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Graphene: The Revolutionary 2D Material

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Abstract: Graphene is considered as the initial laboratory-made 2D material which initiated a new revolution in the field of materials science. Since its discovery, lots of researchers have discovered various properties and tested it for many potential applications. The present report discusses a brief overview of graphene, mainly concentrating on the structure, synthesis, and applications of graphene. The mechanical exfoliation and CVD techniques for the synthesis of graphene. Some of the applications of graphene in the field of flexible electronics, sensing, and photovoltaic are reviewed in this report

Keywords: Graphene; Graphene applications; Synthesis of graphene; 2D Material

Introduction

Carbon-based materials are present on the earth constitute the major backbone of our modern society and plays vital role in human civilization (Tiwari et al., 2020). Different allotropes of carbon like diamond, graphite, fullerenes, etc. were known previously for a longer period of time. Graphite single sheet which is commonly known as graphene was discovered by Andre Geim and Konstantitn Novoselov in 2004 (Novoselov et al., 2004).

The discovery of graphene led to motivate the researchers to explore its unique properties and potential application. Graphene is considered as the foremost laboratory material made of two-dimensional sheets (thickness 0.34 nm) of sp2 hybridized carbon atoms having honeycomb or hexagonal crystal structure as shown in Figure 1 (Meyer et al., 2007). The C atoms are single-bonded with a bond length of 0.142 nm. The honeycomb network serves as the fundamental building block of other allotropes of carbon; the layers can be stacked to form 3D graphite, rolled to form a 1D nanotube, and wrapped to 0D fullerenes.

Various peculiar properties of graphene which includes mechanical strength, elasticity, electrical and thermal properties are attributed to the long-range π-conjugation (Allen et al., 2010). These properties project graphene to be a permanent replacement for the conventional materials for various applications in flexible and microelectronics, energy harvesting and storage devices, catalysis, biomedical devices, sensors, etc. (Tiwari et al., 2018).

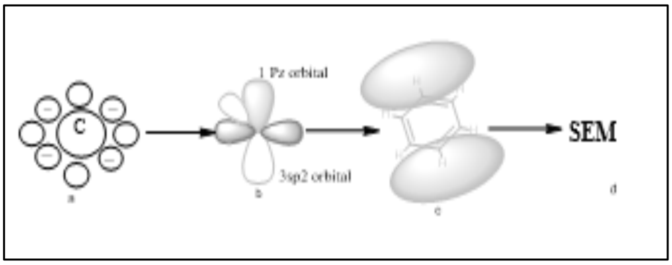

Figure. 1. (a-c) Bonding and properties; (d) SEM of uni-layer graphene (Tiwari et al., 2020)

Based on the explanation above, the research aims to provide an overview of graphene, mainly concentrating on the structure, synthesis, and application of graphene.

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Method

This research uses the method of literature study on various international journals that discuss graphene in the fields of chemistry, material physics, electricity and energy, as well as nanotechnology.

Result and Discussion

Synthesis of Graphene

There are two methods for the synthesis graphene: top-down and bottom-up approach (Ambrosi et al., 2014; Edward et al., 2013). The top-down approach contains the isolation and delamination of the layers of graphite into single-, bi- and few- layer graphene (Novoselov et al., 2004). The precursor like graphite or other carbonaceous materials are destroyed to form 2D nanosized layers. Some of the common top-down approaches for graphene synthesis are mechanical exfoliation, arc discharge, unzipping of CNT, hummers method, etc. Among these techniques, some of them are really highly scalable for high quality graphene but major challenges like low yield and depending mainly on graphite precursors (Novoselov et al., 2004).

On the other hand, the bottom-up method synthesized graphene from the atomic cluster sized precursors mainly involving in the chemical reactions. Several techniques in this approach involve chemical vapor deposition, epitaxial growth, template route, etc. This method produces high quality graphene with low defect density but faces challenges like sophisticated operational techniques and high cost per yield. In this section, only two techniques have been discussed in brief.

Mechanical Exfoliation

The most prominent technique to produce graphene first from top down is mechanical exfoliation. On the basis of directional forces like normal force and shear force vectors, it may be divided into categories. Recent research suggests that the wedge-shaped ultra-sharp diamond crystal performs the usual force exfoliation of graphite (Jayasena et al., 2011). By cutting labor costs and time, this procedure simplifies the synthesis process. In addition, a three-roll mill is employed to produce graphene layers up to 1.4 nm in thickness (J. Chen et al., 2012). The three-roll mill machine's drawback is that it hinders graphene purity by using polyvinyl chloride (PVC) as an adhesive. The complexity of the purifying procedure also raises the cost of producing graphene. Both methods using normal force lacks lots of in-depth synthesis and parametric studies.

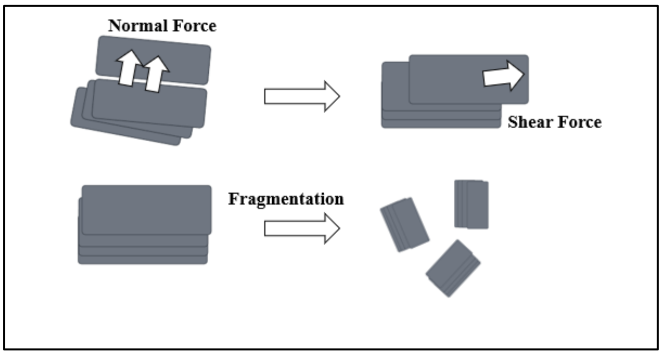

Figure 2. Routes for mechanical exfoliation of grapheme (Meyer et al., 2007)

The other technique involving shear forces are ball milling and fluid dynamic method. Metal balls that apply mechanical force to exfoliate graphite flakes are often used in the ball milling process to grind minerals, cements, ceramics, etc. The process of ball milling breaks down the larger graphite into thin layered graphene at nanoscale thickness. It is also used for making various graphene-based nanocomposites and also its functionalization. The parameters like type of balls, rotation speed, medium of grinding, time, precursor size, etc determines the quality of the graphene (Zhuang et al., 2017). Exfoliating graphite in a ball mill takes a very long time—up to 24 to 48 hours—and is merely desirable for large-scale operations. The elimination of many undesirable factors is still a difficult part of scaling up this process.

Chemical Vapor Deposition

One of the most popular and straightforward methods among the several bottom-up techniques for the synthesis of graphene is the chemical vapor deposition technique. CVD uses a transition metal catalyst like Ni and Cu thin film or foil annealed at high temperatures (800-1100°C) where the precursor gas of hydrocarbons like methane, acetylene, ethylene, etc. are decomposed at those higher temperatures to produce graphene layers on the surface of the metal catalyst (Min et al., 2014). The whole process will be divided into three major parts viz annealing, growth time, and cooling. The annealing part determines the overall quality of graphene. When the catalyst is annealed at a high temperature, the precursor gas is discharged into the tube for a short period of time. When this gas comes into contact with the hot catalyst surface, it divides into free carbon and hydrogen. Free carbon atoms diffuse and when the carbon solubility limit is reached it forms the sheet of graphene layers onto the surface of the metal catalyst (Lee et al., 2012).

The third and last step in the synthesis process is cooling, during which the tube and furnace are cooled to room temperature using a fan or cooling system. Several substrates, including sapphire, silicon, and glass, are used to optimize the growing process, as has been used by Chen et al. (2016). The CVD process has lots of advantages for graphene synthesis as compared to the other methods like low defect density, high quality, large surface area, connected structure, tunability of the structural properties, etc. But, it suffers some disadvantages like high cost and expertise of operation, post-synthesis purification for removal of the catalyst, complexity in the transfer of graphene, etc (Gupti et al., 2014). Plasma Enhanced Chemical Vapor Deposition (PECVD) and Low-Pressure Chemical Vapor Deposition are two low-temperature and pressure synthesis processes that may be used to make further advancements to solve CVD problems. Using PECVD, Kalita et al. (2014) produced graphene at 450 °C. Researchers are still exploring the CVD technology, which has to be enhanced prior to being implemented on a large scale economically.

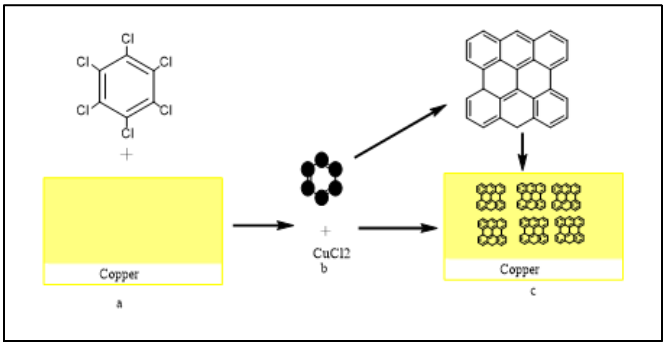

Figure 3. Schematic of the graphene flake growth process (Gan et al., 2012)

Graphene Applications

In the twenty-first century, graphene is considered as a revolutionary material. Many research publications have been published by scientists across the world since the graphene discovery. The various potential applications have been studied and many are yet to be conceived of (Amiri et al., 2015; Goli et al., 2014; He et al., 2017). Still, handful of graphene-based devices has been commercialized. Further research and development are required for achieving the proper application of this material. In this section few of the device applications are discussed here in brief.

Graphene Based Flexible Transistor

Nanoscale technology is used in the single-layer graphene-based transistor. The movement of a single electron at a time is involved (Gan et al., 2012). These transistors have become popular since its inception because of various advantages like compatibility at room temperature, low operating voltage, and high selectivity (He et al., 2017). These qualities of graphene-based transistors have proved to be better than conventional silicon-based transistors and have eventually surpassed microelectronic technology.

The intrinsic properties of graphene like high flexibility make these transistors more effective for nano device level applications. The electron mobility in graphene is very high (almost 10000 times higher than the silicon) which makes it even better than silicon for electronic applications. Still, the pristine graphene could not replace the silicon due to the major issue of bandgap. Besides that, the electron flow in case of graphene is similar to that of phonon, which limits the movement capabilities.

Photovoltaic (PV) Cell

PV cell works on the principle of Einstein's photoelectric effect. The device converts light energy to electrical energy. The use of graphene has been demonstrated in various solar cells like dye-sensitized, organic bulk heterojunction, and Silicon-based PV cells. The use of functionalization of graphene has been demonstrated for engineering various parameters like work function, junction barrier, and surface properties. The electric field in an organic solar cell is produced by the different work functions of two conductors located within the organic layer. In 2011, Wan et al. (2011) were capable of raising the power conversion efficiency (PCE) of the organic solar cell made from graphene to up to 2.6%. The value of PCE is very low as compared to the conventional ITO electrodes-based organic solar cells (approx. 20 % to date). The PCE of graphene-based OSC must be improved for making it a prominent candidate for OSC and thus its commercialization.

Graphene Based Sensors

A device that perceives physical change like motion, temperature, chemical, moisture, pressure, etc. occurring in its vicinity and produces an output in the form of the electrical or optical signal is called a sensor. Graphene-based sensors show excellent performances due to the high electrical conductivity, large surface to volume ratio, excellent charge mobility, thermal conductivity, etc (Goli et al., 2014; Zhao et al., 2016). Taking an example of a graphene-based biosensor, the large surface graphene provides a larger surface loading concentration of biomolecules. The higher conductivity provides easy movement of electrons from the biomolecules to the electrode surface of the receptor.

The performances of a sensor are characterized by its selectivity and sensitivity. The layered structure of graphene helps to detect even minute change within its encompassing condition thus imparting higher sensitivity. The particles attached to the surface of graphene is presented to the encompassing condition which helps graphene to recognize the nature of particles thus giving higher level of selectivity even at micrometer measurement (Zhao et al., 2016). Pristine graphene is able to distinguish even a singular perturbation on atomic scale. Besides this, there are many significant characteristics of graphene which are proved to be helpful for sensing application. Overall, graphene can be used as a part of a sensor in different type of sensors like gas sensor, biosensor, chemical senor, mechanical sensor, thermal sensor, etc (Zhao et al., 2016).

Conclusion

In this report, we have discussed an overview of graphene as a 2D material. Discovery of graphene since 2004 has fuelled the interest and curiosity of scientist to explore the unique properties and their potential applications at the commercial scale. Synthesis of graphene by top-down approach like mechanical exfoliation is found to be easy and scalable but has low quality with high defects density. Whereas the bottom-up approach like CVD technique has low yield and high cost, but has good quality. Recent applications of graphene are photovoltaic cell, flexible electronics, high mobility FET, sensing, etc. The efficiency of these graphene-based devices needs to be improved for proper commercialization. The other potential applications of pristine graphene and its derivatives are still being explored by the researchers.

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Author Contributions
Author 1 contributed to the review's conception by describing the key fields and areas to be covered in graphene research. Author 1 took the lead in writing the first draft of the review article, which included the introduction, background, and sections on the fundamental properties of graphene. She also conducted a comprehensive analysis of the existing literature on graphene, identifying trends, key findings, and gaps in knowledge, and she created figures and diagrams to visually represent the structural and electronic properties of graphene as well as its potential applications in various fields. Authors 3 assisted with the review and editing process by providing critical input, ensuring the accuracy and clarity of the text, and recommending modifications in the graphene synthesis and characterization parts. Throughout the review process, Aris Doyan provided general supervision and guidance, contributed significantly to the manuscript's assessment and editing, and secured funding for the research project that supported the review article.

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Conflicts of Interest
There is no conflict of interest among the authors.

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