Graphene
material of the future

Scientists have high hopes for graphene, visualising its potential to transform technology and solve a range of problems in industry. Their optimism is fuelled by the fact that the last 10 years of R&D on this material has seen substantial progress.

Graphene, a 2D carbon material, has existed in the imagination of scientists for years and been studied since 1947, but it was not until 2004 that it was first produced from graphite. A roll of adhesive tape was found to produce the thinnest ever material. Andre Geim and Kostya Novoselov at the University of Manchester, UK, used a method called mechanical exfoliation, essentially stripping off layers of material, to create the single layer of carbon atoms in a hexagonal lattice array: graphene. In one of Geim and Novoselov’s ‘Friday night experiments’, where they would experiment with ideas not linked to their professional work, they were polishing graphite by peeling tape off the material to examine the smooth surface under a microscope – a common technique for surface scientists. When Geim and Novoselov looked at the tape instead of the graphite, they realised they had produced an incredibly thin material. This rapidly became an attractive topic for research globally and spawned a huge range of potential applications. In 2010, Geim and Novoselov’s work on graphene earned them the Nobel Prize in Physics.

Graphene has an incredible set of properties. As it is only one atom thin, it is extremely light and highly transparent. However it is also very robust, many times stronger than structural steel, as well as being flexible and elastic. In addition, its thermal and electrical conductivities are extremely high and it has potentially higher electrical conductivity than copper at room temperature. Graphene has inspired the investigation of other 2D crystalline materials, including boron nitride, niobium diselenide and tantalum (IV) sulphide. Such 2D crystals can be specialised for different functions by layering them with other 2D lattices, opening up the range of materials that can be produced.

One of the biggest limiting factors for graphene currently is the method of production. High quality production of graphene films will create a material with the highest electrical and thermal conductivities. Additionally, it is difficult to produce large quantities of graphene in one process and existing conventional production methods require toxic chemicals. Existing methods include chemical vapour deposition (CVD), mechanical exfoliation, unzipping of carbon nanotubes and reduction of single layer graphene oxide. If these processes are optimised or greener methods of production found, the impact on industry and technology could be huge.
<table>
<thead>
<tr>
<th>Material</th>
<th>Strength of Steel</th>
<th>Copper vs Steel</th>
<th>Graphene Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>130 GPa</td>
<td>35% Less Resist</td>
<td>200,000 cm² V⁻¹ s⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Than</td>
<td>(Theoretical)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Then</td>
<td>(Theoretical)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>THINNER</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>THAN A HUMAN HAIR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 MIllion TIME</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>THAN A HUMAN HAIR</td>
<td></td>
</tr>
</tbody>
</table>

Copper is less resistant than steel 35% times.

1 m² = 0.77 mg

Very Light

1 million times

Graphene + substrate:

- Silicon: 1,400 cm² V⁻¹ s⁻¹
- Indium Antimonide: 200,000 cm² V⁻¹ s⁻¹

Electron mobility of graphene:

- Actual: >15,000 cm² V⁻¹ s⁻¹
- Graphene + substrate: 200,000 cm² V⁻¹ s⁻¹
Using the new supermaterial

A broad variety of applications have been proposed to make the most of the unique combination of graphene’s properties. These novel technologies range from very small, such as tiny electronic components, to extremely large, in the form of aircraft.

SUPERCONDUCTORS

Superconductors are materials that can conduct electricity with zero resistance. The majority of materials that exhibit this property must be cooled to extremely low temperatures, making them uneconomical. It has been proposed that graphene would be a good candidate as a superconductor due to its high electrical conductivity. So far, scientists have observed superconductivity in graphite with interspersed crystals of pure calcium. This paves the way for nanoscale electronic devices.

IMPROVED PHOTOVOLTAICS

Solar cells currently use silicon, but researchers are looking at replacing the silicon with graphene, which is more thermally and electrically conductive, transparent and flexible. Graphene photovoltaics would also be cheaper to produce than silicon cells. Graphene-based photovoltaics have recently been produced with a combination of graphene, with titanium dioxide as the charge collector and the mineral perovskite absorbing the sunlight. The efficiency still needs to be improved however if they are to replace silicon cells completely, but if successful all the potential flexibility of the cells mean that photovoltaics could be incorporated into curtains or other household objects.

LIGHT AS AIRCRAFT

Graphene has received a lot of interest for its potential as a replacement for carbon fibres in the production of aircraft. Carbon fibres are used currently as they are very strong and light, but graphene is even more so. Graphene could be incorporated into plastics that could even replace steel in the aircraft structure resulting in a stronger and lighter plane, thereby improving fuel efficiency and range of travel. Due to its electrical conductivity it could additionally be used as a surface material to detect changes in stress levels at different parts of the aircraft, improving safety.
**BIOLOGICAL ENGINEERING**

Graphene lends itself particularly well to biological engineering applications as it absorbs to DNA well, is protected from enzyme cleavage and is chemically stable. However, a better understanding of the effects of graphene in the human body such as toxicity is required. Research areas include biosensing, bioimaging, drug delivery, antibacterials and cancer therapies.

**FLEXIBLE ELECTRONICS**

Current electronic devices require a combination of different technologies and materials. In contrast, graphene could be used to build a multitude of electronic components such as transistors, batteries, optoelectronics (e.g., light-emitting devices, touch screens) and photovoltaics. Graphene’s ideal properties inspire ideas related to light and foldable electronic devices made of graphene components.

**NANOPOROUS MATERIAL**

Graphene sheets are impervious to very small molecules of gases and liquids but will allow water to pass through, making it ideal as an ultra-small filter. Researchers have already created filters with pores of 5 nm in size, outcompeting current membranes of 30-40 nm pore sizes. These could potentially replace those currently used as well as simultaneously measure pressure and strain between substances either side of the filter.

**BETTER BATTERIES**

Capacitors can be charged quickly, much faster than traditional batteries, but store less energy, limiting their use in devices such as electric vehicles. Supercapacitors can hold far more energy however, while still delivering the benefit of a fast charge time. Unfortunately, supercapacitors are currently very expensive to produce, making them unsuitable for large scale industrial production. Graphene is now being investigated as a potential new material for supercapacitors. It would be better at storing electrostatic charge and more ecologically friendly, unlike other forms of battery.

**CARBON NANOTUBES**

Carbon nanotubes are essentially rolled up graphene and have had a range of uses. These include structural enhancers such as vehicles and sports equipment, filtration systems to produce drinking water without a need for chemicals, heat or power and toxin or gas sensors for the military, food industry and environmental sciences. In addition, these tiny tubes have many potential applications in healthcare as biosensors and medical devices. As an example, nanotubes can be internalised by cells and therefore lend themselves well to possible drug delivery systems.

**ANALYSIS**