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Graphene: The Material of Today and Tomorrow

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Abstract

Graphene has astounding aptitudes owing to its unique band structure characteristics outlining its enhanced electrical capabilities for a material with the highest characteristic mobility known to exist at room temperature. Graphene, one-atom-thick, a planar sheet of carbon atoms densely packed in a honeycomb crystal lattice, has grabbed considerable attention due to its exceptional electronic and optoelectronic properties. Reported properties and applications of this two-dimensional form of carbon structure have opened up new opportunities for the future devices and application in various fields. Though graphene is recognized as one of the best electronic materials, synthesizing single sheet of graphene has been less explored. This review article aims to present an overview of the progression of research in graphene, in the area of synthesis, properties and applications. Wherever applicable, the limitations of present knowledge base and future research directions have also been discussed

Keywords: Nanomaterials; Synthesis; Coatings; Electronic materials.

1. Introduction

In 2004, two scientists, Konstantin Novoselov and Andre Geim successfully synthesized graphene which was assumed as a concept material that was not able to be manufactured in large quantity [1].

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Conversely, some synthesis techniques were reported after few years of the discovery of graphene and attracted many scientists to do more research about it [2,3]. Therefore, numerous reports were published in the following years from the synthesis to application of graphene [4,5]. In addition, graphene oxide and reduced graphene oxide have been studied extensively [6-8] Recently, graphene and graphene oxide (GO)-based coatings have been anticipated as anti-corrosive coatings for metals [4–8]. To date, several attempts have been made to synthesize graphene on a large scale to report the needs of various industries, specifically the composite industry, in which the use of graphene has dramatically transformed the global market for the production of up-to-the-minute composite materials. The addition of graphene to a host matrix has achieved a number of improved properties that has promising applications in various industries which include aerospace, electronics, structural, mechanical, energy, environmental, medicine, food and beverage. The extraordinary properties of graphene make it a “magic bullet” for the world of composites. There is large number of articles published on graphene graphene-based nanocomposites in recent years. According to the scientist named Geim [9], graphene research has reached surprisingly great height in the field of applied sciences mainly. A simple search tools like Science-Direct, Google scholar and web of science produces several thousands of papers only on graphene and its applications. The present review boons the current research trends in graphene synthesis and graphene-based nanocomposites. It describes related publications and applications of graphene and graphene-based materials. It also highlights previous reviews that have been published about graphene-based composites [10-13].

2. Synthesis Approach

After long and continuous efforts, a team of researchers headed by Novoselov presented a thorough research to develop easy and approachable method to synthesize graphene at laboratory scale [14-16]. This team repeatedly barked a graphite crystal with a help of an adhesive tape up to a specific limit and later transferred the thinned-out graphite onto an extremely thin (<300 nm) appropriately colored, oxidized silicon wafer [18]. This significant discovery directed to the onset of mass-scale production of graphene and its employment in various polymeric and applied industries. In the history of last forty years, various unsuccessful attempts have been made to achieve large-scale production of pure, defect-free graphene sheets [18]. Recently, the method of epitaxial growth on metal carbide, the CVD method, has shown promise for production of graphene [19-20]. Various methods have been devised and categorized into “top-down” and “bottom-up” processes. The following sections describe synthesis routes for graphene. The first approach may be considered as cost effective, which cruces mainly on the material employed. In general, it is limited to a lab scale only having lowered quality control aspects as it is hasardous [21]. In this approach, graphene sheets are synthesized by separation, peeling, or exfoliation of graphite or its derivatives like graphite oxide [22]. Scientists have got success in fabricating a few layers of free-standing graphene sheets on both micro and nano scales [21]. Though, this approach involves great investment and produces relatively less yield, the requirement remains for mass scaled-up production to address the need of industries economically. Various mechanical processes have been involved in producing high-quality, defect-free graphene: mechanical exfoliation of graphite, sonication, functionalization, electrochemical exfoliation, super acid dissolution of graphite, alkylation of graphene derivatives, chemical reduction of aqueous/organically treated graphene oxide (GO), thermal exfoliation, and chemical reduction of GO [23,24]. Potts and his colleagues reviewed in detail the synthesis of graphene by the exfoliation method [25]. He provided thorough insight into the procedures which was followed by various authors. In the same way, Daniel and his colleagues (2012) [26] reviewed and extensively outlined the synthesis of graphene via several routes and changed resources. Many articles are available online which outlined the review of graphene synthesis using the top-down approach [27] in detail. The second approach also known as bottom-up approach includes standard techniques like epitaxial growth which practices metallic substrates using CVD (chemical vapor deposition) [28–35] or organic synthesis [34,36], which counts on the choice of precursor chemicals and thermal degradation and decomposition of the SiC [35]. Numerous other processes, like arc discharge [42-45], chemical conversion [47, 48], CO reduction [49], CNT unzipping [50-52], and self-organization of surfactants [53–55] have also been tried for synthesis of graphene. Of all these processes, CVD and epitaxial growth [56], may in future be eye-catching for production of mass-scale graphene, in contrast to mechanical cleaving. Graphene sheets find their way into fundamental research with a multitude of applications ranging from electronics to polymeric nanocomposites by employing CVD and epitaxial methods [57]. Large scale production of graphene is also dependent on the chemical precursors used during synthesis. Particularly, graphite oxide (GO), chemically reduced graphite (CRG), and thermally reduced graphite (TRG) are key materials for polymer nano-composite solicitations [57-64]. As written earlier, the bottom-up approach using small molecule chemicals and catalysts are determining factors for the specific control of properties of graphene nanosheets [65]. Hydrocarbons can also be employed for the production of graphene via CVD process along with various metal catalysts [65-68]. Presently, Ni (69) surface is considered the best template for deposition of graphene. This is because of the small discrepancy in its lattice heterogeneity [69]. CVD is considered to be the most appealing technique for fabrication of graphene at a controlled level [69]. Though, this method faces a major challenge in the control of its morphology [69]. Epitaxial growth of graphene on a SiC substrate is another common technique, in which decomposition of SiC results in the formation of graphene layers.

2.1 Wide-reaching Study on Graphene

Ever since the discovery of graphene, this material has developed and completely redefined modern day technology because of its high known properties. The study has exponentially grown by numerous universities, R&D establishments, and many more private and governmental bodies around the world. Today research on graphene can be found in every discipline. In the present section, looking into current scenarios; an outline of a number of published works is provided, which illustrates the impetus in graphene research around the globe. The following sections briefly address the present scenario and the importance of graphene research today. The several review articles published through the recent years highlight the quality and quantity of graphene research on the basis of publications with an aim towards patent obtaining. Here, we make an effort to update this development and showcase the current growth of publications and patents. Using the Web of Science tool, a clear representation of the publication trend for graphene is shown, indicating the quantity of graphene research being carried out globally. Figure 1 shows the publication trend since the year 2008 (January) that the amount of research has grown exponentially from 0.92 million articles in the year 2008 to 5.43 million articles in the year 2017 (December). A total of 25,350 million articles were retrieved through this search using the syntax string <graphene>. Using the same tool (Web of Science), the results were further refined to assess the top research areas in which graphene is extensively used and the number of articles published since 2008

2.2 Graphene based Composites

The unexceptional properties of graphene in thermal, mechanical, and electronic point of view [72, 73], it stands out as the most favorable contender to be a major filling agent for wide range composite applications. Graphene nanocomposites at very low loading show considerable improvements in their multifunctional features, associated to conventional composites and their derivatives. This makes the material stronger and lighter in weight, so that it may be used in multidimensional applications [74,75]. The outstanding properties of graphene are able to improve the physicochemical qualities of the matrix/base material upon scattering. The interstitial bonds will be improved considerably because of the distribution of graphene in base material. It is this bonding that commands the emergence of the increasing possessions of graphene in reinforced nanocomposites [106]. Kuilla and his colleagues (2010), presented a broad review article on graphene-based polymer nanocomposites. His team has thoroughly explained the importance and use of graphene in several base materials. In addition, they also worked out on a remarkable comparison of various nanofillers and explained its applications in comprehensive way [76]. If we look in the world of composites, hypothetical analysis plays a vital role in understanding their molecular interactions, mechanisms and physical properties. A number of simulation tools gave growing results for composite analysis. With the help of these modern tools, a wide knowledge and guide to successful research can be obtained. A brief review regarding the processing of graphene nanoplatelets (GNPs) for fabrication of composite materials was placed by [77]. Mack and his colleagues (2005) prepared nanocomposites of polyacrylonitrile (PAN) nanofibers aided by graphene nano particles, having improved mechanical properties [78]. Study of Hansma and his colleagues (2007) showed successful fabrication of graphene-based nanocomposites. His team successfully optimized the amount and combination of adhesives and high-strength nanostructures (graphene) which were required to yield a strong, low-density, lightweight, and damage resistant composite material [79]. Ramanathan and his colleagues (2008) described an unprecedented shift in the glass transition temperature (Tg) of a polymer nanocomposite with additional graphene sheets as filler material. He observed that, by the addition of functionalized graphene sheets (1wt%) to the polyacrylonitrile (PAN), the Tg of the composite material increased considerably by 40∘C, whereas, when only 0.5wt% was added to polymethyl methacrylate (PMMA), they observed a 30∘C rise in Tg [80]. Also, they perceived that by addition of 1wt% graphene to PMMA, an 80% increase resulted in the elastic modulus and a 20% increase resulted in the ultimate tensile strength of the material. Their comparative research settled that monolayered functionalized graphene serves as the best nanofiller among all examined nanofillers [80]. Das and his colleagues (2009) employed the nanoindentation technique to the graphene-reinforced nanocomposite fabricated by using polyvinyl alcohol (PVA). The results showed significant improvement in crystallinity, elastic modulus, and hardness through the incorporation of only 0.06wt% of graphene. The authors summarized that the enhancement was because of close mechanical interaction between the polymer matrix and the layers of graphene. This interaction successively provides and dictates a better load transfer within the host matrix and the nanofiller [81]. Yu and his colleagues (2007) researched that epoxy based few-layered graphene nanocomposites show attractive properties for the electronics industry, ideal for development of thermal-interface-based materials [82]. Zhang and his colleagues (2009) and Liu and his colleagues (2009) successfully synthesized graphene-fullerene-based hybrid nanocomposites [83,84]. Booth and his colleagues (2008) studied the successful synthesis of robust 100 μm thick macroscopic graphene membranes that can bear heavy loads [85].

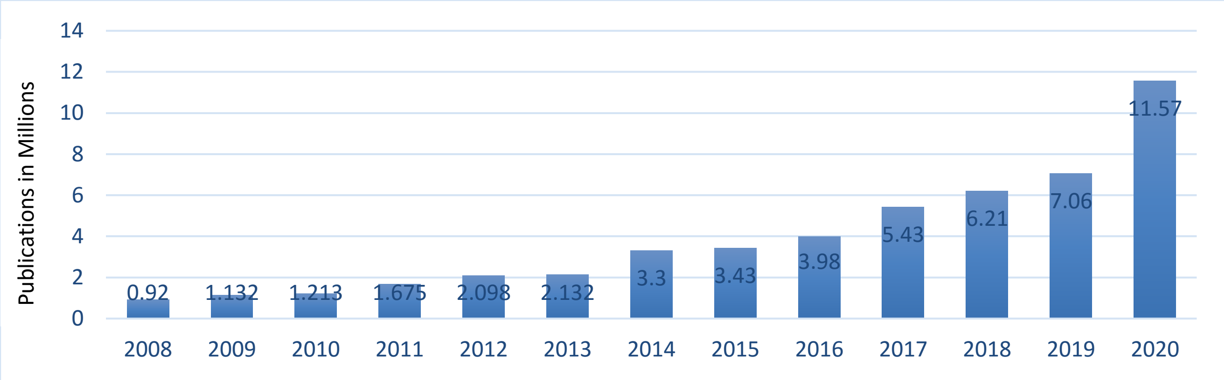

Table 1: Publication trend in graphene chronology since 2008– 2020

2.3 Conclusion

Key nanocomposites which are manufactured on Graphene and Polymers show much progress in technology and wide range applications in many fields [86]. Still, a few challenges still remain which must be taken into attention to recognize the prospective of graphene-based nanocomposites concerning development methods and applications. For example, if the physical synthesis methods are taken into count like sonication, exfoliation, and cleaving of GO, the resultant product (graphene) can have a reduced aspect ratio, which can significantly degenerate the properties like reinforcement, thermal and electrical properties [87] of graphene-based nanocomposites. The review study clearly shown that both graphene and its derivatives have confirmed their potential as candidates for high performance nanocomposites [88]. Many reports have debated the effects of graphene and its derivatives on composites, which result in high levels of strength [88]. Some reports have also reported the good dispersion quality of graphene nano particles in various matrices. Due to the high-quality work, graphene has attracted much attention in the recent years span. The number of publications has generated a chain return in the field of electronics and other applications. It is expected that, by the year 2028, the graphene market will rise by a CAGR of 90%. This remarkable growth in the coming ten years predicts an exponential boom in graphene research and development worldwide.

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