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# FOCUS ON NANOTECHNOLOGY

## Reaping the benefits of nanomaterials

June 2014 physicsworld.com

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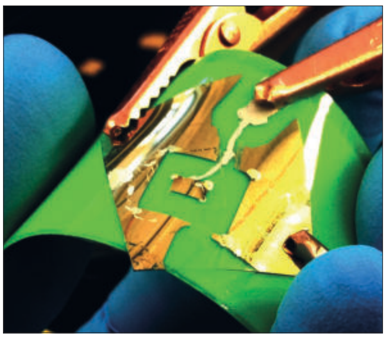
University of Manchester



2D nanosheets show great promise for novel materials applications 9

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# Focus on: Nanotechnology

Welcome to this focus issue of *Physics World*, which contains our pick of some of the best recent advances in nanoscience and technology. It includes a special review of the fast-growing field of 2D materials and a report about a new project to develop an alternative to CMOS transistors based on nanoscale piezoelectrics. We survey the potential of water-repellent nanocoatings and hear about a new project at Lund University aimed at nanomaterials for cleaner energy. Finally, we look back on 25 years of the journal *Nanotechnology*, which helped kick-start the nano revolution. Let us know what you think about any of the topics covered by e-mailing us at pwld@iop.org.

**Matin Durrani**, Editor, *Physics World*



**On the cover**
A nanoscale polymer film can repel water 19 *(P2i)*

Research news

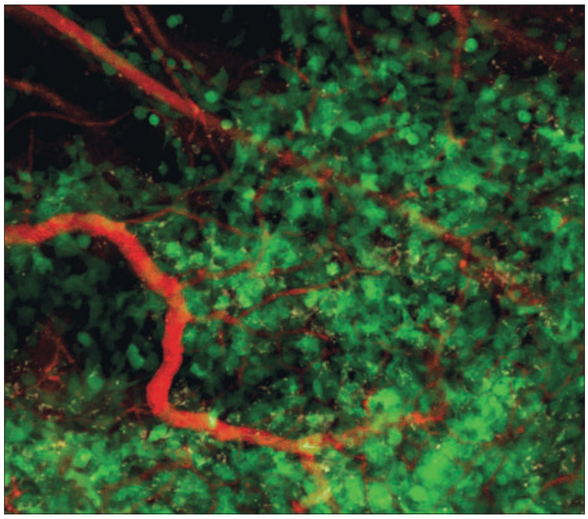
# Nanotube-loaded cells target tumours

Single-walled carbon nanotubes (SWCNTs) can be rapidly taken up by white blood cells and delivered directly to tumours, according to a new study by researchers at Stanford University in the US (*Nature Nanotechnology* 10.1038/nnano.2014.62). The surprising discovery could ultimately help fight diseases including cancer, atherosclerosis and diabetes, according to the team. "Our finding points to a novel mechanism of nanoparticle targeting to disease and opens up a whole new area of research in cell-based delivery of nanotherapeutics," says lead author Bryan Ronain Smith.

One of the biggest obstacles confronting nanomedicine is the inefficiency of delivering nanoparticles to desired sites. Smith, however, thinks that his team's approach could in principle be used to treat all types of solid tumours because Ly-6C$^{hi}$ monocytes – a type of white blood cell that is important for the immune system – naturally enter cancerous tissue and deposit their nanoparticle load there. "[It's] rather like a Trojan horse," says Smith.

The Stanford team made the discovery while investigating how SWCNTs interact with tumours in live mice. Using intravital microscopy, the researchers observed that the mice cells "gobbled up" nanotubes that were circulating in the bloodstream. On analysing blood samples, it became clear that of all the many different types of cells in blood only Ly-6C$^{hi}$ monocytes took up nanotubes to any degree.

The team also found that by targeting ligands called RGD peptides conjugated to the nanotubes, the number of SWCNT-loaded monocytes reaching a tumour was significantly enhanced. Although the mechanisms behind this increased uptake are not yet known, experiments suggest that the peptides remain on the monocyte surface after they are taken up by the nanotubes. The studies are still at an early stage but the discovery could be used as a tool to help diagnose and treat diseases in which Ly-6C$^{hi}$ monocytes are directly implicated, including cancer, heart disease and diabetes.



B R Smith

**On track**
Micron-scale image of a tumour in a live animal containing cancerous cells (green), blood vessels (red) and carbon nanotubes (greyscale) sequestered in Ly-6C$^{hi}$ monocytes within the tumour.

Kostas Kostarelos of the Nanomedicine Lab at the University of Manchester in the UK, who was not involved in the current study, describes the observations as "peculiar". "The specific materials used were heavily coated with PEGylated lipids and it will be interesting to interrogate the role and physiochemical characteristics of the coating in the seemingly monocyte-specific internalization of the materials," he told *Physics World*. "Clearly, there is a lot of mechanistic work that is pertinent before any expectations of enhanced therapeutic activity."

The Stanford team now plans to investigate whether its findings can be used for specific tracking, manipulating or treating immune cells.

**Belle Dumé**

**Solar cells**

## UK and India collaborate on renewable energy

Researchers from the University of Surrey, Queen's University Belfast and the Indian Institute of Science Education and Research have joined forces to explore how nanotechnology can impact the future of renewable energy. Initiated by a £150 000 grant (about $250 000) from the UK India Education and Research Initiative (UK-IERI), which will then be topped up by commercial funding, researchers will undertake two projects lasting two years each that involve collaboration with Tata Steel Research and Development UK.

In one of the projects, researchers from Surrey and Hyderabad will investigate cheaper and more-efficient solar cells based on carbon nanomaterials such as graphene. Tata Steel will develop coating techniques and investigate the use of steel bipolar plates as potential substrates that could provide an interface with existing power-generation technology. "The work will attempt to integrate novel functionality into a single-material platform that has not previously been achieved in any materials format, much like the iPad or iPhone did," explains Chris Mills of Surrey's Nanoelectronics Research Centre.

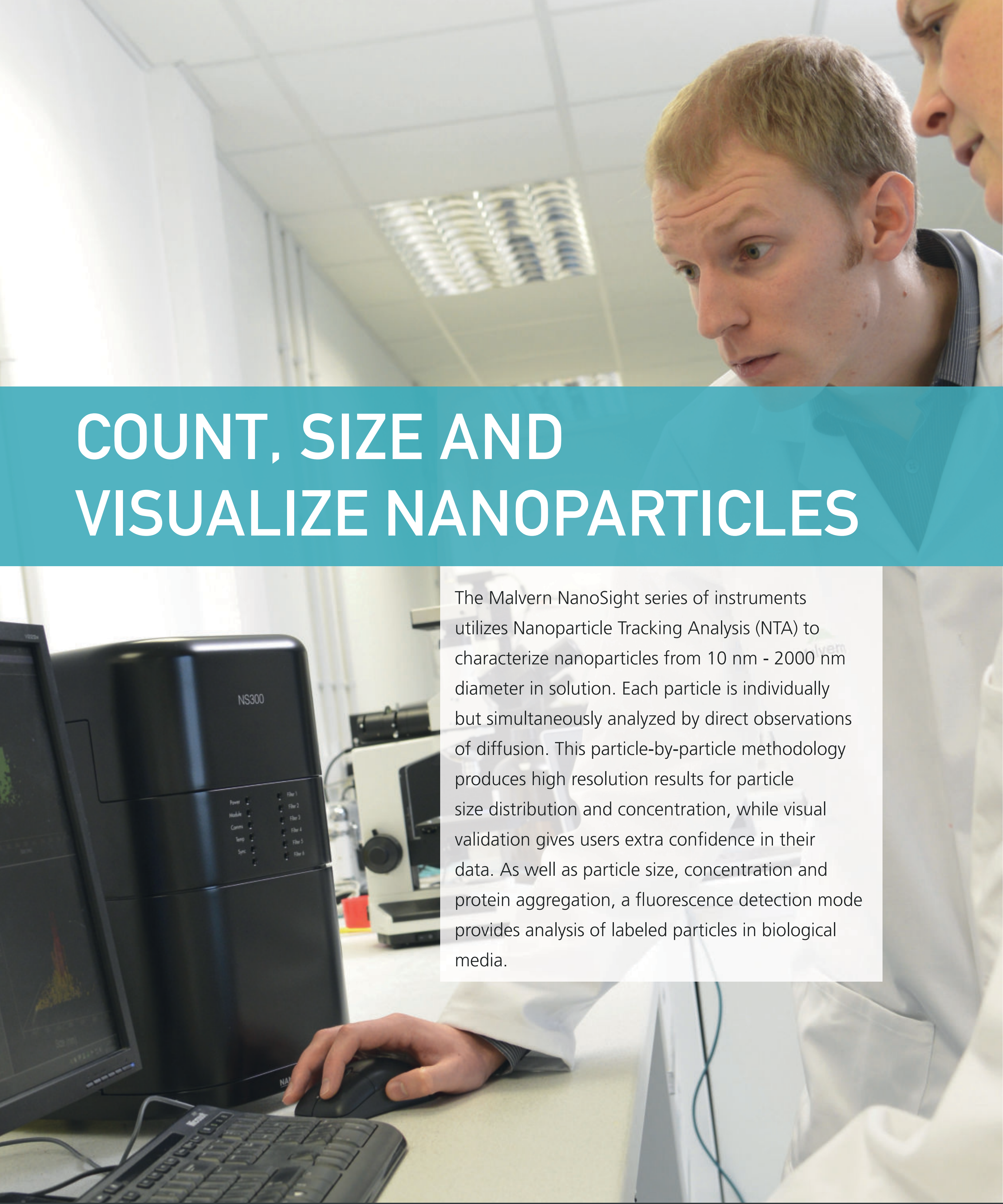
**Joining forces**
India and the UK are involved in several nanotechnology projects via the joint UK-IERI.

IGCAR

The other project will examine the use of zinc-oxide nanomaterials in ultra-high-sensitivity gas sensors for environmental monitoring. In addition to making sensors more energy efficient, the nanomaterials could also be used in breathalysers or for sensing potentially explosive leaks in hydrogen-storage facilities, says the team.

"Nanotechnology projects such as these are hugely exciting and offer direct solutions for the key challenges that the energy sector faces," says project leader Ravi Silva, who is head of Surrey's Advanced Technology Institute. "Working with cutting-edge nanomaterials such as zinc oxide, graphene and carbon nanotubes, we can revolutionize energy storage and capture."

**Matthew Chalmers**




# COUNT, SIZE AND VISUALIZE NANOPARTICLES

The Malvern NanoSight series of instruments utilizes Nanoparticle Tracking Analysis (NTA) to characterize nanoparticles from 10 nm - 2000 nm diameter in solution. Each particle is individually but simultaneously analyzed by direct observations of diffusion. This particle-by-particle methodology produces high resolution results for particle size distribution and concentration, while visual validation gives users extra confidence in their data. As well as particle size, concentration and protein aggregation, a fluorescence detection mode provides analysis of labeled particles in biological media.

Food labelling

# Nanolabels counter olive-oil fakes

In an operation carried out late last year, the Europol and Interpol law-enforcement agencies confiscated more than 1200 tonnes of fake or sub-standard food and more than 400 000 litres of counterfeit drinks, including 131 000 litres of oil and vinegar. However, the days of inferior oils posing as more expensive brands could be numbered thanks to a new nanoscale magnetic tag that can be dispersed throughout a product to guarantee its authenticity. Developed by researchers at ETH Zurich, just a few grams of the substance could be enough to tag the entire olive-oil production of Italy, they claim.

The cost-effective tag is based on artificial DNA, which offers millions of configurations that can be used as codes, explains co-inventor Robert Grass. If counterfeiting is suspected, he explains, particles added at the place of origin can be extracted from the oil and analysed, enabling a definitive identification of the producer. "The method is equivalent to a label that cannot be removed," says Grass.

To isolate the DNA from the environment, the team first encapsulated the tag in a silica coating and then magnetized it by attaching iron-oxide nanoparticles, which make it straightforward to extract the particles from the oil. The DNA code can then be recovered using standard laboratory techniques. Indeed, the team found that it is possible to authenticate oil containing just micrograms of particles per litre and using volumes of just a millilitre (*ACS Nano* **8** 2677).

iStockphoto/Okea

**Poor quality** Adding inferior products to premium olive oils is big business.

Although the tags do not result in any visual changes, and tests show they remain stable when heated and over time, discerning consumers might question the idea of eating nanoparticles. But we are already ingesting such things, points out Grass. "Silica particles are present in ketchup and orange juice, among other products, and iron oxide is permitted as a food additive," he says. "Of course, the new technology must yield benefits that far outweigh any risks, but I need to know where food comes from and how pure it is."

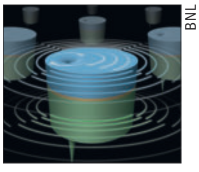
**Matthew Chalmers**

Nanoelectronics

# X-rays probe nano-antennas

Stacked nanoscale magnetic vortices separated by an extremely thin layer of copper could provide a powerful nano-antenna for a new generation of mobile phones and computers, according to researchers at the Brookhaven National Laboratory in the US. Such devices harness the quantum-mechanical spin rather than electric charge of electrons and could lead to novel "spintronic" components including memory and logic devices.

Magnetic materials comprise different domains in which all the electron spins point in the same direction. But when a magnetic disc is shrunk to a diameter of 500 nm and a thickness of 25 nm, the spins all align in a vortex-like pattern in a clockwise or anticlockwise direction. This provides four possible states: up or down paired with clockwise or anticlockwise.



BNL

**In a spin** Nanoscale magnetic vortices (blue and green) separated by an extremely thin layer of copper can be made to oscillate in unison.

Using synchrotron X-rays, the researchers found that thinner separating layers led to stronger vortices, which could help to overcome the power limitations of current vortex-based spintronic antennas by creating arrays of synchronized nano-oscillators in coupled 3D stacks (*Nature Communications* **5** 3760).

"Magnetic-vortex-based oscillators can be tuned to operate at different narrowly defined frequencies, making them extremely flexible for telecommunications applications," says physicist and lead author Javier Pulecio. "They are also self-contained elements about 100 000 times smaller than oscillators based on voltage instead of spin, so they could prove to be less expensive, consume less electricity, and won't take up as much room on the device."

**Matthew Chalmers**

## Research briefs

**Nanobubbles sense malaria**
A team at Rice University in the US has developed non-invasive technology that accurately detects low levels of malaria infection through the skin in seconds without the use of blood sampling or reagents. The new diagnostic technique takes advantage of the optical properties and size of hemozoin – a nanoparticle produced by the malaria parasite inside red blood cells. A low-powered laser creates tiny vapour nanobubbles if hemozoin is present, providing a unique acoustic signature that allows for extremely sensitive diagnosis. In a preclinical study, the technology was able to detect a single malaria-infected cell among a million normal cells with zero false-positive readings, says the team (*PNAS* 10.1073/pnas.1316253111).

**Invisibility cloaks go large**
Bending light around an object so that it appears invisible is the ultimate in stealth technology. The feat is impossible using natural materials, but artificial nanostructures called metamaterials have already been shown to cloak small objects. Researchers at the University of Central Florida in the US now claim to have found a way to make sufficient quantities of such metamaterials to cloak much larger objects. Using a technique called nanotransfer printing, the team fabricated metal–dielectric composite films stacked together in a 3D architecture patterned with nanoscale features that allow precise control over the propagation of light (*Advanced Optical Materials* **2** 255).

**Cash for UK nano-based healthcare**
The UK's Engineering and Physical Sciences Research Council (EPSRC) has awarded grants worth £2m ($3.4m) to investigate nanotechnology-based solutions for healthcare. Researchers at Swansea University will receive almost £1m to see how nanoparticle fluorescence-imaging techniques can be used to analyse abnormal microstructures in blood clots, while £750 000 will be given to researchers at University College London to develop a new generation of nanocomposite polymer-coated stents to improve blood flow. A third grant of £350 000 will enable Loughborough University researchers to develop nanomaterials and structures for superior implants based on zirconia nanograins. The grants will each run for three years.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The Apollo and Soyuz spacecraft met, combining their efforts for the first time on 17 July 1975.
5 µm
3 µm
Confocal Raman and AFM topography image of a polymer blend on glass
AFM (left) and Raman (right) images of a graphene flake
WITec's Raman AFM combines the materials analysis capability of confocal Raman imaging with the ultra-high topographic and lateral resolution of an AFM. These two complementary techniques are available in a single instrument for more flexible and comprehensive sample characterization.
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Industry news

# Nanosensors target indoor air quality

Fatigue, headaches and eye irritation are just some of the effects of poor indoor air quality (IAQ), with some people experiencing severe respiratory reactions. But relief could be in hand thanks to a new €5m ($7m) project launched late last year by the European Commission that aims to address the growing problem of poor air quality in closed spaces such as buildings and cars. The three-year-long IAQSense project seeks to develop a unique integrated nanosensor that can deliver real-time information about the gases and volatile pollutants present. It includes researchers from the CEA Laboratory of Innovation for New Energy Technologies and Nanomaterials in France along with scientists at nine European businesses.

Poor air quality is linked to a huge variety of volatile organic compounds (VOCs) in concentrations as low as a few parts per billion. The only way to obtain reliable measurements is to use expensive, heavy-duty analytical equipment, but new approaches based on nanotechnology promise low-cost sensors that can detect multiple gases quickly and with high sensitivity. "The objective of IAQSense is to transfer these scientific results to a reliable sensing system ready for mass production that can operate for long periods with extremely low energy consumption," says Mathias Holz, chief executive of NanoAnalytik, which is the technical project leader.

iStockphoto/sturti

**Invisible threat** Poor indoor air quality has major health and associated economic implications.

The consortium will look at three technologies to explore different aspects of air pollution. The first, which will identify the type and concentration of the most common VOCs, is an on-chip spectrometer that measures the mobility of ions. Ionized molecules landing on a porous surface are first made to accumulate on one side of the device by an electric field, which is then reversed to force the ions to travel back again – a process that will automatically be repeated every few minutes during operation. Since each type of molecule moves at a certain speed governed by its own surface mobility, its time of arrival at the other side of the device provides a clear signature of the species present.

The second technology is based on mounting a transistor on a silicon tip. Charge stored in the vicinity of the insulator layer by the presence of a pollutant affects the band structure of the transistor in a particular way that allows specific chemical identification at very low concentrations. The third approach is based on nanomechanical resonators coated with carbon nanotubes, the resonant frequency of which changes slightly when trace amounts of specific molecules are adsorbed. IAQSense members will also develop the associated integrated electronics and wireless communication, and calibrate the device so that it is sensitive to the most common molecules present indoors.

"For the last 20 years, there has been a growing concern regarding pollutants in closed environments and the difficulty in identifying their critical levels in real time at low cost," explains project co-ordinator Claude Iroulart of Efficience Marketing in France, who co-invented the on-chip spectrometer concept. "This project will provide a major step in the analysis and control of air quality, and significantly it paves the way for integration into portable devices."

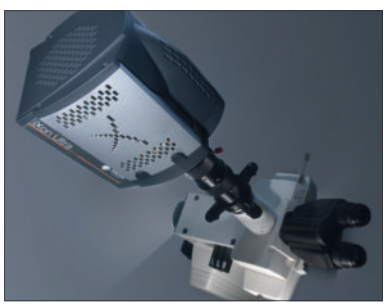
**Matthew Chalmers**

**Business**

# Oxford Instruments moves into nano-bio

Specialist technology firm Oxford Instruments has acquired Andor, a leading supplier of high-performance cameras, microscopes and software for the physical and life sciences industries. The £176m (about $240m) takeover is part of a strategic expansion into the "nano-bio" arena – an emerging interdisciplinary field that combines nano- and biotechnology. Both firms have their roots in the UK university sector, with Oxford Instruments having being founded in 1959 by researchers at Oxford University and Andor being spun off in 1989 from Queen's University in Belfast.

"We want to be part of a future that sees the use of nanotechnology tools in the biological arena, for both analysis and eventually fabrication of bio materials," says Oxford Instruments' current chief executive Jonathan Flint, who is a physicist by training. "Andor brings extensive knowledge of this market, a range of innovative products and a strong brand that will accelerate our expansion into this new market."



Andor Technology

**Bio sense** Andor offers a range of digital cameras for biological imaging.

The move builds on the company's 2012 acquisition of US firm Asylum Research, which manufactures atomic-force microscopes for materials and bioscience applications. "We want to look at opportunities in areas where sciences are converging, which is especially exciting in the nano-bio area," says Flint.

For Andor, joining the group will bring increased investment in R&D, expansion of its product range and the opportunity to broaden its reach into new markets and applications, explains managing director Conor Walsh. "Andor has a deserved reputation for innovation and excellence, which will continue to be at the core of our growth and success as part of Oxford Instruments," he says.

**Matthew Chalmers**

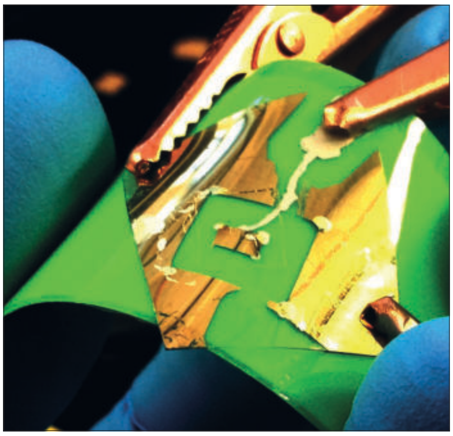
# 2D materials: graphene and beyond

Graphene might be the wonder kid of the materials world but other 2D nanosheets also show great promise for novel applications, says **Belle Dumé**

The unique electronic, optical, chemical and mechanical properties of 2D materials are creating a flurry of interest in laboratories around the world. Made up of individual atomic planes weakly held together by Van der Waals forces, these apparently simple systems behave very differently to their 3D counterparts and are therefore seen as a promising route for new electronic and other devices. The most widely studied 2D crystal is graphene: a planar sheet of carbon atoms arranged in a honeycomb lattice that is thinner and stronger than any other known material.

Since it was first isolated in 2004, graphene has continued to surprise. Some researchers believe that it might even become as important as silicon for the electronics industry. This is because electrons whizz through its 2D lattice at extremely high speeds, behaving like "Dirac" particles with no rest mass, which leads to extremely high conductivity. Graphene also shows great promise for photonics applications because it has an ideal internal quantum efficiency: almost every photon absorbed generates an electron–hole pair that could, in principle, be converted into electric current. And thanks to its Dirac electrons, graphene can also absorb light of any colour and has an extremely fast response, which could lead to much quicker optoelectronics devices for telecommunications.

However, graphene's extreme conductivity is also a problem because the material remains conducting even when the power is switched off – wasting energy and preventing graphene components from being packed into computer chips as silicon components are today. There are other reasons why all is not plain sailing with this 2D wonder material. Although graphene is a semimetal or "zero-gap" semiconductor, it is unlike familiar semiconductors such as silicon because it does not have an energy gap between its valence and conduction bands. Such a band gap allows a semiconductor to switch the flow of electrons on and off, which is the principle by which transistors operate. Researchers have proposed various schemes to overcome this problem, for example cutting graphene into nanoscale ribbons or chemically modifying the material to make it properly semiconducting, but such approaches damage the material and spoil its high electron mobility.


University of Manchester

**New dimensions** Heterostructures based on 2D atomic crystals called semiconducting transition-metal dichalcogenides could lead to flexible photovoltaics and solar cells.

These drawbacks have turned researchers' attention to 2D materials that naturally possess a band gap, such as transition-metal dichalcogenides (TMDCs), hexagonal boron nitride and layered oxides. These monolayer materials might even be combined with graphene to make novel hybrid heterostructures that have exceptional electronic and mechanical properties. "This new class of materials promises all: insulators, metals, semiconductors and superconductors," says Sefaatin Tongay of Arizona State University in the US.

## Semiconductor promise

TMDCs consist of a layer of transition-metal atoms sandwiched between two layers of chalcogen atoms, such as sulphur, selenium or tellurium, and they can be made using similar methods employed to obtain graphene. In bulk form, TMDCs are indirect band-gap semiconductors, but when scaled down to monolayers, the strong coupling between the neighbouring layers turns them into direct band-gap semiconductors. The material is therefore very efficient at absorbing and emitting light, and because TMDCs can be placed on a variety of substrates, they are ideal for optoelectronic devices such as LEDs and solar cells.

> Perhaps the next-best material to graphene in terms of mechanical and thermal properties is hexagonal boron nitride

One much-studied TMDC, which is made from molybdenum and sulphur ($MoS_2$), shows particular promise. But others discovered in the past few years include $MoSe_2$, $NbS_2$, $ReSe_2$ and $WSe_2$ (see table on p10). These materials could find similar applications as proposed for graphene or, if combined with graphene's unique electronic and mechanical properties, could be used to make superior nanoelectronic circuits.

Earlier this year, however, Tongay and colleagues discovered a new 2D material called rhenium disulphide. Despite officially being a member of the semiconducting layered TMDC family, the material behaves as though it is a pure monolayer. Unlike other 2D materials though, it does not undergo an indirect-to-direct band-gap transition when scaled down to monolayers. The system therefore provides researchers with a 3D crystal in which they can study 2D phenomena without the difficulty of preparing large and high-quality monolayers.

Perhaps the next-best material to graphene in terms of mechanical and thermal properties is hexagonal boron nitride (hBN). Also known as "white graphene", hBN is an ideal substrate for graphene because the two materials have very similar lattice constants. Unlike graphene, hBN is an insulator with a very large energy band gap, which means that monolayers of hBN integrated with graphene can be used as gate dielectrics and tunnel barriers with very few defects.

Indeed, hBN has particularly strong phonon resonances in the technologically important infrared band, which some physicists believe could be used to process information in nanodevices. "Flexible nanoelectronics could be the main application for the portfolio of 2D materials where graphene, TMDCs and hBN might be combined to make high-performance ultra-flexible transparent transistors on plastics and soft substrates," says Deji Akinwande of the University of Texas at Austin.

## Graphene derivative

Since graphene first rocked the materials world a decade ago, researchers have been exploring derivatives such as fluorog-

# 2D materials

## The most promising 2D materials

### Graphene family

**Graphene**
Extremely high conductivity and mechanical strength but no band gap in pristine state

**Graphene oxide**
Promising for molecular sieves, hydrogen storage and polymer solar cells

**Graphane and graphone**
Large on–off current ratio and large band gap but gradually lose hydrogen

**Graphyne**
Naturally contains conducting charge carriers

**hBN (white graphene)**
Good mechanical and thermal properties; an insulator and exceptional substrate for graphene

**Fluro- and chlorographene**
Often called the 2D version of Teflon, demonstrating insulating properties

**BCN**
Electronic properties ranging from insulating to semi-metallic

### 2D dichalcogenides

**$MoS_2$, $WS_2$, $MoSe_2$, $WSe_2$**
Good at absorbing/emitting light and high charge mobility

**Semiconducting dichalcogenides (e.g. $MoTe_2$, $WTe_2$, $ZrS_2$, $ZrSe_2$, $ReS_2$)**
Good for low-friction applications, such as lubricants

**Metallic dichalcogenides (e.g. $NbSe_2$, $NbS_2$, $TaS_2$, $TiS_2$, $NiSe_2$)**
Some become superconductors below a certain temperature

**Layered semiconductors (e.g. GaSe, GaTe, InSe, $Bi_2Se_3$)**
Can be exfoliated onto a number of different substrates

### 2D oxides

**Micas, BSCCO**
Wide band gap; potential for all-oxide electronics, thermoelectrics and fuel cells

**Layered copper oxides**
Could become high-temperature superconductors when charge carriers are added to the layers

**$MoO_3$, $WO_3$, $SnS_2$, $SnSe_2$, $SnTe_2$**
Might be good for doping carbon nanotubes

**$TiO_2$, $MnO_2$, $V_2O_5$, $TaO_3$, $RuO_2$**
Wide-ranging electronic, chemical and mechanical properties; has potential for thermoelectrics

**Hydroxides (e.g. $Ni(OH)_2$, $Eu(OH)_2$)**
Strong redox properties

**Perovskite-type (e.g. $LaNb_2O_7$, $Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$)**
Good substrates for growing cuprates, colossal magnetoresistive manganites and multiferroics

### Others

**Silicene**
Unstable as free-standing sheet

**Phosphorene**
Natural semiconductor but is difficult to produce in larger sheets

**Germene**
Natural semiconductor but hard to grow and environmental stability is unknown

Adapted from A K Geim and I V Grigorieva *Nature* **499** 419

raphene, which is a wide-gap insulator made by fluorinating graphene. Similarly, the large band gaps in "graphane" and "graphone" (hydrogenated and semi-hydrogenated versions of graphene, respectively) could be used to make transistors with a large on–off current ratio, although researchers first need to find a way to prevent these materials from gradually losing their hydrogen atoms. Researchers are also exploring "graphynes": 2D carbon allotropes built from double- and triply-bonded carbon atoms instead of just double bonds. These materials naturally contain conducting charge carriers and therefore could be made into semiconductors without the need for external doping.

According to some researchers, one of the most promising graphene-based derivatives is graphene oxide. This material is just like ordinary graphene but is covered with molecules such as hydroxyl groups or oxygen, which remove electronic states and turn the graphene into an insulator. Sheets of graphene oxide can easily be stacked on top of each other to form extremely thin but mechanically strong membranes, which could serve as molecular sieves. In addition to applications in water filtration and desalination, such systems might also be used for hydrogen storage, polymer solar cells, and flexible colour displays and smart textiles.

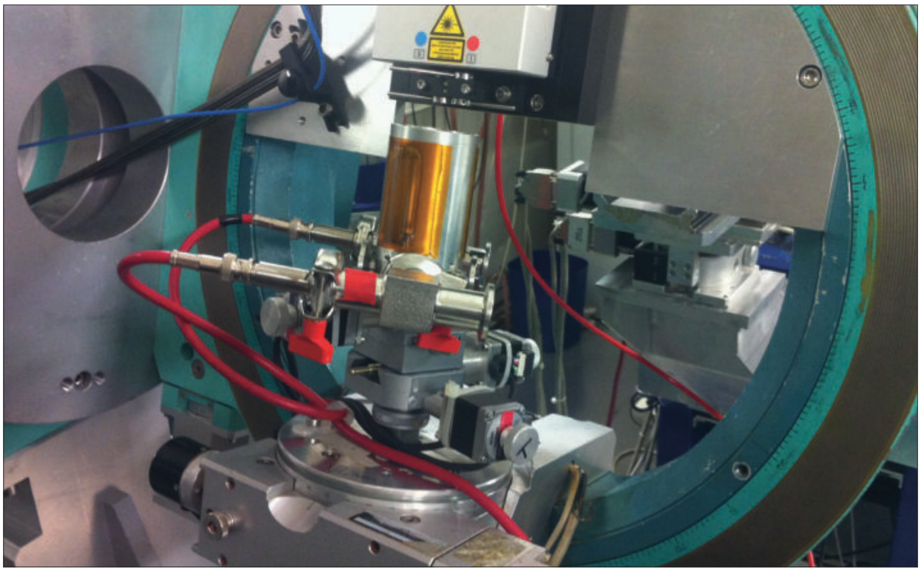
It is not yet clear whether graphene will live up to its promise and "win out" over other 2D materials, nor when the 2D-materials revolution will really start to affect our lives. According to Tongay, it is likely that there will be many winners in the race and that more competitors will appear relatively soon, such as phosphorene and silicene. "Graphene kick-started the 2D materials field and will remain an integral member of the 2D family, but the other 2D materials will bring new functionalities," he says. "The 2D-materials revolution is here and I very much hope to see these materials integrated into our daily lives in different forms, from flexible electronics and solar cells to applications that we have not even dreamed of yet."

● For more information, see IOP Publishing's new journal *2D Materials* (http://iopscience.iop.org/2053-1583/)

Nano-piezoelectrics

# Mechanical promise for Moore's law

A decade of stagnation in computing speeds may be about to give way to the biggest step change in processing power in history thanks to a new project called Nanostrain that seeks to develop nanoscale piezoelectric transistors, explains **Markys Cain**



NPL/XMaS

**Precision tool** By subjecting materials to synchrotron X-rays in sample environments like this one at the XMaS beamline at the ESRF, the Nanostrain team will be able to measure strain at the atomic level.

Over the past 40 years, advances in semiconductor-processing techniques have vastly reduced the size and improved the capabilities of microelectronic devices. In accordance with Moore's law, the dimensions of individual devices in an integrated circuit have been steadily halving every two years or so. Today's processor chips contain more than a billion transistors compared with around a million in Intel's ground-breaking Pentium processor of the early 1990s.

But the rate of miniaturization of the basic building blocks of modern electronics – based on complementary metal–oxide–silicon (CMOS) technology – is tailing off and computer processing speeds have stagnated for the past decade. Further scaling down of CMOS devices faces serious difficulties owing to leakage currents, passive power dissipation and other detrimental effects. Indeed, CMOS switching speeds are now power limited: you cannot remove heat from a chip fast enough before the device melts. Unless we can reduce the effective operating voltage of the switch, then this limit (which is intrinsic to material properties such as loss and impedance) cannot be overcome.

Faster computational speeds, reduced device weight and lower energy consumption could, however, all be within reach if the excitement around a new transistor based on piezoelectric materials can be turned into technological reality. Piezoelectric transistors could operate at a 10th of the voltage of today's CMOS equivalent, consuming 100 times less power, and be switched at much faster rates. With the US electronics giant IBM having recently filed the first patents for piezoelectric transistors, European physicists, materials scientists and metrologists have joined forces in a project called Nanostrain to develop novel electronic devices based on controlling strain at the nanometre scale. Launched in late 2013, the three-year, €4m ($5.7m) project funded by the European Union's European Metrology Research Programme under the direction of "EURAMET" aims to take us beyond Moore's law to faster, more reliable and greener computing.

## Shape-shifting

Piezoelectric materials exhibit a close relationship between their mechanical and electrical properties. Applying a voltage, for example, reorients the molecular dipole moments, and causes rotational and translational strains in the complex domain structures found in many such materials, resulting in a net macroscopic change in shape. Because this relationship is reversible, strain generated by a piezoelectric actuator can deliver sufficient force to cause a "piezoresistive" material to switch from being an insulator to a conductor and back again, offering the possibility of reading and writing digital information.

Although carbon nanotubes also display large changes in resistance depending on the chirality of the tube, piezoelectric materials have been around for far longer, which means that we can benefit from our much greater scientific understanding of them. Indeed, piezoelectrics are already used in a wide range of commercial settings, including car engines and in production lines where they act as energy harvesters that turn mechanical strain into a power source for autonomous sensors.

Several paths are currently being explored to try to end the stagnation of CMOS transistor speeds. These include spintronics, in which the spin of electrons as well as their charge would be used to process information, and quantum computers that harness the non-classical rules of superposition and entanglement. But it is only recently that researchers have considered using the mechanical properties of materials to control changes in transistor technology.

Specifically, interest in such materials took off in 2012 when IBM developed the first piezoelectric-effect transistor (PET). The prototype device consisted of a piezoresistive material clamped between a slab of piezoelectric material and a rigid frame made from a nano-indenter and a sapphire plate. The resulting microscale sandwich can switch between an overall conducting and an insulating state by applying a voltage, which changes the morphology of the piezoelectric layer such that it exerts a very large strain-induced stress on the piezoresistive material.

This sequence of events occurs nearly instantly (on picosecond timescales) and far more efficiently than the laws of physics allow for CMOS transistors. The big question for the Nanostrain team concerns scalability. Do these attractive properties replicate down to the scale of CMOS transistors?

Despite the undoubted potential of piezoresistive electronics, the success of the technology relies on the development of new and more accurate techniques to characterize these materials at the nanoscale. To address this final piece of the jigsaw, Nanostrain brings together European national laboratories, world-class research

**LANCASTER UNIVERSITY**

**Three Postdoctoral positions** (Research Associates, each for 3 years) are available at the Lancaster Centre for Nanoscale Dynamics [http://www.physics.lancs.ac.uk/research/centre-for-nanoscale-dynamics], for theoretical research in fundamental physical properties of atomic two-dimensional crystals (including graphene, boron nitride, chalcogenides of various metal, etc.) and modelling electronics and optoelectronics devices based hybrid structures of such materials. Theoretical work will be coordinated with a massive experimental effort in the European Graphene Flagship and ERC Synergy Grant Hetero2D. Applicants should hold or be close to acquiring a PhD in theoretical physics with specialisation in the theory of two-dimensional materials (analytical and/or density functional theory), mesoscopic physics using quantum transport theory and Green functions; strongly correlated systems; or quantum optics. The initial search closes on 30 May, 2014 (http://hr-jobs.lancs.ac.uk/Vacancy.aspx?ref=A971): after that, directly contact Prof V Fal'ko [v.falko@lancaster.ac.uk].

Fully-funded studentship for **PhD in Experimental Nanoscience** (http://www.physics.lancs.ac.uk/study_here/postgraduate/phd-in-nanoscience) is available to work on the project on graphene-based multilayer structures and devices. Graphene will be combined with other 2D materials (boron nitride, dichalcogenides of transitional metals and layered high-Tc superconductors). The project will be carried out at the state-of-the-art nanofabrication facility at Lancaster Quantum Technology Centre (http://www.qtc.lancs.ac.uk/) and will involve magneto-transport measurements at low temperatures. The studentship is for 3.5 years for (UK/EU), 3 years (OS). For details, contact Dr L Ponomarenko [l.ponomarenko@lancaster.ac.uk].

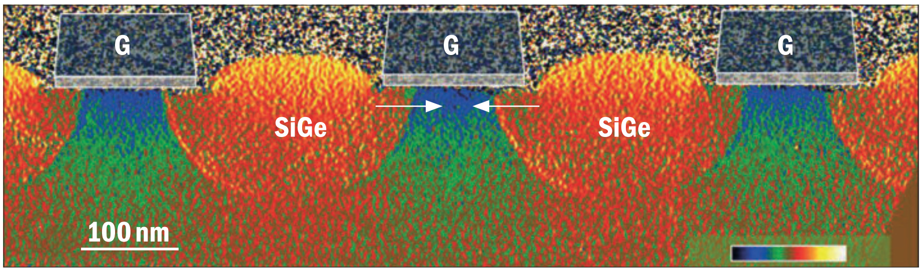
Fully-funded studentship for **PhD in Experimental Nanoscience** (http://www.physics.lancs.ac.uk/study_here/postgraduate/phd-in-nanoscience) is available in the Nanoscale Microscopy Group (www.nano-science.com) at Lancaster, to work on Nanoscale Thermal Metrology, to explore fundamental mechanisms of nanoscale heat transport in materials and nanoscale devices using advanced scanning thermal microscopy. This project is a part of a European network QUANTIHEAT. The position is for 3.5 years. For details, contact Dr O Kolosov [o.kolosov@lancaster.ac.uk].

**CDT GrapheneNOWNANO** is a newly established Centre for Doctoral Training , jointly run by the University of Manchester and Lancaster University. It builds on the world-leading expertise in the science and technology of graphene and other two-dimensional (2D) materials available on the two campuses, where staff offer a broad range of project on fundamental science and technology of graphene and 2D material, and their applications ranging from optoelectronics to biomedical. Visit www.graphene-nownano.manchester.ac.uk for information on the training programme and admissions process. For information on the Manchester site of the CDT, email to graphene-nownano@manchester.ac.uk; details on the Lancaster site can be obtained from Prof V Fal'ko [v.falko@lancaster.ac.uk].

GRAPHENE NOWNANO CDT

instrument facilities and companies to provide highly accurate measurements and a unique set of methodologies to help drive the commercialization of next-generation electronic devices.

We plan to make measurements at small length scales under industrially relevant conditions such as high stress and electric fields, and the results will be made available for other piezoelectric applications to benefit. These include ultra-high-speed and resolution printing, chemical and optical sensors, telecommunications, and innovative electronics in the automotive, power, oil and gas, and medical sectors. The Nanostrain project will, we believe, have a profound impact on a number of different fields through improved understanding of piezomaterials and new metrology capabilities at the nanoscale.




**Taking the strain** Strain distribution from a standard transistor array measured by dark-field electron holography, demonstrating how the technique can be used to visualize strain in piezoelectric transistors.

## Multiple techniques

The project has been divided into several key research areas. At the UK's National Physical Laboratory (NPL), Carlo Vecchini and colleagues will use a combination of X-ray diffraction and optical interferometry to measure displacements (and hence strain) in very-small-scale piezoelectric materials. A major aspect of this work is the use of synchrotron X-rays via a partnership between the universities of Warwick and Liverpool with the "XMaS" beamline facility at the European Synchrotron Radiation Facility (ESRF) in Grenoble. These techniques have never been combined and they will allow strain at the atomic level (as measured from crystallographic information such as lattice changes, phase transformations and ionic displacements as a function of applied voltage) and macroscopic displacements from the nanometre to the micrometre level to be measured in the same sample at the same time.

It is not without its challenges, however. Interferometry is very sensitive to vibrations and other environmental factors, whereas synchrotron X-ray measurements are typically performed in a noisy environment surrounded by vacuum pumps and involve continuous movements of the sample to fulfil different X-ray diffraction conditions. As a result, the NPL team, working with commercial partner SIOS in Germany, is building a differential sample-reference surface-interferometer system to mitigate and correct for vibrations.

Once the set-up is in place in autumn this year, we expect to be able to capture displacement measurements at length scales spanning eight orders of magnitude. This will take our understanding of current micron-scale PET set-ups down to the nanometre scale of CMOS components, providing valuable insights to help engineer new materials and

# Nano-piezoelectrics

devices. The measurement programme will also include the effect of other factors such as temperature, magnetic field and switching frequency. Although PETs are expected to reduce the operating temperatures of chips, higher switching frequencies will create heat that increases the operational temperature and could affect performance and durability.

In France, meanwhile, Martin Hytch and co-workers at the Centre d'Elaboration de Matériaux et d'Etudes Structurales in Toulouse will use destructive methods such as transmission electron microscopy (TEM), novel holographic TEM and scanning electron microscopy to measure the electric-field-induced strain in piezoelectric materials and compare it with theoretical models. TEM holography, which provides a map of how strain varies across a sample rather than just measuring it in one place, provides micron-scale fields of view at nanometre spatial resolution.

The third major prong of the Nanostrain project will be carried out at Germany's Physikalisch-Technische Bundesanstalt (PTB) by Peter Hermann and colleagues, who will make unprecedented high-precision strain measurements based on Raman and infrared spectroscopy techniques. Raman spectroscopy uses monochromatic laser light to excite particular vibrational and rotational transitions in molecules or lattice vibrations in crystals, providing information about the spatial chemical and stress distribution.

The complementary technique of infrared scanning near-field optical microscopy, which is sensitive to the change of dipole moment during vibrations, can achieve a spatial resolution significantly below 100 nm. Broadband synchrotron-radiation infrared spectroscopy, meanwhile, allows measurements to be performed over a much broader spectral range than by using conventional laser sources.

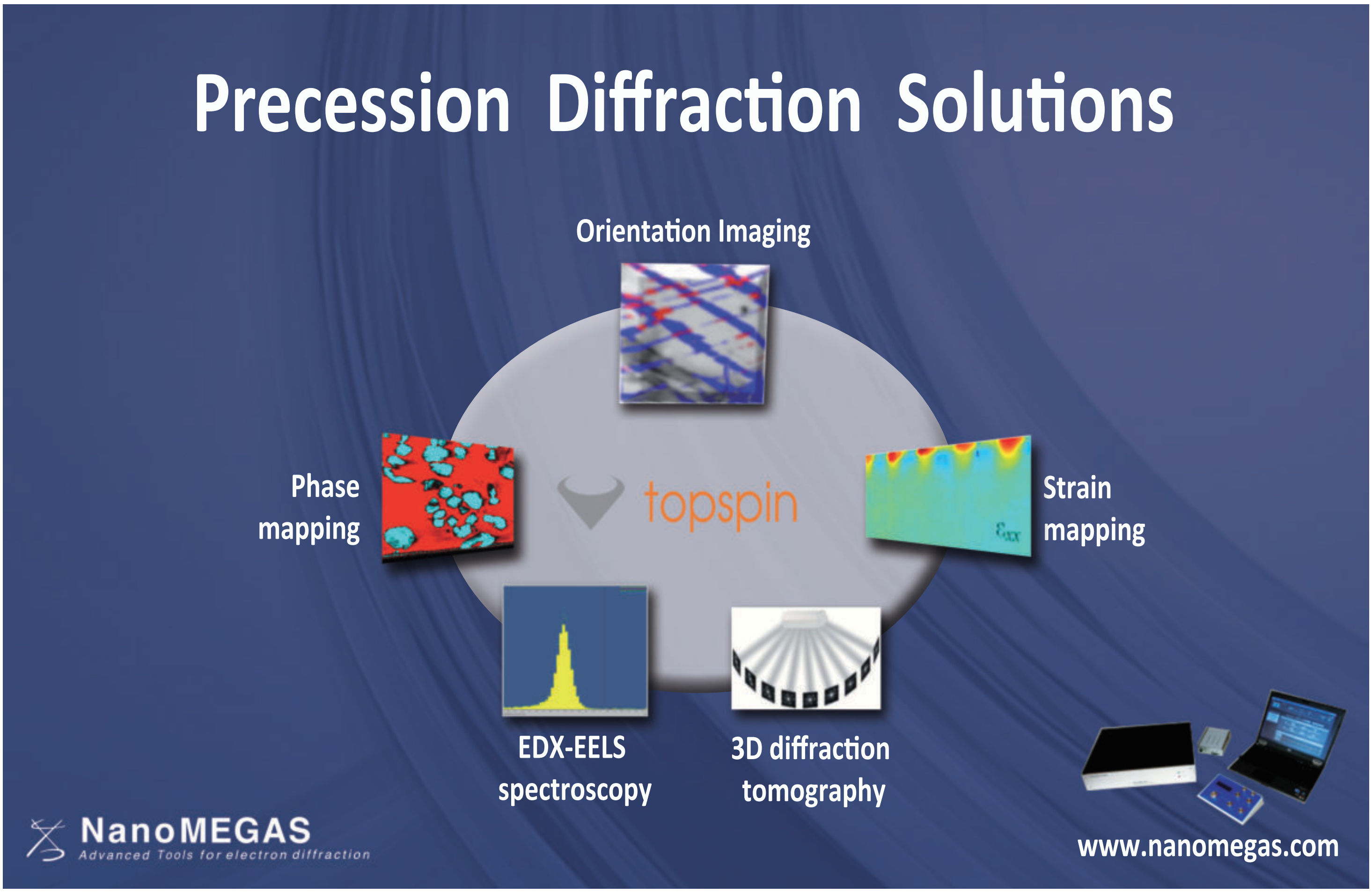
Finally, a range of modelling and visualization techniques, including atomic simulations, finite-element and continuum modelling, as well as digital image correlation, will be used to understand and characterize the properties of piezoelectric devices across different length scales. This work will be led by Anna Kimmel and colleagues from NPL in partnership with researchers at PTB, the BAM Federal Institute for Materials Research and Testing in Germany, and the Czech Metrology Institute.

Investigating the scalability of PET transistors could unlock one of the most exciting new areas of materials science and electronics R&D for decades. If experimental results match what we expect from theory, the impact could be seen within the next two decades and will directly influence our experience and enjoyment of all computing and electronics devices, as well as opening up new areas of scientific discovery through faster data processing.

Although we have known about conventional piezoelectric materials for some time, modern manufacturing techniques make it possible to create new high-performance versions. To understand the behaviour, stability and performance of these and other materials it is crucial that we can study them at the nanoscale because microstructural defects and interfaces, not to mention geometrical constraints, define the properties of entire nanostructures.

After decades of scaling the heights of processing power, CMOS technology has now reached a limit beyond which the laws of physics provide an impenetrable ceiling. It is a measure of the ingenuity of science to find another route to higher levels of speed: a new technology to be refined and a new area of physics to be opened for investigation.

**Markys Cain** is leader of the Nanostrain project at the National Physical Laboratory, e-mail markys.cain@npl.co.uk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# Nanocoatings keep water at bay

**Ultrathin polymer and nanostructured coatings are not only setting records for their ability to repel water, but also attracting significant commercial interest, writes Matthew Chalmers**

Of all the reasons given to mobile-phone manufacturers for broken handsets, top of the list are rainwater, toilets and washing machines. But perhaps not for much longer, thanks to nanocoatings that cause water droplets to simply roll off a surface as they might a plant leaf. UK firm P2i has recently installed numerous plasma-deposition machines in Motorola production lines to coat handsets with a tough, splash-proof polymer layer. More than 60 million electronic devices have already been treated using the technique and the company is about to release a "dunkable" coating that will keep a device functioning after being submerged for up to 30 minutes.

P2i, which was spun out from the UK's Ministry of Defence a decade ago, developed a pulsed-plasma deposition process that applies an ultrathin polymer coating onto the internal and external surfaces of mobile devices. The invisible, Teflon-like layer dramatically lowers the surface energy of a material, which makes the water bead and allows "pretty much anything" to be coated with it in a matter of seconds, according to the firm's chief technology officer Stephen Coulson. "It can be applied to any material, such as clothing, shoes and cardboard," he says. "Such coatings also have low liquid retention, so you get less cross contamination between surfaces, and they could also be used for filtration and even to make fire-retardant surfaces."

P2i

**Off you go** A nanoscale polymer film deposited on mobile devices makes water bead and roll off.

Non-wetting technology first garnered attention in the 1930s and 1940s when scientists started to understand how nature does it. Studies of duck feathers, for instance,

# Water-repellent surfaces

revealed the crucial role of trapped air in keeping water off but it also became clear that the microscopic structure of a surface was vital too because it controls the angle that a droplet creates with it. A droplet landing on a textured surface, such as the lotus leaf, has a contact angle of up to 170°, making it almost spherical and classifying the leaf as "superhydrophobic".

Numerous sprays and products have been engineered to mimic the lotus leaf's behaviour, but our ability to characterize and fabricate structures at the micro- and nanoscale has led to an explosion in this subject over the last 20 years, says Kripa Varanasi of the Massachusetts Institute of Technology (MIT) in the US. Texture amplifies the intrinsic wetting properties of a material, allowing researchers to design even more extreme hydrophobic coatings, including those engineered to deal not just with static droplets, but impacting ones.

Last year, Varanasi and co-workers set a new record for superhydrophobicity by structuring materials including silicon, copper and aluminium with ridges that make droplets rebound more easily when they strike the surface. The patterns, which are similar to those found on butterfly wings and nasturtium leaves, minimize the contact time between the drop and the surface, and make the material 40% more hydrophobic than previously thought possible (*Nature* **503** 385). The principle could have important industrial applications in enhanced waterproofing, says Varanasi, for example to reduce the formation of ice on power lines and aero-engine turbines.

## Tough challenge

The main hurdle in getting such coatings widely adopted is to ensure they are durable. The plasma technology used by P2i to coat mobile devices bonds the coating covalently to a material surface, which is hardy enough to survive the rigours of everyday use. But hydrophobic coatings that can withstand the much harsher environment of a steam turbine could deliver massive energy savings because up to 20% of losses in such machines come from tiny droplets settling on the blades and forming a thin film, explains Varanasi. His group is currently investigating the use of special ceramics and other covalently bonded coatings for commercialization in the energy industry, and is also targeting clathrate-proof surfaces for the oil and gas sector.

In 2012 the MIT group founded "Liquiglide" to commercialize coatings that allow 100% dispensing from containers by replacing the air pockets between structured surfaces with a lubricant. The technology, which is due to hit the market next year, generates a very thin Van der Waals film between a product and the substrate allowing consumers to extract every drop of ketchup or toothpaste from a container. "The beauty with this is that you don't have to rely on polymers, you just need a lubricant that doesn't dissolve in your product," Varanasi told *Physics World*.

According to Coulson, who was a PhD student at Durham University in the UK when he invented P2i's polymer-coating technology to provide soldiers with protective clothing, we are on the brink of a smart-coating revolution. Today, P2i has 62 patent families and is focusing on making electronic boards not only hydrophobic but electrically isolating, as well as developing protecting filters that repel water while allowing air to flow. "There are lots of liquid-based solutions out there, but most tend to shrink-wrap a product rather than bind to it," says Coulson. "The key is how you apply coatings and make the process cost-effective."

● P2i's story can be read in full in the inaugural issue of IOP Publishing's new journal *Translational Materials Research* (http://iopscience.iop.org/2053-1613)



# Nano centre eyes up clean energy

**Heiner Linke**, director of the Nanometer Structure Consortium (nmC) at Lund University in Sweden, tells Matthew Chalmers about a new project to develop nanomaterials for energy

### What is the nmC in a nutshell?

The Nanometer Structure Consortium (nmC) engages more than 200 scientists from three faculties to work on interdisciplinary nanoscience. Our scientific focus is on the materials science, physics, chemistry and safety of designed functional nanostructures, and their use in a wide range of applications including sustainable energy, optoelectronics and the life sciences. We have a particularly strong position internationally in semiconductor nanowires based on groups III and V of the periodic table.

### Were you one of the first nanotechnology centres to be created?

The centre was founded in 1988 by Lars Samuelson, who led it until last year, with inspiration from the University of Glasgow and IBM Research in Zürich. In comparison, the US National Nanotechnology Initiative came along about 10 years later, so it is true that we were one of the first centres.


Mikael Risedal

**Clean-energy vision** Physicist Heiner Linke became director of the nmC in 2013.

### How has the group's focus changed?

Throughout the past 25 years, the nmC has consistently emphasized materials science and quantum physics as its core competences. In the first decade, the scientific focus was on self-organized quantum dots and 2D electron gases. Then in around 2000 a conscious decision was made to pursue group III-V semiconductor nanowires, initially with expected applications in nanophysics research but also in electronics and optoelectronics. Over the past five years we have expanded our range of applications to include sustainable energy, neuroscience and other biomedical research. We also added a large nano-safety group that is working to understand the effects of nanowires and other nanoparticles on cells, organisms and the environment to ensure that we will be able to address any safety concerns early.

### How can nanotechnology deliver cleaner energy?

Nanotechnology is about controlling and applying the new phenomena that occur at the nanoscale. In the case of nanowires, there are several such phenomena that are important for energy applications. First, they can be grown in ordered arrays, which allows them to act as photonic systems for more effective light harvesting in nanowire-based solar cells. Second, the small diameter of nanowires lets one combine different materials, even with drastically different lattice constants, into radial or axial heterostructures that may be used to create cheaper multi-junction solar cells and LEDs with higher efficiency and better colour rendering. Third, quantum-confinement effects can be used to tune the energy of photons emitted by nanowire LEDs and to enhance their thermoelectric power output. Finally, the interfaces formed in nanoscale materials can be used to control heat flow in thermal management or to suppress parasitic heat flow in thermoelectrics.

### How will your PhD4Energy project help bring this about?

The project is part of the European Union's Marie Curie Innovative Doctoral Programme and will run for four years. Worth €3.2m (about $4.46m), it will place 12 PhD students at the nmC to work on nanostructures for clean-energy applications. PhD4Energy is important for us because it adds critical mass and engages all parts of our very broad consortium of research groups, helping us to maintain a joint focus. The project ranges from applied research, such as nanowire-based solar cells, LEDs and thermoelectrics, to fundamental research on novel paradigms for nanoscale energy conversion, such as artificial molecular motors. Studies on the safety of nanowires are an integral part of the project.

### What impact do you expect the project to have?

Scientific goals include studying cost-competitive, nanowire-based multi-junction solar cells, high-efficiency solid-state lighting and developing methods to increase the power output from nanoscale thermoelectrics. Each PhD student will also take up an internship with one of the eight firms that are associate partners of the project. In addition, we will collaborate closely with spin-off companies that commercialize nanowire-based devices from our environment. Specifically for LEDs, we have already created Glo and for solar cells we have Sol Voltaics.

### What are the group's long-term plans in energy research?

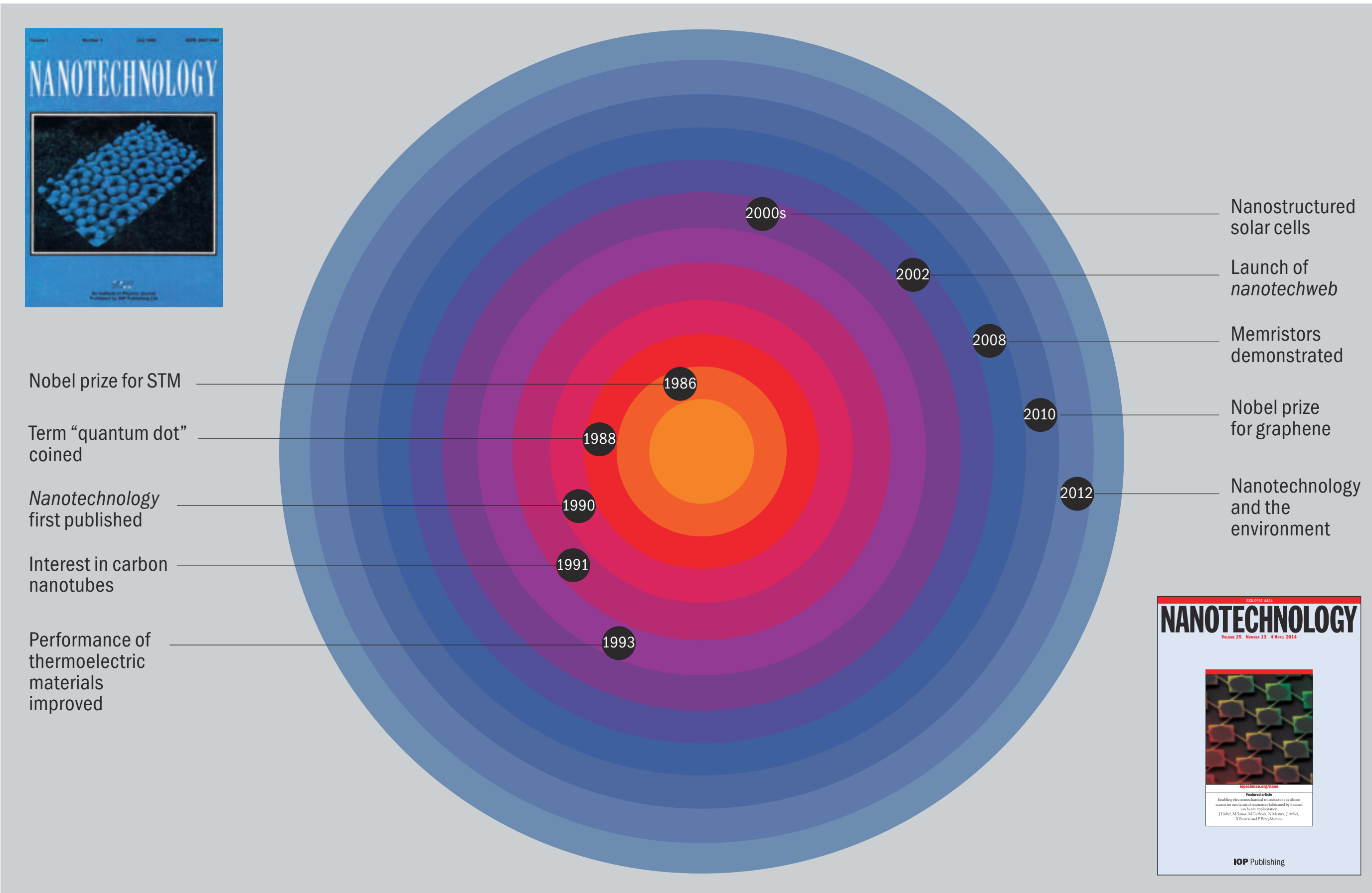
Using this project as a platform, we hope to build a lasting internship programme with many more participating Swedish and international companies. Scientifically, a long-term aim is to develop and then realize entirely new device paradigms that use nanophysics for efficient energy use or for energy conversion.

### Has too much hope been placed on nanotechnology to solve society's problems?

Our group has deliberately stayed away from unrealistic science-fiction dreams of what "nano" could bring – we won't see true nanobots, for example. But the emerging approaches for drug delivery, diagnostics and therapy achieve things that were hard to imagine 25 years ago. Also, the way that information technology has changed our society has only been possible because of nanotechnology. So, I would say that nanotechnology is living up to expectations and will probably even exceed them for some time to come. The important thing is to keep investing in fundamental science along with applied science because real breakthroughs require the combination of both.

# Nanotechnology turns 25

As IOP Publishing's journal *Nanotechnology* celebrates its 25th anniversary, founding editor **David Whitehouse** reflects on the birth and evolution of a new field of science




**Cover story** The journal *Nanotechnology* has tackled key developments in the field for 25 years and currently has around two million full-text downloads per year.

Although nanoscience and engineering had been practised since at least the 1960s, and although Richard Feynman had outlined the physical implications of miniaturization in his famous 1959 lecture "There's plenty of room at the bottom", it was not until 1974 that the late Japanese engineer Norio Taniguchi coined the word "nanotechnology". Taniguchi did not have in mind semiconductor devices and other miniature applications that we associate with nanotechnology today. Rather, he intended the term to describe the predicted accuracies of precision tools by the turn of the millennium.

By the early 1980s, the scanning tunnelling microscope had just been invented and nanoscale electronic-device research was progressing fast at firms such as Texas Instruments, IBM, Fujitsu and Philips. Thin-film technology was at the forefront of applications in microsensors, and terms such as "surface micromechanics" and "microdynamics" were routinely being used to describe the fabrication and performance of sensors smaller than fractions of millimetres, with a growing awareness of the importance of nanosized features and properties. Metrology and manufacturing tolerances were being described similarly, so it can be seen that although there was considerable activity in various disciplines bordering on the nanoscale, there was no clear motivation for bringing the subject "nanotechnology" together in a practical and formal way.

## Birthing pains

There were particular obstacles. From the point of view of traditional mechanical and production engineers, it should have been possible to refine conventional precision-engineering techniques indefinitely to cater for the manufacture of very small parts and to produce finer finishes. Conventional theory too was expected to remain valid in the nano regime.

But these assumptions were not correct. It simply was not realized that material and dynamic properties change with size, and that environmental effects increasingly had to be taken into account when working at small scales. Consequently, there was a growing frustration with our inability to tackle the new challenges, leading me to liken the situation to trying to perform a surgical operation with a blunt instrument on an excited jelly.

It was clear that the new technology was

# History

likely to be much more interdisciplinary than previously, so I decided to take action. Having originally considered writing a book about the subject, my concerns eventually attracted the attention of IOP Publishing, which publishes *Physics World*. And so it was 25 years ago – on 17 March 1989 to be precise – that we decided that a new journal would be an ideal way to propagate and disseminate scientific and technological issues surrounding nanotechnology. The first issue of *Nanotechnology* was published in July 1990 and the second in October of that year. The first article was "Nanoelectronics" by R T Bate of Texas Instruments.

It was, though, very difficult to get authors for the first few issues. Engineers generally did not understand the term "nanotechnology" or were not even familiar with the "nano" prefix. Others did not appreciate its relevance and some, particularly in the electronic and sensor industries, were reluctant to divulge information in the form of technical papers that might jeopardize commercial advantage. Academics – in particular physicists and engineering scientists – were doubtful about submitting papers to a new journal that had no obvious pedigree in terms of subject matter. It was a struggle.

## Beyond expectations

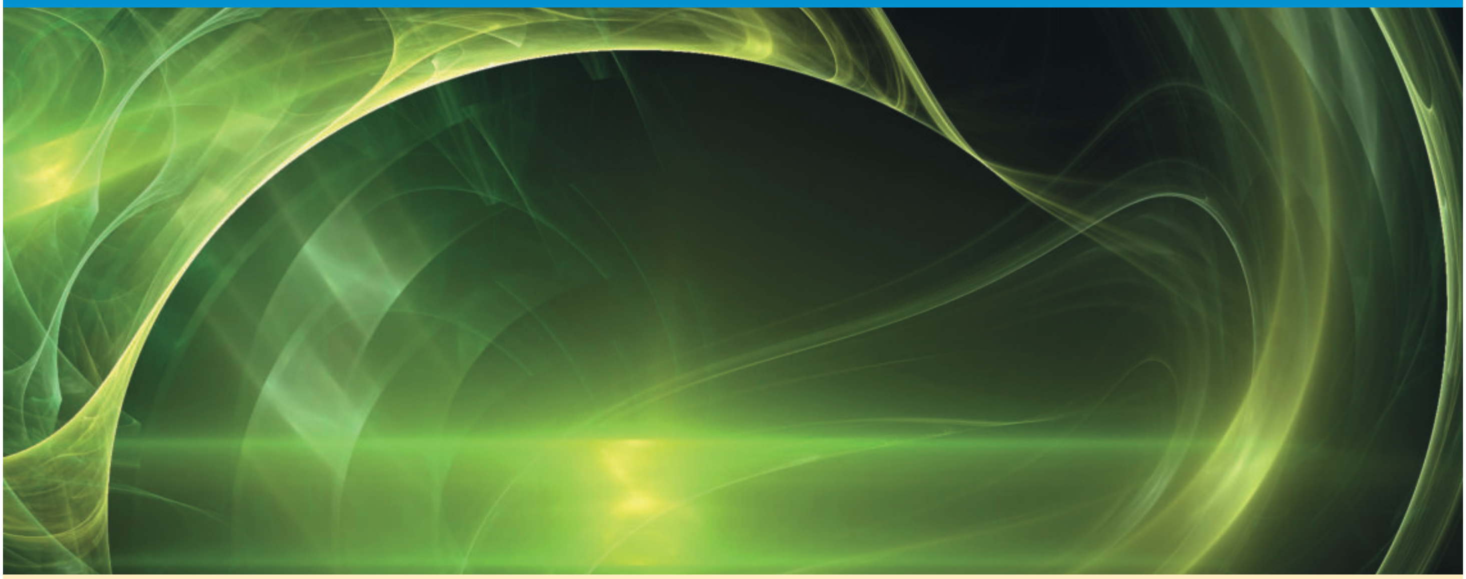
Many of the first papers were concerned with ultra-high-precision technology for instrument design and manufacturing processes, often incorporating optical and X-ray metrology, and surface characterization. Miniaturization began to drive structures and patterning at ever-smaller dimensions in the semiconductor industry, but the emphasis soon began to shift towards molecular and then atomic subjects. The use of quantum mechanics and single electrons or photons might today be routine when explaining nano-behaviour, but it certainly was not back then. The shapes and structures of materials at the nano level, such as rods, wires, ribbons, sheets, tubes, flakes and particles, eventually came to dominate nanotechnology applications – especially those derived from carbon. What is now emerging, however, is the use of 2D atomically thin structures, e.g. for organic electronics. This shift towards 2D rather than 3D materials was not expected, but with hindsight it now seems obvious.

The benefits of small scales are seen most in areas rather than volumes, and this is especially true in medical and biological applications where surface effects are paramount, for example in anti-cancer research and drug transportation. Medicine and biology were not predicted to be of particular interest when *Nanotechnology* was launched, but today they make up a significant proportion of papers in the journal.

The other, more recent, trend is towards environmental and energy issues, as seen in many applications involving solar panels as well as the health-and-safety aspects of nanotechnology. It is also now being appreciated that nanotechnology controls the integration of atomic and molecular properties, for example in composite materials, and that it is the key to understanding the basic functionality of macroscopic structures.

By all conventional publishing yardsticks, it would seem that *Nanotechnology* is not only completely fulfilling its original aspirations, but also exceeding them. An impressive and rising impact factor, an increase in publication frequency from four to 50 issues per year and the fact that the number of accepted papers is a fifth of those submitted all suggest that we can look forward to another 25 years of success.

**David Whitehouse** is Emeritus Professor of Engineering Science at the University of Warwick in the UK and a metrology consultant for Taylor Hobson (AMETEK); e-mail djwhitehouse@sky.com



# Events Diary

**Key meetings, conferences and exhibitions in the nanotechnology calendar**

## 2014

**Graphene Commercialisation & Applications 2014**
Manchester, UK
12–13 June
Focusing on turning graphene into industrial reality, the event will include more than 20 exclusive case studies, including supply scalability, processing ability, integration and other 2D materials.
**www.graphene-applications-summit.com**

**Nanotech 2014**
Washington, DC, US
15–18 June
Billed as the world's largest nanotechnology event, discussions will focus on technology trends, development tools, research and development collaborations, and commercial opportunities.
**www.techconnectworld.com/Nanotech2014**

**International Conference on Nanotechnology for Renewable Materials (TAPPI)**
Vancouver, Canada
23–26 June
TAPPI's ninth annual conference will cover hydrogels, foams, rheological modifies, flexible films, membranes, bioactive materials and more, with a focus on additive manufacturing, 3D printing and other industrial-processing applications.
**www.eiseverywhere.com/ehome/14nano/home**

**Graphene Week 2014**
Gothenburg, Sweden
23–27 June
Get up to speed with the latest graphene research, including fundamental studies of graphene and related 2D materials; applications in electronics, photonics, spintronics and sensing; photovoltaics, energy storage, fuel cells and hydrogen storage; and large-scale graphene production.
**http://graphene-flagship.eu**

**Nanofair 2014**
Dresden, Germany
1–3 July
With the slogan "new ideas for industry", the event will play host to more than 60 international speakers and focus on application-orientated research.
**www.nanofair.com**

**NanoKorea**
Seoul, Republic of Korea
2–4 July
Korea's largest symposium on nanoscale science and technology will present the latest research trends and provide opportunities for institutes to promote the commercialization of their core technologies.
**http://sympoeng.nanokorea.or.kr**

**27th International Vacuum Nanoelectronics Conference (IVNC)**
Engelberg, Switzerland
6–10 July
Devoted to the nanoscience and technology of vacuum electron sources and their applications, the event aims to promote understanding of emission physics and beam properties of field-emitter arrays and nanoemitters.
**www.ivnc2014.org**

**XII International Conference on Nanostructured Materials (Nano14)**
Moscow, Russia
13–18 July
One of the largest international congresses, bringing together scientists and engineers working on nanostructured materials.
**www.nano2014.org**

**International Conference on Nanoscience + Technology (ICN+T)**
Denver, US
20–25 July
Up to 700 participants and 50 plenary and invited presentations will offer an overview of the latest developments in nanoscale science and technology, and scanning-probe microscopy techniques.
**www2.avs.org/conferences/ICNT2/index.htm**

**International Conference on the Structure of Surfaces (ICSOS-11)**
Coventry, UK
21–25 July
Organized by the UK Institute of Physics, the event will assess the current status of atomic-scale and nanoscale structure determination of surfaces, interfaces and nanostructures.
**http://icsos11.iopconfs.org**

**14th International Conference on Nanotechnology (IEEE-NANO)**
Toronto, Canada
18–22 August
The flagship IEEE conference will address the interface of nanotechnology and the many fields of electronic materials, photonics, bio- and medical devices, alternative energy and environmental protection.
**http://ieeenano2014.org**

**Nanoforum**
Rome, Italy
22–25 September
In its 10th year, the event focuses on the latest applications of micro, nano and advanced technologies, and provides an opportunity for scientists to build relationships with potential commercial partners.
**www.nanoforum.it**

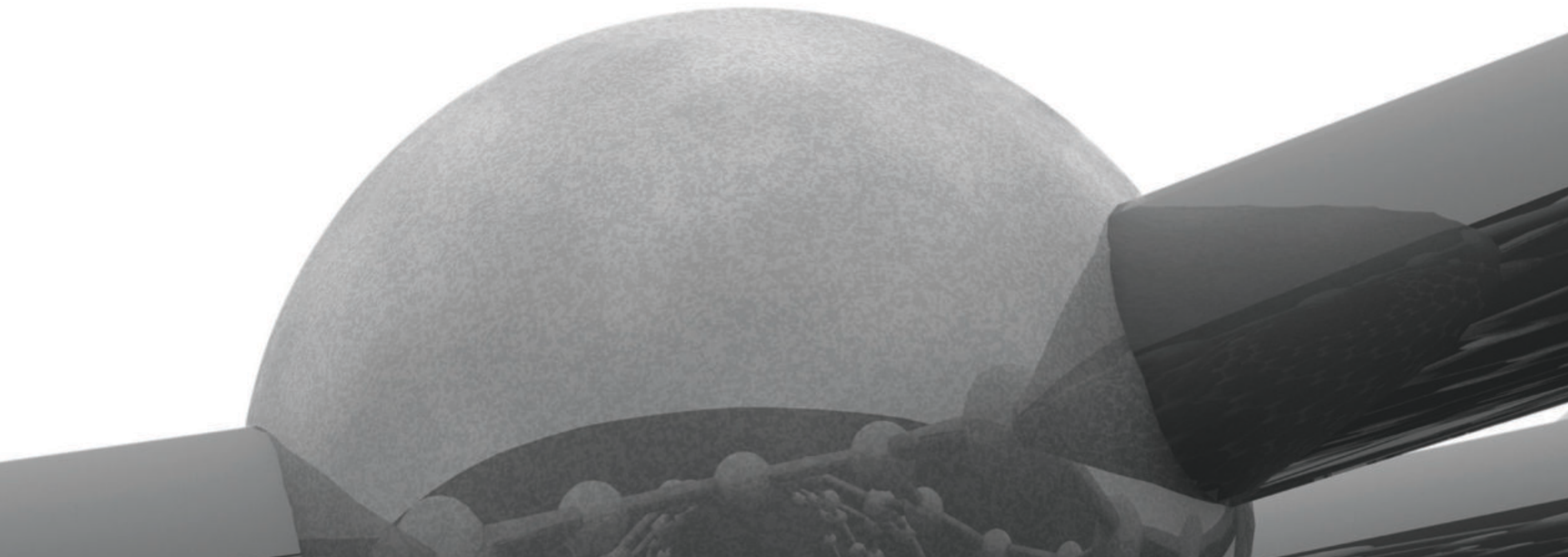
**International Conference on Micro and Nano Engineering**
Lausanne, Switzerland
22–26 September
The 40th event of the series brings together up to 800 engineers and scientists to discuss progress in the fabrication, manufacturing, operation and application of micro- and nanostructures and devices.
**www.mne2014.org**

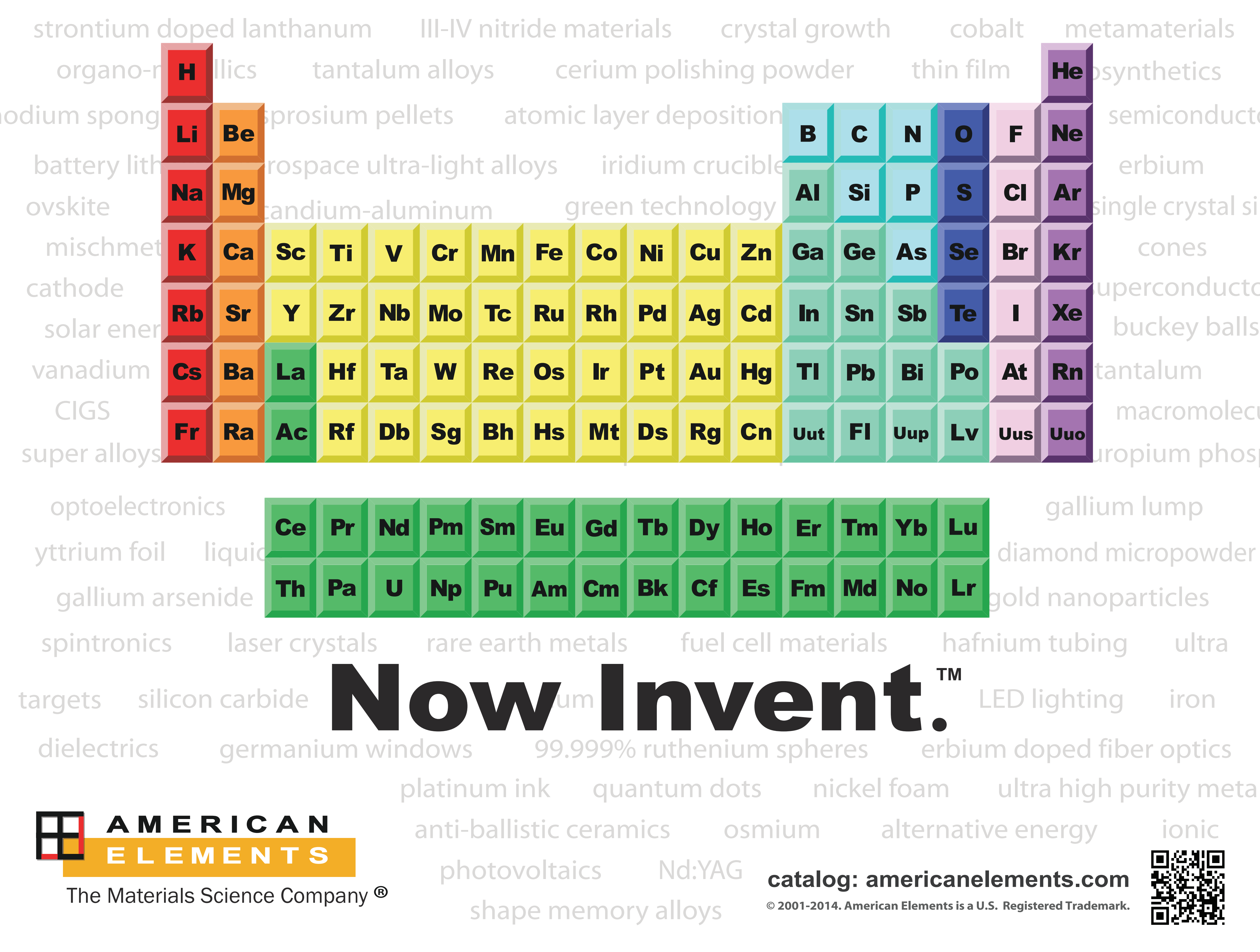
**1st International Conference on Two-Dimensional Layered Materials**
Hangzhou, China
12–15 October
The event will cover all 2D materials, focusing on graphene, silicone, germanene, transition-metal dichalcogenides, and group-IV and group-III metal chalcogenides.
**www.2dmat.net/**

**Nanosafe14**
Grenoble, France
18–20 November
Topics will include new applications of nanomaterials; exposure, detection and characterization; toxicology; environmental interactions; nanomaterials release; industrial production; and commercial issues.
**www.nanosafe.org**

**NanoThailand 2014**
Pathumthani, Thailand
26–28 November
With the theme "nanotechnology for better living", the focus will be the integration of engineering, materials science and nanotechnology.
**www.nano-thailand.com**

**MRS Fall Meeting**
Boston, US
30 November – 5 December
One of the biggest events in the materials calendar, including topical sessions on biomaterials and soft materials, electronics and photonics, energy and sustainability, nanomaterials and synthesis.
**www.mrs.org/fall2014/**





strontium doped lanthanum
III-IV nitride materials
crystal growth
cobalt
metamaterials
tantalum alloys
cerium polishing powder
thin film
atomic layer deposition
iridium crucible
green technology
erbium
cones
cathode
vanadium
CIGS
tantalum
optoelectronics
gallium lump
yttrium foil
diamond micropowder
gallium arsenide
gold nanoparticles
spintronics
laser crystals
rare earth metals
fuel cell materials
hafnium tubing
ultra
targets
silicon carbide
LED lighting
iron
dielectrics
germanium windows
99.999% ruthenium spheres
erbium doped fiber optics
platinum ink
quantum dots
nickel foam
anti-ballistic ceramics
osmium
alternative energy
ionic
photovoltaics
Nd:YAG
shape memory alloys
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
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