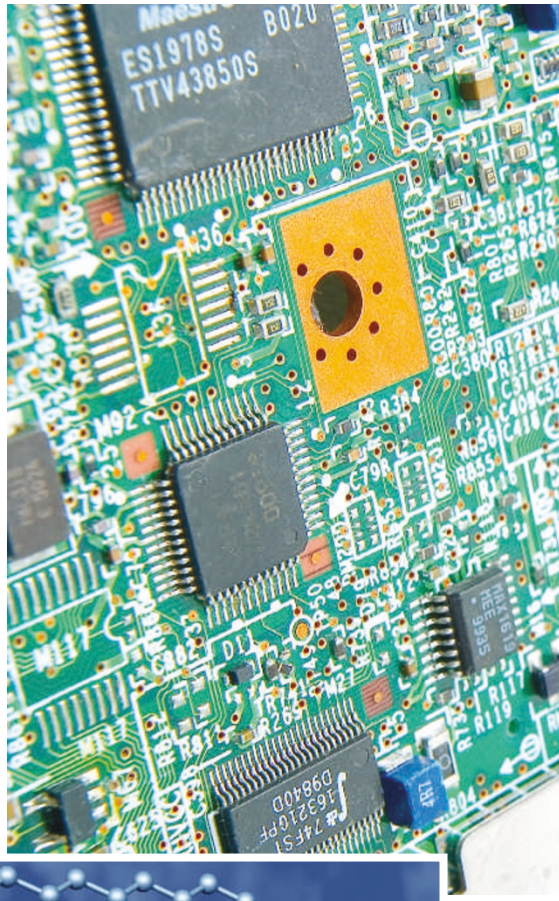
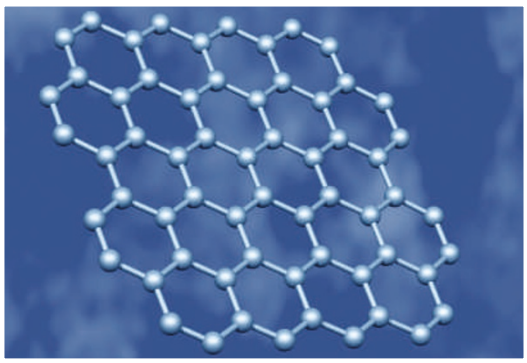
NEWS

Moving towards a graphene world



PROMEDIA/ALAMY



Welcome to graphene: the flat carbon sheet with revolutionary aspirations. This thinnest possible pencil-lead shaving has already interested theoretical physicists with its electronic properties, and is predicted to edge aside silicon in the microchips of the future. Now it's ready for its first practical application.

Carbon exists in many forms: 'buckyballs', diamond, nanotubes and graphite to name a few. In 2004, André Geim of the University of Manchester, UK, together with Russian colleagues, created another form — carbon layers just one atom thick, called graphene (K. S. Novoselov *et al. Science* **306**, 666–669; 2004). Physicists have since documented some remarkable properties of this material. But industrial applications have seemed some way off, as graphene has proved difficult to produce on a large scale. It was made by unwieldy methods such as rubbing flecks off a piece of graphite, as Geim did, or boiling up silicon carbide in a vacuum.

Now, Rodney Ruoff and his team at Northwestern University, Illinois, have come up with a way to make large amounts of graphene embedded in a polymer matrix. The researchers start with graphite oxide — graphite with oxygen-containing chemical groups attached. After further chemical modification and treatment with ultrasound, the material separates into layers, and disperses through a solvent in which a polymer such as polystyrene is also dissolved. Chemical reduction removes most of the oxygen groups, and removing the solvent leaves behind graphene sheets crumpled within the solid polymer (see pages 282 and 254).

The resulting material is strong, and electrically and thermally conducting. Such properties are similar to those of carbon nanotube composites, which isn't surprising as a sheet of graphene is basically an unrolled nanotube. But the graphene-based composites produced by Ruoff's chemical method are cheaper and more reliable to manufacture, so could be perfect for things that need to be lightweight, strong and conducting, such as aircraft fuselages.

Although graphene's first foray into industry is likely to be as a composite, several groups are working on unlocking the potential of the isolated sheets. For one thing, the sheets' electronic properties make graphene a candidate to replace silicon in a fresh era of microchip electronics. "Graphene is quite different from conventional semiconductors such as silicon," explains Philip Kim, a physicist from Columbia University in New York. Electrons move though silicon in a series of collisions; these generate heat and limit the speed and size of silicon transistors. The density of components on silicon chips has doubled every 18 months or so since the 1960s, a trend known as 'Moore's law' after Intel's co-founder Gordon Moore predicted it in 1965. But many believe silicon chips will soon reach their limit.

> **"Nothing is an insurmountable problem. All the lights are still go."**

In graphene, however, electrons shoot along with minimal resistance. This, says Kim, may allow for low-power, faster-switching transistors. "But it's difficult to turn graphene off, which will make it hard to use in an electrical switch," he notes. "Really, we need new types of electronic architecture to make best use of graphene."

Trumping silicon

Also enthusiastic about graphene's potential in computing is Walt de Heer, of Georgia Tech's School of Physics in Atlanta. His team, with French collaborators at the National Centre of Scientific Research in Grenoble, is attempting to etch electronic structures into layers of graphene wafers grown on silicon carbide. He points out that carbon nanotubes would give the same electronic advantages as graphene sheets but that it is difficult to produce them in large amounts and organize them on a chip, and that high electrical resistances occur when nanotubes are connected with metal wires in an electronic circuit.

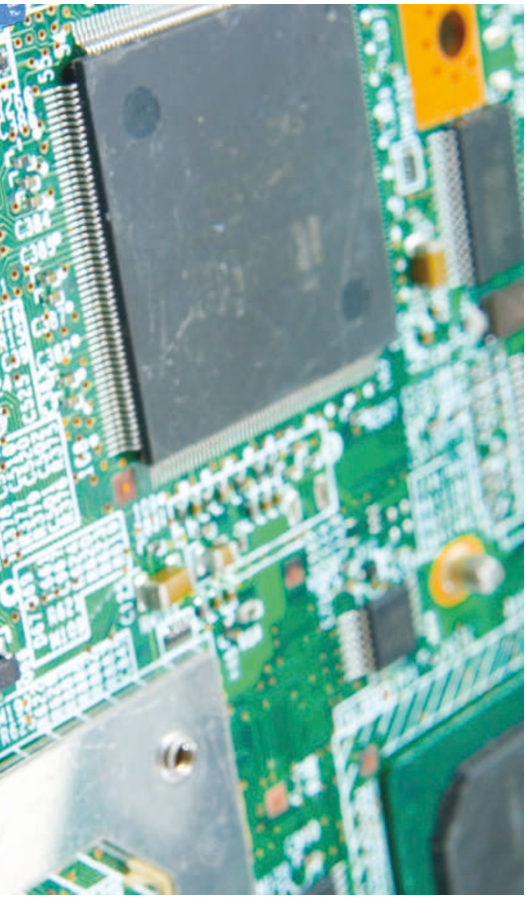
"No one sees nanotubes as a serious avenue," says de Heer. In contrast, flat graphene wafers are easily etched using conventional lithography techniques. De Heer also hopes that connecting wires won't be necessary. He envisages future electronic circuits made up of continuous graphene sheets, saying that cutting graphene into ribbons of different widths controls its conducting properties.

De Heer, who along with his team has attracted funding from Intel, is confident in graphene's electronic potential, although he cheerfully predicts that the revolution won't come just yet. "Industry has no reason to switch over from silicon until the end of Moore's law in 10 or 15 years," he says. Geim is more wary. "Electronic applications require reliable large-scale production of graphene," he says. "At the moment the quality is rather mediocre."

Geim is more excited about graphene's usefulness as a research tool. The carbon lattice in the sheets is extremely regular, giving the electrons within the lattice unusual properties. "The electrons move collectively in a manner that mimics particle behaviour at close to light speed," explains Geim. He and other teams are using graphene to investigate quantum

AP

JAVA HIT BY TSUNAMI AFTER EARLY WARNING
An alert was issued minutes before the wave struck.
www.nature.com/news



Electrons pass through graphene (left) with less resistance than through silicon, making the carbon sheet a good candidate for future chips.

mechanical effects previously thought to occur only in dense plasmas around black holes and neutron stars, or in powerful particle accelerators. One example is the Klein paradox, in which fast-moving particles pass straight through a seemingly impenetrable barrier.

Meanwhile Ruoff believes his composites might yet trump other applications. By chemically modifying the sheets within the polymer matrix and studying the resulting properties, he hopes to usher in a new class of graphene-based materials. He suggests that chemically tuned composites could be used as electrically conductive plastics in solar panels, for example, or to dissipate excess heat within computer parts: "The technology wizards will take this in various directions."

One thing researchers agree on is that we're likely to hear a lot more about graphene. "Nothing is a sure deal," says de Heer. "But nothing is an insurmountable problem. All the lights are still go." ■

Richard Van Noorden

It's legal: Italian researchers defend their work with embryonic stem cells

Embryonic stem-cell researchers in Italy have reacted strongly to comments made by a Catholic cardinal earlier this month that anyone involved in destroying human embryos — including scientists deriving stem cells for research — should be excommunicated.

Concerned at the press coverage that followed the cardinal's statements, which implied that human embryonic stem-cell research is illegal in Italy, scientists from six different groups held a conference in Rome on 14 July to defend and explain their work.

The organizers included Carlo Flamigni of the Institute of Clinical Obstetrics and Gynaecology in Bologna, Maurizio Mori, a bioethicist at the University of Turin, and Elena Cattaneo, a stem-cell researcher at the University of Milan.

They also sent an open letter to Italian prime minister Romano Prodi stating that their work is legal under Italian law, and asking the government to actively promote stem-cell work and guarantee the freedom to carry out such research. "Freedom of scientific research is a principle enshrined in our Constitution. We would like reality to reflect that," the letter says.

Cardinal Alfonso López Trujillo ignited controversy when he became the first top Vatican official to publicly support excommunication of those involved in destroying embryos to derive stem cells for research. The comments by Trujillo, who heads the Vatican's Pontifical Council for the Family, were published in Italy's leading Catholic magazine *Famiglia Cristiana* on 2 July.

The Catholic Church opposes the destruction of embryos for any purpose, as it believes that life begins at conception. The researchers behind the Italian protest say they are worried that such comments could affect political support for embryonic stem-cell research in their strongly Catholic country.

Alfonso López Trujillo wants researchers excommunicated.

AFP/GETTY

Italy already has some of the world's most restrictive laws regarding embryo research, and does not allow embryos to be created or destroyed for research purposes. However, researchers are allowed to work on imported embryonic stem-cell lines.

Cattaneo, one of the organizers of the Rome conference and a Catholic herself, says she fears further restrictions and funding cuts for the already small number of Italian groups working on embryonic stem cells. "We will remain dependent on science done abroad," she says. "In the future, I'm not sure this will entitle our country to benefit from such research."

Luca Gianaroli, scientific director of the SISMER reproductive-medicine unit in Bologna, agrees that the Vatican has a powerful influence over Italian politicians. Italy's current stem-cell law, approved by parliament in 2004, was what the Vatican wanted, he says. "It was drafted by the Church." But he doesn't believe Trujillo's comments will trigger further cuts: "It's like adding water to an already full glass."

Trujillo may also have hoped to influence politicians beyond Italy — his comments have come as politicians in both the United States and the European Union debate the use of public funds for embryonic stem-cell research. A blocking minority of countries threatens to overturn the European Parliament's decision to include such work in its latest round of research funding. And as *Nature* went to press, the US Senate was preparing to vote on a bill that would loosen restrictions on federal funding for embryonic stem-cell research.

How much influence the statement will have is likely to depend on whether Pope Benedict XVI, whose words carry far more power than those of a cardinal, feels the same way.

Since Trujillo's comments, the Vatican has remained silent on the issue. It has not voiced support for Trujillo's stand, but — perhaps more importantly — nor has it said that Trujillo was speaking personally and not for the Church leadership. ■

Jacopo Pasotti and Ned Stafford