NANOMATERIALS

Paper powers battery breakthrough

Researchers have combined carbon nanotubes and nanoporous cellulose to make lithium-ion batteries and supercapacitors that are both lighter and more flexible than existing devices.

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Batteries power a wide range of electronic devices including phones, laptop computers and medical devices such as cardiac pacemakers and defibrillators. In the near future, batteries may also help fight global warming by improving the performance of electric or hybrid vehicles with zero or reduced carbon emissions. With the ever-increasing demand for efficiency and design, there is a need for ultrathin, safe and flexible energy storage options.

A battery is generally made up of a negative electrode (the anode) and a positive electrode (the cathode) that are separated by an electrolyte, which is generally a liquid solution embedded in a felt (the separator). Electrochemical charge-transfer reactions occur at the interface between the electrodes and the electrolyte, and these reactions convert chemical energy into electric energy that is used to power the various devices. This process is reversible, so the battery can be recharged by supplying electrical energy from an external source.

One of the most successful commercial batteries is the lithium-ion battery[1] (see Fig. 1a), which is now produced at a rate of 2.4 billion units per year[2] to power phones, laptops and other portable electronic devices. The lithium-ion battery owes its success to its long cycle life (that is, it is able to undergo many cycles of charging and discharging) and its high energy density. However, despite its commercial success, the lithium-ion battery is still far from being the ultimate solution in portable power technology because it is expensive, has a relatively low power output and is prone to catching fire or even blowing up when operated under the wrong conditions.

Writing in the *Proceedings of the National Academy of Sciences USA*, Pulickel Ajayan and co-workers[3] at Rensselaer Polytechnic Institute describe the fabrication of a paper-thin and flexible energy storage device by combining nanoporous cellulose — the main constituent of paper — with carbon nanotubes. The novelty of this device lies in its mechanical flexibility, which allows it to change shape to meet the space requirements of modern devices, and the elegance of the design, with all the components (the electrode, electrolyte and separator) being integrated into a single unit that acts as a building block for the final battery structure.

The devices are made by growing uniform films of vertical carbon nanotubes on a silicon substrate and impregnating them with cellulose to form a nanocomposite paper. The cellulose is partly dissolved in an ionic liquid that also acts as the electrolyte in any device made from the paper. After solidification and removal of the excess liquid, the composite film is peeled from the substrate and can be used as a supercapacitor or as a component in a battery.

The composite paper, which is typically a few tens of micrometres thick, can be rolled up, twisted or bent to any curvature, and then returned to its original shape, all the time maintaining its useful properties. The device showed a wider operating temperature range than commercial devices and continued to work even after more than 100 charge/discharge cycles and after

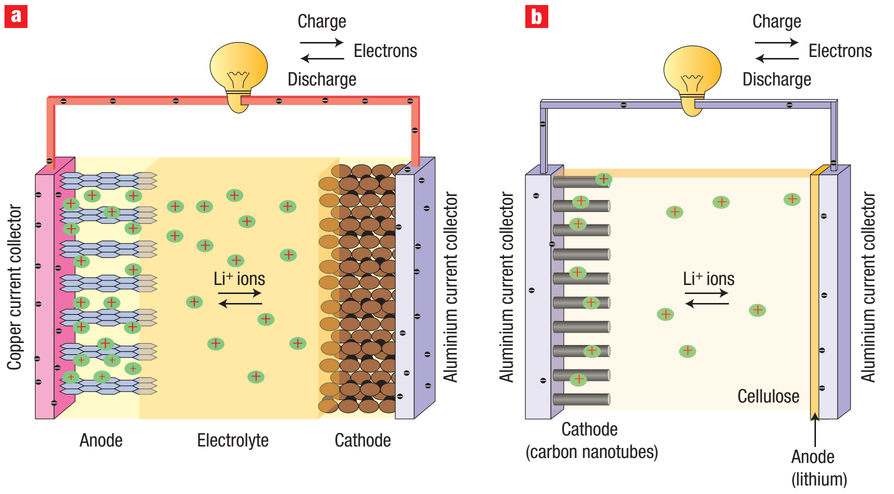

Figure 1 Schematic of different battery configurations. **a**, A conventional lithium-ion battery contains a graphite anode (grey hexagons), a lithium cathode (lithium cobalt oxide in this case; brown circles), and a liquid electrolyte containing lithium ions (green) in a fibre separator (orange). The removal of lithium ions by the simultaneous oxidation of cobalt in the cathode and insertion of lithium ions into the graphite anode charges the battery. Electricity is produced when ions move in the opposite direction and the cobalt is reduced. **b**, A lithium-ion battery made from nanocomposite paper is more compact and weighs less than a conventional lithium-ion battery. The paper, which is made by infiltrating cellulose into carbon nanotubes grown on a silicon substrate, is impregnated with the electrolyte, thus combining the cathode (the nanotubes) and the separator (the cellulose) in a single unit. Depositing a thin film of lithium on one side of the paper and adding aluminium current collectors completes the battery configuration. Electricity is produced when lithium is oxidized to form lithium ions, which are inserted into the nanotube cathode. Charging occurs when the ions move in the opposite direction and are deposited as lithium metal.

being kept at temperatures as low as 77 K (–196 °C). Moreover, liquids as diverse as sweat, blood and urine also worked as electrolytes. Conventional supercapacitors have independent separator and electrolyte components, but these are not necessary in the latest devices because the working electrode (the nanotubes), the separator (the cellulose) and the electrolyte (the ionic liquid) are already integrated. This means that the paper-based devices are compact, lightweight and environmentally friendly.

Ajayan and co-workers also fabricated the paper into a lithium-ion battery by evaporating a thin layer of lithium metal as the anode, using a lithium conducting organic solution as the electrolyte, and attaching aluminium foil on both sides to collect the current (Fig 1b). This battery operates under full mechanical flexibility and can light up a tiny light-emitting diode over several tens of charge/discharge cycles. Furthermore, it is also possible to combine the supercapacitors with batteries to make hybrid devices.

Nanomaterials have already been used to improve the power capabilities and life cycles of batteries[4–6], but there is a trade off between the increased reactivity associated with the large surface-to-volume ratio of nanostructured electrodes and the related reduction in volumetric energy density. The configuration developed by Ajayan and co-workers, however, is different in that it is expected to maintain the benefits of having nanostructured components yet remain relatively safe to use owing to an integrated structure based on materials that are inherently resistant to ignition.

Although this new device is promising, further optimization is required to make it commercially viable. First, alternative combinations of electrolyte, electrodes and current collectors should be explored to increase the voltage level and to avoid side processes that can reduce the battery lifetime. Second, it will be necessary to scale up production rates. Nevertheless, this latest work is a significant advance in the field of battery technology.

References

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CARBON MATERIALS

Nanosynthesis by candlelight

Carbon nanoparticles are a by-product of making carbon nanotubes in an arc melter and have potentially useful optical properties. A recent discovery shows that these particles can be obtained by simply lighting a candle.

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Candles create atmosphere — be it for a romantic dinner or a ceremonial ritual. However, they are also a source of polydisperse and ultrafine particles that can seriously damage paintings and artefacts in historic churches and cause respiratory and cardiovascular problems. Now, a report in *Angewandte Chemie International Edition* suggests that not all nanoparticles produced from candle soot are bad; indeed, some may prove to be useful.

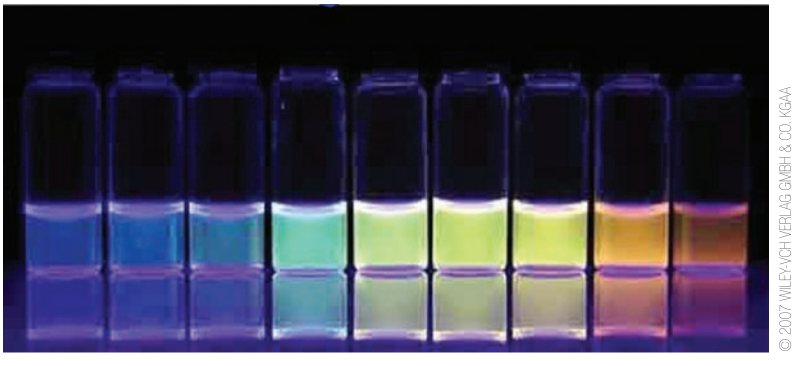

Figure 1 The carbon nanoparticles produced in the flame of a burning candle have a number of potentially useful optical properties, including luminescence in the visible portion of the spectrum, which depends on the particle size.

Chengde Mao and colleagues at Purdue University in the US have discovered an inexpensive and reliable method for producing luminescent carbon nanoparticles (CNPs) from soot produced from a burning candle[1]. The soot, which was collected by placing either aluminium foil or a glass plate above a candle flame, appeared to be composed of micrometre-sized hydrophobic agglomerates. To break these clusters apart, the Purdue group oxidized the raw soot product with an acid to obtain a solution of hydrophilic and individually dispersed carbon particles[2]. They then centrifuged the acid and neutralized the liquid — or 'supernatant' — above the precipitant.

The supernatant solution luminesced when it was excited with an ultraviolet