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GRAPHENE: A FASCINATING MATERIAL

Shahnawaz Uddin[1] and Iffat Rehman Ansari[2]

[1,2] *University Women's Polytechnic, Aligarh Muslim University, Aligarh 202002, U.P., India*

Graphene: Inside-Outside

ABSTRACT

Graphene may be the most fascinating 2D material ever synthesised and it is supposed to be the most ultimate and fundamental building block, which has the ability to create various carbon-based materials such as graphite, fullerene and carbon nanotubes. Due to the presence of geometrical electronic structure of graphene, it has diverse chemical, electronic and magnetic properties. One of the remarkable electronic properties of graphene is the presence of charge carriers whichare rooted on the honeycomb lattice of the carbon atoms, and behaves such as they would have no mass (Dirac fermions). This insight provides a unique opportunity in such a way that the honeycomb lattices of materials other than carbon can be created, the effects conferred by the atoms can be combined with those conferred by the honeycomb lattice and novel materials due to which a variety of unexpected and surprizing properties may emerge. Graphene and graphene-based nanocomposites are the most currently investigated materials in the fields of nanotechnology, electronics, material science, chemistry, physics, and biomedicine because of their fascinating properties and promising applications. With its many unique properties, graphene has shown great potential in various applications of day to day life.

Keywords: Graphene, 2D Material, Carbon Nanotubes, Honeycomb Lattice.

1.1 INTRODUCTION

The humanity has been gifted by many wonderful materials in the universe, one of those is Graphene- world's first 2D material means, it is very thin, i.e., only 1-atom thick sheet-nearly transparent as shown in fig.(1).

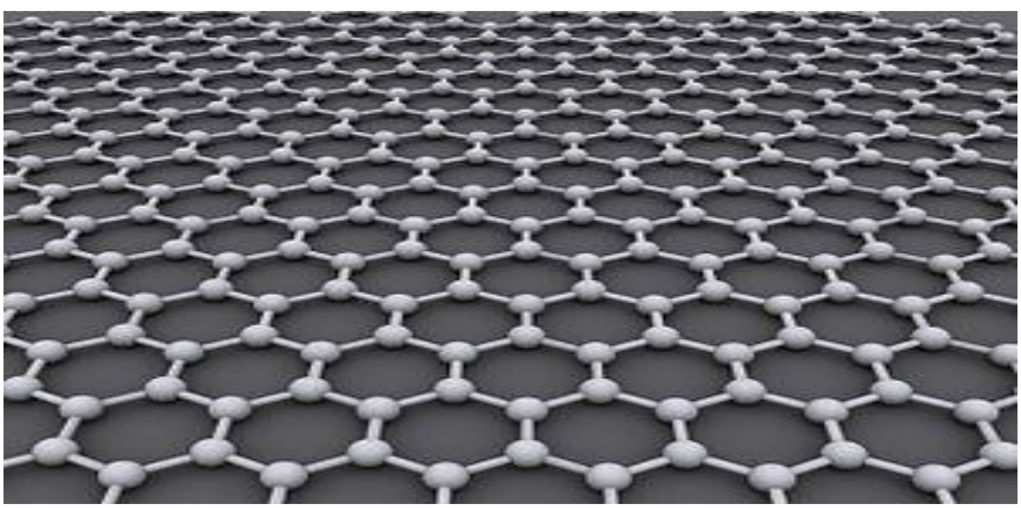

Fig. (1) Graphene: Atomic-scale Honeycomb Lattice made of carbon atoms

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Graphene is the strongest & thinnest material known to exist for its remarkably low weight (more than 100 times stronger than steel) yet incredibly flexible and it conducts electricity &heat with very high efficiency.While many scientists had theorized about graphene for decades, it was first produced or isolated in the labat the University of Manchesterin 2004 [1] as shown in fig.(2) by scientist Andre Geim and Konstantin Novoselov. In 2010, they won the Nobel Prize in Physics "for ground breaking experiments relating the 2D material graphene". Since it is 2D material virtually, it interacts oddly with electromagnetic waves and with other materials. Researchers have recognized and acknowledged that graphene has bipolar transistor effect, ballistic transport of charges and large quantum oscillations.IDTechEx released and provided us a latestgraphene material market report (Graphene Markets, Technologies and Opportunities 2014-2024) in which they predict that the graphene market (at the material level) will grow and raise from approximately $20 million in 2014 to over $390 million in 2024 - a 44% yearly CAGR (Compound Annual Growth Rate) from 2014as shown in fig. (3).

Fig. (2) A lump of graphite, a graphene transistor and a tape dispenser. Donated to the Nobel Museum in Stockholm by Andre Geim and Konstantin Novoselov in 2010.

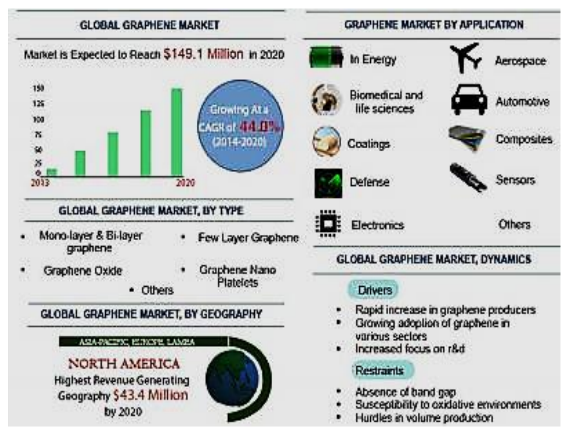

Fig. (3) Graphene Markets, Technologies and Opportunities 2014-2024.

II STRUCTURE

Graphene is basically a crystallineallotrope of carbon in which the atoms are densely packed and they have a regular sp^2-bondedatomic-scale chicken wire that is hexagonalpattern and shape as shown in fig. (4) [2-4]. In other words, it is the basic structural element of many allotropes such as graphite, charcoal, carbon nanotubes and fullerenes. As far as these carbon atoms are concerned, they are bound by strong bonds within the plane into a honeycomb array consisting of six-membered rings. The well-known and very famous 3D graphite crystal is formed by stacking of these layers on top of each other. Thatswhy, it is supposed to be a fundamental and elementary building block for graphitic materials of all other dimensionalities. It can be available in many shapes and forms such as wrapped up into 0D fullerenes, rolled into 1D nanotubes or stacked into 3D graphite as shown in fig. (5). The monocrystalline graphiticfilms are also possible, that are few atoms thick, metallic, and having high quality but never stable under

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ambientconditions. These films are basically two-dimensional semimetal having a very little overlap between valence and conductance bands, and they show a strong ambipolar electric field effect [5].

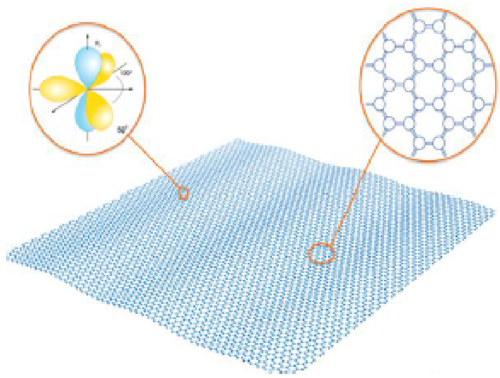

Fig. (4) Graphene: 2D crystal of carbon atoms, arranged in a honeycomb lattice, each carbon atom is sp^2 hybridized & is bound to its 3-neighbors

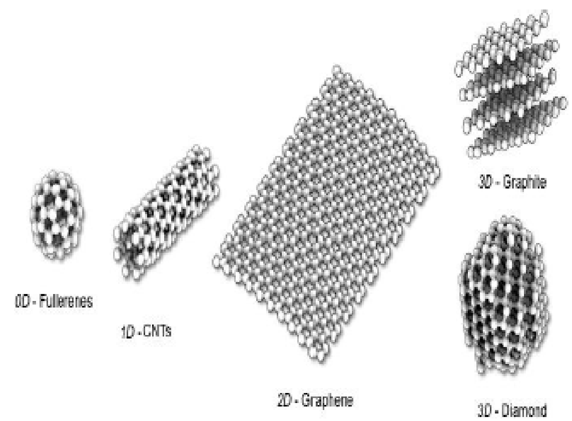

Fig. (5) Different forms of Graphene

III CHEMICAL PROPERTIES

As far as chemical reactions are concerned, graphene is one of the most reactive form of carbon. It is the only form of carbon in which each single atom due to the 2D structureis exposed for chemical reaction from both the sides as shown in fig. (6), and at the corner of graphene sheets, carbon atoms have very special type of chemical reactivity. It is easy to burn graphene at very low temperature (around 350 °C), and it has the highest ratio of edgy carbons as compared to same type of materials like carbon nanotubes. Graphene is usually modified and improved with oxygen- and nitrogen-comprising functional groups. If graphene is encapsulated in hexagonal boron-nitride, then this type of encapsulation makes graphene almost independent to the ambient atmosphere and, also permits the use of boron nitride as an ultrathin top gate dielectric [6].

IV ELECTRONIC PROPERTIES

Graphene is actually a zero-overlap semimetal of very high electrical conductivity having holes and electrons as charge carriers. It is very easy for electrons to flow through graphene than through even copper as shown in fig. (7). As far as graphene sheet is concerned, the electrons travel very fast through it approximately one hundredth that of the speed of light just like they carry no mass. It has high charge carrier mobility around 10,000 cm^2/Vs, and in some cases 200,000 cm^2/Vs were obtained.Graphene is around 10^6times more conductive electrically measured at room temperature than copper [7]and inside graphene, electrons behave as light ("Massless Dirac fermions") [8]. As far as graphene is concerned, it has tunable electronic properties (bandgap for transistors, FETs) [9]. When this property is combined with the remarkable electrical transport properties of graphene, then this type of electrostatic

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bandgap control suggests novel nanoelectronic and nanophotonic device applications based on graphene [10]. Graphene also conducts heat even better than diamond (around 5000 W m^{-1} K^{-1}) [11].

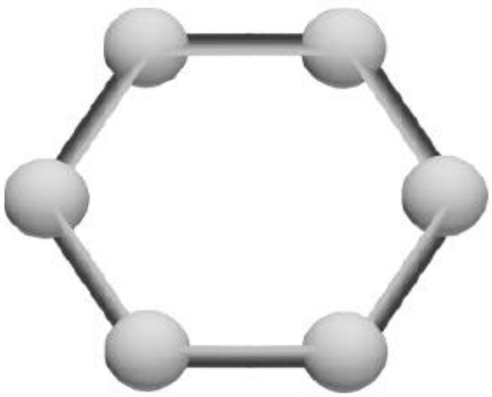

Fig. (6) Graphene atoms exposed on both sides for chemical reaction

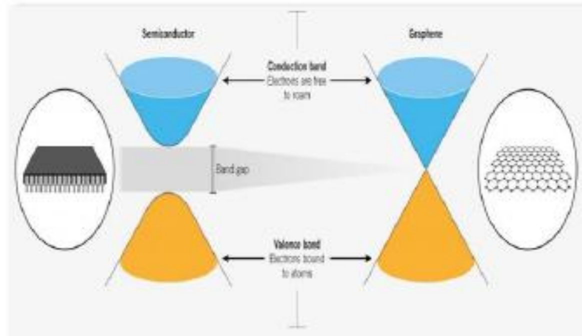

Fig. (7) In an insulator or semiconductor, an electron bound to an atom can break free only if it gets enough energy from heat or passing photon to jump the 'band gap'. But in graphene the gap is infinitesimal. This is the main reason why graphene's electron can move easily and very fast.

V MECHANICAL PROPERTIES

In order to calculate the strength of graphene, a techniquecalled Atomic Force Microscopywas used by scientists. Graphenewas found to be more than 100 times stronger than steel and harder than diamond.It is supposed to be one of the thinnest material imaginable (around 0.345 nm thick) [12, 13].The tensile strength of graphene is around 1TPa as depicted in fig.(8), and it is stretchable upto 20% of its original length. The mechanical properties of graphene find applications into making of super strong composite materials of new generation and when combined with its optical properties, it is very useful for making flexible displays as shown in fig.(9).

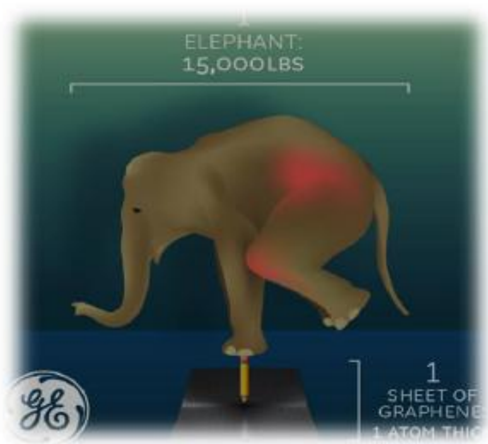

Fig. (8) Tensile Strength of Graphene is very high

Fig. (9) Flexible Displays

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VI THERMAL PROPERTIES

Graphene is supposed to be a perfect thermal conductor. It has higher thermal conductivity of value greater than 5000 W/m/K at room temperature as compared to other carbon structures such as carbon nanotubes, graphite and diamond. Graphite being a 3D version of graphene shows a thermal conductivity about 5 times smaller (1000 W/m/K). The graphene has isotropic (that is same in all directions) type of ballistic thermal conductance. The high electron mobility and high thermal conductivity of graphene are extremely helpful in making chips which are not better at dissipating heat as illustrated in fig. (10), but fast as well.

VII OPTICAL PROPERTIES

It is the fact that graphene is only one atom thick, but is still visible to the naked eye. Fig. (11)depicts this property. When light is passed through the graphene, it absorbs around 2.6% of green light and 2.3% of red light due to its exceptional and unique electronic properties. Many researchers have found that it is able to make a graphene film which can absorb around 95% of light falls on it.Graphene is transparent and it is one atom-thick layer sheet which absorbs around 2.3% of visible light [14].

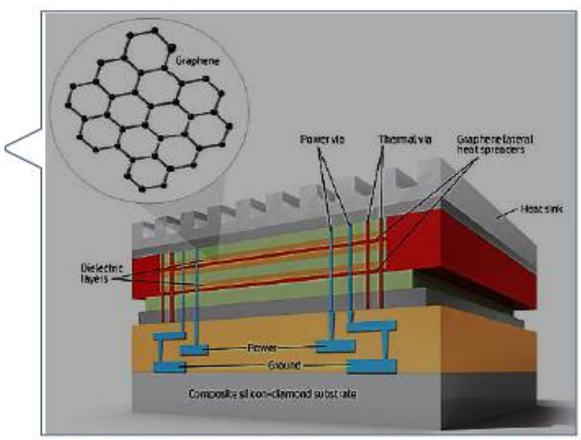

Fig. (10) This schematic shows a 3D stacked chip with layers of graphene acting as heat spreaders

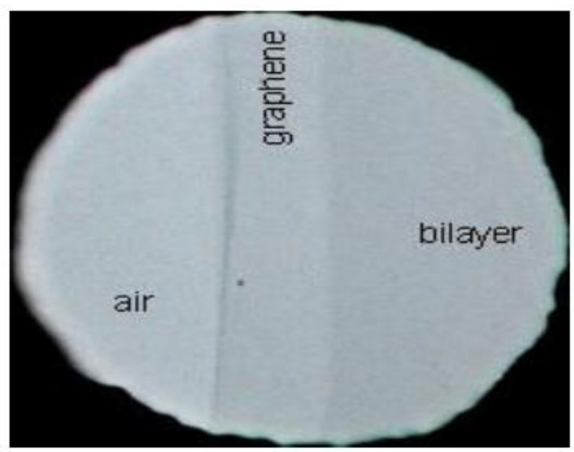

Fig. (11) Photograph of graphene in transmitted light: 1-Atom thick crystal can be seen with the naked eye

VIII APPLICATIONS

According to 2015 study, graphene is not used in commercial applications, but several have been proposed and many of them are under active development, in a number of areas like electronics, biological engineering, filtration, lightweight/strong composite materials, photovoltaics and energy storage. Sometimes, graphene is produced in the form of powder and as a dispersion in a polymer matrix. This type of dispersion is supposed to be more suitable for advanced composites, paints and coatings, lubricants, oils and functional fluids, capacitors and batteries, applications of thermal management, display materials and packaging, solar cells, inks and 3D-printers' materials, and barriers and films.

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(a) Biomedical

In order to analyze DNA, graphene can be used at a record-breaking pace. One of the physicist in the US has proposed a new way of reading the sequence of chemical bases in a DNA strand which is performed by sending the molecule through a tiny slit in a graphene sheet as depicted in fig. (12).

(b) Integrated Circuits

The high carrier mobility and low noise properties of graphene allow it to be used as the channel in a field effect transistor.The Processors using 100 GHztransistors on 2 inch (51 mm) graphenesheets are possible. The integrated circuits based on graphene as shown in fig. (13), canhandle frequencies of the order of around 10 GHz. Transistors printed on flexible plastic can operate at around 25 GHz and terahertz speed transistors are also compatible with it. In radio frequency electronics, graphene has found much interest and attraction as a future channel material due to its superior electrical properties. Fabrication of a graphene integrated circuit without significantly degrading transistor performance has proven to be challenging, posing one of the major bottlenecks to compete with existing technologies [15].

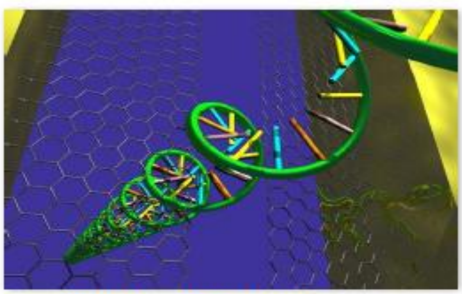

Fig. (12) DNA Structure

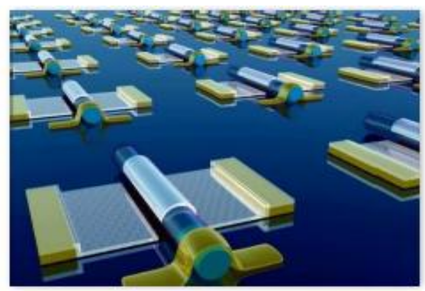

Fig. (13) Integrated Circuit with FIN FETs

(c) Optical Electronics

Graphene is supposed to be a good candidate for transparent conducting electrodes as shown in fig. (14), due to high electrical conductivity and high optical transparency. It is one of the strongest material ever measured and is around 200 times more stronger than steel (around 1100 TPa/ 125 GPa). It has flexibility and can be stretchable as well. In fact, it is the first 2D crystal which is of elastic type [16].Graphene also works very fairly in optoelectronic applications like touchscreens, liquid crystal displays, organic photovoltaic cells, and organic light-emitting diodes due to its mechanical strength and flexibility as compared to indium tin oxide that is brittle in nature.

(d) FiltersDesalination

As far as desalination is concerned, graphene oxide filters givebetter performance as compared to other techniques by a significant margin through very precise control over the size of the holes in the graphene sheet.

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Ethanol distillation: Graphene oxide membranes could transform the economics of biofuel production and the alcoholic beverage industry since they allow only water vapor to pass through them and are impermeable to other liquids and gases.Graphene can be used as a membrane to separate liquids. It provides more efficient desalination plants and has found huge progress in water purificationand treatment in developing countries as shown in fig. (15).

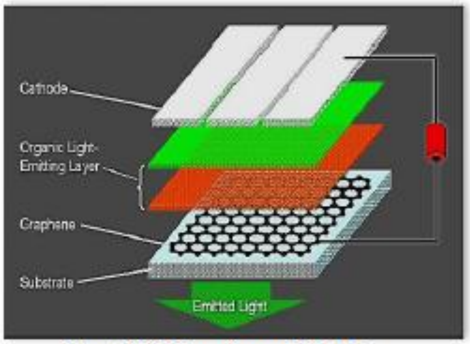

Fig. (14) Graphene OLED

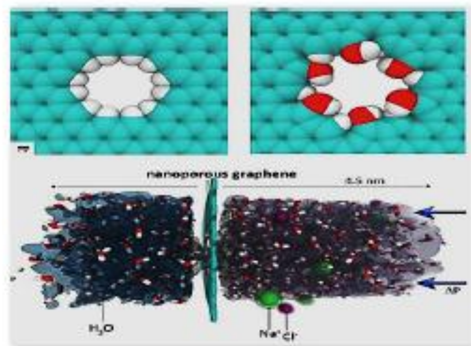

Fig. (15) Water Filtration

(e) Solar Cells

In dye sensitized solar cells, graphene is supposed to be a promising material for photo-electrochemical energy conversion as shown in fig. (16). In order to fabricate the transparent, conductive, and ultrathin graphene films, exfoliated graphite oxide followed by thermal reduction is used. These films show a high conductivity of the order of 550 S/cm and a transparency of more than 70% over the wavelength ranging from 1000-3000 nm.

(f) Energy Storage Devices

Another important application of graphene lies in the formation of conductive plates of supercapacitors as given in fig. (17), due to its extremely high surface area to mass ratio. It is expected that graphene could be used to make supercapacitors having high energy storage density than is presently available.

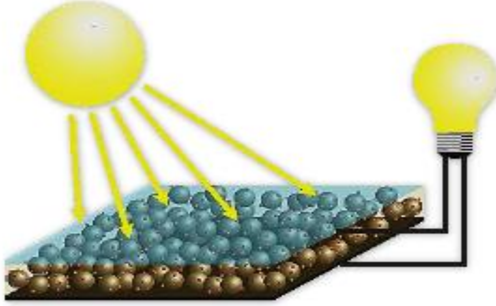

Fig. (16) Graphene Solar Cell

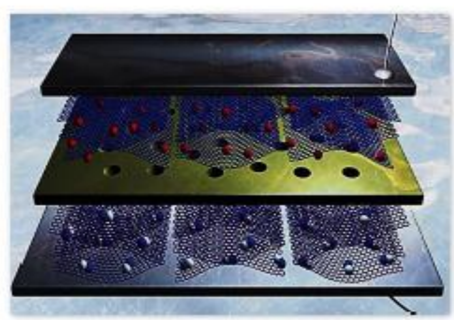

Fig. (17) Graphene Supercapacitor

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(g) Anti-Bacterial

The Chinese Academy of Sciences in 2010 has found that as far as the sheets of graphene oxide are concerned, they are highly effective to kill bacteria as shown in fig. (18), such as Escherichia coli. It means that graphene could be used in applications like hygiene products or packaging that will help in keeping food fresh for much longer time.

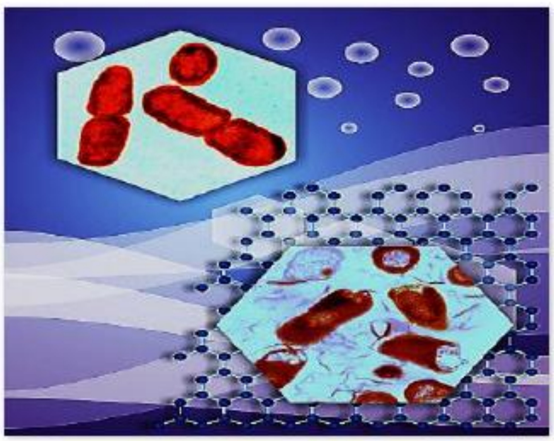

Fig. (18) Bacteria Structure

Fig. (19) Graphene in other Applications

(h) Other Applications

- Nanoribbons
- Infrared Detectors
- To detect Single-Molecule Gas
- Materials having Piezoelectric Effect
- Energy Conversion
- Complex/ Composite Materials
- Liquid Cells used in Electron Microscopy
- Materials used for Thermal Management
- As Optical Modulators
- As Chemical Sensors

IX CONCLUSION

This article discusses the structure, properties, and applications of graphene. It also briefs the exfoliation synthesis process of graphene production. From the recent technology developments (especially electronics), the importance of graphene is felt in all spheres of life and the attitude of researchers towards graphene is changing. Despite the media hype, the success of graphene will not be overnight, the people must be vigilant and patient. From the point of view of manufacturer and consumer, how to utilize graphene in a most beneficial manner- is the main challenge

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before the industry. There may be various unknown properties of graphene that will drive research about graphene to record levels and will continue to shine out as a unique & fascinating material as far as the field of material science is concerned. Researchers are actually working in the area of non-electronic properties of graphene and trying to bring up amazing phenomena that may be proved equally interesting, fascinating and sustain the graphene boom. And the logo **"Graphene: inside-outside"** may be going to get realized very soon.

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