Graphene: Physical Properties and Applications

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***Abstract*—Graphene is one of the most popular materials in modern science. The recently discovered material is not only remarkably easy to make, but also consists of the commonly found periodic element, carbon. Graphene exhibits some of the most impressive properties known to a wide variety of scientific fields including physics, electronics, optics, mechanics and chemistry. These features are already being exploited in some applications, and it is expected that the amount of applications will increase in the near future. The most anticipated application is the use of graphene in the semicondutor industry, even though this technology still is not sophisticated enough at its present condition.**

It is believed that graphene still is not fully explored, and that the research of graphene will escalate in various scientific fields in the future.

I. Introduction

When graphene was discovered in 2004, it introduced differences and breakthroughs that the nanotechnology and the solid state physics had not seen in a long time. A 2-dimensional material with superior electrical properties could potentially re-invent the semiconductor technology. Large computer manufacturing companies like Intel and IBM currently fund multiple graphene research projects in anticipation that it might be the ”new Silicon”, allowing these companies to enable the new technology in future processors [2]. Even though Graphene already displays impressive conductive and electron mobility characteristics, researchers are still trying to enhance these parameters. The development of other significant features is also increasing and constantly growing in popularity.

The central topic of this paper is the various physical properties of graphene that enables its use in a wide spectrum of applications. Discussions on how graphene can be exploited in older applications, and how the unique properties of graphene create new applications will also be given.

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II. Graphene : The Material in 2 Dimensions

Graphene is the name used for a monoatomic layer of carbon (C) atoms sp^2 bonded in a honeycomb lattice [16]. The lattice is hexagonal and the lattice vectors $\mathbf{a}_1$ and $\mathbf{a}_2$ are described in equations (1) and (2) [12] with the adjacent atom distance $a \simeq 1.42$Å[12]. The lattice structure with the corresponding brillouin zone is shown in Figure 1.

$$\mathbf{a}_1 = \frac{a}{2}[3, \sqrt{3}] \tag{1}$$

$$\mathbf{a}_2 = \frac{a}{2}[3, -\sqrt{3}] \tag{2}$$

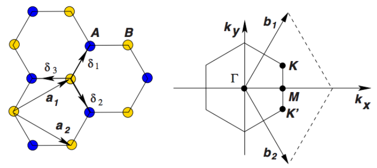


Fig. 1. Lattice cell and corresponding Brillouin zone cell [12]

The monoatomic lattice is of such a small thickness that it is in general regarded as 2-Dimensional. The thickness t_g of graphene has been estimated to $t_g \simeq 0.23$ Å[16], which is considerably smaller than the adjacent atom length a. Graphene can easily be visualized as a basic building element for other Carbon based structures, as seen in Figure 2. A 3-D structure can be created by stacking graphene sheets on top of each other, and a nanotube can be crafted by rolling a graphene sheet into a cylinder [2]. Similarly, a fullerene can be created by folding the lattice together, forming a ball [2].

More than 70 years ago, scientists Peierls and Landau argued that 2-D materials could not exist [7] [6]. The main reason for this was that the thermal fluctuations would melt or disintegrate any 2-D lattice at any finite temperature [7]. The proof they made was later confirmed and extended by scientists Mermin and Wagner, which concluded that perfect long range crystalline order could not exist in 2-D space [10].

Despite these theoretical results, graphene was discovered by Geim and Novoselov in 2004 [6], as a nearly perfect crystal structure in 3-D space [7]. Not only did it truly exist, but it was also surprisingly easy to make [3] [9].

However, graphene is not only of substantial interest in the field of quantum physics. The rapidly growing popularity

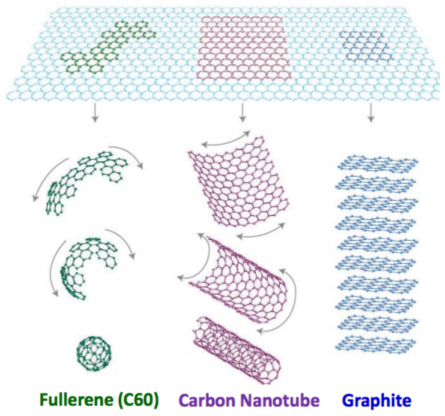


Fig. 2. Carbon Structures made with Graphene sheets [2]

of graphene is due to the many unique properties it displays. Remarkable electronical, mechanical, optical, chemical and physical features have so far been explored, and it is believed that there is still others that remain unknown.

III. ELECTRICAL PROPERTIES

The electrical features of graphene are some of its most remarkable, and also believed to be of significant importance in the future of electrical and computer technology. It is not easy to categorize graphene in terms of a material type, because it displays properties that resemble those of both metals and semiconductors [12]. Examples of such properties include that graphene has no net bandgap, but that the density of states is zero [12]. Because of this, it is commonly referred to as a 2-D semimetal [6]. Graphene also possess features that does not resemble other solid materials.

When electrons propagate through the lattice of a regular solid, they do so while displaying a finite effective mass. In graphene, this is not the case. The electrons are able to propagate through the lattice while losing effective mass, which results in an unusual quasiparticle [3]. Unlike regular solids, this quasiparticle is well described by a Dirac-like function, and not the Schrodinger equation [3]. This is quite controversial, since the Schrodinger equation has described numerous other materials effectively.

Graphene also experiences ambipolar electric field effects. This effectively means that charge carriers, both holes and electrons, are affected by applying a voltage across the material.

Another interesting feature in graphene is the long mean free path that can be obtained. This is because of the strong bonding that occurs in the honeycomb lattice, which makes it difficult for foreign atoms to replace the carbon atoms [12]. The mean free path in graphene can reach up to 1μm in length [12].

The mobility μ is a parameter that provides information of how quickly a charge carrier can move through a material, and is given by $\mu = |v_d|/E$ where v_d is the *drift velocity* and E is the *applied electric field* [5]. The mobility of a material affects the conductivity σ as seen in equation (3), where n and p denotes charge carrier concentration and e the elementary charge.

$$\sigma = (ne\mu_e + pe\mu_h) \tag{3}$$

The mobility μ_g of graphene on a substrate ranges from $2000 - 30000\text{cm}^2\ \text{V}^{-1}\text{s}^{-1}$, while mobilities in excess of $200,000\text{cm}^2\ \text{V}^{-1}\text{s}^{-1}$ have been achieved by suspending the graphene over a trench [1]. Mobilities of $250,000\text{cm}^2\ \text{V}^{-1}\text{s}^{-1}$ have also been documented [14]. By means of comparison, it is useful to consider the fact that silicon has a mobilty μ_s of around $1300\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ [13].

It is easily seen that even the lowest measured mobilities of graphene are still considerably higher than the corresponding values of silicon.

Another astonishing feature is its ability to sustain very high current densities. Current densities of more than six orders of magnitude greater than similar values of copper have been reported ($> 10^8\text{Acm}^{-2}$) [3] [6].

IV. MECHANICAL PROPERTIES

Even though the electrical properties of graphene are truly amazing and likely to affect the electronics industry in the future, there are also several significant non-electrical properties that provide latitude for a whole different spectrum of applications. As mentioned earlier, graphene can seem contradicting in its behavior because of displaying features of opposite effects, and this is still the case for its mechanical properties.

Graphene is a very stiff material. It has been proven that suspended graphene is able to support loads that that are millions of times heavier than the graphene sheet itself [16]. A way to visualize such a remarkable stiffness is by considering a paper sheet suspended over 100 m in length, without bending [16]. The breaking strength of a defect-free sheet of graphene is measured to be 42 N/m, which makes it the strongest measured material ever [17]. Despite these facts, it strangely enough also exhibits high pliability and ductility [3].

A currently uncontended example of the ductility of graphene is its ability to be stretched more than 20% in length [18]. This is considerably much more than any other crystal material [3]. It is also shown that putting the graphene under severe strain can alter the Fermi Surface, the bandgap [21] and move the drift of the Dirac points away from the high symmetry points in the honeycomb lattice

[18]. In other words - the graphene structure and transport characteristics can be altered by imposing strain [18]. The electrical properties are therefore tunable. Equally impressive is the fact that a graphene sheet with the thickness of one atom layer is impermeable to various gases and liquids (for instance helium) [19].

Graphene also exhibits some properties that have not been observed in any materials before it. Graphene actually features a negative thermal expansion coefficient ($\simeq -7 \times 10^{-6}$ K^{-1} at 300 K) [20], which means that it shrinks with increasing temperature. This is due to dominating membrane phonons in 2-D [3].

It goes withuout saying that combinations of these mechanical properties can be employed in a wide variety of applications.

V. APPLICATIONS

When it comes to considering the span of possible applications of graphene, it is difficult to be exact. Mostly because of the fact that graphene still is a fairly young material under development, but also because previously unexplored properties keep emerging and thus provide new possible applications. The most prominent applications are probably those who take advantage of the useful electronic properties, but there is also some that exploits the mechanical features. Two different applications of graphene will be presented in the following.

A. *Graphene in FET Transistors*

According to the speculations of Moore's Law, the need for smaller transistors is constantly increasing. Over the last few years, the focus on making more energy efficient circuits has also increased, and materials of higher conductivity is therefore required in order to scale components down.

It is believed that graphene might be ideal for such applications, and speculations around it replacing silicon (Si) in the semiconductor industry is not uncommon [3] [21].

In order for a transistor to respond quickly to voltage variations, it is necessary with small gates and fast charge carriers [21]. By using a very thin gate controlling region as in Figure 3, it is possible to decrease the gate size while avoiding short channel effects such as threshold-voltage roll-off, drain-induced barrier lowering, and impaired drain-current saturation [21]. The overall effect is minimizing the scale of the entire transistor.

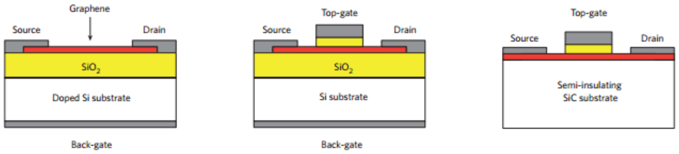


Fig. 3. Schematics of different graphene MOSFET types [21]. The red layer denotes the graphene, which can be deposited by various methods.

Graphene is readily available in a monoatomic thickness, and exhibits very good ballistic properties [3] [21], suitable for transistor applications.

However, graphene cannot be employed directly for FET transistor purposes. As mentioned earlier, graphene does not have a bandgap which is problematic in terms of the semiconducting properties required. A bandgap must be opened in the graphene, so that it can function properly as a switch (i. e. have a conducting and a non-conducting operation mode). There are several ways to do this, including contstraining the graphene in 1-D by creating a nano-ribbon or imposing strain [21] [18] to alter the bandgap.

B. *Graphene as Mechanical Lubricant*

The remarkable properties of graphene can also be put to good use for lubrication purposes in mechanical structures. Traditionally, oils and gas have been used to lubricate machinery. Even though they fulfill their purpose, they are severely inefficient and need to be refilled often. Graphene possess properties that can be employed to lubricate more efficiently than traditional remedies.

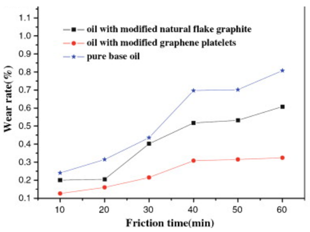
Solids are commonly not used for means to reduce friction, but because graphene has incredibly small dimensions it can easily be wedged in between surfaces to minimize the friction that occurs during movement. The mechanical strength of graphene makes it significantly resistant to mechanical wear [11]. As mentioned earlier, graphene also exhibits impermeability to various gases and liquids [19], which slows down corrosive and oxidative processes [11].

The wear of tradional lubricants is strongly dependent on the thickness of the material. A typical lubricant requires about 1000 layers to withstand 1000 cycles of wear [22]. One of the major advantages of graphene is that one layer (momoatomic) is capable of withstanding a lot more than the aforementioned lubricants.

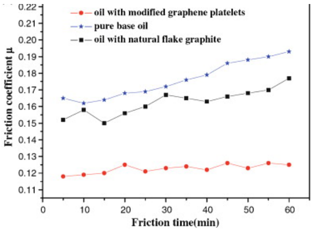
It has been documented that the friction between two steel interfaces lubricated with one layer of graphene is reduced 5-6 times, and that the wear is reduced by more than four orders of magnitude after 15000 wear cycles [11]. Graphene therefore exhibits longer life-cycles than traditional lubricants while also providing substantially lower friction between the surfaces.

Researchers have also found that adding graphene to existing lubricants can minimize the friction and wear even more. Both the wear and friction coefficient measured in an experiment with a four ball machine is plotted in Figure 4(a) and 4(b), and it is easily seen that using graphene as an additive is highly effective.

This strongly suggests the use of graphene as either a lubricant or as an additive in lubricants for future applications [11] [22].



(a) Wear vs time [11]



(b) Friction Coefficient vs time [11]

VI. CONCLUSION AND FUTURES

In this paper, several physical properties of graphene have been briefly discussed. The focus has mainly been on the electronic and mechanical properties of graphene, but it must be made clear to the reader that there are also several chemical and optical properties that should be included in a complete description.

Furthermore, a selection of applications that exploit some of the remarkable properties of graphene has been given.

Among the most compelling features that is exhibited by graphene, the electronic properties is probably the most prominent. Graphene offers latitude for enhancing a wide variety of old and creating numerous new applications within the computer and electronics industry. As mentioned earlier, there is currently an ongoing discussion on whether graphene someday may replace silicon as the most important material in the semiconductor industry. This is not only a question of time, but also a question of whether the development of graphene will reach the necessary level in order to replace silicon.

Graphene does possess potential for such a revolution, but there are still problems that need to be solved in order to implement it effectively as a semiconductor. The lack of a bandgap in graphene is especially of importance [3]. Even though there are ways to open bandgaps in graphene, these methods are not optimal for use in electronics since they have side effects such as decreasing the mobility [21]. Another problem is the insufficient precision in modern tools for defining structures of atomic scale [3].

Even though the semiconductor properties of graphene still need more development, there are other ways for graphene to contribute to electronics. The use of graphene in composite materials is believed to be one of the first real applications. The production of uncoagulated micrometre-size crystallites is already available [2], and it has been documented that conductive plastics is achievable for less than 1 % material volume filling [23] [2].

Another small but very useful application, is the use of graphene in TEM support films [3]. A mechanically strong, highly conductive and very thin material like graphene is ideal for use in TEM in order to obtain high resolution images [24]. Speculations on using graphene powder in electric batteries have also been made, as it is believed that it can increase efficiency considerably [2].

The mechanical properties of graphene are also of rapidly increasing interest. Even though this is an area that still needs more maturing, research has already benefitted greatly from it. An example of this is the stiffness that was exploited in order to suspend a graphene sheet. This allowed a minimum amount of contamination in the sample that was used to study the intrinsic transport properties of graphene, which resulted in the documentation of mobilities in excess of $200,000 \mathrm{cm}^2 \mathrm{V}^{-1} \mathrm{s}^{-1}$ [1]. The advancements in research on mechanical properties pave the way for research within other areas.

The initial interest of graphene might be due to the unique electronic properties, but the interest today comes from a variety of technologies. It seems like graphene has managed to puzzle almost every scientific field. From the discussions provided in this paper, and most scientific articles, letters and proceedings, it is evident that the discovery of graphene has come a long way, but that there is also a lot left to discover.

Because of the unique electrical properties of graphene, this will most likely be the main area of research in the future. However, there is no doubt that other technological fields also will focus more on graphene in the future, and probably discover new properties and applications that can further enhance research and development.

Graphene still has much more to offer.

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