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CONTEMPORARY DEVELOPMENTS IN GRAPHENE: SYNTHESIS & APPLICATIONS

Physics

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ABSTRACT

Graphene has emerged as a primary research area over the recent years. Its discovery has given a new dimension to research in material science and nanotechnology. Amongst several 2-dimensional materials, graphene has got attractive properties, having varied functionalities and applications across multitude of disciplines. This paper outlines and reviews the contemporary developments in graphene and materials based on graphene. The first part of this paper focuses on the developments in graphene synthesis. The next part describes the graphene applications such as lithium batteries, electrochemical sensors, etc.

KEYWORDS

Graphene; Two dimensional Materials; Graphene Oxide, Fullerenes, Carbon nanotubes

INTRODUCTION

The modern industrial society is based on 'material technology'. Carbon-based materials have come to assume a primary role in the advancement of human civilization. One of the best examples of carbon based materials is graphene.

Graphene can be described as a 'tightly packed two-dimensional structure' comprising of 'flat monolayer of carbon atoms like honeycomb lattice' and can assume varied structures. It may be enfolded into zero dimensional fullerenes. Fullerenes include honeycombed cylinders which are known as carbon nanotubes and soccer ball–shaped molecules known as buckyballs. Fullerenes further may be rolled into one-dimensional carbon nanotubes having only hexagons and no pentagon. Carbon Nanotubes are obtained by reworking of carbon bonds in uni-directional rolled graphene.

Graphene can also be transformed to a two dimensional graphite stack (A.K. Geim, 2007; Saito, 1992 a; Saito, 1992b). Graphene has specific material properties which are utilized in multifarious ways. The properties depend on the variations in "number of layers" and "defects". Graphene is identified as a semi metal having low band gap metallic layers (Santosh K. Tiwari, 2020; Y. Yang, 2015; K.S. Novoselov, 2004; S. Das, 2018). This property of graphene having very low "valence and conduction band" has proven to be very useful for the applied and fundamental research (Santosh K. Tiwari, 2020; Y. Yang, 2015; S.K. Tewari, 2016; S.K. Tewari, 2018). This is basically due to electrons and these electrons behave as massless relativistic particles.

Surface area of single layer graphene is higher than that of graphene oxide, graphene derivatives and carbon nanotubes research (Santosh K. Tiwari, 2020; Y. Yang, 2015; S.K. Tewari, 2016; S.K. Tewari, 2018). Due to these extraordinary properties, this material is treated as a perfect material for many modern technologies (Santosh K. Tiwari, 2020; Y. Yang, 2015; Liao 2014). Graphene has emerged as one of the primary cornerstones of condensed-matter physics showing exceptional 'high crystal and electronic quality'. Graphene has remarkable properties like less cost, high electrical conductivity, large surface area etc (J. Wang, 2017).

Graphene scores very high on the parameters of thinness and strength (Lee, 2008). It can sustain current densities six orders of magnitude higher than that of copper (Lee, 2011). Graphene has outstanding electrical properties with a high electrical conductivity of the order of 104 Ω−1 cm−1. (Lee, 2011) and it plays a significant role for next-generation technologies.

Graphene has excellent optical and thermal characteristics (Ye Ting, 2023). Graphene has high thermal conductivity around 103 W/m-K at room temperature (D. Akinwande, 2017; D. G. Papageorgiou, 2017). Graphene has got high transparency i.e. around 97.7% transmittance in the visible spectrum (J. Wang, 2017; A.K Geim, 2009). There is only less than 2.5% white light absorbance and less than 0.1% reflectance, making it highly transparent (Ye Ting, 2023). Both absorbance and the number of layers of graphene are related to each other. The absorbance increases rapidly with increase in the number of layers (Ye Ting, 2023). Graphene is structurally malleable and its different properties like electronic, optical and phonon properties can be strongly changed by strain and deformation techniques (V. M. Pereira, 2008). The "tensional strain effect" was examined by (V. M. Pereira, 2008) in the "electronic structure" of graphene. Strain can create a bulk spectral gap when there is no electron-electron interactions. Strain-induced anisotropy as well as local deformations are utilized as a resource to affect transport properties in graphene devices. (K.S. Novoselov, 2004; V. M. Pereira, 2008). Different properties of graphene are shown in Table 1.

Table 1: Properties of Graphene

S.No.	Properties	Graphene	Reference
1	Thermal conductivity	~5000W/m-K	(A. A. Balandin, 2008)
2	Specific surface area	2630 sqm/gm	(M. D. Stoller, 2008)
3	Young Modulus	~ 1 TPa	(Lee, 2008)
4	Current density	~1000000 m/s	(M. Dragoman, 2009)
5	Optical Transmittance	~ 97%	(R. Nair, 2008)
6	Mobility (typical) Mobility (Intrinsic)	200000 sqcm/V-s 100000000 A/sqcm	(X. Du, 2008) (M Y. Tianhua, 2010)

Graphene Synthesis

The outstanding properties of graphene sheets may be harnessed by manufacturing 'composites' using graphene. This requires production of graphene on an industrial scale. Graphene can be synthesized through various methods such as employing mechanical exfoliation, chemical vapour deposition, arc-discharge method.

These methods are also classified as bottom-up and top down approaches for synthesis of graphene (A. Santhiran, 2021) as shown in Fig. 1. In Mechanical Clevage process, graphite is broken down into a new material named as graphene and it is top-down approach. On the other hand, Chemical vapour deposition method (CVD) is bottom- up approach. Mechanical cleavage method utilizes mechanical exfoliation where graphite is repeatedly peeled. In this method, high purity graphene is obtained from graphite by breaking down weak van der Waals forces between graphene sheets using mechanical energy.

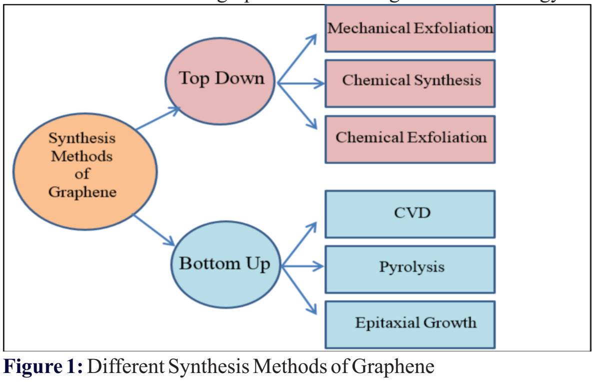

Figure 1: Different Synthesis Methods of Graphene

CVD involves insertion of hydrocarbon gaseous species in a reactor. It passes through a hot zone results into molecular degradation into carbon radicals and its deposition on the surface. The metal surface plays the role of a catalyst impacting deposition and synthesis mechanism of graphene (Y. Zhang, 2013). Epitaxially grown single- and few-layer graphene utilizing 'Chemical Vapour Deposition (CVD)' on metal substrates technique is also demonstrated (T.A. Land, 1992; Nagashima, 1993).

In 'Arc discharge method', gas or liquid medium is kept in a reaction chamber. The medium separates on passing of electricity producing plasma at high temperature. This helps to sublime the precursor (N. Arora, 2014). Li et al. described a water arc discharge system using a petroleum asphalt precursor (Y Li, 2013). This method is cost efficient due to the use of carbon rich asphalt and water medium and produce graphene at a lesser price.

Though graphene can be synthesized in multiple ways but only few methods are effective in obtaining graphene, fit for studying its electronic properties and use in sensing and bio-sensing electrochemical applications (Martin Pumera, 2010).

Graphene produced by mechanical exfoliation and CVD do not fit for mass production and applications (Jiping Zhu, 2014). For industrial production of graphene, chemical reduction of graphene oxide is considered a good method.

Graphene based polymer composites can be synthesized using “complete exfoliation of graphite” (Stankovich, 2006) and “molecular-level dispersion of individual” and “chemically modified graphene sheets within polymer hosts”. Krishnan et al. has obtained ≈100 layers graphite films (A. Krishnan, 1997). Thermal decomposition of SiC was studied further (Van Bommel, 1975; I. Forbeaux, 1998). Then films were analysed by studied by surface science techniques (Santosh K. Tiwari 2020; C. Berger 2004; C. Berger 2006). Castro et al has carried out deep study of graphene (Ah. Castro, 2009). The impact of 'electron-electron' and 'electron-phonon' interactions in graphene were discussed and both 'single-layer' and 'multi-layer' graphene were considered (Ah. Castro, 2009).

Applications

Graphene is very important for studying the electronic properties in different allotropes of carbon. Graphene has got attractive properties having varied functionalities and applications across multitude of disciplines. Its discovery has given a new dimension to research in material science and nanotechnology (Santosh K. Tiwari, 2020; S.K. Tiwari, 2016). It has attracted researchers in the different sectors like electronics, sensors, composite materials, medical science etc. (S.K. Tiwari, 2018; D. Shahdeo, 2020). This material has also got a broad area of applications like quantum dot devices, chemical sensors, thin-film transistors etc. (S.K. Tiwari, 2016; S.K. Tiwari, 2018; D. Shahdeo, 2020).

The paper outlines recent developments in graphene applications specifically focusing on applications in LIBs, optoelectronics, Nanoelectromechanical systems (NEMs) etc. Commercially viable micrometer sized uncoagulated crystallites of graphene can be obtained on an industrial scale. This makes usage of graphene-based composite material as a low cost alternative in a large number of applications (S. Stankovich, 2006). Due to the extraordinary properties, graphene has got a large number of applications. For e.g. it is used in energy storage, electronics, photonics and optoelectronic circuits. (V. Berry, 2013; Y. Zhao, 2013).

Also used in flexible, thin, display screens etc. (W. Han, 2014,; X. Yu, 2017; Y. Song, 2016). Graphene is of great use in energy-efficient applications (S. Jang, 2015; X. Wan, 2012; M. F. El-Kady, 2016; H. Y. Kwok, 2017; X. Cai, 2017; Q. Cheng, 2017; Q. Ke, 2016; W. Yang, 2015). Graphene can be used as “functional layers” in solar cells for energy efficient photovoltaic devices (R. Won, 2010; Z. Shi, 2017). Due to the remarkable properties of graphene such as electrical conductivity, strong mechanical and thermal strength, it can be utilized in various applications e.g. electrochemiluminescence sensor (Y. Han, 2020), solar cells (N.A.A. Ghany, 2017). Because of its high surface area, Graphene is applied in energy storage devices such as batteries and supercapacitors (M. F. El-Kady, 2016). At room temperature, since the carrier mobility of graphene is very high at room temp. this material is used in transistors too (F. Schwierz, 2010).

Nano-graphene has been used for photothermal therapy, drug delivery, biosensors etc. (K. Yang, 2016; A.Nag, 2018; S.M.Lee, 2015; S. Karoui, 2010; Y. Wu, 2011; K.Yang, 2010; B. Vestince, 2021).

Graphene for Lithium-Ion batteries (LIBs)

Graphene powder finds application in electric batteries. The battery efficiency is shown to be increased due to the use of graphene powder utilizing its high surface-to-volume ratio and higher conductivity (Lee, 2008). Graphene high surface to volume ratio can also increase energy storage capacity of a battery. Graphene can also enhance chemical stability, safety performance and also capacity of LIBs. (Pouria Nazari, 2024; Y. Mishra, 2024).

Graphene oxide is utilized in electrode for the purpose of enhancing the mechanical stability so that good life span of LIBs can be achieved. Carbon nanotubes can also be utilized as they have the same efficiency parameters but graphene powder scores over CNTs due to lower cost. Graphene can be used directly for electrodes due to its good excellent intrinsic electrical conductivity.

Graphene Application In Optoelectronics

Graphene also finds applicability in the field of optoelectronics (Kim, 2009; X. Wang, 2008). Optoelectronics deals with the study and applications of electrical devices which detect and regulate light. Graphene has great potential for solar cells and other optoelectronic devices because of its thin structure and 2-d flexibility (S. Das, 2019). Graphene has high transparency and conductivity due to which it can be used as the electrodes in solar cells. (M. Czerniak-Reczulska, 2015). Graphene coatings are flexible, chemically stable and robust. They can even be folded due to which are suitable for touch-screens and other applications requiring 'flexibility' and 'bendability'. Due to exciting optical and electronic properties, two dimensional materials have attracted attention of researchers.

Now a days, solar cells have played a great role in the production of large electrical power. They convert light energy into electricity (M. Stuckelberger, 2017). Graphene is used as electrodes to improve the efficiency of photovoltaic cells (Roy-Mayhew, 2014). Surface plasmon resonance biosensor is an example for optical biosensors and it is applied in medical diagnostics and also environmental monitoring. Graphene based coatings can be obtained by spinning or printing using suspensions. Alternatively films grown on Ni may also used for the coatings (Kim, 2009; A. Reina, 2009). They are a low cost alternative to the other traditional materials such as ITO (indium tin oxide) for application solar cells and liquid crystal displays (Kim, 2009; A. Reina, 2009). Graphene is shown to score over other materials on cost but faces a drawback, as it cannot be used in applications dependent on the level of resistivity.

Graphene application in Nanoelectromechanical systems (NEMS)

Nanoelectromechanical systems (NEMS) integrate on a nano scale “electrical and mechanical functionality”. Graphene is a promising candidate for numerous applications in NEMs. These applications might range from sensing to applications in field of biotechnology. Devices with greater functionality can be invented by merging both mechanical and electronic properties of graphene. Graphene has remarkable electronic properties which are combined with nanoscale moveable structures and it leads to the development of new devices which can interact with single atoms. Very good current carrying capacity and high thermal conductivity makes the use of graphene as interconnects in electronic chips, potentially replacing copper. Graphene has been shown to have utility as a base material for NEMS. (J. T. Robinson, 2008; J. S. Bunch, 2007). The essential prerequisite properties used in designing NEMs are 'Lightness' and 'Stiffness'. These properties are employed for sensing applications (J. T. Robinson, 2008; J. S. Bunch, 2007). Graphene NEMS have a bright future and research is ongoing to sightsee the possibilities offered by this material.

CONCLUSION AND FUTURE PROSPECTS

Graphene and its derivatives have got much attention as the basic and vital candidate for material science, nanotechnology, biomedical science, chemistry etc. Because of their extraordinary properties like high surface area, electronic, chemical and thermal properties. Graphene and its derivatives have been proven to be suitable for many commercial applications in various sectors e.g. nanoelectronics, composites, bioimaging, and nanomedicines. Functionalized nanosheets have “enhanced interfacial interaction” and “adhesive properties” with “microbial and human cells” leading to multifunctional bioengineering applications. Reductions in cost and attainment of higher purity have emerged as areas of further research. Commercial applications and research in different sectors like piezoelectric applications, microelectronics, optoelectronics, Spintronics, ultraviolet lens, radio wave absorption, waterproof coating etc. hold huge promise in the future. Comparative and competing nanosheets synthesized from materials like Germanene, Silicene, Phosphorene and Boron nitride can also be explored. It is found that in some cases, these nanomaterials are quite better than graphene. Further research on such nanostructures is in pipeline. Intense research and funding is required for their industrial-scale applications. These materials are new challenges for the researchers and also a great opportunity for further research and development.

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