NANOTUBE ELECTRONICS

A flexible approach to mobility

An innovative and scalable strategy for making high-density arrays of aligned nanotubes could lead to the mass-production of high-performance, high-power flexible electronics.

Seunghun Hong* and Sung Myung
are at the School of Physics and Nano-Systems Institute, Seoul National University, Seoul 151-747, Korea.
***e-mail: seunghun@snu.ac.kr**

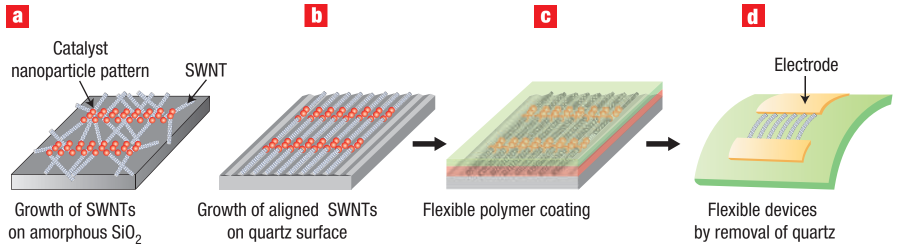

Figure 1 How to make a flexible electronic device. **a**, Growth of randomly orientated single-walled carbon nanotubes on an amorphous SiO_2 surface. **b**, Growth of dense aligned nanotubes on a quartz crystalline surface, followed by the direct transfer of the nanotubes onto flexible substrates (**c**,**d**) for flexible, high-performance, high-power electronic devices.

Rapid progress in flexible technology[1,2] allows us to imagine a large number of innovative products such as electronic paper, wearable displays, smart gloves and so on. Single-walled carbon nanotubes[3] have great promise for applications in flexible electronics, but it has been very difficult, if not impossible, to prepare flexible high-performance integrated circuits based on them. On page 230 of this issue, John Rogers and co-workers[4] report an innovative solution to this problem, which involves growing dense arrays of aligned nanotubes on a crystalline quartz substrate, and then transferring the arrays onto plastic materials to make flexible, high-performance, high-power electronic devices.

Just as circuit miniaturization revolutionized the electronics industry in the 1950s, and continues to do so, flexible electronics might also change the world in the future — if suitable materials can be found. Most high-performance electronic materials such as silicon are not flexible, whereas materials that are flexible, such as conducting polymers, have poor electric properties. The speed of an electronic device is essentially determined by the mobility of the charge carriers in the material used to make it. The mobility — which is measured in units of cm^2 V^{-1} s^{-1} — determines the speed at which charge carriers (that is, electrons and holes) can move in the material.

For example, the mobility of electrons in silicon is $\sim$1,000 cm^2 V^{-1} s^{-1}, but the mobility of a charge carrier in a conducting polymer is usually less than $\sim$1 cm^2 V^{-1} s^{-1} (ref. 5). This means that polymer devices will perform at least one thousand times slower than silicon-based circuits. In other words, a computer that relied on chips made from the best conducting polymer would be slower than a silicon-based machine from the 1970s. Flexible electronics might sound good, but nobody will buy such a slow computer.

Single-walled nanotubes (SWNTs) usually have diameters of 1–2 nm and lengths of a few micrometres or longer. They are generally produced by adding nanoparticles made of a transition metal to a carbon-based gas such as methane and heating it to 900 °C. Transition metals such as iron or nickel are known to catalyse the formation of carbon–carbon bonds, and each nanoparticle basically 'eats' carbon atoms from the surrounding gas and produces a single nanotube, just like a silkworm produces silk.

SWNTs have excellent electronic properties: they have a carrier mobility of $\sim$10,000 cm^2 V^{-1} s^{-1}, which is better than that of silicon[6], and they can carry an electrical current density of $\sim 4 \times 10^9$ A cm^{-2}, which is three orders of magnitude higher than a typical metal, such as copper or aluminium[3]. Moreover, they are flexible owing to their small diameter. SWNTs are therefore an ideal candidate material for high-performance, high-power, flexible electronics. However, there is a catch.

In fact, there are two problems. First, present production methods always produce a mixture of semiconducting and metallic nanotubes. This is a serious problem because high-purity semiconducting nanotubes are needed to build transistors. Fortunately, a number of promising methods for removing metallic nanotubes have been reported recently[7].

The second problem concerns the fabrication of devices. Unlike conventional microelectronics, in which semiconducting wafers are 'carved' to make integrated circuits, SWNTs are first synthesized in a powder form. Therefore, one has to 'pick-up and place' individual nanotubes onto specific locations on a wafer to build functional devices. As there are over 40 million transistors in a typical microprocessor, this is extremely time-consuming. Furthermore, most of the methods used to mass produce such devices result in a relatively poor mobility of $\sim$10 cm^2 V^{-1} s^{-1} (ref. 5) because the SWNTs usually form randomly oriented networks with contaminated contacts between nanotubes.

One method for making high-mobility devices is to pattern a surface with catalyst nanoparticles and then grow nanotubes on this pattern (Fig. 1a). However, since nanotubes tend to grow in random directions, external forces (such as electric fields) must be applied to control the direction of growth. This method usually produces low-density arrays of nanotubes with relatively poor alignment. Moreover, the high temperatures needed for this approach are not suitable for most flexible substrates.

Rogers and co-workers at the University of Illinois, Urbana-Champaign (UIUC), Purdue University and Lehigh University, all in the USA, started by using this approach to grow nanotubes on a crystalline quartz substrate, which is not flexible (Fig. 1b; ref. 8). The nanotubes grew along the crystalline direction of the quartz, resulting in perfectly-aligned arrays of nanotubes. Significantly, devices based on these arrays exhibited mobilities of ~1,000 $cm^2 V^{-1} s^{-1}$, which is comparable to silicon-based devices. Furthermore, the number density of the nanotubes can be high, which makes this method suitable for high-power electronics. Using this strategy, they demonstrated SWNT-based devices that can withstand electrical currents of more than 1 A.

In another important breakthrough, the UIUC–Purdue–Lehigh team transferred arrays of aligned nanotubes onto various substrates, including flexible plastics and SiO_2 (Fig. 1c,d). To do this, they coated the arrays with a polymer layer and then peeled it off, thus transferring the highly aligned arrays from the quartz to a flexible substrate. This allowed them to overcome the temperature problem described above and make flexible high-performance electronic devices.

The method developed by Rogers and co-workers represents a major step forward in nanotube electronics, but what else needs to happen before we see this technology in our shopping malls? As the arrays were still a mixture of semiconducting and metallic nanotubes, it was necessary to burn off the metallic nanotubes by applying a high bias voltage to individual transistors. Although this process produced high-performance transistors, it is impractical to treat individual transistors one by one. But once this problem is solved, flexible nanotube electronics might become an everyday reality.

References

1. Sun, Y., Choi, W. M., Jiang, H., Huang, Y. Y. & Rogers, J. A. *Nature Nanotech.* **1,** 201–207 (2006).
2. Lu, X. & Xia, Y. *Nature Nanotech.* **1,** 163–164 (2006).
3. Dai, H. Javey, A., Pop, E., Mann, D. & Lu, Y. *NANO: Brief Reports and Reviews* **1,** 1–4 (2006).
4. Kang, S. J. *et al. Nature Nanotech.* **2,** 230–236 (2007).
5. Bradley, K., Gabriel, J.-C. P. & Gruner, G. *Nano Lett.* **3,** 1353–1355 (2003).
6. Zhou, X., Park, J.-Y., Huang, S., Liu, J. & McEuen, P. *Phys. Rev. Lett.* **95,** 146805 (2005).
7. Zhang, G. *et al. Science* **314,** 974–977 (2006).
8. Kocabas, C., Shim, M. & Rogers, J. A. *J. Am. Chem. Soc.* **128,** 4540–4541 (2006).

News & Views contributions

The News & Views section is where new advances in nanoscience and nanotechnology, reported in papers or at meetings, are communicated to a broad audience. Many News & Views pieces are linked to Articles and Letters that appear in *Nature Nanotechnology*, but they can also focus on important papers that are published elsewhere. Unsolicited contributions will not normally be considered, although we welcome advance warning about forthcoming papers of exceptional significance. As a general guideline, News & Views pieces are about 800–900 words, with one or two display items (figures, boxes or tables). They should make clear the advance (the 'news') and communicate a sense of excitement, yet provide a critical evaluation of the work in the context of the rest of the field. We encourage personal views, criticisms and predictions, but authors should not refer to their own work, except in passing.

Detailed guidelines are available on request from naturenano@nature.com.