An Overview on Properties, Production Mechanisms and Applications of Graphene

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Abstract
Recent years have witnessed a revolution in graphene and its applications. Today, it is a hot topic in science and engineering circles, and attracts more and more interest. This short review article presents the main contributions of research on graphene and its properties, production mechanisms and potential applications. The bibliographic review was performed searching in the Scopus, Web of Science, ScienceDirect, SciELO and Google Scholar scientific databases. As can be seen, the optimal properties of graphene makes it a revolutionary precursor key-material for research and development (R&D) to be applied in many fields such as: energy storage, electronics, purification and decontamination, oil and gas, catalysis, thin films, sensors and biosensors, composite materials among many others applications to be discovered.

Keywords: *Graphene, Carbon nanotubes, Nanotechnology, Nanosciences, Nanoengineering.*

I. INTRODUCTION

The current focus on graphene research and development (R&D) followed the innovative ideas and experiments made by A.K. Geim and K. Novoselov in 2004 who were awarded the Nobel Prize for Physics in 2010 [1].

From graphite and diamond, graphene is undoubtedly the most revolutionary material of today and it's considered to be much superior to plastic and silicon. It is a light material, excellent thermal and electrical conductor, almost transparent and has excellent mechanical resistance. Graphene is the thinnest known material in the universe and the strongest ever measured. Its charge carrier's exhibit giant intrinsic mobility, has zero effective mass, and can travel for micrometers without scattering at room temperature. Graphene can sustain current densities six orders of magnitude higher than copper, showing thermal conductivity and stiffness, is impermeable to gases, and reconciles such conflicting qualities as brittleness and ductility. Graphene is a rapidly rising star on the horizon of materials science and condensed-matter physics. This strictly two-dimensional material exhibits exceptionally high crystal and electronic quality, and, despite its short history, has already revealed a cornucopia of new physics and potential applications [2].

This one-thick carbon crystal has distinct physicochemical properties, tremendous mechanical performance and excellent thermal and electric conductivity, and these characteristics are making graphene a revolutionary alternative to replace many traditional materials in various applications [3].

The electronic structure of graphene is very unusual; electrons behave more like relativistic massless particles than the charge carriers in day-to-day electronics, which leads to higher device speeds and potential for electronics, much faster than we have today [4-5].

Graphene is almost transparent, absorbing only 2.3% of incident light [6] and is very suitable for photovoltaic applications (PVA) in optoelectronics, as screens and solar cells [7].

Due its fineness modulus, graphene is very flexible, and at the same time it's the strongest material we know, being about 300 times stronger than steel with the same weight [8] as well as the best heat conductor, allowing developing not only flexible electronics, but also many other applications such as conducting light and strong composites [9].

Some of the superlative properties of graphene are given in Figure 1:

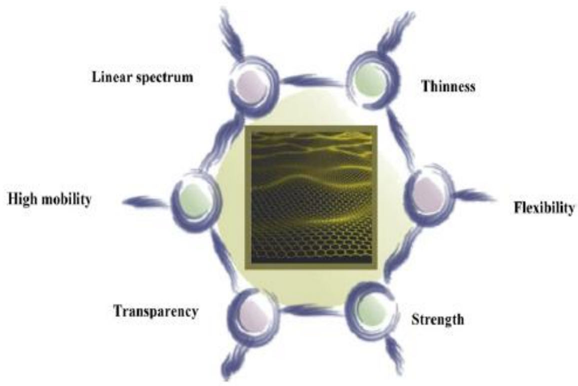

Fig. 1: The Unique Properties of Graphene Can Be Utilized, Either Separately or in Combination, to Create Novel Applications Such as Flexible Transparent Electronics, Conducting Light and Strong Composites, and Many More [10].

In specific, graphene have outstanding properties that make it an excellent candidate for advanced applications in future electronics and photonics [11].

In sum, graphene represents a conceptually new class of materials providing a fertile ground for diverse applications. Inside this context, this short review presents the main contributions of research on graphene properties, production mechanisms and potential applications. For this, a bibliographic review was performed searching for publications in the Scopus, Web of Science, ScienceDirect, SciELO and Google Scholar scientific databases.

II. LITERATURE REVIEW

A. *Processing Technology*

Graphene consists of a single layer of carbon atoms arranged in a hexagonal lattice with several properties ideal for various applications. Its unique structure gives graphene superior properties, high electrical and thermal conductivity, transparency, good mechanical strength, inherent flexibility and huge specific surface area [12].

Before being discovered, graphene was considered a purely theoretical material, only serving to explain the formation of other allotropic carbon forms, since researchers believed that its structure would not be stable as shown in Figure 2:

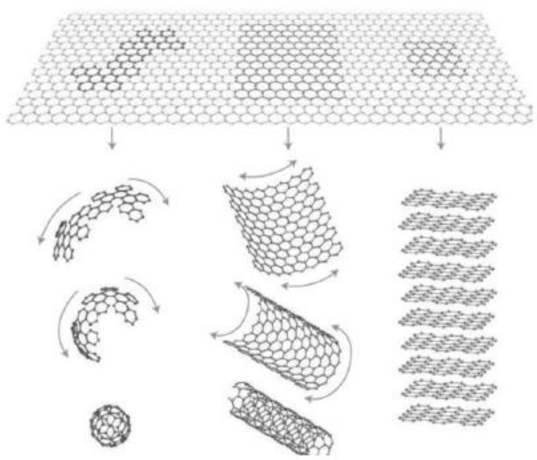

Fig. 2: Graphene as a 2D Building Material for Carbon Materials of All other Dimensionalities. it Can be Wrapped to Form Fullerenes (0D), Rolled to Form Nanotubes (1D) or Stacked to Form Graphite (3D) [2].

Graphene layers can be obtained by various methods, including mechanical exfoliation (Scotch-Tape method) [13] chemical vapor deposition (CVD) [14] and chemistry of graphene oxide [15].

The Scotch-Tape method is based on mechanical cleavage and has a major drawback due low graphene yields obtained, making it unsuitable for large scale use [16].

The defect-free or highly crystalline surface of graphene appears to be chemically inert. The surface of pure graphene usually interacts with other molecules via physical adsorption (π-π interactions). In order to turn graphene surface more reactive, defects or surface functional groups are generally introduced. For example, by chemical doping it with atoms of boron (B) and nitrogen (N) and by introducing functional groups such as carboxyl, carbonyl or amine which can adjust their surface and electronic properties [17].

The Table 1 shows a comparison among different routes to obtain graphene:

TABLE 1. COMPARISON OF DIFFERENT GRAPHENE PREPARATION METHODS [18].

Preparation Methods	Starting Materials	Operation Techniques
Mechanical exfoliation	HOPG (highly oriented pyrolytic graphite)	Scotch-tape
Epitaxial growth on SiC	4H-/6H – SiC wafer	Thermal desorption of Si from the SiC substrate under high temperature (> 1000 ° C) and UHV (ultrahigh vacuum)
CVD epitaxial growth	Hydrocarbons (such as CH_4)	Chemical vapour deposition under high temperature
Chemical reduction of graphite oxide	Graphite	Exfoliation and oxidation of graphite, subsequent reduction of graphite oxide
Exfoliation in liquid phase	Graphite	Dispersion and exfoliation of graphite in organic solvents
Carbon nanotubes unwinding	Carbon nanotubes	Solution based on the oxidative action of $KMnO_4$ and H_2SO_4, or plasma attack

B. *Graphene Properties*

The electrical conductivity of graphene is up to $2{,}10^4$ S/cm and its electronic mobility is $2{,}10^5$ $cm^2/V.s$, which is more than 100 times higher than silicon. Its conductivity at room temperature can reach 5000 W/m.K (copper is 400 W/m.K), which suggests its potential use for thermal applications. It has a very high surface area (2600 m^2/g), much larger than graphite (10 m^2/g) and carbon nanotubes (1300 m^2/g) [19].

In terms of optical properties, graphene has almost total transparency; however, it can absorb a 2.3% fraction of light [20]. Its optical properties are strongly related to its electronic properties as well as its low electronic energy structure, where conical bands meet at the Dirac point. The graphene system exhibits behavior that allows the tuning of ultra-fast optical properties [21].

Recently, graphene based materials were successfully fabricated by electrophoresis deposition technique and exhibited extraordinary properties. Some graphene-based materials prepared by the electrophoresis include films, non-metallic-graphene composites, metal-graphene-based nanoparticles composites, and graphene- polymer composites [22].

These remarkable properties make graphene a promising material in polymer-composite materials, photo-electronics, field-effect transistors, electromechanical systems, sensors and probes, hydrogen storage, electrochemical energy systems [23] among others.

C. Industrialization of Graphene Technology

During the past 32 years, more than 103.000 research articles have the term graphene in their title in the Scopus database. This exceptional reputation of graphene is due numerous reasons; the most significant one appears to be its incomparable physical properties, resulting in real time-application in many fields of science and technology [24].

Graphene research is an example of an emerging translational nanotechnology where discoveries in academia are rapidly transferred to applications. The concept translational nanotechnology is typically associated with biomedicine where there's a well-established link between basic research and clinical studies, but the principle can be also applied to Information and Communication Technology (ICT). The most striking example is the giant magneto-resistance discovery allowing dominant information storage technology. Thus, graphene has the potential to make a profound impact in ICT in the short and long term, by integrating graphene components with silicon-based electronics, and gradually replacing silicon in some applications, allowing not only substantial performance improvements, but more importantly, enabling completely new applications [11].

Increasingly, modern society depends on advances in Wireless Communications (WC). The backbone of wireless systems is using radio frequency transistors enabling to amplify the signals and providing electronic gain at high frequencies. Unfortunately, these abilities often degrade more and more [25]. Graphene-based transistors can improve performance in radiofrequency applications due to the high electronic mobility observed in graphene [26]. Significant results can be observed both at high frequencies and at cryogenic temperatures, increasing the range of operation compared to conventional devices [5].

The application of graphene in the oil and gas industry has only been popularized in the last few years, with the bulk of research taking place within the last ten years or less. Due to its unique properties, it shows applicability for many areas within the oil and gas industry areas including: drilling, lubrication, desalination, anti-corrosion coatings, cementing, oil-water separation, oil spill cleanup, and emulsion stabilization [27] among others.

D. Energy Storage and Electronics

Energy saving is one of the biggest challenges of this century and it's related to the global sustainable economy. The growing demand for world energy consumption requires the development of high-performance systems and devices that enable more efficient consumption, as well as avoiding damage to the environment and long-term resources depletion. As a result, efforts are being made in order to research and develop new materials for use in energy storage systems [20].

Carbon-based materials have been the focus of several recent studies aimed at electrochemical applications, by virtue of their properties, structure and abundance coupled with the fact that they are environmentally benign. Among these materials, graphene is the most recent allotrope form of carbon [19].

Graphene is one of the most promising materials for electronics in this post-silicon era, its unique 2D networks of sp^2 hybrids of carbon atoms organized in a honeycomb structure make graphene a material with exceptional potential for electronics, being used in applications such as: photo-detectors, photovoltaic cells, sensors, diodes, organic light emitters, organic thin film transistors, super capacitors and catalytic applications [28].

In the past two decades graphene has been emerged with the concept of ideal photovoltaic material and exhibited a significant role as a transparent electrode, hole / electron transport material and interfacial buffer layer in cell devices. The power conversion efficiency surpassed 20.3% for graphene-based perovskite solar cells and hit the efficiency of 10% for bulk heterojunction (BHJ) organic solar cells. Except the part of charge extracting and transport the electrodes, graphene has another unique role of device protection against environmental degradation via its packed 2D network structure providing a long-term environmental stability for PV devices [29].

The use of graphene and carbon-based materials for the manufacture of electrodes intended for electrochemical energy storage has been widely reported [30-31].

Graphene electrodes can increase the capacitance of supercapacitors by 20-30%. The fact that the material has a high surface area allows a greater storage capacity of ions in the electrolytes used to manufacture the device [32].

Several papers report the advantages of using graphene or its nanocomposites as electrode material in lithium-ion batteries [33-34-35-36-37] exhibiting a higher reversible capacity and a much better cyclic performance when compared to graphite electrodes [38].

E. Other Applications

A search in the literature involving carbon nanotubes and graphene shows the potential of these materials in various areas, and some are briefly summarized below:

1) Composites

Undoubtedly the greatest possibility for the application of carbon nanotubes (multi-wall type) is in the area of materials, mainly with polymers [39]. Aspect ratio (length/diameter ratio) of the nanotubes makes the percolation limit of these dispersed in extremely low matrices, the introduction of variable quantities (from 0.01% by mass up to 20%) of nanotubes in polymers leads to increased mechanical strength materials with good conductivity and thermal properties [40]. In the case of composite materials, one of the greatest promises is graphene [41].

Sensors and biosensors: because their properties are strongly dependent on the environment, carbon nanotubes (both walls and multiple walls) and graphene have been used as extremely sensitive sensors in the most diverse analytics, including biomolecules [42-43]. Also, variations in conductivity, fluorescence, optical properties, impedance, piezoelectricity, spectroscopic changes, among others, as a function of adsorption of target molecules on the nanotubes walls of graphene surface, are easily detectable, resulting in sensors with very low detection limits and high selectivity. Sensors for gases, toxins, DNA fragments, diverse types of biomolecules, drugs, among many others, have been continuously described in the literature [44].

2) Thin Films:

In recent years, one of the most popular applications for carbon nanotubes, graphene and its different nanocomposites (including conductive polymers and nanowires) is in the preparation of conductive transparent electrodes, aiming to replace the ITO (indium oxide doped with tin oxide), for use in touch screens, LED's and OLEDs, flexible solar cells, among others [45-46]. Films for coating and anti-corrosion protection also find strong application appeal for these materials [47].

3) Environment:

Various applications of carbon nanotubes in purification and decontamination processes as filters and membranes [48] or as photo- and electro-catalysts for oxidation of contaminants have been reported [49].

4) Catalysis:

Carbon nanotubes and graphene are ideal materials to support catalysts (oxides, metallic or even molecular); various reactions are also catalyzed by carbon nanotubes or graphene [50].

III. CONCLUSION

The optimal properties of graphene makes it a revolutionary precursor key-material for research and development to be applied in many fields such as: energy storage, electronics, purification and decontamination, oil and gas, catalysis, thin films, sensors and biosensors, composite materials among many others applications to be discovered.

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