Condensed matter
Foreword

Physics and physicists play a vital role in underpinning our way of life, improving its quality and contributing in a major way to wealth creation. Innovations as powerful and diverse as the World Wide Web and magnetic resonance imaging (MRI) have emerged from studies in basic physics, becoming everyday technologies in just two decades. It is, therefore, a worthwhile challenge to speculate where similar explorations today will lead us in the future.

This booklet, the first in a series covering the main areas of physics, attempts to do just that: highlight and showcase world-class UK work that has the greatest potential for commercial exploitation. It is jointly sponsored by the Institute of Physics – the professional body and learned society for physics and physicists – and the Engineering and Physical Sciences Research Council (EPSRC) – one of the largest UK funders of physics research.

We hope that this booklet illustrates how the research investment made by the EPSRC and the support provided by the Institute to its membership, will enable the UK’s economy, and society at large, to benefit from the discoveries and advances in physics being made.

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Physics is the study of Nature at its most fundamental level; it involves developing detailed mathematical descriptions of how matter and energy are organised and behave – from the microscopic to the cosmic scale. Practical applications can then be developed from the insights gained.

The science of everyday materials
Condensed matter research represents one of the most important areas of physics. It covers both solids and liquids, and the aim is to understand their bulk physical properties in terms of the structure and behaviour of the atomic or molecular constituents. Many of the everyday materials and consumer items on which we now depend have been developed as a result of knowledge attained through this kind of approach.

Electronic materials
Condensed matter systems are often extremely complex. They may be solids with crystalline structures in which the atoms or molecules are arranged in orderly arrays, for example diamond, metals, minerals and many organic materials. The electrons constituting their atoms may show a bewildering variety of behaviour such as magnetism, electrical conductivity, superconductivity and optical properties, all of which can be exploited technologically.

Physicists continue to uncover unusual structures with unexpected electronic behaviour. For example, in the past 20 years, a series of copper-oxygen ceramic compounds were discovered to be superconducting (conduct electricity without resistance) at temperatures that could be reached by cooling with liquid nitrogen. Previously, superconductivity had been seen in a few metals, alloys, and exotic materials but only at temperatures not much above absolute zero. When the first discovery was made, it took everyone by surprise and caused great excitement. A huge amount of research has since gone into understanding these materials. Even now, theorists do not have a detailed understanding of how higher-temperature superconductivity works. Materials scientists also have been investigating the best way of processing the ceramics into wires and other physical shapes for applications. The work is exciting because the economic pay-off is potentially enormous, offering the prospect of cheaper, greener, more efficient power transmission, travel and communications.

Many of the materials with unusual electronic properties result from manipulating their crystal structures in some way, such as replacing or removing single atoms to create what are called defects. The semiconductor devices – memories and processors – found in computers and mobile phones have evolved from a profound understanding of the underlying physics of such structures.

Glasses and plastics
Other materials have a completely disorderly structure, forming solid ‘glasses’ or liquids. Understanding how a glass melts into a liquid may be important in determining its robustness and usefulness, or method of manufacture. Polymers such as polythene consist of
long chains of carbon atoms arranged randomly, making the material soft and flexible, but they can also have regions of crystallinity which impart hardness. Being able to control the arrangements of the chains, and how they move when they start to melt, is essential in the industrial processing of plastics.

Complex fluids
A field of growing commercial and medical importance involves liquid or gel-like materials called colloids containing many different kinds of molecules which may be self-organised into minute particles with a complex structure tailored to produce required physical and chemical properties. The average washing-up liquid, paint or cosmetic is extremely sophisticated in design, to give the characteristics the consumer wants.

Nanotechnology
Increasingly, condensed matter physicists are able to engineer structures in solids and liquids at the scale of nanometres (billionths of a metre), when individual atomic and molecular interactions become significant, and the system behaves according to the laws of quantum mechanics. Today, much of condensed matter research is focused in this area.

This booklet describes six examples of cutting-edge research carried out in the UK, much of it at the nano-scale:

- A novel type of fast nano-electronics based on carbon.
- New electronic devices exploiting the spin of the electron.
- Current efforts to make the smallest possible transistor.

A vibrant area
All of the work involves theorists who predict how potentially useful physical systems will behave, as well as experimentalists who make and characterise them. This often requires high-performance computing, and advanced fabrication methods and analytical techniques.

Although some of the fundamental research that physicists carry out may seem far removed from commercial application, it has proved notoriously difficult to tell where individual lines of enquiry will eventually lead and what discoveries may be made. The fabrication of graphene and of carbon nanotubes (p.6) are just two more recent examples of exotic structures originally discovered by accident in the laboratory, which have huge technological potential. Condensed matter research is a very vibrant area and we can expect many more similar surprises.

Condensed matter research has produced:
- Computer hardware
- Mobile phones
- Flat panel televisions
- CDs and DVDs
- CCD digital cameras
- Supermarket scanners
- Energy-saving 'K' glass
- Batteries
- Solar cells
- Dishwasher-safe tableware
- Advanced shampoos and cosmetics
- Modern cleaning materials
- Thiocatic paints
- Advanced fuels
- Composite materials for furnishings, building, transport and sport
- Daily contact lenses
- Medical implants
- Miniature hearing aids
- Medical analytical equipment
- Medical imaging scanners

PHYSICS FOR FUTURE TECHNOLOGY research and why do we need it?
n important characteristic of particles just a few nanometres across is that they are of the right scale to interact with biological molecules and living cells in a specific and guided manner. Metal nanoparticles, in particular, possess physical characteristics that make them ideal diagnostic probes or even therapeutic agents. A number of UK research groups are focusing on developing novel strategies involving gold, silver and magnetic nanoparticles to aid the treatment of disease.

Gold and silver owe their colour and shininess to oscillations of free electrons on their surface called plasmons which control how light is reflected. The plasmon frequency is also affected by the size and shape of the metal surface. Consequently gold nanoparticles are deep red but change to blue when the particles cluster into larger objects; for silver particles the colour change is from yellow to orange. David Russell at the University of East Anglia has been exploiting this effect to develop a test for detecting bacterial toxins such as cholera toxin. Gold nanoparticles are attached to carbohydrate molecules designed to recognise the toxin. When the carbohydrate binds to the toxin, the gold particles aggregate and the colour changes.

DNA multi-probes

A team at the University of Strathclyde led by Duncan Graham has developed a particularly sensitive biomedical sensor based on the fact that the plasmons of silver-nanoparticle aggregates enormously enhance the characteristic wavelengths of light scattered from an attached probe molecule – an effect called surface enhanced resonant Raman scattering. The silver particles are coated with a DNA sequence designed to bind to a specific target biomolecule or gene. When the particles recognise their target, they scatter the light illuminating them at a different wavelength which is then detected. The probe is sensitive and discriminating enough to be used in the clinic to identify several types of DNA simultaneously and could be used to diagnose sexually transmitted infections in urine samples simply and quickly.

Another type of multi-tasking DNA probe is being developed by Tracy Melvin and Tom Brown at the University of Southampton. It is based on gold nanoparticles and semiconductor quantum dots (p.9) combined to create an optical ‘nano switch’. Cadmium sulphide (or selenide) quantum dots fluoresce with a wavelength that depends on their size. However, on contact with gold nanoparticles, the fluorescence is switched off. The principle is to attach a strand of the target DNA to the quantum dot, and then link the DNA strand with the complementary base sequence to a gold nanoparticle. When mixed so that the strands...
bind, the light emission is turned off. If complementary DNA is then introduced from a clinical sample, it displaces the gold-linked DNA sequence and light emission is switched on again (see figure opposite left).

Dr Melvin aims to use the probe to detect the small amount of DNA that is shed into the bloodstream from a tumour. Cancer diagnosis usually involves a biopsy – an uncomfortable and time-consuming process, and there is no instant way of telling whether the cancer has spread to other tissues. By incorporating quantum dots that emit at different wavelengths, the technique can be adapted to detect DNA sequences from several cancers simultaneously in a blood sample, thereby considerably speeding up therapeutic intervention.

Cancer treatment
Gold nanoparticles could also be used to make cancer radiotherapy quicker, more effective and cheaper. David Hirst, Fred Currell and their interdisciplinary team at Queen's University Belfast are building a prototype X-ray system based on the principle that tumours have very porous blood vessels which preferentially accumulate injected metal particles. Gold atoms readily absorb X-rays of particular energies, releasing a shower of electrons. Unlike X-rays, they travel only a short distance before wreaking havoc on the surrounding tissue, in this case the tumour; in effect, each nanoparticle has a ‘sphere of destruction’ around it. Using gold nanoparticles in conjunction with tailored X-ray beams would reduce the number of treatments needed, as well as limiting damage to surrounding healthy tissue, which are notoriously difficult to treat. Dr Currell envisages a portable machine that could be transported to clinics to deliver ‘therapy in a lorry’ so making radiotherapy more accessible and less traumatic for patients.

Magnetic medicine
Magnetism is another property of metals that is being exploited in medicine. Magnetically responsive nanoparticles are already used as contrast agents in magnetic resonance imaging (MRI). Now, researchers are considering how to apply them to deliver drugs and even genes into cells. Jon Dobson of Keele University has been attaching DNA sequences, which express a target protein, to nanoparticles with iron-oxide cores, and then using an oscillating magnetic field to encourage cells to take up the DNA. In a further project, his research group is exploring how to deliver the corrected cystic fibrosis gene into the lungs of a sufferer using an external magnetic field to pull the nanoparticles through the thick mucus typically secreted by the lung tissue. The patient would lie on a table with an oscillating-magnet array underneath and inhale the particles from a nebuliser. Another application, which his team is investigating, is tissue engineering. By attaching molecules that recognise specific ion channels in cell membranes to magnetic nanoparticles, various cellular processes can be regulated to activate, for example, the formation of bone or cartilage.

Quentin Pankhurst at University College London is using magnetic nanoparticles in another way. An exterior magnetic field can be manipulated such that it heats up the particles enough to kill targeted cancer cells. He is also commercialising a simple system for detecting whether breast cancer has spread into the lymph nodes. The paths of magnetic particles, tagged with molecules that recognise cell receptors specific to cancer cells, can be followed by passing a magnetometer over the patient. A surgeon would use the hand-held device to check whether lymph nodes need removing – a painful procedure for the patient – as well as the breast tumour.

None of these developments could happen without the combined efforts of physicists, chemists and life scientists. This burgeoning area of nanotechnology typifies how understanding the basic physics and properties of matter underpins applications that can improve the quality of life.
Carbon is the most chemically versatile of all the elements and is, of course, the basis of life. It exists in many forms – the two most well-known being diamond, a three-dimensional network of single bonds; and graphite, a two-dimensional hexagonal network of electron-rich double bonds arranged in layers. Graphite is the most common and most stable form, and found in coal and soot. Despite the fact that it is known to conduct electricity along the layers, it is only recently that graphite’s potential as an electronic material has come to the fore. Recent research has uncovered that the basic chicken-wire network – graphene – can exist in architectures with a rich and surprising array of properties that could lead to a new generation of carbon-based electronic and photonic devices.

Nanotube devices

The structures that first excited interest were the fullerences – amazing football-shaped molecules of 60 and 70 carbon atoms discovered in 1985. Made from hexagons and pentagons of carbon atoms, they form hollow structures that can encapsulate metal atoms to become electrically conducting or even superconducting.

Six years later, another carbon variant was discovered, in which graphene sheets are rolled up into concentric nanotubes capped at each end with a fullerene structure. Nanotubes can be single or multi-walled, with diameters from 1 to 20 nanometres (nm) and up to hundreds of micrometres long. They offer exciting technological possibilities, in combining the strength, lightness and chemical stability of carbon with the high electrical and thermal conductivity of a metal. The tubes are long and thin, allowing electrons to zip down them with little encumbrance. The single-walled nanotubes can also be either metallic or semiconducting depending on the way in which their graphene sheet has been rolled up.

It is no surprise, therefore, that carbon nanotubes are candidates for wire connects and logic devices in future nanoelectronic circuits. The bulk materials are already commercially available, prepared from a carbon source by either an electric arc discharge, laser ablation or chemical vapour deposition. However, exploiting individual nanotubes for electronics requires improved methods of production to control their size and structure.

Bill Milne and researchers at the University of Cambridge have been optimising the control of the growth and positioning of nanotubes using the chemical vapour deposition method in which a metal catalyst decomposes a hydrocarbon at high temperatures. The catalyst acts as a template for the forming nanotubes so that altering the size of the catalyst particles and the reaction time controls their diameter and length. Working in collaboration with the UK innovation company Thales Research and Technology, the team has applied the method to produce a neat forest of vertically aligned nanotubes directly integrated into microcathodes, tiny devices that release electrons. They can be grown at a height and spacing such that when a voltage is applied, an
intense stream of electrons is emitted. The ‘forest’ can be used in field-emission displays (flat screens in which an array of minute cathode-ray tubes provide the display elements), and the emission from an individual nanotube can be applied in an electron microscope. Because of the huge current-carrying capacity of nanotubes, such cold-cathode electron sources promise to be much more efficient than current systems relying on thermionic emission. One immediate application that the team is working on is a small, lightweight microwave amplifier for satellite communications.

The semiconducting nanotubes have energy levels comparable to those in silicon and gallium arsenide, and could be employed in optical applications including sensors and photovoltaic cells. Robin Nicholas’s group at the University of Oxford has been studying how to achieve this by looking at the way the emission and absorption of light is affected by the nanotubes’ chemical and physical environment. As well as external factors such as magnetic fields, strain, temperature and pressure, the properties of the tubes can also be controlled by inserting molecules inside them. Oxford researcher David Britz and colleagues have even managed to perform chemical reactions inside nanotubes, taking them into the Guinness Book of World Records by making the world’s smallest test-tube (main image, opposite page). They inserted fullerene molecules to form a ‘peapod’ structure and then showed that the fullerenes would polymerise to form a long chain only when inside a nanotube.

**Ultrafast transistors**

While some physicists have been exploring the potential of nanotubes, others have been studying the fundamental two-dimensional building material for graphite and nanotubes – graphene. Although long-studied as a theoretical model and used to explain properties of other graphitic materials, graphene itself was thought to be too unstable to exist. However, three years ago, physicists at the University of Manchester led by Andre Geim made free graphene for the first time in a surprisingly simple way. They used an adhesive tape to peel off a one-atom-thick layer from a graphite surface – the equivalent of drawing with a graphite pencil.

The graphene crystals obtained were good enough to reveal some bizarre behaviour, which has got the attention of both theorists and experimentalists, rapidly becoming one of the hottest research topics in physics. The unusual quantum characteristics of graphene’s electronic structure result in the conducting electrons behaving like massless particles (like photons with an electric charge). The electron mobility is thus enormous and offers a real possibility of making ultra-fast transistors based on the motion of individual electrons without scattering (ballistic electrons). Graphene may also find use in spintronics (p. 10), in field-emitting devices, and as gas sensors since it absorbs gas molecules which then alter its resistivity. Researchers are already looking at the feasibility of patterning electron microprocessors on a single graphene sheet. This is a brand new field of research and we can expect many exciting developments in the next few years.

**Superconducting graphite**

While graphene was revealing its potential, another curious side of graphite’s electronic character has been uncovered. Mark Ellerby, Tom Weller and Neal Skipper at University College London made two new compounds of graphite, with ytterbium (C6Yb) and calcium atoms (C6Ca) sitting between the graphene layers. With Montu Saxena and Rob Smith at the University of Cambridge, they discovered that the two materials became superconducting (lose electrical resistance) at temperatures of 6.5 and 11.5 kelvin respectively. Although superconductivity had been seen in previous similar compounds with intercalated potassium and lithium, their superconducting transition temperatures were very low. Superconductivity in the calcium compound was particularly unexpected and has provided a challenge for the theorists. Dr Weller, now working with Steve Bennington at the Rutherford Appleton Laboratory near Oxford, is exploring how to manipulate the electronic properties of graphite further by introducing defects into the structure, perhaps inducing magnetic behaviour. There is already some evidence that carbon can be magnetic. With the potential to replace metals, semiconductors, superconductors and magnets – all on the nanoscale – carbon may truly be the new wonder material of the age.
In the past 20 years, semiconductor lasers have become ubiquitous. They are found in supermarket scanners, CD players and computer printers. The field is still moving fast – recent developments are the result of a reduction in the size and dimensionality of the light-emitting device. The next generation of lasers will be based on minute semiconductor structures called quantum dots.

Quantum dots are typically only 10 to 50 nm across and contain just a few hundred or thousand atoms. They are designed to confine the movements of the electrons responsible for semiconducting activity within the dot. The result is an object with electrons trapped in discrete quantised energy levels, as in an atom. These electrons can be excited into higher energy states, at the same time leaving behind a positively charged ‘hole’. Recombination of the electron-hole pairs results in the emission of light whose wavelength depends on the size, shape and configuration of the dots.

Quantum dots form when a very thin film of one semiconductor is fabricated on the surface of another with a slightly different crystal-lattice size, for example, indium arsenide grown on a substrate of gallium arsenide (InAs/GaAs). The mismatch creates stresses which cause the film to buckle and form tiny three-dimensional blobs. Further layers of the semiconductors can be grown on top to build up a lasing device comprising several layers of millions of dots.

Lasers for optical communications
Quantum-dot lasers are more stable and use less power than the current generation of so-called quantum-well lasers (in which the electrons are confined in two-dimensional layers); they can also be made cheaply (an important consideration for the consumer electronics market) and the frequency output is more stable. They are also less affected by temperature. This is an advantage in one potential use: in optical communications, which may be subject to a variety of environments. This application relies on laser pulses operating at 1300 and 1500 nm – the wavelengths at which light dispersion and attenuation respectively are minimised in optical fibres. Research groups both in industry and academia are striving to attain these wavelengths with quantum dots, and 1300-nm quantum-dot lasers are just starting to become commercially available.

The quantum-well lasers currently used to couple light into optical fibres are based on indium phosphide (InP), but teams involving Ray Murray at Imperial College London and Maurice Skolnick at the University of Sheffield are working with InAs/GaAs quantum dots which have the advantage of being easily integrated onto the same gallium arsenide chips as the electrical drive circuits. By manipulating the size and composition of the dot, the researchers have demonstrated lasing at 1520 nm in different quantum-dot systems. According to Professor Skolnick, covering...
the quantum dots with a thin layer of gallium arsenide doped with antimony could increase the wavelength further. University research groups at Sheffield, Oxford and Cambridge are also working on indium gallium nitride quantum dots which emit blue and violet light.

Peter Smowton’s group at Cardiff University is studying indium phosphide/gallium phosphide quantum dots, in collaboration with Sheffield. These structures can produce lasing action at shorter wavelengths between 650 and 780 nm. He points out that quantum dots can be manipulated to emit over a range of wavelengths, so can be used to create ultra-fast or tunable lasers. They are ideal for integrating onto a single multi-functional optoelectronic chip, and work is underway to develop them as ‘lab on a chip’ devices for medical and biosensing applications.

Because the distribution of electrons in the energy levels can be tailored, quantum dots can also be made to lase at two wavelengths simultaneously. This could be useful in producing single-chip devices for the next generation of DVD players, which would then remain compatible with old designs requiring lasers working on a different wavelength. His team is working on this idea with a local company, IQE Europe.

Beating bank fraud

The versatile nature of quantum dots and their ease of manufacture will lead to many applications other than lasers, such as optical amplifiers in integrated optical circuits and superluminescent light-emitting diodes that emit over wide wavelength ranges. However, exploiting the quantum properties of these structures will result in applications in IT that are simply not possible today. Because a quantum dot holds just a small number of electrons and holes, it can be used to generate photons one by one. Sending signals coded upon single photons makes possible completely secure communication over an optical fibre network – useful to organisations needing to send sensitive information, such as banks, large companies and government departments.

Researchers led by Andrew Shields at Toshiba Research Europe Ltd in Cambridge, together with the University of Cambridge and Imperial College London, in a project funded by the DTI Optical Systems for the Digital Age programme, have successfully demonstrated single-photon quantum cryptography. This seeks to distribute securely a digital key (a string of 1s and 0s) that can be used to scramble information communicated between parties. If the key is encoded upon a stream of single photons, then it is impossible for a hacker to tap into the stream without destroying its integrity in a detectable way.

An even more intriguing way of sending information securely is to create pairs of photons whose quantum properties are ‘entangled’ such that, even when they are far apart, any changes made to one photon, for example in its orientation, also affects the other. The Toshiba group recently used quantum dots to generate pairs of entangled photons. They behave like single photons of half the wavelength (and thus twice the energy) and could therefore be useful for high-resolution microscopy or to define finer features on a semiconductor chip.

More speculatively, such linked quantum states are a key feature of quantum computing – a potentially powerful way of encoding and processing large amounts of information. Quantum dots offer several potential routes to generating the required coupled states, or qubits. In one approach, the qubit consists of coupled spins of electron-hole pairs in neighbouring quantum dots.

In another intriguing proposal, being explored at Sheffield, spin-encoded electrons injected into a quantum dot can switch the spins of the nuclei on and off. This could lead to a completely different type of spin-based memory suitable for quantum computation (see diagram below).

Large-scale quantum computers may be far from realisation but the quantum-dot architecture offers one of the most plausible approaches. In the meantime, the next few years should see some significant commercial applications of the quantum-dot technology being developed now.

Quantum-dot nanocrystals

The structures described in the main text are called self-assembled quantum dots because of the way they are formed. Nanocrystals of semiconductors such as cadmium sulphide or cadmium selenide in colloidal suspension also form quantum dots which emit light with a wavelength that depends on their size. They are already used as markers in biological analysis (p. 4) and show promise as elements in colour displays.
he past 10 years has seen a revolution in electronic storage capacity. The latest devices such as the iPod rely on magnetic technology that can store 100 million times more data than was possible on a computer hard disk of 50 years ago.

Memory devices rely on recording and storing data as magnetised domains in metallic films. The magnetism is the result of the electrons in the material having a quantum property called spin which can be oriented ‘up’ or ‘down’. As the disk turns, a read-head above detects the minute magnetic field changes resulting from the two possible magnetic orientations of the domains. This produces corresponding variations in the head’s electrical resistance – an effect called magnetoresistance.

In 1997 IBM introduced a new type of read-head based on another effect, discovered only a few years before, called ‘giant magnetoresistance’ (GMR); with GMR, the change in electrical resistance is 10 times as great. GMR is seen in ultra-thin layers of magnetic materials such as cobalt interleaved with a layer of a nonmagnetic metal such as copper. A current passing through the layers consists of spin-up and spin-down electrons, and those that are aligned with the electron spins in a magnetic layer pass through much more easily than those aligned in the opposite direction. When the spin orientations in the layers are the same, more electrons pass through than when they are oppositely aligned. If the alignment in one layer is altered by a nearby magnetic field, the resistance changes quite dramatically. Today, all computer disks are based on very sensitive spin-filter devices that work on this principle.

More powerful computer memories

Physicists are now exploring other ways of manipulating electron spins to create a new generation of ‘spintronic’ memory and circuit elements. They promise to be smaller, more robust and more versatile than the current generation. The first application has been to devise magnetic random access memory (MRAM) chips, which have the advantage of being ‘non-volatile’ – information is not lost when the computer is switched off. MRAM chips started to be manufactured in 2004 and further design improvements are continuing apace.

A particular type of MRAM based on a ‘magnetic tunnel junction’ (MTJ) has received much attention. An MTJ consists of two magnetic layers separated by a thin insulating layer through which electrons can tunnel depending on their spin orientation (see diagram, left). This produces an even bigger change in resistance of up to several hundred per cent. Bryan Hickey’s group at the University of Leeds is leading a UK consortium researching into spintronics, which also involves industry, called Spin@RT. One of the goals is to study and improve MTJ technology. The first devices used aluminium oxide as the insulator, but now magnesium oxide has been shown to produce much larger changes. MTJs are already in the marketplace in new hard-disk read-heads.

The researchers are also working on a newer technique which exploits a current of electrons with aligned (polarised) spins, instead of a magnetic field, to reverse the spins in a magnetic layer. With this spin-transfer approach it would be possible to write (and read) data on structures as small as 60 nm (not easily achievable with magnetic fields), and to create a...
spintronic-based switching device.

The possibility of manipulating spins with an electrical current offers the prospect of developing magnetic logic devices. However, MTJ devices would require high switching currents. A simpler logic element might be based on a moving interface – a domain wall – between two regions of opposite magnetisation, with the 1s and 0s needed for binary logic represented by the opposite directions of propagation. Russell Cowburn at Imperial College London has developed a complete set of domain-wall logic elements using flat magnetic nanowires of a nickel-iron alloy. The shape of the wires ensures that domain walls travel along the wires when an external magnetic field is applied. He envisages that the wires could be built into complex three-dimensional networks with a neural network architecture for processing, or for dense memory storage (inset top right). A solid-state three-dimensional data storage device of the type envisaged by Professor Cowburn would have sufficient storage capacity to replace the hard-disk drive in laptop computers, and would bring enormous data-storage capacity to mobile phones.

While he is already looking to commercialise his novel devices, his team is continuing to explore the properties of other magnetic materials that might work better.

Imaging magnetic structures

In all these devices it is essential to characterise their structure in order to understand the factors that affect their efficiency. John Chapman’s team at the University of Glasgow has been developing a type of electron microscopy that images magnetic structures. It is based on the idea that a beam of electrons is deflected by a magnetic force; the deflections can then be processed and translated into quantitative maps of magnetic induction. The technique allows the researchers to see into very small structures of about 100 nm, such as domain walls and various device components, at different temperatures and under different magnetic field strengths. Using another type of microscopy in which an electron beam scans the sample with a resolution of 0.2 nm, they can also study the interface regions of magnetic layers, from which they learn more about the efficiency of the spin-filter process and its relation to the position and chemistry of the atoms present.

While work on metal-based magnetic materials has progressed rapidly, industry would ideally prefer to combine memory and processing by integrating spintronic technology onto a single semiconductor chip. Finding a suitable magnetic semiconductor is a tough challenge. Many university research groups, including teams at Nottingham, Sheffield, and Cambridge are working on materials which introduce magnetic atoms such as manganese and cobalt into a semiconductor. Bryan Gallagher and colleagues at Nottingham have pushed the transition temperature of the well-understood material, ferromagnetic semiconductor gallium manganese arsenide, up to 173 kelvin, and are exploring several promising routes to increase it.

Researchers are already investigating candidate nano-spintronic devices. New device concepts such as the magnetic-field controllable single-electron transistor developed by Jörg Wunderlich at Hitachi Cambridge Laboratories and the Nottingham group could find their way into conventional ferromagnetic metal systems quite soon. Dr Wunderlich is also working on another interesting effect with potential, which involves separating spin-up and spin-down electrons in a semiconductor by passing a current. It is a variation of the classic Hall effect whereby electrons are deflected to one side of a conductor by passing a current at right angles to a magnetic field. In the ‘spin Hall’ version, electrons with opposite spins accumulate on opposite sides of a gallium arsenide strip. They can then be siphoned off to create spin-polarised currents for use in spintronic devices.

Researchers are looking ahead to using spin-based technology in the nano-electronics of the future. These might involve injecting spin-polarised electrons into molecular devices such as nanotubes (p.6) or trapping them in structures such as quantum dots for applications in quantum information processing (p.9). The potential of spintronic technology clearly stretches far ahead.
Over the past decade or so, understanding the motion of everyday materials such as polymers and emulsions has become an increasingly important field of study. The aim is to link the structural properties of so-called ‘soft matter’ at the microscopic level to its dynamic behaviour in a predictable way. The theories developed can then help industry to make materials such as polymers and emulsions more efficiently, as well as to design novel structures for specific uses.

Soft matter comprises a wide range of familiar materials – from plastics to the gels and thick liquids associated with foods, cleaning materials, paints and cosmetics. Biological structures such as cell walls are also complex forms of soft matter. They all have one thing in common: their basic components – which may be clusters of atoms, very large molecules or complex molecular assemblies – form structures on a scale of 10 to 100 nm, which are held together by quite weak forces. This means that under everyday conditions they are very sensitive to increased pressure, shear forces and to small changes in temperature.

Understanding plastics

Amongst the most studied forms of soft matter are polymers. These are long-chain molecules, which may be randomly arranged and entangled, or crystallised into more ordered arrays. On heating, the chains become more mobile, and the material becomes softer (hence the name plastic) – eventually melting. Understanding exactly how the chains move – whether they stretch out or become more entangled – is particularly important in their industrial processing, as it affects properties like viscosity, and therefore the rate at which the material flows. These characteristics also determine the final structure, and thus the strength, of the solidified product.

The basic theory of polymer dynamics was developed more than 30 years ago by the UK physicist Sam Edwards, together with fellow Nobel Laureates Pierre-Gilles de Gennes and Masao Doi. They imagined each polymer chain as snaking through a tube created by the spatial confinement imposed by neighbouring chains. Other processes are also involved: the free ends of the chains can flip back into the tube; and under strong flow conditions, parts of the tube may rapidly reconfigure as neighbouring tangles of chains move in and out of the way.

The bulk movement of a melted polymer is deeply influenced by its composition and structure – the range of chain lengths in the melt, and the degree and type of chain branching. For instance, although the strength of polythene is improved by keeping all the chains the same length, the resulting unstable flow properties mean that it processes poorly. Introducing a few branched chains makes it flow much better.

Tom McLeish at the University of Leeds and a collaboration of theorists and experimentalists from
eight university groups have been exploring why. They have extended the tube description to show theoretically how the flipping-back behaviour of free ends in any branched chains present helps to untangle the polymer and improve the flow. They predicted that even H-shaped chains, which have a central cross-bar with no free ends, would disentangle in strong flows because the arms of the ‘H’ can withdraw back into the tube occupied by the crossbar in a kind of breathing-in action. The ideas were probed experimentally using both optical and neutron scattering (like X-ray diffraction, they can map structure at molecular scales), which identified signals from these and other subtler molecular motions. These kinds of detailed predictions about the microscopic dynamic behaviour of polymers open up the way to optimising manufacturing processes to match a particular product, and vice versa, in advance of expensive process-development trials at the pilot-plant stage.

The physics of yoghurt
Another set of soft materials with complex flow properties are colloids – minute solid particles, or liquid droplets of one phase suspended in another. Because colloidal suspensions are often not at equilibrium (they are stuck in a metastable state), they behave in even more exotic ways than polymers. They can suddenly solidify when a shear force is applied or when cooled – undergoing what is called structural arrest. This ‘jamming’ when flowing down a pipe can be a problem in processing. The stability (shelf-life) and flow of colloidal structures are also key in developing and selling many consumer products including yoghurt, vaccines and paint.

Mike Cates, Wilson Poon and colleagues at the University of Edinburgh have been investigating the underlying processes of structural arrest – when the particles become immobile, stuck in a disordered ‘glassy’ state. The simplest explanation considers the particles to be hard spheres: each particle becomes imprisoned in a cage composed of its neighbours. However, the team was interested in what happened when the hard spheres were ‘sticky’. They discovered that two distinct glassy states formed.

They started with a model hard-sphere colloidal system composed of polymethylmethacrylate particles, which becomes a glass when the concentration of particles is high enough to create the cages. The particles were then made sticky by adding polystyrene, which pushes them together, effectively introducing a short-range attraction. The particles now form clusters – opening up spaces in the cages through which they can escape – in other words, the glass melts. However, as more and more particles stick together, another glassy state forms, this time based on mutual attraction. Recently, the Edinburgh researchers discovered that the two kinds of colloidal glasses yield (start to flow like a liquid), under a shear (parallel) force, in qualitatively distinct manners. Yielding in the pure hard-sphere system is a relatively sharp affair, while a glass of sticky particles yields under shear in a more protracted, two-stepped process.

A chemical microreactor
Professor Cates has also theorised how one unusual glassy colloid could form and how it could be exploited practically. Using computer simulations, his team designed a novel material called a bicontinuous interfacially jammed emulsion (a ‘bijel’). They envisage a system of two fluids which are miscible at high temperatures but separate when cooled. If colloidal particles, which are equally attracted to both fluids, are first added however, they increasingly collect along the interfaces between the fluids as the mixture cools, eventually jamming together to form a glass. The resulting rigid network stabilises a bicontinuous state in which two fluids interpenetrate each other. Although bijels do not yet exist, they could have great potential. They should be very stable and could be used as microreactors in chemical processing.

Many soft materials can be created by such forms of self-assembly. Indeed, biology is adept at building incredibly complex soft structures in this way. Increasingly, physicists are learning from Nature how to assemble hierarchical nanostructures that could form the next generation of electronic and mechanical devices. Understanding the dynamics and stability of the underlying systems will be vital in this endeavour.
The phenomenally fast evolution of microchip technology has had a huge economic and societal impact. Consumer demand for the latest games console or more advanced telecommunications continues to drive the ongoing upgrading of processing performance. Improvements in chip design and fabrication have enabled the electronics industry to shrink the size of transistors so as to squeeze ever more of them onto a chip in the bid to make cheaper, faster processors.

Indeed, the prediction made some 40 years ago by Gordon Moore, the cofounder of Intel, that the number of transistors on a chip would double about every two years has more or less held true. The scaling of feature dimensions has gone from 10 micrometres to tens of nanometres. However, it seems likely that the rate of shrinkage will now slow, coming to a halt at the end of the next decade at a feature size of around 16 nm. Below this scale, silicon-chip technologies will no longer work.

Nevertheless, electronics companies are striving to push on to this limit by tweaking various aspects of transistor operation. The modern transistor found in a computer has a highly complex design but is based on a simple idea. It is a switching device built on a semiconducting silicon substrate. Electrons flow through a channel between two terminals, the source and drain; a voltage applied across the channel, via a third terminal called the gate, controls the electron flow. The metal gate has a layer of insulator called a dielectric – currently silicon dioxide – so that no actual electrons flow across the gate dielectric, and it is just the electric field that controls the gate in the channel. Such devices are called MOSFETs (metal oxide semiconductor field effect transistor, bottom left), even though polysilicon replaced the metal some years ago. Commercial MOSFETs comprise two types of device, one in which the charge carriers are electrons and the other in which they are the positively charged holes vacated by electrons. This so-called complementary metal oxide (CMOS) configuration has been universally adopted because it is very reliable and uses negligible power in standby mode.

**Shrinking the transistor**

CMOS technology has been incredibly successful in the race to scale down transistors, thanks to ever more sophisticated lithographic processes now capable of etching features on the new generation of silicon...
chips as small as 90 and 65 nm. Shrinking the transistor this far has, however, thrown up problems. Although shortening the gate channel (so that the electrons and holes have less far to travel between the source and drain) increases the operating speed, the amount of current passing through is also less, offsetting the overall performance of the chip. In the past three years, a new approach called strain engineering has been adopted to increase the mobility of electrons in the channel. Germanium atoms are introduced into the crystal lattice of the silicon, which effectively stretch the lattice and allow electrons to move more easily. A UK consortium of universities and companies have been developing processes to make strained silicon devices and test their efficiency.

Leaking currents
To scale down further to 45 nm, chip-makers have had to tackle another issue: as the gate dielectric thins, current starts to leak through. The answer has been to look for a replacement material for silicon dioxide with a higher dielectric constant. The best candidate turns out to be hafnium dioxide. Unfortunately, not much was known about its properties as an electronic material, so a huge effort has gone into its characterisation. Hafnium dioxide suffers from defects which tend to trap charge and that affects the turn-on voltage of the transistor. Sasha Shluger and Jacob Gavartin at University College London, and John Robertson at the University of Cambridge, have been modelling its electronic structure on a computer to try and understand what was causing the trapping. Another issue has been that amorphous hafnium dioxide tends to crystallise on processing, which affects leakage. It also reacts with silicon, reintroducing the silicon dioxide that it is supposed to replace and so losing the benefit of the higher dielectric constant. By mixing silicon dioxide with the hafnium dioxide to give what is termed ‘hafnium silicate’, the crystallisation can be suppressed but the dielectric constant is lowered. Alan Craven and colleagues at the University of Glasgow, in collaboration with the Belgian research institute IMEC, have been studying the behaviour of hafnium dioxide and ‘hafnium silicate’ to understand how these materials are affected by deposition and processing. A further necessary development is to replace the polysilicon gate electrode by a metallic gate, so turning the clock full circle. Again, understanding the interaction between thin layers of these materials is crucial to success.

The final frontier
Eventually, other semiconductors capable of allowing higher electron speeds, such as gallium arsenide, indium phosphide or germanium, will have to take over some functions. The University of Glasgow leads a large UK consortium investigating new devices and materials aimed at tackling the 22-nm scale and beyond. In this collaboration with Freescale Semiconductor in Arizona, the Glasgow researchers are developing a gallium-arsenide MOSFET with a gallium-oxide interface capped with gallium gadolinium oxide to give low leakage. Professor Craven says that this project has demonstrated the world’s best performing gallium arsenide MOSFET device to date, and modelling shows that scaling to 22 nm should be possible. Full success is likely to require ‘hyper-integration’ of a number of semiconductors on a silicon platform.

Beyond this scale, MOSFETS of any material or design will run out of steam. It is unlikely that they could be made with features scaling below 10 nm, when heat dissipation from the energy produced becomes a major problem. With just a handful of electrons switching the transistor, quantum phenomena also take over. To achieve any further advantage will mean turning to a different type of technology based perhaps on the spins of electrons (p.10), or on the electronic properties of molecular structures such as carbon nanotubes (p.6) or quantum dots (p.8). Such approaches might exploit the quantum properties of single electrons and could be the means to an entirely different type of processing based on manipulating quantum states – quantum computing. One approach, that of Marshall Stoneham and his team at University College London, uses electron spins controlled by a laser in a way that is compatible with the silicon technology of near-future fabrication plants. Unlike most quantum computing schemes, it might even work at room temperature!

However, it could be some years before such schemes become a commercial reality. In the meantime we can expect to see the scaling down continue, if not quite at the speed predicted by Moore’s law.
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