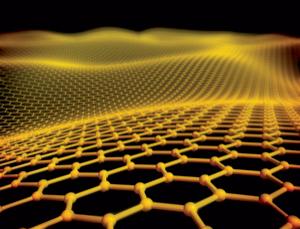
**Graphene: Super-properties**

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*Graphene consists of sheets of carbon just one atom thick* *(Image: Pasieka/Science Photo Library)*

**If carbon is a wonder element, then graphene is a wonder material. Just one atom thick, it is a million times thinner than a piece of paper and can be folded and scrolled like plastic film. Yet it is stronger than diamond and conducts heat and electricity better than copper or gold. It is no wonder that of all the new nanoscale forms of carbon, graphene is attracting the most attention.**

**The isolation of graphene**

Graphite, fullerenes and nanotubes are essentially stacked, wrapped and rolled examples of a more basic material: graphene. If diamond is three-dimensional and graphite something less than that, graphene reduces things to just two dimensions: it consists of a single layer of graphite just one atom thick.

Nature, in general, abhors low-dimensional structures. To make them, thermal vibrations must be suppressed in one direction, or the layer will crumple or be chemically modified into a three-dimensional structure. So although graphene is the most basic form of crystalline carbon, it was the last to be isolated, at the University of Manchester, UK, in 2004.

That was done slightly unconventionally, using sticky plastic tape to strip single layers of carbon atoms from a graphite block. In general, graphene's inclination to crumple as soon as it is produced can be countered by first laying it down on a good substrate, thus weakening its thermal vibrations, and then using modern lithographical techniques to carve it into the required shape. Individual sheets must be attached to a substrate or held under tension to stop them scrolling up.

**Mechanical supremo**

Being just one atom thick, graphene is a very soft, pliable material, like a thin tissue. Even its existence is something of a marvel. A thin film of any metal - gold, say - even 10 times thicker than graphene would not survive at room temperature and pressure, as its thermal vibrations would cause it to coagulate into rounded clusters. Carbon owes its stability to a quantum-mechanical effect called hybridisation, which makes four of its six orbiting electrons available to create short, but very strong bonds.

That has a number of consequences. It makes graphene a superb conductor of heat, because the structure can vibrate at very high frequencies without breaking up, and it makes it chemically inert; graphene survives at temperatures up to 300°C in air and much higher in a vacuum. And it really is strong: a hammock made from graphene would be strong enough to swing a cat weighing a kilogram.

Applying a similar lateral force will extend a graphene sheet elastically by about a quarter of its length. But whereas most materials behave like a plastic and become stretched into filaments under such a force, graphene maintains its structure; the distance between the carbon atoms simply increases. That in turn affects the hybridisation of the atomic electrons, and hence also the material's bonding. Apply strain in the right way, and it is even possible to start manipulating graphene's electronic properties, converting it from its normal conducting state into an insulator (see "Conductive chameleon, below").

**Conductive chameleon**

It is not just the speed of electrons in graphene that is impressive: the great strength of the structure's bonds means it can carry large numbers of electrons without breaking. What's more, those numbers can be changed by orders of magnitude simply by applying an external voltage, altering the material from a highly conductive metal with many free electrons, to a semiconductor with only a few of them, to (at least in theory) an insulator with virtually none at all.

A material with these chameleon characteristics is known as a semi-metal. The response of graphene's electrons to an applied voltage - its electron mobility - is almost 100 times that of electrons in silicon. It is, in fact, just about the most electrically responsive material known.

Similar conductive changes can be achieved by straining the graphene lattice (see "Mechanical supremo") or by adding other chemical elements into the mix. Brought into contact with hydrogen at high temperatures, for example, the free electrons in graphene bind with the hydrogen, turning it into an insulator - an entirely new material known, in its fully hydrogenated state, as **graphane**. By heating this material up again, these hydrogen atoms fly away and graphane reverts to graphene. That suggests graphene could have a potentially crucial role as a structure in which to store hydrogen in any future energy economy where hydrogen takes the place of fossil fuels.

**Ballistic electrons**

In general, the thinner a solid material is, the lower its conductivity becomes: there is less space for electrons to manoeuvre without colliding with rough surfaces, being captured by atoms of other elements present as impurities within the crystal, or being pushed off course by atomic vibrations. In an ultra-high vacuum and at ultra-low temperatures, vibrations and the effects of impurities are suppressed, which does help a little. Yet graphene's one-atom-thick film has better electronic qualities than any three-dimensional material, whether a metal like gold or a semiconductor like silicon - and not just at low temperatures.

That is all down to quantum effects. According to the quantum theory of solids, free electrons within metals and semiconductors do not move along well-defined trajectories, as particles do, but behave more like spreading waves whose passage is influenced by the general structure of the surrounding material. In the case of graphene, the hexagonal honeycomb of the lattice causes a destructive pattern of interference between electron waves that, back in the particle picture, is akin to the electrons losing their mass. As a result, they go ballistic, racing through the material at a speed just 300 times slower than the speed of light. These speedy, massless electrons are one reason why graphene has been proposed as a "desktop particle accelerator" to probe the behaviour of particles travelling close to the speed of light in extreme environments, for instance close to neutron stars and black holes.

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