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Hon 301

Graphene

I. Introduction

Imagine a world where the oceans are a major source of drinking water, the sun is a major source of our energy, and computing and electronics are faster and more efficient than ever. Graphene, a carbon material, may be able to help realize these goals. Carbon exists in a variety of forms, from diamond, the hardest mineral on Earth, to graphite, soft enough to use as pencil lead. At the molecular level, carbon molecules can arrange themselves into spherical “buckyball” structures and long tubes called nanotubes (What is Graphene). These structures have seen use in cancer treatment applications as well as medical tracing techniques. Graphene is another form of carbon which is actually a single layer of graphite. Our knowledge of the structure and properties of graphite is nearly a century old, but until recently graphene was beyond the reach of science due to the difficulty of producing single sheets of graphite. However, in 2004, researchers Andre Geim and Kostya Novoselov at the University of Manchester figured out a way to produce true single-atom-thick graphene layers from graphite, and won the 2010 Nobel Prize in physics for their research into graphene (Scientific). This marked the start of a great interest in the science and applications of graphene.

Graphene is a single-layer hexagonal honeycomb lattice of carbon atoms which can span indefinitely in two dimensions, and is a true 2-D material, with a thickness of only one atom. Graphite consists of many layers of graphene stacked and held together by weak electrical interactions between layers. When we write with pencil lead, we are sloughing off innumerable layers of graphene into the paper. This seemingly commonplace material holds some amazing physical characteristics. It is an excellent conductor both of electricity and heat: graphene is 150% as electrically conductive and ten times more thermally conductive than copper. It is practically transparent due to its thinness, absorbing only two percent of incident optical light. It is also extremely strong, approximately 100 times stronger than a hypothetical steel layer of the same thickness(Scientific). These unique properties have spurred research into the application of graphene in many areas of technology. For example, graphene has the opportunity to replace brittle indium tin oxide as stronger, more flexible transparent conducting electrodes in touchscreen and liquid crystal displays. It has also been used to increase the efficiency of much-used DNA-copying procedures used for applications such as DNA sequencing, functional analysis of genes, and the diagnosis of hereditary and infectious diseases. But these applications pale in comparison to the possibilities in other fields (What is Graphene). As an upcoming material, graphene has the ability to advance computing and electronics on a large scale, increase the efficiency of renewable energy production and storage, and more effectively desalinate water, leading to significant implications in the search for solutions to the problems of the world’s future.

II. Graphene in Electronics and Computing

Graphene has significant potential in electronics in integrated circuits and transistors.

Because graphene has high electrical conductivity and can also transport electrons more quickly than other metals, it is a good material for a transistor. Modern science puts billions of transistors on individual computer chips, and the transistor is the fundamental element in electronics today. In 2002, enough transistors were manufactured to give sixty million to each person on Earth, and production has only increased from there. Graphene offers the possibility of not only smaller, but faster transistors than the traditional silicon variety (What is Graphene). A typical silicon transistor may be thirty nanometers in size, but in 2008, the smallest transistor yet, a single atom thick and ten atoms wide, was made from graphene. Researchers also created graphene transistors which outpaced the on/off speed of similar-sized silicon transistors. The most promising application in transistor technology, however, is graphene nanoribbons. These are long thin "ribbons" of graphene which act as a better semiconductor, like silicon, than regular graphene does. Transistors made of these ribbons could increase the transistor density on computer chips by a predicted 10,000 times (ExtremeTech). Furthermore, since graphene is so good at heat conduction, it can dissipate heat more efficiently than metal. In short, graphene-based chips could transport electrons faster inside a large amount of exceptionally small, quicker, more heat-efficient transistors.

On the slightly larger scale, graphene also sees application opportunities in integrated circuits. In 2011, IBM researchers created the first graphene-based integrated circuit, which performed the simple task of receiving broadband radio signals. Promisingly, this circuit was unaffected in temperatures exceeding 127 C. Recently, IBM improved the speed of graphene integrated circuits by 10,000 times by using different building methods(ExtremeTech 2). While larger, more complex circuitry is still out of reach, graphene's alluring properties are keeping researchers interested and constantly innovating.

To the layman, the above may sound a bit muddled. In 1965, Gordon Moore famously predicted that the number of transistors on integrated circuits would double every two years. This held true for a surprisingly long amount of time, and in recent years has slowed down to a doubling every four years or so. The modern technique of keeping up with Moore's Law has mostly involved packing transistors ever closer together on a chip. However, with stagnating materials and techniques, there is only so much more tightly transistors can be packed and only so much more room for improvement. Graphene nanoribbon transistors not only offer a way for closer packing and smaller size, but also for faster electron transport, the speed of which is important at such microscopic levels. Furthermore, high heat conductivity means such chips and circuits would dissipate heat more easily, leading to lower costs and waste in cooling large server farms. Graphene has the potential to replace silicon and other conventional materials across a variety of electronic applications. The importance of this advancement in a world so dependent on electronics is striking. Graphene can take electronics into a faster, more efficient future.

III. Graphene in Energy

Similar to the electronics field, graphene offers attractive advancements in energy production and storage.

In a solar cell, photon energy is converted into electronic excitations as electricity, which can then be stored for later use. The unique properties of graphene as a material with high electrical conductivity and high transparency make it a promising candidate in solar cells as a transparent conductor. Traditional materials used for such purposes, mainly silicon and gallium arsenide, generate one current-driving electron per photon absorbed. However, typical photons from the sun carry much more energy than these electrons absorb, and the remaining energy is dissipated as heat. This is where graphene changes the game: it can motivate multiple current-driving electrons per incident photon. This means that graphene can outperform conventional solar cell materials as a high-efficiency charge collector. Today, the best silicon solar cells have a theoretical efficiency of 30%. Therefore, the amount of energy converted into usable electricity is at best a mere 30% of the total light energy being absorbed. However, graphene solar cells already have a theoretical efficiency of twice that, at 60%, and efficiencies of over 50% have already been observed in working graphene solar cells(Tielrooij).

Graphene can not only improve the collection of energy, but also its storage and use. Capacitors are devices that store electrical energy, and are very commonplace—if you name a piece of electronic technology, it probably has capacitors in it. Capacitors are made of two electrically conductive “plates” which are thin, flat and wide, and have very little space between them. The exceptionally thin, flat 2-D structure of graphene, along with its high electrical conductivity and light weight, gives it impressive application in capacitor technology. Researchers at Vanderbilt recently built a “supercapacitor” made of graphene-coated silicon, where the graphene improved the energy density of the small chip by over one hundred times (Augmented). This simple supercapacitor is thus capable of storing more energy than the large, heavy capacitors found in a variety of commercial applications. Substitution of graphene into lithium-ion battery anodes also yielded significantly higher energy storage than traditional lithium-ion batteries.

Today, solar power in the United States is still a niche energy supply, delivering only 0.23% of the country’s total electricity. This is due to the scarcity of solar power plants and residential solar cells, as well as the underlying efficiency. However, the number of photovoltaics installed in 2012 nearly doubled the total already installed, which had already doubled the previous year. This near-exponential trend is expected to continue in the coming years, with large numbers of plants being planned in the sunnier climes of the US. When graphene-based solar cells become commercially available, they will greatly increase solar energy generation, not only by greatly increasing the efficiency, but also by proving that solar energy is a promising and dependable resource. Unlike the burning of coal and fossil fuels, solar energy is a completely renewable, nearly waste-free (apart from construction) resource that humanity can safely depend on for the very long term. If we want to realistically look toward a sustainable, non-destructive future, the transition to renewable energy, in part in the form of solar energy, is vital.

The battery is a simple, common thing, yet we rely on it so much to power all kinds of electronics, whether they are crucial systems, essential to a job, or for entertainment and communication. As a replacement to ordinary batteries, graphene supercapacitors would charge hundreds of times faster, hold more energy, and hold it longer, as well as being rechargeable. The potential to replace batteries would also mean much less chemical waste, in the form of by-products of battery production as well as discarded single-use batteries themselves.

IV. Graphene as a Water Filter

Although probably the least complex application of graphene mentioned thus far, water filtration and desalination through the use of graphene has enormous potential.

As a thin film-like material, graphene has regular pores in its structure, in between the honeycomb lattice of carbon atoms. This means that certain atoms or molecules can pass through it, depending on their size and other properties, while others may not. Researchers at MIT found that nanoporous graphene acts as an effective filter for of salt water, allowing water molecules to pass while blocking the sodium and chlorine atoms. Furthermore, the water molecules pass hundreds of times more quickly than in conventional reverse osmosis membranes, traditionally used to filter and purify water. Additionally, graphene-based membranes were shown to have the interesting property of easily passing water, but being completely impermeable to other gases, vapors, and liquids, including even the small helium atom(Cohen-Tanugi).

This discovery of the ability of graphene and graphene-based materials to effectively filter water is an extremely important discovery. Only about 2.5% of the Earth's water is in the form of freshwater, with the other 97.5% being saltwater. In addition, most of this freshwater is frozen in places like the polar icecaps, meaning that only about 0.007% of all water is available for human consumption. With the seven billion and growing people on the planet, one billion of which are without access to clean drinking water, as well as the finite freshwater stores in many underground aquifers from which many humans draw their water, it is clear that a solution is needed to decrease the scarcity of clean water. However, if we can cheaply and effectively desalinate and filter the water of the oceans, these problems can be greatly reduced. Water desalination is a promising solution to supplying freshwater, and techniques are already employed in areas where freshwater is scarce, such as Israel, but it is expensive and energy-costly compared to treatment and filtration of freshwater supplies or even wastewater. As a much more efficient filterer of a wide variety of substances, including salt, graphene is a promising possibility. Not only does it expand our ability to cheaply desalinate seawater, but extends to the filtration any kind of liquid water available, and can yield significant improvements in this budding technology. Water is a person's first basic need, and we must address this before we can hope to solve the bigger problems of the present and move into a better future.

V. Potential Problems with Graphene

Graphene was one of the most expensive materials on to manufacture on Earth as recently as 2008, hindering research into its numerous applications. However, since then multiple cheaper methods have been found, and companies sell graphene in large sizes and quantities for fairly cheap. These methods only continue to improve, and are at the point where graphene no longer has the hindrance of being scarce or expensive. However, graphene is still in its infancy, and there are many challenges it faces. Being a two-dimensional material, although it is relatively strong, it is still fragile by itself, and certain manufacturing techniques will not work in the same way they do with silicon, for instance. That being said, the IBM integrated circuit and the silicon-graphene supercapacitor were both created using standard processes. In time, the implementation and manufacturing difficulties of using graphene will be solved for these applications in large as well as many others.

While the chemical composition of graphene is safe, as it is composed of only carbon atoms, its toxicity toward humans is more questionable, at least on the microscopic scale. Pieces of graphene have been shown to pierce cell membranes and disrupt the function of those cells. A light material as it is, one could envision a situation in which broken-up tiny pieces of graphene, from production or otherwise, may mix with the air and enter the lungs, with unknown consequences. Also, as with most manufacturing processes, there is not insignificant waste involved in the production of graphene, but this waste is not particularly harmful compared to other typical waste by-products. We must also consider that we already been exposed to graphene in the form of graphite for a long time now, with no obvious health issues arising. Students break graphene onto their notebook pages every day, even chew on their pencils, and the production of pencil lead carries many of the same potential risks as graphene. In light of these facts, graphene is probably not a large health concern, and itself is not a pollutant, but we must be careful to monitor it and the by-product baggage that comes with it as it finds more of a foothold in technology.

VI. Conclusion

As an emerging technology, the long-term impacts of graphene are not yet well understood. Nor is it entirely certain that graphene will be the revolution it seems to be in so many applications in today's society. However, the research and experimentation done thus far casts graphene as a material with fantastic potential in the areas of electronics and computing, energy, and filtration, among others. This potential is the potential to advance the current technology in each respective field in a meaningful and significant way, a way that will make the basic needs of society, such as clean water and more sustainable energy, as well as the more modern needs of today's society, such as fast and efficient computing, much more attainable. As we solve the basic problems of the world and society, we can begin to focus on more complex problems such as environmental, political, and economic issues. This is what graphene offers: a shortcut to being able to realistically face the biggest problems of our future.

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Excellent paper. Very well written and to the point. Well researched. I learned a lot from it, and even feel excited and optimistic about the applications of this new material.

A model paper. Now the only question that remains is how you will use this strong foundation in your final project.

Just one thought – when I taught "History of Computing" I was struck by one maxim – "Materials Replace Machines". The reference was to how silicon replaced vacuum tubes in computers making them feasible for widespread adoption. How will you cast the implication of this emerging technology into the future and its impact on society?

Sources:

"Augmented Reality at Work." MIT Technology Review. N.p., n.d. Web. 24 Feb. 2014. <http://www.technologyreview.com/news/511751/research-hints-at-graphenes-photovoltaic-potential/>.

Cohen-Tanugi, David, and Jeffrey C. Grossman. "Water Desalination across Nanoporous Graphene." Nano Letters 12.7 (2012): 3602-3608. Print.

"ExtremeTech." ExtremeTech. N.p., n.d. Web. 24 Feb. 2014. <http://www.extremetech.com/extreme/176676-graphene-nanoribbons-could-be-the-savior-of-moores-law>.

"Scientific Background on the Nobel Prize in Physics 2010." nobelprize.org. N.p., n.d. Web. 24 Feb. 2014. <http://www.nobelprize.org/nobel_prizes/physics/laureates/2010/advanced-physicsprize2010.pdf>.

"ExtremeTech." ExtremeTech. N.p., n.d. Web. 24 Feb. 2014. <http://www.extremetech.com/extreme/175727-ibm-builds-graphene-chip-thats-10000-times-faster-using-standard-cmos-processes>.

Stoller, Meryl D., Sungjin Park, Yanwu Zhu, Jinho An, and Rodney S. Ruoff. "Graphene-Based Ultracapacitors." Nano Letters 8.10 (2008): 3498-3502. Print.

"This Graphene-Coated Silicon Power Cell Signals a Battery-Free Future." Gizmodo. N.p., n.d. Web. 24 Feb. 2014. <http://gizmodo.com/this-graphene-coated-silicon-power-cell-signals-a-batte-1452245250>.

Tielrooij, K. J., J. C. W. Song, S. A. Jensen, A. Centeno, A. Pesquera, A. Zurutuza Elorza, M. Bonn, L. S. Levitov, and F. H. L. Koppens. "Photoexcitation cascade and multiple hot-carrier generation in graphene." Nature Physics 9.4 (2013): 248-252. Print.

"What is graphene? Here’s what you need to know about a material that could be the next silicon — Tech News and Analysis." Gigaom. N.p., n.d. Web. 24 Feb. 2014. <http://gigaom.com/2013/07/15/what-is-graphene-heres-what-you-need-to-know-about-a-material-that-could-be-the-next-silicon/>.

More Websites:

http://www.technologyreview.com/news/409449/graphene-transistors/

http://www.sciencemag.org/content/335/6067/442 Unimpeded Permeation of Water Through Helium-Leak–Tight Graphene-Based Membranes

http://phys.org/news/2013-04-xgs-silicon-graphene-anode-materials-lithium-ion.html