2021
8(2), 51-63

Journal of
MATERIALS NANOSCIENCE

Graphene - properties, production and rising applications: A review

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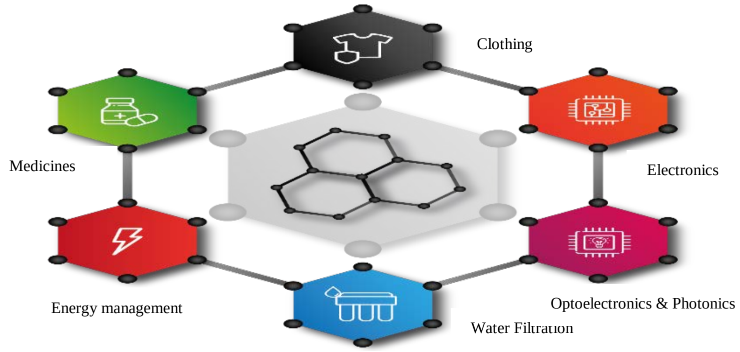
Submitted on: 05-Jul-2021, Accepted and Published on: 31-Aug-2021

Tutorial Review

ABSTRACT

Out of all the 2D materials discovered until now Graphene has been the extensively explored material. Graphene is a two dimensional-sp^2 bonded, single-layer membrane of a carbon atom tightly bonded in a hexagonal honeycomb lattice. The layers of graphene are piled up to form graphite. The single layers of graphene are held together by weak Vander Waal forces in graphite, which are then separated by exfoliation of graphene from graphite. Graphene has marvelous electrical, mechanical, and optical properties which makes it suitable for use in many modern technologies towards an excellent replacement to the other materials used by the industries. The remarkable properties and nature of graphene makes it a very promising material for the future. This review discusses about fundamentals of graphene, properties that makes graphene an extraordinary material and its vast number of applications.



"Due to the unremarkable properties of graphene and feasible production methods, it is an emerging star in various sectors of technology."

Keywords: Chemical Vapour Deposition, Graphene oxide, Indium Tin Oxide, Field Effect Transistors, Personal Protective Equipment

INTRODUCTION

The field of elemental two-dimensional (2D) has been an emerging area in development of new materials. These materials have been interesting for researchers due to their outstanding physical and chemical properties in comparison with their bulk counterparts. The 2D materials came into existence in the year 2004 when Andre Geim and Konstantin Novoselov discovered graphene and subsequently they won the Noble Prize for Physics in 2010.

Multi-layer graphene is formed by single layers of graphene held by weak Vander Waal forces in graphite.[1] Graphene is the thinnest (with one square meter of area), lightest (around 0.77 milligrams) and the strongest material discovered.[2] It possess excellent conductivity and thermal conductivity, and it has been referred as "black gold" by scientists.[2] Graphene has an impressive mechanical property that makes it stand out as a reinforcing agent in composites and in fact it has a high stability due to sp^2 bond that forms a hexagonal lattice. Strong and anisotropic bonding along with the low mass of carbon atoms gives graphene and other 2D materials a distinct thermal property. The potential difference developed at the ends is perpendicular to the current direction and the magnetic field, which specifies its unique carrier property and outstanding electrical properties. Graphene absorbs a significant amount of incident light and hence even though graphene is only one atom thick, it has unusual Optical properties. Defects in graphene structure have been known to alter these properties in one way or another. To reduce these defects various nanomaterial composites like nanoribbons, semiconducting materials of graphene, etc are formed.[3]

For the huge and feasible applications, big manufacturing and commercial availability of graphene are the prerequisites. Exfoliation of graphite to give graphene is one of the maximum promising approaches to large-scale manufacturing at an extraordinarily low cost. Chemical vapour deposition (CVD) is another

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URN:NBN:sciencein.jmns.2021.v8.263

ISSN: 2394-0867
https://pubs.thesciencein.org/jmns

useful technique and provides a high-quality monolayer of Graphene. The mechanism of producing the graphene is to synthesize the graphene film onto metal foils such as Cu by CVD, then the metal is removed.[4] Liquid phase exfoliation (LPE) has higher yielding, lower cost, shorter preparation time, and large-scale production, and hence is also used in the production of graphene.[5]

PROPERTIES OF GRAPHENE

Graphene has attracted a significant amount of attention from scientists all around the globe because the experiment conducted on it has resulted in it being of great mechanical, electrical, thermal property. The various properties of graphene that makes it it a special material has been discussed below.

1.1. Mechanical Property

Graphene has its existence as either monolayer attached to a substrate made of another material (mostly SiC or metal) or freestanding sheets, which means graphene sheets, are sufficiently isolated from their environment.[5] Taking into consideration the graphene without any dislocation or defects has an impressive mechanical property that makes it stand out as both individual material and a reinforcing agent in composites. Why this has an exceptional mechanical property, the answer lies in the fact that it has a stability of sp^2 bond that forms a hexagonal lattice. Lee and co-workers did the first systematic experimental analysis of the mechanical properties of a freestanding monolayer. In this experiment, a graphene membrane was mechanically deposited onto a substrate with arrays of circular wells with an atomic force microscope around it (or we can say Nanoindentation in an AFM).[6] Experimentally it was found that it shows both elastic property and breaking stress.

Apart from stress and strength, fractural toughness is one of the most important mechanical properties of graphene as it is a property relevant to the engineering applications. In the experiment conducted by Zhang et al.[7], they developed a micromechanical-testing device and a nanoindenter within a scanning electron microscope for the determination of the fracture toughness of CVD-synthesized graphene. Further, the central crack was obtained in the graphene membrane by using FIB, and hence a brittle fracture was observed when a load was applied. The fracture toughness of graphene was measured in critical stress intensity factor (KC) that came out to be 4.0 ± 0.6 MPa.[7]

However, the presence of various defects like vacancies, Stone-Wales defects, dislocations, and grain boundaries (GBs) are capable of crucially influencing its plastic deformation and fracture.[8] Some reports have shown variable values of stiffness probability arising from intrinsic crumpling of graphene in the out-of-plane direction of monolayer. The possible reasons for crumpling are either out-of-plane flexural phonons or static wrinkling, that are caused due to uneven stress at the Graphene boundary or point defects at a finite distance, such as the Stone-Wales defect.[9] The experimental results of Nicholl et al.[10] were in accordance with Ruiz-Vargas et al.[11], who reported the decreased stiffness of crumpled CVD graphene by using nanoindentation measurements. Zandiatashbar et al[12] have investigated the effect of different defects on the stiffness and intrinsic strength of graphene. Modified oxygen plasma technique was used to induce defect, while AFM nanoindentation was used for the quantification of stiffness and strength of defective graphene. Based on the $I_D/I_{D'}$ ratio of the Raman peaks the defects were categorized as sp^3-type or predominantly vacancy type, while the I_D/I_G and I_{2D}/I_G were used for quantification of the level of defects. Here the D and D' modes in the Raman spectrum are caused by the disordered structure of graphene and they are activated by a single-phonon inter-valley and intra-valley scattering process. The G-mode implies the doubly degenerate phonon mode at the Brillouin zone centre E_{2g}, while the 2D-mode comes from a double phonon scattering.[13,14] An intriguing picture came out of this, strength and stiffness of graphene were found to be maintained even at higher densities of sp^3-type defects, but the breaking strength was found to be 14% lower than the pristine graphene (in the sp^3-defect regime).

Table 1: Mechanical properties of Graphene

Properties	**Values**	**Properties**	**Values**
Young Modulus [6]	1TPa	Critical strain release rate [7]	15.9 J/m^2
Intrinsic strength [6]	130GPa	Poisson's ratio [15]	0.186
Fracture toughness [7]	4.0 ± 0.6 MPa		

1.2. Electrical Property

The Hexagonal lattice of graphene we have stated initially does not belong to the Bravais lattice section. It is divided into two equivalent carbon atom sites: A atom and B atom as shown in Figure 1. The lattice constant of carbon-bond length is 1.42 A^o and the lattice constant id is 2.460 A^o. The unit vector of the lattice can be written as:[16]

$$\boldsymbol{a}_1 = \frac{a}{2}\left(3, \sqrt{3}\right) \ , \ \boldsymbol{a}_2 = \frac{a}{2}\left(3, -\sqrt{3}\right) \tag{1}$$

The reciprocal-lattice vectors can be expressed as [16]:

$$\boldsymbol{b}_1 = \frac{2\pi}{3a}\left(1, \sqrt{3}\right) \ , \boldsymbol{b}_2 = \frac{2\pi}{3a}\left(1, -\sqrt{3}\right) \tag{2}$$

The electronic configuration of graphene is $1s^2$ $2s^2$ $2p^2$ where 1s electron is inert and does not contribute to the chemical bond. The 2s $2p_x$ $2p_y$ orbitals hybridise to form three new planar orbitals called sp^2 (i.e. 3 σ bonds).[17] The three orbitals are essentially directed along the lines with an angle of 120^o and hence form a hexagonal lattice structure. The p_z orbital of all the carbon atoms is perpendicular to the hybridization plane of sp^2. It forms a delocalized π bond in a side-by-side manner that runs over whole graphene.[16,18] Graphene is a system with one electron per lattice site as each p_z contributes one electron. This is called a Half-filled system. The energy spectrum originating from the pi-orbital has two energy bands, the valence band with lower energies and the conduction band with higher energies. The electrons in the conduction band and the holes in the valance band are together called electron-hole pairs. Electron and holes moving freely creates a directional motion under the applied external electric field to form a macroscopic current.[19]

Each unit lattice of graphene has six points at the corners, which is a group of three that are equivalent. Considering only two equivalent corners (***K*** and ***K***') points at the edge of the Graphene Bazillion zone in Figure 2, called Dirac points.[20,21] The coordinates of them in the momentum space are:

$$\boldsymbol{K} = \frac{2\pi}{3a}\left(1, \frac{1}{\sqrt{3}}\right) \ , \ \boldsymbol{K}' = \frac{2\pi}{3a}\left(1, -\frac{1}{\sqrt{3}}\right) \tag{3}$$

From the Figure 1, we can write the nearest neighbour vector in real space for A sub lattice.[16]

$$\boldsymbol{\delta}_1 = \frac{a}{2}\left(1, \sqrt{3}\right) \ , \boldsymbol{\delta}_2 = \frac{a}{2}\left(1, -\sqrt{3}\right) \ , \ \boldsymbol{\delta}_3 = -a(1,0) \tag{4}$$

In ordinary material, the dispersion relation is parabolic. In graphene, the dispersion relation is linear given as:

$$E = \pm \hbar \nu_f \, \boldsymbol{k} \tag{5}$$

Where,
ν_f → fermi velocity
$\hbar$ → reduced Plank's constant
E → energy
$k = (k_x + k_y)$ → 2D vector around the K point (where valence and conduction band touch each other) in the hexagonal Brillion zone.

As energy at the intersection point is linearly related to the wave vector ($E = \pm \nu_f \, p$) like the dispersion relation of a photon ($E = pc$) , the effective mass of an electron is zero and the hole and electrons are known as Dirac fermions.[22,23] The valence band and conduction band are represented in Fig. 3. From the figure, we can study no. of interesting and peculiar features. The intersection points where the valence band and conduction band touch each other are Dirac points. So, the energy gap of the graphene spectrum is zero. The valence band and conduction band represent a conical shape with negative and positive energy values respectively.

When the current flows perpendicular to the outer magnetic field through the conductors at room temperature, the mobility of pi electrons and the massless Dirac fermi characteristics allows for the occurrence of the Hall effect and anomalous quantum effect. The potential difference developed at the ends is perpendicular to the current direction and the magnetic field which specifies its unique carrier property and outstanding electrical properties.[24,25,26]

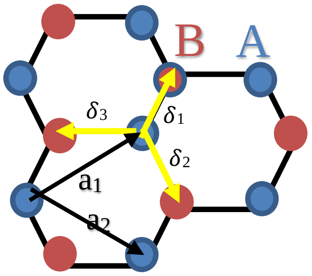

Figure 1: Structure of graphene [19]

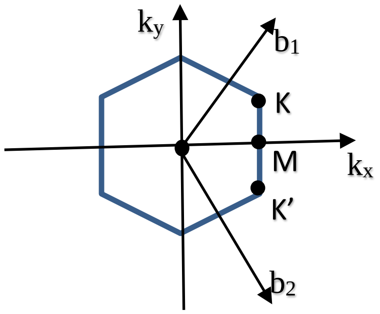

Figure 2: Graphene Bazillion zone [19]

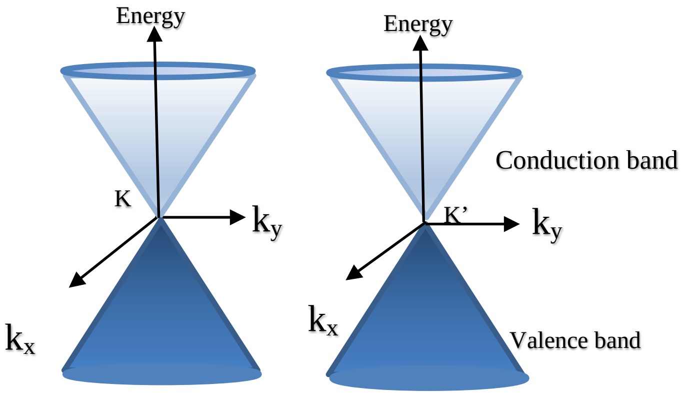

Figure 3: Conduction and valence band in the form of cone [19]

Defects in Graphene have been seen altering the Electrical Properties.[27] Considering the vacancy defect, one or more atoms are removed from the lattice. The energy required to knock out a single atom is 18-20 eV which is provided by bombarding ions in plasma or by electrons with an energy >86 keV, which is typically achievable in a TEM.[28] These vacancy defects act as strong scattering centers for the charge carriers in graphene, decreasing the localization length and disrupting the ballistic nature of electronic transport in graphene. In an impurity defect, vacancy is formed in graphene; one carbon atom is replaced by another atom of a different element filling the void. Zhao et al.[29] experimented with graphene with N impurities by adding ammonia (NH3) as a precursor (during growth process) and obtained Chemical vapor deposition (CVD). In a topological defect, the bonding angles between the carbon atoms are rotated.[30] One of the disclinations is a single disclination, the presence of a 5 or 7 ring that alters the regular 6-ring structure. Isolated disclinations are unexpected to develop in monolayer graphene because they require out-of-plane bulging of the graphene sheet and therefore have high formation energies. As two or more complementary disclinations combine to form a dislocation, the most frequently occurring dislocation is the Stone-Wales defect, which is composed of two 5-7 ring pairs.[31,32] An extended dislocation called grain boundaries (GB) is formed in graphene whenever two separate domains (grains) with different crystallographic orientations are linked together. GBs deteriorate the electronic transport in graphene as observed from experiments conducted on CVD-grown graphene.[30]

1.3. Optical Properties

Even though Graphene is only one atom thick, it has unusual Optical properties. Due to its appreciable electrical properties, Graphene absorbs a significant amount of incident light. In the case of normal incidence, the transmissivity T_G and reflectivity R_G of single-layer graphene are calculated to be

$$T_G = \left(1+\frac{\sigma_0}{2C\epsilon_0}\right)^{-2} = \left(1+\frac{\pi\alpha}{2}\right)^{-2} \sim 1-\pi\alpha \sim 0.977, \qquad (6)$$

$$R_G = \frac{\pi^2\alpha^2}{4} T_G \sim 1.28 \text{ x } 10^{-4}, \qquad (7)$$

Where σ_0 is the optical conductivity of graphene, ϵ_0 permittivity of vacuum and α is the fine structure.[33,34] The above equation implies that $1 - T_{G} = R_G \sim \pi = 2.3$ % of white light is absorbed by the Graphene layer.

Non-linear Optical properties: Assuming an instantaneous dielectric response on an isotropic material, the relation between induced polarisation ($P(t)$) and electric field ($E(t)$) is given by –

$$P(t) = \epsilon_0(\chi^{(1)}E(t) + \chi^{(2)}E^2(t) + \chi^{(3)}E^3(t) + \cdots) \qquad (8)$$

Where ϵ_0 is the permittivity of vacuum, $\chi^{(1)}$ is the linear susceptibility, $\chi^{(2)}$is second-order non-linear susceptibility and $\chi^{(3)}$ is the third-order non-linear susceptibility.[35,36]

Second-order non-linear susceptibility ($\chi^{(2)}$) is non-zero for the material that lacks inversion symmetry at the molecular level and as graphene being a honeycomb structure has an inversion symmetry; it does not possess second-order non-linearity. However, third-order non-linearity ($\chi^{(3)}$), is shown in graphene.[37]

Saturated Absorption: When the incident optical intensity is high, atoms in the ground state are excited into an upper energy state. Thus, saturation of absorption occurs as the rate at which the atoms decay back to the ground state is not enough for them to decay before the ground state becomes depleted, resulting in decreasing attenuation. In other words, at higher excitation intensity there is an increase in the photo generated carrier, which causes the states near the edges of the conduction and valence bands to fill, obstructs further absorption, and reduces the optical absorption.[38-40]

For Dirac fermions, the high-frequency dynamic conductivity is constant, so the optical absorption of graphene is independent of the wavelength. This potentially makes Graphene a great saturable absorber with a wide optical response to cover all telecommunications bandwidths and the mid-and-far- infrared.[38]

1.4. Thermal Properties

From the Fourier's Law, the Thermal conductivity (K) is given by $Q=-k\nabla T$ where, Q is the heat flux per unit area, ∇T is the temperature gradient. As K is related to the specific heat ($K \approx \Sigma C\vartheta\lambda$), where ϑ is average phonon group velocity, λ is the mean free path.[41] So as specific of graphene is dominated by phonon transport, Thermal conductivity is also dominated by phonon transport. A method of measuring K was experimented with using the non-contact Raman Optothermal method. [42,43] The Raman G peak is strongly dependent on temperature and is narrow. This high temperature dependence of G peaks allowed monitoring of the local temperature change.[44,45] Due to the atomic thickness of graphene, it limits the heat flux providing chance to use Raman Spectrometer with a conventional low power laser to measure high conductive crystalline materials.

The suspension of graphene over the trenches, fabricated on Si/SiO_2 substrates by reactive ion etching (RIE) is another essential consideration of this method and is necessary to determine the power dissipated in the graphene and ensuring the heat flux propagation along with a graphene layer towards heat sink.[46,47] Thermal conductivity observed is 2000~ 5000 W/mK for freely suspended graphene near room temperature using the Raman Optothermal method and is the highest value for any sample (Confirmed by other scientists also, Table (ii)).[42,46,47] For high quality exfoliated graphene thermal conductivity is 3000~ 4000 W /mK, whereas for high quality CVD polycrystalline graphene is 2500 W/mK.[48]

Experimental values are not always accurate they show some discrepancy because of the presence of defects. The range of measured values are influenced by the following reasons: accuracy in measuring is limited by error in experimental techniques, presence of strain and stress (mechanical) in the suspended samples and due to sample quality and geometry differences.[49]

Table 2: Different methods confirming the thermal conductivity value[50]

Reference	Method	Thermal conductivity
Balandin et al [41]	Optothermal Raman technique at room temperature	~ 2000 W/mK
Ruoff et al [44]	Suspended monolayer graphene with various sizes in vacuum and gaseous environment using Optothermal method	(2.6 ± 0.9) to $(3.1\pm1.0) \times 10^3$ W/mK
Yoon et al [48]	Obtained the value of residue-free graphene by thermal microscopy with improvised single to noise ratio for suspended graphene bridge at 335-366 K	(2430 ± 190) to (2100 ± 160) W/mK

PRODUCTION OF GRAPHENE

Ever Since the discovery of stable graphene sheets by Novoselov and Geim in 2004 [51], it has been an intelligent material with an ability to grow the industrial market. The one-atom thick carbon material has attracted great interest because of its excellent physical, mechanical, and chemical properties. Recent studies on a polymeric composite of graphene show an improvement in mechanical and electrical properties. Although there has been intensive research to find new methods for the preparation of monolayer graphene sheets in the last few years, the large-scale production of graphene remains challenging. Since graphene was discovered, various fabrication methods are being tried out to produce high quality, stable, defect free and cost-effective techniques. Some of the production methods that have left an impact are discussed below.

2.1. Mechanical exfoliation

The simplest method to obtain the graphene out of the graphite is Mechanical exfoliation, which led to Geim and Novoselov being awarded the Nobel Prize in 2010.[51] In this technique, graphene can be exfoliated from the big chunk of graphite layer by layer. For that the resistance between layers i.e. the van der Waal attraction between the layers needs to be overcome. Figure 4 shows that one can apply normal force to break this attractive force such as micromechanical cleavage by scotch tape or through exerting lateral force to give a relative motion to the graphene layers,).[52] The number of graphene layers produced can be assessed by a variety of methods, Raman spectroscopy, atomic force microscopy, and a simple optical microscope. This method is not suitable for large-scale production but is a good option for laboratory-based experiments.

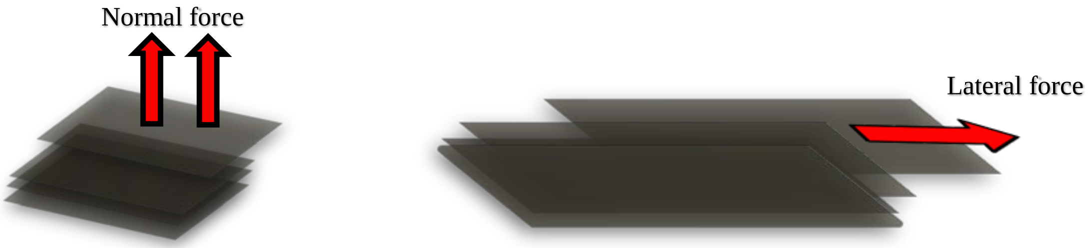

Figure 4: Mechanical exfoliation by applying normal and lateral force

2.2. Chemical Vapour Deposition (CVD)

CVD is the most useful technique and is used in producing industrial graphene layers. This method provides a high-quality monolayer of graphene. For a large area sample, the metal is exposed to different hydrocarbons already at high temperatures. The mechanism of producing the graphene is to synthesize the graphene film onto metal foils such as Cu by CVD then the metal is removed.[53] After that, graphene film is transferred to a substrate of interest and if needed the film is then doped for reduced sheet resistance. Due to the chemically inert nature of graphene, it is difficult to transform it from growth substrate to required substrate. Along with it, the transfer process brings defects and wrinkles in material. Moreover, thermal fluctuation can also inhibit the grown material's stability.[54] The CVD method requires low pressure around 0.1 Torr, which also can be carried out at ambient pressure.[55] Although Cu accounts for more than half of the cost still on an industrial scale removing Cu by chemical etching has been efficiently used to produce graphene. For the protection of graphene during the transfer, it is covered with a polymer film that is removed after the graphene film has been transferred onto the target substrate. There is another way, applying the adhesive between the target substrate and the graphene on Cu, which enables the Cu etching to leave graphene on the target substrate with the adhesive layer in between.[56]

2.3. Liquid Phase Exfoliation

Liquid Phase Exfoliation is another widely used method for the production of graphene. Compare to low-yielding processes such as micromechanical exfoliation and epitaxial growth on SiC, LPE has higher-yielding, lower cost, shorter preparation time, and large-scale production. Initially, LPE of graphite was done through sonication of graphite powder in N-methyl pyrrolidone (NPM).[57] Liquid Phase Exfoliation is done by two methods Sonication and High-shear mixing. Sonication is an effective way to produce monolayers of graphene at high concentrations. The power of sonication generates cavitation bubbles and induces physical and chemical changes into the system.[58] The occurrence of cavitation consequently results in high-speed micro jets and shock waves, which in return produces normal and shear forces on graphene.[59] This plays an important role in the exfoliation of graphene. In Sonication the production of graphene can widely be divided into 3 steps, firstly graphite is dispersed into a specific solvent, then the dispersion is exfoliated, and lastly purification of graphene.[60] The main factors on which exfoliation depends are the power of sonication, a liquid medium used, and centrifugation rate.[61] Higher concentration graphene can be achieved by longer sonication time, which consumes more energy, and by increasing the centrifugation speed, thinner flakes of graphene can be produced but have a very small lateral size which is not of much use in applications such as composites.

Another method through which graphene can be exfoliated is High-shear mixing. In 2014, Coleman and his colleagues did a great job in the advancement of the production of graphene by shear extraction,[57] which was a very encouraging development of a method of shear exfoliation. They showed that high shear mixing of graphite in the suitable liquid can result in a highly concentrated dispersion of graphene nanosheets. Graphene flakes thus obtained were unoxidized and had no basal-plane problems. Significantly, exceeding the local shear rate further than 104 s^{-1} resulted in exfoliation of graphene in both turbulent and laminar regions.[62]

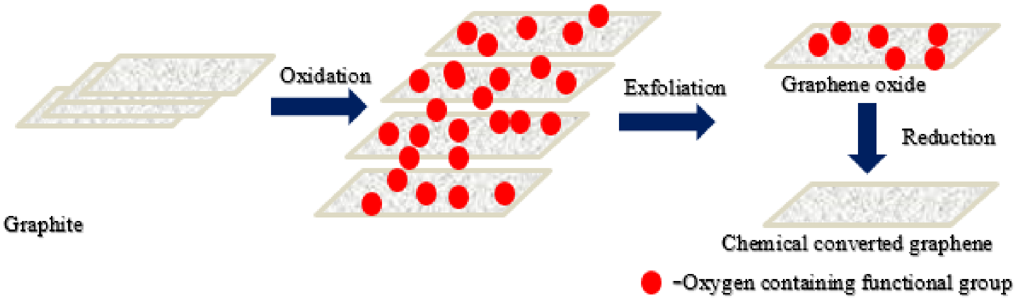

Figure 5: Production of graphene after reduction of graphene oxide [69,70]

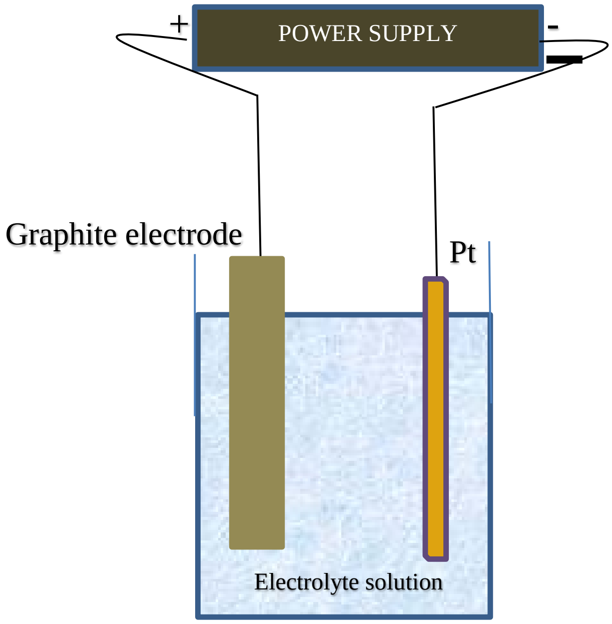

Figure 6: Electrochemical exfoliation for graphene production [70]

2.4. Electrochemical Exfoliation

This method requires an electrolyte and an electric current, which consumes an electrode of graphite (Fig. 5). [63 64] Further, graphite is oxidized to produce hydrophilic graphite oxide, which by sonication are separated as graphene exfoliated sheets. Graphene oxide gets hydrophilicity character from the oxygen functional group such as –OH, -COOH, and C-O-C, which are removed in chemical reduction.[65] Graphene becomes well dispersed because of the electrostatic repulsion induced between graphene sheets by ionization of the remaining –COOH and –OH in alkaline conditions.[66] This method has a privilege over other methods as it is a single-step method and does take less time, but the graphene thus produced through this method has a lot of oxygen functional group and structural defects.

Various reducing agents like hydrazine monohydrate, hydroquinone, and sulphur-containing compounds can be used to remove the oxygen-containing group from graphene (Figure 6).[67,68,69,70]

GRAPHENE: THE WONDER MATERIAL THAT CAN CHANGE THE WORLD.

The discovery of graphene has ignited an intense level of research work, global activity, and popularization of graphene in the commercial sectors. Various Research labs and graphene-oriented councils as well as organizations are analysing graphene so that they can give birth to a graphene-centred technology that will be more efficient and reliable and yet no one knows what kind of technology wave it would be. We are going to look at some of the recent discoveries that will give us an idea of how powerful graphene is and how it can lead us into a better future.

3.1. Graphene in Medical treatment.

New technology added in medicinal drug open up new horizons for our knowledge of disorder entities and is stimulating extraordinarily powerful diagnostic and healing algorithms. Due to its specific properties, graphene can be viewed as a prospect for various applications in biomedicine. In addition to examining possible ways of using graphene and other nanomaterials in medicine, the safety of their interaction with the human body is also examined.[21]

In vitro and in vivo studies showed that small nanosheets of graphene oxide has the potential to impair of locomotor behaviour in a rat model having Post Traumatic stress disorder (PTSD).[71] In this model, a single dose of s-GO nanosheets administered in order to prevent excitatory neurotransmission from long term enhancement and act as act as synaptic and behavioural modulator.[72]

In medical science, new treatments and clinical solutions, which can selectively target only Cancer stem cells (CSCs), are in demand .[73] Graphene oxide facilitates this selective nature. It can inhibit tumour spheres or onco spheres in 6 independent types of cancer cell lines.[74,75] Breast, Prostate, Ovarian, lung, and Pancreatic cancer can be cured. It has shown prominent results in curing glioblastoma (brain cancer) also. GO targets the highly conserved phenotypic property of CSCs. GO flakes can also be used to remove the peritoneal cavity and tumour excision site of left-out CSCs to avoid tumour reoccurrence.[76]

Recently, graphene-based nanomaterials have been extensively studied for various biomedical applications, e.g. for blood biomarkers, carrier therapy, drug delivery, diagnostic development at the treatment site, vaccines, separation of bacteria from water and detection of viruses such as Ebola hepatitis C. virus, H9N2 bird flu, etc.[77-83]

3.2. Energy Management using Graphene.

Heat and Energy management has become important in various fields. To increase the life and efficiency of instruments and electronics, excessive heat generation must be prevented. Hence, technologies with high power heating density are required. This will increase the performance, reliability, and lifetime of electronics.[84,85] Heat management can be done by using materials with high thermal conductivity. Devices generally have Al, Cu because they have relatively high thermal conductivity and are cost-efficient.[86,87] But when these materials are fabricated in structures having a thickness in the nanometre range, their thermal conductivity is not enough as there is a linear relationship between thermal conductivity and thickness.[88] Graphene is one of the prominent and practical solutions to this problem. Graphene has the required high thermal conductivity property.[89] Moreover, due to its strong bonding with numerous matrix materials, it is used with Phase change materials (PCMs) to form hybrid PCMs. These hybrid PCMs with graphene enhance the property of thermal conductivity further. These are promising applicants in reducing the temperature and enables thermal or power control in batteries and devices.

Researchers studied pool boiling of hybrid graphene/single-wall carbon nanotubes (SWCNTs), graphene and SWCNT films. These were deposited on surfaces of ITO; thereby proving that graphene and SWCNT have the highest heat transfer coefficient.[100] It was found that the critical heat flux (CHF) and maximum heat transfer coefficient (HTC) values of hybrid graphene/ SWCNT heaters improved by 18.2% and 55% respectively to that of ITO heaters. It was found in an experiment that structures having graphene-based filmed deposited on functionalized GO decreases the temperature of the hotspot by 17 ℃.[90] It was seen graphene nanosheets fabricated by graphene powder and sodium lignosulfonate (LS) using the ball-milling method supports high thermal conductivity.[91] Therefore, it is quite evident that graphene can be used as a substitute, and with it, Energy/ Heat management can go hand in hand with the growing technology so that we can have sustainable devices in the future.

3.3. Graphene based semiconducting nanostructures.

Electronic equipment and gadgets are advancing more and more with time. But we have reached the saturation limit of these materials. Now, it is becoming tougher to improve the quality of these devices further. The only way to upgrade the performance of the devices is by introducing a new material that has more capability of development and enhancement in nanomaterials. Graphene is that material. The main reason for facilitation in the technological sector is ohmic contacts. Recently, it was possible to make good contacts to form graphene 2D semiconductors [92]. The remarkable properties like high mobility, wide tunability carrier concentration, mechanical, thermal, optical, and electrical nature make it more suitable than the traditional materials we use today.[92,93]

In electronic devices, some would like to use graphene in sensors or transistors. Certainly, there is no bandgap in graphene and has small resistivity changes. One method to overcome this challenge is by carving graphene in narrow ribbons.[94] These graphene strips are long, thin, and have straight edges; generally known as graphene nanoribbons (GNR). These are 1D semiconducting graphene and can gently change from semimetals to semiconductors (i.e., bandgap is inversely proportional to these GNRs ribbons width).[95,96] This transformation happens due to the presence of edge effects and quantum confinement. The other way that researchers found to use this quantum confinement effect is to punch a graphene sheet having a high-density array of nanoscale holes. Thus, the structure that formed is known as graphene mesh (GNM). GNMs can be thought of as a highly interconnected network of GNRs. The most delicate properties of GNM structures are periodicity and neck width. By managing these two properties, we can obtain various structures that can replace the traditional devices as periodicity and neck width severely affects its electronic properties. Huang and Duan at the University of California, along with other researchers were able to develop uniform structures of GNMs with high controllability in the parameters using block copolymer lithography. In these structures, they were able to achieve periodicity and neck width versatility.[92] FETs oriented GNMs can have currents 100 times (approximately) more than the individual devices.[94]

Some researchers have created embossed graphene sheets using inkjet printing. They achieved high resolution and stable conductivity. Inkjet printing is considered as a possible method for fabricating graphene electronics over large areas. All these studies and researches are evidence all these graphene-based semiconductor materials promise more technologically enhanced electronic devices in the future.[92]

3.4. Graphene based Photonics and Optoelectronics.

The wealth of optical and electronic properties of graphene has gathered a lot of interest. Optical transparency, flexibility, strength, and high mobility has made graphene an attractive material. Already, usage of graphene has been made in elementary and electronics devices. However, researchers tend to believe that it can provide a great usage in photonics and optoelectronics. We can benefit from a combination of its exceptional optical and electronic properties.[97] However, the challenge is the fabrication at the wafer scale. The venture is to plan growth and manufacturing protocols supplying excessive mobility gadgets with dependable performance.[113,114]

Photoelectric gadgets which include displays contact screens, LEDs, and solar cells demand substances with low sheet resistance and excessive transparency. Currently, Transparent Conductors (TC) are based on semiconductors. The dominant material in these semiconductors is ITO,[98-100] which suffers limitations due to process requirements,[98,100] lack of indium, difficult modelling, and sensitivity to acidic and alkaline media.[98] In addition, ITO is very fragile and can simply wear out or crack after being used in applications that require bending, such as touch screens and multifunction displays.[101] This requires new TC materials with improved properties. Since the first attempt at GO-based TCF (Graphene Oxide-based Transparent Conductive films (GOTCF)), considerable progress has been made.[102] Various experiments have shown that when combined with doping, GTCF (Graphene-based Transparent Conductive films) derived from CVD flakes can outperform ITO.[103-105] The photoelectric response of graphene has been extensively investigated, theoretically and through experiments.[106-109] Graphene absorbs ultraviolet radiation to the terahertz range.[110-113] As a result, graphene-based PDs (photodetectors) can transmit a much wider wavelength range. The response time depends on the mobility of the user. Graphene has immense mobility.[114] Hence, GPDs (Graphene-based photodetectors) may be ultrafast. Recently, a graphene-based touch screen was reported on CVD samples cultured by screen-printing. GTCF can be combined with a high level of surface uniformity to meet the requirements of resistive touch screens.[102]

Future efforts on nonlinear optical devices can concentrate on demonstrators at very different wavelengths to exploit graphene's ultra-wide broadband capability. Ultrafast tuneable lasers have become a reality, and more and more laser groups have entered the field. The mix of graphene photonics with plasmonic might alter a range of advanced devices.[97]

3.5. Fabrication of protective clothing using graphene.

Personal protecting vesture is meant to shield the user from numerous hazards (mechanical, biological, chemical, thermal, radiations, etc.) and adverse environmental conditions.[115] First responders (medical professionals, law enforcement, national defence, paramedics, and firefighters) play a fundamental role, in case of emergency things like natural disasters, pandemics, forest fires, or terrorist attacks. They will subsume various hazards, starting from chemical, mechanical, biological, physical to electrical, and place themselves at high risk of hurt or maybe death at work. Protecting clothing act as a barrier and protect the wearer from health hazards, therefore is effective in decreasing activity injuries and economic loss. New textiles fabrics for protective clothing are increasingly becoming the subject of research.

Most of the PPE article of clothing that is used nowadays has serious weight issues, cause discomfort, reduced mobility, and torturesome sensation. Unpredictable service life is the main disadvantage of the present technology. It is vital to develop advanced lightweight and multifunctional PPE for the front liners.[117] Graphene and its derivatives will be wonderful candidates for protecting clothing with multi-functionality love like chemical protection, wearable sensing, flame resistance, and energy harvesting.[21]

Table 3: Key Applications of Graphene in different field

Area of Scope	Key Applications
Medical Treatment	Graphene-based substitutes proved to be an asset in treating PTSD, cancer stem cells, and in the detection of various viruses.
Energy Management	Due to high thermal conductivity, Graphene Carbon nanotube is a promising candidate for Heat and Energy management.
Semiconducting Nanostructures	Graphene nanostructures like GNMs and GNRs are widely used in transistors and sensors (or electronic devices).
Photonics and Optoelectronics	Using graphene, higher quality transparent conductors can be manufactured. These are used in photoelectric and optoelectronic devices.
Fabric or Clothing	Electronic graphene fabric is used in preparing personal protective clothing, which is more reliable.

In research in this field, researchers made a long-lasting multifunctional electronic graphene fabric for PPE to resist the shortcomings. The graphene on Cu foil was directly placed with a clear and versatile hot softened adhesive layer. The other facet of the adhesive layer was at the same time hooked up to focus on substrates within the commercially available roll laminator. Then, the Cu foil was removed to end the process. The large-area graphene was with success transferred onto the adhesive layer, which is powerfully bonded to cloth substrates. Graphene fabric exhibits wonderful electrical conductivity, comparable to graphene, which is indirectly transferred on SiO_2/Si wafers with far better mechanical stability. The triboelectric nanogenerator was produced, proving the practical use of the graphene e-textile industry. Chemical warfare agents have also been shown to demonstrate the practical use of graphene fabrics in multifunctional fabrics.[118] Hence, graphene-based intelligence can help in the manufacturing of protective clothing, which is more reliable and efficient.

CONCLUSION

The promising thermal, electrical, optical, and mechanical traits of graphene opens a huge variety of sectors for application like in medicine, electronics, photonics, thermal applications, energy management, machinery, clothing and so forth in which these properties can be manipulated depending upon requirement. The graphene proves to be an asset in altering the properties of materials. Graphene has shown this kind of ability that it may cause industrial dealing totally dependent on graphene in near future. No one knows what kind of technological wave awaits us in the future. But, what all realized is that it might be substantiated by graphene because it has low-price manufacturing and powerful end effect properties. Researchers are seeking to update conventional techniques with graphene-based strategies and the results are pretty encouraging.

ACKNOWLEDGEMENT

We would like to express our gratitude to our former Physics teacher Dr. Gurpreet Kaur Chahal for her support and guidance. With her encouragement and advice, we were able to complete this review article. The icons in the graphical abstract are by Freepik from

Flaticon. We would like to extend our gratitude towards our parents for providing us all the facilities that were required as well as the mental support that was needed in completing this paper during the pandemic.

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