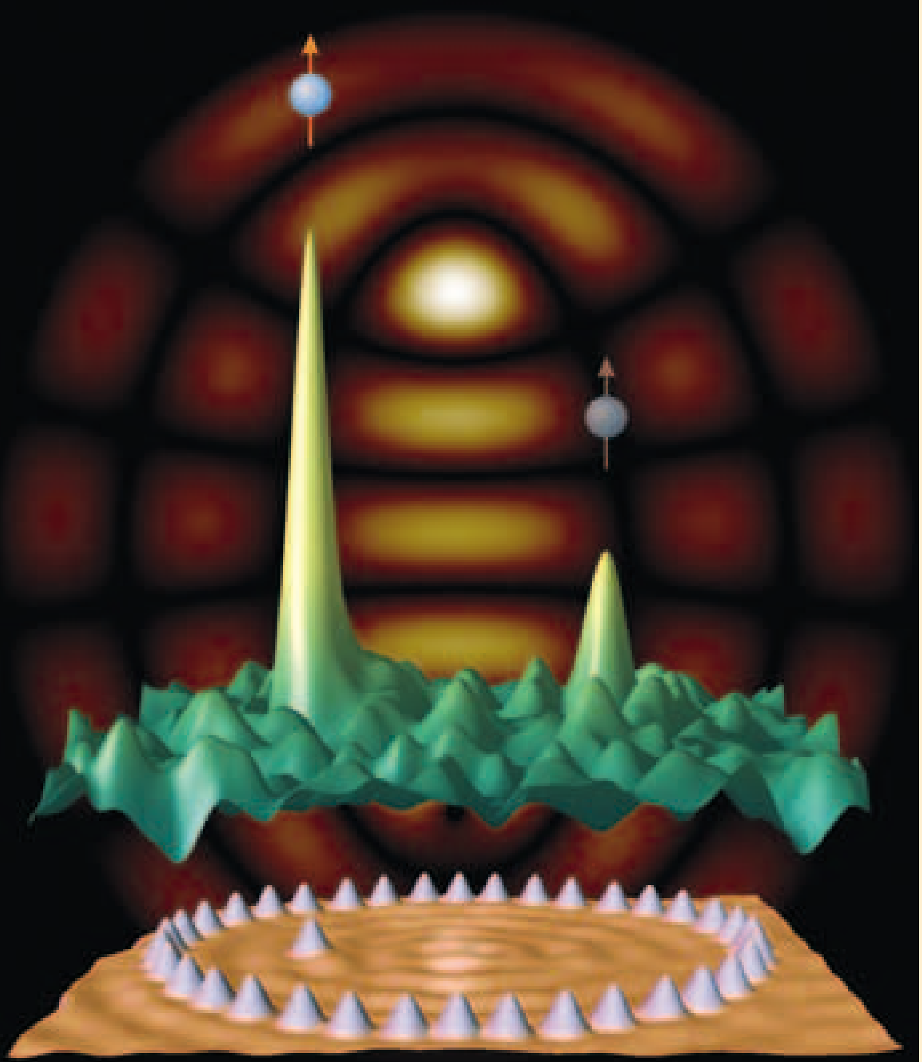

'Quantum mirage' formed by an elliptical 'corral' of cobalt atoms on a copper surface. (Courtesy of IBM Almaden.)

Nanotechnology

Big prospects for *small* engineering

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Nanotechnology has established itself as one of the new buzz topics in science and engineering. It is no longer considered futuristic and its huge potential is now being recognised. Roger Whatmore gives a fascinating overview of what has already been achieved and what is still to come.

Nanotechnology is a subject in which, paradoxically, you first have to think small to think big and, occasionally, make big to make small. To get an idea of where we are going to go in this article, I need you to conceive of yourself as being very small. Look at a human hair and imagine that you are so small that the hair is as big as the trunk of a large tree – about a metre across. That thing a couple of centimetres long on the tree trunk that looks a bit like a caterpillar is, in fact, a bacterium and is only a millionth of a metre (a micron) in size. Now imagine an ant a couple of millimetres in length attacking the caterpillar. The ant is about the size of a virus particle and is really about 100 billionths of a metre (100 nanometres) long; this is the dimension at which our story begins.

On the 'human hair = tree trunk' scale we will be dealing with lengths that go from ant-size, down to the size of a full stop on one of these pages (equivalent to 10 nanometres (nm), or the size of a large protein molecule) and finally down to the thickness of the paper it is printed on (equivalent to 1 nm). Since the mid-1980s, our ability to manipulate objects and make artefacts on this scale of dimensions has brought some remarkable technological developments and promises to bring huge benefits to society in the 21st century.

Precision manufacturing machines

Credit for coining the term 'nanotechnology' must be given to Norio Taniguchi. In 1974 he predicted, from an extrapolation of known trends in precision manufacturing, that mechanical machining methods would be manufacturing parts by the late 1980s with a dimensional precision of less than 100 nm. This prediction has largely been proven correct. The UK has played a leading role in this aspect of the subject through the development of ultra-stable manufacturing machines. A superb example of this was the 'Nanocentre', a world-leading diamond-turning machine capable of fabricating parts of 10s of centimetre dimensions to sub-100 nm precision.

The latest development along this line is the 'Tetraform'. The concept, which originated at the National Physical Laboratory at Teddington, was to place the working volume of the tool at the centre of a tetrahedron, the stiffest structure we know. Cranfield University (under Professor John Corbett) and Loadpoint Ltd were funded by an EPSRC Joint Research Equipment Initiative to produce a useful machine tool and realise this idea (Figure 1). The size of this machine, although not large by machine tool standards, illustrates the point made earlier that sometimes we have to make things big to make things small.

The machine has world-record stiffness, greater than 120 N/µm. (In other words, it takes a force of 120 N – roughly that needed to lift a 25 lb weight – at the cutting tool to distort the machine by one thousandth of a millimetre.) Figure 2 shows a piece of steel ground by using it. This is a stepped test piece where the upper surface was ground using a 200 µm depth of cut and the lower region represents a 500 µm depth of cut, which was stopped part way through to form the 500 µm step. ELID was used in both cases. The two surfaces demonstrate measured R_a values of 2.3 nm and 5.4 nm respectively, as examples of the kinds of surface finishes that this machine can produce.

ELID

ElectroLytic In-process Dressing of a diamond grinding wheel. A current is passed through the grinding wheel during operation. This produces a reaction in the steel bonding that holds the diamonds together in the grinding wheel, so that new diamonds are continuously exposed in a very controlled way. This avoids problems with the tool becoming clogged with grinding debris.

R_a value

This is a parameter that describes the roughness of a surface in terms of the heights and distributions of the peaks and valleys in it.

The stiffness of machines such as this one brings with it the ability to grind brittle materials such as semiconductors, glass and ceramics in a 'ductile' fashion. If the depth of cut is less than a critical value (which is dependent on the material, but typically around 100 nm), then material can be removed from brittle materials (such as glass) in the form of 'swarf' rather than chips. It is rather counter-intuitive to think of glass or a ceramic being cut as if it were a ductile material like copper, but the process dramatically reduces the amount of sub-surface cracking. In turn, this dramatically increases the reliability and lifetime of mechanical components and is a very good example of the benefits conveyed by controlling the fabrication of artefacts with nanometric precision.

The benefits of ultra-precision machines are already feeding directly into many important areas of technology, from the manufacture of more reliable car engines to making silicon integrated circuits at nanometric accuracy and repeatability.

What is nanotechnology?

The subject of nanotechnology has expanded enormously from the ultra-precision engineering field. A

Figure 1: 'Tetraform' ultra-stiff grinding machine.

Figure 2: Piece of steel ground using the Tetraform, showing the excellent surface finish that can be achieved.

reasonable working definition of the term would be 'the study, development and processing of materials, devices and systems in which structure definition on a dimension of less than 100 nm is essential to obtain the required functional performance'. (On the 'human hair = tree trunk' scale, 100 nm is the length of an ant.) Under this definition, the subject would include topics such as:

- machining and fabrication techniques at a scale and precision of less than 100 nm;
- some aspects of electronic device fabrication technologies, including quantum well lasers and silicon or gallium arsenide integrated circuits (ICs) where the line widths are less than 100 nm;
- scanning probe microscopy and its applications;
- materials in which some aspect of structure is defined on a scale of less than 100 nm;
- self-organising and self-assembling molecular structures, including aspects of biological and biomedical systems.

Many of the interesting and useful aspects of doing things on the nano-scale occur because the shrinking of the dimensions of the components on silicon chips has been the major driving force behind the exponential increase in their power (usually referred to as 'Moore's Law'). Signals take less time to travel around the circuit and the power required is smaller. The consequent impact on society that the growth of this technology has had – through its effects on information technology, communications, entertainment, manufacturing, health care and so on – is obvious to everyone.

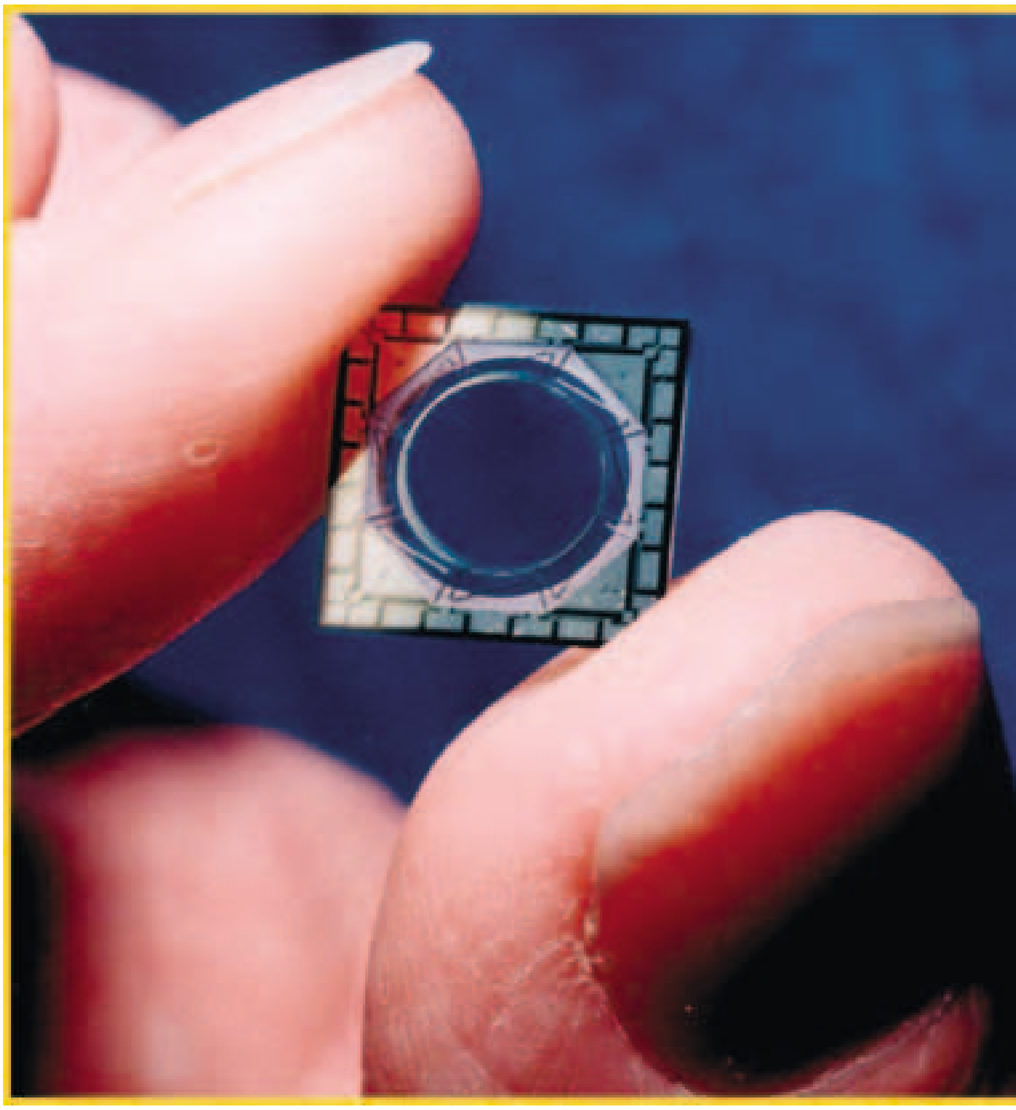

Figure 3: An example of a practical MEMS device, the BASE rate gyroscope. The ring is about 10 mm across. (Photograph courtesy of BAE SYSTEMS.)

Microsystems

Powerful as silicon chips are, they are only useful if given information that they can act upon via external sensors. In many cases they will communicate the results of their computations either with other chips or ourselves through a variety of links (wires, optical fibres, visual display units, etc). They may also demand the generation of some mechanical function via an actuator such as a pump or a motor. These peripheral functions are currently provided through separate components that must be assembled into a complete system. Microelectromechanical systems (MEMS) or microsystems technology (MST) aims to exploit this silicon-chip-based signal processing power by putting it together with sensing, actuation and communications functions into a single, micro-assembled package.

This brings with it the need to make very small moving components to assemble with silicon chips and/or to integrate novel materials for sensing or actuation which would not be compatible with a normal silicon processing environment. So there are new challenges in terms of process integration and device design that go well beyond the normal requirements of IC manufacture.

The UK has a strong position in the field of MEMS technology and is in the forefront of its exploitation. BAE SYSTEMS has commercialised a novel rate gyroscope consisting of a slender ring (see Figure 3) vibrating in a magnetic field. This is made by the bulk

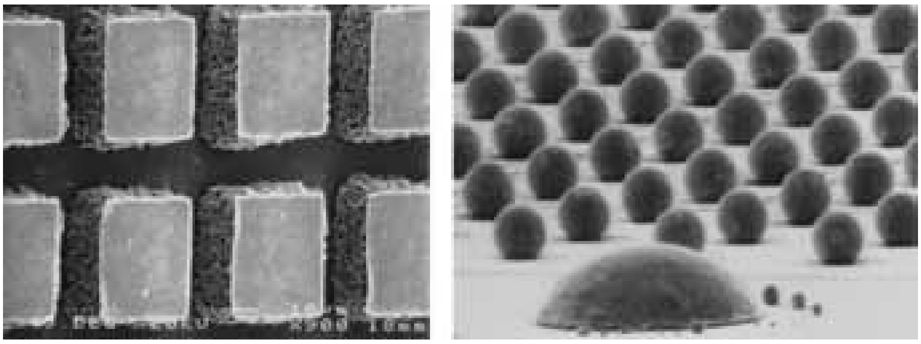

Figure 4: Uncooled pyroelectric thermal imaging array. The device uses micromachined ceramic elements (left) which are about 30 microns square. These are flip-chip bonded to a silicon readout array using 10 micron diameter bumps of solder (right). (Courtesy of BAE SYSTEMS Infra-red Ltd.)

micromachining of silicon. The same company has worked closely with the Defence and Evaluation Research Agency (DERA) at Malvern to develop a world-leading uncooled thermal imaging array based on a ferroelectric ceramic hybridised onto a silicon integrated circuit using flip-chip solder bonding (Figure 4).

Manipulation of atoms

While the 1980s saw the development of ultra-precision manufacturing, it also witnessed (in 1981) the invention by Binnig and Rohrer at IBM Zurich of one of the most significant new instruments for working in the nano-dimensional range: the scanning tunnelling microscope, or STM. This uses the quantum-mechanical tunnelling of electrons from a sharp conducting tip, scanned using a piezoelectric element, to a metallic or semiconducting surface and builds up a picture of the surface's atomic structure.

Don Eigler of IBM Almaden has led a team that uses the STM not only to image the atoms of a surface but to manipulate them, picking up and placing single atoms, and has produced startling images that show interesting effects in quantum mechanics. Figure 5 shows the first of these images, in which 35 xenon atoms were positioned on a nickel surface to spell out the letters 'IBM'. Such experiments, while extremely interesting and exciting, are not yet near practical applications as it takes many hours to manipulate and place the individual atoms and the process must be carried out at very low temperatures (near absolute zero).

The concept of obtaining images at the nanoscale by scanning a sharp tip across a surface has been extended to encompass a wide range of other scanning probe microscopies (SPM), including atomic force microscopy (AFM) and scanning near-field optical microscopy (SNOM). Jim Gimzewski (IBM Zurich) has been exploring the use of the AFM for the manipulation of large molecules on surfaces. He has shown that individual C_{60} molecules (or 'bucky balls') can be immobilised on atomic steps; he has made a 'molecular abacus' as an interesting demonstration of this.

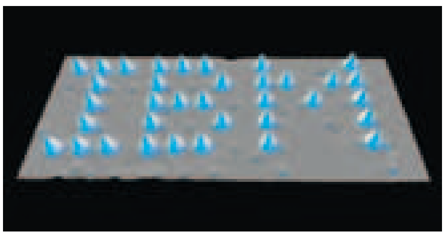

Figure 5: 35 xenon atoms on a nickel surface spelling out the letters 'IBM'. (Photograph courtesy of IBM.)

Wettiger (also at IBM Zurich) is exploring the use of arrays of AFM tips to write and read information by melting tiny depressions in a plastic surface. This system, called 'millipede', which owes a great deal to the MEMS technologies described above, offers the possibility of data storage densities in the 100 Gbit per square inch range and rather nicely shows how MEMS and nanotechnology are becoming increasingly interdependent. (Current storage densities on recordable CD-ROMs are about 65 Mbit/sq.in. and on hard disk drives up to 600 Mbit/sq.in.)

Top-down versus bottom-up

The technologies discussed above all fall into what has now become known as 'top-down' nanotechnology, which attempts to reach structures with ever finer and/or more precise dimensions by increasing the performances of macroscopic machines for material manipulation, such as machine tools, lithographic printers or SPMs. This is an engineering approach to the problem and tends to produce very regular, well-defined structures; it is frequently used for making objects out of stable engineering materials. However, it has problems building complex three-dimensional structures.

There is an alternative approach to nanotechnology that has also emerged over a similar time frame. This is called 'bottom-up' nanotechnology and it attempts to build up complex entities by using the self-assembling properties of molecular systems. This is more like a chemical or biological approach and it has the potential to make complex 3-D structures cheaply and in large quantities. However, self-assembly has its own problems of regularity and repeatability.

One of the areas of 'bottom-up' nanotechnology currently being widely exploited and investigated is the area of nanophase or nanostructured materials. The applications are not new, since over 2000 years ago the Romans discovered that the inclusion of very small amounts (approximately one part in 50,000) of gold in glass produced a deep red colour if the glass was appropriately heat treated. The phenomenon is due to the formation of nanometre-sized particles of metal crystals in the glass, which strongly absorb light of below a certain wavelength, giving the colour that is observed.

Typically, the smaller the crystallite, the shorter the wavelength of the absorption edge. Hence, it is possible to produce powders for which the particle size determines the absorption cut-off wavelength and hence the material's colour. The semiconductor cadmium selenide is a particular example for which crystallites of approximately 1.5 nm in size will appear yellow, while 4 nm particles will appear red. Still larger particles appear black.

This principle is now being applied to tailoring the sizes of particles of zinc oxide and titania for sunscreen cosmetics where it is desirable to shield the skin from particularly damaging wavelengths of the ultraviolet component of sunlight. A further promising application of this quantum confinement principle is in the development of semiconductor lasers for the fibre-optic communications market, where it is highly desirable to be able to tune the wavelength of emission, so that many channels of optical information can be sent simultaneously down a single optical fibre.

Nanoparticles and nanopowders that can be produced in suspensions (colloids), sol-gel, aerosols and so on offer a wide range of new and improved products. Smaller particles have larger active surfaces per unit of mass; this improves their chemical activity (such as providing greater solubility in water). Stronger ceramics, more uniform and durable surfaces on porcelain and better inks for inkjet printing, are some benefits that derive from nanoparticle technologies.

The mechanical properties of bulk materials are also often very different when they are nano-structured. A nanometre-range grain size in metals will produce greatly improved mechanical properties with strengths up to three times higher than the normal, microstructured version.

A whole new range of physics and chemistry has been based upon fullerenes, the so-called 'third form' of carbon. C_{60} 'buckeyballs' may prove to be a very effective nanoparticle dry lubricant in engineering applications. A particularly interesting development has been the discovery that these compounds can also form long cylindrical tubes with nano-sized diameters. These can form the smallest electrically conducting 'wires' ever made and could be a component in future novel nanoelectronic circuits. A 'nanotube' transistor has recently been demonstrated. The nanotubes are much stronger than carbon fibres and offer the potential to produce fibres which have 100 times the strength of steel with only 6 percent of its mass. There has been research into their potential for storing hydrogen, which could lead to a breakthrough in fuel cell technology, possibly engendering the emergence of economical all-electric cars.

Natural systems are frequently driven by thermodynamics to self-assemble into regular, repeating structures (crystallisation is a case in point). Langmuir–Blodgett film technology exploits this natural tendency by floating and compressing a monomolecular film of large organic molecules on the surface of water, causing the molecules to form a regular two-dimensional crystal, which can be picked up on to a substrate. Such technology has shown the potential for making single-molecule electronic components such as diodes. Alkane thiols (long-chain organic molecules with a sulphur atom at one end) will bind to 5 nm-sized gold colloid particles, which will then form self-ordered arrays on substrates.

Biological molecules such as DNA-derivatives are self-recognising in a lock-and-key fashion. Potentially these can be used to 'tag' nanoscale particles or components, which will then self-assemble with other components. Recently, scientists have demonstrated artificially created 'molecular motors' which rotate, powered in a manner similar to the flagella of bacteria. IBM are actively exploring the design of molecules with specific functions, such as rotors, wires and circuits.

Education and the future

The UK is taking a leading role in Europe in education in nanotechnology. The European Society for Precision Engineering and Nanotechnology (EuSPEN), based at Cranfield University and funded through the European Commission Framework V programme, is dedicated to bringing together and educating scientists and engineers working in the field. The Institute of Nanotechnology is also assisting in the education role and is taking a particular interest in assisting scientists and engineers to liase with potential entrepreneurs in the field, helping to bring the technology to exploitation and the marketplace.

Many people look at the subject of nanotechnology and think that it is too 'futuristic' to be worth considering for

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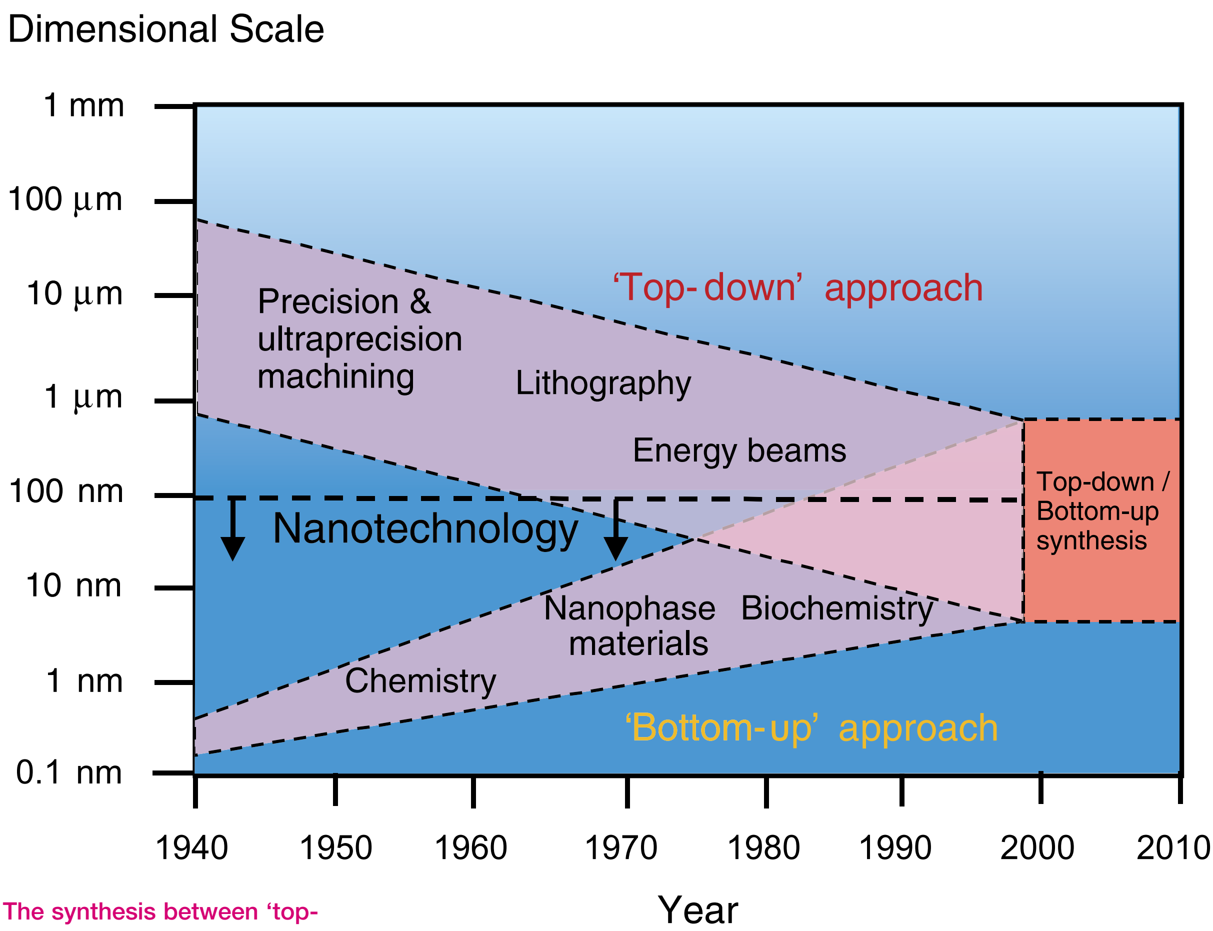

Figure 6: The synthesis between 'top-down' and 'bottom-up' nanotechnology.

exploitation now. Nothing could be further from the truth. Many of the benefits we are currently deriving from advanced technology, ranging from more reliable motor car engines through mobile phones to internet-based communications, come from our ability to manipulate and exploit matter on scales of less than 100 nm.

However, what is clear is that the field has much more to deliver. It is particularly exciting to consider the benefits which might accrue if we combine the 'top-down' and 'bottom-up' approaches to nanotechnology. Figure 6 shows the evolution of these approaches with time and the way in which the dimensional ranges addressed by each of them are now overlapping. There is undoubtedly some very exciting and exploitable new science and engineering to be done in this overlap region that will bring great benefits in the future. ■

Useful and interesting web sites

Paper by R. Feynman entitled 'There's plenty of room at the bottom': http://www.zyvex.com/nanotech/feynman.html

Institute of Nanotechnology: http://www.nano.org.uk/

European Society for Precision Engineering and Nanotechnology (EUSPEN): http://www.euspen.org/

Images of quantum corrals: http://www.almaden.ibm.com/almaden/media/image_mirage.html

Molecular abacus: http://www.research.ibm.com/topics/popups/serious/nano/html/show.html

Nanoscience: http://www.research.ibm.com/nanoscience/

Ferroelectrics, microsystems and nanotechnology – the Cranfield University Nanotechnology web site: http://www.nanotek.org/

Professor R. W. Whatmore has held the Royal Academy of Engineering Chair in Engineering Nanotechnology at Cranfield University since 1994, where he is exploring the applications of ferroelectrics in microsystems and nanotechnology. Before this he worked at the GEC Marconi Materials Technology (formerly Plessey Research) at Caswell, looking at the applications of ferroelectric materials to piezoelectric, pyroelectric and electro-optic devices. He has over 180 publications and filed over 30 patents in the field of ferroelectric materials and their applications.

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