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FUTURE APPLICATIONS OF GRAPHENE: THE EXCEPTIONAL MATERIAL

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ABSTRACT

Amongst the most favorable materials today, Graphene has captured interest of many scientists from various fields including Photonics, Energy, Composites and Electronics. This carbon allotrope has gained attention since 2010 when the Nobel Prize (Physics) was given for groundbreaking testing with 2D graphene. Nanomaterials synthesis based on Graphene show distinctive features and graphene gained interest with researchers which is rapidly growing. The planet's thinnest material is on the brink of bringing in a revolution into our world affecting every facet of our lives. The remarkable properties of graphene and the immense potential it offers has created lot of fascination in this 2-dimensional and 1-atom thick wonder material. We present a study to help comprehend Graphene, its structure and stability. Its unique properties give it an edge over other similar materials. It's envisaged that in times to come it will be all pervasive in life around us. The diverse qualities have made graphene popular for many creative products in the industry. A lot of research with Graphene pivots around Biomedical applications as its specific and unique electronic and mechanical properties makes it a powerful candidate. We present some applications of Graphene expected to bring a sea change soon.

Keywords: *Graphene, Properties, 2-Dimensional, Atomic Structure, Composites, Extrinsic, Semiconductors.*

Introduction

Graphene has remarkable properties and has great potential. This promising material will open new avenues and markets and the scale of its impact may be compared to the one witnessed during the Industrial Revolution. Its real potential is evident when it is used both in a transformational role or to upgrade a prevailing material. Its wide range of superlatives makes it perfect for innumerable applications. It's incredibly flexible and light weight but multiple times stronger than even steel. It is transparent but also thermally and electrically conductive. It is the first and foremost 2- dimensional material in the world. Single-layer Graphene is many times more thinner than a single strand of human hair and is predicted to revolutionize consumer electronics, water and healthcare. Research in Graphene is making substantial impact in various industries like Defence, Energy, Electronics, Medicine, Transportation, Desalination to name a few. This paper is organized as follows. We first discuss the atomic structure of Graphene followed by its comparison with likewise materials. Stability of Two-Dimensional Graphene is explained next followed by futuristic applications of this outstanding material.

Atomic Structure of Graphene

A monolayer of graphene is visualized as a hexagonal 2-D array of C- atoms with sp^2 hybridization, whereas diamond and amorphous carbon has sp^3 hybridization. A single carbon atom has 4 valance electron and 6 electrons in total that are distributed as $1s^2$, $2s^2$, $2p_x^1$, $2p_y^1$, $2p_z^0$, Fig 1 (a). In sp^3 hybridization, 2s orbital mix with three 2p orbital to form 4 sp^3 orbital. However, in sp^2 bonding, out of four valance electrons only 3 participate in the creation of covalent σ bonds which is in plane. The fourth one does not contribute to covalent bonding, rather it contributes to the formation of out-of plane π band between nearest neighbor carbon atoms as shown in Fig 1(c).

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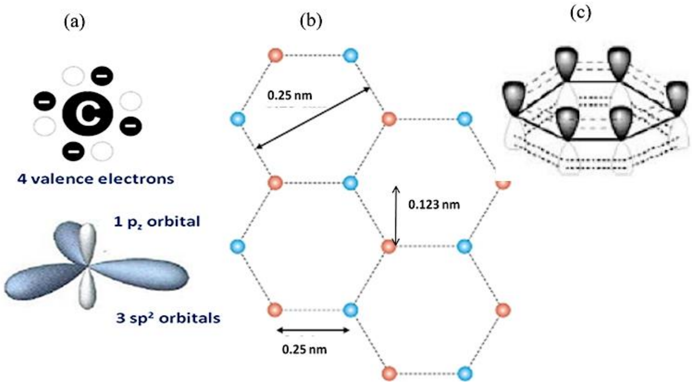


Fig 1: (a) Carbon atom and sp^2 hybridization. (b) Schematic of C- atoms in hexagonal lattice in graphene showing distance between neighboring carbons. (c) Schematic diagrams of formation of sp^2 hybridization in graphene, showing π and σ bonds

The σ bonds are alike to the bonds assembling diamond together and being stronger one. They act as the base of the unique hexagonal structure. They provide analogous remarkable mechanical properties to graphene as in diamond [1,2]. The π bonded electrons contribute in conductivity and govern the interaction of graphene with them and with the outer world. A single layer graphene has lattice constant $a = \sqrt{3}a_0$ where the nearest neighbor interatomic distance is $a_0 = 1.42A^0$ [3]. The interaction between charge carriers of graphene (electrons) and its honeycomb lattice results in the electrons to behave as a massless particle. In contrast to non-relativistic particles, which follows the Schrödinger equation, the electrons in graphene moves relativistically and follows Dirac equation and are known as Dirac fermions (Different from high-energy, zero electric charge particles: neutrinos).This is attributed to the linear band structure near the six corner points (Dirac points: at which conduction band and valence band meet) of hexagonal Brillouin zone as shown in Fig 2. The energy-momentum relation for graphene is linear, as a result of which the electrons have zero effective mass. The exceptional electronic properties (refer next section) of graphene are a direct outcome of a zero-gap semimetal structure.

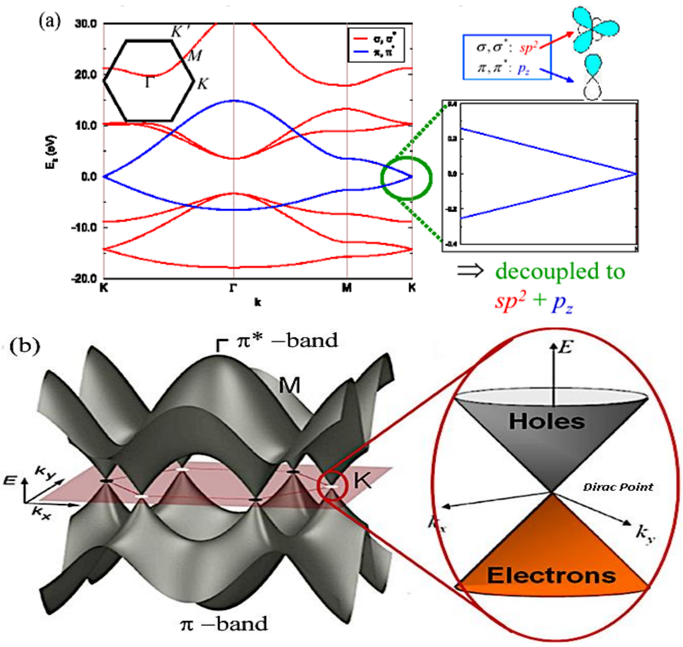


Fig 2: a) Valence and conduction band Structures of graphene in E-K plot [4] b) Band structure of graphene near K Point showing Dirac point and Γ, M and K points [5]

Why Graphene

Metal such as Silver, Aluminum and Copper have the highest conduction among all the materials but their use in devices is restricted due to their high cost and corrosive nature. Extrinsic semiconductors are cheaper and have better electronic properties (larger electron and hole concentrations, hence greater conductivity), hence are always a desirable choice for transistors, solar cells, light emitting diode, integrated circuits and lasers but have lower conductivity and mobility as compared to metals. A comparative study of conductivity and mobility values of some commonly used materials and graphene is shown in Table 1.

Table 1: Conductivity and mobility values of some commonly used materials and graphene [6]

Material	Electrical Conductivity $(\Omega\text{-m})^{-1}$	Electron Mobility (m^2/Vs)
Elemental		
Ag	6.30×10^{7}	-
Cu	5.96×10^{7}	-
Si	1.56×10^{-3}	0.14
Ge	2.2	0.382
Compounds		
GaP	10^{-5}	0.05
GaAs	10^{-6}	0.85
Graphene & related materials		
Graphite	3×10^{4}	10
Graphene	2×10^{5}	10^{3}

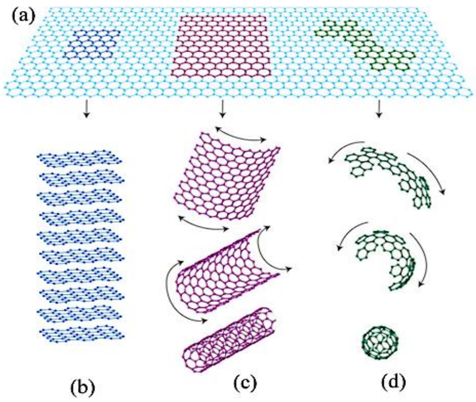


Fig. 3: Depictions of a) Graphene, b) Graphite, c) Carbon nanotubes and d) Buckyballs [9]

By comparing the values of conductivity and mobility of various materials with that of graphene, Table 1, it is observed that graphene has 10-100 times higher mobility than the presently used materials. Owing to its high mobility of graphene, it becomes a popular choice for future applications [7]. The easiest way to understand graphene is comparing it with graphite. Graphite is used world-wide in the form of pencil. A pencil has ability to write due to the weak forces linking the sheets which makes them slide over each other. The stacks of graphene individual sheets are bound together by Vander Waals forces to make a piece of graphite. The separation between these sheets has been reported by Bunch et. al [8] to be 0.3nm. Graphene is the term provided to a monolayer of C- atoms packed densely in a 2-dimensional honeycomb lattice. Various carbon forms, with dissimilar dimensionalities can be obtained by this basic structural element. Graphene when rolled up becomes one dimensional carbon nanotube (CNT), when stacked on each other it takes shape of three-dimensional piece of graphite and it can also be converted into fullerene buckyballs which are zero-dimensional, Fig. 3.

Stability of 2D Graphene

In 1962, Hanns-Peter Boehm and co-workers gave the name graphene to single-layer carbon foils by combining graphite and the suffix –ene [10]. Before the graphene invention (2D material), the existence of any two-dimensional material was questionable, in free form as it segregates or decomposes at a finite temperature due to thermal fluctuations [11]. After a large time, span from its discovery researchers were able to find out the mysterious secret behind the stability of graphene. According to them [12] the stability of 2D graphene is ascribed to the fact that the membrane of Graphene is not perfectly flat, Fig 4, rather it has out-of-plane distortions (called ripples) in its lattice. Meyer et al. [13, 14] found ripples of lateral size 5nm and 20 nm inside the graphene membranes.

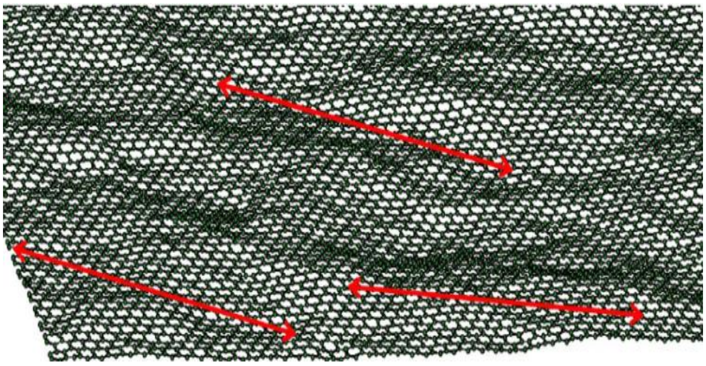


Fig. 4: Diagram showing Ripples at Room Temperature

In 2010, A. K. Geim and K. Novoselov were graced with the Nobel Prize in Physics for their marvelous work of successful extraction of free-standing monolayer graphene from bulk graphite by mechanical exfoliation (also called Scotch tape technique) at Manchester University.

Applications in the Near Future

- **Biomedical**

Graphene based materials like Graphene Oxide, few layer Graphene flakes, pristine Graphene present versatile, unique, and diverse properties and these can be utilized creatively in biomedical industry. Biological agents(antimicrobials), tissue engineering, sensors, transport systems are some of the areas of Graphene applications. Research is ongoing for developing revolutionary and innovative medical equipment that will significantly enhance healthcare, seeing the potential of the graphene's favorable and encouraging properties, Fig.5 [15]

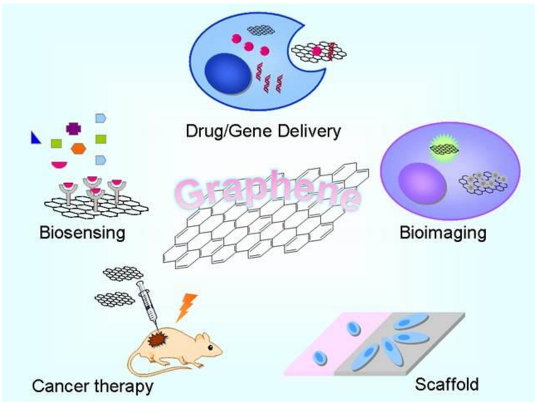


Fig. 5: Biomedical Applications of Graphene

- **Electronics**

Graphene can bring about a paradigm change in the Next-Gen Electronics with bendable phones, faster semiconductors, and transistors, Fig.6. Research is ongoing targeting the challenges in employment of graphene in transistors and reveling the profits over the use of conventional silicon in it [16,17]. Wearable and flexible electronic devices use the benefits of the unique mechanical properties and conductivity of graphene. This wonder material can make a smart phone worn on a wrist a or a rollable tablet a reality. The present-day touch screens for tablets and phones can be improved tremendously by using graphene as a coating. Its capability to conduct electricity at room temperature and thinness (1-atom thick) has spearheaded research to look into its utility as a semiconductor. The computers can be made incredibly faster by using graphene to make its circuitry.

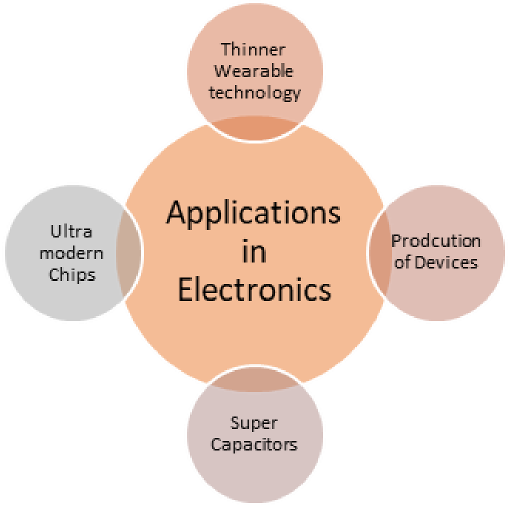


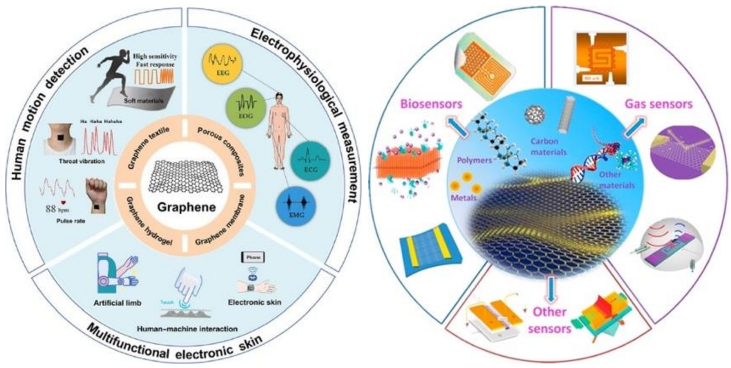
Fig. 6: Popular Applications in Electronics

- **Energy**

Graphene can help charge electric cars and smartphones in minutes. It can enhance the lifespan of lithium batteries tremendously. This indicates that devices can not only charge faster but also contain power for longer period of time. The batteries would be so light and flexible that they can be attached to our body or clothing. This can be a big respite for the soldiers carrying 16 pounds of battery at a time. Huge amounts of power can be provided by Graphene supercapacitors. These would consume much less energy too and could substantially lower the weight of planes and cars. Research is on to investigate its potential in storing solar or wind power.

- **Sensors**

Tiny particles can be detected by ultra-sensitive sensors made of graphene. This can help protect our environment from hazardous particles. In graphene each atom senses the environment and is sensitive to the changes and micro-metre size sensors are possible with graphene. Molecular level events can be detected by these. Graphene coated food packaging can detect rotting food by sensing the changes in the environment thereby preventing disease and wastage of food.



(a) (b)

Fig. 7 (a) Graphne based wearable sensors. (b) Fabrication technologies and sensing applications of graphene-based composite films

Graphene sensors can enhance the vital crops productivity by more effective monitoring. It can help detect dangerous and damaging grasses amongst the crops in the fields. These sensors are so sensitive that they can even help in identifying ideal stretches of land for optimal cultivation given the atmospheric conditions prevalent in that space. Some graphene based wearable sensors, fabrication technologies and sensing applications are depicted in Fig 7, [17]

- **Composites and Coatings**

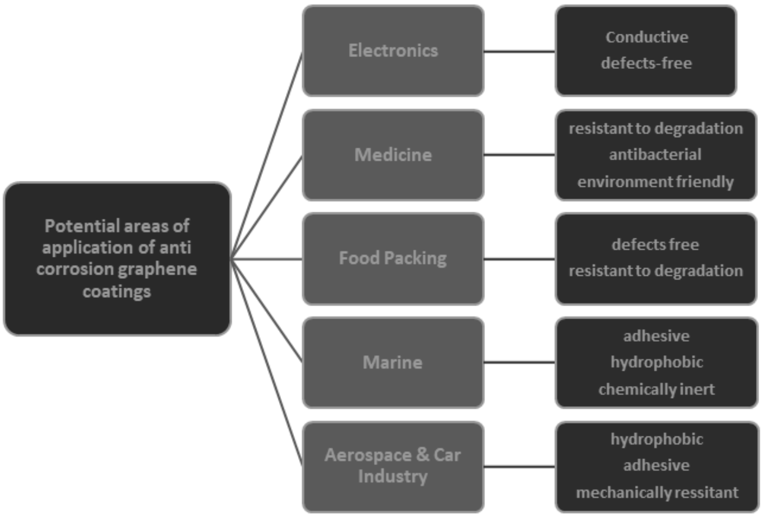


Fig. 8: Potential Areas of Application of anti-Corrosion Coatings

With outstanding qualities of conductivity, lightweight, flexibility and strength, Graphene is a popular choice for creating composite materials i.e combining it with existing products, Fig 8. Combining paint with graphene results in a distinctive coating which arrests rusting. This can prevent deterioration of cars and ships. Applying this coating to stone and bricks weather proves the buildings. Using it in food packaging prevents transfer of oxygen and water into food giving it longer freshness. Sport equipment used in skiing, Formula1 etc too can be enhanced using Graphene coatings and composites. An aircraft wing made from a Graphene composite can result in the safest, strongest, and lightest airplane in the world.

- **Membranes**

Graphene oxide membranes form an ideal barrier when dealing with gases and liquids. They can very constructively separate water from an organic solvent and separate water from a mixture of gases exceedingly effectively. It's believed that they can even stop the hardest gas i.e Helium. Research is on currently to use Graphene for desalination, gas separation and water filtration. Perishable items and food retain their freshness for much longer if the packaging is coated with graphene as it prevents transfer of Oxygen and water. Graphene membranes could also check the CO_2 released by the thermal power stations there by making the environment more heathy. Refer Fig. 9 for recent developments in Graphene based Membranes [18].

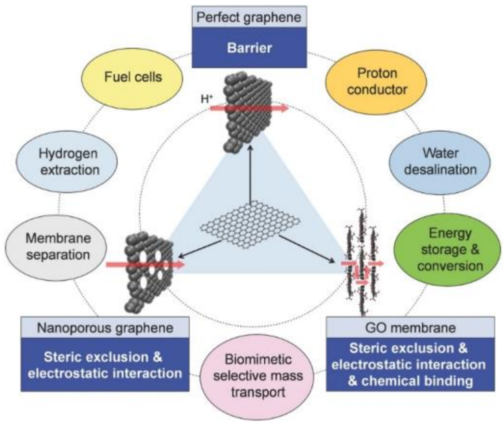


Fig. 9: Recent Developments in Graphene-Based Membranes: Structure, Mass-Transport Mechanism and Potential Applications

Conclusion

Graphene with its extraordinary mechanical, thermal, optical and electronic properties has captured the imagination and interest of increasing number of researchers from diverse fields ranging from flexible electronics to composites. There has been a rapid development in the functionalization and synthesis approaches for Graphene and its derivatives. These have also shown tremendous potential in various fields like Catalysis, Sensors, Energy technology, Composite materials, Nanoelectronics and Biomedical. Graphene- based membranes have helped in the development of separation membranes and filtration due to their unique properties. These are very optimistic and remarkable developments in areas of conversion, energy storage, proton conductors, water desalination, membrane separation etc. The volume of patents and papers related to graphene and graphene-based material are rapidly increasing. In fact it is impossible to do justice to different capability aspects of graphene in one paper. In this article we have introduced upon a few of the recent applications of graphene that is under scrutiny and research. The progress till date has undoubtedly been stupendous but it is also obvious that there is a need for a viable and environment friendly big scale and economical production model for top quality graphene. There are other challenges like understanding toxicity of Graphene and GO (produced by Graphene Oxidation) at in vivo and in vitro levels. A structured standardized study is necessary to rest the safety apprehensions before progressing to mass scale development.

We have focused on the astoundingly exciting and rapid advance in the applications of this remarkable material, Graphene and have reviewed selectively the current areas of research.

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