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Graphene Prospects and Applications

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ABSTRACT

Almost everything surrounding us is made up of carbon-based materials, of them, one of the most important material is possibly graphene. It is a 2D crystalline form of carbon, one atom thick. It has garnered immense interest in the field of material sciences due to its unique set of physical, electrical, thermal, and mechanical properties. This has set it up as a major alternative to many of the conventional materials in a wide variety of fields. This paper discusses some of the uses and applications of graphene, along with techniques employed for its synthesis and some of the most promising prospects of this wonder material.

KEYWORDS: *Graphene, material sciences, applications, synthesis*

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1. INTRODUCTION

Our world as we know it today is made of materials that have widely different origins and properties. These materials form the backbone of contemporary society. Amongst these materials, it won't be an overestimation to say that our life depends the most on carbon-based materials. We are surrounded by materials made up of carbon, it is the fourth most common element in the entire universe. After the discovery of fullerene (C60) by Kroto and coworkers [1] several novel carbon nanomaterials of importance have been isolated. In 1991 carbon nanotube was first prepared by Iijima [2], and as the millennium crossed the most important discovery became that of Graphene in 2004 by Kostya Novoselov and Andre Geim [3]. Graphene has since then gone on to become a subject of intense research and studies, with people referring to it as the 'wonder material'.

Graphene is elegant. It is formed from a single element, carbon, with just one type of bond. Graphene is a 2D crystalline form of carbon; one atom thick, sp2 bonded planar sheet of carbon arranged in a hexagonal honeycomb-like structure [4,5]. The main reason for roar about graphene is its extraordinary combination of electrical, mechanical, optical, thermal, and sensing properties, which had been thought impossible to be found in a single material [6].

The discovery of graphene is a story in itself. Andre and Kostya frequently held 'Friday night experiments' - sessions where they would try out experimental science that wasn't necessarily linked to their day jobs. One Friday, the two scientists removed some flakes from a lump of bulk graphite with sticky tape. They noticed some flakes were thinner than others. By separating the graphite fragments repeatedly, they managed to create flakes that were just one atom thick. Their experiment had led to graphene being isolated for the very first time.

Since that first time, immense research has gone into creating better methods and techniques for the preparation of graphene, its properties have long been studied and established. Graphene is 200 times stronger than steel, touted to be the strongest material known to exist with a very high tensile strength, yet much lighter than paper. It has the highest thermal conductivity to any gases, making it an excellent candidate for application in electronic circuits and lightweight high-performance thermal management systems. It also can sustain extremely high densities of electric current (a million times higher than copper). These properties along with its high surface area make it compatible to use in energy production and storage [6]. Graphene is also said to have high elasticity, high porosity, it is extremely stable, has a tunable bandgap, and is biodegradable as well.

These properties, seemingly impossible, for a single material to have, have led to today graphene being the most attractive nanomaterial, worthy of all the attention. In this paper, we try to have a brief outlook of the utility of graphene, its application in multidimensional fields, the areas of intense research graphene is part of, and the most promising prospects of its use in modern society.

2. USES AND APPLICATIONS

Graphene is considered to be a groundbreaking material. The applications and utilities of graphene are truly limitless, and many of them are yet to be realized. In this section, only a few of these applications have been discussed in brief.

2.1. Super-fast charging batteries and graphene supercapacitors

Researchers at the Samsung Advanced Institute of Technology [7] have found that coating lithium-ion batteries with graphene was able to increase its charging speed by up to five times. The graphene-ball coating improves cycle life and fast charging capability by suppressing detrimental side reactions and providing efficient conductive pathways.

Also, graphene-based supercapacitors could store power much greater than normal capacitors and go through more cycles than batteries, thereby possibly replacing normal batteries with themselves. A capacitor stores charge between two plates and discharges them quickly. Capacitors can store a lot of charge, and supercapacitors can store even more. But capacitors can't hold much power per unit of weight. Graphene supercapacitors can change that, when etched with laser it creates more surface area and in turn allows it to store more energy than its ordinary counterpart. In the future, graphene supercapacitors could power electronics and even electric cars.

2.2. Graphene sieves can be used to clean nuclear waste

Researchers led by Andre Geim from the University of Manchester [8] demonstrated that membranes made from graphene can act as a sieve, separating hydrogen— from the heavier isotope deuterium.

Deuterium is widely used as heavy water required in thousands of tonnes for the operation of nuclear power stations. Again, the heaviest isotope, tritium, is radioactive and needs to be safely removed as a byproduct of electricity generation at nuclear fission plants.

The current separation technologies for the production of heavy water are extremely energy-intensive and have presented a major scientific and industrial problem. Now graphene promises to do so efficiently.

Researchers tested whether deuterons can pass through graphene sheets. They found that deuterons were effectively sieved by graphene's one atom thick membranes, that too with a high separation efficiency. Furthermore, the researchers showed that the separation is fully scalable. The process could mean producing heavy water for nuclear power plants could be ten times less energy-intensive, simpler, and cheaper using graphene.

2.3. Graphene oxide membranes to desalinate sea-water

By 2025 the UN expects 4% of the world's population to encounter water scarcity. Researchers at the National Graphene Institute, University of Manchester [9] have shown that Graphene-oxide sieves can be used to filter common salts from water to make it safe to drink. This technology has the potential to revolutionize water filtration across the world.

Graphene-oxide membranes developed at the National Graphene Institute had already demonstrated the potential of filtering out small nanoparticles, organic molecules, and even large salts. But filtration of common salts requires even smaller sieves.

The Manchester-based group were not only able to overcome the problem of the sieves getting slightly swollen when immersed in water but also were able to develop graphene-oxide membranes in which the pore size of the membrane can be precisely controlled to the atomic level, sieving common salts out of salty water and making it safe to drink.

When the common salts are dissolved in water, they always form a 'shell' of water molecules around the salt molecules. This allows the tiny capillaries of the graphene-oxide membranes to block the salt from flowing along with the water. Building on these findings, a simple scalable method to obtain graphene-based membranes with limited swelling was demonstrated, which exhibited 97% rejection for NaCl.

The researchers believed that these developed membranes would not only be useful for desalination but the atomic scale tunability of the pore size of the membrane would open up new opportunities to fabricate new membranes on-demand and filter out ions according to their sizes.

2.4. First graphene-enhanced commercial product

Even though graphene was first discovered in 2004, it would be at least ten years before the National Graphene Institute, University of Manchester, would unveil the first graphene-enhanced commercial product: an LED light bulb in 2015. Produced by the aptly named Graphene Lighting.

'Graphene Lighting' was a company that spun out of the institute. In this bulb, the bulb's filament is coated with graphene, giving it much greater conductivity and increased efficiency. LEDs, in general, produce a large amount of heat over a small area, unless this heat is removed the temperature will rise and that would lead to significant degradation of its performance.

The main advantage of using graphene lies in its ability to transfer heat more efficiently. By doing so graphene improves the light output of LEDs and extends their life expectancy. With the price of graphene-enhanced bulbs being roughly the same as regular ones, one wouldn't see any reason for it not being a commercial success.

2.5. Graphene-based coating as a rust-proofing agent

Graphene is water repellent and highly conductive and so is a perfect combination to prevent steel from coming in contact with water which causes rusting by oxidizing the iron. Chemists at the University at Buffalo prepared a graphene-based polymer coating that can serve as an alternative non-toxic rust-proof coating. By adjusting the concentration and dispersion of graphene within the composite they were able to prepare a coat which when applied to steel was able to withstand being dipped in a brine solution for up to a month! The coating could be made with existing infrastructure in local steel plants, giving industries a chance to reinvent themselves healthy environment-friendly way.

2.6. Graphene based gas sensors to detect explosives

Continuous nanosheets of graphene that grow into a foam-like structure, developed by researchers at Rensselaer Polytechnic Institute [11] could potentially outperform leading commercial gas sensors in picking up concentrations as small as 20ppm of nitrates and ammonia found in explosives. Of the size of a postage stamp, these sensors are flexible, sturdy, easy to clean, and overcomes the shortcomings that have prevented nanostructure-based gas detectors from reaching the marketplace. Its many advantages and possibly being better than today's commercial gas sensors could lead to these gas sensors being used by bomb squads, law enforcement officials, defence organizations, and in various industrial settings.

3. THE PROBLEM

A lot has been said and done about the ever so useful properties of graphene, with its gigantic reputation, a lot of research has gone into graphene and its derivatives. Then why is it then that graphene has still been not able to change the world as we know it, why has it not been able to 'revolutionize' the world yet?

While on paper it might seem that graphene is the ideal material to work with, the problem is that defect-free graphene is generally difficult and very expensive to produce. Some of the superior properties are only found in the highest quality grades [12,13], and the limitation of producing highest quality samples makes graphene-based products expensive.

Despite the extraordinary properties, the commercial application of this wonder material is limited. Another prime reason behind this is the limitation in bulk synthesis processes. The price of the material varies depending on the production conditions, and the methods used aren't cost-effective for producing it in bulk. The way graphene was first isolated by the team in Manchester, by peeling off layers of graphite with tape, was perfectly good for making few flakes in the lab, but not suitable for production in significant volume.

Mechanically exfoliated graphene, like the ones produced by the scotch tape technique, has the best physical properties, but individual flakes produced by this technique are too expensive for bulk production. But at the same time, extreme research is going on for better the mass production processes to get the highest quality graphene at low costs.

4. TECHNIQUES USED TO PRODUCE GRAPHENE

Like mentioned above making graphene from scotch tape isn't the most economical way to produce graphene and extensive research on the subject had led to various process which are used to produced graphene, both for small samples and bulk quantities.

4.1. Making defect-free Graphene samples from Si Carbide and from any carbon sources

Epitaxial graphene can be grown from silicon carbide. Even though graphene growth from the decomposition of silicon carbide is a complicated process it can be done and advancements have been made in this process as well. Here silicon carbide is sublimed at high temperatures but the atmosphere above the surface layer is variable. Tailoring the environment above the surface has allowed researchers to produce graphene at a good yield [14].

In a twist, three groups from across Germany devised a method in which they glued a plastic made from many aromatic benzene hexagons onto a silicon carbide surface and found that this plastic drastically improved the size and quality of graphene monolayers produced from the silicon sublimation. This work was inspired by an earlier paper, which fused CVD with epitaxial growth to improve the graphene yield. It seems that somehow the combination of these two processes creates a product that is leagues better than either isolated method [15].

Now, it is impossible to look around and not notice that the world around us is carbon-based. From food to plastic, it is all carbon-based, it is imperative that graphene be made reliably from cheap resources and reservoirs of carbon around us. If graphene could be made from these things that would otherwise go to waste, it could significantly decrease the long-term cost of graphene.

James tour took this logic to an extreme in 2011 over a bet. Tour had himself been thinking about utilizing the free carbon already present in the environment. One of the main techniques he used was CVD—Chemical Vapour Deposition. It is a relatively straightforward process that involved growing graphene on a substrate, typically a copper foil. Using this technique, he was successful in converting Plexiglass (polymethylmethacrylate) and sugar into CVD graphene over a piece of copper foil.

Excited over Tour's recent success one of his colleagues challenged him to prepare graphene from six different carbon sources: cookies, chocolate, grass, polystyrene (Styrofoam), roaches, and dog feces. Using the same technique, he used for sugar, he was able to prepare small flakes of high-quality graphene from all of the proposed unusual carbon sources. Tour and his co-workers even stressed that no preparation or purification of these materials was required and that they could be used as it is [16].

Tour's 2011 findings, along with those of the German teams in 2016 could provide a clear route to producing large, high-quality defect-free, cheap graphene samples.

4.2. Graphene made from soya oil

The everyday cooking soyabean oil can be used to make graphene in the lab. A development that has led scientists to believe that cost and complexities of the production of graphene could be decreased significantly. Many of the other production techniques involve using intense heat in a vacuum and expensive ingredients. Research of Dr. Zhao Jun Han of the CSIRO has now shown that graphene can be prepared under normal conditions as well [17].

To produce the graphene, soybean oil is heated in a tube furnace for about 30 minutes where it decomposes into carbon building blocks on a foil made of nickel. It is then rapidly cooled and diffused on the surface of the foil into a thin rectangle of graphene film, about five centimeters by two centimeters and one nanometre thick (about 80,000 times thinner than a human hair). The process is faster and more energy-efficient than other methods.

According to Dr. Zhao the process could potentially cut the cost of production by ten-fold, and thereby accommodate many applications that were previously impractical because of the high cost of producing these films. Scalability is still an issue, the biggest film so far produced is the size of a credit card.

4.3. Graphene made from Hydrocarbon gas

A team of physicists from Kansas State University [18] have discovered a way to mass-produce graphene with only three ingredients: a hydrocarbon gas, oxygen, and a spark plug. The method is straightforward: fill a chamber with either acetylene or ethylene gas and oxygen, use a vehicle spark plug to create a controlled detonation, and collect the graphene that is formed afterwards. The best feature of this method might be that it requires much less energy to make large amounts of graphene, and it lacks the use of nasty chemicals.

The detonations are carried out in the presence of oxygen at a high temperature of around 4000 K. The high temperature is believed to be the cause of the production of graphene instead of soot.

The method allows for the control of the number of layers, shape, and size of the graphene nanosheets and the process can be scaled up for industrial production.

The team is trying to improve the quality of the graphene produced and scale up the laboratory process to an industrial level. By upgrading some of the equipments and accessing the graphene more quickly from the chamber, seconds instead of minutes, the team is hopeful of improving the quality of the material.

5. PROSPECTS OF GRAPHENE

With the possibility of graphene being produced at a cheaper rate at a bulk scale, the prospects of graphene are enormous. Graphene-based materials are extensively investigated over the years and some of the most promising prospects of graphene-based materials are discussed below.

5.1. Using graphene and silver nanowires to make flexible, unbreakable screens

Scientists from the University of Sussex [19] have found a solution to make the smartphone screen more flexible and very less brittle by combining silver nanowires with graphene to make the screens. Smartphone screens are currently made with indium tin oxide, which is brittle and expensive. The primary constituent, indium, is also a rare metal and is ecologically damaging to extract. Its alternative is silver which is still expensive.

Alan Dalton who led the discovery noted that even though silver nanowires were used in making touchscreens before, graphene was never combined with them. He further explained that the graphene particles are floated on the surface of the water then they are picked up with a rubber stamp. The silver nanowire film is then laid on top of them in whatever pattern is necessary. This breakthrough technique is inherently scalable and should be relatively simple to combine the silver nanowires with graphene on a large scale using spraying machines and patterned rollers.

Cutting out the indium oxide makes the process more environmentally friendly. The addition of graphene to silver nanowires also increases its ability to conduct electricity by a factor of ten, this would lead to only of fraction of silver being used for the same or even better performances. It has also been observed that repeatedly bending these hybrid films doesn't change their electrical properties.

5.2. Converting carbon dioxide to graphene

At the moment, NASA is researching ways to process waste carbon dioxide from astronauts' breath on the International Space Station into graphene. This improvement to the life-support system would have a twofold bonus. For one, waste material such as carbon dioxide otherwise requires sequestration with special chemicals that need to be shipped up with special deliveries from Earth. Processing the carbon dioxide into graphene would mean that fewer resupply missions would be necessary. Thereby treating carbon dioxide as an inexpensive raw material for the synthesis of much more valuable product.

It was observed that during photosynthesis it is the job of the metal-based enzyme RuBisCo to absorb the carbon dioxide from the air and make it usable for further chemical reactions in the plant. Inspired by this metal enzyme-based natural conversion, researchers at KIT [20] are now presenting a process in which the greenhouse gas carbon dioxide together with hydrogen gas is converted directly into graphene, with the help of specially prepared, catalytically active metal surfaces.

If the metal surface exhibited the correct copper to palladium ratio the conversion could be a simple one-step process. In further experiments, researchers were able to prepare graphene that was several layers thick, which might find useful applications in batteries, filter materials, and electronic components.

Turning carbon dioxide into graphene would serve another benefit as well, the prepared graphene could be incorporated in solar cells or put to use in other useful applications rather than ejecting it out in the airlock. This possibility helps to lengthen the umbilical cord between the International Space Station and Earth. Eventually, if the dream of sending humans to other planets is to be realized, we need to cut that umbilical entirely.

Again, carbon dioxide is a greenhouse gas in the atmosphere, it is produced upon the combustion of fossil fuels such as coal and oil for energy, but we could treat this carbon dioxide as a raw material to produce graphene. Thereby converting a waste, greenhouse gas on Earth into a very valuable product.

5.3. Converting trash to graphene

In a new process created in the lab of chemistry of Rice University, James Tour and co-workers [21] were able to turn bulk quantities of trash into valuable graphene flakes. Graphene prepared from this method is being called "flash graphene". It is made in about 10 milliseconds by heating the carbon-containing material to up to 3000 K. Atomic-level simulations by Rice University researchers have confirmed that temperature is key to the material formation, essentially speeding up the slow geological process of conversion of carbon into graphite, and when stopped at the right instant graphene is obtained.

The process is quick as well as cheap. The world throws out 30-40% of all food because it is spoilt, plastic is again a cause of global concern, here since the source material can be almost anything with carbon content, the process would be extremely significant. Tour had already shown that any solid carbon-based material could be turned into graphene in 2011 (discussed in section 4.1), this technique takes it a step further by allowing the conversion to take place at a bulk scale. This is a huge improvement from techniques like exfoliation from graphite and CVD on metal foil that requires much greater effort and produces just a tiny amount of graphene. Tour himself was only able to produce about 1 picogram of the material with the earlier methods, but not it can be done on a large scale.

Bulk composites of graphene with plastic, metals, plywood, concrete, and other building materials would be a major market for flash graphene, according to the researchers, who are already testing graphene-enhanced concrete and plastic. According to

Tour, this could provide an outlet for coal on large scale by converting it inexpensively into a much higher-value building material. Also noting that the production of cement emits as much as 8% of human-made carbon dioxide every year. Concentration of as little as 0.1% of flash graphene in the cement used to bind concrete could lessen its massive environmental impact by a third. Even a small amount of 0.02% of graphene added to concreate increases its strength by 35%.

Strengthening the concrete with graphene would mean using less concrete for building, which would dramatically decrease the cost of manufacture and transportation, at the same time increasing the strength of the structure.

5.4. Using 3D structure of graphene to build bridges

Strictly speaking, graphene is two-dimensional, being a single layer of atoms. Researchers at MIT [22] have found, however, that when subjected to heat or pressure, graphene takes on a complex shape called a *gyroid,* which is three-dimensional but filled with holes or pores. The new material, a sponge-like configuration with a density of just 4.6 percent, can have a strength 10 times that of steel. These shapes, which have an enormous surface area in proportion to their volume, proved to be remarkably strong.

The new findings showed that the crucial aspect of the new 3-D forms has more to do with their unusual geometrical configuration than with the material itself, which suggests that similar strong, lightweight materials could be made from a variety of materials by creating similar geometric features.

Now, one could use the real graphene material or use the geometry that was discovered with other materials, like polymers and metals, and gain similar advantages of strength combined with advantages in cost and processing methods. The same geometry could be applied to large-scale structures, like bridges. The concrete for the structure of the bridge could be made with this porous geometry and thus provide greater strength with a fraction of the weight.

5.5. Space Aerogels

Aerogels are one of the lightest solid materials known. They are created by combining a polymer with a solvent to form a gel, and then removing and replacing the liquid from the gel with air. They are extremely porous and very low in density. While there are many types of aerogels, one particular is the centre of attraction—graphene aerogel. A team of engineers and scientists at Stanford University led by Debbie Senesky [23] are researching on this particular type of aerogel. Over the next year or so, Senesky's team is preparing a set of experiments for graphene aerogel that is made in the International Space Station.

Since graphene aerogel is so light, gravity can have a huge influence on its structure and properties. Therefore, the team is planning to see what happens when gravity is removed. By synthesizing graphene aerogel in the microgravity of low-Earth orbit, Senesky and the team hope to learn how to make this wonder material using the limited resources available on the International Space Station.

Thomas Heuser from the team adds, one use for graphene aerosol is in the production of supercapacitors – devices that store large amounts of energy that can be rapidly released. This might lead to phones that forgo batteries for capacitors that could be quickly charged multiple times a day, rather than for one longer period. Graphene aerogel's high surface area and electrical conductivity make it ideal for this type of storage.

Others suggest its porous structure and absorbency might lend themselves to advanced water purification filters or super-mops that sop up oil spills in the ocean. It is believed graphene aerogel can soak up 900 times its own weight in oil, get wrung out, and be used again. Eventually, such research could point to use products that are makeable only in space and are valuable enough to justify transporting the raw materials and machinery required to manufacture them in space.

6. CONCLUSION AND FUTURE PROSPECTS

Graphene has garnered the attention of the scientific community for a long time now. Based on its exceptional electrical, mechanical, and thermal properties—be its ability to sustain high densities of electrical current, or high thermal conductivity, extremely high tensile strength, or its ultralight nature—graphene has been the most attractive nanomaterial.

Staying true to its ground-breaking properties graphene has found its utility in a wide variety of fields. Graphene promises to speed up our batteries, improving its cycle life and fast charging capabilities by suppressing detrimental side reactions. Or change the battery industry altogether with graphene-based supercapacitors, which not only can store greater amounts of power but also run more cycles than batteries, therefore removing the need for batteries in our devices in totality.

Section 2.2 demonstrated that graphene can act as sieves to separate different isotopes of hydrogen and help in cleaning nuclear wastes easily. The process promises to cut down the energy consumption of producing heavy water in nuclear power plants by ten times. Graphene will also be significant in our efforts to provide clean drinking water to the world in the form of graphene-oxide membranes, as seen in section 2.3. The atom-level tunability of the pore size of these membranes would mean them not only being useful for desalination but for all sorts of filtration of ions by fabrication of new membranes according to demand.

Graphene-coated LED bulbs became the first graphene-enhanced commercial product. The graphene helps in improving the light output and extends its life expectancy by transferring the heat more efficiently in the LEDs. Chemists at the University of Buffalo were able to prepare a graphene-based polymer coating that can act as a non-toxic rust-proofing agent. The coating was able to prevent rust from forming on steel for up to 30 days! Graphene nanosheets have also found their use as new gas sensors that were able to detect even small concentrations of nitrates and ammonia found in explosives. These gas sensors could potentially outperform today's commercial gas sensors. (Discussed in section 2.4, 2.5, 2.6)

Even with its wide-scaled applications graphene has yet to find mass adoption. The biggest problem in this till now had been defect-free graphene is generally expensive and difficult to produce. On top of that, the superior properties of the material are found only in the highest quality grades. The biggest bottleneck was the limitation of bulk synthesis methods, the absence of such methods for a long time increased the cost of production for any graphene-based product.

Since then, extensive research has undergone to synthesize new techniques to prepare graphene, both for small samples and bulk quantities. In section 4.1, the use of silicon carbide to produce graphene, and James Tour's technique of using CVD for the preparation of graphene flakes from almost any carbon source were highlighted.

Heating soyabean oil in a tube furnace over a nickel foil followed by rapidly cooling, was found to be an effective technique in scaling up the production of graphene film, as was discussed in section 4.2. Finally, the most effective technique happened to come from a team of physicists from Kansas State University (section 4.3). The straightforward method involved filling up a chamber with a hydrocarbon gas and oxygen and using a vehicle spark to create a controlled detonation. The most promising aspect of this technique is that it can be scaled to an industrial level.

With the possibility of graphene being produced at a cheaper rate at a bulk scale, the prospects of graphene are enormous. Staring in section 5.1, combining silver nanowires with graphene to make flexible and unbreakable phone screens is one promising prospect in graphene's use. The use of graphene makes the screens conduct better and so would lead to less silver being used for the same or better performance.

In section 5.2, a technique to use carbon dioxide to produce graphene was outlined. This technique promises to be of utmost use in the ISS, at the same time help decrease the accumulation of greenhouse gas on Earth.

In section 5.3, James Tour and co-workers possibly created a process to converting trash to graphene by heating up the material at 3000 K for 10 milliseconds. The best part of the technique is that the starting material could be almost any carbon-based material, from plastic to coal, and using coal—a relatively cheaper, environment harming material—and converting it to the more valuable graphene could lead to both keeping the jobs at mining coal at the same time shifting to more environmentally friendly process.

Researchers from MIT were able to create the 3D structure of graphene called 'gyroid', which is a structure filled with holes but 10 times stronger than steel. Analyzing the structure further led to establishing that its strength comes not from the material but from the structure. Therefore, replicating the structure with other materials could lead to having a large-scale structure with greater strength that too at a fraction of the weight. Lastly, in section 5.5 the possibilities with space aerogels were described.

These were only a few of the applications, prospects, and possibilities with graphene and graphene derivatives. Immense amounts of research are still going on and a lot of its applications are yet to be realized. Beyond this graphene has shown a wide range of applications in various fields of science and technology, few of them are discussed in detail in the noted articles [24-28]. For example, the unconventional superconductivity that was generated in the superlattice formed by stacking two graphene sheets twisted to each other over a small 'Magic Angle' [29-31]. Earlier graphene oxide was synthesized through multi-step time-intensive routes, using harsh chemicals, but in a recent development [32], graphene oxide was synthesized within seconds with a green process.

Deep investigations are underway for this new kind of material and more funding would be required for their industrial-scale application. In concluding remarks, it begs to state that graphene has been one of the most important development in material sciences in decades. And is a part of the most promising material of use in modern society and is an even greater opportunity for material scientists for further research.

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