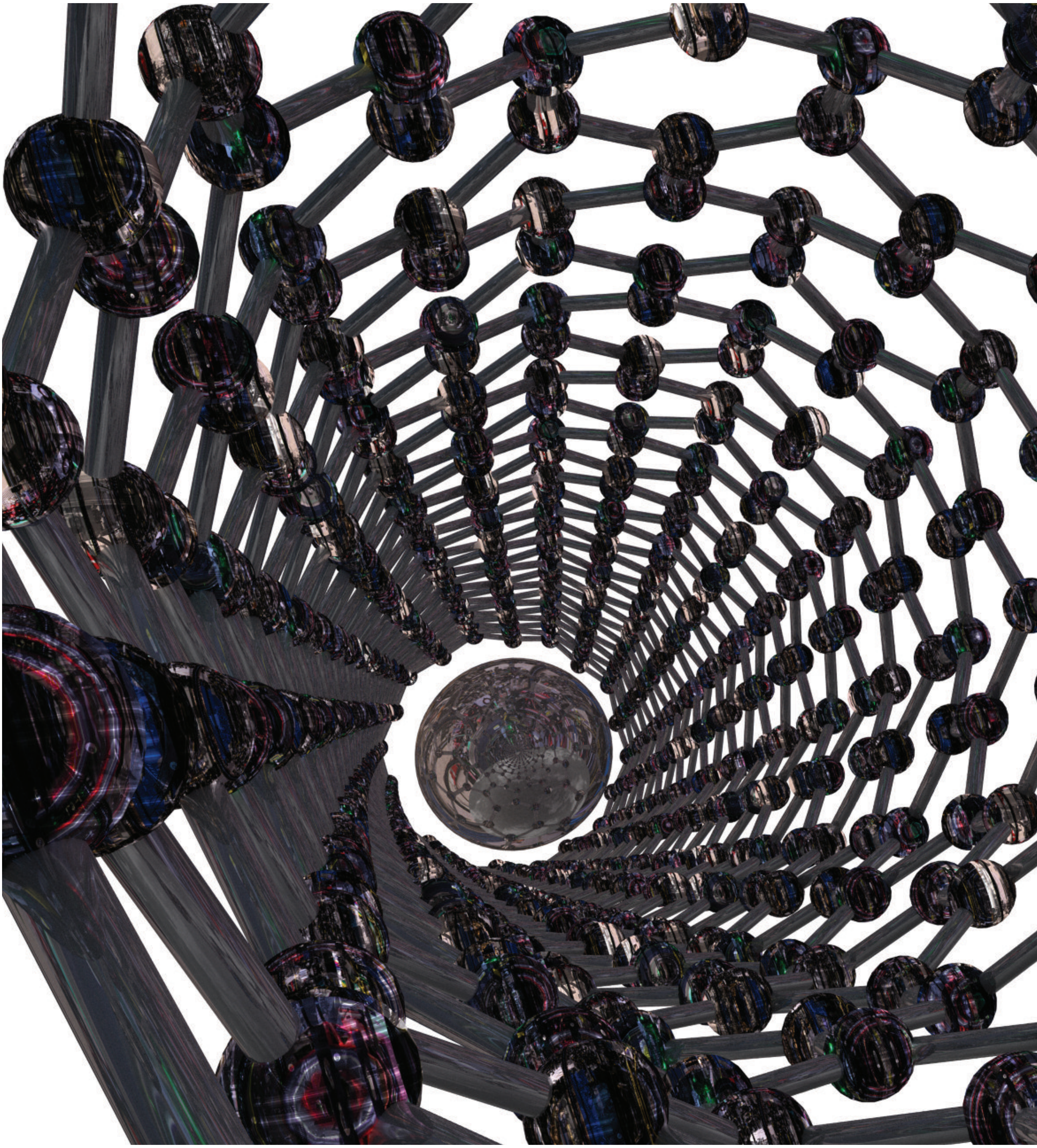
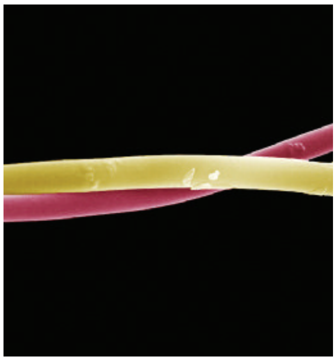
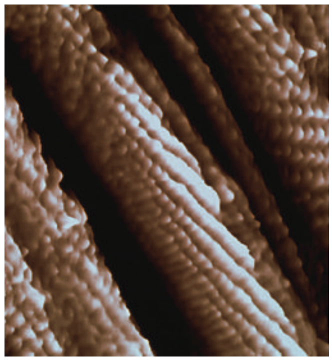
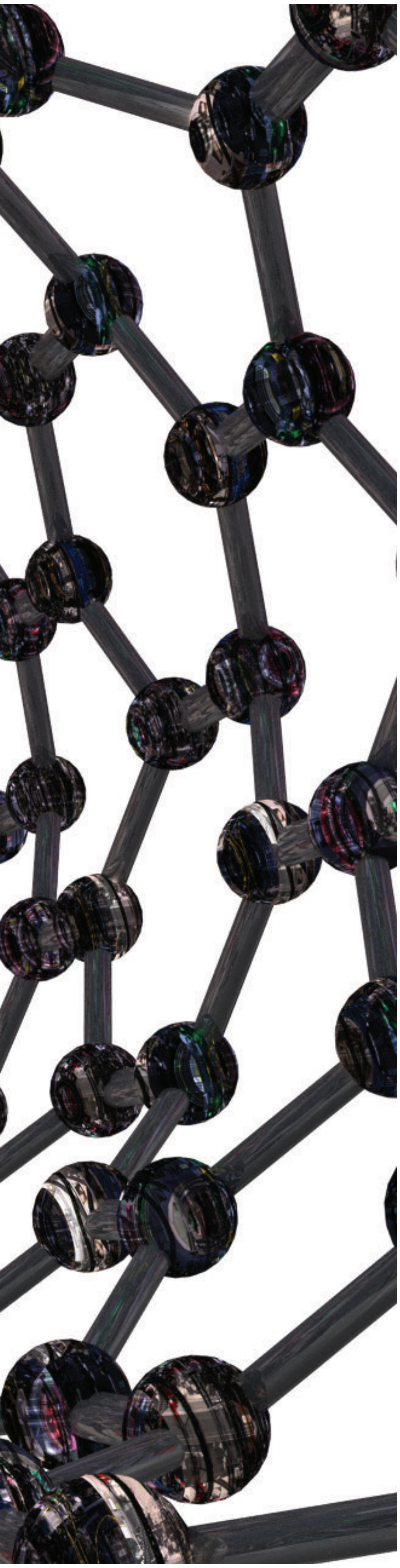


Matt James, Dr Kostas Kostarelos & David McCarthy, Eye of Science, Science Photo Library





Carbon nanotubes have diameters of around 1nm



micro goes nano

Could carbon nanotubes help the semiconductor industry keep growing? Or are there too many hurdles for them to have any impact? **Paul Grad** examines how far researchers have progressed in the battle to shrink transistors.

CARBON NANOTUBES HAVE long been a solution waiting for a problem. Now the microelectronics industry is looking at using them to overcome one of its most pressing issues – continuing to shrink the basic transistors that make up integrated circuits (ICs).

For more than 40 years, IC engineers have shrunk transistors to fit twice as many devices on a given area of silicon every two years. Now, this Moore's Law progression is under threat, as today's device designs reach physical limits. When the insulating layer of a transistor has become just three to five atoms thick, as is now the case, it's hard to see how to make the overall device a lot smaller. It's also difficult to control current flow in such small transistors, making it hard to turn them off, and leading to the leakage currents that explain why everything from laptops to servers run so hot these days.

TAKE THE TUBE

One way forward may be to use minute carbon nanotubes (CNTs) as the active channels in future transistors. The technique is under investigation by companies including IBM, Intel, Nantero, DuPont, and Carbon Nanotechnologies Inc, which holds some of the key patents in the field.

A CNT is made up of a single layer of carbon atoms that are bonded to each other in a regular pattern, of which the best known is a grid of hexagons like chicken wire, although other arrangements also exist. This single layer of atoms rolls up into a hollow tube that is so small that quantum-mechanical interactions between the carbon atoms determine whether the nanotube will act as a metallic conductor, or as a semiconductor. The tube's diameter, at around 1nm or 2nm, also means that it acts as a 'one-dimensional' conductor, of which more later.

In semiconductor form, CNTs could form the active channels of a new generation of field-effect transistors (FETs), to replace the leaky silicon channels used in today's chips. In metallic form, CNTs could provide interconnections between such devices, replacing the copper lines used today and paving the way for a future generation of all-carbon nanoelectronics.

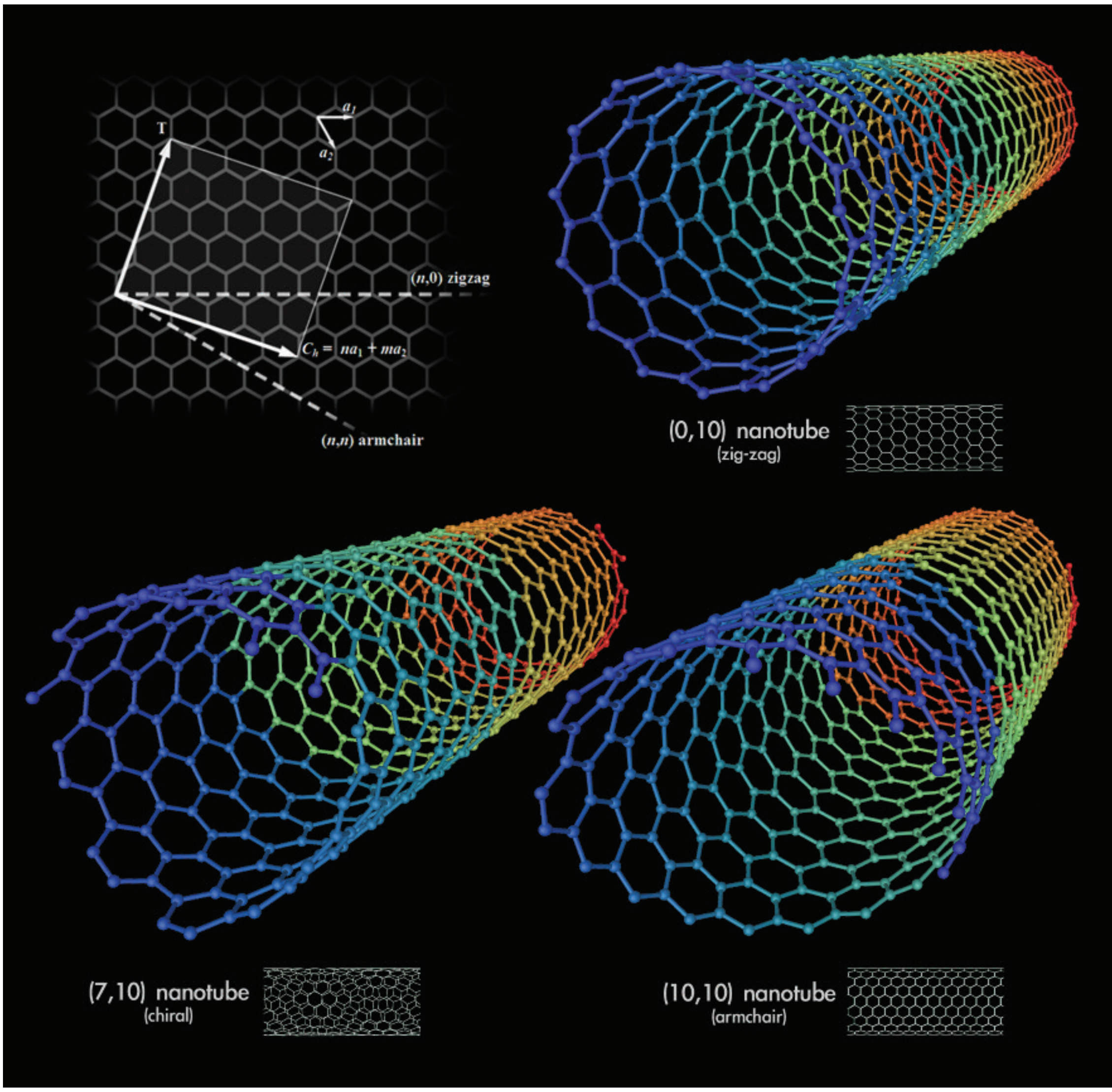
The most useful form of CNT for electronics has a single wall, rather than the multiple concentric walls that can form in certain growth conditions. These single-walled structures act as a one-dimensional conductor, in which charge carriers can only propagate backwards and forwards. This stops charge carriers being scattered by interactions with the structure, as would happen if it were big enough to act as a three-dimensional conductor. This 'ballistic' charge-carrier transport means single-walled CNTs exhibit much lower resistivity than conventional three-dimensional structures, enabling them to carry current densities up to three orders of magnitude greater than the copper lines used in IC wiring.

Ballistic transport can occur over lengths of several hundred nanometres, opening an opportunity for CNTs to take a useful role in IC wiring schemes. Eventually though, the electrons begin to be scattered until at a certain length the nanotube starts behaving like an ordinary conductor, absorbing some of the electron's energy as heat. But even then the electrons are still about 100 times more mobile than in bulk silicon, which means that transistors built using CNTs should be able to switch much more quickly.

HURDLES

So CNTs have some properties, such as their scale and the possibility of ballistic transport, which make them an attractive ▶

'There is currently no reliable way to mass-produce a single type of CNT' Dr Phaedon Avouris, IBM



Carbon nanotubes can be made in a number of different forms, each of which has different electrical properties.

The basic form of a carbon nanotube can be thought of as being based on a single layer of carbon atoms, joined to each other in a flat hexagonal pattern to form a 'graphene' sheet. This graphene sheet is then rolled up to form a seamless cylinder of carbon atoms with a regular structure.

Different forms of carbon nanotube can be made by varying the amount of offset between the edges of the sheet where they join to form a tube. As the edges are offset by one, two, three or more unit cells (the basic hexagon shape of the graphene sheet), varying amounts of twist are introduced into the tube, creating standard arrangements that have been named 'zig-zag', 'armchair', and 'chiral'.

Offsetting the joint in the carbon nanotube introduces varying amounts of strain into its atomic lattice, which changes its electronic properties, making it act as a metal or a semiconductor. Varying the twist (or chirality) induced in the tube can tune the semiconducting properties of the tube, as can changing its diameter or doping it with other atoms.

◀ basis for next-generation electronic devices. Naturally, though, there are hurdles, one of which is making them. There are various ways to make CNTs, such as laser ablation of carbon targets and metal-catalysed chemical-vapour deposition. However, these approaches produce nanotubes in various sizes and with a variety of structures. Electronics applications need to work with a single form of nanotube, in order to gain good control over device properties.

Dr Phaedon Avouris, leader of IBM's nanoscale science and technology group, says: "There is currently no reliable way to mass-produce a single type of CNT, a major problem for the development of nanotube electronics."

He says that groups at Northwestern University and DuPont claim they can isolate a single type of nanotube from mixtures, but that doesn't add up to reliable mass production.

Another issue is that FETs built using nanotubes are naturally ambipolar, that is, both electrons and holes can be injected into the channel at the same time. Conventional transistors are unipolar, transporting either electrons or holes. Ambipolar behaviour makes it more difficult to turn the transistors off, increasing their leakage current.

IBM claims to have solved that problem. Avouris says he and his colleagues have shown that there are two ways to eliminate ambipolar behaviour and obtain clear switching.

The first is to use a 'double-gated' CNT. Switching in many CNTFETs is dominated by Schottky barriers, created at the interface between the metal source and drain contacts and the nanotube, which act as diodes. In the IBM scheme, an electrode (or back gate) is built under the whole device to reduce the effect of these Schottky barriers. A second gate, isolated from the first, controls carrier flow in the nanotube itself.

The second approach is chemical. The contact regions of the transistor are doped with electron-donating or electron-accepting molecules that are absorbed onto the surface of the tube. By doping only the contact regions of the tube and using a central gate for switching, the transistor becomes unipolar and acts more like a bulk-silicon device.

A further obstacle to the use of CNTs is controlling their contamination with soot, graphite and metals such as iron, which would change their properties. Several methods to

'Companies such as Nanotechnologies Inc, of Houston, Texas, hold key patents on methods for growing CNTs, including the single-walled type'

purify raw nanotube materials have been reported. Researchers at the US National Institute of Standards and Technology, and the National Renewable Energy Laboratory in Golden, Colorado, have found a way to clean nanotubes by striking them with carefully calibrated laser pulses. The laser light supplies energy that increases the vibrations and rotations of both the CNTs and the contaminants. However, the nanotubes are more stable and thus most of the input energy is transferred to the impurities. With increased mobility comes increased chemical reactivity, so the impurities react with oxygen in the surrounding air and are eliminated.

CAN WE BUILD THEM?

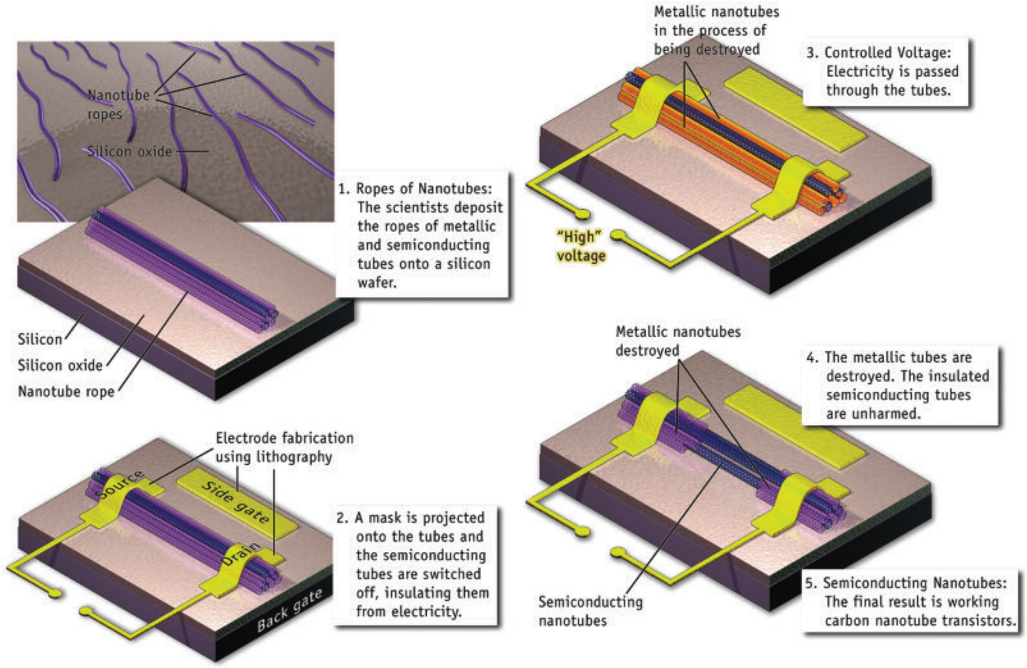
There is some scepticism as to the possibility of building complex circuits using CNT technology. CNT circuits face at least two of the same issues as silicon circuits. The first is that the physical dimensions of these circuits are now well below the wavelengths of the light used in the lithography systems that pattern the circuitry on to each chip, leading to increasingly complex and expensive workarounds. The second is that because CNTs are so small, the characteristics of CNTFETs will vary dramatically from device to device, making circuit design much more difficult.

However, Avouris says IBM and other companies have already been able to fabricate not just single CNTFETs but also simple circuits such as logic gates. His team has also built more complex structures such as ring oscillators. He says these structures show how to integrate a number of CNT devices to achieve a specific function, and that they are compatible with conventional CMOS circuitry.

A Canadian team says it has tackled the other major issue – making large amounts of nanotubes reliably. The team, from the National Research Council Steacie Institute for Molecular Sciences (NRC-SIMS) in Ottawa, and the Université de Sherbrooke, Quebec, combines laser-assisted nanotube growth with inductively coupled thermal plasma technology to make nanotubes at a rate of one to two grams per minute. It says its method could produce nanotubes for less than US$12/g. Industry estimates suggest that current annual world production of single-walled CNTs stands at about 300kg, at a cost of around US$700/g.

One of the project leaders, Dr Benoit Simard of NRC-SIMS, explains: "We vaporise carbon material inside a reactor to create a plasma above 1,200°C. We add metal catalysts to the gaseous carbon as it is cooled under specific conditions to produce single-walled CNTs."

He adds that the process only produces single-walled CNTs, with a fairly closely controlled distribution of diameters centred around 1.4nm. The team is now working on ways to make SWCNT composites, which combine nanotubes with epoxy resins and thermo-plastics. Their next step will be to find the ratio of ingredients that will transfer the nanotube properties to the new material.



IBM has developed a process that puts the right kind of nanotube in the right place

IN POSITION

Nantero Inc, a US nanotechnology company using CNTs for the development of next-generation semiconductor devices, claims it has "resolved all of the major obstacles that had been preventing CNTs from being used in mass production in semiconductor manufacturing".

CEO Greg Schmergel says Nantero has solved two of the main obstacles: metallic contamination and reliably positioning CNTs on a silicon wafer, which have prevented CNTs from being used in silicon CMOS fabs. He says his company has found ways to purify CNTs so they have less than 25 parts per billion of metallic contamination. The company has also developed a method for positioning the nanotubes, using existing equipment.

"The way we do it is to spin-coat the nanotubes on the wafer and then pattern the resulting nanotube fabric using lithography and etching, which means what is left at the end is only the nanotubes in the proper positions," he says.

IN PROSPECT

Technical issues may not form the greatest challenge to the uptake of carbon nanotubes in microelectronics. Companies such as Carbon Nanotechnologies Inc, of Houston, Texas, hold key patents on methods for growing CNTs, including the single-walled type. They also have exclusive licences to a broad array of technologies developed by the late Professor Richard Smalley at Rice University, Houston, who shared a Nobel Prize for discovering buckyballs, the precursors to carbon nanotubes.

You can bet that if carbon nanotubes start to show real promise as a way of ensuring the continued development of the $250bn a year semiconductor industry, legal challenges will soon be as significant as the technical issues. ■