**Graphene: What it's good for**

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Graphene could be used to improve the durability of car tyres *(Image: Frank Siteman/Superstock)*

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Hundreds of applications have been suggested to take advantage of graphene's remarkable properties. Some are more realistic than others, and difficulties remain to be overcome with all - but from computer chips to touchscreens, there are some promising ideas in the pipeline

**Carbon electronics**

Because electrons in graphene move very quickly and scatter little [(see "Ballistic electrons")](http://www.newscientist.com/article/mg21428633.200-graphene-superproperties.html), computer chips made from graphene could in theory be both faster and experience far less noise from electron jostling than existing silicon chips. Semiconductors such as silicon, which are in principle insulators made to conduct by applying an electric field, suffer from a further disadvantage in that an alternating field must oscillate above a certain frequency to free up electrons for conduction. In a semi-metal such as graphene, where there are always free electrons, this restriction does not apply, potentially opening up a broader range of frequencies for use in computing and communications. [High-frequency transistors](http://www.newscientist.com/article/dn11276-atomthick-carbon-transistor-could-succeed-silicon.html), amplifiers, optical modulators, capacitors, photo-detectors and other electrical components made from graphene are all being investigated.

A full-blown graphene chip is still at least a decade or two away, however. For a start, [it is hard to switch off the conductivity of a semi-metal completely](http://www.newscientist.com/article/dn21422-slow-graphene-down-speed-computers-up.html). This ability to effectively "gate" the current passing through is an essential requirement for any practical processor material.

Nevertheless, successes have already been reported. In 2010, [IBM demonstrated a graphene transistor](http://www.nytimes.com/2011/06/10/technology/10chip.html) on a silicon carbide substrate that operated at frequencies up to 100 gigahertz, comparable to the highest frequencies attainable with pure silicon transistors. It is estimated that graphene-based components should be able to reach 1000 GHz.

With silicon technology so well developed, however, the first electronic applications of graphene are likely to be as components to improve the performance of silicon chips. One possibility is to take advantage of graphene's high thermal conductivity to make "heat sinks" to help cool down chips. That would require a better interface between graphene and silicon, however; at the moment, the join creates additional electrical resistance, suppressing the performance of the chip.

**Flexible friends**

Many modern devices and gadgets have flat screens, whether they are liquid-crystal displays or displays based on light-emitting diodes. Often, as in smartphones, they are touch-sensitive. A crucial component in these displays is an uppermost layer that is both optically transparent and highly conducting, so that the device can sense the fingers. That is a rare combination. Indium tin oxide, the current favourite for such applications, is far from ideal: [it is scarce](http://www.newscientist.com/article/mg20827831.000-ten-years-to-save-the-touchscreen.html) and lacks flexibility and mechanical strength.

Graphene is not only highly conductive under the right circumstances [(see "Conductive chameleon")](http://www.newscientist.com/article/mg21428633.200-graphene-superproperties.html), but also largely transparent, absorbing only 2.3 per cent of the light falling on it. Several graphene layers on top of each other would, in theory, make a film that outperforms any existing touchscreen material. In practice, however, technology lags well behind theory. To work in a device, the graphene layer must be married to a flat, clean insulating substrate that does not influence how electrons flow within it. Silicon dioxide, the common substrate for microelectronics, is too bumpy. Current investigations are looking to replace it with boron nitride, which is extremely flat and chemically inert, interacting little with graphene's free electrons.

Such engineering issues will hopefully in time be resolved. Once they are, graphene offers qualities its competitors do not: flexibility and stretchability. Companies including Samsung and Nokia [envisage using graphene](http://techwalls.com/gadget/flexible-screen-smartphone-release-2012/) to produce personal electronic gadgets that can be worn like watches and folded and unfolded as required.

**Material gains**

Even ground to a fine powder, graphene retains much of its outstanding mechanical strength and electronic conductivity [(see "Graphene: Graphene's properties")](http://www.newscientist.com/article/mg21428633.200-graphene-superproperties.html). One idea being explored is to use this powder as an additive to replace more conventional forms of carbon. Take car tyres. For the past century their characteristic black colour has come from carbon black, an amorphous form of carbon added for reinforcement. Graphene's supreme strength might improve their durability still further.

In zinc-carbon batteries, graphite is used as a storage material: ions move between the stack of graphene layers that make a graphite crystal and are held there through electrostatic interactions with the free electrons in the crystal. By increasing the distance between the individual layers, more ions can be stored. The limit comes when the layers are completely decoupled from each other - in other words, when graphite becomes graphene. The large and easily accessible surface area of graphene, coupled with its high conductivity, could increase both the lifetime and storage capabilities of such batteries. That possibility is being investigated by companies such as the chemicals firm BASF. Despite the fanfares and excitement surrounding carbon electronics and the like (see right), [it is as a silent substitute for already familiar materials where graphene is most likely to make its first mark](http://www.nature.com/nature/outlook/graphene/index.html).

**Problems to be solved**

One of the greatest bottlenecks in the practical use of graphene has been producing it in large enough quantities. Early methods that involved stripping graphene layers from graphite (see "The isolation of graphene") were suitable only for small amounts and tiny areas. [Graphene films as large as 1 square metre can now be grown on top of a metal surface](http://www.newscientist.com/article/dn19068-touchscreen-made-from-biggest-graphene-sheet.html) using a method called chemical vapour deposition. This is akin to the catalytic reaction in car exhausts: a hydrocarbon gas hits a hot metal plate, stripping it of its hydrogen and other atoms and leaving behind carbon atoms that under the right conditions grow to form a graphene film.

The quality of mass-produced graphene remains relatively poor, however. A similar purity problem dogged the silicon industry half a century ago, but was eventually solved with time and money. For graphene, it is probably only a question of a similar investment.

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