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GRAPHENE

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An introduction to graphene

Carbon is arguably one of the most flexible and robust elements in the whole periodic table. It is responsible for all organic chemistry, and hence it is present in all living organisms on Earth, and it is also behind countless numbers of different chemical structures. Even in materials that are made out of pure carbon one can find a plethora of crystalline structures: fullerenes or buckyballs, carbon nanotubes, graphite, diamond and, more recently, graphene. All these materials can be characterised by their dimensionality and the nature of the chemical bonding (sp^2 or sp^3) that keeps the atoms together. The main motif behind these structures is the hexagonal benzene ring.

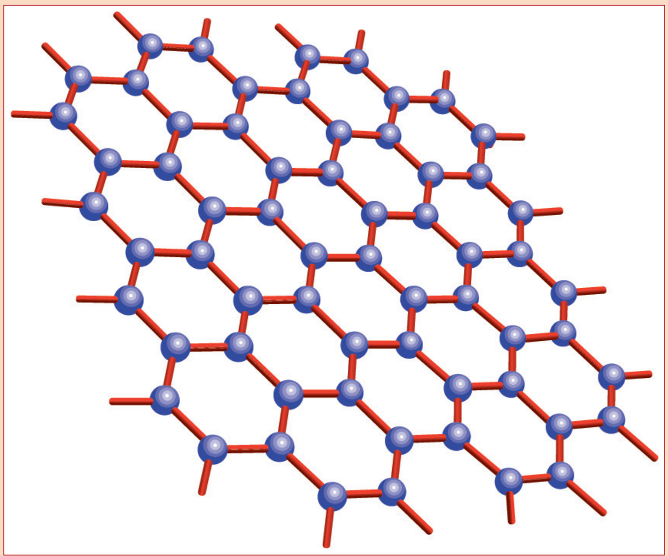

Figure 1. Graphene is a honeycomb lattice made out of benzene rings.

Although graphene was one of the last of these structures to be isolated in a laboratory and studied in detail, it can be considered the reference material for all the other structures. Fullerenes are quasi-spherical molecules that can be obtained from graphene by adding pentagons to the hexagonal structure. Their radius depends on how many hexagons are replaced by pentagons. Carbon nanotubes are one-dimensional crystals that can be obtained by taking a graphene strip and rolling it along a certain direction. Depending on the rolling direction, carbon nanotubes can be either metallic or insulating. Graphite is essentially a stack of graphene layers whose properties depend on the stacking order, that is, on the relative orientation of the graphene planes to each other. The interaction between the graphene layers is weak because the distance between the layers is large, and thus graphite can be easily cleaved. In fact, this is the reason why one can draw with a pencil. Diamond can be obtained from graphene by moving the carbon atoms out of the graphene plane by 11° , changing the sp^2 to a sp^3 hybridization, and adding more layers.

Graphene is a two-dimensional structure that is comprised of a regular hexagonal array of benzene rings (see Figure 1). Hence, graphene is a unique example of an atomically thin membrane. Like any other membrane, distortions of the two-dimensional structure in a three-dimensional environment cost very little energy, and hence graphene has a strong tendency to distort, forming scrolls, folds, blisters, wrinkles, creases, etc. However, when supported by a substrate or a scaffold a graphene crystal can be stabilized and its properties measured experimentally.

Using a simple method for cleaving graphite into graphene flakes (the now famous 'Scotch tape technique'), identifying those flakes with the use of ordinary optical microscopes, transferring them to a silicon dioxide substrate, and finally using modern lithographic techniques to produce electronic devices, Andre Geim and Kostya Novoselov were able to perform controlled electrical measurements of these truly two-dimensional crystals and show that they present unique properties.

Their work, published originally in 2004 (**Novoselov *et al*** 2004 Electric field effect in atomically thin carbon films, *Science* **306** 666), created a new field of research in condensed matter: two-dimensional crystals. Their discoveries gave rise to a research boom that is continuing. Artificial ways to grow graphene were developed (notably epitaxial growth on silicon carbide and chemical vapour deposition on metal surfaces) which has generated a tremendous interest in the high tech industries. For their work, Geim and Novoselov were awarded the 2010 Nobel Physics Prize.

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Many of the remarkable properties of graphene stem from the unusual relation between energy and momentum for the electrons that propagate within it. In ordinary metals and semiconductors, the energy of the electrons is proportional to their momentum squared. In graphene the energy is linearly related to the momentum. This relation mimics the energy–momentum relation of massless relativistic particles (although the velocity of propagation of the graphene electrons is much smaller than the speed of light) leading to very unusual electronic properties and a need to re-evaluate the standard theory of metals.

Because the bonds that make graphene stable are essentially the same as the ones found in diamond, graphene is amazingly strong (200 times stronger than steel), and conducts heat as well as diamond. Furthermore, because of the tight bonds between carbon atoms, graphene comes essentially without any extrinsic impurities and hence it conducts electricity better than copper or silicon. Its optical properties are equally amazing. Because of the linear energy–momentum relation, graphene can absorb light with frequencies from terahertz to ultraviolet and its optical transparency is given by $\pi\alpha \sim 2.3\%$, where α is the famous fine-structure constant, and hence essentially independent of any material property.

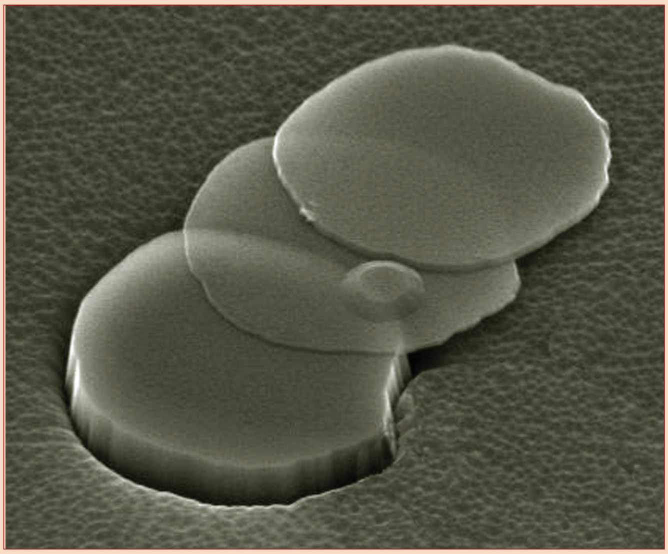

Figure 2. Graphite can be easily peeled or cleaved into thin layers of stacked graphene.

Because of its truly outstanding properties, graphene is being studied for a huge number of different applications. Graphene is highly impermeable (not even helium atoms can go through) and hence it can be used for coating. Its electrical properties are very sensitive to anything on its surface, and hence can be used for chemical sensors. Its structural properties are very sensitive to stress, and hence it can be used in strain and pressure sensors. Because graphene is metallic and transparent, it has an enormous number of uses where transparent electrodes are required, such as solar cells, lighting and lasers.

Because the carbon bonds are so strong, graphene can be used in extremely small structures for nano-electronics in the form of quantum dots and nano-ribbons (beating silicon by one order of magnitude). It can also be used in high-speed electronics and ultra-fast photodetectors due to the absence of impurities in its structure.

Nevertheless, the study of graphene is still a very young field and mostly unexplored. For instance, application of strain can change its electronic properties (so-called strain engineering) in order to create new electronic states, perhaps with semiconducting properties, with a direct impact on digital electronics. Magnetism and superconductivity have not yet been demonstrated in any form of chemically or structurally modified graphene, although either of these properties in a truly two-dimensional crystal would be a fascinating playground for physicists due to extreme quantum mechanical effects. Complex architectures of graphene with other pure carbon forms, such as nanotubes and fullerenes, to create completely new carbon forms, have not yet been synthezised. It is clear that this is still an emerging field, with much to reveal and amaze.

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