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UNIQUE PROPERTIES OF GRAPHENE

Abstract. The article is devoted to the unique material graphene (carbon modification), discovered in 2004 by immigrants from Russia Andrei Geim (Andre K. Geim) and Konstantin Novoselov (Konstantin Novoselov), who won the Nobel Prize in physics for this discovery in 2010. Graphene a two-dimensional monoatomic thick carbon block allotrope building, has attracted enormous attention due to its remarkable physical properties and chemical functionalization capabilities. Graphene is a potential nanofiller that can significantly improve the performance of polymer-based composites at extremely low loading. The article is an excursion through the publications of foreign and domestic authors, revealing the unique properties and prospects of using graphene, in particular, in nanotechnology and nanocomposites. Also, this review presents various mechanical, thermal and electrical, as well as other important properties of graphene, which were also discussed along with their potential applications.

A graphene-based technical breakthrough is possible because this is the finest substance in the world and can simultaneously possess several very important and unique electronic, electrical properties. Firstly, this substance can be an excellent conductor, since it consists of chains of carbon hexagons, through which electric current is very easily transmitted. Secondly, with some modification, graphene can be an effective insulator. You can make a microcircuit, which consists of conductors, semiconductors and insulators. Each of these characteristics of a substance can be achieved based on graphene.

Key words: graphene, electronic properties, mechanical properties, thermal properties, chemical properties.

Introduction. Graphene is another manifestation of the unique chemical properties of carbon. Graphene is one of the most promising materials for the 21st century. Graphene, a single-layer form of graphite, is a planar sheet one atom thick of carbon atoms bound by sp^2, which are located in the hexagonal lattice [1]. Graphene can be described as a monatomic layer of graphite. This is the main structural element of other allotropes, including graphite, charcoal, carbon nanotubes, and fullerenes. It can also be considered as an indefinitely large aromatic molecule, the limiting case of a family of flat polycyclic aromatic hydrocarbons.

Research on graphene has expanded rapidly since the substance was first isolated in 2004. The studies were based on theoretical descriptions of the composition, structure, and properties of graphene, which were calculated decades earlier. High-quality graphene has also proven to be surprisingly easy to isolate, which makes further research possible.

Andre Geim and Konstantin Novoselov received the Nobel Prize in Physics in 2010 "for pioneering experiments with two-dimensional matter graphene" [2].

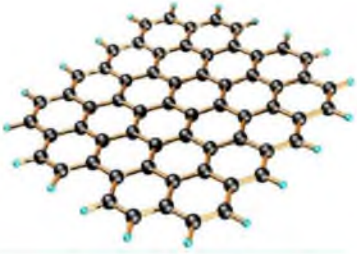
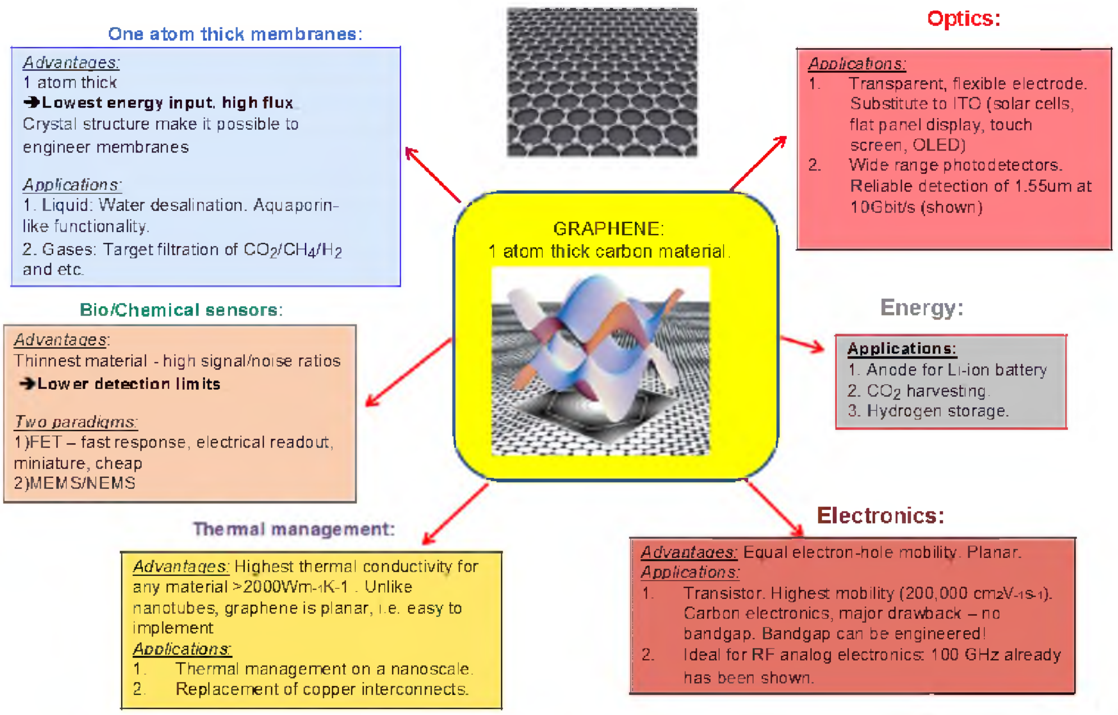


Figure 1- Idealized structure of a single graphene sheet

The remarkable properties of graphene are unique mechanical, thermal, electrical and optical properties. The conductivity, mechanical strength and chemical stability of graphene determine the prospects for its application in various fields (Fig. 2) [4]. That is, due to the aforementioned properties, graphene is widely used as conductive nanoelements for high frequency transistors, solar cells, sensors, supercapacitors, and various composite materials [3-5].

Among the remarkable properties of graphene are unique mechanical, thermal, electrical and optical properties. Most of these features are ideal, intact graphene sheets.



One atom thick membranes:

Advantages:
1 atom thick
➔**Lowest energy input, high flux**
Crystal structure make it possible to engineer membranes

Applications:
1. Liquid: Water desalination. Aquaporin-like functionality.
2. Gases: Target filtration of $CO_2/CH_4/H_2$ and etc.

Bio/Chemical sensors:

Advantages:
Thinnest material - high signal/noise ratios
➔**Lower detection limits**

Two paradigms:
1)FET – fast response, electrical readout, miniature, cheap
2)MEMS/NEMS

Thermal management:

Advantages: Highest thermal conductivity for any material >2000Wm-1K-1 . Unlike nanotubes, graphene is planar, i.e. easy to implement
Applications:
1. Thermal management on a nanoscale.
2. Replacement of copper interconnects.

Optics:

Applications:
1. Transparent, flexible electrode. Substitute to ITO (solar cells, flat panel display, touch screen, OLED)
2. Wide range photodetectors. Reliable detection of 1.55um at 10Gbit/s (shown)

Energy:

Applications:
1. Anode for Li-ion battery
2. CO_2 harvesting.
3. Hydrogen storage.

Electronics:

Advantages: Equal electron-hole mobility. Planar.
Applications:
1. Transistor. Highest mobility (200,000 $cm^2V^{-1}s^{-1}$). Carbon electronics, major drawback – no bandgap. Bandgap can be engineered!
2. Ideal for RF analog electronics: 100 GHz already has been shown.

Figure 2 - Properties and applications of graphene

Optical Properties. The ability of graphene to absorb quite large 2.3% of white light is also a unique and interesting property (Fig.3), especially considering that its thickness is only 1 atom [6]. This is due to the aforementioned electronic properties; Electrons act as massless charge carriers with very high mobility. It was proved several years ago [7, 8] that the amount of absorbed white light is based on a constant fine structure, and does not depend on the characteristics of the material. Adding another layer of graphene increases the amount of white light absorbed by about the same amount (2.3%). The graphene opacity $\pi\alpha \approx 2.3\%$ corresponds to the universal value of the dynamic conductivity $G = e2 / 4\hbar$ (± 2-3%) in the visible frequency range. Because of these impressive characteristics, it was noted [9] that as soon as the optical intensity reaches a certain threshold (known as saturation fluence), saturable absorption takes place (very high-intensity light causes a decrease in absorption).

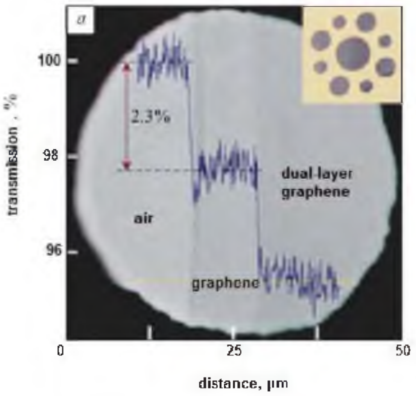


Figure 3 - Light transmission by mechanically exfoliated graphene

This is an important feature with regard to fiber laser mode locking. Due to the graphene properties of the wavelength-insensitive ultrafast saturable absorption, full-band mode locking is achieved using an erbium-doped dissipative soliton fiber laser capable of tuning a wavelength of up to 30 nm [10].

Electronics Properties. One of the most useful properties of graphene is that it is a semimetal with zero overlap (with holes and electrons as charge carriers) with a very high electrical conductivity [11–13]. In graphene, each atom is bonded to 3 other carbon atoms in a two-dimensional plane, leaving 1 electron freely available in the third dimension for electron conductivity. These very mobile electrons are called pi (π) electrons and are located above and below the graphene sheet. These pi-orbitals overlap and help increase carbon-carbon bonds in graphene [14]. Fundamentally, collaborative studies over the past 50 years have proved [15-19] that at the Dirac point in graphene, electrons and holes have zero effective mass. This is because the ratio of energy and motion (excitation spectrum) is linear for low energies near 6 separate angles of the Brillouin zone [20]. These electrons and holes are known as Dirac fermions or decanters, and the 6 angles of the Brillouin zone are known as Dirac points. Due to the zero density of states at the Dirac points, the electronic conductivity is actually quite low. However, the Fermi level can be changed by doping (with electrons or holes) to create a material that potentially conducts electricity better than, for example, copper at room temperature [21]. Graphene has a lower resistivity than any other known material at room temperature, including silver [22].

Tests have shown that the electronic mobility of graphene is very high, with previously reported results exceeding 15,000 cm^2 • V - 1 • s - 1, and theoretically potential limits of 200,000 cm^2 • V - 1 • s - 1 (acoustic photons limited by scattering of graphene) [23-25]. Graphene electrons are said to be very similar to photons in their mobility due to lack of mass. These charge carriers can travel distances less than a micrometer without scattering; a phenomenon known as ballistic transport. However, the quality of graphene and the substrate used will be a limiting factor [26]. For example, when using silicon dioxide as a substrate, mobility can be limited to 40,000 cm^2 • V -1 • s -1 [27]. Although all this makes graphene the fastest and most efficient conductor, it cannot be easily used for the manufacture of transistors, since it does not have a forbidden zone [28]. There are several ways to open the forbidden zone that exist, and some are under development [29-32].

Mechanical Properties

Graphene is one of the thinnest materials in the world - its thickness is only one carbon atom (about 0.34 nm). It is also recognized as the most durable two-dimensional material - much harder than steel or diamond with the same dimensions [33]. Graphene has a tensile strength (the maximum stress that a material can withstand when stretched or stretched to fracture or fracture) in excess of 1 TPa. There is only one material that can be stronger than graphene — carbine [34], which is a chain of carbon atoms, mainly a graphene ribbon, one atom wide. Carbin is very difficult to synthesize.

Since this is a single 2D sheet, it has the highest surface area of all materials. When left to their own devices, graphene sheets will fold and form graphite, which is the most stable three-dimensional carbon form under normal conditions [35]. Graphene sheets are flexible, and in fact graphene is the most extensible crystal — you can stretch it to 20% of its original size [36-39] without breaking it. Finally, ideal graphene is also very impenetrable, and even helium atoms cannot pass through it [40]. Because of the bond strength of 0.142 Nm carbon bonds, graphene is the most durable material ever discovered, with a tensile strength of 130,000,000,000 Pascals (or 130 gigapascals) compared to 400,000,000 for A36 structural steel or 375,700,000 for Aramida (Kevlar) [41-43]. Graphene is not only unusually strong, but also very light - 0.77 milligrams per square meter (for comparison, 1 square meter of paper is about 1000 times heavier). It is often said that one sheet of graphene (only 1 atom thick), sufficient in size and sufficient to cover the entire football field, will weigh less than 1 gram [44].

What makes this especially special is that graphene also has elastic properties that can retain their original size after deformation. In 2007, atomic force microscopes (AFM) were carried out on graphene sheets that were suspended above silicon dioxide cavities [45–49]. These tests showed that graphene sheets (with a thickness of 2 to 8 Nm) had constant springs in the region of 1-5 N / m and Young's modulus (different from three-dimensional graphite) of 0.5 TPa. Again [50], these excellent figures are based on theoretical perspectives using flawless graphene, which does not contain any flaws and is currently very expensive and difficult to reproduce artificially, although production methods are constantly being improved, ultimately reducing costs and complexity.

Thermal management

The stable operation of electronic devices is highly dependent on temperature. There is a constant search for materials capable of dissipating the heat released during the operation of instruments and devices. Graphene is an ideal heat conductor - it has a record thermal conductivity. Graphene conducts heat in all directions - it is an isotropic conductor [51-53]. When measuring the thermal conductivity of suspended graphene, the thermal conductivity at room temperature was 5000 W / m • K (obtained from the measurement of the Raman spectra), i.e. 2.5 times more than that of diamond, whose thermal conductivity was considered the largest of the materials known today. Such a value could solve the problem of heat removal in nanoelectronics [54].

It is believed that the high thermal conductivity of graphenes is due to the structural perfection of those small samples on which it was measured. Unfortunately, this value decreases with increasing size; Thus, the thermal conductivity of graphenes with a length of 1 to 5 μm decreases in the range from 5000 to 3000 W / m • K; Such a dependence is usually associated with the phonon mechanism of thermal conductivity. However, in other experiments, single-layer graphene is usually fixed on substrates, usually dielectric, which leads to scattering by the phonons of the substrate and impurities. So, the graphene layer on the SiO2 surface had a thermal conductivity of only 600 W / m • K [55], which, however, is still greater than that of copper; its thermal conductivity is 400 W / m • K at room temperature, but really thin films are used, whose thermal conductivity is lower (less than 250 W / m • K). For thermal conductivity in the direction perpendicular to the graphene plane, see [56].

Biosensors

It is known that graphene as a two-dimensional material has a unique set of electrophysical properties: high mobility of charge carriers in combination with their low concentration; the maximum possible ratio of area to volume; low noise [57]. The combination of these properties leads to the fact that the adsorption of a minimum amount of impurities on the surface of graphene can significantly change its overall conductivity. Thus, graphene is a very promising material for the manufacture of various types of sensors (figure 4).

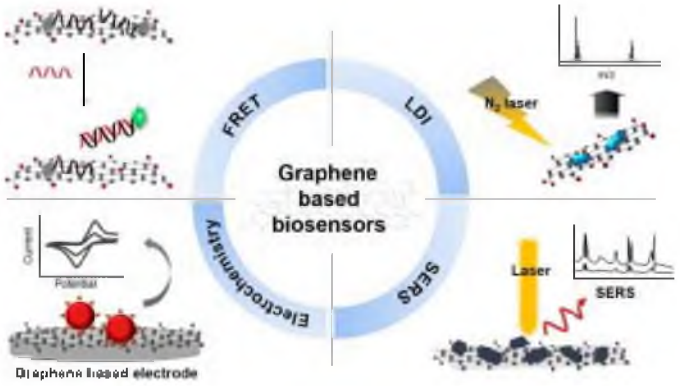


Figure 4 - Graphene based biosensors

In [58], it was shown that graphene is capable of sensing the adsorption of even one molecule. The attached gas molecules, depending on their charge and type of conductivity of the graphene film, behave as donors or acceptors, i.e., they change the concentration of mobile charge carriers. As a result, depending on the type of adsorbed molecule, a decrease or increase in the film resistance was observed [59–60]. It should be noted that one of the serious drawbacks of the graphene gas sensor is the lack of selectivity. Indeed, by a change in conductivity it cannot be said which molecule was adsorbed onto the surface of graphene. Moreover, some molecules contribute the opposite sign; thus, the total change in resistance can be close to zero. The problem of selectivity of the graphene-based sensor can be solved by using the antigen – antibody reaction. The components of this pair can only interact with each other and with no other proteins. t is known that at certain stages of many human diseases in the blood, antigen markers appear that are specific for one or for a group of diseases. These antigens can interact with specific antibodies previously applied to the surface of the graphene sensor. The reaction, as in the case of a gas sensor, leads to a change in the resistance of the graphene film. The use of an antigen – antibody pair allows one to solve the biosensor selectivity problem and opens up very wide possibilities for the use of graphene-based sensors in medicine and biology. This approach can lead to the creation of portable biosensors capable of detecting diagnostically significant disease markers in biological fluids that are currently detected only using a laborious and lengthy enzyme-linked immunosorbent assay [61].

Chemical Properties. Despite the fact that all graphene atoms are exposed to the environment, it is an inert material that does not react with other atoms. However, graphene can "absorb" various atoms and molecules. This can lead to changes in electronic properties, and can also be used for the manufacture of sensors or other applications [62].

Graphene can also be functionalized by various chemical groups [63-64], which can lead to various materials, such as graphene oxide (functionalized by oxygen and helium) [65, 66] or fluorinated graphene (functionalized by fluorine) [67]. Great interest in studying the functional properties of graphene, due to the fact that it is a promising material for many industries, has a high commercial potential [68].

Findings. In this review, we have described some of the distinguishing properties of graphene, such as mechanical, thermal, electrical, and optical properties. Because of these unique properties, graphene is widely used as conducting nanoelements for high-frequency transistors, solar cells, sensors, supercapacitors, and various composite materials. The electrical conductivity, mechanical strength, and chemical stability of graphene determine the prospects for its use in various fields.

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ГРАФЕННІҢ БІРЕГЕЙ ҚАСИЕТТЕРІ

Аннотация. Графен – графиттің бірқабатты күйі, алтыбұрышты торда орналасқан sp^2 байланысқан көміртек атомдарының қалыңдығы бір атомнан тұратын жазық парақ. Графен көміртек атомдарының байланысқан құрылымының ерекше комбинациясының, сондай-ақ сансыз және күрделі физикалық қасиеті болғандықтан материалтану, электроника және нанотехнология болашағына айтарлықтай әсер етуге қабілетті. Ерекше құрылымы мен минималды диаметріне байланысты оны сенсорлық құрылғы, жартылай өткізгіш немесе интегралды схема компоненттері ретінде пайдалануға болады. Мұндай көміртектің екіөлшемді формасыныц қасиеттері мен қолданысы болашақ құрылғы мен жүйеге жаңа мүмкіндіктер ашты.

Графеннің үздік қасиеттері оның релятивистік бөлшектер тәрізді әрекет ететін заряд тасымалдаушысы болғандықтан пайда болады.

Графеннің заряд тасымалдаушылық сипатына байланысты тағы бір эффект – спираль болғандықтан хиралды симметрия пайда болады. Бірқабатты және екіқабатты графендегі электронды күйдің хиралды табиғаты электронның потенциалды кедергі арқылы өтуі барысында маңызды рөл атқарады.

Графен өндірудің түрлі әдісі бар, мысалы, «тотығу - қабыршақтану - тотықсыздану» үдерісі кезінде графит графит оксидіне айналып, графиттің базалық жазықтығы ковалентті байланысқан оттекті функционалды тобымен жабылады. Бұл жағдайда тотыққан графит гидрофильді (ылғал сүйгіш) келеді және ультрадыбыс әсерінен сулы ерітіндіде оңай графен қабаттарына қабыршақтанады. Мұндай графен жақсы механикалық және оптикалық сипаттамаға ие, бірақ «скотч әдісі» арқылы алынған графенмен салыстырғанда электр өткізгіштігі нашар.

Фундаменталды зерттеулер үшін сапалы графен қабаттарын, сондай-ақ электронды микросхема құруға бағытталған графен өсірудің эпитаксиалды әдісі арқылы алуға мүмкіндік беретін скотч негізінде механикалық қабыршықтандырумен қатар, химиктер графенді ерітіндіден алу жолдарын қарастыруда. Бұл әдіс жоғары өнімді әрі арзан келетіндіктен, графен қабаттарын түрлі материалмен біріктіріп, нанокомпозит құруға және оларды түрлі наноқұрылымдарға енгізуге мүмкіндік береді.

Графеннің дисперсиялылығымен шектелетін ерекше қасиеттері бар, әсіресе гидрофобты табиғатына байланысты полярлық полимер матрицаларымен араласқан кезде ерекше қасиетке ие болады. Графен көптеген, мысалы, электроника және функционалды нанокомпозиттер сияқты көптеген басқа қосымшада үлкен потенциалмен қамтамасыз ете алады.

Графеннің жоғары электронды қозғалғыштығы, бір атомның минималды қалыңдығы, төмен меншікті кедергісі сияқты қасиеттері түрлі биологиялық және химиялық сенсорларды құрудың перспективаларын ашады, сонымен қатар күн энергиясын түрлендіруге арналған фотоэлектрлік құрылғыларда немесе сенсорлы экрандарда қолдануға болатын жұқа пленкаларға түрлі нұсқаларды ұсынады.

Графен негізінде жоғары сезімтал фотопленка жасалуы мүмкін. Графендегі плазмалық толқындар терагерц диапазон қабылдағышын құрудың перспективасын ашады. Графен спинінің ерекше әрекеті жаңа сфинтронды құрылғылар пайда болуы мүмкін, ал жылу өткізгіш қасиеті жоғары болғандықтан графен қазіргі заманғы интегралды схемаларда жылу қабылдағыш ретінде қызмет ете алады.

Графен қолданудың басқа бағыттары да перспективалы болып көрінеді. Сонымен, графен пластмассадан жасалған қоспада жоғары температураға төзімді композициялық өткізгіш материалдарды жасауға мүмкіндік береді деп болжанады. Графеннің беріктігі ультра жұқа, жеңіл және икемді жаңа механикалық тұрақты материалдарды жасауға мүмкіндік береді. Болашақта графен негізіндегі композициялық материалдардан автомобиль, ұшақ пен спутник жасауға болады. Энергияны сақтау құрылғыларында – аккумулятор және суперкапакатор, сондай-ақ оттегі мен сутектің араласуынан электр энергиясын өндіретін отын ұяшықтарында графенді қолдану жоспарлануда.

Егер графен зерттеу жұмыстары дәл осындай қарқынмен дамитын болса, онда біз осы ғасырдағы ғылыми-техникалық прогрестің жаңа кезеңіне куә боламыз, ал графенді практикалық қолдануға қызығушылық танытатын мемлекет жетекші техникалық күшке айналады.

Түйін сөздер: графен, электрондық қасиеттер, механикалық қасиеттер, жылу өткізгіш, химиялық қасиеттер.

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УНИКАЛЬНЫЕ СВОЙСТВА ГРАФЕНА

Аннотация. Графен, однослойная форма графита, представляет собой планарный лист толщиной в один атом из атомов углерода, связанных sp^2, которые расположены в гексагональной решетке [2]. Графен с уникальным сочетанием структур связанных атомов углерода с его бесчисленными и сложными физическими свойствами способен оказать значительное влияние на будущее материаловедения, электроники и нанотехнологий. Благодаря своей специализированной структуре и минимальному диаметру, его можно использовать в качестве сенсорного устройства, полупроводника или для компонентов интегральных схем. Сообщаемые свойства и применения этой двумерной формы углерода открыла новые возможности для будущих устройств и систем.

Все эти удивительные свойства графена возникают из-за уникальной природы его носителей заряда, которые ведут себя подобно релятивистским частицам.

Ещё один эффект, обусловленный характером носителей заряда в графене, связан с наличием спиральности, что приводит к существованию так называемой киральной симметрии. Киральная природа электронных состояний в однослойном и двухслойном графене играет важную роль в прохождении электрона через потенциальный барьер.

Существуют различные методики получения графена: например, преобразование графита в оксид графита, когда происходит процесс «оксидирование - расслоение -восстановление», в ходе которого базисные плоскости графита покрываются ковалентно связанными функциональными группами кислорода. При этом окисленный графит становится гидрофильным (влаголюбивым) и легко расслаивается на отдельные графеновые листы под действием ультразвука, находясь в водяном растворе. Такой графен обладает хорошими механическими и оптическими характеристиками, но худшей электрической проводимостью по сравнению с графеном, полученным с помощью «скотч-метода».

В дополнение к механическому отслоению с помощью скотча, позволяющему получить графеновые слои высокого качества для фундаментальных исследований, и эпитаксиальному способу выращивания графена, направленному на создание электронных микросхем, химики работают над получением графена из раствора. Помимо высокой производительности и низкой себестоимости, этот метод позволил бы интегрировать графеновые слои с различными материалами для создания нанокомпозитов и внедрять их в различные наноструктуры.

Графен обладает уникальными свойствами, которые могут быть ограничены его диспергируемостью, особенно в смеси с полярными полимерными матрицами, из-за его гидрофобности в природе. Графен может обеспечить большой потенциал во многих приложениях, таких как электроника и функциональные нанокомпозиты, среди многих других.

Такие свойства графена, как высокая подвижность электронов, минимальная толщина в один атом, низкое удельное сопротивление открывают перспективы для создания различных биологических и химических датчиков, а также различных вариантов тонких плёнок, которые могут найти применение в фотоэлектрических устройствах для преобразования солнечной энергии или в сенсорных экранах.

На основе графена могут быть созданы высокочувствительные фотоплёнки. Плазменные волны в графене открывают перспективы создания источников и приемников терагерцового диапазона. Особое поведение спина в графене может привести к созданию новых приборов спинтроники, а благодаря свойству высокой теплопроводимости графен может служить теплоотводом в современных интегральных схемах, в которых разогрев является серьёзной проблемой.

Многообещающими представляются и другие направления использования графена. Так, предполагается, что в смеси с пластмассами графен даст возможность создавать композитные проводящие материалы, устойчивые к действию высоких температур. Прочность графена позволяет конструировать новые механически устойчивые материалы, сверхтонкие, легкие и эластичные. В будущем из композитных материалов на основе графена возможно будет делать автомобили, самолеты и спутники. Уже сейчас предполагается использовать графен в устройствах для хранения энергии – аккумуляторах и суперконденсаторах, а также топливных элементах, вырабатывающих электроэнергию от соединения кислорода с водородом.

Если графеновая революция пойдет такими же стремительными темпами, то мы явимся свидетелями нового витка научно-технического прогресса уже в этом веке, а страна, которая проявит интерес к практическому применению графена, станет ведущей технической державой.

Ключевые слова: графен, электронные свойства, механические свойства, термические свойства, химические свойства.

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