Graphene: An Overview on the Structural, Physicochemical Properties, and Applications

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Abstract

Graphene, a two-dimensional material composed of a single layer of carbon atoms arranged in a hexagonal pattern, has captured the attention of researchers and industry experts as a potential game-changer for technological advancements in the 21st century. With its exceptional physio chemical properties, it has developed as a leading contender for the advancement of science and industry in the coming years. In this article, we provide a comprehensive discussion of graphene, covering its structure, physical properties, chemical composition, and diverse potential uses. We also highlight the substantial scientific and economic hurdles that must be overcome before graphene-based products can be commercialized on a large scale. However, despite its immense potential, the commercialization of graphene-based products has been slow due to significant scientific and economic obstacles. Although the use of graphene in industrial applications is still in its early stages, ongoing research and development initiatives are expected to lead to new and intriguing uses for this remarkable material. The article delves into the intricate structure, physical properties, chemical composition, and diverse potential uses of graphene.

Keywords: Graphene, 2D material, electrical conductivity, bottom-up and top-down processes

Introduction:

Graphene, an allotrope of carbon, is the first ever two-dimensional crystal material to discover. The name "graphene" is derived from "graphite" and the suffix "ene," indicating its similarities to graphite with multiple double bonds [1]. Every atom in a graphene sheet is strongly connected to its three neighbouring carbon atoms across the sheet. Other materials with similar bonding include carbon nanotubes, polycyclic aromatic hydrocarbons, fullerenes, and glassy carbon [2]. Researchers in 2D materials are exploring ways to bring graphene research to practical applications that could improve people's lives globally. Graphene is a material with remarkable properties, including high strength, remarkable electric conductivity and good optical transparency [3]. It has been the subject of much research and expansion in recent times and set for many potential applications in various fields. This amazing material is extremely light, yet much stronger than steel. Also shows the properties like flexibility, transparency, electrical and thermal conductivity to name a few. Graphene's remarkable properties make it a powerful tool for scientists, engineers and innovators to utilize it as a perfect candidate for all sorts of applications. Graphene, a revolutionary material that has the potential to revolutionize industries, graphene offers remarkable strength and conductivity that can't be matched by traditional materials. Its unique properties make it perfect for applications in energy storage, communications, and beyond [4-5].

One of graphene's most remarkable properties is its high electrical conductivity, being an ultra-thin, flexible, transparent material, made it a suitable material for electronic gadgets like transistors, solar cells, and batteries. Its high strength and flexibility also make it a promising material for various applications, including flexible displays, wearables, and even aircraft and spacecraft. The potential applications of graphene are vast and diverse, and research in this field is rapidly advancing. Its unique combination of properties has the potential to revolutionize various industries, from electronics and energy to biomedical engineering and aerospace. The exceptional combination of high carrier mobility, thermal conductivity, mechanical strength and transparency has led to a wide range of devices based on graphene and its derivatives, like field-effect transistors (FETs), photodetectors, and energy storage devices. One of the key areas of research in graphene electronics is in the progress of graphene FETs, which have shown excellent performance in terms of carrier mobility, high-frequency operation, and low power consumption. Another area of interest is graphene photodetectors, which have been shown to exhibit high responsivity, and low dark current. In energy, graphene's unique blend of strength, flexibility, and conductivity along with high porosity and surface area, its conductivity and high stability makes it an ideal material for the development of energy-storage devices such as batteries and supercapacitors. Its unique mechanical, electrical, and thermal properties make it an ideal material for advanced sensors, allowing for the detection of various physical and chemical parameters with high sensitivity. In electronics, graphene is being researched as a replacement for silicon, the traditional material used in the manufacturing of transistors and other electronic components [6-7].

Furthermore, graphene's low thermal expansion with high thermal conductivity makes it useful for thermal management in electronics, helping to prevent overheating and improve overall performance. In electronics, graphene is being researched as a replacement for silicon, the traditional material used in the manufacturing of transistors and other electronic components. In the field of medicine, graphene's biocompatibility makes it a useful material for implantable medical devices and for use in drug delivery systems. In addition, graphene is biocompatible, making it a potential material for biomedical applications such as drug delivery and tissue engineering [8-10]. Graphene's impact on technology is not limited to these few examples, and its potential applications are vast. Its discovery and subsequent development have led to a new era of materials science and have paved the way for the creation of new technologies that were previously thought to be impossible. The future looks bright for graphene and its role in driving technological growth and innovation.

In conclusion, the development of graphene as high-speed and energy-efficient electronic devices is an active and rapidly evolving field, with many exciting developments and opportunities. Although there are still challenges to be addressed, the unique combination of properties offered by graphene gives us a hope as future material for electronics. With graphene, you can make your products lighter, thinner, faster and more efficient than ever before. Despite the promising results, there are still numerous tasks to be addressed in order to fully utilize the material. One of the major challenges is the large scale production of superior quality graphene at a lower cost and developing a consistent and reliable methods for its large scale synthesis[11]. Another challenge is the integration of graphene into existing device architectures, which demands the development of new fabrication processes with good material compatibility.

Graphene Structure

Two-dimensional graphene has a chicken-wire-like hexagonal arrangement of carbon atoms. Graphene, which is formed of a single layer of carbon atoms, is produced when atoms are arranged in a honeycomb pattern. Multi-layer graphene is formed when many sheets are piled on top of one another, although the exact number of sheets required to make the transition to graphite (often about 30 or more) is still up for debate. Graphene's exceptional stability and tensile strength come from the fact that each carbon atom is covalently bound to three other carbon atoms although, it has the capability to attach top four carbon atoms [12-14]. The flat shape means that all of the atoms are on the surface, where they may more easily interact with other molecules. Moreover this arrangement of carbon atoms makes it highly porous and results in the exceptionally high surface to volume ratio. In addition, graphene has the greatest electron mobility of any substance studied thus far [15].

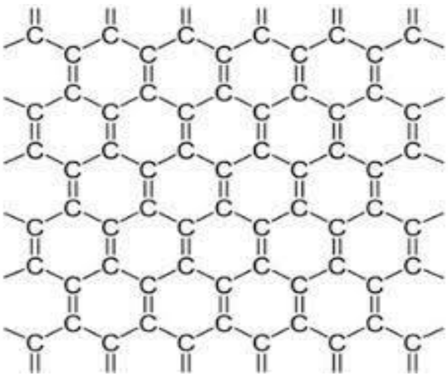

Figure: 1 Structure of graphene

Graphene can also be transformed into various graphitic materials like fullerene, carbon nanotubes, and thin graphene films. Its honeycomb lattice structure enables the study of quantum phenomena in graphene at ambient temperatures due to the transmission of massless electrons over a sub-micrometre distance without scattering.

The stability of the graphene's planar rings is due to the sharing of sp2 electrons covalently with the three neighbouring carbon atoms This makes the bond length to be 1.42 Å, which is shorter than sp3 hybridized carbon-carbon bonds [16-17]. The half-filled π bond in monolayer graphene allows for free-flowing electrons thus forming both valence and conduction bands with minimum band gap energy. Further the weak van der Waals attractive force gets generated between the multiple layers of graphene which makes it much stronger [18].

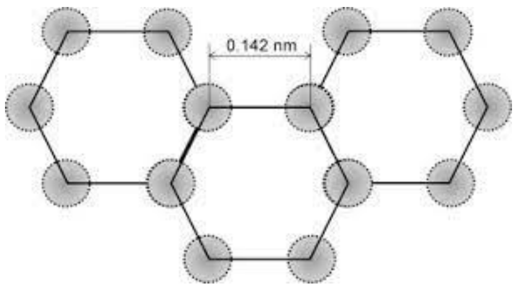

Figure: 2 Bond length of graphene

Properties of Graphene:

Mechanical & Physical

Graphene is very lightweight, with a planar density of about 0.77 mg/m^2. The graphene in this product is very lightweight and has a remarkable planar density of about 0.77 mg/m^2. A tensile strength of 125 Gpa and an elastic modulus of 1.1 Tpa make it the strongest and hardest crystal structure yet found by humans; both of these values are much higher than the elastic modulus of the most common materials, which is about 200 GPa. At 42 N/m, its breaking strength is 100 times that of steel, making it the strongest material ever created mechanically. Because of this, graphene is a promising material for use in a variety of composites[19-20].

Graphene's repeating sp2 hybridised backbone, which allows for flexibility through bond rotations, provides both stiffness and stability, making it capable of supporting additional ions. This combination of flexibility and support is rare among molecules. Additionally, graphene is the toughest crystal, able to be stretched up to 20% of its original size without breaking, and has a spring constant of 1.5 Nm^{-1} and a Young's modulus of 0.5 Tpa. [21-22].

Optical Properties

Graphene is optically transparent with 97.7% of transparency, but it is still visible. Each layer in graphene can be determined since each layer absorbs 2.3% of white light for example; a 5-layer graphene samples absorption capacity is 11.5% and its optical transparency is 88.5%. It also absorbs in a wide range of frequencies and processes unique optical transitions. This is due to its capacity to absorb electromagnetic radiations from different regions of the spectrum owing to its unique band gap, band structure and Dirac fermions in graphene sheet. Graphene may absorb transmission in electric fields, which is referred to as gate-dependent optical transitions, which may also result in photoluminescence properties [23].

Electrical Properties

Graphene's unusual structure, which allows for very high electron mobility, gives it extraordinary electric characteristics. It boasts the highest conductivity of any material at room temperature (10^6 S/m) and the lowest sheet resistance (0.1-2.7 kΩ/sq) due to its very high electron mobility even at room temperature. ($2*10^5$ $cm^2/V/s$). The conductivity of a single layer graphene can be 70% higher than of copper. This is owing to the material's hexagonal lattice structure, which facilitates rapid and unimpeded electron movement. There is no difference in energy level between graphene's valence and conduction bands, making it a zero-bandgap material. Because of this, it is a great conductor of electricity owing to the high electron mobility and electrical conductivity. Graphene is considered a semi-metallic substance due to the presence of finite number of electrons in both valence and conduction bands, even at zero degrees Celsius. Graphene has a lower resistance than any other known material, including silver, at room temperature because a single layer of graphene has 10,000 times the electrical conductivity of a few layers of graphene. Graphene's intrinsic mobility and electrical current density are one million times that of copper (100 times that of silicon) [19-21].

Graphene exhibits a quantum Hall effect, which arises from its unique electronic structure. The quantum Hall effect refers to the quantization of electrical conductance in a two-dimensional material in the presence of a magnetic field. This effect has been observed in graphene due to its unique electronic structure, where the electrons behave as massless Dirac fermions. Due to its high optical transparency, graphene is useful for transparent conductive electrodes in optoelectronics applications. Finally, because to its exceptional electrical conductivity and unique electronic structure, graphene can be successfully used in electronic gadgets, sensors, energy storage devices and FETs.

Thermal Properties

The unusual 2-D structure with strong covalent bonds, graphene has extraordinarily high thermal characteristics, allowing it to swiftly transport heat energy from one spot to another. It has the greatest heat conductivity of any known material, even surpassing copper and diamond.

The thermal conductivity of graphene is 5300 W/m/K, which is 10 times that of copper. There are two forms of thermal conductivity in graphene: in-plane and interplane. The repeating structure of graphene makes it an ideal material for transmitting heat in-plane. Interplane conductivity is an issue, thus other nanomaterials, such as carbon nanotubes, are often utilised to enhance it. As a result, graphene is a great option for use in heat dissipation applications, such as electronics, where it may aid in the prevention of overheating. Moreover, owing to the f=high thermal stability, it can resist high temperatures without degrading or losing its qualities. This makes it suited for use in high-temperature situations, such as aerospace or semiconductor manufacturing. When supported in an amorphous material, however, its thermal conductivity drops to about 500-600 W/m/K. Although the specific heat capacity of graphene has never been directly measured, the specific heat of the electronic gas in graphene has been anticipated to be about 2.6 $Jg^{-1}K^{-1}$ at 5 K. However, graphene's specific heat capacity may be affected by variables such as temperature, pressure, and the presence of impurities, flaws, or other materials. Finally, graphene has a very low thermal expansion coefficient, which means it does not expand or contract much with temperature changes. Because of this feature, graphene is beneficial in situations where thermal expansion might create issues, such as the manufacture of high-precision sensors. Overall, graphene's remarkable thermal characteristics make it a very appealing material for applications in aircraft, energy devices [19-22].

Chemical Properties

With just one carbon atom thick, graphene boasts the biggest surface area of any material while simultaneously being one of the thinnest materials in the world and its specific surface area (26730 m^2g^{-1}), making it an excellent adsorbent for gases and liquids. It can also form stable dispersions in a wide range of solvents due to its hydrophobic nature. The sp2 hybridization of carbon atoms in graphene leads to strong π-bonds, making highly reactive towards chemical functionalization. Graphene also shows remarkable chemical stability, as it resists attack from most chemicals and can withstand high temperatures without decomposing. Perfect graphene is also virtually impenetrable, with even helium atoms unable to pass through it. It can also form stable covalent bonds with other materials, making it an excellent platform for developing advanced composites and hybrid materials. The functionalized graphene derivatives exhibit diverse chemical properties and are being explored in biosensing, energy storage, and catalysis. A potential application for graphene is in the field of medicine. Its antibacterial properties make it an ideal material for wound dressings, as it can help prevent infections and promote faster healing. Additionally, graphene-based sensors could be used to monitor the health of patients and detect diseases at an early stage.

Overall, graphene's unique structure and chemical properties make it an exciting and versatile material with potential applications in numerous fields, including electronics, biomedical devices, and environmental remediation [19-22].

Production Techniques

Numerous techniques were adopted for the exfoliation of graphite into graphene. These approaches are classified into two types: top-down approach and bottom-up approach. Physical processes are involved in top-down process, which reduces the size of the material which is done by various techniques as discussed below. Surface defects with a variety of properties appropriate for applications requiring electrical, thermal, and magnetic performance are only one of the disadvantages of this technology. Some of the processes are explained below.

Top-Down Approaches

The top-down approach, which involves layer-by-layer separation of graphene precursors like graphite, GO, etc. to create graphene sheets, is well shown by mechanical exfoliation. This technology is inappropriate for mass production because to the uneven thickness of the films it produces and the high manufacturing costs. It is also possible to convert graphite to graphene using graphite intercalation. The graphite interlayer gap may be used to introduce various chemical species (GIC) These intercalants increase the distance between the graphite layers, changing the properties of graphene as a result.

Nanotube slicing may create nanoribbons of graphene as thin as a few microns. These methods provide substantial yields of superior graphene. Theoretically, 2D graphene sheets might be created by cracking open nanotubes. Many methods have been developed, such as plasma etching of nanotubes that are partly embedded in polymer film.

Pyrolysis is a straightforward procedure that may be scaled up for production. A sealed reactor vessel is heated to 220° C with a 1:1 molar ratio of sodium (2 g) and ethanol (5 mL) to produce the solid solvothermal precursor of graphene. This is further vacuum filtered and dried for 24 hours in a vacuum oven at 100^{o}C.

Scientists have devised an electrochemical method of exfoliating technique for separating graphene from graphite. The technique uses platinum wires as the cathode, graphite flakes as the anode, and H_2SO_4 solution as the electrolyte and is done at +10V, when the graphite flakes began dissolving in the solution. The substance is dispersed in DMF to made in the form of Electro Graphene sheets.

A few nanometer to micrometer sized graphene flakes or powder is produced by reducing graphite oxide using reducing agents which can be accomplished by chemical and thermal treatments. Further this graphene oxide can be exfoliated in water by ultrasonication. This method might be used to the creation of conductive paints and inks, polymer fillers, supercapacitors, sensors, and other things. Chemical or heat treatment may be used to reduce.

Ultrasonication technique can produce graphene flakes and unoxidized graphene. This technique generates graphene, which may be used as sensors, transparent electrodes, and fillers in polymers. However, this method requires a lot of energy since sonication is the main energy source.

Ball milling process was used for the first time to produce graphene sheets from graphite. This method produces graphene with a greater surface area than graphite and an incredibly low ID/IG ratio of 0.6. Through chemical interactions such as those caused by carbon monoxide poisoning and bisphenol A (BFA), this method inhibits the sheets from stacking again.

By subjecting it to an electron beam, graphene may also be transformed into graphene sheets. Graphene of good quality is produced using this method; however, the yield is not great. Even if such technologies are not commercially feasible for industrialization, it is anticipated that radiation concerns would impede their adoption [24].

Bottom-Up Approaches

Bottom-up approach involves chemical procedures, which were successful in producing graphene with high quality. When carbon from a material like graphite gets in contact with a transition metal and heated to high temperatures, graphene is produced. It is possible to lower the temperature after carbon starts to dissolve in the molten metal in order to minimize carbon solubility. Several other forms of carbons, including thick graphite or layers of graphene, may be obtained by skimming off the precipitate. Prior to being stirred all night in 100 mL of 1 M HCl, Mg must be fully burnt in CO2. Mg and MgO must both be filtered and washed with deionized water since they are both soluble in water. 680 mg (92% graphene) of the residue must be dried overnight under pressure at 100° C.

Vapor species from various chemical processes are deposited during the process of creating graphene using chemical vapors deposition (CVD). CVD involves the deposition of vapour species through various chemical reactions, which play a crucial role in the process. CVD has proven to be an effective method for producing large, homogenous graphene sheets, particularly for large-scale manufacturing and high-quality samples. However, one disadvantage of this method is the difficulty in transferring the graphene onto a different substrate, which can lead to folding, defects, tearing, and wrinkles in the samples. Nonetheless, this is still considered the most reliable and straightforward method for consistent large-scale production of high-quality graphene for commercial and industrial use.

Moreover, graphene can be grown epitaxially on silicon carbide (SiC) substrates by heating SiC to 1100^{o}C. This approach yields epitaxial graphene, whose size is determined by the size of SiC wafers. Unlike exfoliated graphene, graphene generated by this process has poor ant-localization [25].

Limitations of graphene

However, despite its many advantages, graphene also has several disadvantages. These include difficulties in large-scale production, compatibility issues with other materials, reproducibility of the properties, etc. The bulk production of graphene sheets is still challenging, complex, and expensive. Current methods for the synthesis of graphene, like exfoliation and chemical vapor deposition, are time-consuming and require specialized equipment and expertise. Graphene is an electrical conductor but it is not an efficient thermal conductor. This means that it cannot effectively dissipate heat, making it unsuitable for use in certain high-temperature applications. As graphene is a very thin material, and its mechanical strength is limited. This makes it susceptible to damage and which can lead to unwanted interactions with surrounding materials and cause functionalities to be lost. The limited compatibility of graphene with other materials, makes it challenging to integrate into devices and systems. This is particularly true for electronic devices, where graphene's unique electrical and optical properties need to be matched with the materials used in the rest of the device. As a catalyst, graphene is susceptible to oxidative environment. Further research and development are required to overcome these limitations and to make graphene a practical and usable material in various applications.

Although the use of graphene in industrial applications is still in its early stages, ongoing research and development initiatives are expected to lead to new and intriguing uses for this remarkable material. As graphene's physical characteristics and chemical makeup are better understood, it is likely that it will continue to play a crucial role in various fields, such as electronics, energy, and biomedicine. Despite these challenges, graphene's unique properties and vast potential for technological advancement make it an exciting material to watch in the coming years.

Summary

Graphene is revolutionary because it is the first 2D material to be isolated with a thickness of just one atom. Graphene and related materials are special because of its structural peculiarities. The most promising applications of graphene is in the field of electronics. Its high conductivity and transparency make it an ideal material for creating faster and more efficient electronic devices, such as flexible touchscreens and ultrafast transistors, graphene-based batteries which could provide longer-lasting, faster-charging power sources. Graphene's high strength and flexibility make it an excellent material for use in composites, such as in the aerospace industry, where it can improve the strength and durability of materials without adding significant weight. It can also be used to create stronger and more durable sports equipment and even lightweight, bulletproof armor. Graphene's membrane-like property makes it useful as a hydrogen isotope "sieve," its affinity for metallic ions makes it useful in ionising radiation detectors. Thus graphene is a miracle material which is still in the research stage and much more is yet to be discovered.

Overall, graphene has tremendous potential as a material for industrial growth, with applications ranging from electronics and composites to medicine and beyond. As research and development continue, it is likely that graphene will continue to be at the forefront of many industries in the years to come.

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