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Review on Recent Advances on Synthesis, Properties and Application of Graphene and Graphene Oxide

Adewumi Hope Kofoworola[1], Abiodun Ayodele Joshua[2,] Ajiboye Joseph Olumide[1], Alarape Uthman Adeyemi[1], Oyeshola Hakeem Olayinka*[1], Adejumo Kehinde Ezekiel[1], Muka Peter Taiwo[1]
[1]*Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria*
[2]*Lead City University, Ibadan, Oyo State, Nigeria*
Corresponding author's e-mail: hooyeshola@lautech.edu.ng

Abstract
Graphene which is a single-layer carbon atom arranged in a hexagonal lattice has emerged as a revolutionary material with exceptional properties. Its extraordinary electrical conductivity, high mechanical strength and optical transparency have opened up new possibilities in various fields including electronics, energy storage and biomedicine. This review delves into the recent advancements in the synthesis, properties and applications of graphene and its derivative known as graphene oxide (GO). Different synthesis techniques, such as mechanical exfoliation, chemical vapor deposition, liquid-phase exfoliation and reduction of graphene oxide were discussed. The unique structural, electronic, optical, mechanical and thermal properties of graphene and GO were explored, highlighting their potential for various applications.

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I. Introduction

Graphene is a two-dimensional, ultra-thin sheet of carbon atoms arranged in a hexagonal lattice structure which began as a theoretical prediction in the 1940s through 2004 [1,2], Andre Geim and Konstantin Novoselov successfully isolated graphene experimentally which led to a groundbreaking achievement that earned them the Nobel Prize in physics in 2010 [3,4]. As the thinnest known material, with a thickness of just one atom, it has attracted significant interest across disciplines such as materials science and chemistry [5-8]. This discovery ignited intense research interest in its exceptional properties, including extraordinary electrical conductivity, high mechanical strength and optical transparency [9,10]. Graphene oxide (GO), a derivative of graphene has its roots in the 19th century [4,11]. It is produced by oxidizing graphite, introducing oxygen-containing functional groups onto its surface [12-15]. While GO lacks the pristine electronic properties of graphene, its hydrophilic nature and abundant functional groups make it versatile for various applications [16,17]. The material's high electron mobility, mechanical resilience and tunable optical properties in recent years have positioned it at the forefront of advanced material research [18]. Research on graphene and GO has accelerated focusing on advanced synthesis techniques, property enhancement and other professional applications[19-22]. This review provides a comprehensive summary of recent advancements in the synthesis, properties and applications of graphene and graphene oxide. It identified new synthesis methods that enhance scalability, cost-efficiency and environmental sustainability as well as to examine developments in the structural, electronic, thermal and chemical properties that make graphene materials unique. This review explored emerging applications across fields such as energy storage, flexible electronics, environmental remediation and biomedicine, emphasizing the transformative potential of graphene and graphene oxide in addressing contemporary technological challenges. It also identified major trends and existing challenges that will guide future research and industrial application of these materials.

II. Graphene Synthesis

The synthesis of graphene can be carried out in different ways such as mechanical exfoliation, chemical vapor deposition, liquid phase exfoliation and reduction of graphene oxide [23-27]. The process of synthesizing graphene from these methods is explained below involving either bottom-up (from atoms to nano) or top-down (from bulk to nano) methodologies [28-30]. The bottom-up methodologies include growth on SiC and on metals by precipitation, molecular beam epitaxy and chemical vapor deposition [31, 32]. The top-down methodologies include dry and/or liquid-phase exfoliation, unzipping of nanotubes and chemical exfoliation [33, 34].

2.1.1 Mechanical Exfoliation

Mechanical exfoliation, often referred to as the "Scotch tape method," is a straightforward technique for isolating graphene flakes from bulk graphite [35-37]. This method involves repeatedly peeling layers of graphite using adhesive tape, eventually resulting in single- layer or few-layer graphene flakes [38-39]. The first step is the selection of High-quality graphite, such as highly oriented pyrolytic graphite (HOPG) in order to ensure optimal results [40-42]. Adhesive tape is pressed onto the graphite surface to adhere to the top layer and then peeled off, carrying with it thin layers of graphite [43]. This process is repeated multiple times to obtain thinner and thinner layers. The graphene flakes produced on the tape can be transferred onto a desired substrate, such as silicon dioxide or glass [44, 45]. This method can produce high-quality graphene with minimal defects and is versatile for obtaining various graphene thicknesses, it suffers from low yield and inconsistent flake size, making it unsuitable for large-scale production. The mechanical exfoliation technique, while effective in producing high-quality graphene, is limited by its low yield and the difficulty in controlling the number of layers [46, 47]. However, recent advancements in techniques and equipment have led to improved control over the exfoliation process [35, 48]. The use of specialized adhesive tapes and optimized peeling angles has resulted in higher yields and larger graphene flakes [49]. The development of automated exfoliation systems has further enhanced the efficiency and reproducibility of this technique [50]. Mechanical exfoliation remains a valuable tool for fundamental research, its scalability limitations continue to drive the exploration of alternative techniques for large-scale graphene production [51].

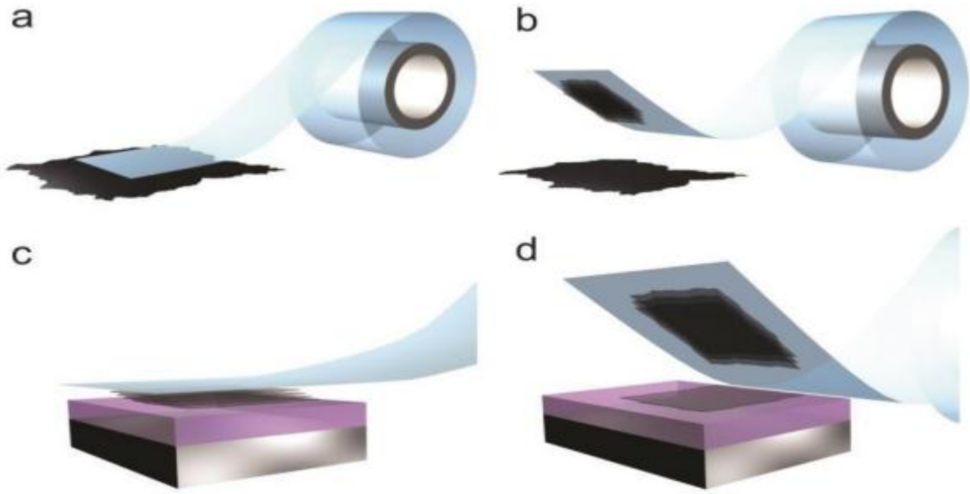
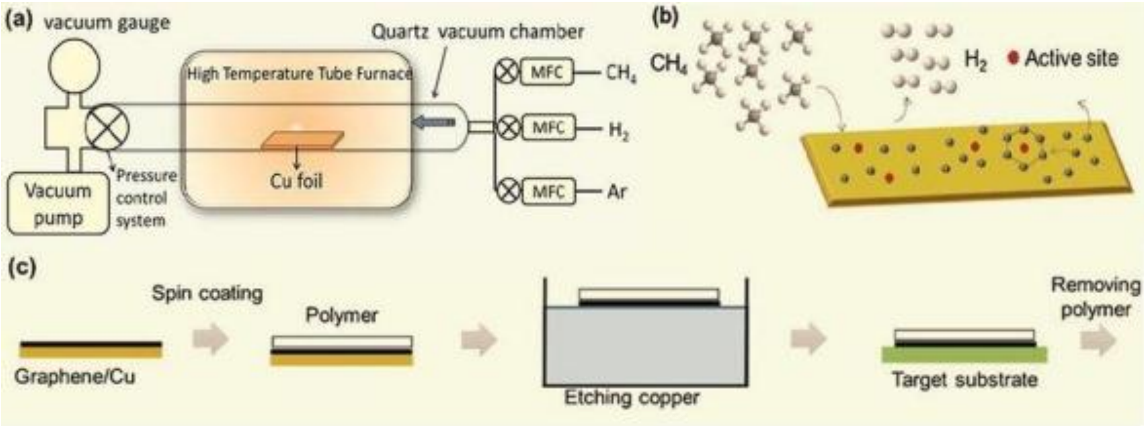


Figure 1: Step by step of a mechanical exfoliation process: (a) adhesive tape is pressed against a HOPG surface so that the top few layers are attached to the tape (b), (c) the tape with crystals of layered material is pressed against a surface of choice and (d) upon peeling off, the bottom layer is left on the substrate.

2.1.2 Chemical Vapor Deposition (CVD)

Chemical Vapor Deposition (CVD) is a versatile technique for synthesizing high-quality, large- area graphene films [52-54]. In this method, a carbon-containing gas precursor, such as methane or ethylene, is introduced into a reaction chamber [55, 56]. A suitable substrate, like copper foil or silicon carbide, is heated to a high temperature, typically around 1000°C, to initiate the thermal decomposition of the gas precursor [57]. Large area uniform few-layer graphene (FLG)/graphite films can be produced by dissolving carbon atoms decomposed from methane in a metal substrate at high temperatures and transferring them to glass slides for transparent thin conducting electrodes [58]. After cooling, the graphene film can be transferred to a desired substrate [59]. This method offers several advantages, including the ability to produce large-area, continuous graphene films with high electrical conductivity and mechanical strength [60]. However, it requires specialized equipment and high-temperature processes, which can limit its versatility and scalability. CVD is a reliable technique for the large-scale production of high-quality graphene [52, 54]. CVD is a poly-parametric process involving the carbon source, the type of the substrate, the auxiliary gases and the dynamic temperature–pressure relationships [61]. Recent advancements in CVD techniques include the use of catalyst-free growth and low-temperature processes. These advancements have led to the production of high-quality, large-area graphene films with improved electronic and mechanical properties [52].



Figue 2: Graphene synthesis via chemical vapor deposition (CVD): (a) Chemical vapor deposition reactor. (b) Growth mechanism of graphene on the copper substrate via deposition. (c) Schematic illustration of the transfer process of the graphene sheet; spin coating with a polymethylmethacrylate (PMMA) polymer, etching copper with $FeCl_3$, graphene on a PMMA support is transferred onto the Si/SiO_2 target substrate and PMMA is removed by acetone.

2.1.3 Liquid Phase Exfoliation

Liquid-phase exfoliation (LPE) is a versatile technique for producing large quantities of high- quality graphene [24,62]. The dispersion of graphite flakes to produce graphene involves overcoming the van der Waals forces between the graphene layers [63]. This is typically achieved by dispersing the graphite in a suitable solvent and applying mechanical energy through methods such as sonication or high-shear mixing [64]. Sonication and shear mixing are effective methods for exfoliating graphite into graphene by introducing significant energy into the system, which helps to overcome van der Waals forces [63].

Surfactants and polymers are being utilized to stabilize graphene dispersions and prevent reaggregation [65]. Post-treatment methods, such as centrifugation and thermal annealing, are employed to purify and functionalize graphene [66-68]. Most commercially available bulk graphene is made by milling graphite into powder and then subjecting the resulting particles to mechanical forces in a liquid solution to separate the powder into flakes, for example, by using sonication; flakes not shown to scale. The flakes are then sorted according to their size and thickness [35, 69].

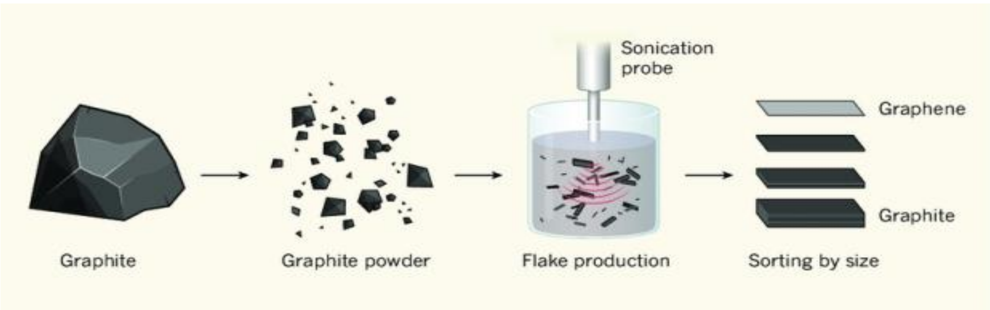


Figure 3: Liquid phase exfoliation of grapheme

2.1.4 Reduction of Graphene Oxide

Reduced graphene oxide (rGO) is a derivative of graphene oxide (GO) that has been partially reduced to restore its conductive properties [70]. This process involves the removal of oxygen- containing functional groups, such as hydroxyl, epoxy and carboxyl groups, from the GO structure [71]. Reduction methods include chemical reduction using strong reducing agents like hydrazine hydrate, sodium borohydride and vitamin C [72-74]; thermal reduction at high temperatures in an inert atmosphere; hydrothermal reduction in water at high temperature and pressure; and microwave reduction using microwave energy [75]. The choice of reduction method depends on factors such as the desired properties of the rGO, the scale of production and environmental considerations [76]. While chemical reduction is a common method, it can introduce impurities into the rGO and damage the graphene structure [78]. Thermal reduction can produce high-quality rGO but requires high temperatures. Hydrothermal and microwave reduction offer more environmentally friendly and efficient alternatives [79]. Microwave reduction also provides a rapid and efficient method for large scale production [80].

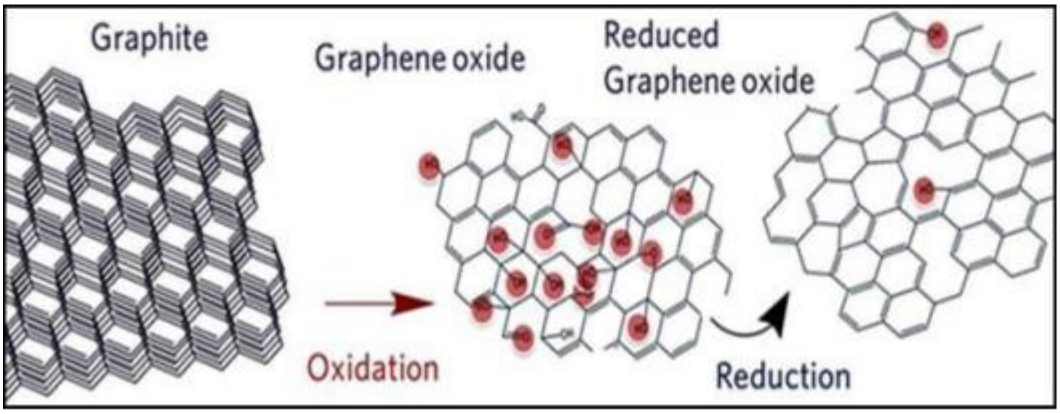


Figure 4: Reduction Process of Graphene Oxide

III. Properties of Graphene and Graphene Oxide Structural Properties

Graphene, a single-layer carbon atom arranged in a two-dimensional (2D) honeycomb lattice [81], possesses a highly ordered crystalline structure [82]. This perfect two-dimensional lattice contributes to its exceptional electronic and mechanical properties [83]. In contrast, graphene oxide (GO) has a more disordered structure due to the presence of oxygen-containing functional groups [84]. These functional groups disrupt the conjugation of the carbon atoms, leading to a decrease in electrical conductivity [85].

3.1 Electronic Properties

Graphene is a zero-gap semiconductor with unique electronic properties [86-88]. Its linear band dispersion near the Dirac point results in high carrier mobility and low electrical resistivity [89]. This makes graphene a promising material for high-speed electronic devices [90-91]. Graphene exhibits extraordinary electronic properties, including high carrier mobility and low electrical resistivity [92]. GO, on the other hand, is an insulator due to the disruption of the π- electron conjugation by oxygen-containing functional groups [93, 94]. However, by reducing GO, it is possible to restore its electrical conductivity to some extent, making it suitable for various electronic applications [95].

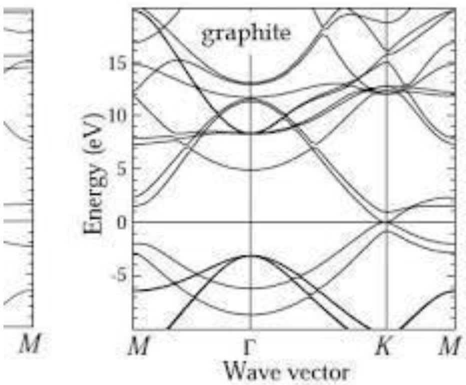


Figure 5: Graphene band structure

3.2 Optical Properties

Graphene exhibits excellent optical properties, including high transparency and strong light absorption in the visible and near-infrared regions [96]. This unique combination of properties makes graphene suitable for various optoelectronic applications, such as transparent conductive films, photodetectors and optical modulators. Graphene's unique optical properties, including its high transparency and tunable optical conductivity, make it a promising material for optoelectronic devices [97]. GO, due to its high optical absorption in the visible region, can be used as a saturable absorber for mode-locked lasers and optical limiters [98].

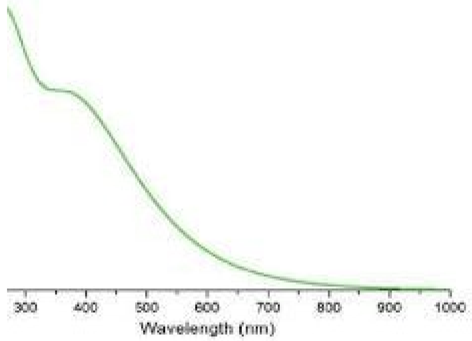


Figure 6: Graphene optical transparency

3.3 Mechanical Properties

Graphene been one of the strongest materials known has a Young's modulus exceeding that of steel [99]. This exceptional mechanical strength is attributed to its strong covalent bonds and two- dimensional structure [6]. It exhibits some mechanical properties which includes high strength and stiffness [100]. GO, while not as strong as graphene, still exhibits significant mechanical strength, particularly when incorporated into composite materials [101].

3.4 Thermal Properties

Graphene is an excellent thermal conductor [102], with a thermal conductivity higher than that of copper [103]. This high thermal conductivity is due to the strong in-plane covalent bonds and the efficient phonon transport in the graphene lattice [104], making it a promising material for thermal management applications [105]. GO, due to its disordered structure, has lower thermal conductivity compared to graphene [106]. However, it can still be used as a thermal interface material as well as thermal management applications [107].

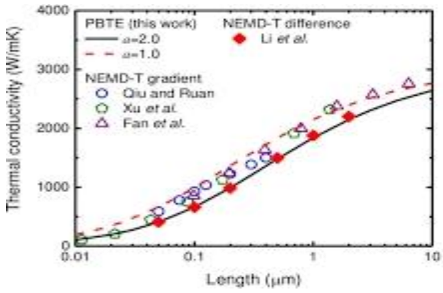


Figure 7: Graphene thermal conductivity

IV. Application of Graphene and Graphene Oxide

Graphene and Graphene Oxide has been explored in numerous areas of application which include but not limited to Electronics and Optoelectronics, Energy Storage, Composite Materials, Biomedical Applications, Water Filtration, Corrosion Prevention and Energy Conversion [108-110]

4.1 Electronics and Optoelectronics

Graphene's exceptional electrical conductivity and optical properties make it ideal for various electronic and optoelectronic applications, including high-speed transistors, sensors, flexible electronics and photodetectors [111-112]

4.2 Energy Storage

Graphene's large surface area and high electrical conductivity make it a promising material for energy storage devices such as batteries and supercapacitors. It can also enhance the performance of fuel cells by improving the efficiency of electrocatalytic reactions [113-115].

4.3 Composite Materials

Graphene can be incorporated into various composite materials to enhance their mechanical, electrical and thermal properties. Graphene-reinforced polymers and metal matrix composites have shown significant improvements in strength, stiffness and conductivity [116-118].

4.4 Biomedical Applications

Graphene and graphene oxide have potential applications in the biomedical field, including drug delivery, tissue engineering and biosensors. Their unique properties, such as large surface area and biocompatibility, make them suitable for these applications [20, 119]

4.5 Water Filtration

Graphene-based membranes can effectively filter water, removing contaminants and impurities. This technology has the potential to address global water scarcity and pollution issues [120]

.4.6 Corrosion Prevention

Graphene coatings can provide excellent corrosion protection for metal surfaces, extending their lifespan and reducing maintenance costs [121-122]

V. Conclusion

This paper reviewed recent advances on graphene and graphene oxide synthesis, properties and its application across various industries. Innovations in fabrication methods have enhanced scalability and quality, while the unique properties of these materials continue to drive breakthroughs in electronics, energy storage and environmental applications. The versatility of graphene-based materials positions them as pivotal components in future technological developments.

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