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Review

General overview of graphene: Production, properties and application in polymer composites

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ABSTRACT

Graphene is a new and exciting material that has attracted much attention in the last decade and is being extensively explored because of its properties, which have been described with so many superlatives. Production of graphene for large scale application is still a major challenge. Top-down graphene exfoliation methods from graphite, such as liquid-phase exfoliation which is promising because of low cost and high scalability potential will be briefly discussed. We also analyze the challenges and possibilities of using graphene as a nanofiller in polymer composites which has resulted in enhanced electrical, mechanical and thermal properties. In this review, we take a panoramic approach to give insight on the different aspects of graphene such as properties, graphite-based production methods and also examples of graphene application in polymer composites and which will be beneficial to both novice and experts.

Contents

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1. Introduction

Graphene was successfully exfoliated just over a decade ago [1]. The discovery of free standing graphene by Andre Geim and Konstantin Novoselov at the University of Manchester in 2004 led to the award of the Nobel Prize in Physics 2010 "for groundbreaking experiments regarding the two-dimensional material graphene" [2,3]. Since then, there has been tremendous interest from academia, industries and government institutions in exploration of graphene properties, production methods and potential applications [4–6].

Graphene is a two-dimensional single layer of sp^2 bonded carbon atoms arranged in a hexagonal lattice. These carbon atoms are bonded together at the length of 0.142 nm [7], as shown in Fig. 1. In other words, graphene is a building block for all graphitic materials. It can be wrapped into 0-dimensional fullerenes, rolled into 1-dimensional carbon nanotubes and stacked into 3-dimensional graphite, as summarized in Fig. 2.

The exceptional interest in graphene is not surprising given the various excellent mechanical and chemical properties exhibited by graphene, such as high surface area (2630 $m^2\,g^{-1}$) [8], excellent thermal conductivity (5000 $W\,m^{-1}\,K^{-1}$) [9], high electron mobility at room temperature around 250,000 $cm^2\,V^{-1}\,s^{-1}$ at electron densities of $2 \times 10^{11}\,cm^{-2}$ [10], very high Young's modulus 1 TPa [11], very high light transmittance ~98% [12], excellent gas impermeability despite only being single atom thick, chemical stability, anomalous quantum Hall effect (QHE) *etc.* [1,13–18]. Due to these properties, graphene has found a wide range of potential applications, from medical to paper to electronics to composite materials *etc.* [19–23]. Graphene can also be modified to generate a band gap that can lead to application in the semiconductor industry for developing devices such as transistors [21,24–26]. Due to all these unique properties, graphene has been often called a "supermaterial" or "miracle material" in the world of materials science.

Before the successful exfoliation of free standing graphene in 2004, scientists believed that two-dimensional materials could not exist independently because of their being thermodynamically unstable at finite temperature, and, therefore, would be expected to decompose, crumple or collapse into other stable carbon allotropes [27,28]. However, graphene is able to remain stable because of the atomic scale ripples that occur on the surface, acting to minimize surface energy [29].

2. Scope of review

The interest in graphene research from 2004 has increased exponentially. Several reviews about graphene have been published all with a different focus [15,27,28,30–34]. In this review, rather, we shall consider a panoramic approach of the synthesis methods of graphene (particularly from graphite), and some properties and application in polymer composites. When needed, the reader will be directed to a more detailed reference.

In the synthesis section, we consider only the methods that use graphite as a raw material. The second part briefly looks at the main properties of graphene. The last part includes a few examples of graphene application in polymer composites and how their properties are enhanced by graphene fillers. The economic aspect of graphene is also briefly considered.

3. Fabrication of graphene

One of the major challenges of graphene since it was discovered has been finding a fabrication method that can not only produce high quality graphene but also at large scale. Utilization of graphene by various industries depends mostly on finding fabrication methods for large scale production. The current lack of viable large scale production method has hindered large scale industrial application of graphene despite its excellent properties. Some of the methods that have been reported so far range from mechanical and chemical exfoliation of graphite include [1,20], epitaxial growth of graphene on silicon carbide (SiC) [35,36], titanium carbide (TiC) [37], tantalum carbide (TaC) [38], and different metal substrates, such as Ni, Cu, Pt, Ru, Ir, Co *etc.* [39–42], and graphene formed from un-zipping of carbon nanotubes [43–45], solvothermal synthesis [46], organic synthesis [47], chemical vapor deposi-

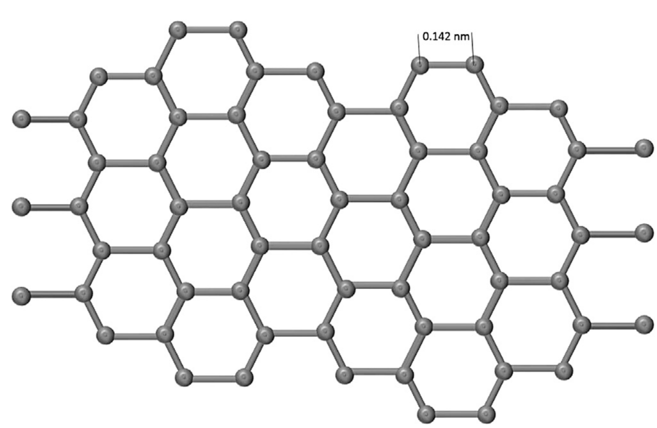

Fig. 1. Carbon atoms bonded in a honeycomb lattice, showing C—C bond length of 0.142 nm in graphene structure.