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GRAPHENE PLASMONICS AND ITS TECHNOLOGICAL FRONTIERS

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Article Info

Abstract

Graphene has made it a revolutionary material in technological and scientific developments due to its 2D structure and by its amazing mechanical, optical, electrical and thermal properties. This review article explores the sp2 structure of graphene including its atomic arrangements in which hexagonally arranged carbon atoms form a honeycomb like structure. It examines the wonderful graphene attributes including chemical functionalization, impermeability, unparalleled tensile strength, remarkable electrical and thermal conductivity and optical transparency from the perspectives of fundamental physics and materials science. In this study thoroughly reviewed the mechanical exfoliation approach for synthesizing the high-quality graphene with a focus of its simple methodology and examines the advanced approaches for modifying the properties of graphene using several doping techniques including electrical and chemical modification and by structural confinement. These methods make it possible to precisely control the chemical as well as electrical characteristics of graphene and create potential for specialized applications. The article additionally discusses graphene's many uses in fields such as flexible electronics, batteries, field effect transistors, photonics devices and touch screens. By combining insight from theoretical and applied research, this review article tries to provide a comprehensive knowledge of graphene's multifaceted nature and its innovative impact on improving modern science and technology.

Keywords:
Graphene, nanotechnology, Plasmonic, Terahertz Technology, Flexible electronics.

Introduction

To gain a comprehensive understanding of the history of graphene, it is crucial to investigate the foundational concepts of carbon, diamond, graphite and graphene. These materials are not only central to its discovery but also play a significant role in its subsequent scientific and technological importance. Carbon, a fundamental element in the periodic table, is one of the most versatile and abundant natural elements. Carbon's distinctive capacity to form stable covalent bonds with other atoms facilitates the formation of a wide array of structural configurations, referred to as allotropes. Notably, the sp^3 and sp^2 hybridized allotropes namely as diamond, graphite and graphene which are particularly significance due to their extraordinary and often divergent physical, chemical and electronic properties [1, 2]. Diamond is a three-dimensional carbon allotrope with sp^3-hybridized atoms arranged in a tetrahedral structure, which confers exceptional hardness, thermal conductivity and optical transparency. Its strength renders it suitable for cutting, drilling and use as a gemstone; however, its insulating properties limit its electrical applications. Graphite is a carbon allotrope with sp^2-hybridized atoms arranged in two-dimensional hexagonal layers held together by weak van der Waals forces. This structure facilitates the sliding of layers, imparting lubricating properties to graphite. It has good electrical conductivity due to its delocalized electrons and is widely used in pencils, batteries and electrodes.

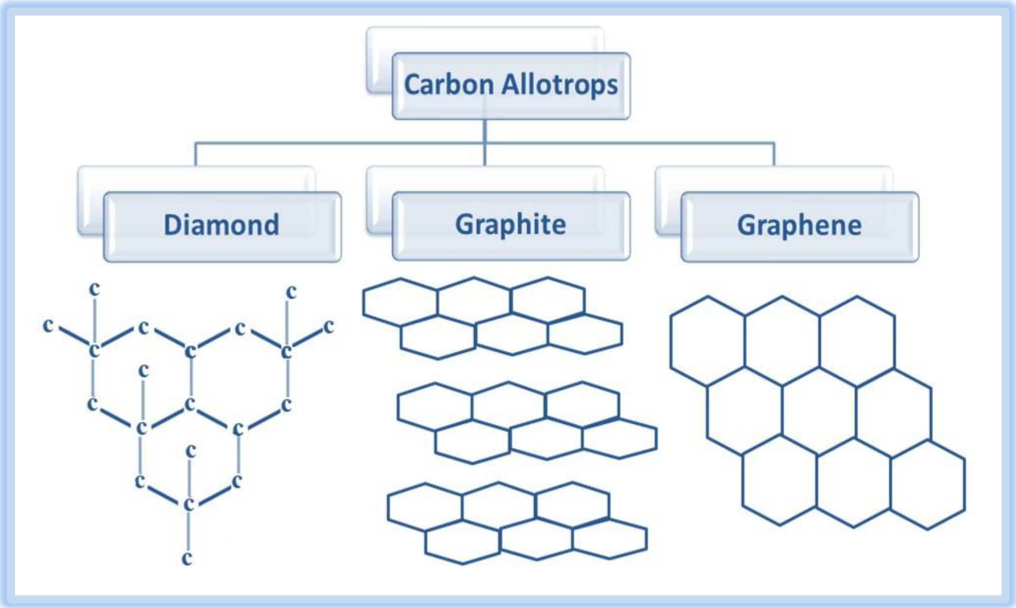

Fig 1: Schematic representation of carbon allotropes.

Graphene is one of the most revolutionary discoveries in the field of materials science. In 2004, professors Konstantin and Andre Geim of Manchester University presented their work on synthesis of a graphene monolayer by pulling off layers from bulk graphite [3, 4]. In 2010, they were awarded the Nobel Prize for this discovery. The mechanical exfoliation method was employed for the creation of graphene. This technique utilized a piece of graphite, which is composed of many graphene layers joined by van der Waals forces. That's why after applying a piece of sticky tape to the graphite surface; the thin graphite layers were removed and these layers were put onto a substrate, like a silicon wafer. When the tape was taken off, graphene layers were visible. This procedure was carried out repeatedly to separate a single-layer graphene. Many technological breakthroughs and innovations have occurred in this progressive natural world, such as the discovery of graphene, which altered the evolution of electronics and photonics devices due to its unexpected light, electrical and mechanical properties [5, 6].

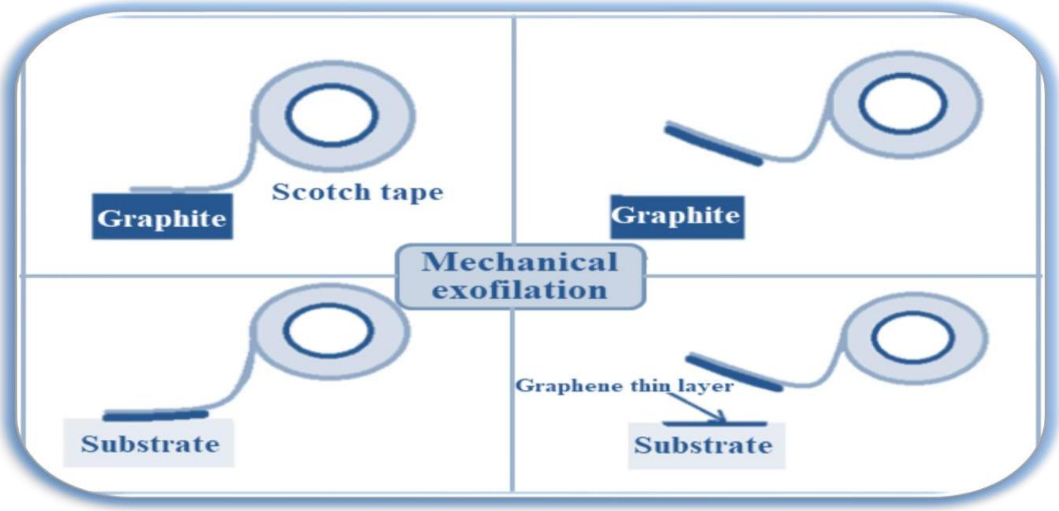

Fig 2: Mechanical exfoliation method for the production of graphene.

Graphene is a monolayer of a sp2 bonded c-atom with a repetition of hexagonal in each ring of hexagonal there are 6 carbon atoms attached and form a honeycomb-like structure. In it, every C atom has 4 valence electrons and 3 of them participate with their closest neighbors forming 3 sigma bonds making 1200 angles with each other. One valence electron is delocalized moves freely and lies perpendicular to the sheet creating π bonding [7, 8]. This delocalized pi bonding is responsible for graphene's electronic properties. Around each carbon atom, there are six Dirac points where the valence and conduction bands intersect, resulting in zero electron density at these points and no band gap [9].

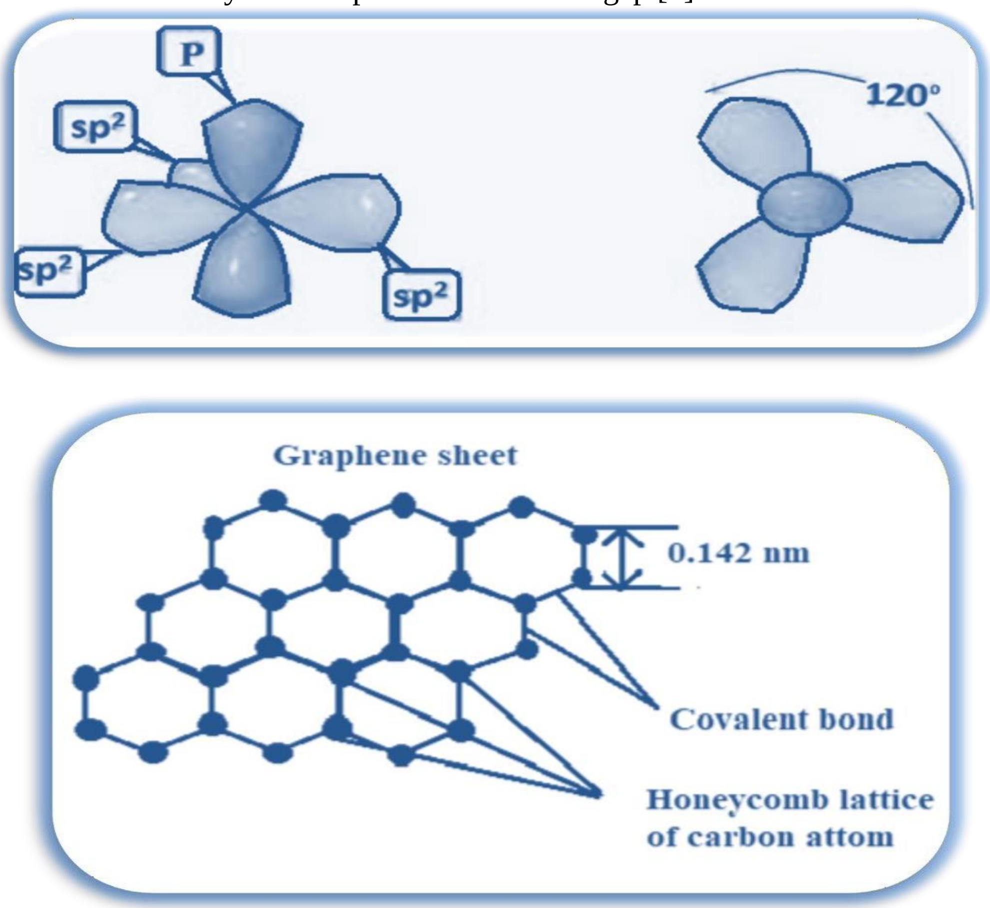

Fig 3: Graphene structure.

Single-layer graphene, bi-layer graphene, few-layer graphene, multilayer graphene, graphene oxide, reduced graphene oxide and graphene nano platelets are some of the different types of graphene. Single-layer graphene is one atom thick; bilayers contain two layers of graphene, few- layers include two to five layers and multi-layers include two to ten layers. Graphene oxide has a C/O atom ratio between 3.0 and 2.0, while reduced graphene oxide has a lower C/O atom ratio. In graphene doping is introduced by adding charge carrier in order to shift the Fermi level which increase its conductivity and enhance its electrical properties. This can be achieved using three important techniques: geometrical restriction, chemical doping and electrical gating. In geometrical restriction, geometric doping allows for the creation of geometric structures or limited regions that change the material's electrical characteristics. This may result in localized variation in carrier concentration that is impacted by edge effect and quantum confinement [11]. Nano ribbon is an example of geometrical doping in which nano ribbons behave as a semiconductor due to their ability to provide energy band gap. Chemical doping means changing the charge carrier concentration in graphene by introducing foreign atoms or molecules. This can alter the material electrical properties by donating or receiving electron. Dopants can be added via chemical reactions, vapor deposition or immersion. Acceptor molecules such as nitrogen and oxygen remove electrons and form holes and make p-type doping in graphene while donor molecules as metals supply electrons to increase the conductivity and raise the fermi level which is beneficial in electronics and sensor devices. In electrical gating an external electric field is applied in electrodes to change the density of charge carriers. In electrical gating an external electric field is applied in electrodes to change the density of charge carriers which shift the fermi level in graphene. In order to avoid direct contact, silicon dioxide as insulating layer is utilized b/w graphene layers [10]. This technique is reversible, enabling dynamic tuning with no permanent chemical changes, but its efficiency depends on the gate voltage and dielectric/insulating material's properties. These methods are beneficial in a wide range of applications and technologies such as in energy storage, high speed transistor, flexible electronics and energy storage devices. As shown below the doping is done in single and bi-layer graphene. Diagram (i) shows the un-doped single layer of graphene which has no gap. Diagram (ii) shows the doping in single layer graphene in which graphene has a band gap between conduction and valence band. Diagram (iii) shows the undoped bi-layer graphene which has no gap while in diagram (iv) there is gap in bi-layered graphene when doping is done in it [12, 13].

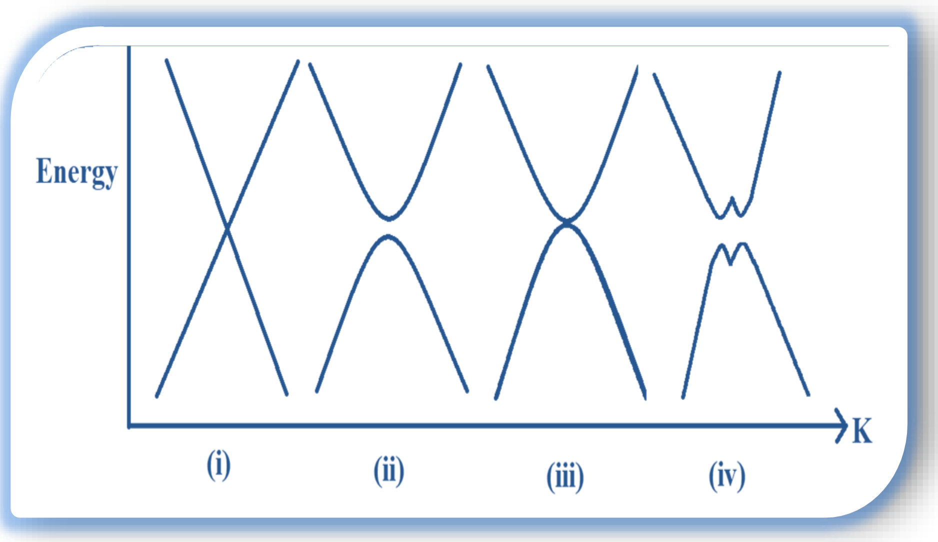

Fig 4: Schematic representation of doping in graphene

In the field of plasmonic, graphene has emerged as a material of immense interest due to its ability to support the propagation of surface plasmon polaritons (SPPs) with exceptional confinement and low propagation losses. The coupling of plasmons to the surface of graphene enables long-range surface wave propagation. The dynamic control of its optical and electronic properties, particularly through the manipulation of its chemical potential and carrier density, has led to significant advancements in plasmonic devices. Pioneering works by Nader Engheta and Ashkan Vakil have proposed graphene as an optimal material for the modulation of surface wave propagation, capitalizing on its tunable conductivity to govern the behavior of SPPs. A variety of graphene- based plasmonic structures have since been developed, enabling the regulation and engineering of plasmonic wave features, with the conductivity of graphene playing a central role in their design and performance [14, 15].

Properties of graphene

Graphene has emerged as a material of great interest to the scientific community due to its extraordinary properties. A single layer of graphene weighs just 0.77 mg per square meter, making it approximately one thousand times lighter than paper. Despite its lightness, graphene exhibits remarkable strength, with carbon-carbon bonds measuring just 0.142 nm in length. It surpasses steel in strength and, when incorporated into composite materials, enhances their durability while reducing weight [16]. Graphene is also harder than diamond, demonstrates outstanding electrical and thermal conductivity and possesses high flexibility, returning to its original form after deformation. The material boasts impressive electron mobility, ranging from 15,000 to 200,000 cm^2/Vs, surpassing most other materials and making it suitable for various electronic and plasmonic applications [17, 18]. A 1 mm thick sheet of graphite can contain approximately three million graphene layers. Graphite can be likened to a book, with graphene serving as its pages. Pencils, commonly used in everyday life, are made of graphite (containing bonded graphene layers). When the bonding is weak, drawing on paper results in graphene spreading across the surface [19]. The chemical potential Fermi energy, of a graphene layer, is determined by the number of charge carriers present and the Fermi velocity of the electrons. By altering the charge quantity through bias voltage or by doping, the chemical potential of graphene is adjusted, which represents one of the goals of the graphene for proper control over scattering behavior. It is observed that the peaks of dispersion curve shifted into the high frequency band as chemical potential increased.

Some graphene properties are as

1. Mechanical strength
2. Thermal property
3. Optical property
4. Electrical characteristics
5. Impermeable property

1. Mechanical strength of graphene

One of the material's notable features is its exceptional strength and maximum tensile strength. The carbon bonds in graphene, measuring 0.142 nanometers in length, contribute to its status as the strongest material, with a tensile strength of 130 GPa (or 130,000,000,000 Pa), making it highly stretchable and flexible. A square meter of graphene weighs approximately one-thousandth of paper, with a monolayer graphene weighing 0.77 mg per square meter [20, 21]. Graphene's elasticity allows it to return to its original size after stretching, withstanding elongation up to 20% without permanent deformation. This unique combination of strength and flexibility is uncommon in materials science, opening possibilities for applications in flexible electronics, wearable technologies and biomedical devices [22, 23]. The mechanical properties of graphene also enhance composite materials. Adding small amounts of graphene to polymers, metals ceramics significantly improve their hardness, tensile strength and fracture toughness while reducing overall weight. Researchers at Columbia University demonstrated graphene's strength, showing it to be 200 times stronger than steel by balancing an elephant on a pencil to a graphene sheet, as illustrated in the figure below.

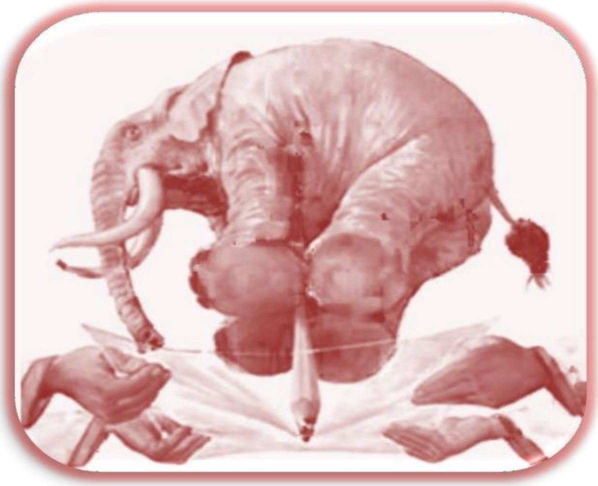

Fig 5: Illustrated the mechanical strength of a graphene sheet.

2. Thermal characteristics

Graphene's thermal properties are characterized by its exceptional heat conduction and dissipation capabilities, primarily due to its unique two-dimensional structure and strong covalent sp^2 bonds. At room temperature, graphene's in-plane thermal conductivity ranges from 2000 to 4000 W/mK, among the highest known for any material. This high thermal conductivity results from efficient heat transfer through phonon transport within the carbon-carbon bonds of its honeycomb lattice [24]. However, out-of-plane heat transfer is considerably less efficient, relying on weaker van der Waals forces between graphene layers or with the substrate. The interaction between graphene and substrate materials significantly affects thermal dissipation, involving interfacial phonon scattering that influences overall heat flow. Heat flow can be controlled by manipulating edges, interfaces and phonon scattering mechanisms, allowing for precise adjustment of thermal properties. These characteristics make graphene a revolutionary material for advanced thermal management solutions, enabling efficient heat dissipation in applications ranging from high-performance electronics to thermal interface materials [25, 26].

3. Optical characteristics of graphene

Graphene displays remarkable optical properties, primarily due to its unique electronic structure and two-dimensional atomic arrangement. A single graphene sheet transmits approximately 97.7% of incident light, absorbing only 2.3% and reflecting a negligible 0.1%. However, as the number of graphene layers increases, the optical transparency decreases due to cumulative light absorption in successive layers, making multilayer graphene less transparent. In optical devices, the concept of band transition is crucial. Graphene, as a zero-bandgap material, facilitates direct band transitions in its electronic structure. In a direct band transition, the conduction band and valence band are aligned at the same momentum, meaning electrons can transition between these bands without requiring additional momentum [27]. For optoelectronic applications like light-emitting diodes and photo detectors, this enables valuable photon emission with conserved momentum and energy. Conversely, conduction and valence bands that are mismatched in momentum are involved in indirect band transitions. In indirect transition by phonons interactions more energy is dissipated in the form of heat and light. Due to these scattering and energy dissipation in indirect transition which is less favorable for optoelectronics and photonic devices while in direct band transition less scattering and losses occurred with high transparency which makes it an ideal material for optoelectronic devices. These include modulators, ultrafast photodetectors, transparent electrodes and other electronics that require efficient and precise light manipulation [28, 29].

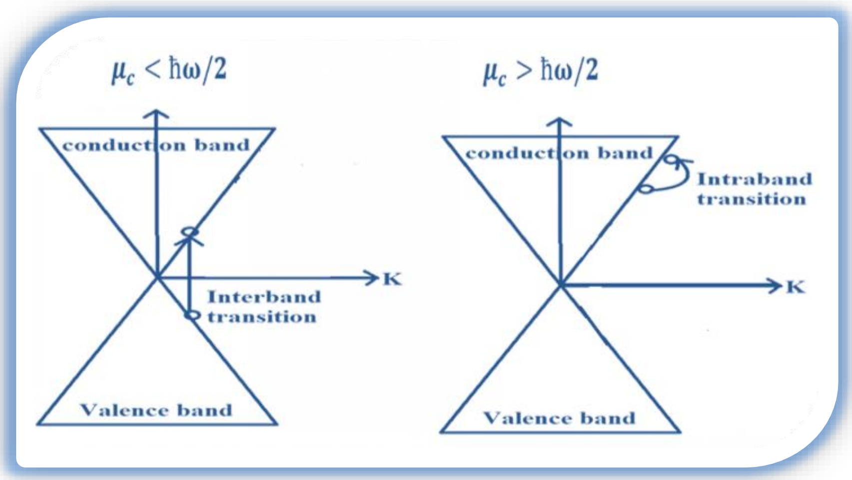

Fig 6: interbond and intrabank transition

4. Electrical characteristics

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, exhibits exceptional electrical properties that have garnered significant attention in the scientific community. The electrical characteristics belong to the major aspects associated with experimental investigation. One of the most significant aspects of early research was the constant, regulated transition of charges from hole to electron state. The quantum hall effect, which may be seen in semiconductor and conductor media, can arise because of the great electronic mobility of this material for both electrons and holes [30, 31]. Graphene's charge carriers behave as massless Dirac fermions, allowing for extremely high electron mobility. This property enables electron transport, with theoretical mobility values exceeding 200,000 cm^2/Vs at room temperature. Graphene can be continuously tuned between electron and hole conduction by applying an electric field. This allows for switching between n-type and p-type behavior with or without the need for chemical doping. While intrinsic graphene is not superconducting, it can exhibit superconductivity when doped with certain elements or in twisted bilayer configurations, opening up new avenues for quantum electronics. These extraordinary electrical properties make graphene a promising material for various applications, including high-frequency transistors, transparent electrodes, sensors and energy storage devices [32, 33].

5. Impermeable property of graphene

Graphene's single-atom thickness renders it an impermeable material. Its tightly bound carbon- carbon bonds in a two-dimensional honeycomb structure are primarily responsible for its exceptional impermeability, creating a formidable barrier that prevents most molecules from passing through. The strength of the sp2 hybridized bonds between carbon atoms is so great that even small molecules like helium, which typically pass through other materials, cannot penetrate a graphene monolayer. A defect-free monolayer of graphene has been demonstrated to be impermeable to most gases, including helium. Graphene oxide (GO), a chemical derivative of graphene, is utilized to create membranes with various specific barrier properties. A pristine monolayer of graphene is impermeable to all liquids and gases. Research has confirmed graphene's impermeability, showing its effectiveness as a barrier against various substances, including gases, liquids and nanoparticles. Studies indicate that a single graphene layer can block atoms and small molecules like nitrogen and oxygen while filtering larger molecules [34]. This impermeability makes graphene ideal for applications requiring strong containment or protective barriers, such as water purification systems, protective coatings for sensitive electronics and impermeable membranes for fuel cells or gas storage. It's important to note that surface defects, functional groups or vacancies can affect graphene's impermeability by creating pathways for molecules. Scientists are actively exploring methods to enhance graphene's barrier properties for various applications by controlling its synthesis, including chemical functionalization and multi-layer graphene structure formation [35, 36].

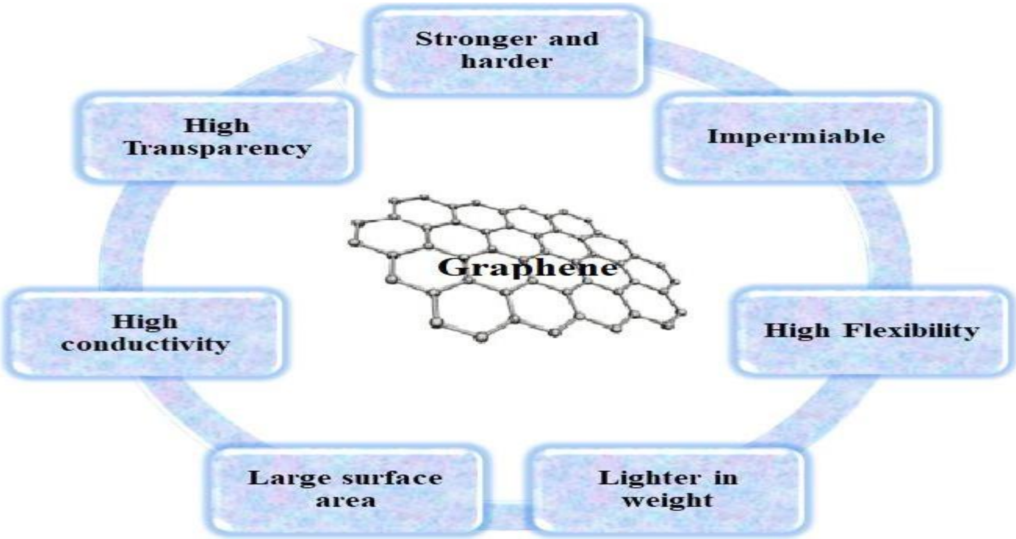

Fig 7: Graphene properties

Applications of graphene

Graphene has potential applications in various devices, including sensors, terahertz beam shifters, broadband THz antennas, modulators and optical broadband absorbers. Its unique electrical, optical and mechanical characteristics have led to advancements in energy storage, nanoelectronics and bioelectronics [37]. However, pristine graphene's zero energy bandgap poses a challenge, particularly in nanoelectronics, as it prevents graphene-based devices from achieving the necessary OFF and ON states for digital logic circuits. This limitation has increased interest in doping graphene to overcome these drawbacks. By introducing suitable dopants and concentrations, a tunable bandgap can be created, enabling graphene's integration into nanoscale electrical circuits and expanding its potential in future electronic devices [38, 39].

1. Photonics device
2. Field effect transistor
3. Flexible electronics and touch screens
4. Batteries
5. Communication system

1. Photonic devices

Graphene is employed in waveguides and plasmonic circuits to control and guide light at the nanoscale, which is crucial for miniaturizing optical communication and computing systems. Traditional devices made from silicon (Si) or germanium (Ge) face issues such as high-power consumption, wide bandgaps and low efficiency, limiting their performance. These issues can be addressed by developing nanoscale devices, where miniaturization enhances efficiency and reduces power consumption [40]. By overcoming the limitations of traditional materials like silicon and germanium, graphene is pushing the boundaries of photonic device capabilities, enabling applications in telecommunications, sensing and quantum optics.

Because of its remarkable electrical and optical characteristics, graphene is a great material for photonic devices. It can efficiently manipulate light due to its incredible variable conductivity, broadband light absorption and high carrier mobility which opens up new possibilities for a range of optoelectronic technologies [41]. Graphene's capacity to adjust refractive index and light absorption in optical modulators makes it perfect for fast speeds processing of signals in communication systems. Graphene is a great material for photodetectors that are capable of identifying light across a wide spectrum with quick response times. Graphene's strong light interaction, despite its atomic thickness, allows it to function as a broadband optical absorber, crucial for energy harvesting and photo-thermal applications. Though intrinsic light emission in graphene is limited, doping and hybrid structures with other materials can enhance its use in light-emitting devices like LEDs and lasers [42, 43].

2. **Field effect transistor** Graphene’s use in field-effect transistors (FETs) has gained significant attention due to its remarkable electrical properties, such as high carrier mobility and tunable conductivity. In graphene FETs, the material's unique two-dimensional structure allows for fast electron transport, enabling high-speed electronic devices. The integration of graphene into FETs also offers advantages like reduced power consumption and the potential for smaller, more efficient devices compared to traditional silicon-based FETs [44]. Graphene has an electrical conductivity of 107 S/m, thermal conductivity is 5000 W/mK, electron mobility is 105 cm2 /Vs and young modulus is

1.2 TPa while the silicon electrical conductivity is 103 S/m, thermal conductivity is 1300 W/mK, electron mobility is 103 cm2/Vs and young modulus is 1 Mpa. It is clear from these values of the several parameters that graphene is a material that beats the conventional semiconductors Si and Ge. However, graphene's lack of a bandgap presents a challenge in switching off the transistor, a crucial function for digital logic circuits. To address this issue, various methods are employed to create a tunable bandgap and modulate the Fermi level, including doping, utilizing graphene nanoribbons or applying an external electric field. These strategies enable the control of current flow in graphene FETs, making them suitable for applications in high-performance transistors, sensors and integrated circuits. The combination of graphene’s high conductivity, mechanical strength and flexibility further opens up opportunities for developing flexible, transparent and wearable electronic devices, making graphene-based FETs a promising technology for next- generation electronics [45, 46].

3. Batteries

A single sheet of carbon atoms organized in a two-dimensional lattice which is highly conductive. It is a perfect fit for batteries, especially lithium-ion batteries, due to its remarkable qualities, which include excellent flexibility, strength and electrical conductivity [49]. The effectiveness of energy storage devices is improved by adding graphene to battery electrodes. A higher density of energy storage is made possible by graphene large surface area, which can boost the battery's power and enhance its life. Additionally, graphene increases the discharge and charge speeds of batteries. Faster electron mobility is made possible by graphene's superior electrical conductivity over conventional materials, which speeds up battery charging and energy discharge. Furthermore, the high thermal conductivity of graphene assists in heat dissipation, lowering the possibility of overheating and enhancing battery safety [50]. Because graphene is lightweight, it helps batteries weigh less overall, which makes them better suited for uses like portable devices and electric automobiles. Moreover, graphene can be combined with other substances, like silicon, to improve battery performance. Increased energy capacity, quicker charging times, longer lifespans, enhanced safety and lighter weight are just a few advantages of using graphene into battery technology. Because of these benefits graphene is a potential material for the upcoming generation of energy storage [51].

4. Flexible electronics and touch screens

Indium tin oxide is typically utilized as a translucent, thin layer of conductivity. Indium tin oxide is rigid, brittle and not flexible. Indium tin oxide is failed for flexible electronics. Graphene has outstanding mechanical flexibility. Graphene has ten-time high flexibility as compared to indium tin oxide. So, graphene is used in transparent, bendable and rollable devices [47]. Due to high flexibility graphene is used in touch screen displays, transparent conductors, photovoltaics, transistors, organic light emitting diode and superconductors and batteries. Graphene is used in touch panel screens because of its transparency which is 90%. Because of its remarkable lightweight nature, mechanical flexibility and electrical conductivity, graphene is the perfect material for flexible electronics and touch displays. Because of its exceptional flexibility, it can be stretched and bent despite losing its conductivity, which makes it appropriate for use in stretchable sensors, wearable technology and flexible displays. For example, graphene-based touch displays provide higher touch sensitivity due to their high transparency and conductivity. Additionally, graphene's superior electrical qualities and excellent carrier mobility allow for greater resolution and quicker touch response times in touch screen displays [48].


5. Communication system

Optical communication networks were first introduced in the middle of the 1980s by 2 technologies laser and transmission sources and after 6 years introduced the silica glass fibers that transmit light waves but with loss of signals. The development of optical cables with light transmitters and receptors in 1970 allowed it to utilize them in data communication systems and telephonic systems but by utilizing these techniques more signals are lost. To overcome these issues graphene is incorporating in telecommunication system. Graphene's special qualities allow it to not only provide speed and cost advantages but also new features. As graphene exhibits both electro-refraction and electro-absorption, it can be used for photo-detection and ultrafast optical modulation [52, 53]. Silicon’s capacity to release and absorb light is limited by an indirect bandgap. This difficulty is overcome by using graphene. As graphene has a large operating bandwidth, it is appropriate for high-speed data transmission. Previously, optical communication photodetectors have been made of indium gallium arsenide and germanium, but their respective bandwidths are only 150 GHz for indium gallium arsenide and 80 GHz for germanium. On the other hand, Graphene has a bandwidth that is more suitable for use in optical communication compared to indium gallium arsenide and germanium. Graphene-based photo detectors have a 1.5 THz bandwidth and negligible optical loss at THz frequency range [54].

Conclusion

This review article provides a thorough introduction to graphene, its discovery and subsequent ascent to prominence as a material of great interest. After that, it dives into graphene's special structure, examining its atomic arrangement and how it relates to its remarkable qualities.

Graphene, with its unique remarkable characteristics, has become a paradigmatic material of the twenty-first century. Its exceptional mechanical, optical, electrical and thermal attributes are due to its structure, which consists of a monolayer of sp2 hybridized carbon atoms organized in a hexagonal lattice. Because of its many advantages, including as its remarkable toughness, strength, stiffness and its outstanding optical transparency, thermal conductivity and high carrier mobility, graphene is a material that appeals for a variety of applications. The review emphasized the many advantages that graphene provides, especially in areas like communication systems, flexible electronics and touch screens, field effect transistors, photonics devices and batteries. It is obvious that graphene will be crucial in determining the future of technology as research continues to solve its mysteries and discover its full potential. Undoubtedly, graphene will lead to new discoveries, stimulate the development of innovative technologies and pave the way to a more promising and sustainable future.

Ethical Approval

Not Applicable.

Conflict of interest

The authors declare no conflicts of interest.

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