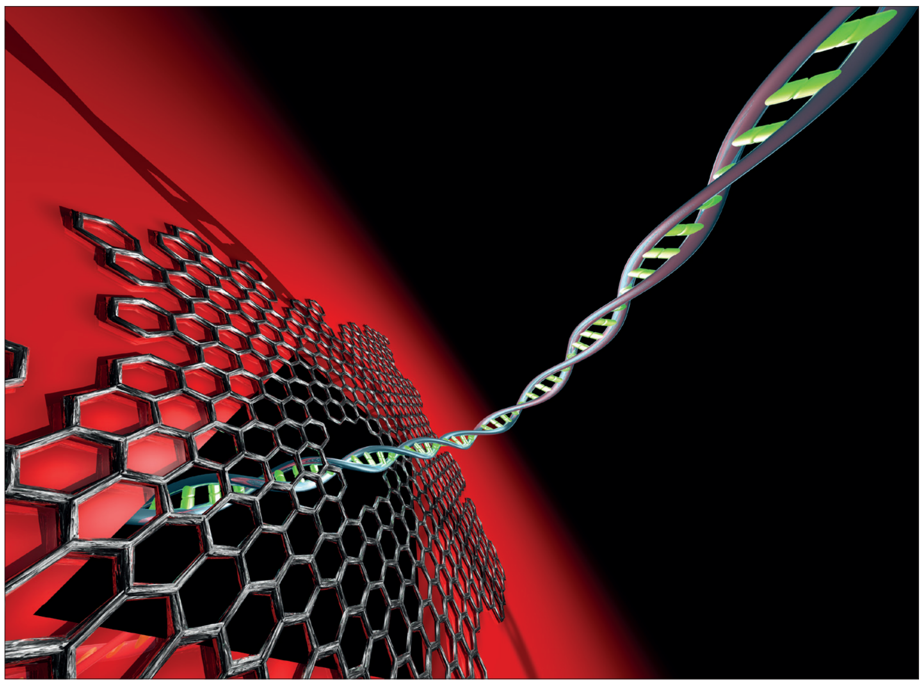
20 things you can do with graphene

Dubbed the "wonder material", graphene has grabbed the attention of developers worldwide thanks to its extraordinary properties and diverse range of uses. **Belle Dumé** and **James Tyrrell** round up 20 exciting applications that have hit the headlines

Graphene – a sheet of carbon atoms arranged in a honeycomb-like lattice just one atom thick – has trumped buckyballs and nanotubes to become the king of carbon nanomaterials. Since its discovery just a few years ago, this "wonder material" has wowed researchers with record-breaking electronic and mechanical properties. According to recent studies, graphene is not only the strongest material ever measured, but also the stiffest, and its current density – a measure of the density of flow of charged carrier particles – is a million times that of copper. But graphene is much more than just a scientific curiosity: it boasts a growing list of real-world applications. To illustrate the point, here are 20 amazing things that you can do with it.



Code breaker Researchers have shown that DNA can go through tiny holes in graphene.

Create rugged sensors

Two-dimensional graphene is very stable electrically and mechanically under high bending deformation, and combining it with vertically aligned metallic nanowires offers a promising way of making flexible hybrid nanostructures. Applications include biochemical sensors, pressure sensors, field emission devices and battery electrodes (*Nanotechnology* **22** 355709).

Researchers from Seoul National University and the Samsung Advanced Institute of Technology in South Korea have developed a simple, but efficient, low-temperature production route. In the method, a graphene layer is transferred onto an anodic alumina-oxide template and vertically aligned gold nanowires are grown on the graphene surface via electrodeposition, which allows the structures to be prepared with a controlled length and diameter.

The technique also avoids any high-temperature steps or unconventional lithography procedures, which means that it can be applied onto versatile substrates including soft materials.

Sequence DNA

By feeding individual strands of DNA through nanometre-sized holes, scientists from Delft University of Technology in the Netherlands say that they have proved the principle of a revolutionary DNA-sequencing technique. The breakthrough is part of a worldwide race to develop fast and low-cost strategies to analyse these codes that underpin the chemistry of life (*Nano. Lett.* 10.1021/nl102069z).

In the study, the team demonstrates that DNA does indeed go through little holes in graphene, and that it does so with great speed. Both of these are important advancements towards using graphene for DNA sequencing.

Re-imagine aircraft design

Picture a deep-space-exploration vehicle fitted out with lightweight actuators that directly convert photons from nearby stars into mechanical motion without the need for solar cells. Or how about an aircraft equipped with solid-state flight-control surfaces instead of rudders and ailerons? These ideas might sound a little like science fiction, but researchers in the US and the UK are developing graphene nanoplatelet-based photomechanical actuators that could pave the way for both concepts (*Nanotechnology* **23** 045501).

By combining graphene with soft elastomeric materials such as PDMS, the scientists from the University of Louisville and the University of Cambridge have created graphene/polymer composites with responses to near-infrared illumination that depend on applied pre-strain. At low levels of pre-strains (3–9%) the actuators show reversible expansion, while at high levels (15–40%) the actuators exhibit reversible contraction. Using these actuators, the team witnessed an extraordinary optical-to-mechanical energy conversion factor of ~7 MPa/W, some three orders of magnitude greater than commercially available light-driven actuating materials such as polyvinylidene fluoride.

Detect concealed weapons

Scientists at the Lawrence Berkeley National Laboratory and the University of California, Berkeley in the US have found a way to adjust the amount of light absorbed by graphene at terahertz frequencies. The findings could lead to graphene-based terahertz metamaterials, which would give developers more options for applications such as medical imaging and security screening (*Nature Nanotechnology* 10.1038/nnano.2011.146).

Terahertz radiation is useful for detecting items such as concealed weapons and explosives because it passes through clothing and packaging but is strongly absorbed by metals and other inorganic substances.

Feng Wang and colleagues say that they have made the "beginnings of a toolset" for experiments in this wavelength range. The team has come up with a prototype device that consists of an array of graphene nanoribbons with a response to terahertz radiation that can be tuned by varying the width of the ribbons and the number of charge carriers (electrons and holes) in the structures.

In graphene, the concentration of charge carriers can easily be increased or decreased by applying a strong electric field – a technique known as electrostatic doping.

Build better electronics

Graphene could be ideal for use in future electronics applications because electrons whizz through the material at extremely high speeds (thanks to the fact that they behave like relativistic particles with no rest mass). Recently, a new method to increase the amount of current that can be carried by graphene has been unveiled by researchers at the University of California, Riverside (UCR) and the Argonne National Lab (*Nano Lett.* 10.1021/nl204545q).

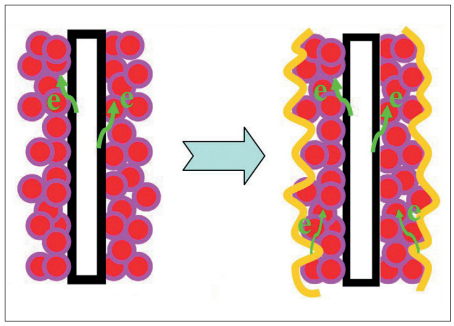
The technique involves growing or transferring graphene on synthetic diamond or ultrananocrystalline diamond rather than on a conventional silicon-dioxide substrate. Diamond conducts heat better than silicon or silicon dioxide, removing more heat away from the graphene, which in turn means that the wonder material can sustain even higher current densities.

Alexander Balandin and Anirudha Sumant, working together with electrical-engineering graduate students in Balandin's lab at UCR, have shown that the current-carrying capacity of graphene can be increased to as high as around $20\,\mu A/nm^2$ by replacing the silicon dioxide with synthetic diamond or inexpensive ultrananocrystalline diamond.

The work could help to develop high-frequency transistors, transparent electrodes and interconnects for replacing copper on silicon dioxide.

Ramp up the performance of supercapacitors and batteries

A new and simple "dipping" technique that significantly improves the specific capacitance and rate capability of metal-oxide-based supercapacitors has been demonstrated by researchers at Stanford University in the US (*Nano Lett.* 10.1021/nl2026635).



G Yu, Stanford University

High-performance coating Graphene/manganese electrodes dipped into a carbon-nanotube solution.

The technique, developed by Zhenan Bao, Yi Cui and colleagues, involves dipping a composite electrode made of graphene/manganese-oxide into a solution containing either carbon nanotubes (CNTs) or a conductive polymer. The CNTs or polymer coat the electrode and greatly improve its electrical conductivity, so enhancing its specific capacitance (or its ability to store charge) by more than 20% for the CNT coating and 45% for the polymer.

Dubbed "conductive wrapping", the method could be applied to a range of high-density but insulating electrode materials. It may even be used to improve next-generation lithium-ion battery electrodes made from sulphur, lithium manganese phosphate and silicon.

As well as having high specific capacitance, the hybrid electrodes also show good rate capability. They can be used over more than 3000 charge–discharge cycles while retaining more than 95% of their capacitance.

Design new types of batteries

Researchers at Hong Kong Polytechnic University claim to have invented a new kind of graphene-based "battery" that runs solely on ambient heat. The device is said to capture the thermal energy of ions in a solution and convert it into electricity. The results are in the process of being peer reviewed, but, if confirmed, such a device might find use in a range of applications, including powering artificial organs from body heat, generating renewable energy and running electronic devices (arXiv:1203.0161).

Zihan Xu and colleagues made their battery by attaching silver and gold electrodes to a strip of graphene. In their experiments, the researchers showed that six of these devices in series placed in a solution of copper-chloride ions produced a voltage of more than 2 V – enough to drive a commercial red light-emitting diode.

Kill *E. coli*

Graphene could be used to make antibacterial paper, according to work by scientists at the Chinese Academy of Sciences in Shanghai, who have found that sheets of the material effectively stop the growth of *E. coli* bacteria without being toxic to human cells. "Ultimately, we would like to develop new antibacterial materials from graphene that could be directly applied onto skin to aid in wound healing," says Chunhai Fan (*ACS Nano* 10.1021/nn101097v).

Print electronic devices

Researchers at the University of Cambridge in the UK have invented a new ink based on graphene, which they have used to print high-performance, transparent, thin-film transistors and interconnects. The work could lead to graphene-based flexible displays, solar cells and electronic paper (arXiv:1111.4970).

To make the ink, the scientists begin by treating graphite flakes in a sonic bath containing the solvent N-methylpyrrolidone for several hours. The flakes are then left to settle for a few minutes after sonication. Next, the team decants the dispersions and centrifuges the samples for an hour to filter out any flakes bigger than $1\,\mu m$ across that might clog the printer nozzle.

The ink suits a variety of substrates, including silicon dioxide and quartz.

Soak up arsenic

A composite material made from reduced graphene oxide (RGO) and magnetite could effectively remove arsenic from drinking water, according to work done in South Korea (*ACS Nano* 10.1021/nn1008897).

The purification process is initiated by dispersing the magnetite–RGO composite in water, where the material soaks up arsenic. Thanks to the presence of the magnetite, the composite can be quickly and efficiently extracted from the water using a permanent magnet.

The contribution of the graphene flakes is to increase the number of arsenic adsorption sites.

Improve electron sources

Few-layer graphene (FLG) has exceptional physical and chemical properties and is considered as a type of field-emission material thanks to its thin edges. However, to achieve a large field-enhancement factor, the graphene sheets must be grown vertical to the substrate rather than in the horizontal configuration that is typical of most synthesis methods (*Nanotechnology* **23** 015202).

One approach, as demonstrated by scientists in China, is to use microwave plasma-enhanced chemical vapour deposition (MPECVD). The team from Sun Yat-sen University has synthesized FLG in a vertical growth direction, and shaped the material by adjusting the growth time and ratio of hydrocarbon gas. Potential applications include high-power vacuum electron sources.

Applications

Focus light
A tiny bubble of graphene could be used to make an optical lens with an adjustable focal length. That is the claim of physicists at the University of Manchester in the UK, who have shown that the curvature of such bubbles can be controlled by applying an external voltage. Devices based on the discovery could find use in adaptive-focus systems that try to mimic how the human eye works (*Appl. Phys. Lett.* **99** 093103).

It turns out that graphene can be stretched by up to 20%, which means that bubbles of various shapes can be "blown" from the material. This property, combined with the fact that graphene is transparent to light yet impermeable to most liquids and gases, could make the material ideal for creating adaptive-focus optical lenses.

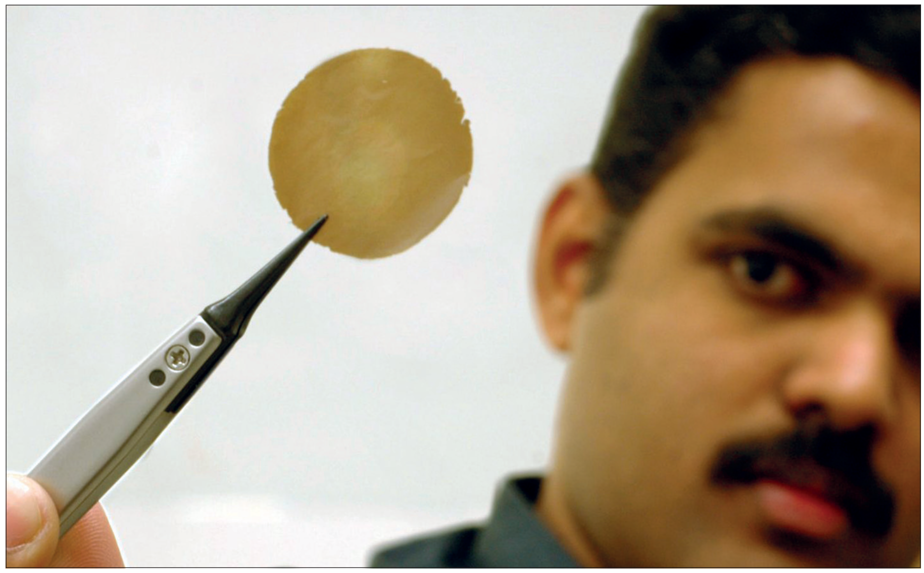
Such lenses are used in mobile-phone cameras, webcams and auto-focusing eye glasses, and are usually made of transparent liquid crystals or fluids. Although such devices work well, they are relatively difficult and expensive to make. In principle, graphene-based adaptive optics could be fabricated using much simpler methods than those used for existing devices. They could also become cheaper to produce if industrial-scale processes to manufacture graphene devices become available.

Make high-performance modulators
A modulator containing a double layer of graphene has been unveiled by researchers at the University of California, Berkeley and the Lawrence Berkeley National Laboratory in the US. The high-performance device, which operates at 1 GHz, has many advantages over silicon photonics, including a small footprint, low power consumption and low optical loss. Applications include telecommunications and on-chip data communication (*Nano Lett.* 10.1021/nl204202k).

"Compared with silicon-based optical modulators, this double-layer graphene device has separate electrical and optical control modules," says team member Ming Liu. "This is a first and allows us to optimize both the electrical and optical design separately, and avoid the trade-off between speed and optical losses."

Store hydrogen
Vehicles and other systems powered by hydrogen have the advantage of emitting only water as a waste product. An important challenge, however, is storing enough hydrogen onboard a car so that it can travel as far as a vehicle powered by fossil fuels. If hydrogen is stored as a compressed gas, it takes up far too much space – and liquefying hydrogen is expensive in terms of both cost and energy.

One solution to this problem is to exploit the fact that many solid materials will absorb large amounts of hydrogen, and researchers have identified stacked layers of oxidized graphene as a promising candidate. Scientists from the NIST Center for Neutron Research in the US have made graphene-oxide frameworks that can hold roughly 1% of their weight in hydrogen. This value is 100 times more than graphene oxide and compares well with MOF-5 (the most studied metal-organic framework to date for hydrogen storage), which absorbs about 1.3 wt% (*Angew. Chem. Int. Ed. Engl.* **49** 8902).


University of Manchester

Magic membranes Flakes of graphene oxide could be used to separate water from other liquids.

Remove water from a mixture
Scientists have reported that membranes made from graphene oxide appear to be highly permeable to water while being impermeable to all other liquids and gases. The membranes consist of millions of small flakes of graphene oxide with nanometre-sized empty channels (or capillaries) between the flakes that favour the passage of monolayers of water and resist other substances (*Science* **335** 442). Graphene oxide is similar to ordinary graphene but is covered with molecules, such as hydroxyl groups (OH).

Remove unwanted heat from electronics
University of California, Riverside scientists say that they have made a new thermal interface material (TIM) that could efficiently remove unwanted heat from electronic components such as computer chips and light-emitting diodes. The material is a composite made of graphene and multilayer graphene (*Nano Lett.* 10.1021/nl203906r).

Unwanted heat is a big problem in modern electronics based on conventional silicon circuits – and the issue is getting worse as devices become ever smaller and more sophisticated. Graphene could be ideal as a filler material in TIMs to carry away heat because pure graphene has a large intrinsic room-temperature thermal conductivity that lies in the 2000–5000 $W\,m^{-1}\,K^{-1}$ range. These values are higher than those of diamond, the best bulk-crystal heat conductor that is known.

Alexander Balandin and colleagues have now succeeded in increasing the thermal conductivity of a routinely employed industrial epoxy-resin-based TIM, or "grease" as it is better known in the industry, from around 5.8 $W\,m^{-1}\,K^{-1}$ to a record 14 $W\,m^{-1}\,K^{-1}$. The filler particles in this case consist of an optimized mixture of graphene and few-layer graphene, with the volume fraction of the carbon-based material in the epoxy being very low at just 2%.

Form transparent electrodes for displays
Tae-Woo Lee of Pohang University of Science and Technology in South Korea and colleagues have developed a way to increase the work function of graphene films and lower the sheet resistance so that the ultrathin material can be made into an efficient anode for organic light-emitting diode applications (*Nature Photonics* 10.1038/nphoton.2011.318).

"The graphene anode demonstrated excellent bending stability with a bending radius of 0.75 cm and a strain of 1.25%," says Lee. "And we observed that the graphene devices maintained almost the same current density even after being bent and straightened 1000 times."

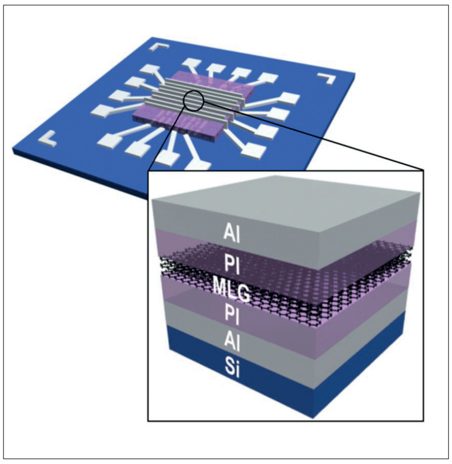
Make rare-element-free magnets
Graphene can be made magnetic by forming honeycomb-like arrays of hydrogen-terminated nanopores on it. So say researchers in Japan, based at Aoyama Gakuin Uni-

Applications

versity and the University of Tokyo, who have observed room-temperature ferromagnetism in graphene nanopore arrays, caused by, they believe, electron spins localized at the zigzag-shaped atomic-structured nanopore edges. The phenomenon, only predicted by theory until now, might help make magnets that are rare-element free, extremely light, transparent and flexible. It could also be used for novel devices that exploit edge-polarized spins (*Appl. Phys. Lett.* **99** 183111).

Store data

Computer memory is another application that demonstrates the versatility of graphene. As part of a study to understand non-volatile memory phenomena in graphene-polymer devices, researchers at Seoul National University and the Gwangju Institute of Science and Technology, South Korea, have fabricated organic memory devices that feature multilayer graphene film sandwiched between insulating polyimide layers. The array-type structures showed write-once-read-many (WORM)-type memory characteristics, with the embedded multilayer graphene film acting as a charge-trapping layer (*Nanotechnology* **23** 105202).



GIST/SNU

Smart storage Multilayer graphene acts as a charge-trapping layer in organic memory devices.

Harness energy from the Sun

Combining graphene with special metallic nanostructures could lead to better solar cells and optical communications systems. That is the claim of researchers in the UK who have measured a 20-fold enhancement in the amount of light captured by graphene when it is covered by such nanostructures (*Nature Communications* 10.1038/ncomms1464).

The team from the University of Cambridge and the University of Manchester has paired up graphene with plasmonic nanostructures – tiny features that enhance local electromagnetic fields in a material by coupling incoming light with electrons on the surface of the metal.

The nanostructures are fabricated on top of graphene samples to concentrate the electromagnetic field in the region of the material where light is converted to electrical current, so as to dramatically increase the generated photovoltage.

This tackles the issue of graphene's low "external quantum efficiency" – it absorbs less than 3% of the light falling on it – and allows developers to make use of the material's ideal "internal quantum efficiency". Almost every photon absorbed by graphene generates an electron–hole pair that could, in principle, be converted into electric current.

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