# Graphene: A Review

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**Abstract –** ***Graphene is first truly two-dimensional crystalline material and it is representative of whole new class of 2D materials. Graphene is a name given to a deceptively simple and tightly packed layer of carbon atoms in hexagonal structure. Being only one atom thick, it is the thinnest compound known to man and the lightest material discovered. The strongest bond in nature, the C-C bond covalently locks the atoms in place giving them remarkable mechanical properties. This paper aims at reviewing the standing of this miracle material. Graphene has leapt to the forefront of material science and has numerous possible applications. One of the most promising aspect of Graphene is its potential as a replacement to silicon in computer circuitry. The discovery of Graphene has completely revolutionized the way we look at potential limits of our capability as Inventors. It is now conceivable to imagine such prospective situations as lightning fast, yet super small computers, flexible displays that we fold and carry in our pockets.***

***Key Words:*** *Graphene, Miracle material, Hexagonal structure, Computer circuitry, Flexible displays.*

## 1. INTRODUCTION

Graphene is a one atom thick flat sheet of $Sp^2$ bonded carbon atoms that are densely packed in a Honeycomb Crystal Lattice. Silicon has constructed the electronics industry a solid base of favorable properties capitalizing on which various advancements in electronics has been made (in terms of speed and size). But now it seems that silicon is approaching its limits [1]. Most of the engineers think that it will eventually become too complicated and expensive to reduce the dimensions of silicon micro-processors. Also, the speed of silicon micro-processors have trapped in the gigahertz range. So as the electronics world is counting for new candidate materials, Graphene seems to offer an extra-ordinary choice. As a conductor of electricity it performs equivalently as copper. As conductor of heat it outperforms all other known materials. It is almost totally transparent, yet very dense, as not even helium, the smallest gas atom, can pass through it. In order to use Graphene for future nano electronic devices it should have a band gap engineered within it, which will decrease its electron mobility to that of same levels which are seen in silicone films. Graphene has swiftly changed its status from being an unwelcomed newbie to a climbing star and to a reigning champion.

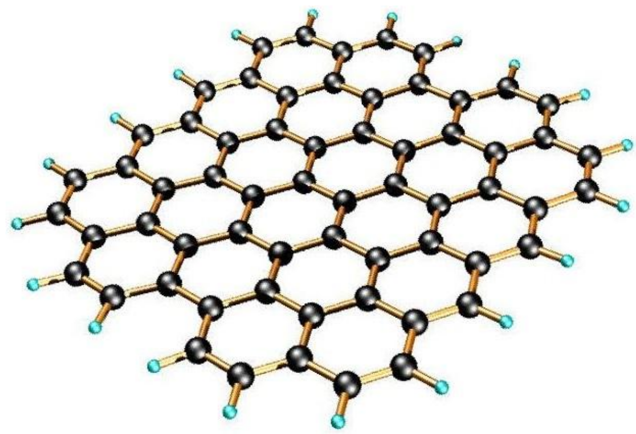

**Fig. 1** Rendition of a 2D sheet of Graphene, showing its hexagonal, honeycomb-like structure.

## 2. HISTORY OF GRAPHENE

Graphene at first, was discussed in 1946, by Canadian physicist Philip Russel Wallace. Wallace didn't believe it was possible to create Graphene, he was interested in studying graphite, the stuff in pencil lead. Graphite, a 3 dimensional honeycomb structure of carbon atoms, was too difficult to handle with the tools which were available with him. Wallace demonstrated that, if you pile enough sheets of Graphene on top of each other, you get graphite. So he used his calculations for Graphene to find information about graphite. Little did Wallace know that his theoretical material could actually be constructed in the real world. One of the very first patents pertaining to the production of Graphene was filed in October of 2002 and granted in the year 2006, Named, "Nano-scaled Graphene Plates," this patent detailed one of the very first mass scale Graphene production processes In 2004, physicists Andre Geim and Konstantin Novoselov were playing with graphite cubes and Scotch tape. They applied tape to a piece of graphite, and then rip the tape off, pulling flakes of graphite with the plate. They did this continuously with the flaked-off graphite, separating it into thinner and thinner flakes, until they ended up with graphite flakes only one atom thick. Materials don't get any thinner than one atom thick, so this stuff was as close to 2 dimensional, as it is physically possible. Geim and Novoselov had invented Wallace's Graphene. Novoselov and Geim received several awards for their pioneering research on Graphene. The growth in this research area has literally exploded since 2005, which eventually lead to an increasingly growing number of papers regarding Graphene. Double layers of Graphene, having distinct properties compared to (single layer) Graphene have been studied thoroughly. Studies at higher magnetic fields are being performed to investigate the fractional quantum Hall effect in Graphene. Furthermore mechanical studies of Graphene shows that it is mechanically very strong, hundred times stronger than the strongest steel.

## 3. PROPERTIES OF GRAPHENE

One of the reasons that Graphene research is progressing so fast is that the laboratory methods making us able to obtain superior quality Graphene are relatively simple and cheap. Many Graphene characteristics measured in tests have exceeded those obtained in any of the other material, with few reaching theoretically predicted limits: room temperature electron mobility of 2.5 X $10^5$ $cm^2$ $V^{-1}$ $s^{-1}$ [2], theoretical limit ~ 2 X $10^5$ $cm^2$ $V^{-1}$ $s^{-1}$. A Young's modulus of 1 TPa and intrinsic strength of 130 GPa very close to that predicted by theory [3]. Complete impermeability to any gases. Capability to bear extremely high densities of electric current, one million times higher than copper. Another property of Graphene is that it can be readily chemically functionalized. However, some of these characteristics have been achieved only for the highest-quality samples. Graphene will be of even greater interest for industrial applications when mass-produced Graphene will have the same outstanding performance as that of the best samples obtained in research laboratories. The electrons pass through the Graphene sheet as if they carry zero mass, as fast as just one hundredth that of the speed of light. Graphene is the most reactive form of carbon. Due to 2D structure of Graphene, each single atom is in exposure for chemical reaction from two sides.

## 4. SYNTHESIS OF GRAPHENE

The market of Graphene is essentially driven by enhancement in the production of Graphene with properties suitable for the definite application, and this condition is to be continued for the next decade or at least until each of Graphene's various potential applications fulfills its own requirements. Currently, there are probably a dozen methods which are used to fabricate Graphene of various size, shapes and quality. In view of the supreme potential of Graphene for commercial and strategic applications, researchers from all over the world are intensively pursuing research and development operations to create a variety of techniques for its synthesis, as evidenced by the huge number of scientific publications and patents which appeared in recent years. Of course, the focus has been on large scale production of high quality Graphene at least cost. Currently, innumerable techniques are usable for the manufacturing of Graphene. However, it can be widely classified into two main categories, i.e. bottom to up (e.g. CVD, epitaxial growth on SiC, arc discharge, chemical synthesis etc.) and top to down (e.g., exfoliation methods) processes. The most common way of Graphene fabrication is exfoliation which finds its roots with a technique that has been around for centuries, writing with a graphite pencil. By writing with a pencil one create many Graphene sheets spread over the paper. Unfortunately this method is uncontrollable because end result comes out to be many sheets of varying thicknesses. If single Graphene sheet is to be studied then it needs to be located. The problem amounts to trying to find a needle in a haystack. Graphene offers numerous opportunities for commercial exploitation because of its boundless potential for applications such as extremely strong and tough composites, touch screens, energy storage, extremely fast transistors and so on. However, to realize its potential for real life applications we need to produce it in mass quantities at an affordable cost, and depending on each application we have to fit it in a suitable form and required quality. In order to meet these difficulties, many efforts are being made by the worldwide scientific community to create innovative approaches for the production of Graphene.

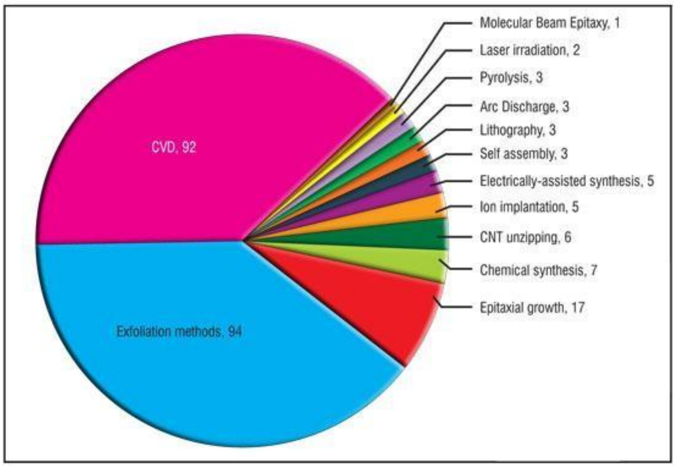


**Fig. 2** Segmentation of Graphene synthesis methods.

Fabrication of Graphene has been differentiated according to the techniques employed by analysing the filed, published and granted patents. Based on this analysis (Fig. 2) it is quite evident that substantial patenting activity is directed towards the development of Chemical Vapour Deposition {92 patents} and exfoliation {94 patents} techniques. Although it is not shown in the pie chart of Fig. 2, it may be noted that exfoliation methods mainly include 1. Mechanical exfoliation of graphite, 2. Liquid phase exfoliation of graphite and 3. Chemical exfoliation of graphite oxide. Other dominant techniques are epitaxial growth on SiC substrates {17 patents}, Chemical synthesis {7 patents} and unzipping of carbon nanotubes {6 patents}. Many of the above mentioned methods have significant ability for scaled-up production of Graphene at an affordable cost. The pie chart also shows other rising techniques like ion implantation, electrochemical deposition, arc discharge, self-assembly, laser irradiation etc. Nickel was the first substrate on which CVD growth of large area Graphene was attempted. These efforts had begun right from 2007 [4].

## 5. APPLICATIONS OF GRAPHENE

The rare electron and thermal transport, barrier properties, mechanical properties and very high specific surface area of Graphene make it a potentially troublesome technology across a raft of industries. In the year 2010, there were more than 400 patents issued on Graphene and 3,000 research papers in total published. The European Union is funding a ten year 1,000 million euro coordination action on this material. South Korea is all set to spend $350 million on commercialization approach and the United Kingdom has proclaimed investment of £50million in a latest commercialization hub. As far as applications are concerned, Graphene based electronics should be mentioned at top. This is because most efforts have so far been concentrated on this direction and companies such as Intel and IBM are funding this research in order to keep an eye on possible developments. As discussed previously Graphene can replace silicon in the electronics industry. Graphene's ability for electronics is usually justified by referring to high mobility of its charge carriers. It is most inevitable that we will see many efforts to develop various approaches to Graphene electronics. Whichever approach suits, there are two immediate challenges. First, despite the recent progress in production growth of Graphene, high-quality Graphene suitable for industrial usage still remains to be demonstrated. Second, one needs to control individual forms in Graphene devices accurate enough to provide adequate reproducibility in the properties. The latter is exactly the identical challenge that the Si technology has been dealing with proficiently. The immediate application for Graphene is probably its use in composite materials [5]. The commercial position held by carbon fibres is so strong that Graphene will be needing huge development before it will be economically feasible to use Graphene as the main reinforcement material. The target is to achieve a 250 GPa Young's modulus [6].

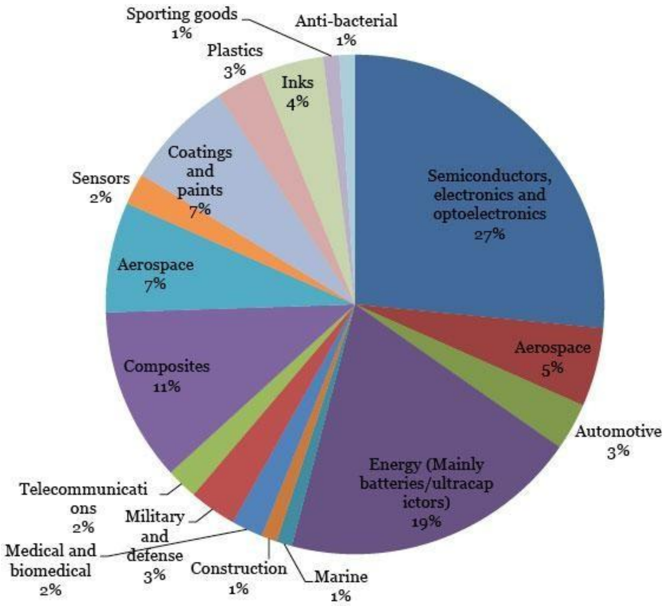


**Fig. 3** Applications of Graphene

A huge potential application of Graphene lies in the electronics sector. Graphene transistors are estimated to be extremely fast than those made of silicon currently. In order for computer micro-processor to become faster and energy efficient they need to become smaller. Silicon has a size boundary wherein the material stops to work. The limit for Graphene is even lower, so Graphene components would be packed on a micro-processor more tightly than today. So far, Graphene computers are nothing but a big dream, except paper-thin transparent computer monitors that can even be rolled up and carried in a bag have appeared in commercials for upcoming consumer electronics. Graphene has opened a new horizon in the field of pharmacological applications in vitro and in-vivo [7]. Graphene and its derivatives have been used for several biomedical applications including anti-cancer therapy [8].

## 6. FUTURE SCOPE

Research on Graphene's electronic properties is in matured state now, but is not likely to start fading any time soon. Graphene will eventually continue to stand out as truly singular item in the arsenal of condensed matter physics. Exploration on Graphene's non-electronic properties is just gearing up, which will bring up new phenomena that can hopefully prove equally captivating and at least sustain the Graphene boom [9]. Recently it became possible to fabricate huge sheets of Graphene. Using industrial methods, sheets with a width of approximately 70 cm have been produced [10]. New class of composite materials based on Graphene with more strength and low weight could also become interesting for applications in satellites and aircraft [11]. Even more enticing is the possibility that Graphene could help the microelectronics industry extend the life of Moore's law. In a broad view, one can visualize entire integrated circuits made out of a single Graphene sheet. Since Graphene is transparent conductor it can also be used in applications such as touch screens, light panels, wherein Graphene can substitute the fragile and expensive, Indium-Tin-Oxide (ITO).

## 7. CONCLUSIONS

Graphene is the very first example of a two-dimensional crystal. There is still much room for the scientific research and development of Graphene-based materials, and devices. Although a lot of effort has already been put together to utilize each and every property of Graphene for the development and welfare of mankind still there is much to be done. Even, below perfect layers of Graphene can be used in many applications. In fact, different applications require distinct grades of Graphene, implying widespread practical implementation of this material. Currently the market for Graphene applications is driven by the cost of producing this material, there is a hierarchy in how long the applications will reach the user. Those which use the lowest grade, cheaper and most abundantly available material will be the first to appear, presumably in a few years, and those requiring highest, electronic quality grades and biocompatibility could take more than 10 years to develop. Also, because developments in the last few years were extremely swift, Graphene's presence in the market will continue to improve. Nevertheless, settled benchmark materials will be replaced, only if the properties of Graphene can be employed into applications that are competitive to justify the cost of replacement of existing industrial processes.

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