NANOTUBE TRANSISTORS

Sorted

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Science **321,** 101–104 (2008)

Single-walled carbon nanotubes are considered potential building blocks for future nanoscale electronics. For example, nanotubes that are semiconducting can be electrically switched on and off as field-effect transistors. Methods for growing carbon nanotubes, however, produce collections of metallic and semiconducting materials, so the ability to separate the different types of nanotubes is critical. Furthermore, for such devices to be practical, the nanotubes must also be arranged into dense, aligned structures.

There are techniques that can carry out these steps separately or on a small scale, but not in ways that could be easily scaled-up. Now, Zhenan Bao and colleagues at Stanford University and Samsung Advanced Institute of Technology have developed a straightforward route to fabricating single-walled carbon nanotube field-effect transistors in which the alignment and type of nanotube is controlled simply through surface chemistry. The transistors are fabricated by spin-coating solutions of nanotubes onto silica surfaces that are functionalized with silanes. By altering the nature of the end group on the silane, Bao and co-workers can dictate whether metallic or semiconducting nanotubes bind to the surface.

By using a surface that selectively adsorbs semiconducting nanotubes, which are aligned and densely packed, they can create devices that exhibit promising transistor behaviour, with on/off ratios as high as 900,000.

NANOFIBRES

Waste disposal units

Adv. Mater. **20,** 2777–2781 (2008)

The need to remove hazardous by-products goes hand in hand with nuclear energy. Radioactive ions are discharged from nuclear power stations, and also by the mining industry, so materials that can irreversibly absorb large quantities of these ions from waste water are needed. To this end, natural materials such as clays and zeolites have proved useful because radioactive cations are preferentially exchanged with cations in the material. This exchange traps the radioactive cations, enabling them to be disposed of. However, synthetic cation exchange materials have been found to have much better selectivity.

Moreover, in absorbent materials that are not completely stable, the exchange process can cause structural collapse, which traps the radioactive ions permanently. Dong Jiang Yang and co-workers at Queensland University of Technology and Nankai University have now demonstrated this property with a layered titanate nanofibre, which has an interlayer containing exchangeable sodium cations. The observed absorption values for cations of similar sizes to various radioactive nanoparticles were higher than those for clays and zeolites, as well as other previously developed synthetic exchange materials.

The nanofibres can be synthesized easily and at low cost, they can be dispersed in solutions more effectively than clays and zeolites, and they can be separated from liquids using simple techniques.

GRAPHENE OXIDE

Hot stuff

Phys. Rev. Lett. **101,** 026801 (2008)

Monoatomic layers of carbon known as graphene are being studied for possible applications in nanoscale electronic circuits (see page 455). The initial goal is the fabrication of field-effect transistors — devices in which the current through a semiconducting material is controlled by the application of an external field. However, it is difficult to significantly change the resistance of graphene with an electric field because it is a semi-metal rather than a semiconductor. The ideal solution would be to change graphene into a semiconductor.

Now, Xiaosong Wu and colleagues at the Georgia Institute of Technology have fabricated an all-graphene device by placing graphene oxide — a semiconductor — between two electrodes of epitaxial graphene. A Schottky barrier of about 0.7 eV was created at the graphene/graphene oxide junction owing to the band gap in graphene oxide.

Changing epitaxial graphene into graphene oxide would be an important boost to device applications. Notably, the group found that annealing graphene oxide at 180 °C for 16 hours changed the Schottky barrier from 0.7 to 0.5 eV. Therefore, annealing could be used to produce a required band gap. Furthermore, electron irradiation of graphene oxide reduced the Schottky barrier to less than 0.5 eV, thus opening up the possibility of localized control of the band gap.

NANOPEAPODS

New moves

Nano Lett. doi:10.1021/nl801149z (2008)

Confinement of molecules inside carbon nanotubes has been shown to modify the chemical reactivity and dynamics of the encapsulated species, as well as the electronic transport and mechanical properties of the nanotubes themselves. Various fullerene molecules have been inserted into nanotubes to form peapod structures, but now researchers have fused together different types of fullerenes inside the peapod to create large chains.

Jamie Warner and colleagues at the Oxford University and Nagaoya University used transmission electron microscopy to induce coalescence of fullerenes and to study their movement. They inserted C_{60} molecules into a single-walled carbon nanotube and then applied an electron beam that was high enough to distort the fullerenes, but not so high as to damage the nanotube. A large C_{300} chain was formed, which exhibited translational motion along the nanotube and also a unique corkscrew rotation. Moreover, by inserting a mixture of C_{60} and scandium-encapsulated C_{82} molecules, large chains of mixed fullerenes were formed, which had a zigzag-shaped structure. The rotational motion of these resulted in expansion and contraction of the nanotube diameter.

These peapod structures could prove useful in nanodevices as they have potential as nanoactuators and can be controlled remotely by an electron beam.

MAGNETIC MICROSCOPY

Diamond with a spin

Appl. Phys. Lett. **92,** 243111 (2008)

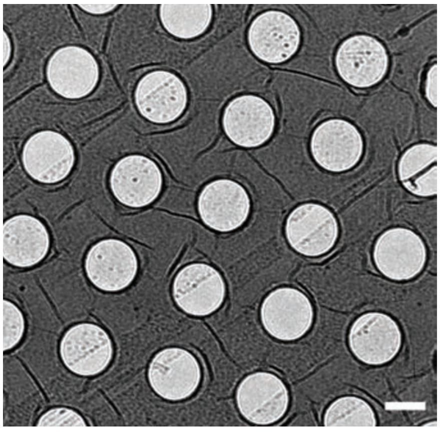
Scanning probe microscopes with ultrasharp magnetized tips are widely used for visualizing localized magnetic fields at the surfaces of materials and devices being developed for applications in data storage and spintronics. The ultimate goal in this field is to be able to study magnetic nanostructures down to the level of single atoms. Chris Degen of IBM's Almaden Research Center has now proposed building a scanning 'single spin detector' by using a diamond probe with a single nitrogen vacancy as the magnetic sensor.

Using defects in diamond to detect extremely small magnetic fields may seem counterintuitive. But exposure of the nanoscale nitrogen vacancy defect to magnetic fields causes a well-defined shift in the electron spin resonance frequency — the frequency at which the nitrogen vacancy absorbs the most microwave radiation. This shift can be used to determine the magnitude of the field being monitored with great accuracy.

Degen's calculations indicate that this device should have atomic spatial resolution and the ability to measure single magnetic atoms even at room temperature, which is not possible with other scanning techniques.

GRAPHENE

Transparent support



Nature **454,** 319-322 (2008)

The accuracy of transmission electron miscopy has been vastly improved by Jannik Meyer, Alex Zettl and co-workers at the University of California at Berkeley by using a single sheet of graphene to support samples. The technique can image hydrogen, the smallest atom of all.

Transmission electron microscopy can only image samples that are thin enough for the electrons to pass through without losing much energy. Graphene is the ultimate thin film for this purpose, having a thickness of only one carbon atom and an ordered crystal structure that can be effectively invisible to the microscope. As a result, the Berkeley team found that graphene appears practically white under a transmission electron microscope.

Against this clean background, the researchers were able to detect single carbon adatoms — extra atoms in the graphene lattice that stick up above the sheet. Then, by superimposing 100 consecutive images, they noticed several grey dots that were identified as hydrogen atoms.

The researchers were also able to watch linear carbon chains moving around on the graphene surface, and saw holes caused by the electron beam knocking atoms out of the graphene lattice. These results suggest that a graphene 'microscope slide' could be used to directly observe complex chemical reactions, or could form the basis of a nanoscale electrical device.

TERS

Look and learn

Phys. Rev. Lett. **100,** 236101 (2008)

Light scattering is widely used to determine the physical properties of liquids, solids and gases. In most cases the scattered photons have the same energy as the incident light, but about one in ten million of the photons undergo Raman scattering, which means that they have less energy than the incident photons. Raman spectra contain a lot of information about the sample, but conventional Raman measurements are not well-suited for monitoring individual molecules at the nanometre scale.

Scanning probe microscopy, on the other hand, excels in probing the properties of materials at the nanoscale. These advantages have been combined with Raman spectroscopy before in a technique called tip-enhanced Raman spectroscopy, which has been used to measure both the topographic and chemical properties of molecules.

Now, Jens Steidtner and Bruno Pettinger of the Fritz Haber Institute in Berlin have performed tip-enhanced Raman spectroscopy on a single brilliant cresyl blue molecule at the same time as performing tip-enhanced Raman imaging with a lateral resolution of ~15 nm. This is possible because the ultrahigh vacuum conditions in the experiment prevent photobleaching of the dye molecules.

TOP DOWN BOTTOM UP

Close to the bone

Polymer scaffolds reinforced with carbon nanotubes can improve the growth of bone tissue in rabbits.

John Jansen and Antonios Mikos first met in 1996 when Jansen, who is professor of periodontology and biomaterials at the University of Nijmegen, was looking for a photograph of the Vacanti mouse — the mouse with what looked to be a human ear growing from its back — for a public lecture he was giving. The request led to Jansen visiting Mikos's lab, and to a collaboration and friendship that has lasted more than 10 years.

Jansen had been studying various bone substitute materials in animals and Mikos — who is now a professor of bioengineering at Rice University — had the know-how in polymers, drug release and bioreactors for improving the behaviour of stem cells. Together, they created a biodegradable composite of single-walled carbon nanotubes and polymers, and implanted them in the thighs of rabbits. The composites promoted threefold greater bone growth and had less inflammation after 12 weeks compared with those implanted with just the polymer scaffold. Though it is still unclear if the composites can induce immature cells to become bone cells, it is suggested that the nanotubes may be the main ingredient in assisting the production of new bone tissue in the implanted area (*Bone* doi:10.1016/j.bone.2008.04.013; 2008).

"The most difficult part of collaborative research is to completely understand each other's language and knowledge, and to always trust each other completely," says Jansen. "Building trust takes some years and you have to put in time but the reward is you become friends and notice that students from completely different backgrounds can cooperate." What advice does he have to achieve this? "Visit each other frequently, exchange students, and let students from different backgrounds work together."

The definitive versions of these Research Highlights first appeared on the *Nature Nanotechnology* website, along with other articles that will not appear in print. If citing these articles, please refer to the web version.