Nanotubes keep rolling on

From single-electron physics and DNA-based sorting techniques to efforts to improve the performance of atomic force microscopes, carbon nanotubes are still at the forefront of research in many areas of nanoscience and technology.

The atomic force microscope (AFM) and the carbon nanotube have both been synonymous with nanotechnology for many years, so it is not surprising that there have been efforts to combine the two in some way. Indeed, the carbon nanotube would seem to be a natural material from which to make the tip of an AFM, as was first demonstrated in 1996 (ref. 1), five years after the first paper on nanotubes[2] and ten years after the first AFM, which used a shard of diamond as the tip[3].

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The ideal AFM tip needs to possess a number of properties: it needs to be small to achieve the best resolution; its shape needs to be known because the images produced by AFMs are convolutions of the tip geometry and the topography of the surface being scanned; it needs to be strong enough to withstand wear and tear and maintain its shape as it is dragged across surface after surface; and it needs to be amenable to modification (such as being coated with metal or functionalized with a variety of molecules).

The carbon nanotube ticks all these boxes and more, as Neil Wilson and Julie Macpherson explain in their Review Article on page 483 of this issue. So why do most AFMs still rely on tips made from silicon or silicon nitride rather than nanotubes? “The answer”, write Wilson and Macpherson, “lies in the fabrication. Even though carbon nanotubes have superior material properties, in order to make the transition to mainstream applicability, nanotube tips must become an off-the-shelf product with an accessible price tag.” Attaching a nanotube to an AFM probe and making the necessary modifications (such as shortening or functionalizing it) is still too time-consuming and expensive compared with the microfabrication approaches that can mass-produce silicon and silicon nitride tips. However, progress is being made on this front and other areas of nanotube research.

The AFM community does not, as yet, worry about the detailed structure of the nanotubes it uses, but other researchers do. For applications in electronics, for example, it is necessary to separate semiconducting nanotubes from their metallic counterparts because as-produced samples of single-walled nanotubes tend to be one-third metallic and two-thirds semiconducting. There has been considerable progress in this area (see ref. 4 for a review), but other applications would benefit from the ability to grow nanotubes with a given chirality or atomic structure. The chirality of a nanotube is denoted by two integer numbers that determine both its diameter and electronic properties. (In the world of nanotubes chirality is not related to handedness — although nanotubes can have handedness[5] — but refers instead to the direction in which a hexagonal sheet of carbon atoms is rolled up to produce a given nanotube.)

Growing nanotubes with a given chirality is still a pipe-dream, but in a recent experimental *tour de force* Ming Zheng and co-workers have shown that short strands of DNA can be used to isolate semiconducting nanotubes with a given chirality from as-produced mixtures (see ref. 6 and page 481 of this issue). Although not fully understood, this approach is thought to involve the DNA strands forming two-dimensional sheets, held together by hydrogen bonds, which then fold around and bind to the target nanotubes to form three-dimensional barrels. This binding depends on the sequence of bases in the DNA strand somehow matching the structure of the nanotube. The different DNA–nanotube structures can then be separated by chromatography to produce samples that are up to 90% pure. One of the impressive aspects of this work is the way in which Zheng and co-workers have been able to reduce the colossal number of possible DNA sequences (10^{18} for a strand containing 30 bases) to a manageable number (about 350), and then identify those sequences that allowed specific chiralities to be targeted.

Elsewhere, nanotube-based devices are being used to explore a variety of phenomena in physics. Last year, for example, three groups showed that it was possible to measure the change that occurred in the resonant frequency of a suspended nanotube when a single atom landed on it, thus forming the basis of ultrasensitive mass sensors[7–9]. Now Adrian Bachtold and co-workers[10] and, independently, Gary Steele and colleagues[11] have explored the coupling between the mechanical motion of a nanotube and the flow of electrons through the nanotube, and shown that it is possible to detect frequency changes caused by the addition of just one electron to the nanotube. Both groups also find that the coupling is strong enough to drive nonlinear oscillations of the nanotube.

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The carbon nanotube has proved to be a remarkably fruitful system for a wide range of researchers, and even if real-world applications of nanotubes have not kept pace with more basic research, the flow of new results and possible applications shows no sign of slowing down. ❐

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