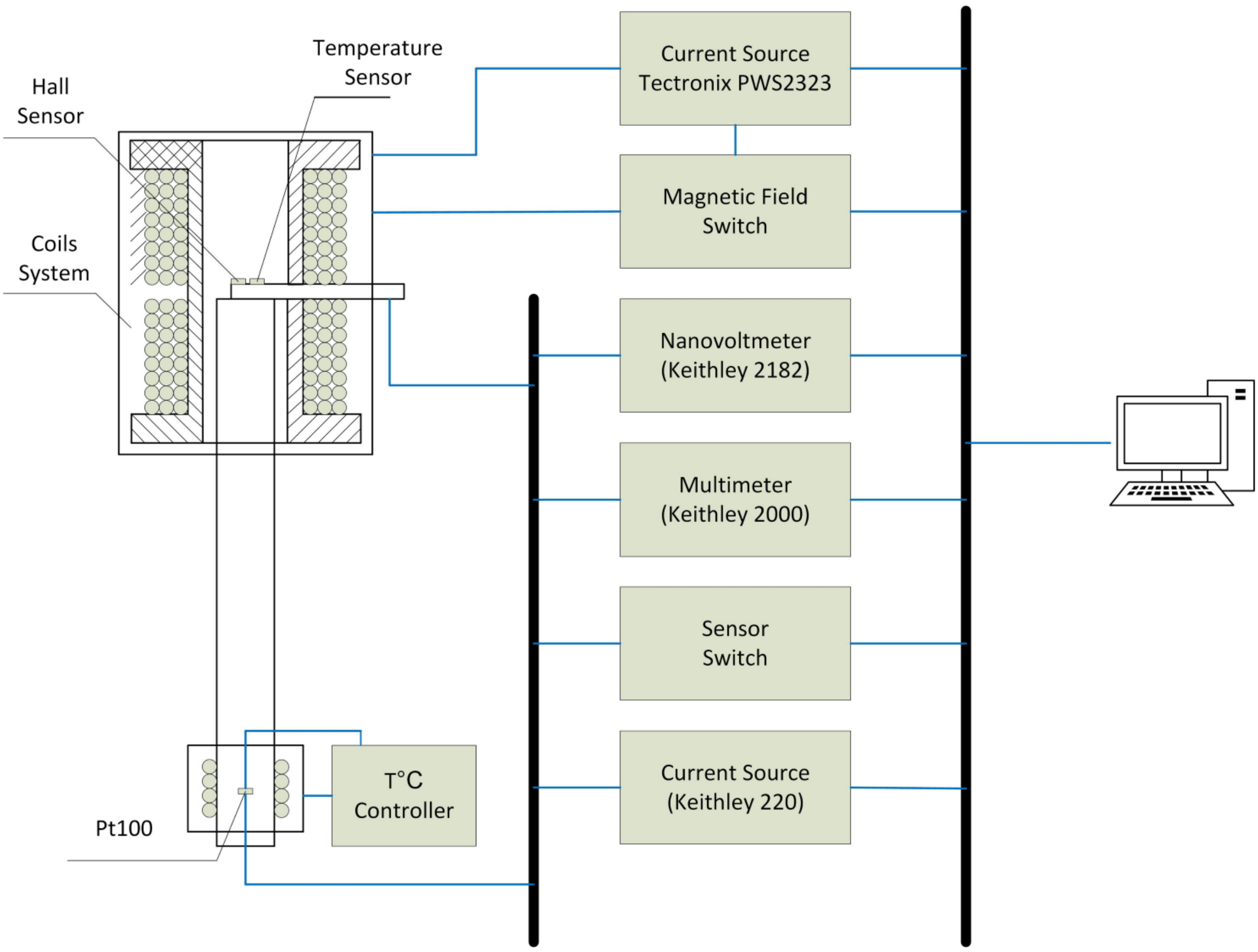

Fig. 3. Hardware of the system for measuring the temperature dependence of Hall sensor signals

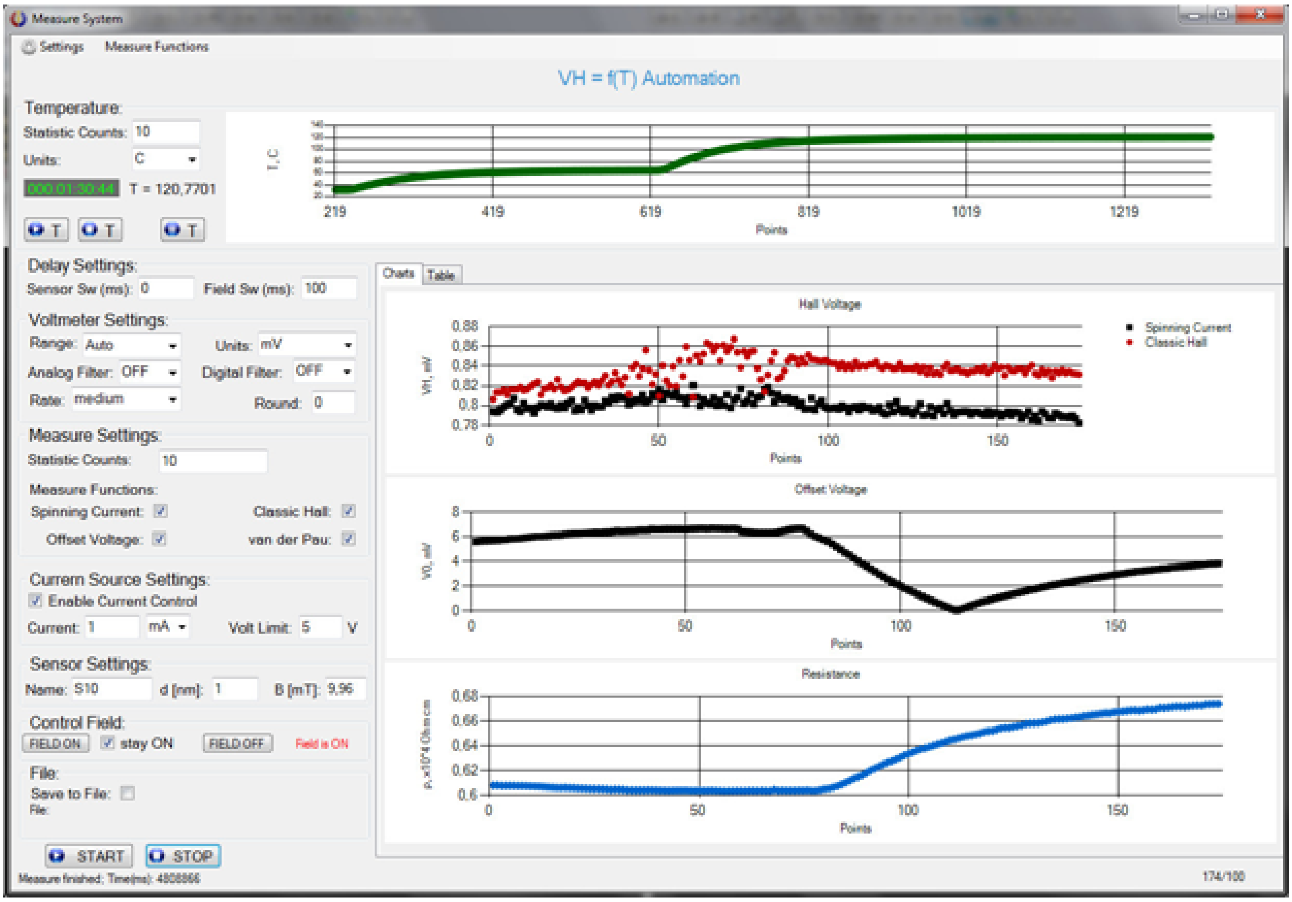

Fig. 4. Software interface of the system for measuring the temperature dependence of Hall sensor signals

The developed software performs a number of key functions necessary for conducting experiments with high accuracy and repeatability. The main ones are as follows:

- automated instrument control – provides centralized control over all active elements of the experimental setup;
- implementation of measurement algorithms – involves the initialization of data collection processes in accordance with a defined protocol;
- automatic calculations – performs the computation of derived values based on measured parameters;
- structured data storage – saves results in a structured format to facilitate further analysis;
- data visualization – generates graphs and tables for rapid evaluation of experimental results.

The software controls the power supply and heating element, reads data from the multimeter and nanoammeter. It also automatically switches the contacts of the Hall sensor and the direction of the applied magnetic field. The data is stored in a tabular format, which makes it easy to use for further processing. The automation of the measuring process largely eliminates the influence of the human factor, which has a positive effect on the accuracy and reproducibility of the results.

2.2 Data analysis and processing algorithms

To determine the sensitivity of the sensors, a traditional signal extraction algorithm was used (Fig. 5), based on four measurements at two different directions of the control current and two different directions of the magnetic field [18].

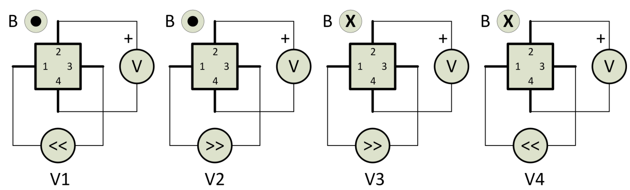

Fig. 5. Traditional method of extraction the Hall signal

Using this method of measurement, the Hall signal can be determined by equation (1):

$$V_H = \frac{V_{I+B+} - V_{I-B+} + V_{I-B-} - V_{I+B-}}{4}, \quad (1)$$

where V_{I+B+} is the voltage at positive current and positive magnetic field, V_{I+B-} is the voltage at positive current and negative magnetic field, V_{I-B+} is the voltage at negative current and positive magnetic field, and V_{I-B-} is the voltage at negative current and negative magnetic field.

Given a known fixed value of the magnetic field B and current I at which the Hall V_H signal was measured, the sensitivity can be calculated by equation (2):

$$S = \frac{V_H}{I \cdot B} \, . \tag{2}$$

The off-set signal was determined [18] in the absence of a magnetic field. To accurately determine this signal and minimize the influence of errors associated with thermal and strain effects, as well as possible parasitic components, that accumulate in the measuring path of the devices, the algorithm shown in Fig. 6 was used.

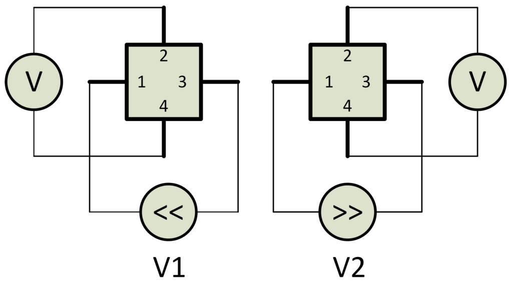

Fig. 6. Algorithm for determining the off-set signal

The measurement is carried out at two different directions of the control current, and the result is determined by the equation (3), observing the signs of the measured signals:

$$V_0 = \frac{V_1 - V_2}{2} \, . \tag{3}$$

The spinning current method from Fig. 6 [19], is used in parallel with the classical method to improve the measurement accuracy of Hall sensors. It has a number of advantages and features that make it useful in certain situations.

The main advantages include off-set compensation. Hall sensors can introduce systematic errors due to imperfect sensor symmetry, material or contact heterogeneity. The spinning current method eliminates these errors by switching the current directions through the sensor in several phases [18, 20].

In addition, the temperature dependence of material and contact properties can cause a shift in the output signal, and the spinning current method helps to reduce these effects, ensuring stable measurements [18, 20].

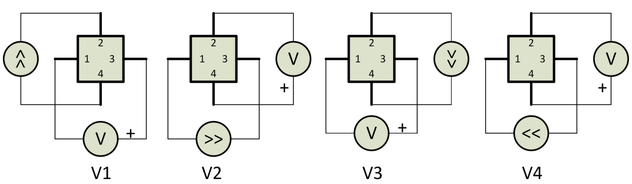

Fig. 7. Spinning current algorithm

The peculiarity of the above algorithm is the ability, after subtracting the results of four measurements, to calculate the Hall signal as equation (4):

$$V_H = \frac{V_1 + V_2 - V_3 - V_4}{4} \tag{4}$$

and the off-set signal as equation (5):

$$V_0 = \frac{V_1 - V_2 - V_3 + V_4}{4} \, . \tag{5}$$

3 Results

The following results were obtained in the course of this study. Firstly, different samples show a different spread of Hall voltage and slightly different temperature dependencies. For convenience, the results are divided into two groups: 1 — samples with a relatively small scatter value Fig. 8, and 2 — samples with a relatively large scatter value Fig. 9.

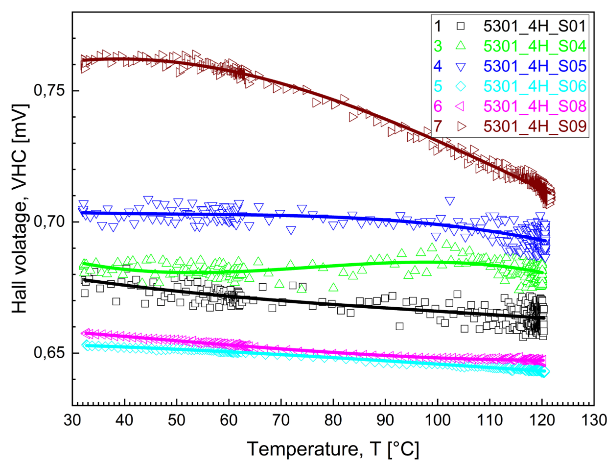

Fig. 8. Temperature dependence of the Hall signal (classical method) for samples with a small scatter

The dependence shows that samples with a small scatter of measured voltage values have a characteristic linear or close to linear temperature dependence of the signal. This is especially noticeable on samples No. 5 (5301_4H_S06) and No. 6 (5301_4H_S08). The scatter of the measured signals for these samples is minimal, and the temperature dependence is close to linear. On average, the signal change for samples with a pronounced linear temperature dependence of the signal is approximately 1.5% (over the entire temperature range under study), or 0.02%/°C. A stronger temperature dependence was observed in sample No. 7 (5301_4H_S09): 6.5% or 0.07%/°C. No obvious temperature dependence is observed for samples No. 3 (5301_4H_S04) and No. 4 (5301_4H_S05).

Similarly, for the rest of the samples Fig. 9, it is difficult to estimate the temperature dependence of the Hall signals, since the scatter of the measured data is significant compared to their temperature changes.

We can only state with certainty that the temperature change of the Hall signal does not exceed (1÷2)% over the entire temperature range under study, or 0.02%/°C.

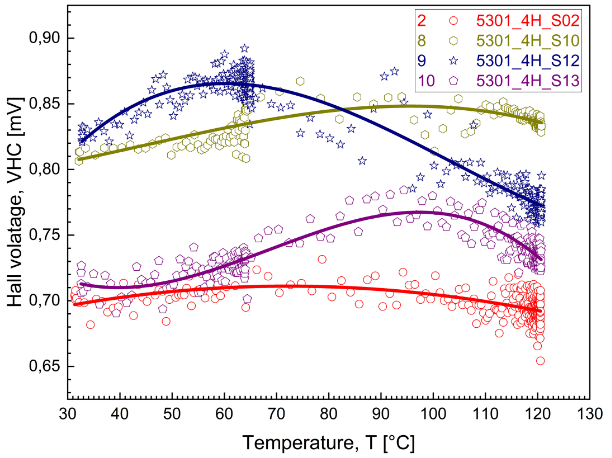

Fig. 9. Temperature dependence of the Hall signal (classical method) for samples with a relatively large scatter

From the results obtained, it can be argued that despite the presence of a certain temperature dependence of the Hall signal, its change is insignificant and close to linear dependence, which should not cause any special problems when taking into account the temperature dependence of signals. A much more significant problem, in the context of manufacturing precision Hall sensors, is the problem of sensor signal noise.

A similar picture is observed for the Hall signal obtained by the spinning current method: the temperature dependence is observed for all samples, it is insignificant and its character is close to linear (Fig. 10). Similarly, the same samples (5301_4H_S02, 5301_4H_S10, 5301_4H_S12, 5301_4H_S13) are distinguished for which a several times greater variation in the measured values is observed. The peculiarity of the spinning current method is the incomplete elimination of the residual signal, and therefore, the obtained dependences contain some of it, which, in turn, also depends on temperature.

The temperature dependence is also important and requires a separate study and analysis. The residual signal is an integral component in the measurement of the useful Hall signal. If such a signal has a significant temperature dependence, it should be taken into account when designing measuring devices based on the Hall effect. Studies of the temperature dependence of the parasitic signal are shown in Fig. 11. As a rule, the temperature dependence of the off-set signal of Hall sensors is unpredictable, which is one of the reasons for using the spinning current method for more accurate separation of the Hall signal, especially in non-stationary temperature conditions. The studies have shown that the off-set signal has a certain close-to-linear temperature dependence; however, for some samples, at temperatures above 110°C, this dependence begins to follow a power law. On average, however, the changes do not exceed (2÷5)%. The exception is sample No. 9 (5301_4H_S10), for which, due to the characteristic signal decries around 118°C, the change is 99%, but given the small values of the off-set signal, this does not create problems with the measurement accuracy.

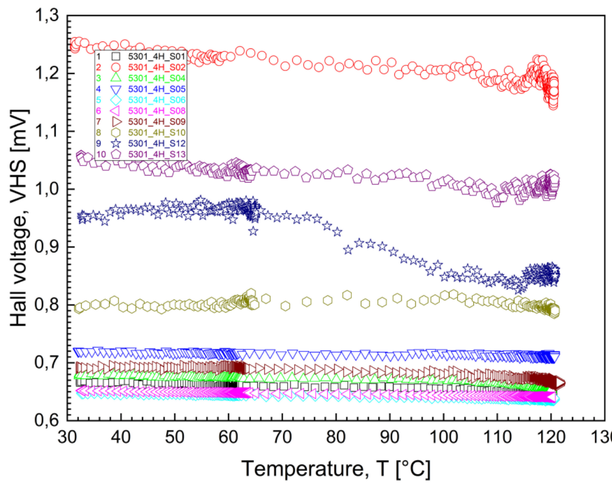

Fig. 10. Temperature dependence of the Hall signal (spinning current method)

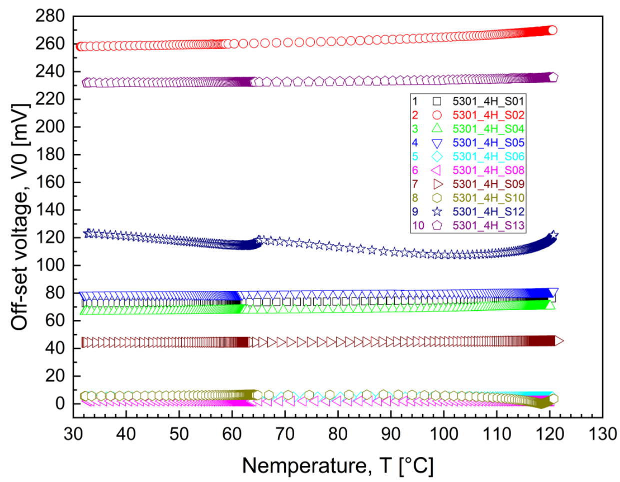

Fig. 11. Temperature dependence of the off-set signal

The nature of the off-set signal is based on the resistive properties of the material, so very often there is a certain correlation between the temperature dependence of the off-set signal and the temperature dependence of the resistivity or surface resistance. In turn, the temperature dependence of the surface resistance is of great importance when designing measuring equipment. If the sensor is powered by direct current, a change in the sample resistance leads to a change in power consumption, and with significant changes in resistance, overheating can occur and the sensor may go beyond the permissible operating range. Changes in resistance with temperature must be investigated and taken into account when designing the power supply unit of electronic equipment that interacts with the sensor. The results of the study of the temperature dependence of the surface resistance are shown in Fig. 12. From the obtained temperature dependence, it was found that the magnitude of the change for all samples falls within (4÷9)%, which is an insignificant change that should not create significant problems in the manufacture of measuring devices. However, it should be noted that the range studied is limited to 120°C, and the linear nature of the change in surface resistance is maintained up to temperatures of about 100°C, and then a more rapid increase in surface resistance is observed with increasing temperature. This is especially noticeable on samples (5301_4H_S05 and 5301_4H_S10). If the trend of increasing sample resistance continues, then at higher temperatures (200-400°C), the sensor resistance can increase significantly.

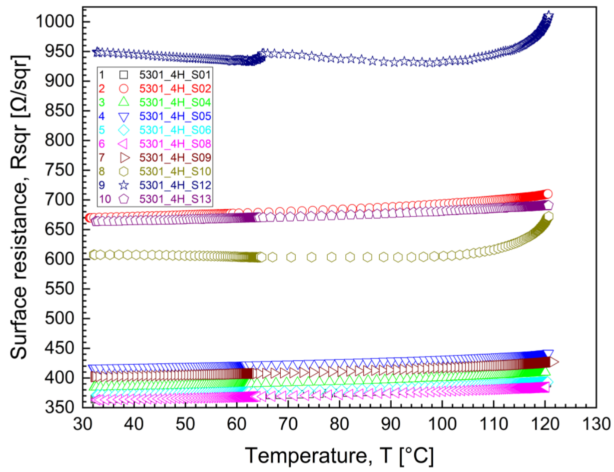

Fig. 12. Temperature dependence of surface resistance

Conclusion

In this study, we analysed the effect of temperature on the stability of the parameters of Hall sensors based on QFC graphene in the temperature range from 30 to 120°C. The results demonstrate that the temperature dependence of the Hall signal is close to linear for samples with a small signal spread, but for samples with a larger spread, this dependence is less pronounced. It was also found that the magnitude of the change in the Hall signal does not exceed 10% over the entire temperature range under study. Such changes are acceptable, as they can be corrected by algorithmic methods, which will minimize the loss of measurement accuracy in the mode of operation under non-stationary temperature conditions.

The study of the temperature dependence of the parasitic off-set signal showed that the changes in this signal are insignificant and linear. In addition, a correlation was found between the temperature dependence of the off-set signal and the surface resistance of the sensors. Changes in the surface resistance with increasing temperature remain within (4-9)%, which indicates the relative stability of the sensors in the temperature range under study.

The data obtained indicate that Hall sensors can function effectively under conditions of temperature change, but the problem of noise and signal scatter remains relevant and requires further research to ensure precise measurements.

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Температурні залежності сенсора Холла для особливих задач

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Досліджено вплив температури на параметри сенсорів Холла, виготовлених на основі квазівільностоячого (QFS) графену. Графенові шари отримані методом хімічного осадження з парової фази (CVD) на підкладках із карбіду кремнію (4H-SiC (0001)). Такий підхід забезпечує високу однорідність матеріалу та зменшує вплив домішок, що дозволяє отримати сенсори з покращеними метрологічними характеристиками.

Експериментальне дослідження проводилося в температурному діапазоні від 30 до 120°C. Для підвищення точності вимірювань використано метод обертального струму, який ефективно зменшує паразитні складові сигналу, що виникають через термоелектрорушійну силу (термоЕРС) та неоднорідності матеріалу.

Результати експериментів свідчать, що залежність сигналу Холла від температури є близькою до лінійної для більшості зразків, що спрощує температурну корекцію в практичних застосуваннях. Деякі зразки демонструють нижчий рівень температурних змін, що може бути зумовлено варіаціями в структурі графенового шару або нерівномірним розподілом залишкових напружень у матеріалі. Загальний рівень змін сигналу не перевищує 10%, що є прийнятним для більшості технологічних застосувань.

Отримані результати підтверджують перспективність використання QFS-графену для сенсорів Холла, здатних працювати в умовах змінних температур. Подальші дослідження можуть бути спрямовані на оптимізацію структури сенсорів, покращення методів їхнього виготовлення та розробку алгоритмів компенсації температурних впливів.

Ключові слова: сенсор Холла; QFS-графен; температурна залежність; off-set сигнал; метод обертального струму