NANOMATERIALS

Graphene rolls off the press

30-inch graphene films have been manufactured on a continuous basis with a roll-to-roll process and used to make a touch-screen device.

Yong P. Chen and Qingkai Yu

The two-dimensional form of carbon, graphene, shows remarkable electronic properties[1,2] that could prove useful in applications such as ultrafast energy-efficient transistors[3,4] for computers and mobile devices, and as flexible transparent conductors for macroelectronic devices such as solar cells, display panels and electronic newspapers. However, to realize the technological potential of graphene, we need to fabricate it on a large scale and with a quality that is reliably better than today's best materials. Now, writing in *Nature Nanotechnology*, Byung Hee Hong, Jong-Hyun Ahn and co-workers report on a new milestone in this effort by growing rectangles of graphene that measure 30 inches in diagonal length[5]. Moreover, the sheets are predominantly made of single-layer graphene — a sheet of paper would need to be 200 km long to have the same aspect ratio. And when used as a transparent conductor, the graphene sheets outperform indium tin oxide (ITO), which is at present the industry standard.

Hong and co-workers — who are based at Sungkyunkwan University and other institutes in Korea, Singapore and Japan — grew their graphene by chemical vapour deposition (CVD) of carbon atoms (extracted from decomposing CH_4 at high temperatures) onto copper foils, and used a roll-to-roll technique similar to a newspaper printing press to transfer the graphene between different substrates (Fig. 1). They also performed a comprehensive set of materials characterization steps to demonstrate the excellent quality of their graphene, particularly as a transparent conductor that is also ultrathin and highly flexible.

CVD onto metal substrates has been around for several decades[6] and represents probably the oldest known method of graphene synthesis, being much older than the 'scotch tape' method used to isolate the tiny flakes of graphene that kick-started present interest in this material in 2004[1]. Since last year, there has been spectacular progress in metal-based CVD

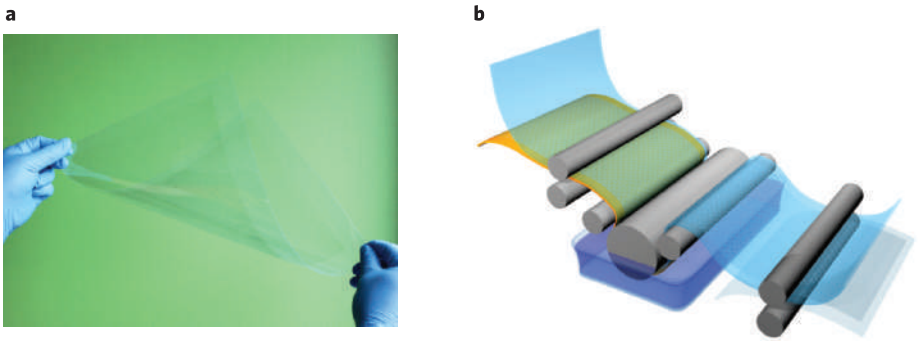

Figure 1 | Production of large, flexible and transparent graphene. **a**, Photograph of a large-area sample of single-layer graphene fabricated by a roll-to-roll process and transferred onto a flexible transparent substrate. **b**, Schematic showing the roll-to-roll process. CVD of graphene onto a copper foil (orange) takes place in an evacuated furnace (not shown). The graphene–copper sheet is then attached to a polymer support (blue sheet, left) by rolling. An etching bath (purple liquid, centre) then etches away the copper, and the graphene is transferred from the polymer onto an arbitrary flexible substrate (grey sheet, right). The graphene remains intact during the entire process. The roll-to-roll process is capable of producing about six inches of 20-inch-wide graphene per minute. Figure courtesy of Byung Hee Hong and Sukjae Jang, Sungkyunkwan University, Korea.

to grow large-scale graphene that can be subsequently transferred (by etching off the metal) to insulating substrates for electronic applications. Although some initial experiments used nickel[7], copper later emerged as the best substrate for growing large-area single-layer graphene[8–11], and the areas produced rapidly increased from a few square centimetres[8] to the sizes that have now been produced by Hong and co-workers[5]. Moreover, in principle there is no upper limit on the size of graphene that can be grown by CVD, aside from, perhaps, the size of copper foil that can be practically placed into the CVD furnace.

In general, an optically transparent material (such as glass) does not have good electrical conductivity and a conductive material (such as copper) does not have good optical transmission. This is because light can easily be absorbed or reflected by exciting charge carriers in a good conductor. Applications such as liquid-crystal displays and solar cells require transparent conductors with both high optical transmission and low electrical resistance. ITO, as well as certain other oxides, can satisfy these competing requirements, which is why it has become the industry's most popular transparent conductor. A good ITO thin film can transmit ~90% of light while having a sheet resistance of under ~100 Ω per square unit (so that any square-shaped area of the film has this resistance). However, steep increases in the cost of indium, combined with the various shortcomings of ITO, such as its fragility and rigidity, have spurred researchers to look for alternatives. Materials based on nanowires, carbon nanotubes and graphene have been previously studied, but the performance of ITO has proved hard to beat. By stacking four CVD-grown graphene layers together and applying chemical doping (and careful graphene fabrication and transfer), Hong and colleagues were able to achieve a sheet resistance as low as ~30 Ω per square unit at ~90% of light transmission — a performance level exceeding that of ITO. This technological milestone indicates that graphene can be a viable replacement for ITO as a transparent conductor, thus dramatically reducing the cost of solar cells, liquid crystal displays and many other related applications.

The Korea–Singapore–Japan team also showed that their graphene transparent conductor is much more flexible than ITO, and shows little change in resistance when strained. They even fabricated and demonstrated a graphene-based touch-screen device. The availability of large-scale, low-cost graphene as a high-performance transparent and flexible conductor could significantly impact consumer electronics (especially mobile devices). Think, for example, about a mobile computer phone as small as a pen, but with a rollable flexible display that can be pulled out to more than a foot in length and integrated with a touch-panel keyboard[13].

The ability to grow and transfer large-area single-layer graphene could have many other implications for both applications and fundamental science. For example, it may be used as a functional coating to exploit graphene's chemical activity (or inactivity), high thermal conductivity, or hydrophobicity. It will facilitate the fabrication of interesting three-dimensional structures such as stacked graphene, electrically insulated graphene bilayers, graphene on previously unexplored substrates, and 'curved' graphene with non-trivial geometry or topology. It can also simplify experiments such as scanning tunnelling microscopy[14,15], which requires conductive substrates. Larger samples will also make it easier to search for exotic physics such as superconductivity and magnetism in graphene. Finally, it is worth pointing out that although the large-scale graphene demonstrated so far can be single layer, it is not single crystalline, meaning that the perfect hexagonal arrangement of carbon atoms is interrupted by defects and grain boundaries. Studies of the mechanisms of domain formation, the role of grain boundaries on materials or electronic properties, and how to grow large single-crystal graphene are some of the future directions for CVD production of this material. ❐

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NANOBIOTECHNOLOGY

Remote control of cells

Using temperature-sensitive ion channels and magnetic nanoparticles attached to membranes of cells, the electrical activity in neurons can be controlled by an externally applied magnetic field.

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A method for remote and non-invasive control of neuronal activity is at the top of the wish list of many neuroscientists because interfering with brain circuits to understand how they work can help to treat diseases. Recent years have seen a wave of new techniques for manipulating the activity of neurons with cellular specificity and temporal precision far beyond the classical methods of physiology and electrophysiology[1]. Of these, 'optogenetics' — an approach that combines genetics and light to specifically activate or silence certain neurons in the brain circuit — is popular[2]. However, poor penetration of visible light into brain tissue means that to reach the deeper brain structures, it is necessary to pierce an optical fibre through the skull and the overlying tissue, making the technique rather invasive.

Writing in *Nature Nanotechnology*, Arnd Pralle and colleagues[3] at the University of Buffalo report on an innovative concept using alternating magnetic fields instead of light to reach a local actuator (an ion channel, in this case). The physical basis of the idea is that magnetic fields penetrate biological tissue with little attenuation, but at specific sites deep in the tissue, membrane-targeted superparamagnetic nanoparticles transform magnetic field energy into local heat, which in turn activates local heat-sensitive ion channels.

To influence the function of neurons, Pralle and co-workers targeted manganese ferrite nanoparticles to specific proteins on the membranes of cells that have been genetically engineered to express the temperature-sensitive transient receptor potential V1 (TRPV1) ion channel. Because thermal effects are known to be highly localized at the nanoscale in a wet environment, the nanoparticles heat up locally when exposed to an alternating magnetic field that continuously flips the magnetization of the particles[4]. Heat generated in this way was sufficient to open and close the nearby ion channel[5], yet the temperature inside the cell changed very little. The opening of these ion channels excites the cell by raising the membrane potential through an influx of cations.

In optogenetics, the remote control of neuronal excitation is based on light-activated ion channels or ion pumps. Using DNA that contains the instruction for the synthesis of these membrane proteins, organisms such as laboratory mice can be genetically modified such that the light-activated control mechanism is expressed in the membrane of specific sets of neurons[6]. By genetic encoding, these actuators become an integral part of the organism. The 'magnetogenetic' method presented by Pralle and co-workers is a hybrid approach in that it combines externally supplied nanoparticles with genetically encoded components, including a temperature-sensitive ion channel and auxiliary proteins for controlling the association of the particles to the membrane (Fig. 1). Although the principle of local heating by magnetic