Graphene

Carbon atoms appear in many different ways in our environment. Pure carbon is found in nature both as diamond and graphite. They have very different properties, even tough they only differ by the arrangement of the carbon atoms. While diamond is insulating and very hard, graphite is conducting and lubricant. In 1985 the first artificial pure carbon material, the spherical molecule called fullerene, was found. Since then an intense research on other pure carbon materials begun. In 1991, carbon was produced in the form of quasi one-dimensional nanotubes. Later, in 2004, a single sheet of carbon, named graphene, has been experimentally discovered. The strictly two-dimensional graphene can be seen as the basic building block for the other graphite materials, having different dimensionalities. However, for a long time it was presumed that graphene in the free state can never be found in nature. This opinion was motivated by an argumentation of Landau and Peierls that strictly two-dimension crystals could not exist, because they are thermodynamically unstable. However, with the experimental discovery of graphene in 2004 by Novoselov and Geim, the common wisdom seems to be flawed. However, one can argue that the theory by Landau and Peierls still holds, since the graphene sheet is gently crumpled in the third dimension, and therefore it is not strictly two-dimensional.

Definition

Graphene is a flat monolayer of carbon atoms tightly packed into a two-dimensional (2D) honeycomb lattice, and is a basic building block for graphitic materials of all other dimensionalities. It can be wrapped up into 0D fullerenes, rolled into 1D nanotubes or stacked into 3D graphite.

Why is graphene important?

The current interest in the graphene can be attributed to three main reasons. First, its electron transport is described by Dirac equation and this allows access to quantum electrodynamics in a simple condensed matter experiment. Second, the scalability of graphene devices to nanodimensions makes it a promising candidate for applications, because of its ballistic transport at room temperature combined with chemical and mechanical stability. Remarkable properties extend to bilayer and few-layers graphene. Third, various forms of graphite and nanotubes can all be viewed as derivatives of graphene and, not surprisingly, this basic material has been intensively investigated theoretically for the past 60 years. The recent discovery of graphene at last allows us to probe it experimentally, which paves the way to better understanding the other allotropes and resolve controversies.

Methods of obtaining graphene

Drawing method (In 2004, the Manchester group obtained graphene by mechanical exfoliation of graphite.) The isolation of graphene led to the current research boom. Previously, free-standing atomic planes were often "presumed not to exist" because they are thermodynamically unstable on a nm scale and, if unsupported, have a tendency to scroll and buckle. It is currently believed that intrinsic microscopic roughening on the scale of 1 nm could be important for the stability of purely 2D crystals.

Epitaxial growth on silicon carbide (In this method heated silicon carbide (SiC) to high temperatures (>1100 °C) to reduce it to graphene. This process produces epitaxial graphene with dimensions dependent upon the size of the SiC substrate.)
Epitaxial growth on metal substrates (This method uses the atomic structure of a metal substrate to seed the growth of the graphene.)

Graphite oxide reduction (Graphite oxide reduction was probably historically first method of graphene synthesis. P.Boehm reported monolayer flakes of reduced graphene oxide already in 1962)

Growth from metal-carbon melts (The general idea in this process is to dissolve carbon atoms inside a transition metal melt at a certain temperature, and then allowing the dissolved carbon to precipitate out at lower temperatures as single layer graphene (SLG).)

Pyrolysis of sodium ethoxide (A process for producing gram-quantities of graphene, by the reduction of ethanol by sodium metal, followed by pyrolysis of the ethoxide product, and washing with water to remove sodium salts.)

Properties

Lattice structure

Graphene is made up of carbon atoms. A carbon atom has six electrons, occupying the atomic orbitals $1s^2, 2s^2$ and $2p^2$. The electrons in the $1s^2$ orbital are strongly bonded and are called core electrons. The four remaining electrons are valence electrons and are distributed to more delocalized orbitals. Since the energy difference between the $2s$ and the $2p$ level is much smaller than their binding energy, the wave functions of these four electrons can mix up easily, in a process called hybridization. Three states lie in the $xy$-plane and draw an angle of $120^\circ$. These so-called $\sigma$ states form covalent bonds with their neighbors and give rise to the hexagonal lattice structure of graphene. The remaining state is the $2pz$ orbital. It is named $\pi$ state and is aligned in the $z$-direction. Electrons in this state are weakly bonded and can hop easily between neighboring atoms. They are therefore relevant for the transport properties, and we will even consider the $\pi$ states only when calculating electronic properties of graphene.

In a graphene layer the carbon atoms are distributed at the edges of regular hexagons. This structure is often called a honeycomb lattice.

Electronic properties

Intrinsic graphene is a semi-metal or zero-gap semiconductor. Understanding the electronic structure of graphene is the starting point for finding the band structure of graphite. If we use the tight binding model to find the band structure of graphene, we can obtain the dispersion relation. Most interesting properties of graphene are due to low energy excitations, and if we make a low energy expansion around the $K$ ($K'$) point the result of energy dispersion is: $E = h\nu_f |k|$ where the Fermi velocity $\nu_f \sim 10^6$ m/s. This linear behavior is the key for many interesting properties of graphene, as it links graphene with relativistic phenomena. Indeed, the energy dispersion of relativistic particles is found from the Dirac equation, and if we put the mass is zero in this equation, the energy dependence is as well linear and resembles the energy dependence of graphene, where the Fermi velocity plays the role of the velocity of light $E = h\nu_f |k|$. One can say therefore that low energy electrons in graphene behave effectively like massless Dirac fermions. That is why the points $K$ and $K'$ are often referred to as Dirac cones. This makes graphene a perfect experimentally accessible system to study relativistic physics in a solid state system.

Electronic transport

Experimental results from transport measurements show that graphene has a remarkably high electron mobility at room temperature, with reported values in excess of 15,000 cm$^2$V$^{-1}$s$^{-1}$. 
Optical properties

Graphene's unique electronic properties produce an unexpectedly high opacity for an atomic monolayer, with a startlingly simple value: it absorbs $\pi \alpha \approx 2.3\%$ of white light, where $\alpha$ is the fine-structure constant. This is "a consequence of the unusual low-energy electronic structure of monolayer graphene that features electron and hole conical bands meeting each other at the Dirac point which is qualitatively different from more common quadratic massive bands".

Spin transport

Graphene is thought to be an ideal material for spintronics due to small spin-orbit interaction and near absence of nuclear magnetic moments in carbon. Electrical spin-current injection and detection in graphene was recently demonstrated up to room temperature.

Anomalous quantum Hall effect

The effect concerns the dependence of a transverse conductivity on a magnetic field, which is perpendicular to a current-carrying stripe. It can be observed only in very clean Si or GaAs solids, and at very low temperatures around 3 K, and at very high magnetic fields. Graphene in contrast, besides its high mobility and minimum conductivity, shows particularly interesting behavior just in the presence of a magnetic field and just with respect to the conductivity-quantization: it displays an anomalous quantum Hall effect. These remarkable anomalies can even be measured at room temperature at roughly 20 °C. It is a direct result of the emergent massless Dirac electrons in graphene.

Nanostripes: Spin-polarized edge currents

Nanostripes of graphene (in the "zig-zag" orientation), at low temperatures, show spin-polarized metallic edge currents, which also suggests applications in the new field of spintronics. (In the "armchair" orientation, the edges behave like semiconductors.)

Potential applications

Single molecule gas detection, Graphene nanoribbons, Graphene transistors, Integrated circuits, Transparent conducting electrodes, ideal for making nanoelectronic devices (because it is a very good electrical conductor as well as being the thinnest material known.)

And Graphene quantum dot may solve some quantum computing problems.