Mini Essay - Graphene

A semi metal of the future, Graphene is an extremely thin material with the thickness of just a single atom making this material two dimensional. However, graphene is not a magical material, but carries the same carbon structure as graphite, a grey allotropic form of carbon that can be most commonly found in pencils' filling. Shockingly, around 3 million layers of graphene are equivalent to 0.0762 cm of graphite showcasing its extreme thinness. This essay will be discussing these fascinating physical properties of graphene, its chemical and physical structure, processes pertaining to its extraction and its boundless applications in several fields such as nanosciences.

At the university of Manchester in the year 2004, Dr. Konstantin Novoselov and Professor Andre Gunn were conducting a study on graphite's efficiency as a transistor. Professor Guyman stuck tape to a piece of graphite, and when they peeled off the tape they saw it captured an extremely thin layer of graphite. They had just discovered graphene and had isolated single layer of graphite which was previously termed impossible by the scientific community. They also won a Nobel prize in 2010 in physics not chemistry as what intrigued the scientists most about graphene was its electronic properties and this falls under the category of physics. Graphene has high electrical conductivity but high intrinsic sheet resistance too. Graphene possesses several unique electronic, optical, thermal and mechanical properties. These resourceful and diverse variety of physical properties make it a powerful tool. It is transparent and thermally conductive, and extremely flexible. However to comprehend this, it is essential to understand the chemical structure of this material first.

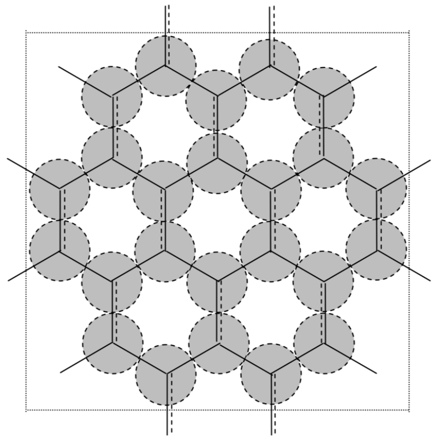

Figure 1 : Schematic illustration of graphene's atomic structure : 24 carbon atoms making 7 hexagons in 0.9 x 0.9 nm (~ 0.8 nm) of graphene.

Structurally, graphene comprises of pure carbon atoms arranged in a hexagonal pattern, its lattice resembling the shape of a honeycomb, in a sheet that has the thickness of a single atom. In other words, it is a monolayer of graphite. In Graphene, every carbon atom (with 4 valent electrons), is sp2 hybridised and bonded to three other carbon atoms via sigma bonds with one electron remaining from each atom. These electrons, located in the p orbitals, are delocalised as a result of resonance and can move freely through the adjacent atoms and between their molecular orbitals. These delocalised electrons can carry the kinetic energy through the lattice and carry electrical charge. The charge carriers in Graphene are also massless because of the presence of K and K Dirac points in the hexagonal Brillouin zone where the upper and lower energy bands touch each other. As mentioned before, the delocalised electrons travel very fast and have large intrinsic mobility. This is called ballistic transport. Its thermal conductivity (of around 5000 W/mK) is very strong and overtakes diamond's. However when the stacks of graphene sheets can be rotated and at

some point it starts to behave as an insulator too, resisting the heat and electricity that it can carry so well as a superconductor!
It is the thinnest material known to man
Graphene's optimal properties are impressive considering its thinness. It is capable of absorbing 2.3% of white light.
Given that Graphene is a unique thin layer of carbon atoms organized in interlocked hexagonal pattern, there exist a numerous number of ways to extract Graphene from different carbon based materials. These methods range from exfoliation (itself with many variants like mechanical exfoliation to electrochemical exfoliation), hydrothermal self-assembly, Epitaxy and many techniques that fundamentally involve coating / growing metal surfaces with a layer of Graphene and then removing that layer to leave behind Graphene.

Basic mechanical exfoliation can be done in a living room using a scotch tape and a graphite pencil or using graphite powder, laminating sheets and a laminating machine. Electrochemical exfoliation and an Epitaxy method called chemical vapour deposition (CVD) are currently the most promising methods for Graphene production. Given that Graphene was only discovered in 2004, scientists are still working on perfecting the production methods. Currently, most methods are only fit for lab use, don't offer consistent quality at scale and result in very high unit cost (upwards to 1000 dollars for 100 microns). The world is still perfecting production methods that are scalable, allow for industrial production with predictable quality in different "forms" at an affordable cost. Hence, it is a bit early to talk about environmental impacts of Graphene production. Given that production involves creation of vacuum, temperature control and precise mixing of hydrogen gas and methane, the impact beyond power requirements is likely to be limited. However, the university of California found out that 'graphene oxide nanoparticles spread quickly through surface water' [1] when exposed to the environment and if e-waste products containing graphene are poorly disposed or the production of graphene is not conducted in strict lab settings, it could lead to the the spread of nanoparticles which are microscopic and can easily travel through the air and settle in water bodies. This poses the risk of contamination of the environment and the inhalation of nanoparticles (which can easily enter the body through the dermis) can injure lungs and cause lung inflammation. The manufacturing processes could also be unsafe for workers and even though the translocation of these nanoparticles from the lungs to the bloodstream, there is still not sufficient evidence and research available to set these theories in stone.

As mentioned before, the physical properties of Graphene are varied and astoundingly unique. It is the thinnest, lightest, strongest, impermeable material known to man. It also happens to be transparent and one of the best conductors of electricity. These sets of properties make Graphene a wonder metal with very wide variety of use cases. The five most common types of uses are the following

[1] 'inhaling nanoparticles may injure lungs' https://www.futurity.org/inhaling-nanoparticles-may-injure-lungs/

1. Make existing materials stronger and more durable (rubber, glass, steel etc) through mixing or coating
2. Create next generation of electronic circuitry and PCBs (replacing silicon)
3. Enable creation of flexible electronic circuits (to build wearables or clothes with inbuilt circuits, folding screens)
4. Build next generation battery and charging technologies that could be 50-100X lighter and more efficient than lithium-ion solutions.
5. Ultra-thin membranes for use cases like ocean water desalination, biological separation etc. This is because it only lets water pass through it making it the perfect candidate for purification processes.

Graphene is also highly applicable to the field of biomedical sciences by performing drug and gene delivery and facilitating cancer therapy. Other biomedical applications consist of Biosensing and Bioimaging. It could be utilised as a nano carrier material for cancer drug delivery in nano-medicine. The conception of new drug-delivery ideas combined with Graphene's special and irreplaceable physical properties such as its surface area, layer number and purity nominated graphene to be used a material in a new drug delivery method.
Graphene in the form of film can also serve as scaffold material in tissue engineering. For example, Mesenchymal stem cells, more commonly known as MSCs, are often used in clinical applications as they are able to facilitate tissue regeneration. Investigations and research concluded that the graphene-based film didnt hinder the 'proliferation' of the MSCs and instead fastens the rate of differentiation (of the MSCs) into bone, cartilage and fat cells. GO, a highly oxidised version of graphene, is an ideal nanocarrier for efficient drug and gene delivery.

Currently, the promise of Graphene is immense and there are already commercial products in market that involve use of Graphene mixed with other materials (Graphene reinforced rubber for running shoes, Graphene coated diodes for charging batteries amongst others). However, it does have its set of disadvantages that include cost and lack of alignment on scaled production methods but most importantly its inability to act as a semiconductor which makes its employment in the field of digital technology impractical and unachievable. These disadvantages can easily be overcome using research and testing. Every new material in the past (plastics, carbon fibres, and even steel) underwent a commercialisation phase where similar challenges had to be overcome.

The potential for Graphene remains unfulfilled and hence it is too early to say which specific materials could replace Graphene one day. Nanotechnology could allow other materials to give better / cheaper performance uplift in specific use cases where Graphene is currently considered the best future bet. Since its discovery won a Nobel prize on 2010, researchers and scientists have been exploring and deeply examining the periodic table to find for a better alternative for graphene and have been trying to combine and form a variety of other molecularly thin materials. Invigorated and motivated by their ardency to discover a material that could cause a technological revolution, a group of researchers efficiently created several examples of two-dimensional materials that share similar properties with graphene. These range from 'metal carbides (MXenes), a family of single-element graphene analogs (Xenes), a number of transition metal dichalcogenides, ultrathin organic crystals, and two-component nitrides.' A group of researchers including a physicist from the University of Kentucky , scientists from Daimler in Germany as well as the Institute for Electronic Structure and Laser (IESL) in Greece are experimenting collaboratively and using elements such as silicon, boron, and nitrogen to produce a material that would overtake graphene in terms of economic viability, stability and serve the purpose of a semiconductor enabling its use in digital processors. However, it continues to exist only on computer simulation as of 2016 and scientists are working on obtaining the same results they did on their computers in real life labs.

In conclusion, Graphene offers a cornucopia of research in the field of physics and its potential applications due to its physical properties including the best thermal conductivity, strength, high electrical conductivity, and thickness of an atom make it an exotic material that is highly open to research in low-dimensional physics.

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