Journal of Material Science and Mechanical Engineering (JMSME)
Print ISSN: 2393-9095; Online ISSN: 2393-9109; Volume 2, Number 10; April-June, 2015 pp. 70-73

http://www.krishisanskriti.org/jmsme.html

A Review on the Properties and Applications of Graphene

Somnath Bharech[1] and Richa Kumar[2]

[1]Maulana Azad National Institute of Technology
[2]Babu Banarasi Das Northern India Institute of Technology
E-mail: [1]sbharech@gmail.com, [2]er.richakumar@gmail.com

Abstract—*Since the advent of automobile and aerospace industry, development of materials with better properties has been the keen interest of researchers. This is the decade which will experience the development of 'future materials', materials having exceptional properties. One such material is Graphene. Graphene is a two dimensional atomic scale hexagonally packed allotrope of Carbon. In this paper, we will discuss the types, properties, applications and future scope of this material. The processes involved in its commercial production will also be reviewed.*

1. INTRODUCTION

Carbon is one of the most abundantly found elements in the earth's crust [1]. It has many allotropes and each of them has proved to be useful to the mankind. Graphene is one of these allotropes. It is a two-dimensional sheet of sp^2-hybridized carbon. It has received the attention of many researchers due to its extraordinary thermal, mechanical and electrical properties. Due to these properties Graphene seems to have many applications in various sectors.

Graphene was already studied in 1947, though theoretically as a textbook example for calculations in solid state physics by P.R. Wallace, National Research Council of Canada [2]. He predicted the electronic structure and derived the linear dispersion relation.

R. Ruoff and others tried and suggested a process for Graphene extraction [3]. It used a simple but effective mechanical exfoliation method for extracting thin layers of graphite from a graphite crystal with Scotch tape and then transferred these layers to a silicon substrate. They were, however unable to identify any monolayers.

Andre K. Geim and Konstantin S. Novoselov of University of Manchester, UK, were awarded with the Nobel Prize in Physics 2010 for their "groundbreaking experiments regarding the two-dimensional material grapheme" [4]. They had succeeded in producing, isolating, identifying and characterizing Graphene [5-6].

2. FORMS OF GRAPHENE

Graphene, being a comparatively new topic of research, lacks standard nomenclature for its family. International editorial team of *Carbon* [7] recommended a nomenclature for the two-dimensional carbon materials after facing contradictory and confusing terms used by researchers. This section classifies Graphene based on their recommendation.

2.1 Graphene

It is a single atom-thick sheet of hexagonally arranged sp^2-bonded carbon atoms which is freely suspended or adhered on a foreign substrate. Its lateral dimensions may vary from several nanometers to microscale. Monolayer (single-layer) is the purest form known and is useful for high-frequency electronics. Bi-layer and tri-layer Graphene, two and three layers respectively, exhibit different properties with the increase in the number of layers.

2.2 Few-Layer Graphene (FLG) or Multi-Layer Graphene (MLG)

They consist of a small number (between two to 10) well-defined, countable, stacked Graphene layers of extended lateral dimension. They can be sheet-like, free-standing films or flakes or a substrate bounded coating. These are useful for composite materials, as a mechanical reinforcement.

2.3 Graphene Oxide (GO)

Graphene Oxide is a monolayer material with high oxygen content, where C/O atomic ratio is in between 2 – 3. It is prepared by oxidation and exfoliation that is followed by extensive oxidative modification of the basal plane. Thin membranes prepared using GO allow water to pass through but restrict harmful gases.

2.4 Reduced Graphene Oxide (rGO)

It is Graphene oxide (as above) which is reductively processed by chemical, photo-chemical, thermal, photo-thermal, microwave or microbial/bacterial methods to reduce its oxygen content.

2.5 Graphene nanomaterials

These include Graphene nanosheets, Graphene nanoribbons, Graphene nanoflakes, etc. They are broadly defined as two-dimensional Graphene materials with a thickness and/or lateral dimension of less than 100 nanometers. They are not an integral part of carbon material, but is freely suspended or adhered on a foreign substrate. They are perfect for electrically conductive composites.

3. PRODUCTION TECHNIQUES

Graphene can be produced using a variety of techniques ranging from simple to state-of-the-art technologies.

3.1 Mechanical Exfoliation

As of 2014, this process produces Graphene with the lowest number of defects and highest electron mobility [8]. This technique was first introduced by R. Ruoff and group [3]. They used an adhesive tape to split the Graphene layer from graphite flakes. Multiple exfoliation steps are required to obtain single layers {see Fig. 1. a) and b)}. After exfoliation these layers were deposited on a silicon wafer using ‘dry deposition’. This technique is also known as ‘Scotch tape’ or ‘drawing’ method.

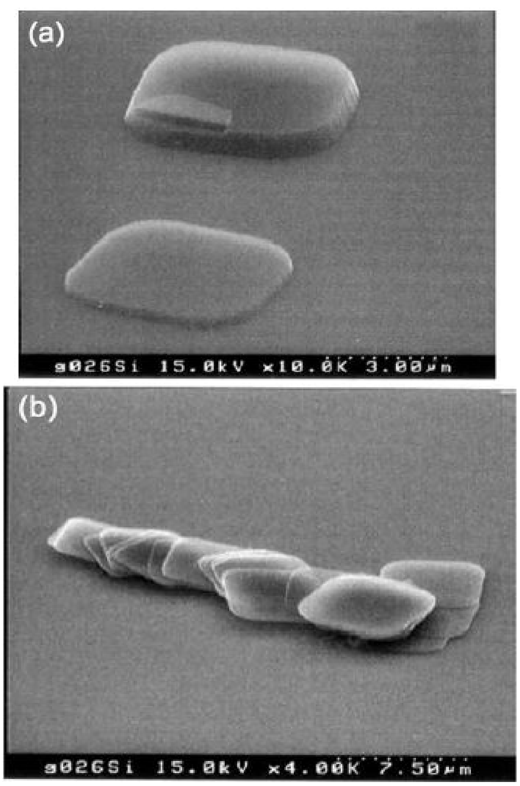

Fig. 1: a) and b) Scanning electron microscope images of early attempts at mechanical exfoliation using graphite flakes by R. Ruoff and group [3].

3.2 Chemically derived Graphene from Graphite Oxide

This method involves production of graphite oxide from graphite and then the synthesis of Graphene {see Fig. 2}. This technique was first demonstrated by R. Ruoff and group in 2006 [10-13]. Graphite is chemically modified into a water dispersible intermediary graphite oxide by oxidizing using Hummers’ method. Graphite oxide is a layered stack of sheets which exfoliates completely application of mechanical force. The biggest advantage of this method is its low-cost and enormous scalability.

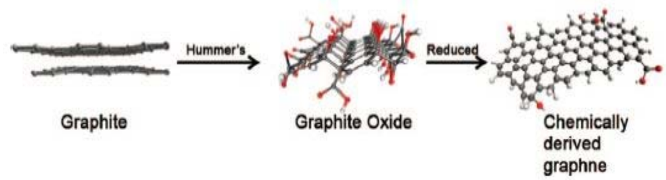

Fig. 2: Molecular models depicting the conversion process from graphite to chemically derived Graphene [9].

3.3 Epitaxial Graphene and Chemical Vapor Deposition (CVD)

De Heer and group at the Georgia Institute of Technology developed an epitaxial method in which Graphene is synthesized from the high temperature reduction of Silicon carbide [14-16]. Silicon desorbs at high temperature around 1000 °C in ultrahigh vaccum, leaving small islands of graphitized carbon. This process is also referred to as ‘Thermal Decomposition of Graphene’.

Chemical Vapor Deposition of Graphene on transition metal films is another substrate-based method. In this method, usually nickel films are used with methane gas. The solubility of carbon in the transition metal decreases upon cooling the substrate and a thin film of carbon is precipitated on the surface [17-19].

One of the major advantages of using these methods for Graphene synthesis is their high compatibility with the existing technology. They are capable in producing a single layer of Graphene over an entire wafer, which is the easiest way to integrate the material into current semiconductor devices.

4. PROPERTIES

Many researchers have reported record-breaking electronic, mechanical and optical properties of Graphene, which may make it a material of great utility.

4.1 Electronic Properties

Graphene has very high electrical conductivity as it is a zero-gap semi-conductor, because its conduction and valance bands meet at the Dirac points [20].

Carbon atoms have a total of six electrons each, two in the inner shell and four in the outermost shell, which are available for chemical bonding. But in Graphene, each Carbon atom is bonded with three other atoms due to sp^2-hybridization. This leaves one electron in the third dimension freely available for electronic conduction.

Electronic mobility of Graphene is very high even at room temperature. It has been experimentally proven that its electron mobility is nearly independent of temperature [21].

4.2 Mechanical Properties

According to Changgu Lee, Graphene is the strongest material ever tested, with a Tensile strength of 130 GPa and a Young's Modulus (defines stiffness) of 1 TPa [22].

Apart from this, Graphene is unbelievably light, weighing about only 0.77 mg/m^2. According to a Nobel announcement which illustrates that 1 m^2 of Graphene hammock would support a 4 kg cat, but would weigh only as much as one of the cat's whiskers [23].

4.3 Optical Properties

Graphene produces a highly opaque atomic monolayer in vaccum, as it has an ability to absorb approximately 2.3% of the white light. Adding another layer of Graphene increases the amount of white light absorbed by approx. the same value (2.3%) [24].

Once optical intensity reaches a certain threshold saturable absorption takes place. Due to Graphene's properties of wavelength-insensitive ultrafast saturable absorption, full band mode locking has been achieved.

5. APPLICATIONS

Graphene has a number of applications in mechanical engineering, electrical engineering, micro-electronics and it is considered to be the most important material due to its wide range of applications in electronics engineering as a component material.

5.1 Low-cost, thinner display screens for mobile devices

Graphene can replace indium-based electrodes in organic light emitting diodes (OLED). These diodes are used in electronic device display screens which require low power consumption. The material is cheap and thinner, see-through and critically is electrically conductive. That makes it ideal for the flat-screen displays used on smart phones that need electricity to power the optical elements, and to respond to the user touch. The use of Graphene instead of indium not only reduces the cost but eliminates the use of metals in the OLED, which may make devices easier to recycle.

5.2 Lithium-ion batteries that recharge faster

These batteries use Graphene on the surface of anode. Defects in the Graphene sheet (introduced using a heat treatment) provide pathways for the lithium ions to attach to the anode substrate. The time needed to recharge a battery using the Graphene anode is much shorter than with conventional lithium-ion batteries. This is achieved because a gram of Graphene has a surface area of 2,600 square meters - the equivalent of about 10 tennis courts – meaning there are more opportunities for a reaction to occur in the battery.

5.3 Ultracapacitors with better performance than batteries

These ultracapacitors store electrons on Graphene sheets, taking advantage of the large surface of Graphene to provide increase the electrical power that can be stored in the capacitor. This would help batteries to be recharged in minutes instead of hours [30].

5.4 Low cost water desalination

Thin membranes prepared using Graphene oxide allows the water to flow through but, blocks the harmful particles and gases. It is believed that it can be used to desalinate sea water at a lower cost than the reverse osmosis techniques currently in use [28].

5.5 Integrated circuits with Graphene Transistors

A production of working transistor with Graphene is a great achievement since Graphene is not a natural semiconductor. Despite the technical challenges, this transistor operated at twice the speed of a comparable silicon transistor. A broadband radio frequency mixer has been constructed that is used in radio applications to process signals at a range of frequencies. It is a stranded IC component and this achievement shows that Graphene transistors can be used effectively in more complex systems.

5.6 Transistors that operate at higher frequency

The ability to build high frequency transistors with Graphene is possible because of the higher speed at which electrons in Graphene move as compared to electrons in silicon. The development of lithography techniques that can be used to fabricate integrated circuits based on Graphene are also in process [25-27].

5.7 Corrosion-resistant coating

It can also be used as a very important metallurgical tool. Corrosion-resistive coatings can be made from Graphene which could protect important building and machinery elements from corrosion. It can help in doing so by conducting the charges responsible for corrosion of a material.

6. SCOPE FOR DEVELOPMENT

The research on Graphene is in its intial stage. Graphene needs a lot of attention and research to fully discover its potential applications.

The list of potential uses of Graphene may also include – as a replacement for the flash memory of our SD card, or to replace antenna that pick up the radio signal. But one which shows just how varied the material's properties can be is its use in the earpiece [29].

Conventional speakers drive sound vibrations by pumping the air. But Graphene can achieve the same thing using heat - much as lightening generates thunder by dramatically heating the air. The trick with Graphene is that it is so thin, it takes almost no current to heat it, but equally it cools in an instant. Pumping audio-frequency currents through a sheet of Graphene- going well into the ultrasound- generates sound waves without the need for any moving parts. In theory this makes devices simpler and cheaper and opens up the possibility of new applications.

Graphene may also replace electrical wires in the near future. We may no longer need separate ducts for wiring. It will surely prove to be a 'future material'.

7. CONCLUSION

Graphene is a promising material for new types of systems, circuits and devices where several functionalities can be combined into a single material.

Presently, highly critical issues with the extensive use of Graphene in electronics are related to manufacturing. Although growth on copper surfaces has made bulk manufacture of large area Graphene layers possible, there are number of technical challenges to be overcome both in terms of cost and quality before the first consumer products using Graphene are actually commercialized.

8. ACKNOWLEDGEMENT

The authors would like to thank their respective institutes for their support.

REFERENCES

[1] "List of Elements of the Periodic Table - Sorted by Abundance in Earth's crust". Israel Science and Technology Homepage. http://www.science.co.il/PTelements.asp?s=Earth

[2] P. R. Wallace, *Physical Review* 71, 476 (1947).

[3] X. K. Lu, M. F. Yu, H. Huang, and R. S. Ruoff, *Nanotechnology* 10, 269 (1999).

[4] "The Nobel Prize in Physics 2010" http://www.nobelprize.org/nobel_prizes/physics/laureates/2010/

[5] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, *Science* 306, 666 (2004).

[6] K. S. Novoselov, D. Jiang, F. Schedin, T. J. Booth, V. V. Khotkevich, S. V. Morozov, and A. K. Geim, Proceedings of the National Academy of Sciences of the United States of America 102, 10451 (2005).

[7] Robert H. Hurt, *Carbon* 65 (2013) 1–6

[8] Kusmartsev, F. V.; Wu, W. M.; Pierpoint, M. P.; Yung, K. C. (2014). "Application of Graphene within Optoelectronic Devices and Transistors".

[9] Tung, V. C.; Allen, M. J.; Yang, Y.; Kaner, R. B. *Nature Nanotechnology*, 2009, *4*, 25.

[10] Stankovich, S.; Dikin, D. A.; Dommett, G. H. B.; Kohlhaas, K. M.; Zimney, E. J.; Stach, E. A.; Piner, R. D.; Nguyen, S. T.; Ruoff, R. S., *Nature* 2006, *442*, 282.

[11] Stankovich, S.; Dikin, D. A.; Piner, R. D.; Kohlhaas, K. A.; Kleinhammes, A.; Jia, Y.; Wu, Y.; Nguyen, S. T.; Ruoff, R. S. *Carbon* 2007, *45*, 1558.

[12] Jung, I.; Dikin, D. A.; Piner, R. D.; Ruoff, R. S. *Nano Letters* 2008, *8*, 4283.

[13] Yang, D.; Velamakanni, A.; Bozoklu, G.; Park, S.; Stoller, M.; Piner, R. D.; Stankovich, S.; Jung, I.; Field, D. A.; Ventrice, C. A.; Ruoff, R. S. *Carbon* 2009, *47*, 145.

[14] Hass, J.; de Heer, W. A.; Conrad, E. H. *J. Phys.: Condens. Matter* 2008, *20*, 323202.

[15] de Heer, W. A.; Berger, C.; Wu, X. S.; First, P. N.; Conrad, E. H.; Li, X. B.; Li, T. B.; Sprinkle, M.; Hass, J.; Sadowski, M. L.; Potemski, M.; Martinez, G. *Solid State Commun.* 2007, *143*, 92.

[16] Berger, C.; Song, Z. M.; Li, X. B.; Wu, X. S.; Brown, N.; Naud, C.; Mayou, D.; Li, T. B.; Hass, J.; Marchenkov, A. N.; Conrad, E. H.; First, P. N.; de Heer, W. A. *Science* 2006, *312*, 1191.

[17] Reina, A.; Jia, X. T.; Ho, J.; Nezich, D.; Son, H. B.; Bulovic, V.; Dresselhaus, M. S.; Kong, J. *Nano Lett.* 2009, *9*, 30.

[18] Kim, K. S. *Nature* 2009, *457*, 706.

[19] Sutter, P. W.; Flege, J. I.; Sutter, E. A. *Nat. Mater.* 2008, *7*, 406.

[20] Cooper, Daniel R.; D'Anjou, Benjamin; Ghattamaneni, Nageswara; Harack, Benjamin; Hilke, Michael; Horth, Alexandre; Majlis, Norberto; Massicotte, Mathieu; Vandsburger, Leron; Whiteway, Eric; Yu, Victor (3 November 2011). "Experimental Review of Graphene". *ISRN Condensed Matter Physics* (International Scholarly Research Network) 2012: 1–56.

[21] Morozov, S.V.; Novoselov, K.; Katsnelson, M.; Schedin, F.; Elias, D.; Jaszczak, J.; Geim, A. (2008). "Giant Intrinsic Carrier Mobilities in Graphene and Its Bilayer". *Physical Review Letters* 100 (1): 016602.

[22] Lee, Changgu (2008). "Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene". *Science* 321 (385): 385–388.

[23] "2010 Nobel Physics Laureates", www.nobelprize.org.

[24] Nair, R. R.; Blake, P.; Grigorenko, A. N.; Novoselov, K. S.; Booth, T. J.; Stauber, T.; Peres, N. M. R.; Geim, A. K. (6 June 2008). "Fine Structure Constant Defines Visual Transparency of Graphene". *Science* 320 (5881): 1308–1308.

[25] Lemme, M. C.; Echtermeyer, Tim J. et al. (2007). "A Graphene field-effect device". *IEEE Electron Device Letters* 28 (4): 282–284.

[26] Bullis, K. (28 January 2008). "Graphene Transistors". Cambridge: MIT Technology Review, Inc.

[27] Kedzierski, J.; Hsu, Pei-Lan; Healey, Paul; Wyatt, Peter W.; Keast, Craig L.; Sprinkle, Mike; Berger, Claire; De Heer, Walt A. (2008). "Epitaxial Graphene Transistors on SiC Substrates". *IEEE Transactions on Electron Devices* **55** (8): 2078–2085.

[28] Cohen-Tanugi, David; Grossman, Jeffrey C. (2012). "Water Desalination across Nanoporous Graphene".*Nano Letters* 12 (7): 3602–3608.

[29] Dodson, Brian (February 3, 2014). "Graphene-based nano-antennas may enable cooperating smart dust swarms". Gizmag.com.

[30] 5 Ways Graphene Will Change Gadgets Forever, Laptop, 14 April 2014, Michael Andronico