Chapter

Graphene: Fabrication Methods, Properties, and Applications in Modern Industries

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Abstract

Graphene research has fast-tracked exponentially since 2004 when graphene was isolated and characterized by Scotch Tape method by Geim and Novoselov and found unique electronic properties in it. Graphene is considered a promising material for industrial application based on the intensive laboratory-scale research in the fields of physics, chemistry, materials science, and engineering, over the last decade. The number of academic research publications related to various aspects of production, material properties, and applications of graphene has got increased substantially. With such a massive curiosity in graphene, it is imperious for both experts and the layman to keep up with both current graphene technology and the history of graphene technology. In the present study, focus has been given to addresses the disseminating graphene research with production, properties, and applicatory approach. The concluding remarks have been drawn from the present work.

Keywords: graphene, graphene production, graphene applications, graphene properties

1. Introduction

Materials research is engulfed globally to create products to solve real world applications. Major focus has given to make ultra-thin carbon films. Among the others, graphene is thinnest form of smart material. Graphene materials were discovered by Andre Geim and Konstantin Novoselov at the University of Manchester and their excellent contributions were recognized with Nobel prize in 2010. Since, graphene was discovered in 2004, it becomes most popular for human civilization' thus, it is one of the most wonderful achievements of science and technology [1]. Graphene is one of the high stable materials, because of very close or tight packing of atoms in the crystal lattice of graphene and its related materials [2, 3]. Due to enormous reputation of graphene, large research communities, had given significant attention to design and development of graphene materials for varies industrial applications like longer-lasting batteries, efficient solar cells, corrosion prevention, circuit boards, display panels, medical purposes, [4] etc. Basic structure of graphene is a two-dimensional single layer of sp^2 bonded carbon atoms systematically formed in a hexagonal lattice. Schematic structure of graphene is clearly shown in **Figure 1**. Graphene is a building block for all graphitic materials as it can be made

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into 0-dimensional fullerenes, 1-dimensional carbon nano tubes and 3-dimensional graphite structures. Graphene and its types are shown in **Figure 2**.

Graphene is considered as smart materials which possesses excellent mechanical, electronic, thermal, barrier, optical and chemical properties such as high surface area, superior thermal conductivity, high electron movement, high young's modulus, excellent high light transmittance, chemically stable, high level of transparent, [5–7] etc. Because of all stated properties, graphene has potential materials which suitable for variety of advanced/smart industrial applications like medical, paper, electronics and many others [8, 9]. Excellent properties of graphene those are well suited for interdisciplinary applications, giving strong

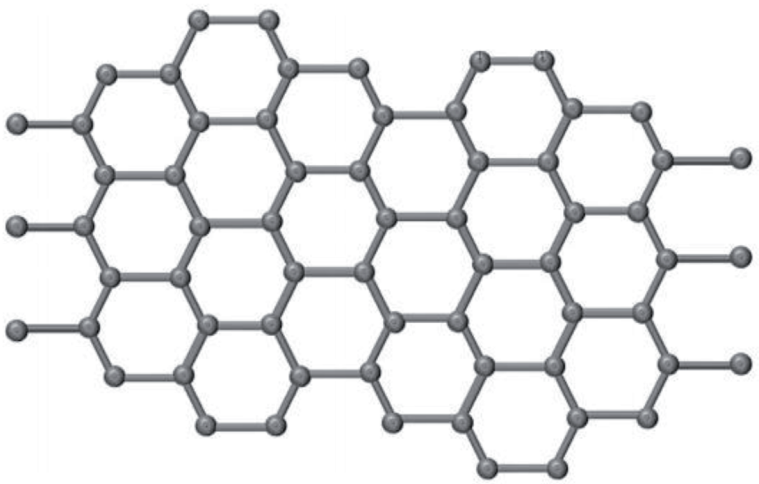

Figure 1.
Basic structure of graphene [6].

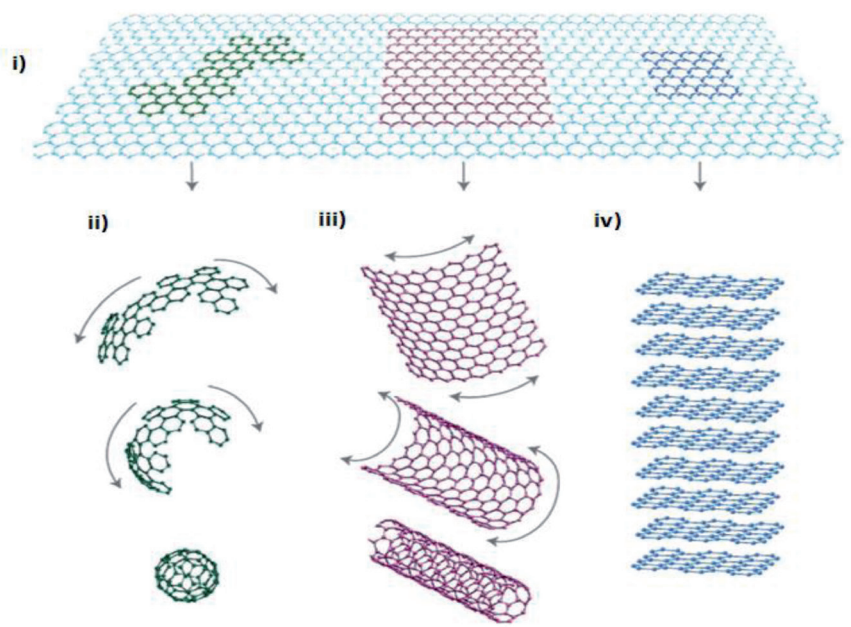

Figure 2.
(i) Graphene and its related structures: (ii) fullerene; (iii) carbon nanotubes; and (iv) graphite [15].

indication for scientists among the physics, chemistry, materials and metallurgy, biology, bio medical, electronics, energy sectors and many other allied fields for mass production of graphene [10–14]. From the buzz of many research communities around the globe, it is mentioned that start-up companies and existing industries have been initiated to use graphene for producing graphene related products.

Various fabrication methods for production of graphene and its related parts are developed but integrating graphene with other materials/products is challenging task. Great open for syntheses of graphene for producing high quality pats with advancements in existing methods. Usage of graphene in various industrial applications is in initial stages, it needs to commercialize rapidly. If commercial fabrication methods are developed, then price ranges of graphene-based products may go down. Graphene has entered into new era in the development field to use in different applications from medical to space to naval. The challenges are enchanting and can showcase scientifically better properties which well suits for various applications. Schematic diagram showing graphene production techniques, properties and application are given in **Figure 3**.

With increasing demands intelligent materials to meet needs of modern world. Graphene is one such material among the others. Several investigators have been given attention to various aspects related to design and development of graphene [17–19]. Number of research papers reported to literature per year is given in **Figure 4**. Now, recent advancements related to graphene research are needed for academicians, scientists, industrialists and investigators. By considering this aspect, present study is planned to discuss recent progress in material engineering related

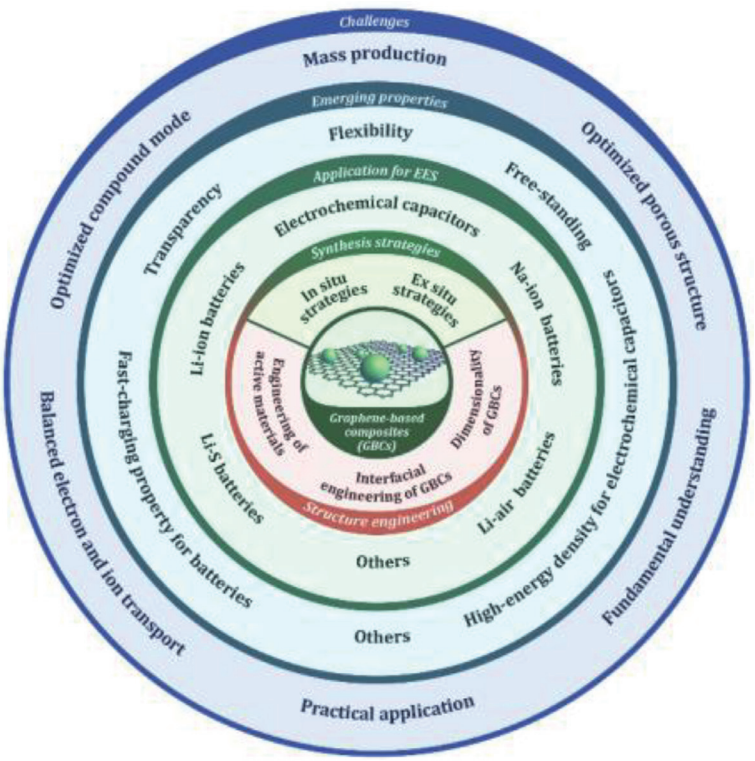

Figure 3.
Schematic illustration related to production, properties and applications of graphene-based composites (GBC) [16].

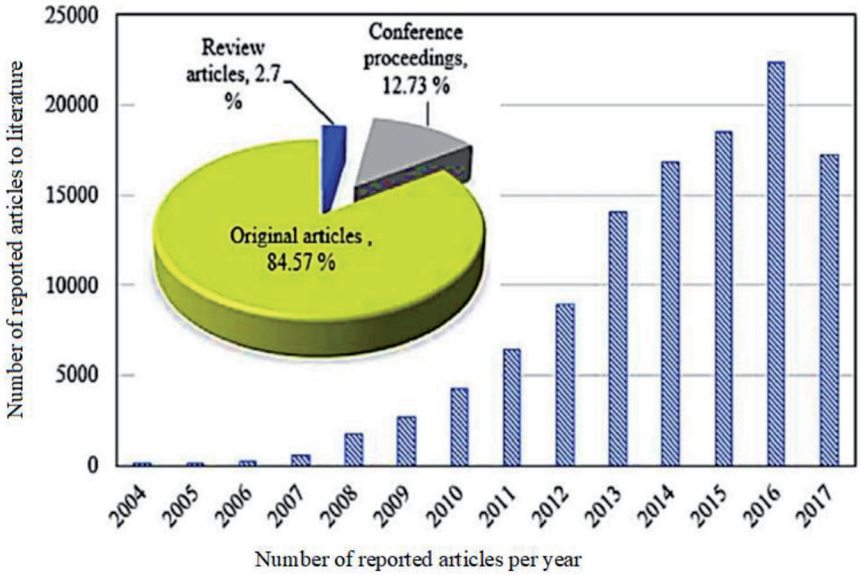

Figure 4.
Status of research publications reported corresponding year [20].

to graphene covering graphene fabrication methods, properties and applications. It is difficult to cover every application of graphene, but, some important aspects of graphene like basic introduction/definition, properties and applications of graphene have been presented.

2. Fabrication methods for graphene

As already mentioned, that graphene is found to be intelligent material for many advanced industrial purposes despite its excellent properties. Since graphene was discovered, industrialists have been finding suitable fabrication methods for producing high quality, defect free, stable and high yield and cost-effective methodologies. Fabrication methodology of graphene is challenging task, because utilization this material for different applications mostly depends on fabrication methods at large scale.

2.1 Micromechanical exfoliation

Micromechanical exfoliation is method of producing graphene-based materials which involves peeling systematically ordered pyrolytic graphite with the use of adhesive tape. It is a methodology of production of graphene, during this process graphene is separated from graphite crystals Peeling is the method used to produce graphene by peeling it off the graphite. After completion of the peeling, multi-layer graphene's are remains on the tape. Graphene is sliced into various flakes of few layers by continuously peeling the multi-layer graphene. In this process layers of graphene are bonded strongly by van der Waals bonding. Schematic diagram of micromechanical exfoliation is shown in **Figure 5** [21]. It is simple easy manufacturing method for producing graphene materials but, it is not suitable for large scale growth of graphene materials. Information related to production procedure to make graphene can available in literature [22, 23].

2.2 Liquid-phase exfoliation (LPE)

Liquid phase exfoliation is method of production of graphene materials by using solvent like acetic acid, sulfuric acid and hydrogen peroxide, to exfoliate graphite through ultrasonication. Sonication methodology is used in LPE to exfoliate the graphene from graphite material, as graphite contains different layers of graphene which attached by Van der Waals forces. This method used to create graphene nanoribbons, but large-scale growth of graphene is difficult task in this method also. Schematic representation of LPE process is shown in **Figure 6**. Details of LPE to produce graphene can get from literature [24, 25].

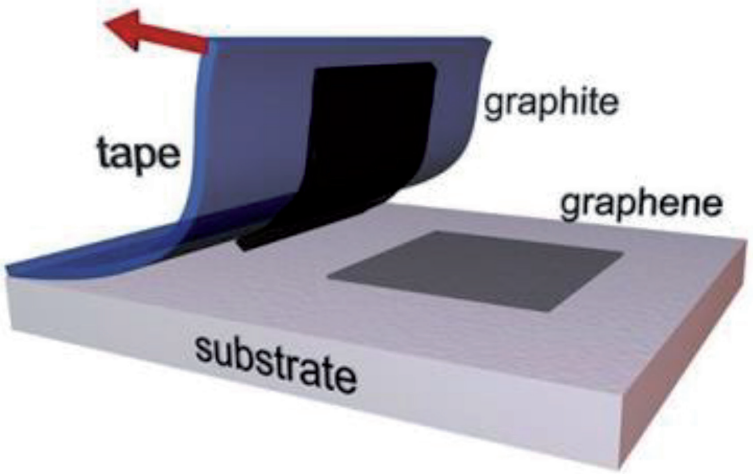

Figure 5.
Working procedure of micromechanical exfoliation process.

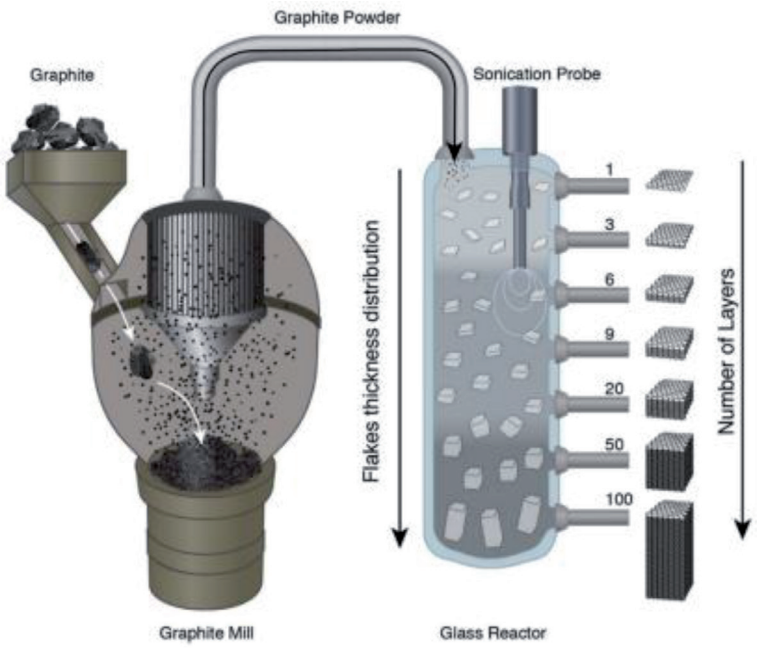

Figure 6.
Schematic diagram of production of graphene in LPE [26].

2.3 Chemical vapor deposition (CVD)

CVD is one of the important deposition methodologies used to transition metals. In CVD process, nickel and copper used for large scale production of graphene. During CVD process, film of metallic catalyst deposits on the substrate. Chemical etching is performed on the deposited material on the substrate. After chemical etching, a mixture which containing the carbon is passed into the reaction chamber. Experimental set up of CVD process is shown in **Figure 7**. The quality of the

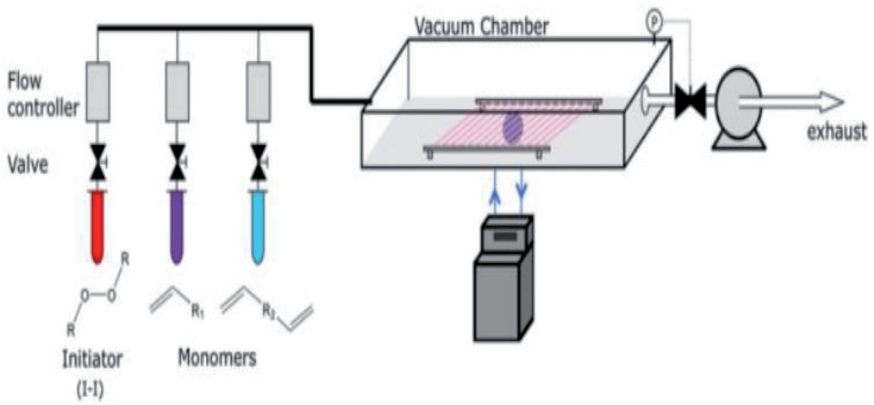

Figure 7.
Schematic diagram of experimental set up of CVD process [29].

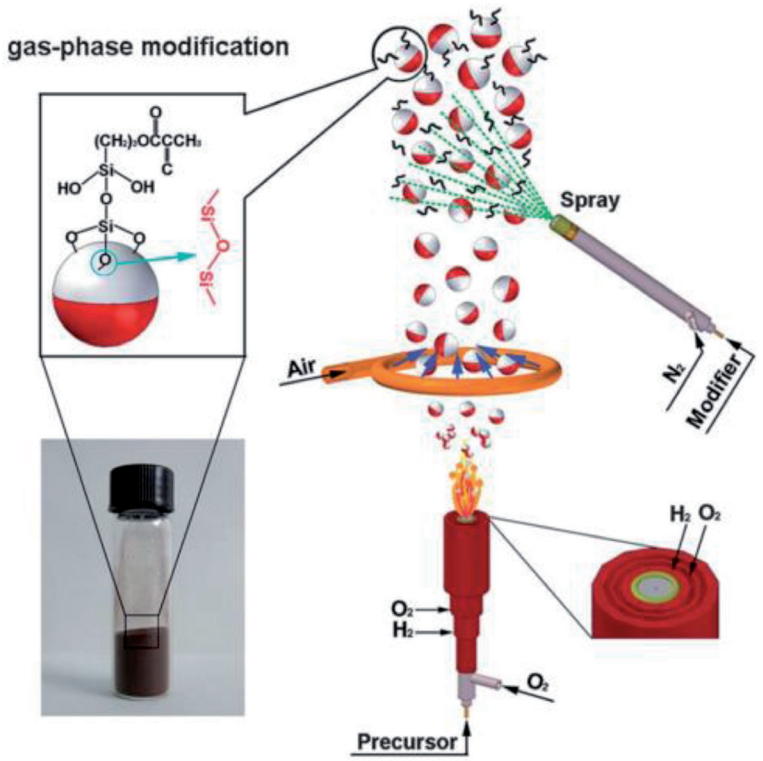

Figure 8.
Experimental set up of production of graphene in flame synthesis.

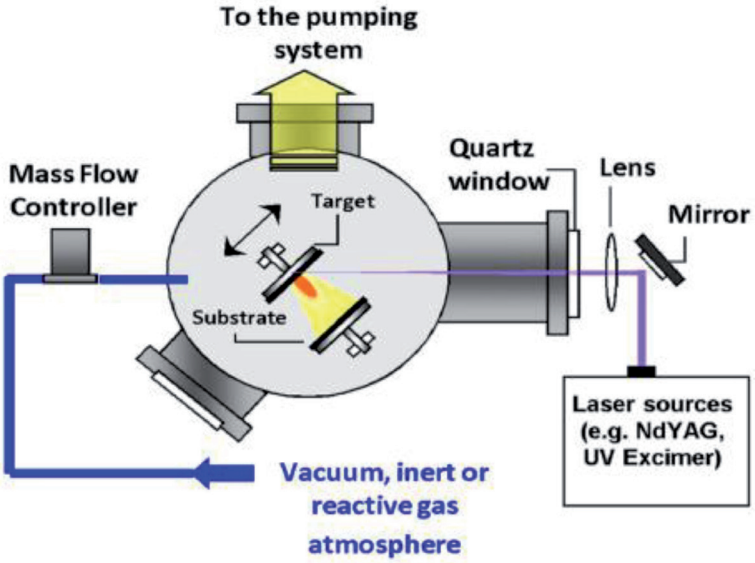

Figure 9.
Working of PLD of graphene [35].

graphene obtained from CVD process is high quality. More information regarding to CVD can be available in literature [27, 28].

2.4 Flame synthesis

Flame synthesis is widely used mass production method for making nano particles. This method is not well adopted for production of graphene as compared to chemical vapor deposition. Some researchers have focused to use of flame synthesis for making graphene materials due to its advantages like scalability and cost effectiveness. Experimental procedure of flame synthesis is given in **Figure 8** [30]. Some researchers suggested that flame synthesis has potential to produce graphene economically [31, 32].

2.5 Pulsed laser deposition (PLD)

PLD is a widely used method of growth approach for producing almost all types of materials. During PLD process, laser energy source is outside the chamber; and chamber is maintained ultrahigh vacuum. Schematic diagram of PLD is given in **Figure 9**. In this process, material is deposited by at an angle of 45° by stoichiometry transfer between ablated target and substrate material. During this process, substrates are added to its surfaces parallel to the target at distance of 2–10 mm. Main advantages of PLD process is low temperature growth rate achieved such that high-quality graphene made without defects. Reader can get more details related PLD in literature [33, 34].

3. Properties of graphene

The rapid interest in graphene has started due its unusual properties exhibits/possesses by graphene materials. Excellent properties of graphene fascinate to be huge potential for various applications. Properties of graphene which reported to literature are mostly single layer defect free. Some of the details about the properties of graphene are discussed in following paragraph.

3.1 Electronic properties

The graphene revolution has started with invention of excellent electrical and electronics properties. The properties of graphene materials are highly depending on number of layers used to produce graphene sheets. It is zero overlap semimetal and it possesses higher electrical conductivity. Graphene is highly suitable for transistors applications due to electron-hole effect.

3.2 Mechanical properties

Graphene and its related materials exhibit excellent mechanical properties. Graphene is strongest material, because of superior mechanical properties of graphene. It is important note that mechanical properties are depends on purity of graphene sheets.

3.3 Optical properties

Optical properties of graphene are highly related to the electronics properties. As mentioned earlier that graphene exhibits excellent electronics properties and this phenomenon indicates graphene possesses better optical properties. Graphene is at can most full transparent materials as it can absorb 2.3% fraction of light [12]. Because of graphene materials exhibits behaviour which enable graphene to extraordinary optical properties. One can get more information related optical properties of graphene from literature [36].

3.4 Thermal properties

Thermal conductivity of graphene is depending on the diffusive and ballistic conditions at higher and lower temperature ranges respectively. Better thermal conductivity of graphene materials is highly depending on quality of graphene sheets. More details of thermal properties of graphene are available from literature [37].

3.5 Chemical properties

In chemical reaction point of view pure form of graphene is mostly not reactive. Chemical properties of graphene are critically influenced by its surface characteristics and thickness of graphene layers. Single layer graphene materials are highly chemically reactive then the multi-layer graphene materials. Reactiveness of graphene materials are controlled by nitrene chemistry methodology [38, 39].

4. Applications of graphene

Graphene is intelligent material which exhibits excellent properties used for various industrial applications. Some of the notable applications where graphene started using to create the parts are given as follows.

4.1 Graphene in high speed electronics

One can found the importance of electronics in most of the industrial applications from medical to mechanical to optical to energy. Conductivity property of electronics need to high for making electronics devices efficient and effective for usage in real world applications. Graphene is one of the advanced materials that exhibits high conductivity which considered as ideal for high speed electronics.

However, commercial applications of graphene have in initial stages only. Graphene is zero band gap material, more studies needed for of usage industrial applications. Research groups indicating that graphene field is advancing fast to create high speed graphene transistors for applying consumer electronic devices very soon.

4.2 Graphene in data storage

Data storage is one of the important areas of research. Investigators are developing the powerful small size hard drives to store higher capacity of data. Researchers suggested that replacing indium tin oxide electrodes with polymers and graphene oxide exhibit write-read-read-rewrite features. Graphene based storage devices are 10 times more powerful than the currently available storage drives. Making small size storage devices is not an issue but increasing capacity levels of storage devices is much importance task. With applications of graphene oxide devices will create big difference in modern industrial environments.

4.3 Graphene in LCD smart windows and OLED displays

Liquid crystal display (LCD) smart window is flexible device which consist of a layer of liquid crystals sandwiched between two flexible electrodes made of flexible polymer and graphene. Organic light emitting diode (OLED) windows are also utilized graphene-based OLED counter electrodes. Currently LCDs and OLED technologies utilize indium tin oxide counter electrodes. These materials are brittle in nature and limited availability in the world. Compared to indium tin oxide, graphene is flexible and availability is more/limitless. Usage of graphene in producing flexible smart devices like mobiles and tablet devices is an important research area due to its excellent properties.

4.4 Graphene in supercapacitors

Present days electronics are occupying almost every industrial application. Energy storage devices are highly required in every electronics to delivering high electric currents within short time. Supercapacitor is one of the important energy storage devices which utilizes high internal surface area to store charge to delivers higher currents compared to normal capacitors. Graphene can be highly suitable for making supercapacitors due to its higher internal area property. More research attempts are performing to create graphene-based supercapacitors for many advanced applications.

4.5 Graphene in solar cells/photovoltaic cell

Solar energy is one of the alternatives, and usage is increasing due to shortage of fusil fuels. Solar cell is important element in solar device which plays critical role to absorb energy from sun light. Presently, platinum-based electronics are using to produce solar cells or photovoltaic cells. Due to higher cost of platinum based solar cells limits its usage in industries. On the other hand, graphene is excellent conductor which is potential material for solar cells. Graphene based electrodes can be made low cost as well as weight while maintaining the efficiency [14].

4.6 Graphene in thermoelectric applications

Thermoelectric materials (TEM) are useful to convert thermal energy to electrical energy and vice versa. TEM are highly used in Peltier coolers and thermoelectric

power generators. Graphene materials exhibits excellent thermoelectric properties which triggering industrialists to make attention to use graphene in thermoelectric applications.

4.7 Graphene in shape memory materials

Shape memory polymers (SMP) are smart materials which have wide range of industrial applications from biomedical to space applications. Graphene is better alternative as shape memory material due to its shape memory, thermal and mechanical properties as compared to existing SMP material namely polyurethane.

4.8 Graphene in self-healing materials

Material properties like long term stability and durability are much needed for structural and coating applications. Presently, polymeric composites are using said purpose and efficiency of these materials depends on many interacting parameters such as environmental condition, erosion, corrosion, etc. Self-healing of material indicates that material should heal basically mechanical properties when material gets damaged. Graphene is found to be potential material among the other materials like polymer composites, metals, ceramics and its related alloys, due to shape memory effect and self-healing ability.

4.9 Multifunctional graphene nanocomposite foams for space applications

Space and aerospace are highly advanced industries need intelligent materials which combine functionalities with low weight, minimized volume and cost effectiveness. Weight and volume of material used for space application are significantly influences cost of the satellite/space vehicles. Joule heating property of metallic parts requires additional cooling devices which adds weight and cost. Graphene is found to be better alternative material for space applications due to its superior electronic and thermal properties. With us of graphene as material for space applications, weight, volume and cost can be optimized and Joule heating can also be suppressing due ballistic electron transport property of graphene.

4.10 Graphene in electrorheology materials

Electrorheology (ER) materials are important smart material where rheological properties of material like viscosity, shear stress and dynamic modulus, can be reversibly transformed by the application of external electric field. ER materials M are widely using for producing damper systems, ER polishing, tactile displays, medical devices, robotic actuators, etc. Graphene is one material which is well suited additive for ER material due to its unique properties.

4.11 Other applications

As mentioned earlier that usage and growth of graphene and related materials are increasing enormously in advanced applications [40] like gene delivery and bio imaging [41], tissue engineering [42], graphene based metal air batteries [43], graphene LED bulbs [44], graphene antennas [45], graphene functional inks [46], graphene based fabric [47], etc.

5. Conclusions

Following summary points are drawn from the present study of status of graphene research related to fabrication methods, properties and applications:

i. Graphene and its related materials are futuristic one's which got enormous importance in modern world.

ii. Production/syntheses of graphene is challenging task.

iii. Some fabrication techniques of graphene are discussed which are using presently.

iv. Various properties of graphene are discussed.

v. Important industrial applications of graphene are addressed in the chapter.

vi. Challenging tasks of graphene production and applications are discussed.

vii. From the study, it is stated that graphene is smart material which is well suited for many advanced industrial applications; various aspects related to graphene production, properties and real-world applications need to explore further to make graphene more intelligent material.

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Conflict of interest

The author declaring no 'conflict of interest.

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