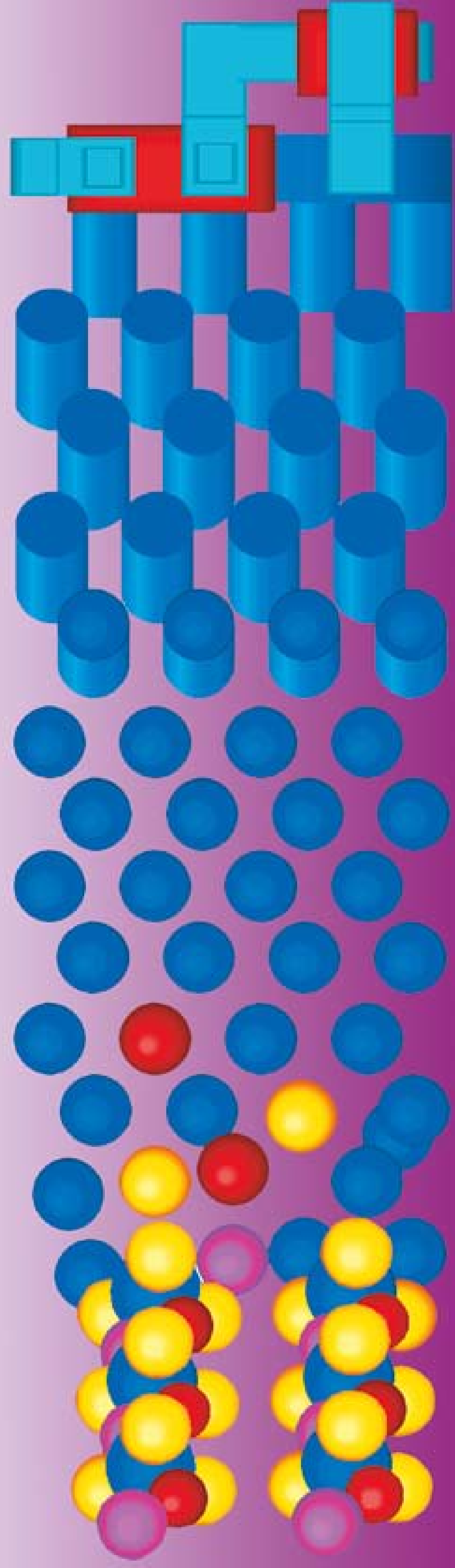
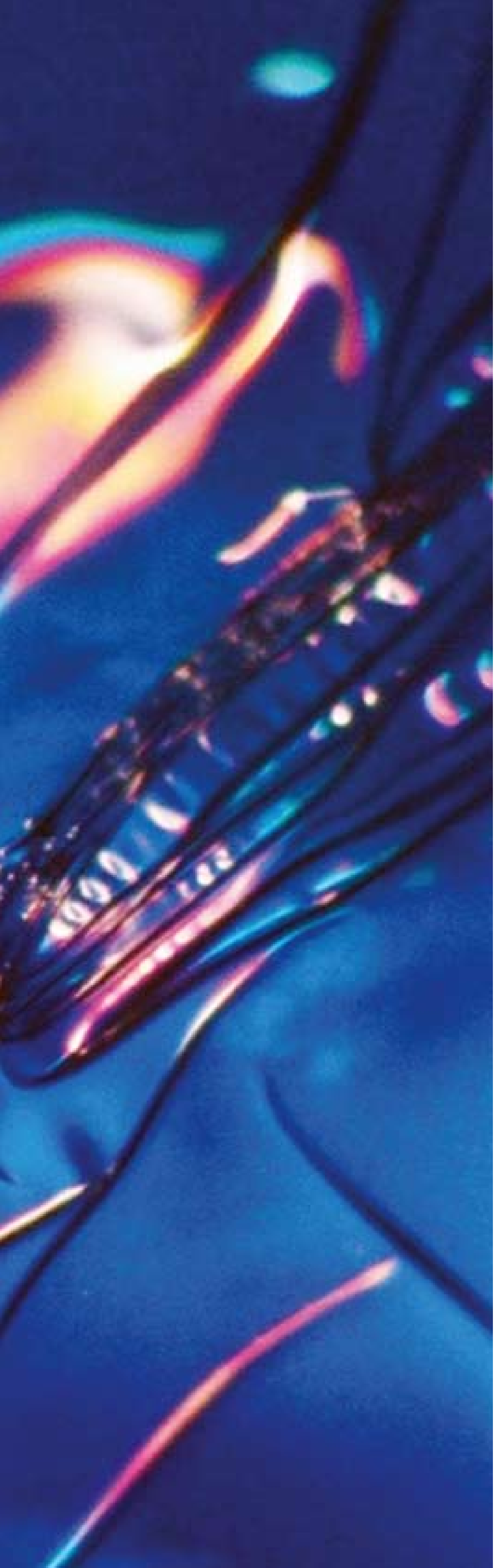


UNIVERSITY OF
CAMBRIDGE

Department of
Materials Science
and Metallurgy

Research Profile

Internal structure of yttrium barium copper oxide (YBCO) ink, prepared by sol-gel methods



Materials Science at the University of Cambridge

The Department of Materials Science & Metallurgy at Cambridge is a leading centre both within the UK and internationally. This booklet does not attempt to catalogue all of our researches in progress (for that it is best to visit our web-site: http://www.msm.cam.ac.uk), but rather focuses on our academic staff including research fellows. At whatever level, from senior professor to rising young star, these staff inspire their research groups and drive the Department's contributions to the development of our subject.

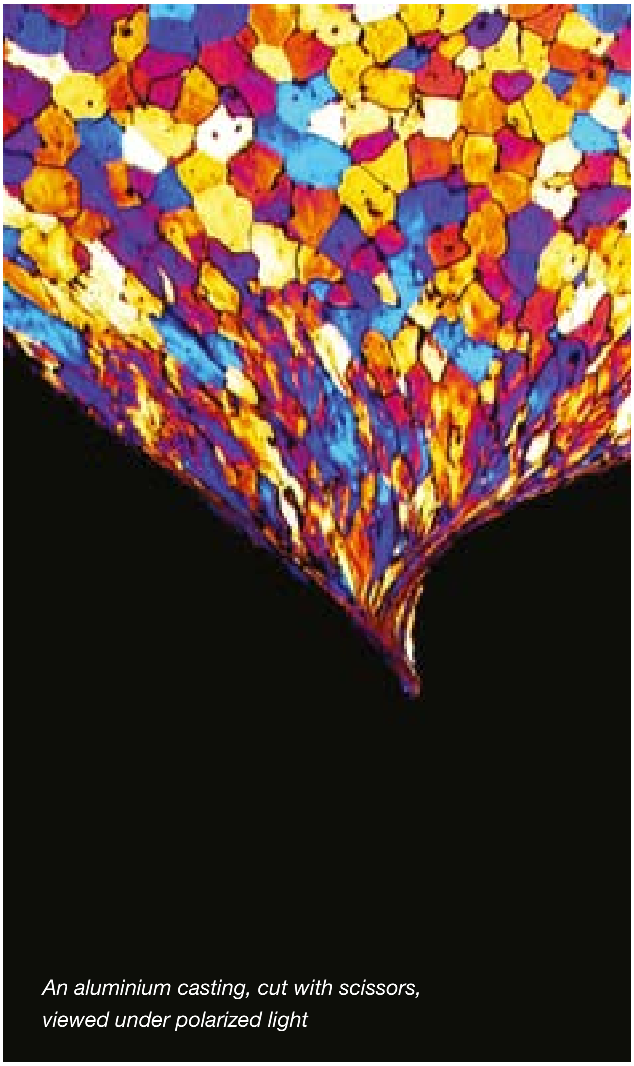
I hope you will find the booklet informative and useful.

Lindsay Greer
Head of Department
March 2009

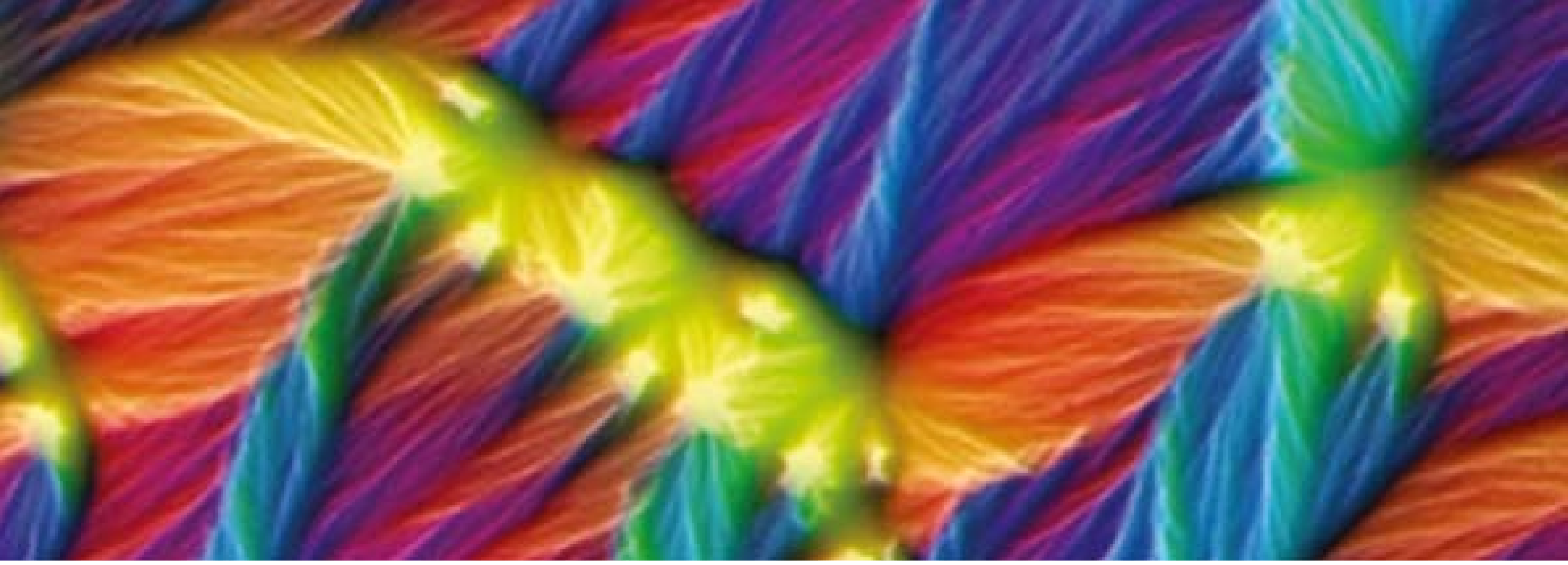
Department of Materials Science and Metallurgy

University of Cambridge
Pembroke Street
Cambridge
CB2 3QZ

Telephone: +44 (0) 1223 334300
Fax: +44 (0) 1223 334567
E-mail: web-responses@msm.cam.ac.uk
Web: www.msm.cam.ac.uk



An aluminium casting, cut with scissors, viewed under polarized light



The Department of Materials Science & Metallurgy is located in the heart of Cambridge, occupying buildings that range from the original home of the Cavendish Laboratory, built in 1873, to modern teaching facilities completed in 2000. We have over 30 academic staff including research fellows, more than 50 administrative, technical and support staff, and roughly 60 post-doctoral researchers, 130 research students and 30 visiting scientists at any time. Our research funding, rising on average by nearly 10% per annum, comes from a range of sources: about 50% from the research councils, 25% from industry, and the rest from the EU, UK government, overseas governments, and charities.

In the RAE 2008 (UK Research Assessment Exercise, covering 2001–07), 95% of our research activity is rated world-leading (4*) or internationally excellent (3*). Across the country in all disciplines, no department exceeded this level, and only 5 matched it. With the highest ranked Quality Profile in the RAE subject area Metallurgy & Materials, our research is recognised as active and world-leading, a conclusion supported by the exceptionally high citation rate of our publications. Our research has five applications-oriented themes.

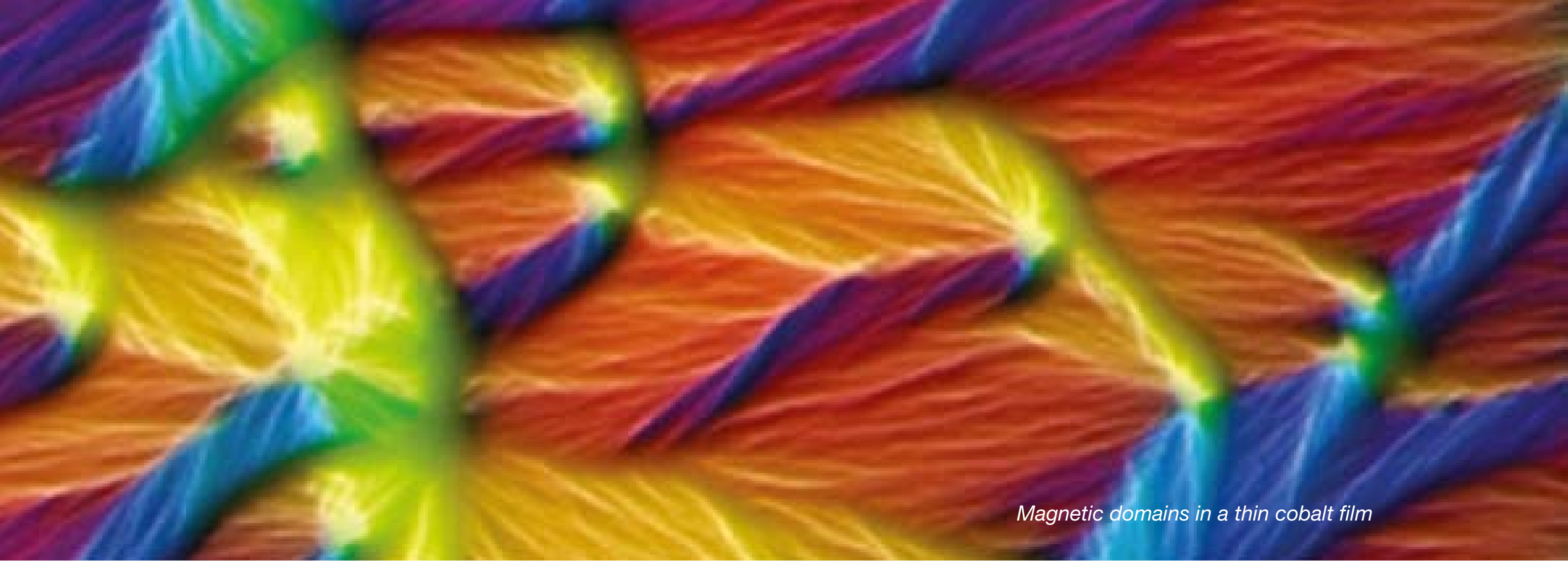
Structural Materials The diverse research under this heading involves mechanical testing, modelling of microstructural development and processing, and microstructural characterization. Key areas of focus are: steels, superalloys, carbon nanotubes, composites, coatings, metallic glasses and joining of materials. The Cambridge Micromechanical Testing Centre opened in 2006.

Device Materials Our work in this area focuses on understanding, development and application of functional materials, in particular, magnetic, ferroelectric, semiconducting and superconducting materials for device applications. Research is based around established facilities for very-high-quality thin-film deposition (ultra-high vacuum, as well as a wide range of chemical and electrochemical techniques), processing, device manufacture, measurement and microscopy.

Materials Chemistry Research in this area embraces fundamentals and applications, including work on novel materials synthesis (including characterization and applications of inorganic and hybrid inorganic-organic framework materials), on corrosion and electrocatalysts, and on solid electrolytes and electrodes for sensors detecting species in the environment and molten metals. The world-leading FFC Cambridge Process for electro-deoxidation of metal oxides has attracted widespread industrial interest.

Medical and Pharmaceutical Materials Work in this area focuses on bioactive biodegradable composites, polymers and ceramics, surface patterning and topography and tissue engineering scaffolds, and on orthopaedic applications and nerve-tissue regeneration with further work on surgical glues, wound dressings, breast-tissue engineering and 3D imaging. Collaborations include development of neuroelectronic interfaces with flexible electronics for the repair of peripheral nerves, and multiscale materials modelling at the bio-inorganic interface.

Electron Microscopy The characterization of microstructure is at the heart of materials science. Research involves development and application of state-of-the-art techniques to probe the physical, chemical and structural nature of materials at sub-nanometre level. Our focus is on electron holography (mapping electrostatic potentials in semiconductor devices, and permitting the study of complex magnetic systems) and electron tomography (for 3D mapping of composition, of dislocation structures and of the distribution of nanoparticles).



Magnetic domains in a thin cobalt film

The breadth of research highlighted above permits us to undertake cross-disciplinary initiatives, and our current focus is on “Materials for Sustainability”. One of many projects under this heading links research on nitride semiconductors by Colin Humphreys with that on phosphors by Tony Cheetham. A key objective is to match the wavelengths emitted by nitride-based LEDs to the excitation wavelengths of novel phosphors, permitting much wider use of high-efficiency solid-state lighting.

The Department of Materials Science & Metallurgy sits at the hub of a broader Cambridge effort in materials research, having well developed links to other departments (Chemical Engineering & Biotechnology, Chemistry, Earth Sciences, Engineering, Nanoscience, Orthopaedics, Physics). An example is the Pfizer Institute for Pharmaceutical Materials Science, a close collaboration with Department of Chemistry and the Cambridge Crystallographic Data Centre, focusing on cross-disciplinary strategic research. Its research spans all length scales from molecular crystallization to better powder compaction, tableting, diffusion and release.

Nearly half the Department’s research output involves collaboration outside Cambridge. Across the UK we have links with more than 20 universities. Internationally, recent years have seen active research collaborations with some 45 countries.

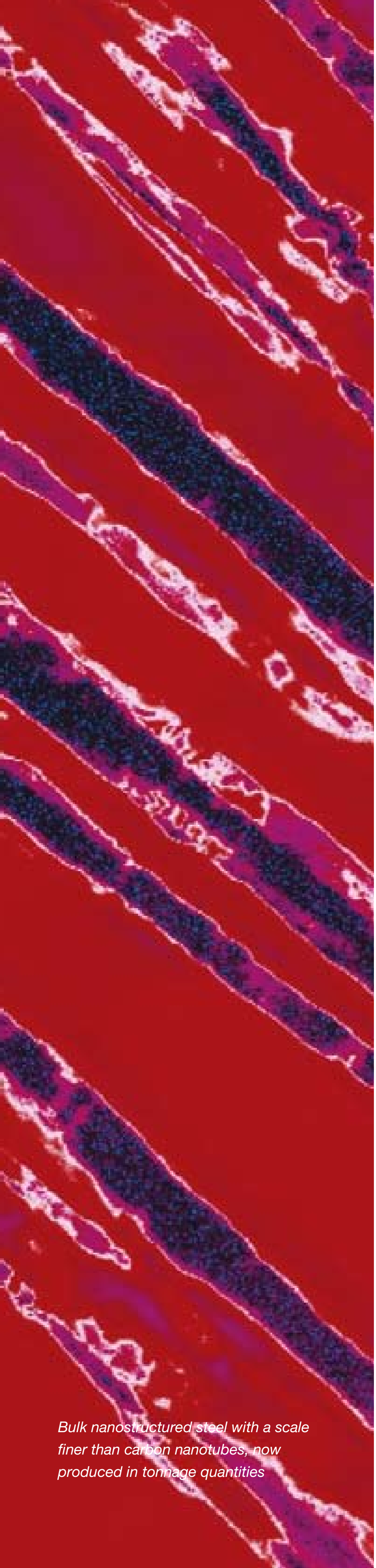
The Department’s oldest (founded 1994) ongoing relationship with industry is its Rolls-Royce University Technology Partnership, for which the focus is on raising the efficiency of aeroengines through higher-temperature operation. This is but one of many strong links: overall we collaborate with over 100 companies, covering the structural, device, chemistry and medical materials areas. The Department is active in promoting transfer of technology to industry and wealth creation through spin-out companies, of which there have been five in recent years, raising ~£28M in capital.

The Department is home to graduate students from all over the world, mostly studying for the PhD degree. Over 30 new graduate students arrive each year, many with backgrounds in physics, chemistry or engineering. The Department administers the interdepartmental MPhil course in Micro- and Nanotechnology Enterprise; this relatively new course is proving very successful. The Department is always keen to hear from prospective students, who are encouraged to identify possible research areas from the staff profiles in this booklet, by browsing the Department’s web-site, or by direct approach to individual members of staff. Further details of how to apply are given on page 41.

In common with all other university departments, we face new financial pressures and the need for new or upgraded buildings. Despite these challenges, Materials Science in Cambridge is thriving: our income is rising, postgraduate numbers have never been higher, and our research output is a tribute to the excellent contributions of all the staff and students of this Department.

800 YEARS
TRANSFORMING
TOMORROW

Academic staff and research fellows



Bulk nanostructured steel with a scale finer than carbon nanotubes, now produced in tonnage quantities

Zoe Barber
Senior Lecturer

MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334326
zb10@cam.ac.uk
www.msm.cam.ac.uk/dmg/

Thin-Film Deposition

My research interests are based around thin-film deposition using a range of techniques: magnetron sputtering, ionized sputter deposition, pulsed-laser ablation and sol-gel fabrication. Within the Device Materials Group we are developing and optimizing the growth of many different thin-film device materials, which may be amorphous, polycrystalline or single crystal. These include magnetic alloys and compounds, ferroelectrics, dielectrics, superconductors, multiferroics, as well as tunnel barriers, buffer layers, contacts and encapsulation layers.

In relation to a wider range of thin-film applications we are investigating ultra-hard coatings (e.g. nano-composites, epitaxial nitride multilayers); biomedical coatings (e.g. doped hydroxyapatite); shape-memory metals and precise free-standing structures for nanotechnology applications; and multilayers for X-ray mirrors and for studies of interdiffusion.

Film growth techniques are being developed to further improve the control of film structure (e.g. ion-enhanced deposition), and we are using optical emission spectroscopy and plasma probes for detailed diagnostics of the film growth environment.

Spintronics

To optimize spin-dependent transport between ferromagnetic metals and semiconductors we are developing methods for the deposition of ferromagnetic electrodes on insulating tunnel barriers on semiconductors. This requires careful preparation of the semiconductor surface using in-situ surface-cleaning techniques in an ultra-high vacuum deposition system.

Superconducting junctions

Measurement of the spectrum of quantum fluctuations in niobium-nitride-based superconducting tunnel junctions may answer questions about the source of dark energy in the universe. We are developing and optimising the fabrication of very high critical current density, shunted NbN junctions for this application.

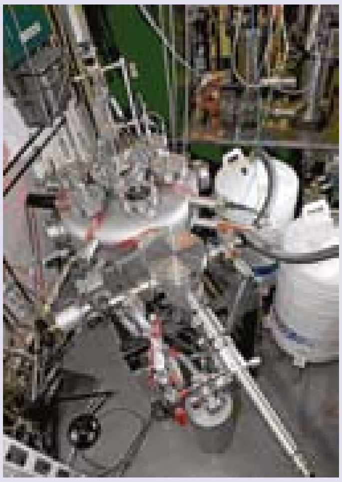
XB Hu, A Garg & ZH Barber, “Deposition and characterization of pulsed-laser-deposited and chemical-solution-derived Sm-substituted bismuth titanate films” *Integrated Ferroelectrics* **79,** 113–121 (2006).

LJ Singh, CW Leung, C Bell, JL Prieto & ZH Barber, “Magnetoresistance of spin valve structures based on the full Heusler alloy Co_2MnSi” *J. Appl. Phys*. **100,** 013910 (2006).

ES Thian, J Huang, ME Vickers, SM Best, ZH Barber & W Bonfield, “Silicon-substituted hydroxyapatite (SiHA): A novel calcium phosphate coating for biomedical applications” *J. Mater. Sci*. **41**, 709–717 (2006).

S Sanjabi, SK Sadrnezhaad & ZH Barber, “Sputter alloying of Ni, Ti and Hf for fabrication of high temperature shape memory thin films” *Mater. Sci. Technol*. **23**, 987–991 (2007).

MA Moram, Y Zhang, MJ Kappers, ZH Barber & CJ Humphreys “Dislocation reduction in gallium nitride films using scandium nitride interlayers” *Appl. Phys. Lett*. **91,** 152101 (2007).



Extremely precise fabrication of thin films and heterostructures is performed in ultra-high vacuum deposition systems. The diameter of the main chamber shown is 0.6 m

Serena Best

Reader in Ceramics and Medical Materials

BSc University of Surrey
PhD University of London

+44 (0) 1223 334307
smb51@cam.ac.uk
www.msm.cam.ac.uk/ccmm/

Bioactive Ceramics, Coatings and Composites

My research within the Cambridge Centre for Medical Materials aims to expand the range and performance of bioactive ceramics and composites in clinical applications.

Skeletal implants: Optimization of substituted hydroxyapatite bone grafts

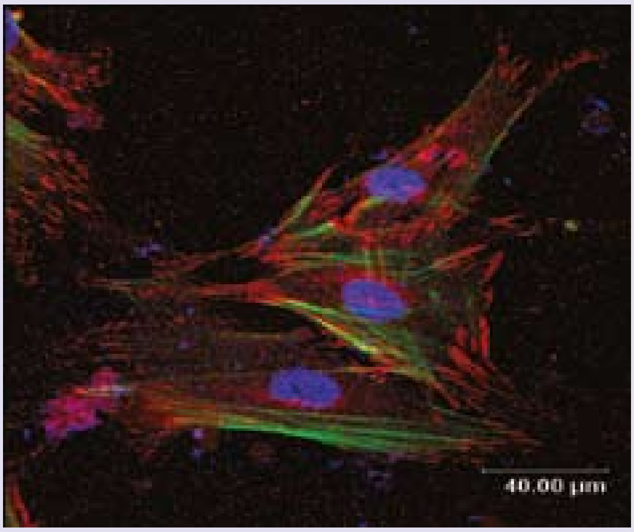
A range of synthetic substituted hydroxyapatite (HA) materials has been developed with physiologically relevant ionic lattice substitutions. The materials are designed for skeletal defect filling and as scaffolds for tissue engineering. The performance of these materials is evaluated alongside phase-pure HA and bioactive glasses and glass ceramics through in-vitro cell culture and in-vivo implantation models.

Surface modification using bioceramics

The repair of bone defects can be enhanced by the control of either the surface chemistry or topography. This research area encompasses a number of projects to deposit bioactive ceramics on a range of substrates. Deposition techniques include RF-sputtering, electrostatic atomization and vacuum plasma spraying to produce a range of surface topographies.

Bioactive and bioresorbable composites for tissue engineering

We aim to develop composites with properties tailored to their specific application. The organic matrices range from collagen to biodegradable polymers. The fillers include bioactive ceramics, glasses and glass ceramics. Filler particles with a variety of morphologies and dimensions are being investigated. The biological response to carbon nanotubes is also being explored with the aim of producing ceramic-matrix composites with optimized mechanical properties.



Confocal image of osteoblast cells attaching on silicon-substituted hydroxyapatite nanocrystals

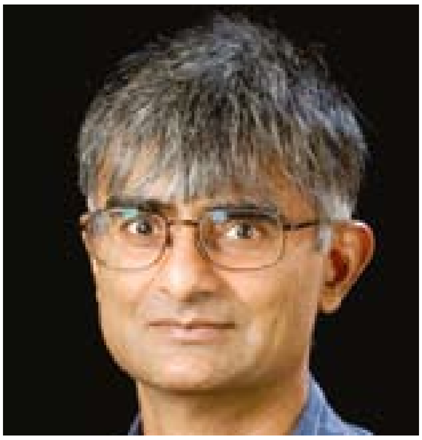
N Patel, RA Brooks, MT Clarke, PMT Lee, N Rushton, I Gibson, SM Best & W Bonfield, "In vivo assessment of hydroxyapatite and silicate substituted hydroxyapatite granules using an ovine defect model" *J. Mater. Sci: Mater. Med.* **16**, 429–440 (2005).

ES Thian, J Huang, ME Vickers, SM Best, ZH Barber & W Bonfield, "Silicon-substituted hydroxyapatite (SiHA): A novel calcium phosphate coating for biomedical applications" *J. Mater. Sci.* **41**, 709–717 (2006).

AE Porter, T Buckland, K Hing, SM Best & W Bonfield, "The structure of the bond between silicon-substituted hydroxyapatite bone and porous bioceramic implants" *J. Biomed. Mater. Res. A* **78A**, 25–33 (2006).

Harry Bhadeshia FREng FRS FNAE
Tata Steel Professor of Metallurgy
BSc City of London Polytechnic
PhD University of Cambridge

+44 (0) 1223 334301
hkdb@cam.ac.uk
www.msm.cam.ac.uk/phase-trans/index.html



Phase Transformations

There are so many phase changes in iron and its alloys that it is possible to generate a seemingly infinite variety of microstructures and properties. This complexity makes the alloys versatile but at the same time difficult to understand and design from first principles. Much of our energy is devoted to the development of solid-state phase transformation theory, and its experimental validation, in the hope of inventing new alloys and processes.

Theory of transformations

We deal mostly with phase changes which are thermodynamically of first order, i.e. they involve nucleation and growth with well-defined mechanisms of transformations and particular constraints to the achievement of equilibrium. In fact, most useful microstructures are far from equilibrium so we build kinetic theory to determine non-equilibrium states. There are complications when many different transformations occur together, complications which have stimulated new theory. Finally, the microstructure must be related to properties which are appreciated by technologists.

Mathematical models

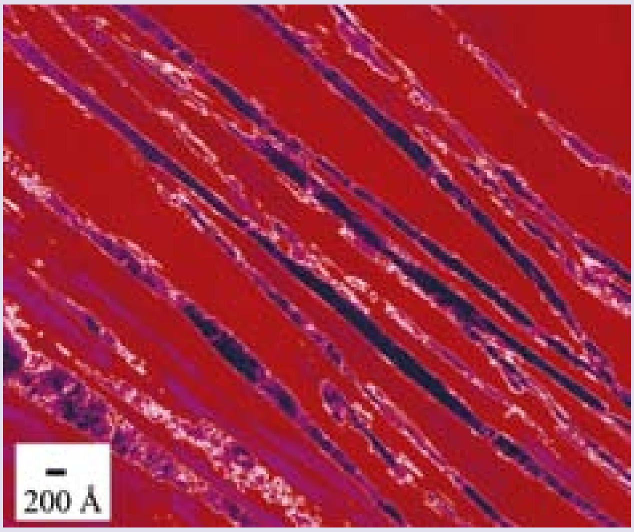
We express the theory and empirical observations in the form of computer models which can be used to greatly reduce the vast number of parameters that have to be controlled during the creation of new alloys and processes. We also produce courses, books and algorithms in addition to research papers to help spread the word about this thriving science of materials.

H Matsuda & HKDH Bhadeshia, "Kinetics of the bainite transformation" *Proc. Roy. Soc. (London) A* **460**, 1710–1722 (2004).

HKDH Bhadeshia, "Large chunks of very strong steel" *Mater. Sci. Technol.* **21**, 1293–1302 (2005).

S Yamasaki & HKDH Bhadeshia, "M_4C_3 precipitation in Fe-C-Mo-V steels and relationship to hydrogen trapping" *Proc. Roy. Soc. (London) A* **462**, 2315–2330 (2006).

S Chatterjee, HS Wang, JR Yang & HKDH Bhadeshia, "Mechanical stabilisation of austenite", *Mater. Sci. Technol.* **22**, 645–649 (2006).



Bulk nanostructured steel with a scale finer than carbon nanotubes, now produced in tonnage quantities

Erica Bithell

Daphne Jackson Research Fellow

MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334566
egb10@cam.ac.uk
www-hrem.msm.cam.ac.uk/

Electron Microscopy and Crystallography

My main research interest is applying transmission electron microscopy and electron crystallography to the understanding of pattern and structure in the world around us.

In September 2007 I resumed my research career after a break caring for my young family. My earlier interests included work on high-spatial-resolution characterization techniques for a variety of inorganic materials, ranging from heterostructures for microelectronic devices to oxide- and metal-particle catalysts. Examples of this research are given in the publications cited below.

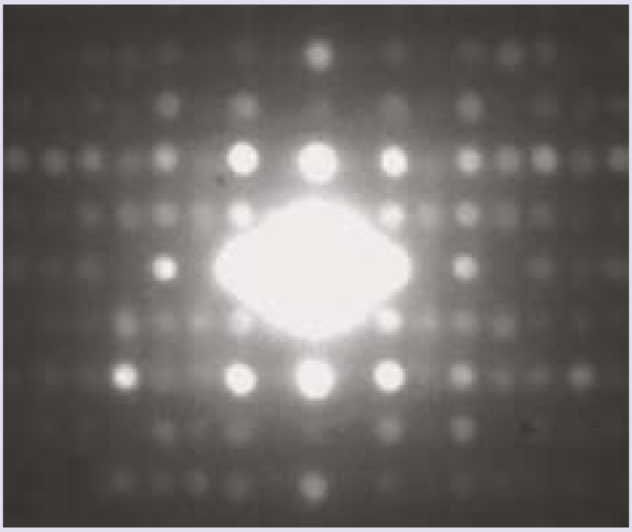
Precession electron diffraction

With the development of commercially available equipment for precession electron diffraction, crystal-structure determination in the electron microscope has become possible with an accuracy which could previously be obtained only using X-rays. I am now building on my earlier experience by developing applications of precession electron diffraction to materials containing organic components, with a particular interest in pharmaceutical crystals.

Pharmaceutical materials

Even the most basic crystallographic details remain unknown for many pharmaceutical compounds, with little being recorded beyond their crystalline form. Many of these materials can form a number of co-existing phases or polytypes, precluding any work on single crystals and limiting the application of X-ray diffraction.

Transmission electron microscopy and diffraction, by contrast, are well suited to work with mixed systems of this type. Different structures are readily distinguished, often simply because each variant has a characteristic morphology. The aim of current research is to collect and analyse precession electron diffraction data from such materials in conjunction with information from X-ray diffraction and molecular chemistry, to establish at least the unit-cell sizes and lattice types for these compounds, to extend this to more detailed crystal structure determination and to develop a protocol for carrying this out as a routine procedure.



Precession electron diffraction pattern from Cr ethylenediphosphonate (P6cc, a = 1.311 nm, c = 0.926 nm)

EG Bithell & WM Stobbs, “Composition determination in the GaAs/(Al,Ga)As system using contrast in dark field transmission electron microscope images” *Philos. Mag. A* **60**, 39–62 (1989).

EG Bithell & WM Stobbs, “III-V ternary semiconductors: the choice of appropriate characterization techniques” *J. Appl. Phys.* **69**, 2149–2155 (1991).

EG Bithell, RC Doole & MJ Goringe, “On the extraction of high quality data from real-time transmission electron microscopy experiments” *Ultramicroscopy* **56**, 172–183 (1994).

Mark Blamire

Professor of Device Materials

MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334359
mb52@cam.ac.uk
www.msm.cam.ac.uk/dmg/

Thin-Film Devices and Nanoscience

My research within the Device Materials Group is built around the deposition, microfabrication and measurement of thin-film heterostructure devices. In particular we apply novel materials and advanced nanofabrication to create new types of functional device.

Multifunctional heterostructure devices

Within a thin-film multilayer or heterostructure, ultra-thin layers of materials with radically different properties (for example superconductivity and magnetism) can be placed in contact so that the interfacial coupling can begin to dominate the equilibrium properties found in the bulk. If currents are passed through such structures then the creation of non-equilibrium charge or spin states is possible and so complex functional properties can be created. Specific examples of this type of work includes studies of spin accumulation in ferromagnetic heterostructures, complex order parameter coupling in superconducting junctions containing magnetic barriers, and the exchange coupling between ferromagnets and antiferromagnets.

The best known of the metallic oxides are the high-temperature superconductors, but materials with complex electronic properties have similar crystal structures and can be grown as thin films by laser ablation. Consequently, a major research programme is the study of epitaxial oxide heterostructure devices which enable tunnelling and direct injection of carriers between materials with very different electronic properties.

Nanofabrication and materials modification

Within a heterostructure, thin-film deposition techniques enable control of layer thickness to much better than 1 nanometre. For many systems of interest, the confinement in the other dimensions is much less critical, but there are several classes of device for which high current densities need to be applied through the layers and so methods of fabricating devices with lateral dimensions of 100 nanometres or better need to be developed.

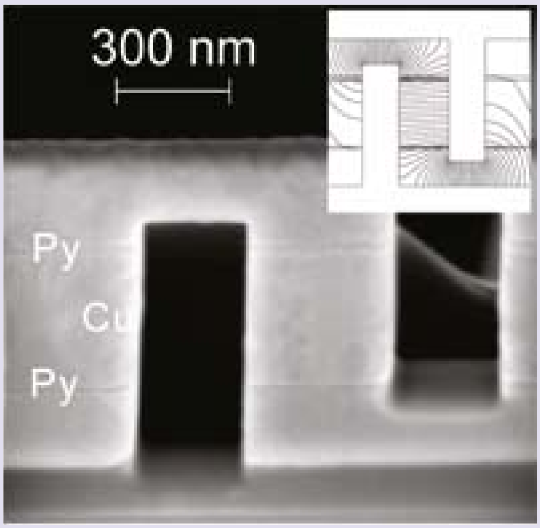
We have developed focused-ion-beam nano-machining within the Department as our primary technique for patterning. This technique can be used not only for imaging device and materials microstructures but also as a nanofabrication tool. As well as direct device fabrication and measurement of device properties while they are being patterned, we are developing highly localized ion implantation for materials modification.

J Dho, X Qi, JL MacManus-Driscoll, MG Blamire & H Kim, "Large electric polarisation and exchange bias in multiferroic $BiFeO_3$" *Adv. Mater.* **18**, 1445–1448 (2006).

JWA Robinson, S Piano, G Burnell, C Bell & MG Blamire, "Critical current oscillations in strong ferromagnetic π-junctions" *Phys. Rev. Lett.* **97**, 177003 (2006).

M.G Blamire, M Ali, CW Leung, CH Marrows & BJ Hickey, "Exchange bias and blocking temperature in Co/FeMn/CuNi trilayers" *Phys. Rev. Lett.* **98**, 217202 (2007).

A Palau, H Parvaneh, NA Stelmashenko, H Wang, JL Macmanus-Driscoll & MG Blamire, "Hysteretic vortex pinning in superconductor / ferromagnet nanocomposites" *Phys. Rev. Lett.* **98**, 117003 (2007).



A device fabricated by 3-D focused ion beam milling used to measure the spin diffusion length of electrons in copper

Paul Bristowe

Reader in Computational Materials Science

BSc University of East Anglia
PhD University of Surrey

+44 (0) 1223 334305
pdb1000@cam.ac.uk
www.msm.cam.ac.uk/asg/

Materials Modelling at the Atomic Level

Our research is concerned with the atomistic modelling of defects, surfaces and interfaces in materials and their influence on physical properties. We apply and develop modern quantum-mechanical methods and focus on functional materials with electronic and optical applications.

Multilayer optical coatings

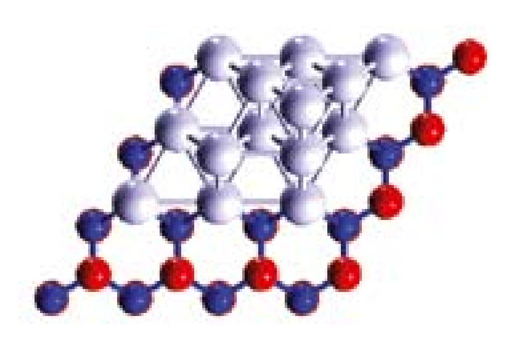
Multilayer thin-film coatings are widely used in many optical applications including UV and infra-red blockers, lighting filters, anti-reflective films on spectacle lenses, solar control films on windows and conductive films on flat-screen displays. The interfaces between the multilayers of the coatings have an important influence not only on the optical properties of the films but also on their mechanical properties. We are using quantum-mechanical density-functional calculations to predict the structure, energy, bonding and dielectric characteristics of various metal/oxide interfaces in these systems with the aim of developing coatings with improved properties.

Ferroelectric materials for memory devices

Ferroelectric memory (FRAM) is a leading alternative technology to silicon flash memory because it is non-volatile, has a short erase time and operates at low voltages. Standard ferroelectric materials for FRAM are the perovskite-type compounds PZT and SBT. To further improve their ferroelectric properties, additional chemical substitutions have been made resulting in complex solid solutions such as PZTN, PLZT and BLT. We are using density-functional methods to predict the structural, chemical and electronic properties of these ferroelectrics in their bulk and thin-film form, focusing on defects, surfaces and interfaces.

Fast ion conductors

Interest in zirconia-based solid electrolytes for fuel-cell and sensor applications has lead to many atomic-scale simulations of these materials aimed at deducing the ionic diffusion mechanisms and relating them to the measured variation in conductivity. We are extending these simulations to consider more complex chemistries and microstructures including grain boundaries with the goal of predicting new materials with enhanced ionic conductivity.



A small cluster of Ag atoms (grey) adsorbed onto a ZnO (0001) surface

ZS Lin & PD Bristowe, "Microscopic characteristics of the Ag(111)/ZnO(0001) interface present in optical coatings" *Phys. Rev. B* **75**, 205423 (2007).

H Chappell, M Duer, N Groom, C Pickard & PD Bristowe, "Probing the surface structure of hydroxyapatite using NMR spectroscopy and first principles calculations" *Phys. Chem. Chem. Phys*. **10**, 600–606 (2008).

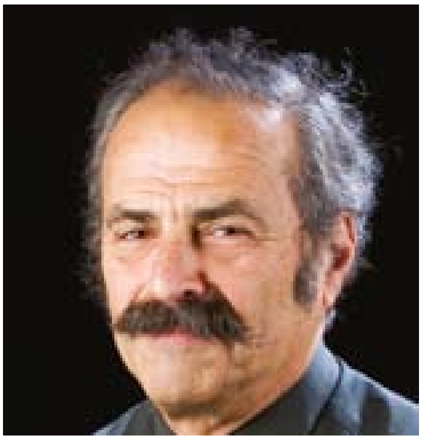
ZS Lin & PD Bristowe, "A density functional study of the effect of hydrogen on the strength of an epitaxial Ag/ZnO interface" *J. Appl. Phys*. **102**, 103513 (2007).

SH Shah, PD Bristowe, AM Kolpak & AM Rappe, "First principles study of three-component $SrTiO_3$/$BaTiO_3$/$PbTiO_3$ ferroelectric superlattices" *J. Mater. Sci.* **43**, 3750-3760 (2008).

Tim Burstein

Professor of Materials Chemistry and Corrosion
MSc PhD University of Auckland
MA University of Cambridge

+44 (0) 1223 334361
gtb1000@cam.ac.uk
www.msm.cam.ac.uk/corrosion/



Corrosion, Fuel Cells and Surface Electrochemistry

This research concerns the corrosion and protection of metals, the development of novel, low-cost fuel-cell systems, and the surface electrochemistry and electrochemical processing of metals.

Corrosion of metals

Corrosion of metals consumes massive resources globally, including cost, materials and the energy required to produce them. We are researching into the genesis of corrosion at a nanoscopic level and how this leads to failure. We have developed new techniques designed to isolate the earliest steps in localised corrosion, using the knowledge acquired to develop unique methods of corrosion control in terms of reliable prediction and of surface treatment. The corrosion and passivity of surgical implant alloys, and of pipeline steels from the oil industry are amongst our current major subjects.

Development of fuel cells

Fuel cells promise efficient conversion of combustible fuels into electrical energy, and thereby energy efficiency. Research in this field covers the development of low-cost base electrocatalysts for electro-oxidation of hydrogen and methanol, and for reduction of oxygen from air. These require an extremely high level of passivity towards corrosion, and it is on these passive surfaces that the catalysis takes place. We are currently designing the passivity and the electrocatalysis. Although they do not yet have a performance comparable with platinum, these low-cost materials should eventually enable much wider use of fuel cells, particularly for electric vehicles. We also research alternative electrolytes for low-temperature fuel cells. Our work has so far revealed remarkable fuel selectivity and resistance to poisoning by CO. Ultimately, we also require solar-powered hydrogen production from water.

Electrochemical processing of surfaces

The development of surface characteristics of metals by electrochemical processing, including electrograining of lithographic aluminium sheet for printing and surface treatment for improved corrosion resistance is being undertaken.

Novel electrochemical methods

Novel new electrochemical methods are being developed which are designed to examine and quantify hitherto inaccessible electrochemical and corrosion processes, including cyclic thermammetry, microelectrodics and slurry erosion-corrosion test systems.

GT Burstein & C Liu, "Depassivation current transients measured between identical twin microelectrodes in open circuit" *Corros. Sci*. **50**, 2–7 (2008).

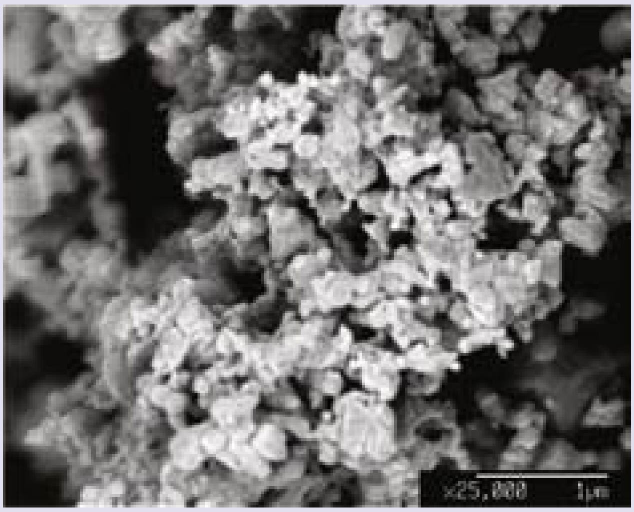
EJ Rees, CDA Brady & GT Burstein, "Solid-state synthesis of tungsten carbide from tungsten oxide and carbon, and its catalysis by nickel" *Mater. Lett*. **62**, 1–3 (2008).

CDA Brady, EJ Rees & GT Burstein, "Electrocatalysis by nanocrystalline tungsten carbide and the effects of codeposited silver" *J. Power Sources* **179**, 17–26 (2008).

K Sasaki & GT Burstein, "Erosion-corrosion of stainless steel under impingement by a fluid jet" *Corros. Sci*. **49**, 92–108 (2007).

GT Burstein, C Liu & RM Souto, "The effect of temperature on the nucleation of corrosion pits on titanium in Ringer's physiological solution" *Biomater*. **26**, 245–256 (2005).

Y Gonzalez-Garcia, GT Burstein, S Gonzalez & RM Souto, "Imaging metastable pits on austenitic stainless steel in situ at the open-circuit corrosion potential" *Electrochem. Commun*. **6**, 637–642 (2004).



A nanocrystalline WC electrocatalyst

Ruth Cameron

Reader in Polymers and Medical Materials

MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334324
rec11@cam.ac.uk
www.msm.cam.ac.uk/ccmm/

Polymers and Medical Materials

My work within the Cambridge Centre for Medical Materials and the Pfizer Institute for Pharmaceutical Materials Science focuses on materials which interact therapeutically with the body. Research is undertaken in both materials and cell-culture laboratories.

Biodegradable polymers and composites

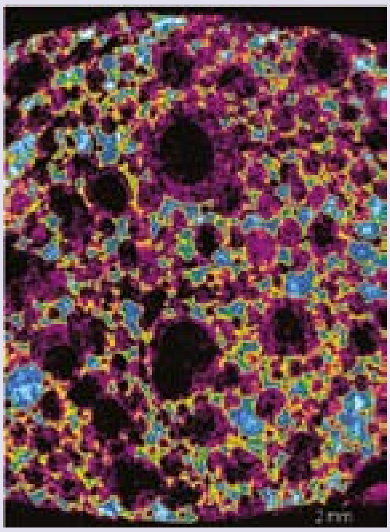
Resorbable polymers may be used in temporary load-bearing applications such as sutures and pins, in scaffolds for tissue engineering and in drug-delivery devices. We are exploring the complex temporal and spatial relationships between the processing and morphology of the polymer, the diffusion rates of water, drug and degradation products, the degradation rate of the polymer and ultimate properties. An understanding of these factors allows informed device design. This work is extended into the study of composites with polymers and ceramics, ranging from the micro co-continuous to the nano-scale, for bone and other tissue repair.

Biostable implants

We are researching materials and devices for applications in which the material must not change in the challenging environment of the body. Problems we are addressing include spinal-disc replacement and prostheses to engineer nerve repair.

Drug delivery and pharmaceutics

We are exploring issues relating to drug delivery to the body including drug polymorphism, tablet design and inhalation delivery systems.



Co-continuous resorbable polymer-ceramic composite for orthopaedic applications

J Braunecker, M Baba, GE Milroy & RE Cameron, "The effects of molecular weight and porosity on the degradation and drug release from polyglycolide" *Int. J. Pharmaceutics* **282**, 19–34 (2004).

JE Taylor, PR Laity, SS Wong, P Khunkamchoo, K Norris, J Hicks, AF Johnson & RE Cameron, "Iron pick-up efficiency in deferoxamine-coupled polyurethane dressings for treatment of chronic wounds" *Biomater.* **26**, 6024–6033 (2005).

AC Renouf-Glauser, J Rose, DF Farrar & RE Cameron, "A comparison of the degradation and deformation properties of a PLLA-lauric acid based family of biomaterials. *Biomacromol.* **7**, 612–617 (2006).

JS Capes & RE Cameron, "Effect of polymer addition on the contact line crystallisation of paracetamol" *Cryst. Eng. Comm.* **9**, 84–90 (2007).

Tony Cheetham FRS

Goldsmiths' Professor of Materials Science

MA University of Oxford
DPhil University of Oxford

+44 (0) 1223 767061
akc30@cam.ac.uk
www.msm.cam.ac.uk/fihm/

Functional Inorganic and Hybrid Materials

We work in the general area of materials chemistry. Our expertise lies in the synthesis of novel phases, their chemical and structural characterization, and the study of their properties.

Hybrid framework materials

A large part of our effort is devoted to exploring the emerging field of hybrid inorganic-organic framework materials, which are crystalline phases containing both inorganic and organic structural elements. Since these can exhibit the functionality of both inorganic and organic materials, they have a diverse range of properties and show potential for applications in many areas. One of the unique aspects of hybrid frameworks is the facility with which homochiral materials can be created by using single-enantiomer organic ligands.

Light-conversion materials

The second main theme of our research concerns new light-conversion materials for applications in solid-state lighting, displays, photovoltaic devices and photocatalysis. One of the challenges for lighting is to develop down-conversion phosphors that will harvest the blue or near-UV light from LEDs and convert it efficiently into the other colours that are required for high-quality white light. We are developing a range of inorganic and hybrid phosphors to achieve this. We also aim to discover new materials for the more difficult task of converting infra-red light to visible light, or visible light to UV. Such materials could be used to enhance the efficiency of solar cells or photocatalytic processes.

Materials chemistry of metal oxides

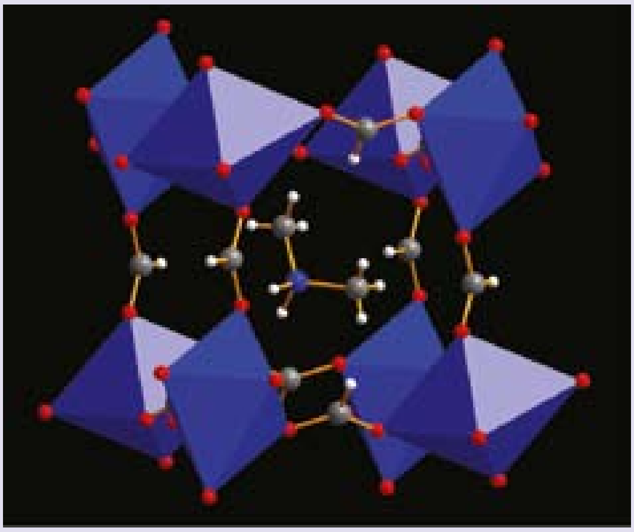
The group has a long-standing tradition of research on transition-metal oxides. The focus of our current work is on the ternary oxides of technetium, a field that is almost entirely unexplored, and on complex rare-earth oxides for optical applications.

G Gundiah, JL Wu & AK Cheetham "Structure-property correlations in Ce-doped garnet phosphors for use in solid state lighting" *Chem. Phys. Lett.* **441**, 250–254 (2007).

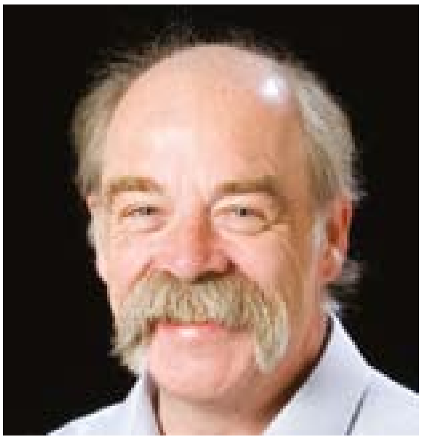
AK Cheetham & CNR Rao, "There's room in the middle" *Science* **318**, 58–59 (2007).

EE Rodriguez, F Poineau, A Llobet, A. Sattelberger, J Bhattacharjee, UV Waghmare, T Hartmann & AK Cheetham, "Structural studies of TcO_2 by X-ray diffraction and first-principles calculations" *J. Amer. Chem. Soc*. **129**, 10244–10248 (2007).

CNR Rao, AK Cheetham & A Thirumurugan, "Hybrid inorganic-organic materials: a new family in condensed matter physics" *J. Phys. Cond. Matter* **20**, 083202 (2008).



$[(CH_3)_2NH_2]Ni(HCOO)_3$ with the perovskite topology



Bill Clegg

Reader in Ceramics

BSc University of Manchester
DPhil University of Oxford

+44 (0) 1223 334470
wjc1000@cam.ac.uk
www.msm.cam.ac.uk/wjc/

Ceramics

My research, within the Gordon Laboratory, is on the processing and thermomechanical behaviour of ceramics and composite structures.

Deformation of small volumes

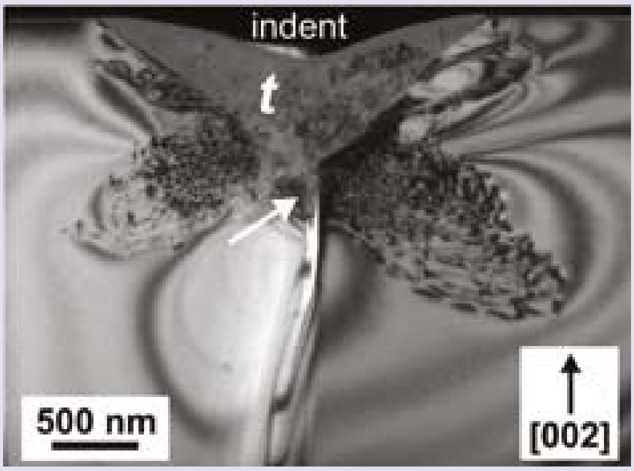
The deformation behaviour of a very small volume of material is found to be very different from that of bulk material and is typical of the deformation processes in localized loading, for instance in wear and erosion, or in small, thin-film devices. As well as studying how the mechanisms of deformation change as the scale is reduced, we are developing an array of techniques around nanoindentation to study plastic flow, fatigue and wear in small volumes and over a range of temperatures and environments.

Materials for extreme thermal loading

There are many applications that require the rapid removal of heat, but which also demand the control of other properties such as thermal expansivity, sometimes outside the limits of most existing materials. We are looking at how materials might be combined into novel structures allowing even greater heat removal.

Stresses in drying colloidal films

The stresses that develop during the drying of a colloidal film can lead to cracking and changes of shape in the film. Although a very old problem, the origin of these effects is still not understood. When liquid evaporates from a colloid, stresses build up that can lead to fracture or shape changes in the films. This imposes a resolution limit on printing techniques used for making fine structures. Attempts are also being made to use these forces to pattern surfaces. To understand the underlying reasons for the build-up of forces, we have been studying the strains that develop during drying, particularly as the particles become very close to one another.



A nanoindentation in silicon showing the transformation that has occurred under the indent. Note how the material has been squeezed into the crack underneath

LJ Vandeperre, J Wang & WJ Clegg, “Effects of porosity on the measured fracture energy of materials” *Philos. Mag.* **84**, 3689–3704 (2004).

SJ Lloyd, A Castellero, F Giuliani, Y Long, KK McLaughlin, JM Molina-Aldareguia, NA Stelmashenko & WJ Clegg, “Observations of nanoindents via cross-sectional transmission electron microscopy: a survey of deformation mechanisms” *Proc. Roy. Soc. (London) A* **461**, 2521–2543 (2005).

DM Holmes, RV Kumar & WJ Clegg, “Cracking during lateral drying of alumina suspensions” *J. Amer. Ceram. Soc.* **89**, 1908–1913 (2006).

WJ Clegg, F Giuliani, Y Long, SJ Lloyd & JM Molina-Aldareguia, “Hardness of multilayered ceramics” in *Ceramic Matrix Composites: Microstructure, Properties and Applications*, ed. IM Low, pp. 216–240, Woodhead Pub. (2006).

Bill Clyne FREng
Professor of Mechanics of Materials

MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334332
twc10@cam.ac.uk
www.msm.cam.ac.uk/mmc/

Composite Materials and Coatings

Our work is within the Gordon Laboratory, a framework for collaboration on the development and improvement of structural materials in various types of industrial and commercial usage. Much of our research is focused on the processing and properties of new types of material and coating, with modelling of both processing and performance characteristics forming an important part of the work. The Laboratory hosts a wide range of facilities for the processing and mechanical interrogation of advanced materials and surface coatings, including a unique set of three nanoindenters, one of which is housed in a vacuum chamber.

Plasma-spray and plasma-electrolytic-oxide coatings

Plasma-sprayed thermal barrier coatings are critical to the performance of gas-turbine engines. Our recent studies have clarified the microstructural changes that can occur under service conditions and the significance of these for the stability of the system. Plasma electrolytic oxidation is a novel surface engineering technology, involving repeated local dielectric breakdown of the growing oxide film. It can generate thick, highly adherent, thermally protective and wear-resistant coatings on a range of metallic alloys. Ongoing work covers process modelling and novel applications.

Metallic-fibre network materials and panels

Highly porous materials made by bonding together metallic fibres (mostly stainless steels) are being studied for various applications, including acoustic damping in gas turbines, with a small aeroengine being used in this work. Similar material is being developed for the core of lightweight metallic panels.

Magneto-mechanical actuation and bone growth stimulation

There is strong current interest in the development of ferromagnetic fibre network layers on prostheses, into which bone tissue growth can be promoted via magnetically-induced straining of the network. This concept is being explored in collaborative programmes, with a new cell-culture laboratory having been created.

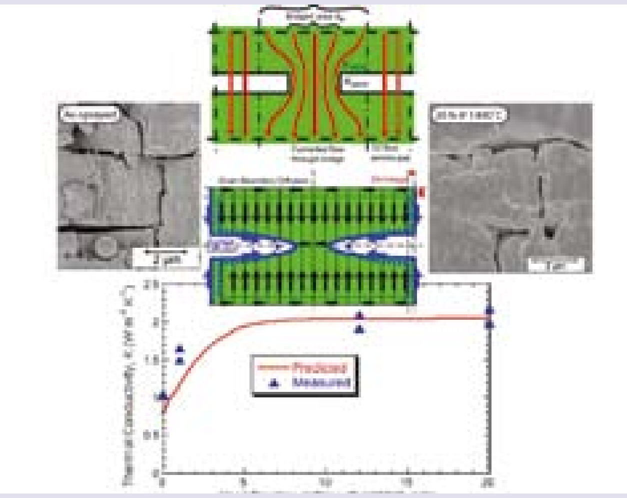
AE Markaki & TW Clyne, “Magneto-mechanical actuation of bonded ferromagnetic fibre arrays” *Acta Mater.* **53**, 877–889 (2005).

JA Curran & TW Clyne, “Porosity in plasma electrolytic oxide coatings” *Acta Mater.* **54**, 1985–1993 (2006).

AJ Muir Wood & TW Clyne, “Measurement and modelling of the nanoindentation response of shape memory alloys” *Acta Mater.* **54**, 5607–5615 (2006).

TW Clyne, IO Golosnoy, JC Tan & AE Markaki, “Porous materials for thermal management under extreme conditions” *Phil. Trans. Roy. Soc. (London) A* **364**, 125–146 (2006).

R Goodall & TW Clyne, “A critical appraisal of the extraction of creep parameters from nanoindentation data obtained at room temperature” *Acta Mater.* **54**, 5489–5499 (2006).



Modelling of the sintering, and associated changes in thermal conductivity, arising during heat treatment of plasma-sprayed zirconia-based thermal barrier coatings

Judith Driscoll

Professor of Materials Science

BSc (Eng) Imperial College
PhD University of Cambridge

+44 (0) 1223 334468
jld35@cam.ac.uk
www.msm.cam.ac.uk/dmg/

Functional Materials

My research is concerned with the materials science of complex functional materials and nanostructures. We grow these materials in many different forms. Our goal is to enhance functional properties. We do this by studying processing – structure – property relations. As well as my position in Cambridge, I am visiting faculty member at Los Alamos National Laboratory.

Functional systems of interest

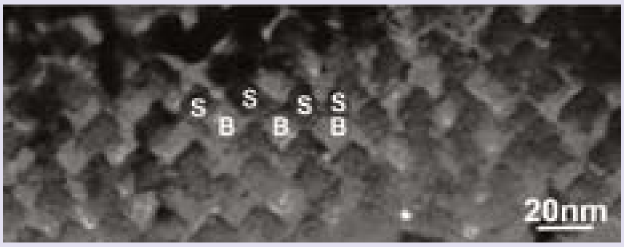
The systems we study are divided between energy-efficient materials and magnetic materials. These include superconductors, dilute magnetic semiconductors (DMS) for spintronics, nanostructured hybrid solar cells, and nanocomposites for multifunctional applications.

Nanomaterials and control of defects

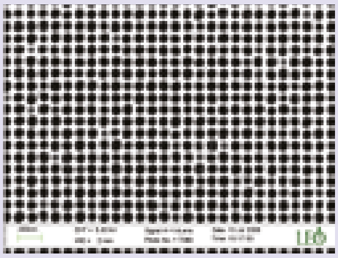
For enhancing functional properties it is necessary to engineer materials and defects on nanometre length scales, e.g. for increasing magnetic flux pinning in superconductors or for controlling carrier concentration and mobility in DMS materials. One way we nanoengineer materials is via a technology we have developed for fabricating ordered anodic alumina nanotemplate thin films on supporting substrates. We are using these nanotemplates in combination with the processing methods below to create large array arrays of magnetic materials, superconductors, or semiconducting oxides for use in hybrid solar cells.

Processing

The processing routes we use for fabricating high-quality materials with controlled structure and composition include both physical vapour deposition and chemical processing routes. We are particularly interested in developing chemically-based soft processing methods including atmospheric-CVD, electrochemical techniques, atomic layer deposition, and hybrid-chemical-physical processes.



Planar TEM of ordered nanocomposite films – image courtesy of H. Wang (Texas A&M)



Ordered alumina nanoporous thin film – courtesy of A. Robinson (Cambridge)

JL MacManus-Driscoll, P Zerrer, HY Wang, H Yang, J Yoon, A Fouchet, R Yu, MG Blamire & QX Jia, “Spontaneous ordering and strain switching in lattice engineered vertical nanocomposite heteroepitaxial oxide films” *Nature Mater.* **7**, 314–320 (2008).

A Robinson, M Hu, G Burnell & JL MacManus-Driscoll, “Large area, ordered, free-standing nanowire arrays on Si grown at room temperature” *Appl. Phys. Lett.* **91**, 143123 (2007).

SR. Foltyn, LCivale, JL MacManus-Driscoll, QX Jia, B Maiorov, H Wang & M Maley, “Materials science challenges for high temperature superconducting wire, *Nature Mater.* **6**, 631–642 (2007).

SK Chen, M Wei & JL MacManus-Driscoll, “Strong pinning enhancement in MgB_2 using very small Dy_2O_3 additions” *Appl. Phys. Lett.* **88**, 192512 (2006).

N Khare, MJ Kappers, M Wei, MG Blamire & JL MacManus-Driscoll, “Defect-induced ferromagnetism in cobalt-doped ZnO” *Adv. Mater.* **18**, 1449–1452 (2006).

Caterina Ducati
Royal Society University Research Fellow

Laurea Università Statale di Milano
PhD University of Cambridge

+44 (0) 1223 334566
cd251@cam.ac.uk
www-hrem.msm.cam.ac.uk/people/ducati

High-Resolution Electron Microscopy of Nanomaterials

My main research interest is nanomaterials, and in particular the relationships between their morphology, their crystallographic phase and their electronic properties, for applications in photocatalysis and electronics. Since the beginning of my PhD, I have been working on the characterization of carbon nanotubes and semiconductor nanowires, aiming for a better understanding of their growth mechanisms. As a member of the High-Resolution Electron Microscopy Group, I have access to a range of advanced tools for the analysis of materials at the nanoscale.

Nanostructured metal oxides

In collaboration with a group in Milan, we are studying nanostructured transition-metal (Ti, Pd, W, Sn) oxides produced by supersonic-beam deposition. We are interested in determining their phase equilibria and the evolution of their crystal structure during thermal treatment, for application in resistive sensors for toxic gases.

Carbon nanotube and inorganic nanowire growth

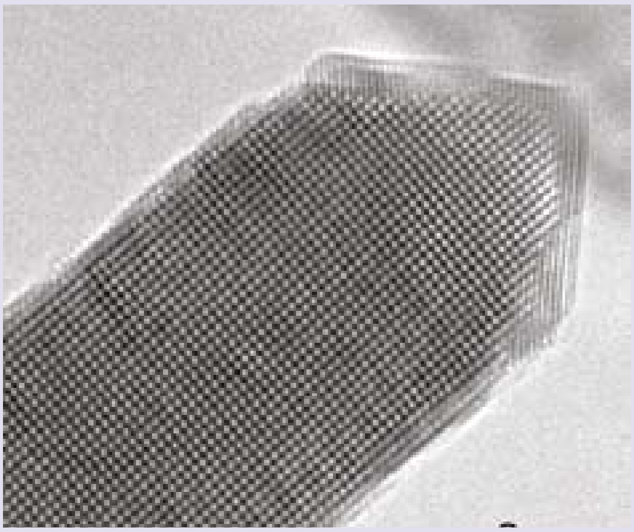
High-aspect-ratio nanostructures such as nanotubes, nanowires and nanorods have attracted a keen interest, both in fundamental research and for advanced applications. Although the synthesis of these nanostructures has been achieved through many different strategies, the exact mechanisms that lead to their formation are not clear and need to be elucidated to control the properties and reliability of these nanoscale "building blocks". We are investigating the growth of nanotubes and nanowires, focusing on the rôle of the metal catalyst that assists the synthesis.

C Ducati, K Koziol, TJV Yates, S Friedrichs, MS Shaffer, PA Midgley & AH Windle, "Crystallographic order in multiwall carbon nanotubes synthesized in the presence of nitrogen" *Small* **2**, 774–784 (2006).

C Ducati, E Barborini, G Bongiorno, S Vinati, P Milani & PA Midgley, "Titanium fullerenoid oxides" *Appl. Phys. Lett.* **87**, 201906 (2005).

C Ducati, DH Dawson, JR Saffell & PA Midgley, "Ruthenium-coated ruthenium oxide nanorods" *Appl. Phys. Lett.* **85**, 5385–5387 (2004).

C Ducati, I Alexandrou, M Chhowalla, J Robertson & GAJ Amaratunga, "The role of the catalytic particle in the growth of carbon nanotubes by plasma enhanced chemical vapor deposition" *J. Appl. Phys.* **95**, 6387–6391 (2004).



High-resolution TEM image of a crystalline ruthenium oxide nanorod synthesized in solution

John Durrell

EPSRC Advanced Research Fellow

MSci Imperial College
PhD University of Cambridge

+44 (0) 1223 331693
jhd25@cam.ac.uk
www.msm.cam.ac.uk/dmg/

Electrical Properties of Superconductors

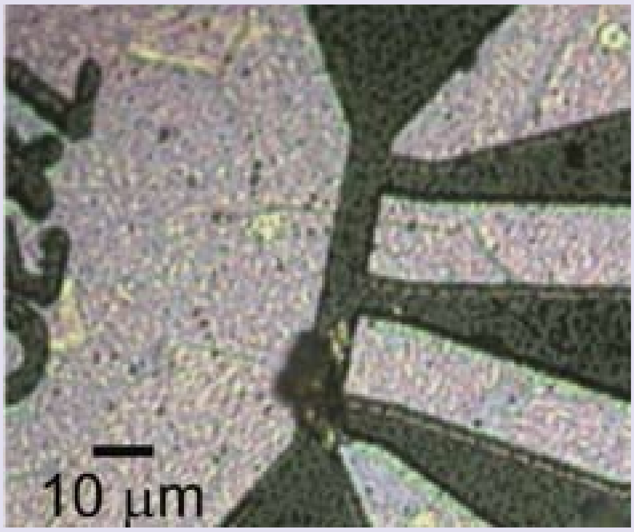
I am interested in the pinning and behaviour of the flux-line lattice in superconductors. This is of importance for the development of commercially useful coated conductor materials, since the critical current (in short the performance) of a superconductor is entirely controlled by the nature and pinning of the vortex lattice. At present I am particularly interested in looking at how the critical currents vary at the micrometre scale in coated conductor materials.

Fundamental properties

The current-carrying capacity, which is the most common figure of merit for a superconductor, is determined by the disposition and pinning of the lines of magnetic flux 'flux vortices' that penetrate into it. I seek to understand how the intrinsic properties of a superconductor affect the flux vortices and by doing so to open routes to improved critical current. This is achieved by studying how the electrical properties of a superconducting material vary with temperature, magnetic field and sample orientation.

Technical materials

Practical superconducting materials are of necessity complex. To reduce the adverse effects of grain boundaries on current flow, a practical material needs to approximate to an infinitely long single crystal; they are thus materials with complex structures varying over tens of micrometres. I study how the critical current in these superconductors varies locally and how this is affected by micro- and macro-structural features. I also study various techniques for enhancing overall critical current.



Micrograph of an isolated grain boundary in a RABiTS superconductor

A Palau, JH Durrell, JL MacManus-Driscoll, S Harrington, T Puig, F Sandiumenge, X Obradors & MG Blamire, "Cross-over between channeling and pinning at twin boundaries in $YBa_2Cu_3O_7$ thin films" *Phys. Rev. Lett.* **97**, 257002 (2006).

NA Rutter, JH Durrell, MG Blamire, JL MacManus-Driscoll, H Wang & SR Foltyn, "Benefits of current percolation in superconducting coated conductors" *Appl. Phys. Lett.* **87**, 162507 (2005).

JH Durrell, G Burnell, VN Tsaneva, ZH Barber, MG Blamire & JE Evetts, "Critical currents in vicinal $YBa_2Cu_3O_{7-\delta\delta}$ films" *Phys. Rev. B* **70**, 214508 (2004).

JH Durrell, MJ Hogg, F Kahlmann, ZH Barber, MG Blamire & JE Evetts, "The critical current of $YBa_2Cu_3O_{7-\delta}$ low angle grain boundaries" *Phys. Rev. Lett.* **90**, 247006 (2003).

James Elliott
Lecturer
MA University of Cambridge
PhD University of Bristol

+44 (0) 1223 335987
jae1001@cam.ac.uk
www.elliotts.org.uk

Materials Modelling

With modern computational techniques, it is now possible to predict the properties of novel materials from first principles using advanced simulation techniques. This has the advantages of being both quicker and cheaper than a trial-and-error experimentation process, and also yields detailed structural and dynamical information that can provide a stringent test of theoretical models. Often, the phenomena of interest in industrial processes occur over much larger length and time scales than those at the underlying molecular level, requiring the use of a multi-scale modelling approach, which is a theme that unifies my research in several diverse materials systems.

Pharmaceutical materials science

The essence of pharmaceutical materials science is the application of fundamental concepts in the physical sciences to the challenges of understanding the behaviour of soft, mostly organic, crystalline, and amorphous materials of relevance to the pharmaceutical industry. My work focuses on the simulation of powder compaction using discrete and finite-element modelling, coupled with use of novel imaging techniques, such as X-ray microtomography, to validate these models.

Polymeric membranes for fuel-cell applications

The archetypal perfluorosulfonic acid membrane (PFSA) Nafion, manufactured by DuPont and utilized as an electrolyte in a wide range of fuel-cell and other redox applications, has been known since the mid-1960s, but continues to elude a self-consistent structural description from the molecular to the macroscopic level. My work involves simulating the morphology and ion-transport properties of PFSA membranes, with the aim of developing novel polymers with improved properties for use in fuel cells.

Nanotubes and composite materials

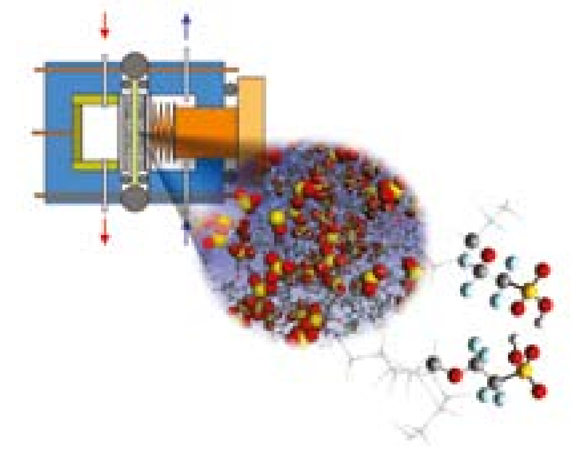
Nanoparticulates, such as carbon nanotubes, can imbue thermoplastic polymers with greatly improved mechanical and electrical properties for use in functional materials. Using molecular and mesoscale modelling techniques, the theoretical properties of novel structures can be investigated and used to inform exploratory experimental studies, and to test hypotheses about interaction of matrix and filler.

JA Elliott, JKW Sandler, AH Windle, RJ Young & MSP Shaffer, “Collapse of single-wall carbon nanotubes is diameter dependent” *Phys. Rev. Lett.* **92**, 095501 (2004).

CY Wu, O Ruddy, AC Bentham, BC Hancock, SM Best & JA Elliott, “Modelling the mechanical behaviour of powders during compaction” *Powder Technol.* **152**, 107–117 (2005).

SJ Paddison & JA Elliott, “Molecular modeling of the short-side-chain perfluorosulfonic acid membrane” *J. Phys. Chem. A* **109**, 7583–7593 (2005).

SS Rahatekar, M Hamm, MSP Shaffer & JA Elliott, “Mesoscale modelling of electrical percolation in fibre-filled systems” *J. Chem. Phys.* **123**, 134702 (2005).



Schematic of a hydrogen fuel cell (left), showing enlarged sections of the membrane electrode assembly (middle) and atomic structure of polymer electrolyte membrane (right) generated using molecular dynamics and electronic density functional calculations, respectively

Derek Fray FREng FRS

Professor of Materials Chemistry

BSc Imperial College
PhD Imperial College

+44 (0) 1223 334306
djf25@hermes.cam.ac.uk
www.msm.cam.ac.uk/djf/

Sustainability, Sensors and Nanostructures

Our motivation is to apply materials chemistry to problems that are scientifically interesting and technologically challenging.

Reduction of metal oxides

A novel electrochemical method is being investigated for the reduction of metal oxides where the metal oxide or mixture of metal oxides is the cathode in a bath of molten calcium chloride. The oxygen ionizes, dissolves in the electrolyte, and is discharged at the anode. This process has also being considered by NASA for the production of oxygen on the moon from the moon regolith. Two companies have been set up to exploit this technology.

Development of sensors

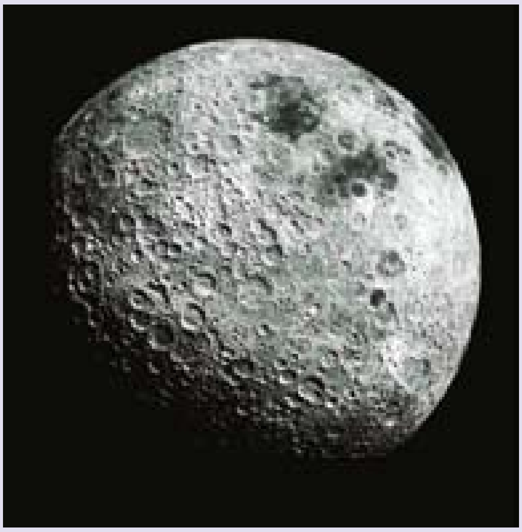
It is important to be able to instantaneously measure species in gases, liquids and solids. Sensors, based upon solid electrolytes have been developed to measure hydrogen in molten aluminium, hydrogen in steel and SO_x from power stations. Ion Science Ltd and Environmental Monitoring and Control Ltd have been set up to market these devices.

Nanostructures

Carbon and sulfide nanotubes are being synthesized by novel routes. These interesting materials are being investigated as electrodes in supercapacitors and batteries.

Recycling

The world has finite resources and it is important to be able to recycle waste products. Processes for treating galvanized scrap, batteries and electronic scrap have been devised and are now being developed industrially.



Surface of the moon

XY Yan & DJ Fray, “Electrosynthesis of NbTi and Nb_3Sn superconductors from oxide precursors in $CaCl_2$-based melts” *Adv. Funct. Mater.* **15**, 1757–1761 (2005).

C Schwandt & DJ Fray, “The titanium/hydrogen system as the solid-state reference in high-temperature proton conductor-based hydrogen sensors” *J. Appl. Electrochem.* **36**, 557–565 (2006).

JKS Tee & DJ Fray, “Separation of copper from steel” *Ironmaking & Steelmaking* **33**, 19–23 (2006).

Y Li, VP Kotzeva & DJ Fray, “Electrochemical performance of CdS nanomaterials synthesized by microemulsion techniques” *Mater. Lett.* **60**, 2743–2746 (2006).

Bartek Glowacki

Reader in Applied Superconductivity

MSc University of Wrocław
MA University of Cambridge
PhD Polish Academy of Sciences

+44 (0) 1223 331738
bag10@cus.cam.ac.uk
www.msm.cam.ac.uk/ascg/

Applied Superconductivity and Cryoscience

We take a broad, multidisciplinary approach to applied superconductivity. Our research is focused on the phenomena associated with high- and low-temperature superconductivity, where quantum physics blends with heavy industry; this includes aspects from most materials disciplines, including physical metallurgy, composites, materials chemistry, modelling, electromagnetic devices and medical materials. We are also actively promoting superconductivity using animation and film in collaboration with research centres across Europe: http://www.msm.cam.ac.uk/ascg/lectures/.

Superconducting conductors for applications

Development research includes the design and fabrication of advanced superconductors, and their characterization and optimization, for applications including high-resolution MRI, NMR, fusion, energy storage and fault current limiters. Materials under investigation span the entire T_c range, including $REBa_2Cu_3O_7$, MgB_2, Nb_3Sn and Nb_3Al. We are developing advanced multi-ceramic ink-jet printing of 3D multifilamentary magnetic-superconducting heterostructures with nanosize artificial pinning centres, to reduce hysteretic AC losses in high-current coated conductors. Our innovative pulsed transport current (4 kA) and magnetic field (32 T) testing facilities enable rapid definition of the pinning force of conductors under development. Characterization of the percolative character of the critical current in superconductors involves the use of sophisticated magnetic and magneto-optic sensors combined with electron backscattering microscopy and computer modelling of current flow. We are also expanding our materials modelling activities, using the new CamGrid high-throughput computing network, to better understand and optimize $REBa_2Cu_3O_7$, MgB_2 and Nb_3Sn conductors.

Hydrogen technology and cryoscience

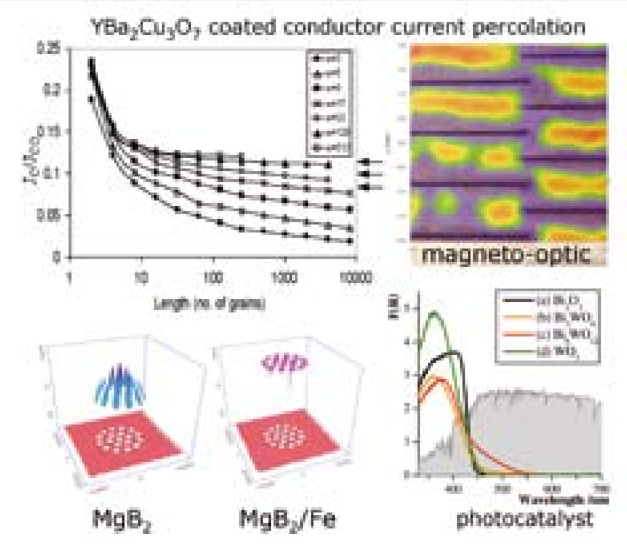
Our cryoscience research integrates research into photocatalytic hydrogen-oxygen production using Bi-W-O for fuel and cryogenic purposes with MgB_2 materials development. We are engaged in an academic and industrial partnership to develop MgB_2 coils for an adiabatic demagnetization refrigerator, and are also developing advanced cryocooler-based laboratory systems for in-depth low-temperature materials and cryogen characterization.

BA Glowacki, M Majoros, M Eisterer, S Toenies, HW Weber, M Fukutomi, K Komori & K Togano, “MgB_2 superconductors for applications” *Physica C* **387**, 153–161 (2003).

M Majoros, RI Tomov, BA Glowacki, AM Campbell & CE Oberly, “Hysteresis losses in YBCO coated conductors on textured metallic substrates” *IEEE Trans. Appl. Supercond.* **13**, 3626–3629 (2003).

BA Glowacki, “High-T_c superconducting conductors for AC and DC applications” in *Studies of HTS superconductor applications: Advances in Research and Applications*, vol. 1 *Materials*, ed. A Narlikar, pp.239–279, Springer (2003).

AP Finlayson, E Ward, VN Tsaneva & BA Glowacki, “Bi_2O_3-WO_3 compounds for photocatalytic applications by solid state and viscous processing” *J. Power Sources* **145**, 667–674 (2005).



Lindsay Greer

Professor of Materials Science

MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334308
alg13@cam.ac.uk
www.msm.cam.ac.uk/mkg/

Microstructural Kinetics

My interest is in how materials change their structures. Understanding the mechanisms of these transformations is relevant not only for assessing the stability of materials, but also for developing new microstructures, properties and functionalities.

Metallic glasses

One route to new structures is to move further from equilibrium, and metallic glasses are a good example. Now that metallic glasses are available with minimum sections of the order of 1 cm, there is much interest in their mechanical properties, notably their exceptionally high strength, elastic strain and elastic energy-storage capacity. We focus on the mechanisms of plastic flow under ambient conditions.

Phase nucleation

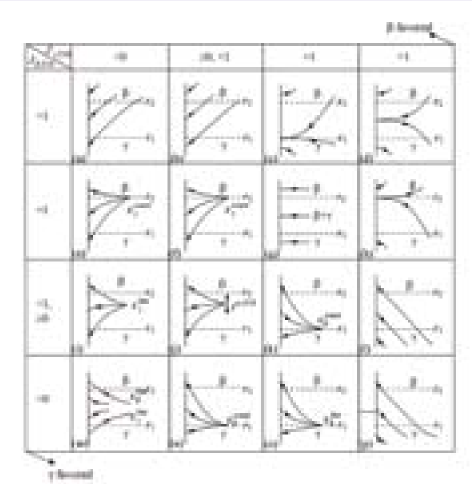
Nucleation is the first step in phase transformations. Deliberate promotion of nucleation, whether in industrial processing such as the grain refinement of aluminium, or the control of ice formation by living systems, remains imperfectly understood, but our recent work shows that the nucleation kinetics can be quantitatively predicted.

Chalcogenides for data storage

Chalcogenide alloys can be reversibly switched between glassy and crystalline states. This switching can be exploited in data storage, whether in DVDs or RAM. It is also of interest in cognitive computing. Our research, challenging because of the ultra-short switching times, focuses on maximizing data-storage density.

Electromigration

The migration of atoms when an electrical current flows in a material gives reliability problems in integrated circuits, but can also be used to develop novel structures. The competition between the effects of current and those of composition gradient (shown in the figure) is highlighted and exploited in our work.



Theoretical survey of how imposed electrical currents can dramatically influence the growth of intermetallic layers at bimetallic junctions

TE Quested & AL Greer, “Athermal heterogeneous nucleation of solidification” *Acta Mater.* **53**, 2683–2692 (2005).

AL Greer & ND Mathur, “Materials science: Changing face of the chameleon” *Nature* **437**, 1246–1247 (2005).

JJ Lewandowski & AL Greer, “Temperature rise at shear bands in metallic glasses” *Nature Mater.* **5**, 15–18 (2006).

HT Orchard & AL Greer, “Electromigration effects on intermetallic growth at wire-bond interfaces” *J. Electron. Mater.* **35**, 1961–1968 (2007).

Colin Humphreys CBE FREng

Emeritus Goldsmiths' Professor of Materials Science

BSc Imperial College
PhD University of Cambridge
MA University of Oxford
Hon DSc University of Leicester

+44 (0)1223 334457
colin.humphreys@msm.cam.ac.uk
www.msm.cam.ac.uk/GaN

Gallium Nitride, Electron Microscopy and Aerospace

My research is broad and covers three main areas: gallium nitride materials and devices; advanced electron microscopy; and high-temperature aerospace materials.

Gallium-nitride materials and devices

Gallium nitride (GaN) is probably the most important semiconductor material since silicon. It emits brilliant light as well as being a key material for next-generation transistors. The Cambridge Centre for Gallium Nitride in the Department has world-class growth and characterization facilities. On the same site we have a six-wafer MOCVD growth system, plus a range of world-class characterization equipment, including advanced electron microscopy and analysis, high-resolution X-ray diffraction, atomic-force microscopy, photoluminescence mapping, etc. My group of about 20 works at the cutting edge of GaN research worldwide. Our research goes from fundamental studies through to applications in LEDs and lasers, including next-generation solid-state lighting and UV LEDs for purifying water in the developing world.

Advanced electron microscopy and analysis

We are developing and applying a range of advanced electron microscopy techniques. For example, we have pioneered energy-filtered secondary-electron imaging in scanning electron microscopy for the mapping of dopants in silicon and other semiconductor devices. We are applying high-resolution electron microscopy, electron-energy-loss spectroscopy and electron holography to gallium nitride based structures in particular. An aberration-corrected and monochromated electron microscope will shortly be delivered, which together with a new dual-beam focused-ion-beam instrument will keep electron microscopy at Cambridge as a world-class centre (see www.msm.cam.ac.uk/hrem).

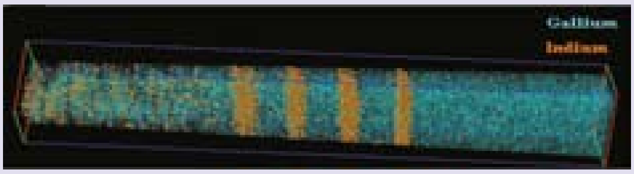
High-temperature aerospace materials

The Department contains the Rolls-Royce University Technology Partnership in Advanced Materials. We are designing and developing higher-temperature advanced alloys that will improve the efficiency of gas-turbine engines, resulting in reduced fuel consumption and reduced emissions.

P Kazemian, SAM Mentink, C Rodenburg & CJ Humphreys, "High resolution quantitative two-dimensional dopant mapping using energy-filtered secondary electron imaging" *J. Appl. Phys.* **100**, 054901 (2006).

MJ Galtrey, RA Oliver, MJ Kappers, CJ Humphreys, DJ Stokes, PH Clifton & A Cerezo, "Three-dimensional atom probe studies of an In$_x$Ga$_{1-x}$N/GaN multiple quantum well structure: Assessment of possible indium clustering" *Appl. Phys. Lett.* **90**, 061903 (2007).

DM Graham, P Dawson, GR Chabrol, NP Hylton, D Zhu, MJ Kappers, C McAleese & CJ Humphreys, "High photoluminescence quantum efficiency InGaN multiple quantum well structures emitting at 380 nm" *J. Appl. Phys.* **101**, 033516 (2007).



3-D atom-probe image of InGaN/GaN quantum wells. Each dot represents a single atom: light blue is gallium and orange is indium

Kevin Knowles

Senior Lecturer

MA University of Cambridge
DPhil University of Oxford

+44 (0) 1223 334312
kmk10@cus.cam.ac.uk
www.msm.cam.ac.uk/kmk10/

Inorganic Microstructures

We focus on the relationship between microstructure and the mechanical and electronic properties of engineering ceramics. In addition to mathematical modelling, transmission electron microscope techniques are routinely used, as well as scanning electron microscopy, X-ray diffraction, mechanical testing and electrical characterization.

Anodic bonding

Anodic bonding is one of the most important silicon-packaging techniques currently used in industry. Work has been undertaken to understand the complex nature of this process. This has required an understanding of a wide range of materials science, ranging from the science of asperity contacts in the presence of electrostatic fields to the subtleties of electrochemical reactions and the formation of cation depletion layers at anodic interfaces in the presence of d.c. electric fields.

Zinc-oxide-based varistor materials

Varistor materials based on the ZnO–V_2O_5–MnO system which can be sintered at 900°C offer the prospect of replacing current multi-component systems that require higher processing temperatures. These varistor systems are also of interest in their own right for basic scientific studies on varistor action because of their relative chemical simplicity.

van der Waals forces at interfaces in ceramic materials

Although van der Waals forces are weak at micrometre-scale particle separations, they become significant at the nanometre level and are significant contributors to the cohesion and interfacial energies of engineering ceramics in which nanometre-thick films reside at grain boundaries after high-temperature processing. The extension of van der Waals theory to interactions between anisotropic media at the nanoscale is being explored in the context of novel nanomaterials such as graphene and carbon nanotubes, as well as highly optically anisotropic ceramics such as particles of rutile and calcite, and anisotropic biomaterials.

Transmission-electron micrograph of dendritic nanocrystalline γ-alumina structures at an anodically bonded Pyrex-Al interface

ATJ van Helvoort, KM Knowles, R Holmestad & JA Fernie, "Anodic oxidation during electrostatic bonding" *Philos. Mag.* **84**, 505–519 (2004).

H Pfeiffer & KM Knowles, "Effects of vanadium and manganese concentrations on the composition, structure and electrical properties of ZnO-rich MnO_2–V_2O_5–ZnO varistors" *J. Eur. Ceram. Soc.* **24**, 1199–1203 (2004).

KM Knowles, "Dispersion forces at planar interfaces in anisotropic ceramics" *J. Ceram. Proc. Res.* **6**, 10–16 (2005).

KM Knowles & ATJ van Helvoort, "Anodic bonding" *Int. Mater. Rev.* **51**, 273–311 (2006).

Krzysztof Koziol
Royal Society University Research Fellow
MSc Silesian University of Technology
PhD University of Cambridge

+44 (0) 1223 334335
kk292@cam.ac.uk
www.msm.cam.ac.uk/polymer/

Chirality Control of Carbon Nanotubes

My research work within the Macromolecular Materials Laboratory involves exploration of the synthesis and applications of substrate-bound and gas-phase-grown carbon nanotubes further spun into fibres. My major focus is to understand the chemistry during the nanotube synthesis in order to achieve chirality control.

Synthesis of monochiral carbon nanotubes

This project is intended to explore a new synthesis method discovered during my PhD research that promises chirality control of nanotubes. Although that goal has not yet been reached, using this process multi-walled nanotubes can be made in which each layer shows the same graphene chirality with crystallographic registry between the layers.

High-performance carbon-nanotube fibres for power transmission

I am developing and optimizing different spinning routes for carbon-nanotube fibres with unique chemical structure. Two promising methods are via a liquid crystal base and directly from the gas phase from the reactor. These carbon-nanotube fibres have potential as lightweight materials to deliver high electrical conductivity and high current density.

Mechanical and thermal properties of carbon-nanotube fibres

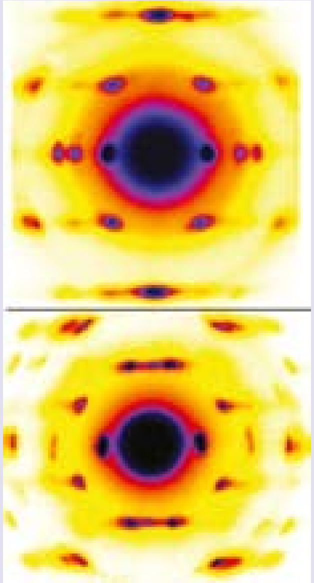
High strength, stiffness and thermal conductivity are important properties in high-performance materials used in advanced technologies and under extreme conditions. In this project I am exploring different post-spin treatments of the nanotube fibres, involving physical or chemical methods.

S Zhang, K Koziol, I Kinloch & AH Windle, "Macroscopic fibres of well-aligned carbon nanotubes by wet-spinning" *Small*, **4** 1217–1222 (2008).

K Koziol, J Vilatela, A Moisala, M Motta, P Cunniff, M Sennett & AH Windle, "High-performance carbon nanotube fiber" *Science* **318**, 1892–1895 (2007).

K Koziol, T Kasama, P Barpanda, R Dunin-Borkowski & AH Windle, "Electron holography of ferromagnetic nanoparticles encapsulated in three-dimensional arrays of aligned carbon nanotubes", *Mater. Res. Soc. Symp. Proc.*, **962E**, (2006), J. Fassbender, J. Chapman & C.A. Ross, Eds., Materials Research Society, Warrendale, PA, pp. P13-03.1–6.

K Koziol, M Shaffer & AH Windle, "Three-dimensional internal order in multiwall carbon nanotubes grown by chemical vapour deposition" *Adv. Mater.* **17**, 760–763 (2005).



Electron diffraction patterns of armchair and zigzag multi-walled monochiral carbon nanotubes

R Vasant Kumar

Senior Lecturer

BTech IIT Bombay
PhD McMaster University

+44 (0) 1223 334327
rvk10@cam.ac.uk
www.msm.cam.ac.uk/djf/

Materials Chemistry

Energy devices

We are advancing innovative approaches to develop the next generation of ultra-high-energy and power-density batteries based on novel Li chemistries, new electrolytes and specially engineered electrodes. Research on solid-oxide fuel cells is based on optimizing the atomic architecture of the solid electrolytes to improve conductivity and stability for low-temperature applications. A novel method of doping electrolytes and electrodes has also been developed.

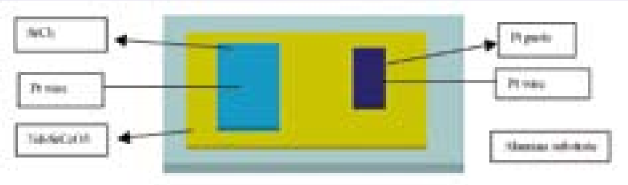
Sensors

Investigation into operating solid-state ionic sensors in electrochemically active mode has led to many practical applications such as on-board diagnostics in gas sensing, self-cleaning chemical sensors and mixed potential sensors for industrial usage. We have also pioneered the use of electrochemical chains by interfacing several solid-state ionic systems in series or parallel for responding to molecular species such as SO_x, NO_x, H_2S, HCl, H_2O, CO, CO_2 and many others. We are also working on: achieving smart sensors that can self-actuate and self-tune; miniaturization; bio-sensing; safety; energy reduction; and solving many environmental problems.

Recycling and sustainability

New strategies for recycling lead-acid batteries have been developed and patented such that precursors for battery plates are directly produced in an environmentally sound process that is sustainable with respect to both materials and energy. Using MATLAB, modelling work has been used to advance environmentally friendly processes using low-energy and low C-print for metal production, refining and recycling.

Hydrogen probe in plant trial



Schematic diagram of an HCl gas sensor fabricated by screen printing

B Khoshandam, RV Kumar & E Jamshidi, “Producing chromium carbide using reduction of chromium oxide with methane” *AIChe. J.* **52**, 1094–1102 (2006).

RV Kumar & VP Kotzeva, “Measuring carbon monoxide with a solid electrolyte system” British Patent Application, GB 0520779.0 (2005).

MP Hills, C Schwandt & RV Kumar, “An investigation of current reversal mode for gas sensing with a solid electrolyte” *Int. J. Appl. Ceram. Technol.* **3**, 200–209 (2006).

RV Kumar, “Electrical conducting properties of rare earth doped perovskites” *J. Alloys Comp.* **408,** 463–467 (2006).

RV Kumar, S Sonmez & VP Kotzeva, “Lead Recycling” British Patent Application 2006, GB0622249.1; PCT Application No. PCT/GB2007/004222

John Little
Senior Lecturer
MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334376
jal4@cam.ac.uk

High-Temperature Degradation

Whilst much research effort is aimed at producing novel materials, these materials have, ultimately, to be used in appropriate applications. Many materials, e.g. those used in power generation, be that in a commercial power station or in a jet engine, need to survive exposure to extremes of temperature and pressure if they are to perform their function. My interests lie in understanding the processes involved in high-temperature degradation and in methods that might be used to reduce that degradation.

Metal dusting of commercial heat-resistant alloys

Many industrial processes now utilize chemical conditions which can be highly reducing and contain high pressures of carbon containing gases. We are interested in the process whereby otherwise protective alloys can be attacked in such conditions leading to pitting, internal carbide formation and the ultimate break-up of the alloy into a mixture of particulate metal, oxide and alloy.

Biomaterials as feedstock to power stations

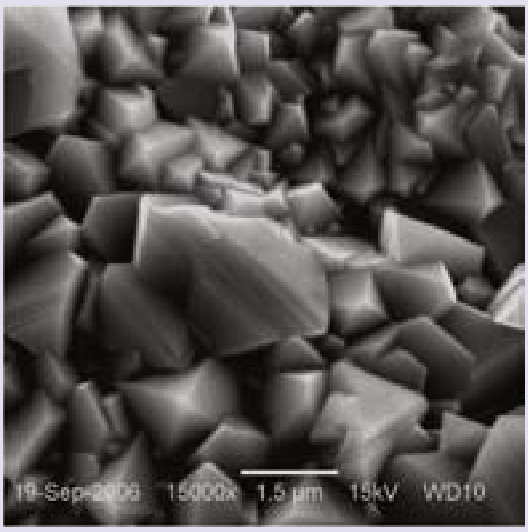
In many parts of Europe there exist large stocks of carbon-containing biomaterial e.g. straw, wood, spent oil and even olive kernels which could be used to augment conventional coal and oil as feedstock to power stations. These materials present very different corrosion problems when used in conventional plants. We are interested in the different problems presented by such biomaterials and in understanding the different chemical processes occurring with the aim of identifying alloys which will better withstand the chemical degradation.

Erosion-corrosion

In many power systems the combined effects of erosion and corrosion present greater problems than either degradation mechanism alone. We are interested in understanding these problems in a range of commercial alloys.

JA Little, C Liu, P Henderson & P Ljung, “Corrosion of X20CrMoV121 and Esshete 1250 heat exchanger alloys under biomass ash deposits” *Corrosion* **57**, 417–430 (2001).

JA Hearley, JA Little & AJ Sturgeon, “The erosion behaviour of NiAl intermetallic coatings prepared by high velocity oxy-fuel thermal spraying” *Wear* **233**, 328–333 (1999).



Surface of 36Fe, 25Cr, 35Ni, 1.6Si, 0.45C heat-resistant alloy after oxidation for 1000 hours at 750ºC

James Loudon

Royal Society University Research Fellow

MA MSci University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334564
jcl25@cam.ac.uk
www-hrem.msm.cam.ac.uk/people/loudon

Imaging Flux Vortices in Superconductors

I work in the High-Resolution Electron Microscopy Group researching the structure and dynamics of flux vortices in superconductors using real-time imaging. Previously, I studied the unconventional phases of mixed-valent manganites at Cambridge and Cornell Universities.

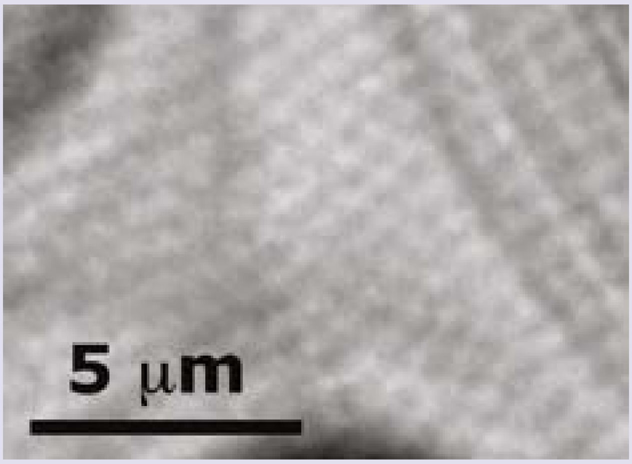
Superconductors and flux vortices

Superconductors have two remarkable properties: they have no electrical resistance whatsoever and expel magnetic flux from their interiors. Applying an increasing magnetic field to an ideal (type-I) superconductor, no flux enters until a critical field strength at which the material suddenly ceases to be superconducting. In contrast, in type-II superconductors, the superconducting state is not wholly destroyed at once but magnetic flux penetrates the material along narrow channels of non-superconducting material called flux vortices. Each vortex contains one quantum of flux: the smallest amount of magnetic flux allowed by the laws of quantum mechanics. To emphasize their quantum nature, they are often called 'fluxons'.

The behaviour of fluxons is crucial to the performance of almost every superconducting device, including superconducting power lines, SQUIDs for very sensitive measurements of magnetic fields, superconducting magnets in medical MRI scanners, and future technologies such as superconductor-based quantum computers. To improve performance, it is necessary to observe fluxons in action to determine their response to pinning sites and other constraints and stimuli.

Imaging flux vortices

We use transmission electron microscopy to observe individual vortices in real time. This technique has a higher resolution than the alternatives and can measure the magnetic fields quantitatively. Worldwide, it had been successfully employed by only two collaborating groups using specially adapted microscopes. However, we have recently imaged vortices with a modern commercial electron microscope (see figure), opening up a world of possibilities. We shall investigate the structure of individual vortices, observe and quantify their dynamics and investigate their response to pinning sites and constrained geometries.



Flux vortices in superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$: A pseudo-hexagonal array of flux vortices in superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ at 20 K in a field of 30 G. Individual vortices are seen as black-white features

JC Loudon, LF Kourkoutis, JS Ahn, CL Zhang, SW Cheong & DA Muller, "Valence changes and structural distortions in 'charge ordered' manganites quantified by atomic-scale scanning transmission electron microscopy" *Phys. Rev. Lett.* **99**, 237205 (2007).

JC Loudon & PA Midgley, "Comparison of the ferromagnetic phase transitions in $La_{0.7}Ca_{0.3}MnO_3$ and single crystal nickel by micromagnetic imaging" *Philos. Mag.*, **86**, 2941–2956 (2006).

JC Loudon & PA Midgley, "Micromagnetic imaging to determine the nature of the ferromagnetic phase transition in $La_{0.7}Ca_{0.3}MnO_3$" *Phys. Rev. Lett.* **96**, 027214 (2006).

JC Loudon & PA Midgley, "Real-space imaging of coexisting charge-ordered and monoclinic phases in $La_{1-x}Ca_xMnO_3$ ($x = 0.67$ and 0.71)" *Phys. Rev. B* **71**, 220408 (2005).

JC Loudon, S Cox, AJ Williams, JP Attfield, PB Littlewood, PA Midgley & ND Mathur, "Weak charge-lattice coupling requires reinterpretation of stripes of charge order in $La_{1-x}Ca_xMnO_3$" *Phys. Rev. Lett.* **94**, 097202 (2005).

Neil Mathur
Reader in Materials Physics
MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 762980
ndm12@cam.ac.uk
www.msm.cam.ac.uk/dmg/

Thin-Film Device Physics

I use thin-film devices to study the physics of materials that display notable electrical and magnetic properties. Thin films present large areas for interfacing and imaging, and thin-film devices collect information from precisely controlled materials and materials combinations. My scientific goals are academic but reflect long-term technological challenges.

Multiferroic and magnetoelectric materials

It is possible to address magnetic materials via an electrical signal, or vice versa. The magnetoelectric coupling that permits this cross-talk suggests applications in sensors, actuators and data storage. Meanwhile, the related challenge of finding multiferroic materials that are both ferromagnetic and ferroelectric remains a hot topic.

Electrocaloric materials

These materials permit the interconversion of heat and electricity. The ability to heat and cool a material via a voltage-driven phase change provides the basis for an electrically driven solid-state heat pump. The reverse effect permits electrical power generation from waste or other heat. Thin films and large electric fields offer an exciting avenue for exploration.

Manganites

Complex magnetic and electronic textures arise naturally in these crystalline perovskite oxides of manganese. By controlling these textures it is possible to explore the links with macroscopic measurements. Studies of this type provoke dreams of some future nanotechnology based on self-organized devices.

Spintronics

Electrons can carry magnetic information over long distances in non-magnetic materials, provided they travel sufficiently fast. Carbon nanotubes are fast electronic conductors, and therefore constitute plausible building blocks for e.g. proof-of-principle spin transistors, or quantum computers based on magnetic qubits.

C Israel, ND Mathur & JF Scott, “A one-cent room-temperature magnetoelectric sensor” *Nature Mater.* **7**, 93-94 (2008).

LE Hueso, JM Pruneda, V Ferrari, G Burnell, JP Valdés-Herrera, BD Simons, PB Littlewood, E Artacho, A Fert & ND Mathur, “Transformation of spin information into large electrical signals using carbon nanotubes” *Nature* **445**, 410–413 (2007).

W Eerenstein, ND Mathur & JF Scott, “Multiferroic and magnetoelectric materials” *Nature* **442**, 759–765 (2006).

AS Mischenko, Q Zhang, JF Scott, RW Whatmore & ND Mathur, “Giant electrocaloric effect in thin-film $PbZr_{0.95}Ti_{0.05}O_3$” *Science* **311**, 1270–1271 (2006).

*Size and cost comparison for a one-cent multilayer capacitor that inadvertently functions as a room-temperature magnetic-field sensor that requires no electrical power [A one-cent room-temperature magnetoelectric sensor. C Israel, ND Mathur & JF Scott, Nature Materials **7**, 93–94 (2008)]*

Paul Midgley

Professor of Materials Science

BSc University of Bristol
MSc University of Bristol
PhD University of Bristol

+44 (0) 1223 334561
pam33@cam.ac.uk
www-hrem.msm.cam.ac.uk

Electron Microscopy

My research is based on the development and application of new electron microscopy techniques to study the structural and functional properties of a variety of materials with high spatial resolution in 2 and 3 dimensions.

Electron tomography

By recording a tilt-series of transmission electron micrographs, using a variety of novel imaging modes, electron tomography can be used to reconstruct the 3-dimensional morphology, defect structure and composition of materials systems with nanometre resolution in all 3 dimensions. Materials studied range from cell sections and bacteria to heterogeneous catalysts, semiconductor quantum dots and aerospace alloys. Recently we have started a research programme developing mesoscale tomography using the dual beam SEM-FIB to link the length scales probed by TEM with those investigated by X-ray methods.

Electron holography and phase-sensitive imaging

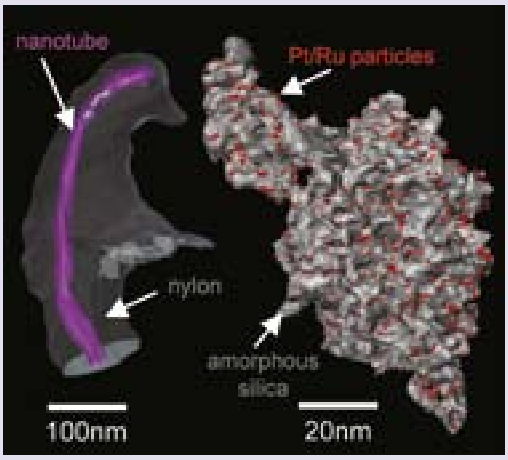
Quantitative off-axis and in-line (Fresnel) electron holography is being used to study the electrostatic potentials at unbiased and biased device junctions in two and three dimensions. Magnetic fields in ferromagnetic thin films and nanoparticle arrays are also being mapped with electron holography. Low-temperature microscopy is being carried out to investigate the structure and dynamics of flux vortices in high T_c superconductors. Vortex contrast is amplified by energy-filtered Lorentz imaging or by the use of a phase plate.

Electron crystallography

Precession electron diffraction is being developed to determine the atomic structure of sub-micrometre particles. This technique, which minimizes the effects of dynamical interaction, can now be used to determine atomic positions to an accuracy approaching that of X-ray diffraction. Why the technique works, and over what range of sample thickness and precession angle, is being investigated. The technique is being used to determine the structure of inorganic and organic crystals, including metal oxides, metal-organic frameworks and pharmaceutical crystals.

Nanoscale structures

Novel structures, including mesoporous catalysts, organic and inorganic nanotubes, and semiconducting nanowires, are being characterized by high-resolution electron microscopy, electron diffraction and electron tomography. The cellular toxicity of fullerenes and carbon nanotubes is investigated by chemical assay and electron tomography.



3D electron-tomographic reconstructions showing (left) a carbon nanotube-nylon composite and (right) a heterogeneous catalyst composed of bimetallic nanoparticles supported by mesoporous silica

PA Midgley & M Weyland, “3D electron microscopy in the physical sciences: the development of Z-contrast and EFTEM tomography” *Ultramicroscopy* **96**, 413–431 (2003).

I Arslan, TJV Yates, ND Browning & PA Midgley, “Embedded nanostructures revealed in three dimensions” *Science* **309**, 2195–2198 (2005).

MH Gass, K Koziol, AH Windle & PA Midgley, “Four-dimensional spectral tomography of carbonaceous nanocomposites” *Nano Lett.* **6**, 376–379 (2006).

JS Barnard, J Sharp, JR Tong & PA Midgley, “High-resolution three-dimensional imaging of dislocations” *Science* **313**, 319 (2006).

Michelle Moram

Oppenheimer Research Fellow

BSc University College Cork
PhD University of Cambridge

+44 (0) 1223 331952
mam65@cam.ac.uk
www.msm.cam.ac.uk/GaN/

Gallium Nitride and Related Materials

The III-nitride semiconductor materials system (currently including AlN, GaN and InN) can be used to create energy-efficient solid-state lighting, solar cells and UV-emitting devices for water treatment. My work is aimed both at understanding the fundamental issues limiting device performance and at creating new techniques and materials to overcome these problems.

Novel III-nitrides

Although AlN, GaN, and InN are currently used in devices, I am interested in the growth and study of transition metal nitrides and their alloys with III-nitrides for potential device applications, as well as in conventional III-nitride films grown in novel nonpolar and semipolar crystal orientations.

Defect reduction

Defects (including dislocations and stacking faults) can limit the efficiency of III-nitride devices such as UV LEDs and lasers. I am interested in understanding defect generation processes and defect properties, as well as finding new ways to reduce defect densities.

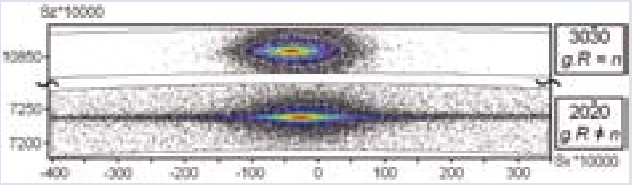
X-ray diffraction

X-ray diffraction (XRD) is rapid, non-destructive and can be used to characterize defect densities in III-nitride films. In particular, I am interested in extending XRD analysis methods to III-nitride quantum dots, network structures and other low-dimensional systems.

MA Moram, ZH Barber & CJ Humphreys, “The effect of oxygen incorporation in sputtered scandium nitride films” *Thin Solid Films* (2008) in press

MA Moram, Y Zhang, MJ Kappers, ZH Barber & CJ Humphreys, “Dislocation reduction in gallium nitride films using scandium nitride interlayers”, *Appl. Phys. Lett.* **91**, 152101 (2007).

MA Moram, ZH Barber & CJ Humphreys, “Accurate experimental determination of the Poisson’s ratio of GaN using high-resolution X-ray diffraction”. *Appl. Phys.* **102**, 023505 (2007).



X-ray diffraction reciprocal-space maps of the GaN $20\bar{2}0$ and $30\bar{3}0$ reflections, the former showing a weak streak due to the presence of stacking faults in the film

Rachel Oliver

Royal Society University Research Fellow

MEng University of Oxford
PhD University of Oxford

+44 (0) 1223 334469
rao28@cam.ac.uk
www.msm.cam.ac.uk/GaN/pages/research/oliver.htm

Nitrides at the Nanoscale

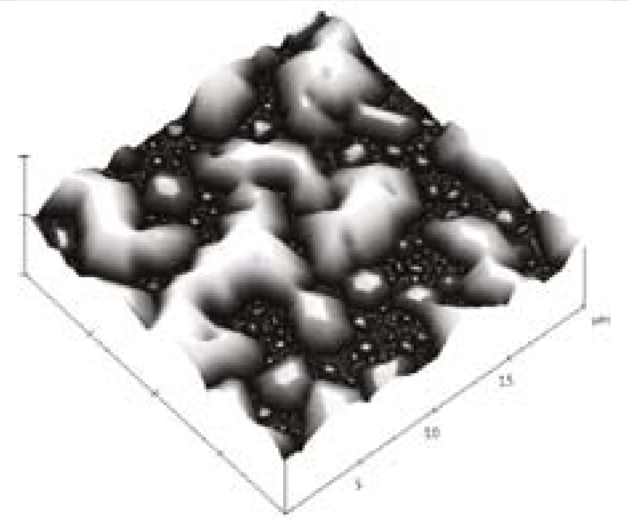
Working in the Cambridge GaN centre, my research focuses on the characterization and exploitation of nanoscale structures in GaN-based materials. The broad aim of my work is to achieve improved performance in GaN-based optoelectronic devices and to develop and implement novel device concepts.

Novel microscopy techniques for nitride semiconductors

To improve the performance of GaN-based devices we need to understand their structure and electronic properties on a micro- to nano-metre scale. New techniques are being developed to meet the demands of this unusual semiconductor. Our work involves: (a) applications of atomic-force microscopy (AFM) to studies not only of nitride surface topography but also of the electrical properties of nitride materials at length scales as small as 10 nm; and (b) exploiting the three-dimensional atom-probe microscope (3DAP) to determine the composition of GaN alloys, particularly InGaN quantum wells, in 3D, at a sub-nanometre scale.

GaN-based single photon sources

Early single-photon sources emitting in the visible spectral region were based on heavy attenuation of a laser; such sources are intrinsically unreliable, and may emit multiple photons. In contrast, we aim to build a single-photon source, based on InGaN quantum dots, that is reliable and easy to operate. Such a device would find broad application in quantum cryptography and quantum computing, particularly as the emission wavelength of the InGaN dots is rather convenient in terms of available detectors. However, the high defect density and unusual electrical properties of GaN make realising the device a challenge.



Three-dimensional render of an atomic-force micrograph of hexagonal GaN islands grown on sapphire

AF Jarjour, RA Taylor, RA Oliver, MJ Kappers, CJ Humphreys & A Tahraoui "Cavity-enhanced blue single-photon emission from a single InGaN/GaN quantum dot" *Appl. Phys. Lett.* **91**, 052101 (2007).

MJ Galtrey, RA Oliver, MJ Kappers, CJ Humphreys, DJ Stokes, PH Clifton & A Cerezo, "Three dimensional atom probe studies of an $In_xGa_{1-x}N$/GaN multiple quantum well structure: assessment of possible indium clustering" *Appl. Phys. Lett.* **90**, 061903 (2007).

RA Oliver, MJ Kappers & CJ Humphreys, "Insights into the origin of threading dislocations in GaN/Al_2O_3 from atomic force microscopy" *Appl. Phys. Lett.* **89**, 011914 (2006).

RA Oliver, GAD Briggs, MJ Kappers, CJ Humphreys, JH Rice, JD Smith & RA Taylor, "InGaN quantum dots grown by MOVPE employing a post-growth nitrogen anneal" *Appl. Phys. Lett.* **83**, 755–757 (2003).

Cathie Rae

Lecturer

MA University of Oxford
DPhil University of Oxford

+44 (0) 1223 334333
cr18@cam.ac.uk
www.msm.cam.ac.uk/utc/

Mechanical Properties and Microstructure

Over the last 50 years turbine entry temperatures (TETs) have risen from 800ºC to 1600ºC. Materials developments in all turbine components, are critical to achieving this, but engine designers are looking for a TET of 1800ºC to increase engine efficiency and reduce environmental impact. We focus on understanding the fundamental mechanisms determining the mechanical properties of turbine materials and use this to produce tools and strategies for materials development and life prediction.

Alloy development of fourth-generation single-crystal alloys

Nickel-base single-crystal superalloys can be strengthened by the addition of tungsten and rhenium, but doing so while maintaining reasonable density, stability and environmental resistance requires careful optimization of the composition and microstructure. Our work is aimed at understanding the mechanical properties at all temperatures experienced in service and involves creep LCF and TMF testing, combined with TEM and SEM of the deformed microstructures. In fourth-generation patented alloys developed at Cambridge, the role of ruthenium in stabilising and strengthening the alloys is being investigated. As part of the ‘Alloys by Design’ project, the interactions of dislocations with the γ' precipitates are being modelled using phase-field techniques.

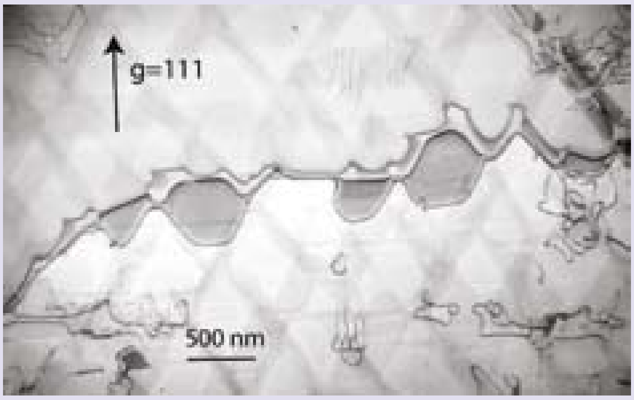
Oxidation and coatings

Thermal-barrier coatings are an integral part of component design: understanding both the oxidation kinetics of nickel-based alloys and their long-term interaction with various coating systems is vital to component lifing and future design strategies. Projects involve the time-dependent oxidation behaviour and oxide morphology, and the compatibility of various coatings with both commercial and experimental nickel-base superalloys. New methodologies, developed in Cambridge, have been adopted by Rolls-Royce as part of their worldwide component lifing strategy.

RA Hobbs, S Tin & CMF Rae, “A castability model based on elemental solid-liquid partitioning in advanced nickel-base single-crystal superalloys” *Metall. Trans. A* **36A**, 2761–2773 (2005).

CMF Rae, MS Hook & RC Reed, “On the precipitation of topological close packed phases at aluminide coatings on superalloys and the effect of precipitate morphology” *Mater. Sci. Eng. A* **396**, 231–239 (2005).

CMF Rae & RC Reed, “Primary creep in single crystal superalloys: Origins, mechanisms and effects” *Acta Mater.* **55**, 1067–1081 (2007).



The picture shows the nickel-based superalloy TMS82 during the early stages of primary creep showing an a⟨211⟩ dislocation ribbon passing through both precipitates and matrix

Noel Rutter

Teaching Fellow

MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 762965
nar20@cam.ac.uk
www.msm.cam.ac.uk/dmg/

Functional Thin Films

My work within the Device Materials Group focuses on the fabrication, modelling and microstructural and electromagnetic characterization of functional thin-film materials, in particular superconducting wires and tapes.

Functional thin-film growth

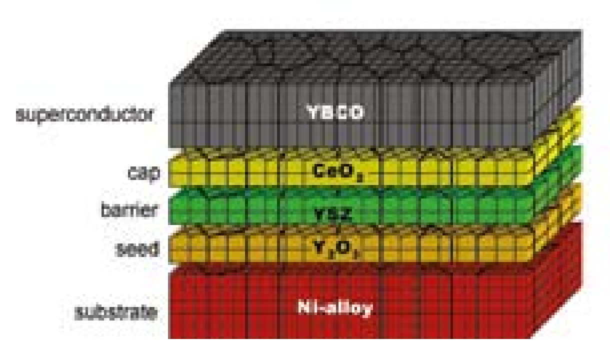
We are interested in optimizing the growth parameters of thin films in order to optimize their functional properties. One example of this is the development of buffer layers and superconducting films for coated conductor tapes. A crucial factor in improving the performance of these materials is a firm understanding of how epitaxial growth occurs for different thin-film deposition methods.

Characterization of superconductors

In order to be commercially viable, superconducting wires must be able to carry substantial currents in magnetic fields. We aim to understand how the microstructure of the superconducting layer in a coated conductor tape determines its maximum current. This is achieved by characterizing the microstructure of films using techniques such as XRD and EBSD in parallel with measurement of the electromagnetic properties of the tapes.

Modelling superconducting current flow

We aim to understand how the microscopic influence of grains and grain boundaries in superconductors determines the macroscopic properties of wires and tapes. We develop mesoscale network models in order to discover which properties are the most important in limiting the performance, depending on the conditions of temperature and magnetic field appropriate to the application. An understanding of the statistical variations of properties within these materials and of the dependence of such variations on processing is required in order to determine the most effective wire configuration.



Schematic of a coated conductor – a stack of thin films on a metallic substrate

NA Rutter, JH Durrell, MG Blamire & JL MacManus-Driscoll, "Benefits of current percolation in superconducting coated conductors" *Appl. Phys. Lett*. **87**, 162507 (2005).

NA Rutter & A Goyal, "Modeling current flow in granular superconductors" in *Studies of High Temperature Superconductors*, New York: Springer (2004).

NA Rutter, BA Glowacki & JE Evetts, "Percolation modelling for highly aligned polycrystalline superconducting tapes" *Supercond. Sci. Technol*. **13**, L25–L30 (2000).

Karl Sandeman
Royal Society University Research Fellow
MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 762982
kgs20@cam.ac.uk
www.msm.cam.ac.uk/dmg/

Magnetic Phase Transitions and Cooling

My work in the Device Materials Group aims to improve fundamental understanding of the transitions between magnetic states in materials. In these days of environmentally aware science, one potential application of this research is in a new, high-efficiency, gas-free cooling device: the magnetic refrigerator.

Magnetic refrigeration

A conventional refrigerator uses the energetic difference between gas and liquid to provide cooling via the expansion and contraction of a volatile refrigerant. In an analogous way, we can harness the energetic differences between magnetic states in suitable solid refrigerants by reversible magnetization and demagnetization. The resulting “magnetocaloric effect” manifests itself by a change in temperature of a magnetic material on adiabatic (de)magnetization. In most cases, magnetization is accompanied by a temperature increase, largest around magnetic phase transitions accompanied by a sharp change in the magnetic state of the material.

Negative magnetocaloric effect

I have focused on an unusual subset of magnetocaloric effects, where magnetization brings about a decrease in the temperature of the magnetic refrigerant. Work to-date is pioneering the study of a new material in this area, and we are now combining ab-initio models, neutron-diffraction experiments and bulk magnetization studies to understand the subtle interplay of magnetic interactions which brings about the negative magnetocaloric effect in our material and in other related systems. This work has led to the foundation of a spin-out company, Camfridge Ltd., which has built several prototype magnetic-cooling engines.

Minimizing magnetic fields

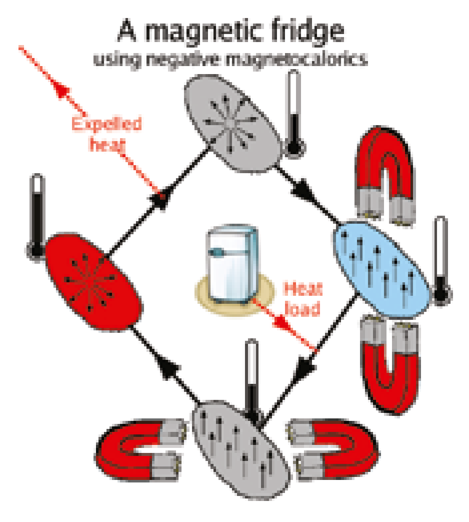
A question of technological importance, and one that also creates interesting scientific possibilities is how to minimize the magnetic fields that are needed to drive the changes of magnetic state we examine. To this end, I am currently combining different applied fields (magnetic, stress etc.) in single phase and multi-phase systems to explore and drive phase transitions in new ways.

KG Sandeman, R Daou, S Özcan, JH Durrell, ND Mathur & DJ Fray, “Negative magnetocaloric effect from highly sensitive metamagnetism in CoMnSi$_{1-x}$Ge$_x$” *Phys. Rev. B* **74**, 224436 (2006).

JHT Ransley, SH Mennema, KG Sandeman, G Burnell, EJ Tarte, JE Evetts & MG Blamire, JI Kye & B Oh, “The normal-state resistivity of grain boundaries in YBa$_2$Cu$_3$O$_{7-\delta}$" *Appl. Phys. Lett.* **84**, 4089–4091 (2004).

KG Sandeman, GG Lonzarich & AJ Schofield, “Ferromagnetic superconductivity driven by changing Fermi surface topology” *Phys. Rev. Lett.* **90**, 167005 (2003).

KG Sandeman & AJ Schofield, “Model of anisotropic scattering in a quasi-two-dimensional metal” *Phys. Rev. B* **63**, 094510 (2001).



Howard Stone

Assistant Director of Research

MA University of Cambridge
PhD University of Cambridge

+44 (0) 1223 334320
hjs1002@cam.ac.uk
www.msm.cam.ac.uk/utc/

High-Temperature Materials

The ongoing drive for improved fuel efficiency and reduced emissions from gas-turbine aeroengines continues to demand materials capable of tolerating ever higher service temperatures. The majority of these applications are served by nickel-base superalloys, but new materials are now also being considered as potential successors to these alloys in many applications.

Nickel-base superalloys

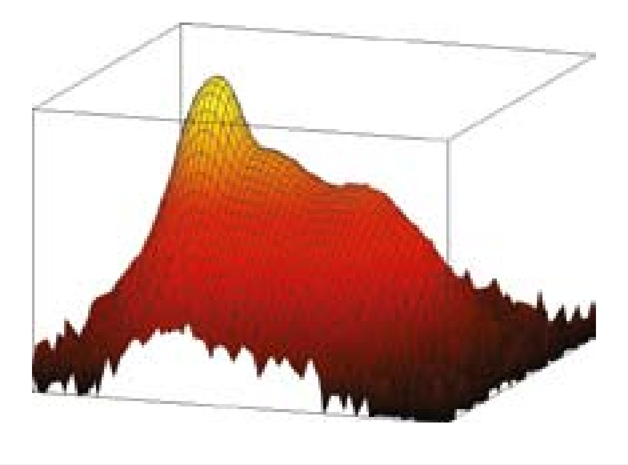
The outstanding combination of properties of nickel-base superalloys has led to their widespread use in hot-section aeroengine components. After many years of research, continued improvements are still being achieved in the conditions that may be tolerated by these materials in service. My research is to develop our understanding of the relationship between the alloy composition, microstructure and properties, and how these are influenced by the processing and service conditions, in order to further improve the properties of these alloys and extend their lives in service.

Novel high-temperature materials

We are investigating novel materials that may provide viable alternatives to nickel-base superalloys in high-temperature applications such as aeroengines. While no material improves on conventional nickel-base superalloys in all regards, an understanding of the conditions that must be tolerated by individual components is leading to the identification and development of novel materials that may enable higher temperatures, stresses, longer lives or lighter components to be achieved.

In-situ characterization of phase transformations

Modern diffraction-based techniques using neutron and synchrotron sources such as the ISIS and ILL neutron sources and the European Synchrotron Radiation Facility offer powerful methods for the in-situ characterization of crystal structures in metals and alloys. With these methods, phase transformations are being studied on timescales of milliseconds and with very high resolution, providing unique insights into these processes.



Reciprocal lattice point of a fundamental reflection from a fourth-generation single-crystal nickel-base superalloy obtained by synchrotron X-ray diffraction

HJ Stone, TM Holden & RC Reed, "On the generation of microstrains during the plastic deformation of Waspaloy" *Acta Mater.* **47**, 4435–4448 (1999).

D Dye, HJ Stone & RC Reed, "Intergranular and interphase microstresses" *Curr. Opin. Solid State Mater. Sci.* **5**, 31–37 (2001).

HJ Stone, MG Tucker, FM Méducin, MT Dove, SAT Redfern, Y Le Godec & WG Marshall, "Temperature measurement in a Paris-Edinburgh cell by neutron resonance spectroscopy" *J. Appl. Phys.* **98**, 064905 (2005).

Rob Wallach
Senior Lecturer

MA University of Cambridge
MSc Queen's University, Canada
PhD University of Cambridge

+44 (0) 1223 334330
erw1@cam.ac.uk
www.msm.cam.ac.uk/joining

Joining of Materials

Individual materials are becoming more specialized and are designed to optimize their performance for specific applications. However for most applications, these highly developed materials have to be joined to others in a manner that ensures a minimal loss in properties or performance. This requires developing new processes and/or the refinement of existing approaches. This forms the basis of my research which is focused on joining materials, generally advanced but not exclusively so, with the emphasis on modelling processes, joint formation and predicting the properties of materials after they are joined.

Diffusion bonding

Our work has focused on fundamental modelling of various processes and on devising a flux-free diffusion-based approach using gallium to join alloys with oxide films. This patent-protected approach has been proven for aluminium, stainless steel and nickel-base superalloys, and has been extended to joining metallic foams to solid metal components. Strengths matching the parent materials are attainable and as well as the fabrication of dissimilar metal joints.

Predicting the performance and modelling the reliability of lead-free soldered joints

Lead-free solders are replacing conventional tin-lead eutectic solder on environmental grounds. These new alloys are being evaluated (e.g. data on creep and fatigue properties) and likely failure mechanisms identified.

High-energy welding processes (electron-beam and laser welding)

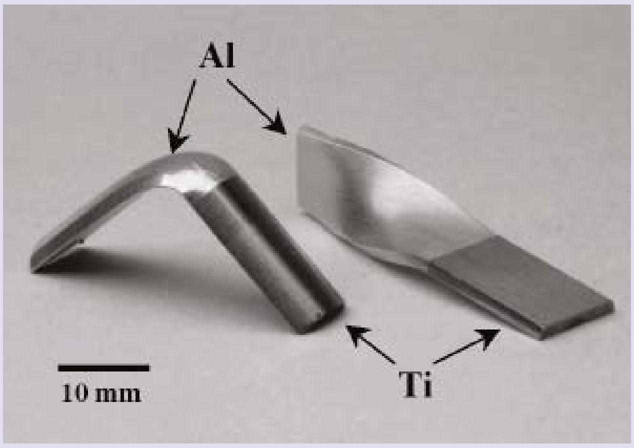
We have modelled the microstructures and properties of laser and hybrid welds in structural and pipe-line steels. Existing models for predicting weld metal and heat affected zone microstructures, and the mechanical properties of laser welds in structural steels are being evaluated. This follows previous research on predicting the formability after laser welding automobile steels to aid lightweight car production.

H Assadi, AA Shirzadi & ER Wallach, "Transient liquid phase diffusion bonding under a temperature gradient: Modelling of the interface morphology" *Acta Mater.* **49**, 31–39 (2001).

AA Shirzadi & ER Wallach, "To provide a non-chemical method to remove the surface oxide from various alloys to improve bonding, and coating processes." British Patent Application 2005, GB2380491; USA Patent Application 2003, 6,669,534 B2, 30.

S Turan, D Turan, IA Bucklow & ER Wallach, "The effect of metal coating on the strength of capacitor-discharge joining of oxide ceramics" *Key Eng. Mater.* **264–268**, 687–690 (2004).

P Moore, D Howse & ER Wallach, "Microstructure and properties of laser/arc hybrid welds and autogenous laser welds in pipeline steels" *Sci. Technol. Welding Joining* **9**, 314–322 (2004).



Diffusion bonds between dissimilar metals (aluminium and titanium) showing excellent mechanical strength

Stuart Wimbush

Leverhulme Trust Early Career Fellow

MPhys University of Salford, UK
PhD TU Dresden, Germany

+44 (0)1223 767140
scw42@cam.ac.uk
www.msm.cam.ac.uk/dmg/

Superconducting Materials

As a member of the Device Materials Group, I am concerned with the pulsed-laser deposition of thin films of high-temperature superconducting materials and the investigation of their properties. My work seeks to bring these materials of the future closer to application through the development of new approaches and techniques to enhance their electrical performance and structural properties.

Practical approaches to enhancing critical current by magnetic pinning

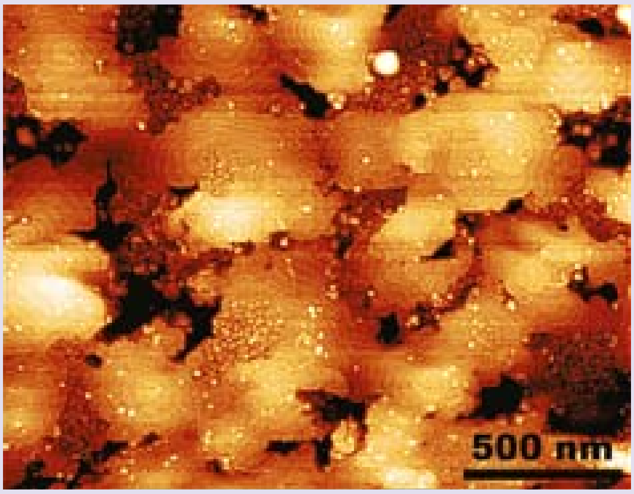
The primary focus of my work is currently the development of practical, industrially relevant processes for enhancing the current carrying capability of the second generation high-temperature superconductor material YBCO by the incorporation of magnetic 'defects' into its crystal structure. Only by achieving first control and then optimization of these dopant materials and their behaviour within the superconductor matrix can the full potential of these materials be realised.

Biomimetic approaches to superconductor synthesis

In collaboration with researchers at the University of Bristol, I investigate novel biotemplating techniques for the chemical synthesis of superconducting phases. By means of these nature-inspired processes, we are able to relax some of the extreme conditions generally required for synthesis of these materials, as well as to achieve improvements in their electrical and mechanical properties.

Novel superconducting materials

As new superconductors are proposed or discovered, I apply the processing techniques at my disposal in the attempt to synthesize these novel phases.



Atomic-force microscopy image of the surface of a YBCO thin film revealing monolayer growth steps and a dispersion of ~10 nm flux-pinning precipitates

SC Wimbush, MC Li, ME Vickers, B Maiorov, DM Feldmann, QX Jia & JL MacManus-Driscoll, "Interfacial strain-induced oxygen disorder as the cause of enhanced critical current density in superconducting thin films" *Adv. Funct. Mater.* (2008) submitted.

ZAC Schnepp, SC Wimbush, S Mann & SR Hall, "Structural evolution of superconductor nanowires in biopolymer gels" *Adv. Mater.* **20**, 1782–1786, (2008)

T Kolodiazhnyi & SC Wimbush, "Spin singlet small bipolarons in Nb-doped $BaTiO_3$" *Phys. Rev. Lett.*, **96**, 246404, (2006).

Alan Windle FRS

Professor of Materials Science

BSc (Eng) Imperial College
PhD University of Cambridge

+44 (0) 1223 334321
ahw1@cam.ac.uk
www.msm.cam.ac.uk/polymer/

Carbon-Based Nanostructures

My research team is based around the creation and exploitation of carbon nanostructures in materials science. In addition, as Director of the Pfizer Institute for Pharmaceutical Materials Science, I have overall responsibility for a wide range of pharmaceutically related materials projects.

Carbon nanotubes

In many ways single-wall carbon nanotubes can be seen as the ultimately rigid polymer molecule, and this perspective has stimulated new routes for processing. Current research centres on a process by which carbon nanotubes form an aerogel in the CVD reaction zone, and are then wound out of the reactor as a continuous fibre. The properties of these fibres show huge promise as a cheaper and better replacement for carbon fibre. The science ranges from reactor thermodynamics and kinetics through issues of orientation and condensation of aerogels to an understanding of the physics of the exceptional properties of the fibre. In addition to their mechanical potential, several projects address the electrical properties of nanotubes, including interaction with electromagnetic radiation, for applications as diverse as power transmission, EM shielding and cancer therapies.

Sequence-controlled self assembly

The availability of peptide oligomers with pre determined amino acid sequences, has opened up the possibility of creating different self-assembled nanostructures to order. Research projects are focused on ‘smart’ coatings for drug particles and also peptide scaffolds to aid healing.

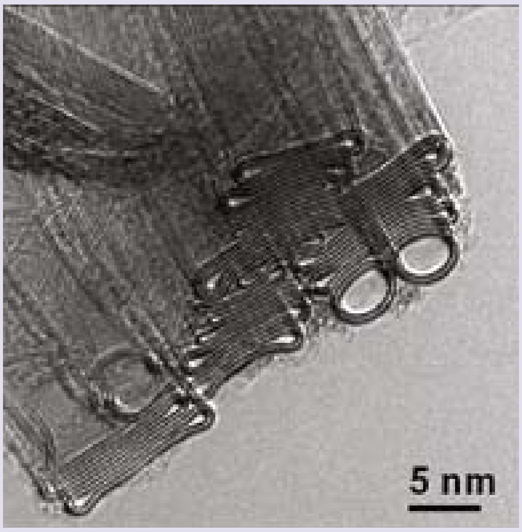
MF Perutz & AH Windle, “Cause of neural death in neurodegenerative diseases attributable to expansion of glutamine repeats” *Nature* **412**, 143–144 (2001).

WH Song, IA Kinloch & AH Windle, “Nematic liquid crystallinity of multiwall carbon nanotubes” *Science* **302**, 1363 (2003).

YL Li, IA Kinloch & AH Windle, “Direct spinning of carbon nanotube fibers from chemical vapor deposition synthesis” *Science* **304**, 276–278 (2004).

K Koziol, M Shaffer & AH Windle, “Three-dimensional internal order in multiwall carbon nanotubes grown by chemical vapour deposition” *Adv. Mater.* **17**, 760–763 (2005).

K Koziol, J Vilatela, A Moisala, M Motta, P Cunniff, M Sennett & AH Windle, “High-performance carbon nanotube fiber” *Science* **318**, 1892–1895 (2007).



Autocollapsed double-wall carbon nanotubes of a high-performance fibre

Dr Rachel Hobson
Research and Business Development Manager

+44 (0)1223 334328
rjh24@cam.ac.uk

Research and Business Development with Industry

With the Department's internationally distinguished record in Materials Science and Metallurgy, it is no surprise that we work with some of the best materials companies in the world, helping them to further their understanding of their materials technology and develop leading-edge products. We have also created a number of successful spin-out companies turning inventions and discoveries into commercial reality.

We would like to hear from companies who would like to explore opportunities to support our research. We are happy to host tailored visits to the department during which we can explore the many priorities for fruitful interaction, including:

Research Collaborations

Sponsorship of a research project close to a company's technical interests and under the direction of a particular academic can bring immense benefit to a company. The sponsorship includes the support of highly motivated and excellent postgraduate researchers for periods of 2–5 years.

Corporate University Technology Centres (UTCs)

The Department has a number of these industrially funded research centres, typically staffed by 6 to 25 researchers. These allow companies to stimulate interactive research within the technical and collaborative environment of the Department. From these centres it is possible for companies to harness excellent research facilities for their own strategic research and to leverage public funding in a specific area of research.

Studentships

The Department is always pleased to hear from companies who will provide support for students on specific projects.

Tailored courses / Brainstorming sessions

Our strength as a department includes our quality of teaching, as well as our research, and we can design specific short courses, or seminar days to suit a company's specific needs or arrange for a group of academics to spend time with your people brainstorming around a specific theme.

Consultancy

Have you a specific problem which you need to solve? Please enquire and we will help you find a suitable consultant to help you solve your problem. We also offer a range of analytical services including X-ray, polymer / thermal characterization, TEM and SEM microscopy and mechanical testing.

Dr Rosie Ward
Academic Secretary

+44 (0)1223 331955
remw2@cam.ac.uk

Further Information and Graduate Admissions

The Department has a thriving graduate school with approximately 130 PhD students on the Graduate Register at any one time. Around 20 students are admitted to the MPhil in Micro- and Nanotechnology Enterprise in October each year. In addition, the University has recently added the EngD to the range of degrees it awards, and it is expected that a small number of EngD studentships will become available in the next year or so.

Admission of graduate students, whether for the PhD, EngD or MPhil degree is co-ordinated by the University's **Board of Graduate Studies, 4 Mill Lane, Cambridge, CB2 1RZ**. Applications may be made on paper, or on-line (for which a charge, currently £25, is payable). Further details of the application procedure, and the Graduate Studies Prospectus, are available from the Board of Graduate Studies at **www.admin.cam.ac.uk/offices/gradstud/app-grad.html**.

A range of studentships and bursaries are available for particularly well qualified candidates; prospective students, particularly those from overseas, should check in the Graduate Studies Prospectus (**http://www.admin.cam.ac.uk/univ/gsprospectus/funding/**) for the closing dates applying to those schemes for which they are eligible. In general, candidates for postgraduate study should have a UK 2:1 honours degree or higher and/or Master's level qualifications (or overseas equivalents). On occasion, funding is available from industrial organisations. The Department has strong links with industry and has within it technology centres in collaboration with Rolls–Royce, Pfizer and SKF.

PhD students are initially registered for the Certificate of Postgraduate Study and registration for the PhD takes place once the first-year requirements (satisfactory *viva voce* examination on a 15,000 word dissertation, short seminar, and obtaining a pass in the assessment tests for two short courses) are met.

The MPhil in Micro- and Nanotechnology Enterprise combines an in-depth multidisciplinary scientific programme with a global perspective on the commercial opportunities and business practice necessary for successful exploitation. Students are based in the Department of Materials Science and Metallurgy, but attend some programmes in other parts of the University, particularly the Judge Business School. The programme is modular in structure and lasts ten months.

Within the Department of Materials Science and Metallurgy, graduate admissions are administered by Dr Rosie Ward, who is very willing to give informal advice to prospective students and put them in contact with members of the academic staff with appropriate interests.

The New Museums Site of the University of Cambridge is in the historic centre of Cambridge. The entrance to the Department of Materials Science and Metallurgy is indicated by the red dot.

Department of Materials Science and Metallurgy
University of Cambridge
Pembroke Street
Cambridge CB2 3QZ

Tel: +44 (0) 1223 334300
Fax: +44 (0) 1223 334567
E-mail: web-responses@msm.cam.ac.uk

www.msm.cam.ac.uk

Designed and printed by Cambridge University Press. www.cambridge.org/printing