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Graphene-Based Hall Sensors: Materials and Production Approaches

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Graphene remains one of the most studied materials due to its unique physical properties and two-dimensional structure. The article examines the current state of the graphene market, which is growing at a rapid pace, with a projected volume of USD 1.5 billion by 2027. Technologies for the production of graphene Hall sensors are discussed, in particular, the chemical vapor deposition (CVD) method, which is widely used to create industrial sensors. An important role in the properties of the sensors is played by the choice of the substrate, which can be both rigid (silicon, sapphire) and flexible (polyimide). Attention is paid to metal-graphene contacts, where edge contacts have significantly better conductivity than surface contacts. The authors emphasize that at the current stage of development of graphene electronics, there is no single technological process, as in the classical semiconductor industry, which requires further research to create more efficient sensors.

Keywords: Graphene, Hall sensor, Two-dimensional materials, Graphene-based devices, Sensor fabrication.

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Content

Introduction

Today, graphene is one of the most actively researched materials in the world [1]. Its unique properties and two-dimensional structure causes the interest in this material [2, 3]. Graphene is being researched and developed by various technology giants such as Intel, IBM, HP, Samsung, LG, Bosch [4-8] and many others. Companies are being created that work exclusively with this material, such as Paragraf [9], Graphenea [10], and

General Graphene Corporation [11]. Some of them manufacture graphene-based devices of their own design, while others can produce a graphene-based device according to your project.

At the present stage, the graphene industry is an example of a rapidly developing materials market. The first graphene-based products have already entered various markets, although so far mostly on a niche scale. Many small graphene producers are seeking to expand their customer base and scale up production [12].

Significant market growth over the next few years will lead to a projected market size of USD 1.5 billion in 2027 (projected range between USD 0.34 and 5.5 billion). Considering that many industries are quite conservative in the use of new materials, this rapid expected growth is impressive and reflects the superior physical properties of graphene (mechanical, electrical, etc.) that can enhance products in a variety of ways [12].

Space research of graphene-based devices is underway. Recently, SpaceX successfully launched the Fourth Transporter mission [13], which, in addition to commercial purposes, also included scientific research. Scientists from the Netherlands and Chile have developed devices with graphene-based elements to study the impact of space travel and space conditions on graphene components [13].

I. Graphene for sensors

Graphene is a material that can be produced in many ways [14]. For electronics, this material is typically produced by chemical vapor deposition (CVD) [15-31], as this method is scalable, controllable (the speed and thickness of graphene can be controlled), and best suited for industrial sensor fabrication. By CVD, graphene can be grown on a substrate, which will be the subsequent basis of the sensor [20, 22, 26, 30], or grown on a Cu, Ni substrate and then transferred to another substrate [15-19, 24, 27, 28], and the graphene-containing material can be fabricated from the substrate material [32], as was shown for a flexible polyamide sensor.

However, in experimental laboratory samples, graphene can be obtained in other ways, for example, by exfoliation [33, 34].

II. Substrate for graphene-based sensors

One of the key aspects in the development and use of sensors is the choice of substrate [35]. The choice of substrate for graphene sensors depends on several factors, including the desired sensor efficiency, fabrication technology, and compatibility with the application environment [35]. The most common substrates used for graphene sensors are silicon dioxide (Si/SiO_2) [15, 22, 26, 29, 32], silicon carbide (SiC) [24, 28, 35], sapphire (Al_2O_3) [16, 25], hexagonal boron nitride h-BN as a heterostructure element with graphene [31, 33, 34], and flexible substrates such as polyimide [17-19, 32].

One of the important aspects of the substrate's influence on graphene is its surface charges. Studies have shown that the p-doping level in CVD-grown graphene can vary significantly depending on the pretreatment of the substrate surface [36]. For example, when using different methods of cleaning the SiO_2 substrate, such as sonication in water, treatment with acetone and isopropanol, ultraviolet ozonation, and oxygen plasma treatment, it was found that each of these methods affects the position of the Dirac point and, accordingly, the level of p-doping in graphene. The most aggressive treatment methods, such as ozonation and plasma treatment, lead to a significant shift of the Dirac point in the positive direction, indicating an increase in the hole concentration in graphene [36].

Si/SO_2 substrates are widely used in graphene sensors due to their excellent thermal and electrical properties [37]. These substrates provide a stable platform for graphene deposition and have high electrical insulation, which helps reduce background noise in sensors.

Silicon carbide SiC substrates have high thermal conductivity and can withstand high temperatures, making them suitable for applications in harsh environments [38]. Also, high quality graphene can be grown directly on this material, which does not require further transfer to another substrate. Thus, efficient and high-quality sensors can be industrially produced on this substrate [22, 26].

The substrate material can also affect the flexibility and mechanical properties of graphene sensors. Flexible materials, such as polyethylene terephthalate or polyimide, allow graphene sensors to be integrated into various wearable devices or flexible electronics, which makes it possible to develop flexible sensors [37].

Thus, the substrate has a significant impact on the electrophysical properties of graphene due to changes in the doping level and charge carrier behavior. Different methods of substrate processing can significantly change the transport characteristics of graphene, which must be taken into account when developing graphene electronic devices.

III. Graphene metal contacts

An important aspect of graphene applications is the creation of efficient metal-graphene contacts that provide low contact resistance and stability. The main metals used for graphene contacts include gold (Au) [39], palladium (Pd) [40], titanium (Ti) [41], chromium (Cr), and nickel (Ni) [42]. In practice, contacts are often made of several metals. The first layer is usually made of Ti or Cr to improve the adhesion between graphene and other metals, which ensures good adhesion and stability [43, 44]. Chromium-based contacts have lower contact resistance compared to Ti [29]. For the next layer, Au is usually used, as it is one of the most commonly used metals for contacts with graphene due to its high conductivity and chemical stability [45]. In practice, more complex contacts are also used, consisting of several layers of different metals [33].

By type, contacts can be divided into two types: surface and edge.

IV. Top contacts

Surface contacts are formed when a metal is on the surface of graphene, forming weak Van der Waals bonds.

This is the most common type of contact [16-18, 20-28, 30-32], but it is characterized by relatively high contact resistance due to weak interatomic interactions between metal and graphene [47]. Surface contacts, in turn, can be divided into three subtypes (Fig. 1): metal on the surface of graphene (Fig. 1a), metal contacts applied to a substrate with a layer of graphene on top of the metal (Fig. 1b), and contacts in which graphene is sandwiched between metal layers (Fig. 1c) [47].

Regarding the standard configuration, in which metal is deposited on top of a graphene layer, it has been shown that by implementing a metal-on-bottom configuration, contact resistance can be improved [47]. The standard "metal on top" configuration originated from the first available graphene layers that were mechanically exfoliated (peeled off) and had a size of several microns, placed on Si/SiO_2 substrates. The devices were formed on top using a lithographic process, which often caused contamination by photoresist residues between the graphene and metal electrodes, causing large fluctuations in contact resistance. On the other hand, the availability of CVD graphene allows the placement of graphene layers on pre-organized structures, opening up the possibility to study the "metal-on-bottom" (metal-beneath) contact architecture. [47].

V. Edge contacts

Edge contacts (Fig. 2) are formed when metal contacts the edges of graphene layers. This type of contact has a much lower resistance due to the formation of strong covalent bonds between metal and carbon atoms at the edges of graphene. This allows for more efficient injection of current into graphene, bypassing the tunnel resistances between the layers [47].

The edge contacts show significantly better conductivity values compared to the surface contacts. This is because covalent bonds are formed in the edge contacts, which provide a stronger interaction between metal and graphene atoms. Studies have shown that the resistance of edge contacts can be several times lower than that of surface contacts [46, 47].

The advantage of surface contacts over edge contacts is that they are easier to manufacture and less sensitive to structural defects. At the same time, edge contacts can withstand a higher current when switched on, have a smaller resistance spread, and inject current more efficiently into individual graphene layers, since there is no tunneling barrier for current carriers [46, 47].

Metal-graphene contacts are a key element in the development of high-performance graphene-based electronic devices. Edge contacts, due to their better conductivity characteristics and low contact resistance, have a significant potential to improve the performance of such devices. However, the technology of manufacturing these contacts requires further research and improvement to achieve full reproducibility and reliability in industrial conditions.

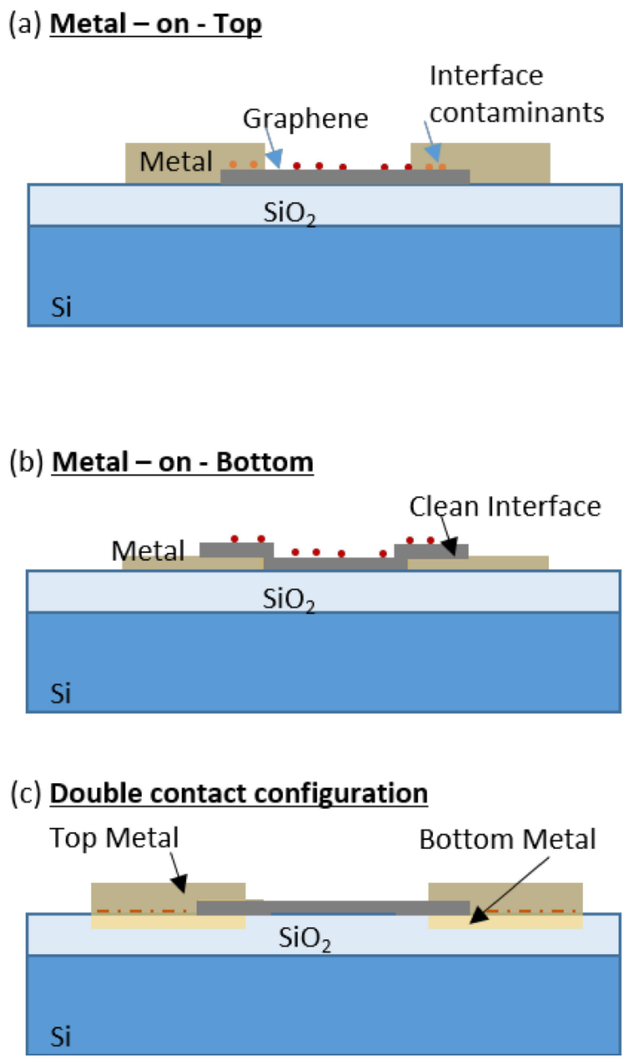

Fig. 1. Comparison of (a) Metal-on-Top and (b) Metal-on-Bottom configuration to contact graphene layer. A clean M/G interface is obtained for Metal-on-Bottom fabrication process. (c) Scheme of double contact configuration in which graphene flake is sandwiched between two metallic layers. Bottom contacts can be embedded in the oxide [47].

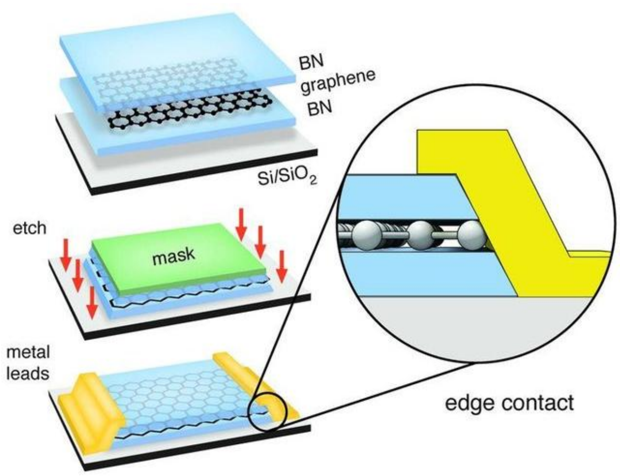

Fig. 2. Schematic representation of the process of manufacturing edge contacts for encapsulated graphene [47].

VI. Production of graphene Hall sensors

One of the classic graphene-based devices is the Hall sensor. Devices based on the Hall effect are used in automobiles, aviation, space technology, machine tools, computers, medical equipment [48, 49], as well as in chemical and biological research [15]. The development of fusion energy [16, 26] has not bypassed this small but necessary sensor. To control a fusion reaction, it is necessary to monitor the state of the plasma inside the reactor. This imposes new requirements on the sensors, in particular, they must be resistant to high temperatures (350°C) and high neutron fluence. It is evident from the literature [16, 26] that graphene has higher radiation resistance than classical semiconductor sensors.

With the development of prosthetics, robotics, and portable electronics [18], the demand for flexible devices, including flexible Hall sensors, will also increase. The main requirement for such sensors will be that they remain operational after deformation loads, retain their original properties, and withstand thousands of deformation cycles.

VII. Types of Hall sensors on graphene

Hall sensors on graphene can be divided into two groups according to the type of substrate: sensors on a flexible substrate [17-19, 32] and sensors on a rigid substrate [15, 16, 20-32], which are the majority. According to the number of contacts, sensors can be divided into classic 4-pin cross-shaped sensors (most of them are available, they can be either on a rigid substrate [16, 20-25] or on a flexible one [17, 18]). There are also sensors with a shutter, both on flexible [20] and rigid [30, 31] substrates, and multi-electrode Hall sensors [15, 27, 28, 31].

The control electrode in the sensor design allows to control the density of charge carriers in graphene and can be easily adjusted by means of a neighboring top and/or rear gate. Magnetic sensitivity at low temperatures can also be significantly improved by using devices with a gate [50].

VIII. Hall sensors on a flexible substrate

Graphene Hall sensors on a flexible substrate are promising types of sensors and will find their application where classical sensors on a rigid substrate cannot be used due to instability to deformation. Studies have shown that sensors of this type do not lose their properties after 1000 cycles of deformation [17]. These sensors are also resistant to high temperatures, maintaining their sensitivity at 400°C [32].

Graphene-based flexible Hall sensors demonstrate voltage and current sensitivity on par with sensors on a rigid substrate and an order of magnitude higher than flexible sensors based on other materials [17].

As a rule, the substrate for flexible Hall sensors is polyamide [17-19, 32], a material on the basis of which printed flexible boards and cables are made. An example of such a material is 25 µm DuPont, Kapton IM301449, which was used in [32]. At all stages of sensor fabrication, an additional silicon substrate was used to ensure the stiffness (Fig. 3) [17] of the sensor during its manufacture. After manufacturing the sensors, the silicon substrate was removed [17-19].

Graphene for this type of sensor was grown by chemical vapor deposition on copper foil. It was then transferred by a standard wet chemical release process using polymethyl methacrylate (PMMA) as a support layer [17-18].

In another study [32], a three-dimensional porous conductive carbon structure with a high content of graphene flakes, which was obtained by rapid laser heating of the substrate (laser-scribed graphene) (Fig. 4), served as the sensor's sensing element [32]. For heating, a pulsed CO_2 laser (Universal Laser Systems PLS6.75, 10.6 µm, peak laser power 75 W) was used.

IX. Holland sensors on a monocrystalline substrate

The classic substrate for most sensors is a single crystal substrate, which can be monocrystalline, polycrystalline, or amorphous. Devices of this type are easier to manufacture and there are many manufacturing technologies available.

Graphene for Hall sensors of this type is mostly

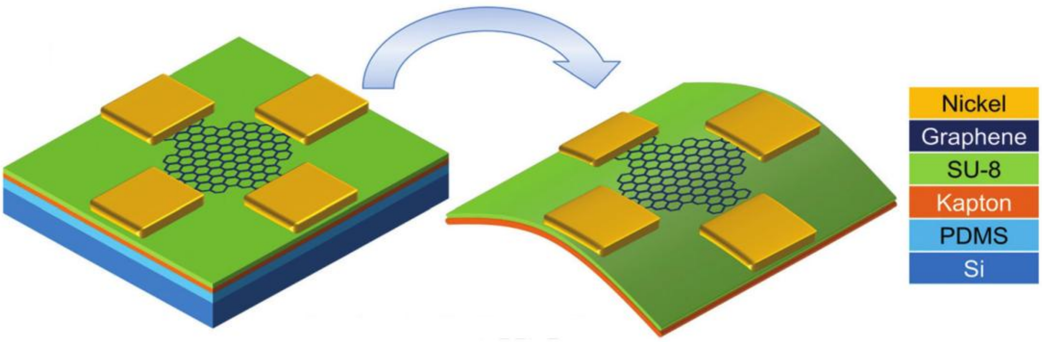

Fig. 3. Schematic representation of the sensor during fabrication on a temporary rigid substrate and after its separation [17].

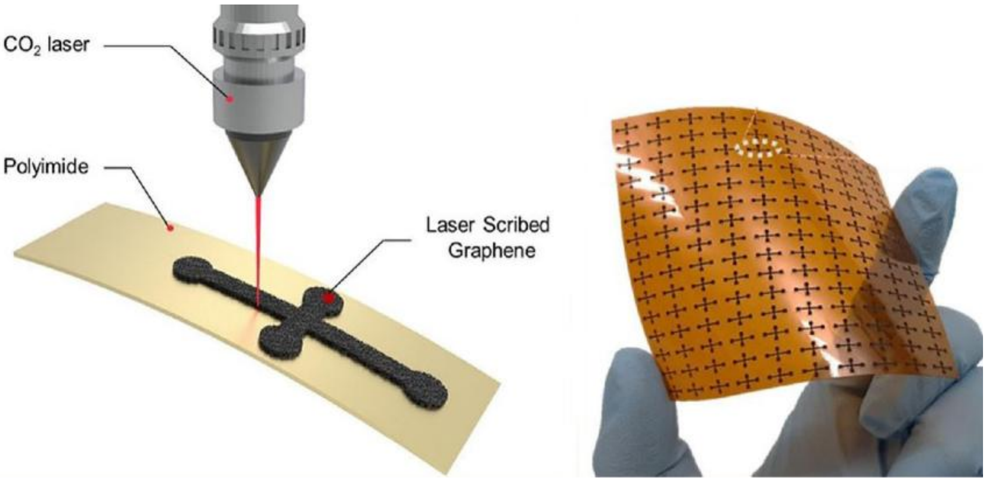

Fig. 4. Schematic representation of the manufacturing process of the sensor sensing element using laser-scribed graphene technology and the image of the finished sensors on a lumpy substrate [32].

produced by CVD, synthesized from different precursors and on different substrates under different conditions. Often, graphene is grown on one substrate and later transferred to another.

X. Hall sensors based on graphene directly deposited on a substrate

A multicontact Hall sensor with a gate is reported in [30]. For the growth of graphene, 4H-SiC semiconductor substrates were used, which became the basis for the sensors. The substrates are pre-treated with hydrogen etching at 1600°C for 5 minutes, after which the samples are cooled to below 700°C [30]. The formation of graphene on the substrate surface is rapid at a growth temperature of 1500 to 1650 °C in a vacuum. For the specific sensor described in the paper, growth was performed at 1600°C for 10 minutes [30]. The dielectric for the gate was 30 nm Al_2O_3, which was deposited at 300°C using an ASM F-120 reactor using triethyl aluminum and water vapor as precursors.

Sensors with silicon carbide as a substrate have also been studied in other works [23], in particular, 4H-SiC [26] and 6H-SiC [22,31] polymers. For these sensors, graphene was grown in an Aixtron VP508 reactor by CVD in an argon stream at 1600 °C, with propane as a carbon source.

In their work, the team [20] grew graphene on an oxidized silicon substrate, the process of creating a sensor is shown in Fig. 5.

After growth, the graphene was annealed at 300 °C in a nitrogen stream for three hours. The desired sensor topology was obtained using a lithography process. The wafer was then subjected to a dry etching process in an oxygen plasma for 13 minutes to remove graphene that was not protected by the photoresist. After removing the photoresist, a similar lithography process was performed to fabricate the contacts [20].

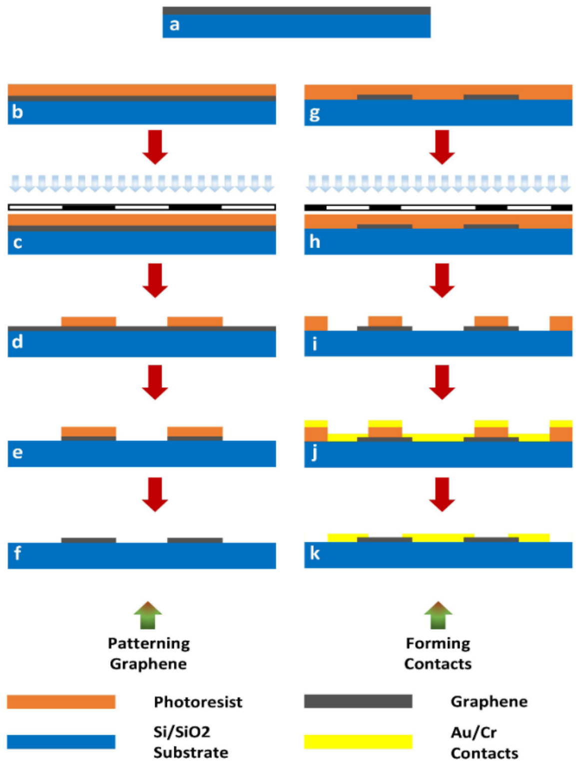

Fig. 5. Schematic of the process of forming graphene Hall microsensors. (a) High-quality graphene grown by CVD on a Si/SiO_2 substrate. (b) The wafer is coated with AZ5214E photoresist and pre-annealed at 90°C for 15 minutes. (c) UV irradiation for 14 seconds using a patterned mask. (d) Photoresist development to obtain the corresponding patterns. (e) Oxygen plasma etching process to remove unprotected graphene [20].

XI. Hall sensors with transferred graphene

Many researchers use technologies that first grow graphene on one substrate or obtain it by another method, and then transfer it to the main sensor substrate. However, these technologies are not so efficient and scalable that they can be used on an industrial scale.

In [15], a multicontact Hall sensor was studied, the contacts of which were deposited on a silicon substrate, after which graphene was transferred to the contact structure Fig. 6 [15]. The graphene was produced by CVD using a mixture of CH_4 and H_2, which passed through a copper foil reactor at 1020 °C for 20 minutes in a chamber pumped to 50 mTorr. After that, the graphene was transferred to the substrate by bubble transfer [15]. A lithographic pattern was applied to the graphene layer using positive resist photolithography, after which it was etched in oxygen plasma for 30 seconds (Fig. 6c). To remove residual photoresist, the sensor was annealed in a mixture of H_2 and Ar gases at 225°C for 1 hour.

The team [16, 25] also used Hall sensors in their studies, for which graphene was grown on a copper substrate and then transferred to a 450 μm thick sapphire substrate using an intermediate PMMA layer [25]. Other studies have demonstrated Hall sensors with graphene grown on copper foil (Alfa Aesar 46365, 99.8% purity) as in [15] and then transferred to a substrate made of another material [28].

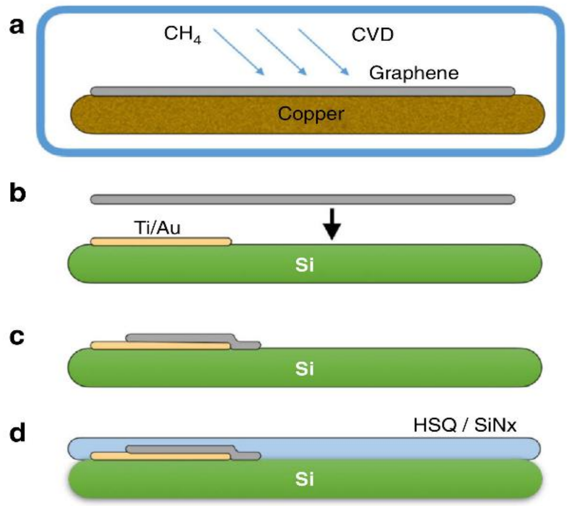

Fig. 6. The process of forming a sensor with contacts located under a graphene layer.

In [24], an interesting example of a Hall sensor was demonstrated, which is characterized by the use of bilayer graphene as a sensing material. The thickness of bilayer graphene is approximately 1.5 nm. The graphene was grown on copper foil in a two-step growth process using CH_4 and H_2 at 1030 °C. The copper foil with graphene was coated with PMMA. The copper foil was then dissolved by electrolysis in a 0.1 mol/L NaOH solution. Finally, the graphene was transferred to a silicon substrate, and the PMMA was dissolved in acetone.

XII. Hall sensor contacts

Single-component sensor contacts are made of various materials. For example, in [17, 19], Ni was used as a contact material. The contacts were fabricated by sputtering and blast lithography followed by oxygen plasma etching. The thickness of the contacts was 50 nm. In another work [32], the contacts were made of Au with a thickness of 100 nm.

Usually, contacts are made not from one material but from several. The first layer in Hall sensors is usually Cr or Ti, which is used as a layer to create adhesion between graphene and the substrate [43]. In [29], it was shown that Cr/Au contacts are linear and have low resistance, while Ti/Au contacts have nonlinear tunneling behavior with high resistance.

The thickness of the adhesion layer is typically from a few nanometers to several tens of nanometers. The top layer of the contact consists of gold, its thickness is much higher than the thickness of the first adhesive layer and usually ranges from several tens of nanometers to several hundred nanometers [16-33]. There are also contacts with more layers, where additional metals such as Pt and Pd are used [33].

One-dimensional contacts in Hall sensors are formed in complex heterostructural systems, such as the combination of graphene with h-BN. First, an angle is formed to create a one-dimensional graphene-metal contact [29, 33]; this angle is approximately 15° [33]. In work [33], edge contacts of two compositions were made: 3 nm Cr/40 nm Pd/40 nm Au and 3 nm Cr/80 nm Au for samples with monolayer graphene, and 5 nm Ti/30 nm Au/10 nm Pt for samples with multilayer graphene. Table 1 compares the different technological parameters of the hall sensors considered in this study.

XIII. Protective layer (Passivation)

One of the most important stages in the production of Hall sensors is the passivation stage. This procedure is performed to protect the graphene from environmental influences. If graphene is not coated, Hall sensors degrade over time and lose their properties [28], even in laboratory storage.

One of the typical materials for passivation is Al_2O_3 [18]. It is used because this material is a dielectric, cheap, and resistant to the environment, and because the passivation process is standard for the manufacture of micro- and nanosystem devices. The thickness of this layer is from several tens of nanometers when it is used as a dielectric for the gate. For example, in [30], the thickness of the gate dielectric was 30 nm. The aluminum oxide was deposited at 300 °C. In other studies, where Al_2O_3 was used as a protective layer, the thickness of such a layer is approximately 100 nm [16, 22, 26].

Another material that is often used for passivation is PMMA [15, 28]. This material is convenient and easy to use. For its application, a centrifuge and an oven are used, in which the material can be annealed.

In [15], the influence of an aggressive environment, namely blood plasma, on the operation of the sensor was studied. Different types of materials for sample encapsulation and their combinations were investigated: plasma-chemical SiO_2, HSQ, PMMA, SU-8, and plasma-chemical SiO_2-Si_3N_4. The best results were demonstrated by the sensors coated with HSQ + Si_3N_4. Such sensors worked for 2 days in the presence of blood plasma, which indicates the reliability and reusability of the device.

Promising and one of the most difficult to manufacture are Hall sensors encapsulated with hexagonal boron nitride (h-BN). Hexagonal boron nitride can be used to improve the performance of a Hall sensor. Sometimes called "white graphene," this material also has a hexagonal structure, but with boron and nitrogen atoms. Its structure is very close to graphene and their difference is 1.7%. Due to its wide band gap of 6 eV, it is an excellent candidate material for electronics and optics [51].

This material is used both in flexible sensors [19] and in sensors on a rigid substrate [29, 33]. Sensors of this type were studied in [29] and manufactured by Graphenea. Each Hall element consists of CVD graphene sandwiched between multilayer CVD h-BN. The two-dimensional heterostructure was obtained on a Si/SiO_2 wafer using PMMA-based wet transfer technology and annealing each layer in Ar/H_2.

In practice, other materials are also used to protect the sensor from the environment, such as SU-8 photoresist [15, 21], HfO_2 [52].

Table 1.

Technological features of graphene hall sensors

	Substrate	Contacts	Coatings	Physical dimensions
Monocrystalline substrate				
[15]	Si/SiO_2 280 nm (grown on Cu)	Ti/Au (2/40 nm)	HSQ, PVD SiO_2, PVD SiO_2/Si_3N_4, PMMA, SU8, HSQ/Si_3N_4	28 × 70 μm, a width - 8 μm
[16]	Al_2O_3 450 μm. (grown on Cu)	Ti/Au	Al_2O_3 80 nm	12 × 12 μm
[20]	Si/SiO_2 285 nm	Cr/Au (30/250 nm)	-	10 ×10 μm
[21]	Si/SiO_2	Ti/Au (5/45 nm)	SU-8	13 ×13 μm
[22]	6H-SiC,4H-SiC	Ti/Au (10/90 nm)	a -Al_2O_3 100 nm	100 × 300 μm
[23]	SiC	Cr/Au (20/30 nm)	-	-
[24]	Si/SiO_2 500 nm grown on Cu)	Ti/Au	-	-
[26]	4H-SiC (0001)	Ti/Au (10/60 nm)	Al_2O_3 100 nm	-
[27]	Si/SiO_2 (675 μm/90 nm)	Cr/Au (5/50 nm)	-	50 × 50 μm
[28]	Si/SiO_2 (grown on Cu)	Cr/Au (5/50 nm)	PMMA	30 × 6 μm
[29]	Si/SiO_2	Cr /Au (5/95 nm) , Ti/Au (20/60 nm)	CVD h-BN	-
[30]	4H-SiC	Ti/Au	Al_2O_3 30 nm	10 × 22 μm
[33]	Si/SiO_2 285 grown on Cu	Cr/Pd/Au (3/40/40 nm), Cr/Au (3/80 nm), Ti/Au/Pt (5/30/10 nm)	h-BN	-
Flexible substrate				
[17]	Polyamide 600 nm (grown on Cu)	Ni 50 nm	-	13 × 13 μm
[18]	Polyamide (grown on Cu)	Ni 50 nm	Al_2O_3 40 nm	100 ×100 μm
[19]	Polyamide	Ti/Au (20/500 nm)	PMMA, hBN	200 × 500 μm, 12 × 30 μm
[32]	Polyamide laser-scribed graphene	Au 100 nm	-	8 × 3 mm width of the working zone of the sensor 870 μm

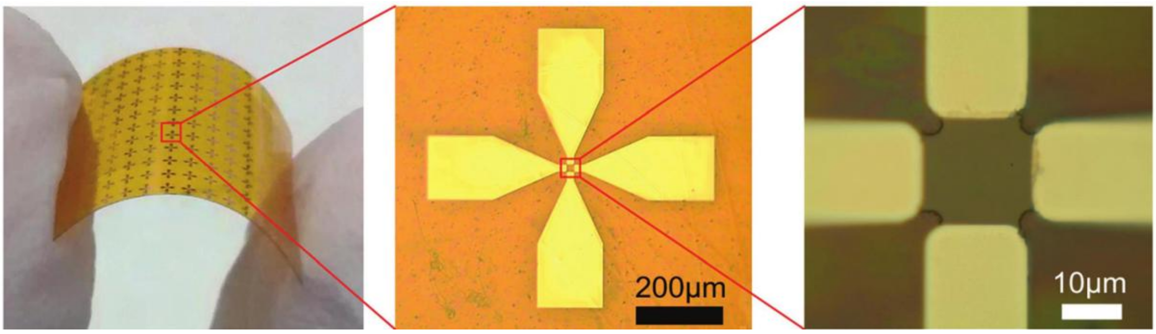

Fig. 7. Photo of Hall's flexible sensors [17].

XIV. Physical dimensions of Hall sensors

The physical dimensions of the sensing elements of sensors vary considerably in different studies, which affects their characteristics and applications. The classic view of the sensor is shown in Fig. 7 [17].

The variety of sensor sizes is due to their design and the technological capabilities of manufacturers. As a rule, such devices have dimensions of several tens of micrometers [15-17, 20, 27, 30]. Most sensors are made in a standard cross-shaped pattern [16, 17, 20-25], which provides approximately the same width and length. Sensors made according to the multi-contact scheme often have an elongated side.

The smallest working areas of the sensors were 10x10 μm [20] and 12x12 μm [16], and the largest size is a sensor made of graphene-containing material [32], where the linear dimensions are 8x3 mm and the width of the working area is 870 μm.

XV. Geometry of Hall sensors

In almost all of the successful experiments reviewed, Hall sensors were shaped like a Greek cross. Theoretically, ideal devices involve infinite length and negligible contact impact [53].

The geometry of the sensor affects its performance. For example, the shape of a "cross" (Fig. 8a) allows for a high value of the geometric factor, even with large contacts, while square shapes (Fig. 8c) demonstrate better sensitivity. In practice, it is necessary to take into account the trade-off between efficiency and power consumption, which depends on the aspect ratio of the sensor ($l/w \approx 1$) [53].

Thus, the shape and size of Hall sensors significantly affect their characteristics, and the choice of the optimal shape is important both in theory and in practice.

To improve the measurement accuracy, the "spinning current" technique is often used, which is applicable only to symmetrical sensors.

The Spinning Current Modulation Technique (SCMT) is used to measure the Hall signal in sensors to eliminate several problems associated with low-frequency noise, offsets, and parasitic phenomena. This method provides a significant improvement in measurement accuracy even in ultra-low magnetic field ranges, which can reach nanotesla [54].

Discussion and conclusions

Graphene is a promising material for electronics. The graphene market is growing every year. Contrary to early predictions, graphene cannot immediately turn all of its theoretical advantages into a stunning market success. The spread of this new class of one-dimensional materials takes time [12].

New niches are emerging. You can order the manufacture of devices from external companies, such as Graphenea [10], to create devices according to your specifications. Several sources were used in this paper [17, 19, 27, 29], whose researchers used the services of this company.

There are also companies on the market, such as Graphene Supermarket [51] and others, from which you can purchase graphene semi-finished products and further create the necessary devices based on them, as was done in some studies. Thus, the manufacture of graphene-based devices becomes much easier for researchers, as they do not need to have all the technological capabilities to create them.

One of the key aspects of creating effective graphene sensors is the choice of substrate. Different types of substrates, such as silicon dioxide, silicon carbide, sapphire, and polyimide, have a significant impact on the electrophysical properties of graphene and the characteristics of sensors. Flexible substrates make it possible to create devices that can be used in portable electronics and medical devices, maintaining their performance after numerous cycles of deformation.

The contacts between graphene and metals are critical to ensure low contact resistance and sensor stability. Different types of contacts were considered, including surface and edge contacts, where the latter show significantly better conductivity due to the formation of covalent bonds between metal and graphene atoms.

A review of scientific sources shows that at the present stage of development of graphene-based devices, there is no single universal technological process for creating sensors based on it, as is the case with classical semiconductors. For graphene, there is no unambiguous technology and material for substrate manufacturing, and

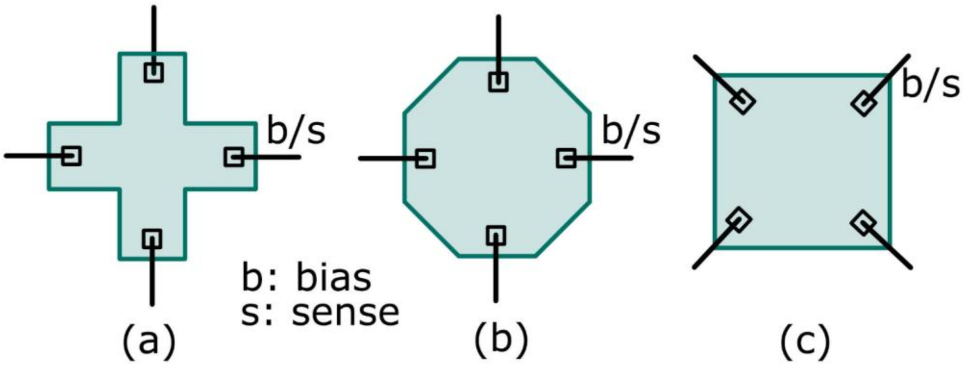

Fig. 8. Different types of geometry of the active region of Hall sensors (i.e., n-type wells) for Hall plates: a) cross-shaped b) octagonal c) square with contacts at the corners[53].

the same problem with contacts. But the search is ongoing and there are already some promising results. Such success in the search for substrates and contacts is evidenced by the fact that Paragraf [9] is the first company in the world to produce industrial graphene-based Hall sensors.

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Consent to participate

The authors declare their consent for publication.

Declaration of competing interest

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Biliak R. V. – postgraduate;
Liakh Kahui N.S. – doctor of science, associate professor, professor;
Kost Y.Y. – Ph.D., assistant.

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Сенсори Холла на основі графену: матеріали та підходи до виробництва

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Графен залишається одним з найбільш досліджуваних матеріалів завдяки своїм унікальним фізичним властивостям та двовимірній структурі. Стаття розглядає сучасний стан ринку графену, який розвивається стрімкими темпами, з прогнозованим обсягом у 1,5 мільярда доларів США до 2027 року. Обговорюються технології виробництва графенових сенсорів Холла, зокрема, метод хімічного осадження з парової фази (CVD), який широко використовується для створення промислових сенсорів. Важливу роль у властивостях сенсорів відіграє вибір підкладки, яка може бути як жорсткою (кремній, сапфір), так і гнучкою (поліімід). Увага приділена метал-графеновим контактам, де крайові контакти мають значно кращу провідність, ніж поверхневі. Автори підкреслюють, що на поточному етапі розвитку графенової електроніки немає єдиного технологічного процесу, як у класичній напівпровідниковій промисловості, що вимагає подальших досліджень для створення більш ефективних сенсорів.

Ключові слова: графен, сенсори Холла, двовимірні матеріали, пристрої на основі графену, виготовлення сенсорів Холла.