Methodological Production Processes of Graphene As It Affects Its Nature and Application

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ABSTRACT

Graphene, a two dimensional monoatomic thick building block of a carbon allotrope, has emerged as an exotic material of the 21st century, and received world-wide attention due to its exceptional charge transport, thermal, optical, and mechanical properties. Graphene and its derivatives are being studied in nearly every field of science and engineering. Recent progress has shown that the graphene-based materials can have a profound impact on electronic and optoelectronic devices, chemical sensors, Nano composites, energetic technologies, Nano electronics, biomedicine including gene therapy, cell imaging or tissue engineering are only few from all possible applications for graphene, the thinnest known carbon configuration and a basic element for other more complicated, better discovered and widely used nanostructures such as graphite, fullerenes and carbon nanotubes. The number of researches concerning graphene applications is rising every day which proves the great interest in its unique structure, properties and the production processes involved for the possibility of other applications to revolutionize the material and electronic world of today and future.

Key Words: Production Process, Nature and Properties of End Product –Graphene.

INTRODUCTION

The age of stone, copper, and iron is now prehistory. Nowadays, steel, carbon, and almost perfect silicone are the materials of choice. Nevertheless, carbon is the one which still gets a lot of attention. Carbon is a known nonrenewable source of energy; carbon is a ubiquitous molecule capable of forming many allotropes with many potential applications whose values are superb in engineering design and developments. The major known crystalline carbon is graphite and diamond but with recent research carbon has become again an object of intense scientific research which resulted in many discoveries. In 1996,Smalley and his colleagues received the Nobel Prize in Chemistry "for their discovery of fullerenes," zero-dimensional Nano-spheres formed by 60 carbon atoms which resemble the soccer ball and exist only in the molecular form of carbon in contrast to the crystalline forms of the graphite and diamond. Iijima in 1991 described one-dimensional helical microtubules of graphitic carbon called nanotubes. Again the Nobel Prize in Physics in 2010 was awarded jointly to Andre Geim and Konstatntin Novoselov "for groundbreaking experiments regarding the two-dimensional material graphene". The scientists obtained 2D graphene only one atom thick, strikingly reminiscent to a honeycomb structure by the simple use of ordinary sticky tape. Not only did they make graphene but they also studied and described its unique properties and possible applications for the society usage. Graphene is a basic element for the other graphitic materials possible to transform one structure to another under appropriate conditions. The last 20 years of research have shown many possibilities of chemical functionalization of different synthetic carbon varieties such as fullerenes or carbon nanotubes which led to many significant achievements in improving the solubility, processing capabilities, fixing with other compounds, and exploring the

unique properties of graphene. Different distribution of the benzene rings in the two-dimensional structure of graphene determines the shape, size, edges, and number of layers and additional covalent or non-covalent bonds with other atoms which results in modifications of the electrical or chemical properties of graphene.

"Graphene: The Magic of Flat Carbon" was the title of a series of lectures by pioneers of Graphene science, Prof. Andre K. Geim and Prof. Konstantin S. Novoselov from University of Manchester who were recognized by the Nobel Prize in Physics in 2010. Graphene is a single, one atomic thick layer of the common mineral graphite and is the first example of a truly two-dimensional material. There is no doubt that Graphene is a magic material. Graphene is transparent, extremely flexible yet still rigid, and is the best electrical and thermal conductor ever known. It could be used to create products that are lighter, more robust, transparent, flexible and stretchable such as electronic paper, bendable personal communication devices, and more energy-efficient airplanes. Graphene based batteries could enable electric cars to drive longer and smart phones to charge faster. It filters salt, heavy metals, and oil from water and enables more efficient solar energy conversion. Graphene coatings prevent steel and aluminium from rusting and, in the longer term; promise to give rise to new computational paradigms and revolutionary medical applications, including artificial retinas and brain electrodes. What sets Graphene apart is its remarkable combination of superior properties which will enable a multitude of applications in different fields and increasingly begin to impact our daily lives over the next 10 years.

Early Graphene results were limited to academic research but increasingly industry giants are in the running too. IBM has produced several electronic component prototypes, while Samsung has produced a flat screen (70cm in the diagonal) with Graphene electrodes. The tennis racket maker Head used tennis champions Novak Djokovic and Maria Sharapova to promote rackets made with Graphene. BASF and Daimler-Benz have designed a concept electric car called Smart Forvision incorporating Graphene in a conductive e-textile. In 2012, BASF produced a report on the future of Graphene, forecasting a market worth $1.5bn in 2015 and growing to $7.5bn in 2025; this outlook significantly exceeded previous Graphene market forecasts.

Graphene has many interesting properties such as a high surface area per mass of 2630 m2/g, the strongest known electrical conductivity, impermeability to gas, and an immense capability of transmitting light with a transparency of about 98%. These properties make graphene the most highly anticipated and most useful material to be developed today.

Graphene is derived from graphite ore or synthesized. There are a large number of synthesis processes, and these processes begin with an array of material sources such as graphite, carbon nanotube, carbon precursor, CO_2. Yet, only 10 years since Geim and Novoselov first used adhesive tape to isolate graphene from graphite, graphene sheets are being produced in hundreds of tonnes and tens of thousands of square metres. Five years ago, only a few USA-based small start-up companies, such as Angstron Materials, Vorbeck Materials and XG Sciences, were making large volumes of small graphene sheets. Since then, tens of graphene manufacturing companies have sprung up all over the world, which produce not only small graphene sheets but also large-area, high-quality graphene films on an industrial scale. In particular, the production industry of graphene materials in China has been developing very rapidly, and its total annual production capacity of small graphene sheets and graphene films exceeds 400 tones and 110,000 m^2, respectively. While some scientists and engineers venture to find methods of large scale production processes, others have begun testing its practicality and

applications into everyday life. These production processes enable other expedient applications of graphene for future uses.

Graphenes' Production Processes

Graphenes' production processes are those of highest interest at industrial level so as to aid further advancement in the application of various field of study in today's manufacturing process and in future prospect. At an industrial level it would require high-quality graphene produced in quantity. Unfortunately, scaled-up production is where graphene faces some of its greatest hurdles.

Graphemes' production processes can be specifically classified into:

➤ Top-down methods (includes exfoliation, the splitting of graphite down to micro layers of graphene and the Scotch tape method is a rudimentary version of it or breaking down of graphite into graphene using external forces such as mechanical, electrical, Liquid Phase Exfoliation etc.)

➤ Electrochemical treatments can also be used. For example, graphite-in-solution bombarded with ultrasound to create flakes of graphene that can be further processed in a centrifuge.

➤ Bottom-up methods (include chemical synthesis or gas-phase growth. For example, chemical vapour deposition uses a substrate placed in a furnace through which methane and hydrogen gases are passed. The carbon atoms within the methane then fall to the substrate and form a graphene layer or Building up graphene from molecular building blocks or from carbon sources.).

Therefore, with these aforementioned graphemes' production approaches, different methods for producing graphene are discussed carefully below as used in the materials world of today.

Micro Mechanically Produced Graphene.

This is top-down method, exfoliation (the breaking of bulk graphite ore into its constituent Graphene layers) takes place by peeling the layers upon exerting external or mechanical forces overcoming the van der Waals forces attraction between the layers where these separate sheets of graphene from graphite accomplished by adhesion or by friction between a source of graphite and other surface (to cause the sliding of one graphene sheet). It is the most commonly known method called micromechanical cleavage or "*Scotch tape*" method in which, a piece of bulk graphite e.g. highly ordered pyrolitic graphite (HOPG) is repeatedly peeled in between the Scotch tape, thus overcoming the van der waals attraction between the flakes, thereby reducing its thickness each time to achieve optically transparent flakes upon transferring it to a substrate usually SiO_2/Si wafer, to electrically isolate it and facilitate handling. In recent years, various manufacturers have used Hummer's technique in which graphite is initially oxidized and converted to Graphene oxide. Graphene oxide is then reduced to Graphene using specific reducing agents and the initial oxidation process is highly exothermic resulting into explosion risks thus toxic gas release that hinders the scalability of the conversion process. Most recently, novel exfoliation techniques have been developed in which graphite is directly exfoliated into Graphene without intermediate oxidation steps. Currently these techniques are the lowest cost production methods for Graphene; however optimization is needed to produce larger Graphene sheets. This optimization is much easier whenthe input graphite has large flakes and higher purity. Canadian Graphene producers such as NanoXplore and Grafoid are leaders in these novel exfoliation techniques. Till-date, this method produces the large-area high-quality flakes that are preferred for fundamental research. However the method is not practical for bulk manufacturing as it is very labour intensive with a low-turn output, very thick developed graphene layer and does not produce uniform quality graphene films.

Nature of graphene produced: Few layers (thickness), μm to cm (lateral), large size and unmodified graphene sheets.

Applications: production of graphene flakes used for fundamental research.

Liquid-Phase Exfoliation Produced Graphene

Among the top-down approach, liquid-phase exfoliation has been considered as one of the most feasible approach for industrial production of graphene due to its scalability, low cost and it is the most common method of producing graphene from bulk graphite. This approach typically involves sonication of graphite or graphite oxide powders in solvents and ultra-sonication-assisted liquid exfoliation can be achieved either using suitable solvents or surfactant/stabilizer molecules in aqueous media. Depending on the graphite precursors, liquid-phase exfoliation of producing graphene has been carried out using:

  I.   Graphite oxide,
  II.   Natural graphite, and
  III.   Graphite intercalation compound

Liquid-phase exfoliation of graphite oxide is now one of the most widely used methods for preparation of graphene. This method begins with intercalation of graphite with strong oxidizing agents followed by expansion of graphite layers via sonication. The reduction of the obtained graphene oxide to graphene is usually conducted by either thermal or chemical approaches. Although this method is capable of high-yield production of graphene, the use of large quantity of acid and oxidizing agents requires time-consuming washing steps and produces hazardous wastes. In addition, the vigorous oxidation of graphite often leads to incomplete restoration of the sp^2 hybrid carbon bonds and presence of residual oxygen functional groups resulting in poor electrical conductance.

Liquid phase exfoliation of natural graphite is easy to implement and can circumvent the oxidation of graphene. This method involves ultrasonic treatment of graphite in solvents such as N-methyl-2-pyrrolidone, N'N-dimethylformamide and γ butyrolactone. Among all the solvents, N-methyl-2-pyrrolidone gives the highest graphene yield due to its surface energy approaching that of graphite that is sufficient to overcome the interacting forces between graphene layers. Although technically it is similar to the liquid-phase exfoliation of graphite oxide, this method is unique with the absence of oxidative intercalation steps. Graphene prepared by this method was demonstrated to have low concentration of defects and oxygen functional groups. However, the yield is usually very low (~1 wt.%) as only the surface layers of graphite were peeled off during sonication.

Liquid-phase exfoliation of graphite intercalation compounds for production of graphene begins with intercalation of graphite followed by expansion of graphite via rapid increase in the vapor pressure of the volatile intercalated substance under microwave or thermal treatment and it has attracted great interest recently. As nonoxidative agents are applied for intercalation of graphite and microwave or thermal treatment of graphite intercalation compounds leads to large expansion of graphite, high-yield production of graphene with high quality can be achieved using this method. For example, it was reported that, by solvothermal-assisted exfoliation of expanded graphite obtained from graphite intercalation compounds in acetonitrile, Qian et al. successfully prepared monolayer and bilayer graphene with 10-12 wt% yield without significant structural defects. However, these recipes are limited by using either poisonous chemical agents or dangerous chemical reactions.

Nature: Single and multiple layers (Thickness), μm or sub-μm (Lateral), Unmodified graphene and inexpensive.

Application: Polymer fillers, transparent electrodes and sensors.

Electrochemical Exfoliated Produced Graphene

Electrochemical methods to prepare graphene materials typically utilizes the application of electric current to encourage structural expansion through cathode reduction or anode oxidation of a graphite working electrode normally in form of rod flake or HOPG, in a liquid electrolyte (aqueous: acidic or surfactant, or non-aqueous: organic). In general, during the electrochemical exfoliation approach, upon application of potential to the electrodes, intercalation of anions or cations from the electrolyte results in the production of graphite intercalation compound, which are then further exfoliate into graphene layers that disperse in the electrolyte. A common method is to intercalate anions into graphite anodes to exfoliated graphene sheets with surface oxidation or chemical functionalization. Whereas, utilizing cations to intercalate graphite cathodes have shown to produce graphene sheets with a lower degree of surface oxidation or chemical functionalization, thereby retaining the pristine nature of graphene. Electrochemical approaches using anions or cations for intercalation, HOPG and exfoliation of graphene flakes.

Nature: Single and few layers (Thickness), 500–700 nm (Lateral), Single step functionalization and exfoliation; high electrical conductivity of the functionalized graphene.

Application: It opens up new opportunities for creating of multifunctional nanostructured carbon materials, dispersion and hybrid composites, used in catalysis, power engineering, biomedicine, smart materials and systems.

Chemical Exfoliated Graphene Production

Chemical method is one of the best appropriate methods for synthesis of graphene. In chemical method producing colloidal suspension which modify graphene from graphite and graphite intercalation compound. Different types of paper like material, polymer composites, energy storage materials and transparent conductive electrodes used chemical method for production of graphene. Chemical exfoliation is a two-step process. At first reduces the interlayer van der Waals forces to increase the interlayer spacing. Thus it forms graphene intercalated compounds. Then it exfoliates graphene with single to few layers by rapid heating or sonication. For single-layer graphene oxide uses ultrasonication and various layer thicknesses using Density Gradient Ultracentrifugation. Graphene oxide is readily prepared by the Hummers method involving the oxidation of graphite with strong oxidizing agents such as $KMnO_4$ and $NaNO_3$ inH_2SO_4/ H_3PO_4. Ultrasonication in a DMF/water (dimethyl formamide) mixture used and produced single layer graphene. Single layer graphene sheets are dispersed by chemical reduction with hydrazine monohydrate and polycyclic aromatic hydrocarbons has used for synthesis of graphene. Using a dendrict precursor transformed by cyclo-dehydrogenation and planarization produce small domains of graphene and Poly-dispersed hyper branched polyphenylene, precursor give larger flakes. Thermal exfoliation and reduction of graphite oxide also produce good-quality graphene, generally referred to as reduced graphene oxide.

This method is somewhat similar to the mechanical exfoliation method except that here the graphite is immersed in a mixture of sulphuric acid and nitric acid in order to increase the spacing between different layers of graphene present in the graphite material, so that these can be extracted easily. By adding layers of atoms between graphite layers facilitate easy peeling off graphene layers.

Nature: Mostly single layer (Thickness), 300–900 nm (Lateral). Unmodified graphene; scalable

Application: Conductive inks and paints polymer fillers, battery electrodes, super capacitors and sensors.

Chemical vapor deposition produced graphene.

Among the bottom-up methods for producing graphene, CVD technique is one of the most investigated approaches, especially holding promises in producing large-area graphene on inexpensive transition metals. The principle of chemical vapor deposition is to decompose a carbon feedstock with the help of heat to provide a source of carbon, which can then rearrange to form sp^2 carbon species, normally achieved over a catalyst. In case of graphene, generally hydrocarbon gases (*e.g.,* methane gas, CH_4) are generally utilized as feedstock and successful catalysts by far are transition metal surfaces (*e.g.,* Ni and Cu). The chemical vapor deposition process mainly depends on the carbon saturation of a transition metal upon exposure to a hydrocarbon gas at a higher temperature. It is likely known method to produce graphene on various substrates like Cu, Ni, Co, Si. In this method, the substrate is placed in the heated furnace and the carbon source gas is passed through it. The carbon is deposited on the surface of the substrate after the chemical reaction such as a mixture of gases like H_2, Ar, CH_4 in controlled amount is allowed to flow in a horizontal furnace and the substrate heated to the temperature in the range of 700 ℃ -1150℃ to obtain thin graphene layer as shown in the figure below:
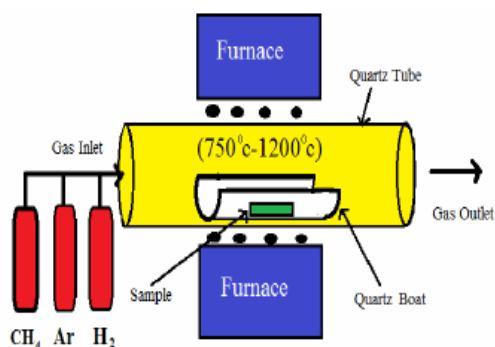

Figure 1.Graphene layer Synthesis by chemical vapor deposition method.
Source: Randhir singh Dinesh Kumar & CC Tripathi (2015)

In this process,graphene is formed by hydrocarbon decompositon on the metallic substrates,thick layers of graphene can be formed even on insulating substrate, carbon is absorbed from the carbon source onto the heated metallic substrate and graphene has been reported to form on Ni substrate by decomposition of ethylene. The deposition of high-quality graphene from chemical vapor deposition process is usually done onto various transition-metal substrates like as Ni, Pd, Ru. Ir and Cu. Different hydrocarbons such as methane, ethylene, acetylene, and benzene were decomposed on various transition metal substrates such as Ni, Cu, Co, Au, and Ru. Single crystals using an ethylene precursor was found to yield. Therefore, this method is widely used because it is suitable for large scale commercial purposes.

Nature: Few Layers (Thickness), Very large (cm) and large size; high quality.

Application: Flexible transparent conductors for organic photovoltaic cells and in field effect transistor (FET), Touch Screen, smart windows, flexible LCD and OLEDS

Graphene Pyrolysis

Solvo thermal method was used as a chemical synthesis of graphene in bottom up process. In this thermal reaction the molar ratio of sodium and ethanol was 1:1 in closed vessel at 220 °C for 72 hours to obtain the graphene precursor: solid solvo-thermal product. This is then rapidly pyrolysed and the remaining product washed with deionized water. The suspended solid is then vacuum filtered and dried in a vacuum oven at 100 °C for 24 hours. Graphene sheets could be smoothly detached by pyrolization of sodium ethoxide using sonication. This produced graphene sheets with dimensions of up to 10μm. The crystalline structure, different layers, graphitic nature, band structure were inveterate by SAED, TEM and Raman spectroscopy. Raman spectroscopy of the resultant sheet showed a broad D-band, G-band, and the intensity ratio of IG/ID*1.16, representative of defective graphene. The benefits of this process were low-cost and easily fabricated of high-purity, functionalized graphene in low temperature.

Yet, the quality of graphene was still not suitable because it comprised a large number of defects.

Nature: Multiple layers of 10μm, high purity functionalized graphene.

Application: Super Capacitors.

Graphene epitaxial growth.

Epitaxial thermal growth on a single crystalline silicon carbide (SiC) surface is one of the most praised methods of graphene synthesis. The term 'epitaxy' was derive from the Greek word 'epi' which means ''over'' or ''upon'' and 'taxis' which means ''order'' or ''arrangement''. When the deposition of a single crystalline film on a single crystalline substrate produces epitaxial film, the process is known as epitaxial growth. It fabricates high-crystalline graphene onto single-crystalline SiC substrates. There are two general epitaxial growth processes depending on the substrate, homo-epitaxial and hetero-epitaxial growth. When the film deposited on a substrate is of the same material it is known as a homo-epitaxial layer, and if the film and substrate are different materials it is called a hetero-epitaxial layer. Sic first used as on electrical measurements on patterned epitaxial graphene. The growth rate of graphene on SiC depends on the specific polar SiC crystal face and graphene forms much faster on the C- than on the Si-face. On the C-face, larger domains (*200 nm) of multilayered, rotationally disordered graphene are produced while On the Si-face, UHV annealing leads to small domains, *30–100 nm.Growth on SiC. Gold and grey spheres represent Si and C atoms, respectively. At elevated T, Si atoms evaporate (arrows), leaving a carbon-rich surface that forms graphene sheets.

Graphene on molecular beam epitaxy is widely used and well suited for the deposition and growth of compound semiconductors, such as III-V, II-VI. It was used to grow graphitic layers with high purity carbon sources on a variety of substrates such as SiC, Al2O3, Mica, SiO2, Ni, Si, h-BN, MgO, and so on in the 400 – 1100 °C range. However, these films have a large domain size distribution of defective crystals with lack of layer control, because MBE is not a self-limited process relying on the reaction between the deposited species. Epitaxial graphene growth on SiC has been visualized as a very promising method for large scale production and commercialization of graphene for applications into electronics. Hence, graphene on SiC produces high-frequency electronics, light emitting devices, and radiation hard devices although this process is very expensive.

Nature: Few layers Up to cm size and Very large area of pure graphene.

Application: production of high-frequency electronics, light emitting materials and radiation hard devices, Circuits, Transistors, Memories and semiconductors.

Graphene unzipping.

Chemical and plasma-etched method uses in unzipping a carbon nanotube. Graphene nanoribbon (GNR) defines a thin elongated strip of graphene which demonstrates straight edges. Transformation of electronic state from semimetal to semiconductor depends on the width of nanotube. Multi-layer graphene or single layer graphene produces if the starting nanotube is multi walled or single walled. The width of the nano-ribbons thus produced depends on the diameter of the precursor nanotubes. Multi-walled carbon nanotubes established by lithium (Li) and ammonia (NH_3). Liquid (NH_3) (99.95 %) and dry tetrahydrofuran (THF) used in growth of Multi-walled carbon nanotubes (MWNTs) retaining the dry ice bath temperature of -77 ℃. It was found that *60 % fully exfoliated and (0–5 %) unexfoliated or partially exfoliated nanotubes of Multi-walled carbon nanotubes and for Oxidation of CNT's side wall used H_2SO4, KMnO4, and H_2O_2 in step by step process. In controlled unzipping technique a pristine Multi-walled carbon nanotubes (dia. *4–18 nm) suspension was put on to a Si substrate pretreated with 3-aminopropyl-

triethoxysilane, a polymethyl methacrylate solution. Therefore a single- to few-layer graphene nanoribbon also depends on the plasma etching time.

Another method for unzipping Multi-walled carbon nanotubes to Graphene nanoribbons used electric field. An electric field was applied to a single Multi walled nanotube using a tungsten electrode and perceived that the noncontact end of the Multi walled carbon nanotube started unwrapping and forming graphene nanoribbon. The fabrication process of graphene nanoribbons achieve a high-purity, defect-free controlled synthesis process for scalable device in modern electronics.

Nature: Single or Multiple Layers, Few μm long nano- ribbons and Size controlled by selection of the starting nanotubes.

Application: Electrode material for batteries and super capacitors, polymer composites to lower the permeability of gases (alk-GNRs) ,food packaging and light weight mobile gas storage(composite films).

Other Methods Of Graphene's Production

There are several other ways for graphene's production such as electron beam irradiation of polymethylmethacrylate nanofibres, arc discharge of graphite, thermal fusion of polycyclic aromatic hydrocarbons, and conversion of nano diamond. Graphene can synthesis by arc discharge method in the presence of H_2 atmosphere with two to three layers having flake size of 100–200 nm. By rapid heating process Arc discharge in an air atmosphere resulted in graphene nano sheets that are 100–200 nm wide predominantly with two layers. The conditions that are favorable for obtaining graphene in the inner walls are high current (above 100 A), high voltage (50 V), and high pressure of hydrogen (above 200 Torr). The vintage of graphene layer depends strongly on the initial air pressure. He and NH_3 atmosphere are also used as arc discharge method. In Helium atmosphere has considered gas pressure and currents to obtain different number of graphene sheets. In molecular beam deposition technique used ethylene gas source which deposited on a nickel substrate. Large-area, high-quality graphene layers were produced dependent on cooling rate.

Nature: In Arc discharge method, single, bi and few layers, Few 100 nm to a few μm and can produce ~10 g/h of graphene.

Mass Production Methods of Graphene

Small sheets and large-area films are two major forms of graphene used for various applications. Small graphene sheets can be used in composites, functional coatings, conductive inks, batteries and super capacitors. Large-area graphene films can be used as transparent electrodes in touch panels, displays and photovoltaic devices with potentially low cost, and more importantly, they are expected to be used in next-generation electronics and optoelectronics such as flexible and wearable devices. Exfoliation of bulk graphite (the top-down approach) is the most commonly used method for the mass production of small graphene sheets. This can be through direct exfoliation in a liquid, with or without the use of a surfactant, or in the solid state by edge functionalization, or by first inserting a chemical species between the graphene layers in graphite to weaken their interaction followed by exfoliation. Bottom-up approaches such as substrate-free chemical vapour deposition (CVD) and solvothermal and combustion processes have also been developed. Depending on the strategy used, there are considerable differences in yield, efficiency, cost, accompanying pollution, ease of production and scalability of the manufacturing process, and in the morphology, structure and properties of the products such as thickness, lateral size, surface chemistry, solubility, defect and impurity contents, and electrical and thermal conductivities. To produce uniform monolayer and few-layer graphene sheets with high yield and high efficiency is a universal challenge for all these mass production methods.

Chemical assembly of small graphene sheets and CVD are two methods to produce large-area graphene films. Chemical assembly can be easily realized on various substrates at low temperatures, but the films obtained suffer from poor quality, for example low electrical conductivity. CVD produces high-quality graphene films by the catalytic decomposition of hydrocarbons on a metal (for example, Cu, Ni, Pt or alloy) surface at high temperatures, and the films are then transferred to transparent substrates such as glass and polymers by etching away the metal or by non-destructive electrochemical bubbling for transparent conductive film applications. Roll-to-roll CVD growth and transfer techniques have been developed to fabricate large-area transparent conductive film. Films produced over a large area, however, usually show performance inferior to high-end indium tin oxide films but with higher cost. How to realize direct growth of large-area uniform defect-free few-layer graphene films on arbitrary substrates, and how to transfer the films intact and cleanly from a metal substrate without sacrificing it, so that it can be re-used, are two big challenges for the CVD production of high-performance, low-cost graphene transparent conductive films.

CONCLUSION

Although the large-scale production of graphene materials has been realized, many issues need to be addressed to advance their industrial applications. As any other product, the cost/performance ratio is the greatest concern for industries when determining whether graphene can be used in their products. To compete with existing materials, the cost of graphene is a big problem. Improving the controllability of mass production techniques to produce uniform graphene sheets, realizing direct growth of large-area, uniform, defect-free, few-layer graphene films on arbitrary substrates at low temperatures, and the efficient, intact and clean transfer from metal substrates without sacrificing the

metals so that they can be re-used are still challenges that need to be overcome. Methods for the sorting, modification, functionalization, stable doping and dispersion of graphene in various matrices are also required for its more universal use. Where and how far will graphene materials go, and when will graphene manufacturers start to make a profit from the material? The biggest challenge is to find 'killer' applications that demand a large quantity of graphene. Maintaining close collaboration with downstream application industries is necessary for the development of future applications. But no material can do everything, and graphene has to find its proper use. Graphene manufacturers must be very careful, when expanding their production scale, to ensure that there are appropriate uses for the material.

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