

## NANOTUBES

## A step in synthesis

The extraordinarily high strength and stiffness of single-walled carbon nanotubes promises a myriad of unique applications, but many of these are reliant on the growth of ultralong, continuous nanotubes. A new synthetic procedure takes us a step closer to this goal.

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Single-walled carbon nanotubes (SWNTs) were first synthesised in 1993 by Sumio Iijima<sup>1</sup> and Don Bethune<sup>2</sup> and colleagues. They have since attracted wide interest from both the research community, who find them an extraordinarily rich system for fundamental studies of one-dimensional structures, and the commercial world, keen to exploit their remarkable properties of enormous stiffness, great strength and very high carrier mobility. Despite this huge interest and the great number of researchers attracted to the field, synthesis of carbon nanotubes still presents a challenge. Most researchers are still trying to solve the daunting problem of preparing a sample in which all the nanotubes have the same diameter and chirality, as characterized by the structural indices  $(n, m)$  (ref. 3). Now Yuntian Zhu and colleagues<sup>4</sup>, writing in this issue, have come a step closer to this goal by reporting the synthesis of uniform, single-walled carbon nanotubes with no apparent length limit.

Each  $(n, m)$  nanotube can be considered to be a distinct molecule with a unique structure, because the indices  $n$  and  $m$  specify the unique manner in which the single layer of graphite is rolled up seamlessly to form the carbon nanotube<sup>3</sup>. It can easily be shown that carbon nanotubes can be either metallic (if  $n - m = 3p$ , where  $p$  is an integer) or semiconducting (if  $n - m = 3p \pm 1$ ). A small change (less than 1%) in nanotube diameter can result in a dramatic change from a nanotube that is metallic (and could serve as an interconnect in an electronic circuit) to one that is semiconducting (and could become the active component of a field-effect transistor).

From the earliest days of carbon nanotube research, visionaries like Smalley captivated the general public with images of space elevators<sup>4</sup> based on a continuous thin rope of carbon nanotubes that would link the Earth to objects in space. The 'space elevator' (Fig. 1) and other such applications would exploit the remarkable strength and stiffness of carbon nanotubes, which are an order of magnitude higher than those of steel. In this context, the successful growth of a carbon nanotube four centimetres long, with a length-to-diameter ratio



**Figure 1** One of the earliest visions for nanotube applications was the 'space elevator'. An ultra-high-strength cable woven from carbon nanotubes would deliver payloads from the Earth into space.

Image: Victor Hubbrick, Science Photo Library

of over 3 million and a weight of around 0.1 picograms, represents an impressive first step in the development of ultra-strong lightweight yarns for space (as well as other more earthly) applications.

From a scientific standpoint, too, this is impressive work. By controlling the growth of a SWNT over a long length, and characterizing it by sensitive techniques, Zhu and colleagues have also begun to address the grand challenge in nanotube synthesis. They used atomic force microscopy to verify that the diameter remained constant over a 5- $\mu\text{m}$  growth segment. Raman spectroscopy showed that a commonly observed defect-related feature was essentially absent, suggesting that the rapid nanotube growth rate of 11  $\mu\text{m s}^{-1}$  produces a nanotube that is close to defect-free, and suppresses the deposition of amorphous carbon. A constant G-band Raman lineshape, coupled with observations of straight nanotube growth by scanning electron microscopy, is consistent with the growth of a single  $(n, m)$  molecule over several centimetres. The formation of kink defects in the tube (indicating a transition to another  $(n', m')$  nanotube molecule<sup>3</sup>) was observed only near the termination of the nanotube growth.

If continuous, rapid, essentially defect-free growth of a single  $(n,m)$  nanotube species can next be achieved along a specific, chosen direction, this would go a long way towards reaching the goal of controlled nanotube growth over macroscopic length scales. The particular  $(n,m)$  nanotube grown by Zhu *et al.* appears to be semiconducting along its entire length (based on its G-band Raman spectral lineshape). One could imagine that growth of a unique  $(n',m')$  metallic nanotube several centimetres in length could likewise be achieved. The authors give us some clues about the growth conditions necessary for achieving ultra-long nanotube growth: an alcohol carbon source, fast heating of the substrate to prevent catalyst particle growth, and use of a smooth substrate over which the growing nanotube can glide, as well as controlled conditions of temperature, gas pressure and catalyst type<sup>6</sup>.

Although the work of Zhu and colleagues is an important advance, much further research and development will be needed before we can expect to see large-scale synthesis of specified  $(n,m)$  nanotubes. The next logical step would be to push for improvements in the synthesis conditions to further increase the nanotube lengths produced, to improve the reliability of the synthesis process in producing the same

$(n,m)$  nanotube under the same growth conditions, and eventually to increase the control of the synthesis process to produce any desired  $(n,m)$  nanotube on request. *In situ* nanotube characterization capable of rapidly assessing the chiral angles and nanotube diameters would be needed for quality control of large-scale synthesis. And the process would need to be scaled up by about 12 orders of magnitude to achieve large-scale (gram) quantities of nanotubes. With all of these hurdles overcome, a variety of nanotube applications based on the unique quantum properties of carbon nanotubes would at last become feasible. Their high mobilities could then be exploited for semiconductor electronics, as could their sensitivity to specific adsorbates for biosensors, and their unique mechanical and thermal conductivity properties could usher in a host of nano-electromechanical devices and thermal management applications.

#### References

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## AMORPHOUS MATERIALS

# Finding order in disorder

Describing the structure of amorphous materials such as metallic glasses has been a longstanding problem in materials science. A new technique called fluctuation microscopy allows us to see order on length scales that are difficult to study with traditional scattering techniques.

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At first glance, the structures of amorphous materials seem rather uninteresting—particularly in comparison with crystalline materials, which display a wide variety of structures. But advances in characterization techniques described at a recent symposium\* on *Order in Disorder: Probing the Structure of Amorphous Materials*, show that the structures of amorphous materials are much richer than is commonly appreciated.

The shortest length scale usually used to describe the structure of a material consists of an atom and its

nearest neighbours, out to perhaps two or three atoms distant. All solids and liquids have some structure on this scale, which we call short-range order. For crystalline solids, structural order persists over much longer distances (at least tens or hundreds of atomic distances), such that the atoms occupy sites in a periodic three-dimensional array. Such materials are said to have long-range order and include most metals and many covalently bonded solids. Non-crystalline solids, including glasses, lack long-range order and are said to be ‘amorphous’ (literally, ‘without form’) even though they can have short-range order that is quite well defined.

Most of our knowledge of these structures comes from the ways in which the atoms in the material scatter radiation, particularly X-rays and electrons.

\* *Microscopy and Microanalysis 2004*, 1–5 August, 2004, Savannah, Georgia, USA.