BIONANOELECTRONICS

Viruses show their good side

The tobacco mosaic virus can be combined with metallic nanoparticles to make novel electronic memory elements. Are virus-based memory sticks just around the corner?

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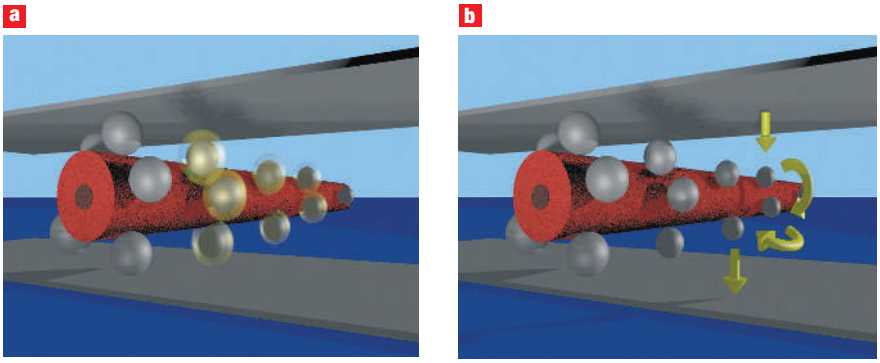

Figure 1 Schematic view of a memory device based on a tobacco mosaic virus (red) coated with platinum nanoparticles (spheres) between two metallic electrodes[1]. **a**, The low conduction ('off') state in the absence of applied voltage is most probably caused by charge transfer between the virus and nanoparticles, as indicated by the semitransparent spheres for some nanoparticles. **b**, When a sufficiently high voltage is applied, this natural charge-transfer process is reversed and electrons can tunnel (yellow arrows) between the nanoparticles to produce a high conduction ('on') state.

Viruses have a bad reputation regardless of where we find them — be they in our bodies or in our computers. But on page 72 of this issue, Yang Yang and colleagues at the University of California, Los Angeles[1] report that tobacco mosaic viruses (TMV) with platinum nanoparticles attached to them could be used as a nanoscale memory device that can be switched on and off electronically. Even though many questions concerning the switching mechanism remain unanswered, this work may pave the way towards the use of biological objects as basic building blocks in electronic memory devices.

In biology, high-level information processing and data storage occur in the brain through a complex set of interactions between electrical signals coupled with an intricate set of biochemical processes. Computers, on the other hand, rely on billions of electronic, optical and magnetic switches to store and process information. It has always been a dream (or, to some people, a nightmare) to combine biological and technological information processing and storage. With the advent of nanotechnology, the investigation of such combinations increasingly emerges from the realm of science fiction into the area of cutting-edge research.

After the legendary frog's leg experiment by Alessandro Volta more than 200 years ago and the subsequent understanding of how nerve signals are transmitted, it became obvious that it might be possible to transfer information electrically between cells using metallic microelectrodes. In a more complex form, the research groups of Fromherz[2] and Lieber[3] have managed to transfer electrical signals from electronic devices to living cells and vice versa.

Another approach for transferring electrical signals combines biological elements such as DNA strands with carbon nanotubes to create nanoscale field-effect transistors[4]. In parallel, a whole research field based on the use of organic molecules as electronic switches has emerged, although these components are frequently not real biological molecules[5]. The intellectual beauty of the work by Yang and colleagues[1] lies in the combination of the tobacco mosaic virus, a rather simple biological entity at the borderline between living and non-living objects, with platinum nanoparticles to create electrically switchable memory devices.

The term 'virus' was introduced by Martinus Beijerinck, one of the pioneers of modern virology, in 1898 to describe the infectious liquid he extracted from infected tobacco leaves[6]. Other natural viruses were soon found and identified, but the TMV has remained a popular subject of research. In 1939 Ernst Ruska and co-workers used the TMV to demonstrate the potential of transmission electron microscopy, and Ruska went on to share the 1986 Nobel Prize in Physics for developing the electron microscope. In order to increase image contrast, Ruska and co-workers attached colloidal gold nanoparticles to the virus[7], which was the earliest work describing structures similar to those used by the UCLA team[1].

About 50 years later, the TMV gained popularity again. Its nanoscale size and our detailed knowledge of its structure begged for a possible use in nanotechnology. The first success came when hybrid bio–inorganic nanostructures were synthesized. The outer surface of the virus was successfully decorated with inorganic nanoparticles from both a liquid suspension[8] and the gas phase[9]. Now the time has come for a bio–inorganic model system in the area of nanoelectronics.

Yang and colleagues attached platinum nanoparticles to the outer surface of the TMV, embedded the virus–nanoparticle hybrid in a non-conductive polymer, and sandwiched it between two metallic electrodes (Fig. 1). By applying an electrical potential between the two electrodes, they observed a marked increase in current when the voltage reached about 3 volts. In this 'on' state electrons were able to tunnel through a seemingly impenetrable barrier because of their quantum nature. The 'on' state remained stable unless the voltage

went below –2.4 volts, which switched the device off. This on/off behaviour allows the structure to be used as a memory device.

This switching effect also occurs if the TMV is replaced by a non-biological polymer nanorod of a similar size[10]. But the difference in switching speed ('on' to 'off' state) indicates that both the shape and (bio)chemistry of the nanorod can influence the system. This leaves plenty of room for optimizing the device. When the platinum particles were not connected to a rod-like structure but randomly distributed within the polymer, the system failed to display this switching effect. Instead, the authors saw a relatively high conduction between nanoparticles occurring through electronic tunnelling processes.

Yang and colleagues speculate that in the absence of applied voltage, there is a charge transfer between the nanoparticles and the TMV. This blocks the tunnelling between platinum nanoparticles and results in an 'off' state (Fig. 1a). A sufficiently high voltage reverses the charge transfer and once again allows current to flow by tunnelling processes between the nanoparticles, thereby turning the device 'on' (Fig. 1b). This charge transfer apparently can be switched back and forth reversibly many times.

What is the outlook for practical use of these virus-based memory elements? Current electronics operate at gigahertz frequencies and there is a push towards terahertz operation. Although the viruses can currently be switched at megahertz frequencies at best, and with a comparatively low number of possible switching cycles, this disadvantage could be a stimulus for more-detailed investigation and improvement of the principle. If we understand how to design electronic systems that can reliably communicate with biological systems in a controlled way, we will step into a completely new (bio)technological field.

On the basis of what we will learn from this primitive biological/nanoparticle hybrid memory device and from future experiments, we might finally begin to see new commercial electronic devices made with biological components including virus-based memory sticks. And if we are unlucky, these might one day be infected by 'real' computer viruses.

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NANOTOXICOLOGY

Signs of stress

What is the best way to find out if nanoparticles are toxic? New results suggest that measuring oxidative stress could eventually allow us to screen the thousands of new nanoparticles made every year.

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The rapid expansion of nanotechnology has resulted in a vast array of nanoparticles that vary in size, shape, charge, chemistry, coating and solubility. Take carbon nanotubes, for example, which have been intensively studied because they have new and unusual mechanical, electronic and other properties. The potential toxicity of these materials has attracted attention because of their apparent similarities to asbestos and other carcinogenic fibres (Fig. 1). Carbon nanotubes are long, thin (just nanometres in diameter) and insoluble — all factors that contribute to fibre toxicity in the lungs[1]. A study by Andre Nel of the University of California, Los Angeles and co-workers now suggests that the hazards are best predicted by examining which nanomaterials cause most oxidative injury within cells[2].

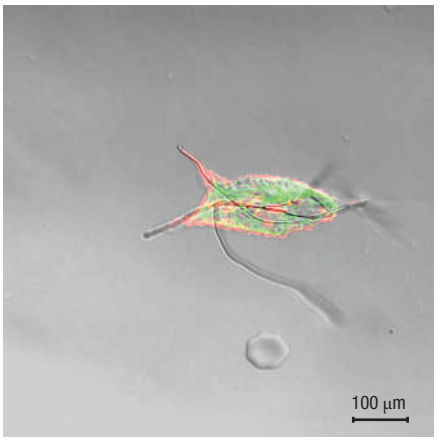

Figure 1 A rat lung cell attempting to ingest carbon nanotubes that are longer than the distance that the cell can stretch, which means that the rat cannot remove such nanotubes from the body. This optical microscopy image is superimposed with confocal images of the protein cytoskeleton that gives the cell structure and its ability to move. F-actin is shown in red; tubulin in green. (Image provided by D. Brown, Napier Univ. and I. Kinloch, Univ. Manchester).

However, when testing the toxicity induced by carbon nanotubes, should we consider single- or multiwalled tubes? Long or short nanotubes? How long or short? Should we remove metal catalysts? Do we use functionalized or non-functionalized particles? Should we use pristine tubes or should they be tested in the form in which they might actually be used? The list of variations is endless and poses a real problem for toxicologists.

However, the challenge for toxicologists is not to test every variation of a new nanoparticle generated but, instead, to identify key factors or tests that can be used to predict toxicity, permit targeted screening and allow materials scientists to generate new, safer nanoparticles with this structure-toxicity information in mind.

Nel and co-workers have now taken a major step in this direction by systematically studying how nanomaterials can induce oxidative injury within cells[2]. The basic idea is that if we know how this process occurs, we can begin to compare the toxic potential