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MATERIALLY BETTER: ENSURING THE UK IS AT THE FOREFRONT OF MATERIALS SCIENCE

CONTENTS

INTRODUCTION – THE SCOPE

> *"Fundamental discoveries in physics dominated the first half of the 20th century, whereas discoveries in molecular biology, such as the structure of DNA, dominated the second half. The 21st-century may well bring forth a new area one of revolutionary discoveries in materials research that result in far reaching changes for society and how we live"*
>
> *Jonathan Adams, David Pendlebury, Global Research Report: "Materials Science and Technology" June 2011*

As Jonathan Adams and David Pendlebury from Evidence Ltd pointed out materials is an immensely important area as witnessed by the fact that their Global Research Report is the first one the company have presented that investigates a specific topic. EPSRC's Physical Sciences theme is concerned that we, and the community as a whole, perhaps do not have a clear enough view about our own strengths to capitalise on this potential.

EPSRC has recently undergone a major exercise characterising its portfolio and setting a direction of travel for the Research Areas that it covers. Whilst this "Shaping Capability" exercise has looked at the relative importance of each Research Area, what it has not done is take an overview of a discipline. For some topics this means that there are priorities identified within individual Research Areas but there is no overarching strategy for the discipline as a whole.

One area that could potentially suffer as a consequence is materials science (as defined by EPSRC – see "Scope" following). Unlike physics and chemistry the area does not have a strategy provided by the community or professional body. The EPSRC's Physical Sciences team is concerned that we do not have a clear idea of the materials science priorities for the UK. Our published Research Area Rationales for materials science are largely descriptive and do not provide a comprehensive strategic view for the area. The Physical Sciences Grand Challenges, although they have a materials science component, are more concerned with pulling together the main disciplines of the physical sciences, rather than offering a strategy for the individual subjects. In addition, unlike chemistry and physics, there does not seem to be a materials roadmap for the UK produced by any independent professional body. There is therefore a lack of clarity about the areas where the UK is strong, the areas that need attention and the opportunities that are open for researchers.

Why do we think this is necessary? Governments both here and abroad are showing an increasing interest in materials. This is all to the good, but without a clear strategy it becomes difficult to decide how best to capitalise on this interest in a way that benefits the UK. In addition, clearly articulating what is best for UK materials science would help inform EPSRC discussions on the links between materials science supported by the Physical Sciences Theme and other EPSRC themes such as Energy, Manufacturing and Engineering. An understanding of what would be best for the UK would also help inform decisions on where best to develop international links ensuring that we enter collaborative agreements with a clear idea of what the UK needs and how it would benefit from those collaborations.

In addition, the present Government has set growth as its top priority and a number of Departments and agencies are contributing to this agenda. For example, the Department for Business Innovation and Skills (BIS) has set out its long-term approach in the recently published (September 2012) *Industrial Strategy UK Sector Analysis.* This includes "a focus on the long-term to build sustainable growth" and recognition to encourage innovation. The Technology Strategy Board has recently identified 22 key industrial developments[1]. Materials research will be vital in the delivery of 16 of these. In addition, Science Minister David Willetts has recently identified eight Future Technologies:

- the Big Data Revolution and Energy Efficient Computing
- Synthetic Biology
- Regenerative Medicine
- Agri Science
- Energy Storage for the Nation: Stockpiling Electricity
- Advanced Materials and Nanotechnology
- Robotics and Autonomous Systems
- Satellites and Commercial Systems

Materials research plays a key role to a greater or lesser extent in all of these – not just advanced materials and nanotechnology.

As many have pointed out (such as the Materials Science and Engineering Expert Committee of the European Science Foundation[2]) innovation is often based on basic research. For many key areas including manufacturing, energy, healthcare and others, that innovation will be based on materials research that leads to the development of new materials, tailored properties, and sustainability across the whole life-cycle. This requires pulling together new discoveries in physics and chemistry and continuing developments in modelling, simulation and processing, along with the development of strong, international science leadership to produce a vibrant and evolving materials science research community.

SCOPE OF THE REVIEW

Materials science is multidisciplinary by its very nature. Its practitioners are chemists, physicists, mathematical physicists as well as materials scientists, all with a desire to understand the behaviour of materials and their application.

As a discipline it underpins all areas of EPSRC's remit by pulling together chemistry, physics and maths, and underpinning and enabling advances in other areas such as energy, ICT, engineering and manufacturing. It also has links to other disciplines outside EPSRC's remit.

Support for materials research in its broadest sense is spread across a number of themes in EPSRC: Physical Sciences, Manufacturing, Engineering, Energy and Healthcare. This spread reflects the continuum from basic research through to the application of specific materials (and, incidentally, underlines the importance of materials science to a wide range of disciplines and application areas).

The purpose of this review is to look at the current state of UK research in materials science in those areas covered by the EPSRC Physical Sciences theme in order to identify the opportunities that exist (both in the UK and internationally) and to suggest ways to capitalise on those opportunities. By so doing we want to ensure that the UK is at the forefront of the materials revolution.

The focus of the review is thus those areas covered by the Physical Sciences theme as defined by the following EPSRC research areas[3]:

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[1] *High Value Manufacturing Strategy* http://www.innovateuk.org/_assets/hvm_1909.pdf
[2] *Materials for Key Enabling Technologies*, European Materials Society/European Science Foundation, April 2011
[3] See Annexe 1 for the description of these and other materials-related Research Areas

- Condensed Matter: Magnetism and Magnetic Materials
- Functional Ceramics and Inorganics
- Graphene and Carbon Nanotechnology
- Materials for Energy Applications
- Photonic Materials and Meta-Materials
- Polymer Materials

The other Research Areas related to materials (for example those covering materials engineering or manufacturing) are not specifically excluded, but they are not the focus of this review. Where there are links to other areas these will be addressed, but it not the point of this exercise to define strategies for those areas of materials that fall outside the remit of the EPSRC Physical Sciences theme.

THE REVIEW PROCESS: PANEL REVIEW AND CONSULTATION

This Report has been produced in discussion with a Review Panel[4]. The Panel carried out a review of the strengths, weaknesses, opportunities and threats for UK materials science. It also looked at the links between materials science and other disciplines and application areas. The findings are encapsulated in this report.

The membership of any Panel of this nature is a balance between full representation and effective working. The need to ensure the latter means there is always a risk of gaps in knowledge. As a consequence and to validate the conclusions and identify any gaps we are circulating this report for comment and discussion. At the end of the consultation period the findings will be incorporated into a final review report which will be considered by the Physical Sciences Strategic Advisory Team and the conclusions used to inform our future strategy.

THE INTERNATIONAL CONTEXT

There have been a number of recent reports highlighting the importance of materials and materials research. These include, from the US: *International Assessment of Research & Development in Simulation-based Engineering and Science* (World Technology Evaluation Centre, January 2009); *The Materials Genome Initiative for Global Competitiveness* (2011); from Europe: *Materials for Key Enabling Technologies* (EMRS/ESF June 2011); *Technology and Market Perspective for Future Value Added Materials* (EC 2012).

EPSRC has also looked at the international context of UK research: *International Perceptions of the UK Materials Research Base* (EPSRC, 2008).

From these it seems to be clear that there is a consensus on where materials have the potential to impact on societal issues. These include sustainable economic growth (if that is not an oxymoron), manufacturing, energy, healthcare and the environment. They also tend to agree on the technologies that will be required to realise these goals: nanotechnology, photonics, biotechnology and advanced materials. There is also agreement on some of the generic requirements to advance the area such as modelling and simulation.

The findings from some of these reports are summarised below.

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[4] See Annexe 3 for Membership

1. US: "INTERNATIONAL ASSESSMENT OF RESEARCH & DEVELOPMENT IN SIMULATION-BASED ENGINEERING AND SCIENCE" (WORLD TECHNOLOGY EVALUATION CENTRE, JANUARY 2009)

This builds on a previous (2006) report that posited that computers and computational methods and advances in Simulation-based Engineering and Science (SBES) could resolve fundamental and complex problems in health, energy, environment, security and quality of life. The study was commissioned to follow up an earlier report by looking at international activities in order to identify specific technical strengths and weaknesses, the sites where the most activities were occurring and the research challenges, roadblocks and new opportunities.

The study looked at a number of areas including: Materials Simulation and Multiscale Simulation.

Materials Simulation

For the area of materials simulation it concluded that this could have significant economic impact in the US. However, it noted that methods and tools development in the US was individual-group-based The reasons for this were because (a) the US system did not encourage collaboration (b) US agencies did not support code development, and (c) resources to perfect, distribute and maintain code were not available. The report contrasted this with the situation in Europe and Japan

On the international front it highlighted activities in a number of countries: Japan – Mitsubishi Chemical; Toyota Central laboratory; China – Joint Laboratory of Polymer Science and Materials, Institute of Chemistry, Chinese Academy of Sciences; and in Germany – Fraunhofer Institute of Mechanics of Materials.

The UK was also highlighted, particularly the work at Daresbury. However, the authors felt the reorganisation under STFC was a threat to the UK future in this area as it risked undermining the previous collaborations that had been so successful. It singled out SERC/EPSRC in the UK for the success of the Collaborative Computing Projects and the development of code that emerged from these which is now used in the US (eg CASTEP)

The report’s conclusions were that:

- computational materials science and engineering was changing how new materials were discovered, developed and applied
- there was world-class research in the US, Europe & Asia, and China was expected to become more creative
- there was a rapid ramping up of simulation especially in China and Germany
- there had been increased investment in science in Germany
- there was greater collaboration between disciplines and groups in Europe than in the US
- undergraduate students are increasingly illiterate in computer programming. This was most acute in the US
- long-term funding (5 years +) was crucial for the US to develop key material simulation codes
- the US was at a strategic disadvantage with respect to crucial foundational codes and was increasingly reliant on codes developed by foreign groups
- the utility of material simulation codes would be enhanced by the development of standards for interoperability of codes

Multiscale Simulation

The other relevant area discussed was Multiscale Simulation. This refers to techniques that allow the modelling of phenomena across disparate time and length scales. Some of this research comes within the scope of this present EPSRC review.

The report highlighted work at Mitsubishi Chemicals and the University of Tokyo in Japan; the Cavendish Lab, Cambridge; and the Blue Brain project in Switzerland.

It concluded that:

- multiscale modelling held the key to many developments in SBES
- attempts to develop general strategies had not succeeded
- the lack of standards for interoperability was a barrier
- US research was on a par with that in Europe and Japan and was aided by the availability of high-performance computing, but US research was diffuse and lacked focus on integration
- interdisciplinary activity was key and here the US was also at a disadvantage.

2. US: "THE MATERIALS GENOME INITIATIVE FOR GLOBAL COMPETITIVENESS" (2011)

The WTEC report, above, underpinned the discussion that led to this report and the subsequent funding for the initiative. The premise is that materials underpin future prosperity and there is a need to speed up the process of innovation from discovery to exploitation in new and improved products, including design for recyclability and sustainability. The report argues that in order to do this interdisciplinary research, bringing together computational expertise alongside materials science, will be needed.

Enabling this will require sharing the largest possible dataset at the discovery stage. This will provide researchers not only with a complete picture of a material's characteristics, but it will also permit a better understanding of the underlying physical and chemical mechanisms. This in turn will require new standards for interoperability and data sharing, including of algorithms and computational methods. The aim is to speed up the process to twice as fast as currently and at a fraction of the cost.

There are three components to the Materials Genome Initiative.

1. Developing a materials innovation infrastructure through the integration of computational, experimental and data informatics tools. These are to be developed using an open platform and will need to fit into existing design frameworks.

2. Achieving national goals with advanced materials: using the infrastructure created to develop new advanced materials

3. Equipping the next-generation materials workforce: focusing on education workforce development and a generational shift towards a new, more integrated approach to materials development

3. EUROPE: "MATERIALS FOR KEY ENABLING TECHNOLOGIES" (EMRS/ESF JUNE 2011)

This report was written in response to the identification by the European Commission of a number of Key Enabling Technologies important for Europe’s future prosperity. These are:

- Advanced Materials
- Photonics
- Nanotechnology
- Biotechnology
- Micro-and Nano-Electronics
- Advanced Manufacturing Systems

As all are dependent on further progress in materials development, materials science and engineering plays a crucial role.

In addition the report's authors conclude that **energy** will also play a key role. There is thus a need for efficient energy production, conversion and storage and this will also require efforts in basic and applied research for new materials.

Advanced Materials

Four areas are highlighted:

- research on new, advanced materials with novel or improved properties
- development of rational approaches in the design of advanced materials or in their integration into structures and systems
- inspiration by nature (eco-design, bio inspiration and use of natural materials)
- anticipation and control of the performance of materials during the life cycle (including self-sensing and self-healing)

Research on a number of advanced functional materials is proposed:

- inorganic materials for photonics and energy
- non-organic materials for advanced multifunctional Microsystems
- materials based on novel functional though molecular organic compounds and polymers
- meta-materials and nano structured materials
- functional and multifunctional oxide films

Materials for Energy

Materials research is needed in:

- energy production from renewable resources (solar energy, biomass, thermoelectrics, nuclear energy)
- energy storage and distribution (Li-ion batteries, super capacitors)
- CO_2 as a raw material
- fuel cells

Nanotechnology

The Nanoworld produces challenges: consideration of the physical and physicochemical phenomena from quantum physics; characterisation and modelling from design through to the intersection of the fabrication process. Particularly highlighted:

- materials and fabrication (including nanotechnology for energy, nano-bio applications, nanocomposites)
- characterisation
- theory and simulation

Materials for Micro-, Nano-Electronics and Silicon Photonics

The report sees micro- and nanoelectronics as the key enabling technology as all other fields are dependent on advances in electronics. Materials science can impact on a wide range of priorities in the sector.

Biotechnology

Materials science and engineering is seen as having a key role in this sector. Materials research will be important not only for advancing areas in healthcare such as diagnostics, regenerative medicine, drug delivery, but also in delivering materials for bioprocessing and making better use of biologiocally produced materials.

4. UK: "INTERNATIONAL PERCEPTIONS OF THE UK MATERIALS RESEARCH BASE" (EPSRC, 2008)

This is one of what has been a periodic review of EPSRC activities. Whilst the review did address some research shortcomings (such as a neglect of metallurgy) a major focus was policy and infrastructure issues. Among those are:

- there is a need to identify potential leaders and equip them for the future
- UK research remains healthy, but there needs to be more fundamental innovation from within universities because of the declining ability of companies to innovate
- there is a need to involve other disciplines (mechanics, multiscale modelling and manufacturing) to aid early implementation
- whilst there are good examples of bottom-up international collaboration, with the exception of EU programmes, top-down programmes are not well organised so their successes are less evident.
- Opportunities for science-driven links with India and China exist and EPSRC needs to draw attention of the UK community to the extent of engagement by other countries with these nations
- links with Japan could be improved

THE REVIEW:

1. STRENGTHS IN UK MATERIALS SCIENCE

The UK has a vibrant research base in materials science. Moreover this base has both breadth and depth. The UK community is good at collaborating not only with other disciplines, but also with industry.

A number of research areas are highlighted as of particular strength:

- Fundamental understanding of complex inorganic materials. This includes structural and functional ceramics, for example ferroics (ferroelectrics), magnetism, bulk materials and thin films (oxides and non-oxides) and their synthesis.
- Polymeric materials. The UK has focused strengths in this area, for example in organic electronics.
- Theory and simulation of materials. The UK is strong in this area which is an important component in materials discovery. UK's software is used by our competitors the world over. The UK also scores because of its ability to link theory to synthesis and experiment.
- Materials discovery and processing into functional devices.
- Graphene. With two Nobel Prize winners and many other groups including researchers in other disciplines involved, such as engineering, the UK is well placed to devise ways of exploring this potentially versatile material.

- Energy materials are another area of strength in the UK, particularly materials for conversion (photovoltaics, fuel cells) and storage (batteries). Many challenges still exist, so the area remains important.
- Other areas include exotic materials, for example superconductivity (where there is a need for better understanding of existing materials to enable the planned design of higher temperature systems), the identification of new materials by synthesis, and novel properties at interfaces and biomaterials.

The UK also has strengths in infrastructure to support materials research, such as characterisation facilities (eg Diamond) and the collaborative links that exist between academia and industry.

2. WEAKNESSES

There are some general weaknesses in the UK environment which will need to be addressed if we are to maintain our current leading position.

The funding infrastructure is one. To remain internationally competitive it is important to sustain a critical mass of research and to maintain continuity in research programmes. The recent funding environment has constrained this ability and has been exacerbated by additional restrictions on capital equipment, provision of which is vital if the UK is to function at an international level. Whilst collaboration and sharing have provided some alleviation it can only be a stopgap. Investment in new equipment will be needed to secure the UK's position.

Investment in people is also important, starting with training. There is a general need for an adequate supply of PhD students to provide the next generation of researchers and skilled people the industry will need if materials science is to fulfil its promise of revitalising the economy.

There are some particular needs for training. The UK's leading position in modelling and simulation has already been mentioned, but needs development to enable modelling and simulation at the mesoscale and thus the application of the techniques to mechanical and materials engineering. This requires an understanding of behaviour. At present, even if money was available for a research initiative in the area, it would be a struggle to find suitable people as insufficient numbers of postgraduates are being trained in the subject.

Characterisation is another area that lacks skills. The key techniques of materials science (electron microscopy, spectrometry, NMR, XRD) require skilled people to operate and interpret. The UK has an age problem currently and there are not enough young people coming through to form the next generation of specialists.

Beyond the PhD, Fellowships are also important. One area in particular that has been highlighted where early career support could be crucial is measurement. Interpretation is a vital skill in this area and requires an understanding of materials behaviour.

Another issue is the difficulty for those involved in applying the techniques to have their contribution recognised when the research is challenge-led. It is thus difficult for those involved in characterisation to have a sustained career. Fellowships can provide an important component of a career path for young experimentalists.

Also needed are ways to pull innovation through to the higher levels of technology readiness. This includes enabling prototype devices to be built from new materials and providing facilities for testing materials and devices, for example batteries. Ensuring better links to Advanced Manufacturing

Centres could form part of the answer. These kinds of facilities could be particularly important in the short term because of the decreasing manufacturing capability in the UK. The companies that are left focus on immediate delivery of applications, which can be a barrier to collaboration.

Amongst topic areas of concern Nanoscience was highlighted. There has been a large investment over the last 10 years but there has been a lack of connectivity between research focussed on nanoscale properties and more conventional approaches in materials science and characterisation.

Materials preparation is another weakness in the UK community. There is a lack of facilities for high quality materials preparation for both bulk and thin films synthesis. This contrasts with the situation with our competitors, especially Japan and Germany.

On the subject of the international context, there is a lack of collaboration with some key international players. China in particular is singled out. It is already an important player in materials and the UK could be doing more to strengthen links. We also face increasing competition from emerging nations and should be identifying which are the key countries and building appropriate research ties.

There is also need to look at ways of improving researchers' ability to collaborate internationally. Given our membership of the EU one would expect it to be easier to build links with European countries. However the Commission focuses on large multilateral programme and the overhead in getting involved in the multi-lateral programmes the Commission supports is too high. What is needed are simplified mechanisms to enable individuals to collaborate. We need to develop unilateral agreements between countries to make the process of collaboration easier. Putting in place simple mechanisms between the UK and France and Germany could have a big impact.

3. OPPORTUNITIES

1. Collaboration: across disciplines, academia/industry and internationally

The UK community is generally open to collaboration across disciplines, institutions and between academia and industry. This is in contrast to many of our competitors. Researchers in many other countries have difficulty in crossing the boundaries or have national laboratories where there is an inertia to overcome (which also reduces the flexibility to pursue new lines of research). The UK's flexibility in this regard is a key strength.

This puts us in a good position to strengthen links between academia and small and large companies in order to speed up the time of exploitation from research to technology application. This is vital as materials research is the route by which step (rather than incremental) changes will be delivered. This will help achieve, for example, the next-generation manufacturing technologies.

The UK is leading in many areas that are important to a knowledge-based economy. Other countries are threatening this position, but we could offset that threat by collaborating more internationally, particularly with countries in Asia. Such collaborations could also help drive inward investment by exposing foreign companies to the strength and vibrancy of the UK research base. However such connectivity is only useful if we can remain competitive.

2. Modelling and simulation

To develop materials science it will be important to invest in improvements in modelling an simulation, the synthesis new materials, including growth and synthesis of bulk materials and crystals and thin films as well as scalable manufacturing and nano-fabrication techniques. Modelling and simulation is an important technique that again links all themes and is fundamental for the continued and accelerated progress of materials research.

3. Synthesis

To enhance the ability to control the synthesis of materials including enhanced understanding of structure-property-composition relationships and better interactions between predictive theory and the various available experimental synthetic methods.

4. Characterisation and measurement

Also important is the need to continue to invest in physical characterisation (where the UK has strengths), including the use of sophisticated techniques some of which have yet to be extensively applied to materials problems. These include HR-TEM, EPR (electron paramagnetic resonance) spectroscopy, which can be used, for example, to explore defects in diamond; SS-NMR (solid state nuclear magnetic resonance) which has applications in the study of catalysis; and spectroscopies such as optical spectroscopy, SIMS (secondary ion mass) and HR-XPS (high resolution x-ray photoelectron). These are not widely used by the community but their application to materials science could be highly important and give the UK the edge on the competition.

Building collaborations with other areas of chemistry and physics research would help extend the techniques to provide better analysis of soft matter (polymers, tissues).

Characterisation will aid the understanding of structure and thus how to measure it over multiple length scales.

Better characterisation facilities in universities would also assist UK industry. The demise of corporate laboratories means that industry will need access to the state-of-the-art characterisation facilities in universities to underpin the measurement, characterisation and interpretation materials in sectors such as manufacturing and energy.

5. Support for research leaders

We need to ensure that research leaders are supported. This includes encouraging overseas leaders to set up in the UK.

6. Topics

In terms of research topics there are opportunities to improve and strengthen research in areas such as polymers, energy (for example clean energy, energy transport, storage) sustainability (polymers from non-petrochemical sources, replacing scarce elements) and materials to support healthcare (stem cells, regenerative medicine) and simulation and modelling where the UK has a world leader.

4. THREATS

Funding is a key threat. Research funding in the UK is reducing in stark contrast to our competitors who are increasing investment in science. This year saw the UK's spending on research as a share of GDP fall below that of China for the first time.

With restrictions on funding come threats:

- the possibility that resources will be given preferentially to projects with an "application" rather than basic research

- a focus on larger projects as being more "cost-effective" as opposed to smaller projects. This jeopardises flexibility and innovation
- lack of long-term funding for the physical understanding of materials.

Allied to this is the propensity for peer review to be risk averse and to back "safe" projects as they are perceived as better value for money. This stifles originality and encourages short-termism.

Reductions in funding could also lead to shortages of PhD places for domestic and overseas students. UK institutions already find it difficult to attract and hold the best overseas students. We have already noted the shortage of skills. Reduction in PhD places in turn reduces the supply postdoctoral researchers and thus the next generation of research leaders. This is especially true if Fellowships are not available to support early career researchers.

UK also faces a shortage of young researchers with skills in metallurgy, composites, polymers, and modelling at the mesoscale. There are also shortages of experimentalists across all areas. Young people need to be able to see a clear career path.

In part connected to reduced funding is a danger of research focusing on new, "hot" topics. Whilst emerging areas, like graphene, do need support, it should be made clear to researchers (and peer review) that research on existing materials is still needed and remains important.

If the UK cannot maintain a critical mass of researchers it will lose out to the international competition whose level increased level of investment will attract the best researchers to move. We need to recognise that we are in competition with other countries in terms of the scale of investment and attractiveness. Not just the traditional competitors such as the US (where, for example, the Department of Energy is investing heavily in materials research) or Germany, but also the emerging economies of China and South Korea. For example, earlier this year the latter established a number of Institutes of Basic Science with a budget of US $4.4 billion over the next five years. The aim is to encourage more adventurous and creative research. At least four of these are in the materials area

The outsourcing of discoveries (allowing exploitation to take place overseas) also risks damaging the UK's reputation. If we cease to appear attractive there will be a knock-on effect: a reduction in investment in new industry (as the UK is seen as being uncompetitive) and a loss of research leaders as innovative researchers either do not come here or the existing ones leave.

5. LINKS TO OTHER TOPICS

A strong driver of research in Materials science is the application of the knowledge generated to application areas. This creates opportunities for collaborations with other EPSRC themes.

<u>ICT</u>

Materials science, especially photonics and photonic materials research, needs to be strongly connected to this theme as it underpins the development of new devices. Examples include Gallium nitride, photonically patterned Silicon, $LiNb0_3$, organic materials.

<u>Energy</u>

The need to link materials with research in this theme prompts a question: is target-driven research effective or good for policy in this area? We believe that to make a difference the area requires sensibly and clearly thought out long term targets that promote research that will lead to step changes. This is needed as the area is fast moving so the arguments for involving materials science need to be continually updated. The long view gives more stability and will encourage the disruptive research the area needs.

The driver for materials research in this area is the need for cheap, safe, sustainable materials for generation (large and small scale, including nuclear), batteries (for example the 100km range for electric vehicles), energy harvesting (such as thermoelectrics, topological insulation and other exotics as yet unknown), thermal scavenging and power for portable electronics.

Healthcare

This another area where there is a need to strengthen links between the research communities as there are many opportunities. These include antimicrobials, negative Poisson's ratio (auxetic) materials, wound dressings, substrates for cell growth, bioceramics and hydroxyapatites, dental ceramics and heterogeneous materials.

The TSB sees this these areas from the perspective of an SME. Because SMEs tend to focus on particular materials they "don't know what they don't know". There is a role for materials researchers to underpin this sector of industry.

Engineering and manufacturing

Materials science is an important enabler of developments in these related areas and the links, again, need to be strengthened.

For engineering work on composites, metals and alloys is important. For manufacturing where the research focuses on the fundamentals of processes there is an opportunity to look for synergies across a wide range of areas. The TSB's High Value Manufacturing Strategy (http://www.innovateuk.org/_assets/hvm_1909.pdf) recognises 22 competencies in five broad themes:

- resource efficiency
- manufacturing processes
- materials integration
- manufacturing systems
- business models

Materials science underpins 16 of the competencies.

Other Research Councils

In the case of other Research Councils, understanding biomaterials is an area where stronger links to biologists via BBSRC could be important. A potential barrier is, however, whether or not biologists realise the importance of understanding biomaterials.

NERC is another Council which has goals that can only be achieved with the involvement of materials science. Tackling climate change, for example, is one area that will require a variety of materials solutions.

STFC is also an important partner because many of the facilities important for materials research are run by this Council. Its recent funding cuts have caused concern, however, as it is restricting the availability of some facilities.

6. EXPLOITATION

Knowledge generation is key to growth and a prosperous economy. Because of its application focus it is important that we take account of opportunities to exploit materials research and identify and capitalise on the opportunities to do so. However it is important to remember that not all research leads to immediate exploitation in industry. Materials research can create scientific impacts, which will form the next generation of industry. Increasingly it will be the ability to produce such impacts that will drive industry as labour costs become less important as a differential between countries. This makes it vital that we ensure the UK retains a strong base of fundamental research capability as we cannot predict what will be needed in the future or from where the next breakthroughs will come. It is thus vital we retain our ability to discover, understand, control and exploit new materials.

That said there is still a need to make sure we have the connections to allow the rapid exploitation of the knowledge currently being generated. The UK academic community is already good at working with industry, but we could do more. There is a particular need for ensuring meaningful evaluation of new materials technologies under realistic operating conditions, which will often require the need for prototyping. We need to remember that industrial collaboration does not mean carrying out very applied research. Large companies in particular are interested in fundamental research.

The academic community could also assist sectors that are under threat from a lack of investment. We need to build dialogues with representatives of these areas.

Exploitation will also be aided by linking to the new Catapult centres.

7. SATISFYING CURRENT NEEDS

The previous sections have highlighted a number of areas where more work is needed to support existing activities and to maintain the UK's position. We would welcome comments on how to meet the following needs. New money for special initiatives in the current climate is very unlikely, but the standard mode of research support, driven as it is by quality, is a powerful way to support research when the community itself has come together to identify priorities through networks, workshops etc. EPSRC can help facilitate such routes to identify opportunities.

The needs include:

- Identifying and applying new novel characterisation techniques for materials.
- Continuing to invest in fundamental materials discovery, for example, by encouraging projects that aim at groundbreaking new materials discoveries (past examples include semiconducting polymers, graphene)
- Developing links to industry (including dialogues with industry sectors, links to Catapults)

8. PULLING TOGETHER – REVITALISING MATERIALS RESEARCH

In addition to the specific topics in the previous section we believe there is a need to bring the materials community together. Materials research in the UK is not only carried out in specialist Materials Departments, but a large proportion is also done in Physics and Chemistry Departments. This has advantages in, for example, the ease with which novel thinking in those subjects can be applied to materials work. The drawback is the risk of the UK community becoming more fragmented that its overseas competitor counterparts. Can we remedy this by pulling the community together in, for example a Materials Grand Challenge?

We think this is an idea worth exploring as a Grand Challenge, as well as tackling important problems will also have the effect of raising the profile of materials, making it easier to argue the importance of the subject to the Government's growth agenda.

Such an approach would also help in the competition with other countries: the US and Switzerland, for example, are setting research agendas for the materials community that bring in engineering and the life sciences.

Some suggestions have emerged in discussions as of what a challenge might comprise.

1. TOWARDS TOMORROW'S MATERIALS

An initiative to encourage fundamental new materials discovery that will be the basis of new research fields in the future and could enable order of magnitude improvements in technology performance. Such an initiative will help to ensure that UK materials researchers continue to discover some of the breakthrough materials of the future. The initiative will need to be basic-research focussed, long term and be encouraging significant risk taking. It will need to attract the brightest and best young researchers.

The motivation is the urgent need to deliver a portfolio of research that will underpin and accelerate the development of new, advanced materials – materials driving advanced technology. This will help secure the UK's economic growth and prosperity. Such a challenge can only be met by a initiative having the scale, extent and sophistication of a multidisciplinary materials programme centred on the targeted and guided design, synthesis and control of New, High-Performance Future Materials.

The great challenges and enormous opportunities associated with the new materials of tomorrow ("Tomorrows Materials") can only be met if a significant number of materials scientists and engineers with diverse perspectives are attracted to such an initiative. Hence the title: Frontier Challenge.

Historically, the preparation and examination of qualitatively "new" materials and phenomena has led to major technological advances in terms of the performance of advanced materials as well as enormous progress in our detailed understanding of compositionally and structurally complex materials (for example, high-strength, high temperature materials, fuel cells, graphene, fullerenes, high-temperature superconductors, giant magnetoresistance superlattices, quantum Hall effect). Across all of the 6 current EPSRC Materials Science the time is correct for a Supragen ("Beyond Supergen") initiative that specifically targets the Guided Synthesis and Application of New, High Performance Materials to speed up the entire process of materials discovery driving advanced technology; this is particularly true of the broad area of inorganic materials discovery. The motivation, then, is the discovery of higher-performance materials not only to drive advanced technology but also unlock the fundamental secrets of materials' phenomena.

ISSUES and QUESTIONS

- What classes of materials, important to new phenomena and new high materials performance technological applications, would benefit most from such a targeted approach?
- What is the state-of-the-art now in terms of materials performance for all sectors?
- What are the materials "log-jams" that could be breached by the discovery of new generation or New, High-Performance Future Materials
- What are the current limitations on predicting or rationalising both the structure and properties of New, Future Materials? A teaser for the computational scientists: With 20-20 hindsight, can one visualise, using presently available computational techniques, the necessity of Cu-O planes in high-temperature superconductors?
- What theoretical/computational predictions can be expected to be a reasonable guide to synthetic materials chemists or materials scientists? Such approaches must be designed to offer optimal synthetic value for any materials search.

- What level of effort and investment would be needed?
- Last, but certainly not least; would such a Frontier Challenge be of interest and relevance to the UK's technology base?

2. PREDICTION OF 3D STRUCTURES - INCLUDING DEFECTS

This is currently difficult to do, but is vital to the understanding of multiscale properties. Without this understanding modelling and simulation cannot be applied to bulk materials. The solution will involve understanding the effects of defects and will thus draw in wider materials participation than just the modelling community.

It would also serve to stimulate the UK modelling community, helping to maintain its world leading position in the face of the threat posed by, for example the US Materials Genome Initiative.

3. OLD CHALLENGES - NEW IDEAS

Over the years many opportunities for advances have emerged only to fade as the problems needed to be overcome prove too difficult or uneconomic to solve. However the world does not stand still - new techniques for synthesis and analysis emerge, new materials are discovered.

Is there scope for re-examining some of these challenges and bringing new thinking into their solution? For example, could a new generation bring new ideas to bear on the development of room temperature superconductors whose invention would revolutionise the way we live?

There is also an opportunity to look at existing materials. In many cases we do not understand fully the materials we use. This lack of understanding means they are not optimised and they are not processed in a way that could improve their performance.

* * * * *

Any Challenge is going to be difficult otherwise there is no rationale for meeting it. In the absence of dedicated funding the community will need to come together to define the research problems to be tackled and to enable the building of a portfolio of research grants. £100k is not going to provide a solution, but £1 million might.

ANNEXE 1: EPSRC PHYSICAL SCIENCES THEME: MATERIALS SCIENCE RATIONALES

There are six Research Areas key to the Physicals Sciences themes coverage of Materials Science:

- Condensed matter: magnetism and magnetic materials
- Functional ceramics and inorganics
- Graphene and carbon nanotechnology
- Materials for energy applications
- Photonic materials and metamaterials
- Polymer materials

Their definitions and the Rationales for their support are given below. There are a number of other materials-related areas that are the responsibilities of other parts of the Physical Sciences theme (Physics and Chemistry) or other themes (for example Energy, Engineering). These are described in a separate paper.

NOTE*: the definitions and rationales are fixed and thus a given for this Review. What we are seeking is to add a strategic element to the core Physical Sciences Research Areas in materials science.*

1. CONDENSED MATTER: MAGNETISM AND MAGNETIC MATERIALS

Related themes:

ICT, **Physical sciences**

Research into magnetic materials and fundamental principles of magnetism. Includes thin film magnetism, magnetic phenomena, characterisation and growth of magnetic materials, ferro and antiferromagnetic materials and frustrated magnetic systems. Early applications into materials for sensors and data storage are included in this research area. Strong links to spintronics and condensed matter: electronic structure.

Status: Maintain

Magnetism and Magnetic materials is an area within the EPSRC portfolio that has significant overlap with many other areas including **condensed matter: electronic structure**, **spintronics**, **functional ceramics and inorganics** and **superconductivity**.

EPSRC is currently supporting nine research fellows that conduct research in this area with standard grants funding a wide range of sub-fields including carbon-based magnetism, molecular magnetism, quantum magnetism, frustrated magnetism, magnetic nanoparticles for biomedical applications, thin-film magnetism and nano-magnetism as well as new emergent areas such as Magnetricity.

Theory and computational modelling has been strongly supported throughout the portfolio in an attempt to address perceived weaknesses in the links between theory and experiment (**International Review of Physics (2005) (PDF 364KB)** - page 22). Access to facilities at Institut Laue-Langevin (ILL), ISIS, Diamond and the European Synchrotron Radiation Facility (ESRF) have also enhanced progress in the experimental aspects within the portfolio and are perceived as a real strength of the UK research base (**International Review of Materials (2008) (PDF 885KB)** - page 36).

Theoretical materials science has been recognised as a UK and European strength (c.f. **European Science Foundation (ESF) MatSEEC - Computational Techniques, Methods and Materials Design (PDF 2.4MB)** - page 4) and many novel underpinning characterisation techniques for functional and multifunctional magnetic materials are supported in the portfolio.

One challenge for the whole magnetism area is to try to develop new materials in order to minimise the dependence of rare-earth elements from China used in current permanent magnets (**UK POSTNOTE (January 2011) – Rare earth metals(PDF 477KB)**).

EPSRC acknowledges the importance of magnetism and magnetic materials in supporting future industrial development with one particular success being magnetic powder processing, where funding has since transferred almost entirely towards industrial sources.

Investment in the research area will be maintained relative to other areas in the portfolio through standard research proposals, postdoctoral research fellowships in theoretical physics and early career and advanced career fellowships in the Physical Sciences Grand Challenges. This will be focussed on supporting key emerging areas as well as underpinning techniques with ongoing support to strengthen links between theory and experiment.

Alongside the input detailed in the **Physical Sciences: Our Approach** page, direct communications with individual researchers nominated by the Institute of Physics have provided additional information on this research area.

2. FUNCTIONAL CERAMICS AND INORGANICS

Related themes:

Energy, **ICT**, **Physical sciences**

The synthesis, characterisation and theoretical understanding of functional ceramic and inorganic materials. This area includes electroceramics (including ferroelectric, multiferroic and antiferroelectrics), complex oxides, solid state materials chemistry, inorganic framework and porous materials. This area does not include materials for energy applications, photonic, magnetic, superconducting, polymeric or composite materials or materials processing as these are all covered in related research areas.

Functional ceramic and inorganic materials have diverse applications for example in electronics and energy related applications. The quality of research in this area in the UK, particularly with respect to Materials Characterisation, was very highly rated by the 2008 RAE panel.

The area is one attracting international attention. In 2011 the **ESF MatSEEC** (European Science Foundation Materials Science and Engineering Expert Committee) report into 'Materials for Key Enabling Technologies', emphasised the importance of maintaining support for continued research into the synthesis and discovery of new materials systems as well as complementing this with work into materials for targeted applications. The US Department of Energy (DoE) has also highlighted the area in publications such as **Directing Matter and Energy: Five Challenges for Science and the Imagination (PDF)**. In particular, DoE talks about the "control age" where research is about controlling function through structure and composition - the strategy at the heart of Functional Ceramics and

Inorganics. The US has recently (2011) launched the **Materials Genome Initiative (PDF)** which aims to speed the process from discovery of new materials through to their application. This will depend on computational techniques an area where the UK leads. European activity in theory and simulation of materials is exceptionally strong and includes activity in a number of UK and European universities. **CECAM** (Centre Européen de Calcul Atomique et Moléculaire) has played an important role in coordinating some of this activity and both STFC and EPSRC support CECAM.

The functional ceramics and inorganics research area has been well funded over the last delivery plan period. Current funding includes four current programme/large grants, around fifteen fellowships and a significant portfolio of standard grants. The materials systems being researched remain important for tackling key technological and societal challenges including addressing problems such as developing high performance lead free alternative electroceramic materials, new and improved multifunctional materials, porous materials for energy storage, and improved materials systems for nanoelectronics.

The opportunities for the future are boundless with new research on synthesis of new materials and nanomaterials. The ability to make functional materials by new methods with atomic and molecular control will create new opportunities for speciality manufacturing at all levels. The opportunity and potential impact of materials research could be huge. In the energy area this could include the development of intermediate temperature solid oxide fuel cells, higher capacity lithium batteries. There are also opportunities for improved materials for data storage. Challenges also exist in finding replacements for materials, for example Platinum, that are in short supply. The UK is well placed to take advantage of these opportunities.

The UK research community is well connected with key groups worldwide. These links include those facilitated by international collaborative grants funded through the NSF/EPSRC Materials World Network programme and joint calls with the Japan Science and Technology Agency (JST). With a buoyant research community we will maintain EPSRC investment in this area, relative to others in the portfolio, and continue to fund high quality functional ceramics and inorganics proposals, including support for new research leaders. We will create opportunities through the **Chemical Sciences and Engineering Grand Challenges** (e.g. nanoscale design of functional materials) and **Challenge Themes**. We will also be discussing ways to encourage better collaboration between those working on new materials and those working on applications, including in industry.

Alongside the input detailed in the **Physical Sciences: Our Approach** page, direct communications with individual researchers have provided additional information on this research area.

3. GRAPHENE AND CARBON NANOTECHNOLOGY

Related themes:

ICT, **Manufacturing the future**, **Physical sciences**

The synthesis, characterisation and theoretical understanding of graphene, carbon nanotubes and other carbon based nanomaterials. This area includes understanding the fundamental properties of carbon nanomaterials, development of new growth methods, understanding the influence of defects on properties and exploring possibilities for nanoscale carbon electronics. This area does not include device fabrication, carbon composite materials or materials processing as these are covered in related research areas.

The UK is a recognised world leader in graphene culminating in the recent award of a Nobel Prize for Physics in 2010. Over the past decade there has been significant growth in investment from EPSRC in graphene research with two major Science and Innovation awards, a platform grant and a number of smaller grants. Key graphene groups are currently well funded so significant further growth in funding for this area is not planned. However, to maintain the UK's leading position in graphene research EPSRC will continue to fund high quality graphene proposals over the delivery plan period.

Grant applications for underpinning synthesis, characterisation and theoretical research on carbon nanotubes and other non-graphene carbon nanomaterials are not commonly received as the majority of research on these materials is now more technology focussed (e.g. for electronic devices or engineering technologies). There will continue to be opportunities for high quality research into the fundamental properties of these materials, but projects of this nature should demonstrate clear links to future technologies and/or relevance to EPSRC Challenge themes.

4. MATERIALS FOR ENERGY APPLICATIONS

Related themes:

Energy, **Physical sciences**

The synthesis, characterisation and theoretical understanding of functional materials to be used for energy applications. This includes fundamental studies into potential materials for photovoltaics, fuel cells, batteries and other energy storage materials. Included in this area are studies into polymeric, complex oxide, nanoionic, electrocaloric, magnetocaloric and porous materials for potential future energy applications. The research covered in this area will evolve as new technologies and materials properties emerge. This area only includes research into the materials systems for current and future energy technologies and does not include technology development which is covered in related research areas.

Research into the synthesis, characterisation and theoretical understanding of materials for energy applications has been well funded in recent years and is essential to the overall RCUK Energy strategy.

The recent **RCUK Review of Energy (PDF)** and ESF Materials Science and Engineering Expert Committee report into **Materials for Key Enabling Technologies (PDF)** highlight the importance of underpinning materials research in order to progress technologies to address the energy agenda. The UK materials research community in this area is buoyant and new academic staff are being recruited. UK industry is also involved: according to the RCUK Review of Energy the UK is internationally leading in the areas of thirdrd generation photovoltaics, fuel cells, and lithium energy storage, areas which rely on high quality materials research. Companies such as Nexeon, Oxsys, Ceres Power and Rolls Royce all have interests in this area so the academic research base provides a strong foundation for their continued development. There will also be opportunities presented by challenges such as decarbonising the energy grid and improving systems for CO2 capture. Materials research will be key to achieving these goals.

The UK already has excellent capacity in this research area, with three programme grants and world leading groups working on research problems in the materials for energy applications area, for example the SUPERGEN Consortia in Energy Storage, Photovoltaic Materials for the 21st Century and Excitonic Solar Cells. There are also nine Centres for Doctoral Training in Energy Related Fields and five Fellowships.

Given this healthy capacity we will maintain investment in this area, relative to others in the portfolio, whilst aligning research with the specific RCUK **priorities for energy research**. These include securing energy supply by funding world-class, speculative research to define future energy supply options, including hydrogen and renewables; Low carbon innovation; and, Reducing energy consumption through technological advances informed by a whole system understanding. These provide many opportunities for materials research and discussions will be taking place over the coming months to identify specific opportunities. We will continue to support high quality research aimed at new disruptive technologies: alignment will ensure added value through meeting the Energy priorities for the future.

Alongside the input detailed in the **Physical Sciences: Our Approach** page, direct communications with individual researchers nominated by the Institute of Physics and Royal Society of Chemistry have provided additional information on this research area.

5. PHOTONIC MATERIALS AND METAMATERIALS

Related themes:

Energy, **Engineering**, **ICT**, **Physical sciences**

Research into the synthesis, characterisation and theoretical understanding of photonic materials i.e. materials which can mould the flow of light under certain conditions. This area includes: liquid crystals, photonic crystals, metamaterials, organic and inorganic semiconductors. This area does not include materials for energy applications, electro- active ceramics or polymers or material integration into devices. This research is included in related research areas.

This topic which can broadly be described as photonic materials covers the synthesis, characterisation and theory of materials which mould the flow of light and/or emit/transmit light upon electrical stimulus.

New advances in the synthesis and characterisation of inorganic and organic semiconductor materials (e.g. OLEDs) are leading to novel applications in electronics (e.g. displays) and solid-state lighting (c.f. European Science Foundation - MatSEEC report - 2011; Materials for Key Enabling Technologies. EMRS, MatSEEC, ESF, June 2011). (Global demand for lighting is expected to be over $110B by 2012 - c.f. BIS Report, 'Ultra Efficient Lighting in the UK', 2009.) The UK is internationally leading in the area of organic semiconductors research and also has key clusters of expertise in inorganic semiconductors (c.f. International Review of Chemistry 2009 and International Review of Materials 2008) especially for optical and photovoltaic applications.

Organic semiconductors research and associated plastic electronics have potential to making a significant contribution to the Energy theme e.g. light-emitting polymers for displays (OLEDs) and Organic Photovoltaics (covered under 'Materials for Energy' research area). Liquid crystals displays of ever increasing performance are ubiquitous whilst phase-change materials such as chalcogenide glasses have the potential to revolutionise data storage and optical communications. The fields of spintronics and molecular electronics are slowly converging to yield a new interdisciplinary area referred to as molecular spintronics, enabled by advances in ultra fast measurement and nanotechnology. There is an opportunity to exploit strengths in the UK organic semiconductor and liquid crystals communities and niches of expertise in spintronics to put the UK on the international map in this area. Liquid Crystals and self-assembly research is directly underpinning the **'Directed Assembly of Extended Structures'** Grand Challenge.

Recent advances in nanofabrication technologies combined to new ideas in transformation optics developed in the UK (Pendry et al.) have led to the design of novel artificial media, called metamaterials, which can control and manipulate light in unexpected ways (e.g. cloaking phenomenon - c.f. Science 'Insights of the Decade' Dec 2010 edition). This leads to a range of potential applications including imaging, sensors, circuit processing and nanolithography (c.f. Nanophotonics European Association Foresight Report 2010). The UK is internationally leading in this area growing from a small base to establish key EPSRC-supported centres at Imperial College London, the University of Southampton and the University of St Andrews. By bringing the UK world-leading expertise in graphene and metamaterials together in collaboration, there may be an opportunity to 'tune' metamaterials and open-up new applications. Other potentially interesting opportunities include superconducting metamaterials and, in the longer term, quantum metamaterials (c.f. 'A Roadmap for Metamaterials', N Zheludev, Optics and Photonics News, March 2011.). A number of UK researchers are turning their effort to the field of acoustic metamaterials: an area currently underdeveloped in the UK and which links strongly with the Engineering and ICT themes (acoustics and electromagnetics).

This topic is also very relevant to the EPSRC physics grand challenge of **Nanoscale design of functional materials**. It is also relevant to **Quantum Physics for New Quantum Technologies**.

Investment in the **Metamaterials** area **will be grown**, relative to other areas of the portfolio, to take full advantage of UK's current rapid growth and internationally competitive research standing, with EPSRC exploring possible strategic bids, alongside standard proposals and working with leading researchers to develop ideas and highlight the area to relevant EPSRC industry strategic partners. **Organic semiconductor and inorganic semiconductor materials** research **will be maintained**, relative to other areas of the portfolio, through standard routes to enable our large internationally recognised research capacity to continue to excel. New potential opportunities, such as molecular spintronics and acoustic metamaterials, will be explored further in partnership with the research community.

6. POLYMER MATERIALS

Related themes:

Energy, **Engineering**, **Healthcare technologies**, **Manufacturing the future**, **Physical sciences**

Research into the synthesis, characterisation and theoretical understanding of novel polymer materials. This area includes studies into novel polymer synthesis, polymer drug delivery, polymer nanocomposites, responsive polymers, block co-polymers and soft nanotechnology. This area does not include research into polymers for energy applications or photonic polymers, this research is included in related research areas.

The research funded within the polymer materials research area is internationally competitive as discussed in the **International Review of Chemistry 2009**. It contributes to many other research areas within **Physical Sciences**, **Engineering** and **ICT** as well as more broadly into life and medical sciences. Polymer materials research underpins many research areas, providing the basic polymer science that enables organic photovoltaics, photonic and meta materials, plastic electronics, drug delivery, colloid science, bio-materials and stem cell technology through synthesis and understanding of, among many other things, block co-polymers, self-assembly processes, polymer brushes and polymer nanoparticles. The area has huge cross over with **Soft Matter Physics** and increasingly **Biophysics** as well as **Materials for Energy Applications** and **Metamaterials and other Photonic Materials**. University researchers in this area work closely with industrial researchers (current project partners include **GlaxoSmithKline**, **AstraZeneca**, **Biocompatibles**, **Renishaw**) as the need for experimental and theoretical polymer materials research from industry is high. Therefore, polymer materials research is an important capability for the UK to protect and support.

EPSRC have funded two programme grants with relevance to this research area and key groups are well supported through standard grants and a variety of other mechanisms, including seven platform grants and ten fellowships. Although there is not a dedicated Centre for Doctoral Training in the polymer materials area there are five centres that contribute to training in this area, two of these have strong industrial support through the Strategic Partnership and Industrial Doctorate Centre mechanisms.

Polymer Material researchers have huge potential to drive forward Physical Sciences Grand Challenges particularly in the areas of **Directed Assembly of Extended Structures with Targeted Properties**, **Nanoscale Design of Functional Materials**, **Utilising CO2 in Synthesis and Transforming the Chemicals Industry** and **Understanding the Physics of Life**.

Polymer materials groups received significant funding from the previous delivery plan's Nanotechnology: through Engineering to Application programme (eight of the sixteen Grand Challenge projects funded involved polymer science), researchers should continue to develop proposals that drive nanotechnology through to application.

Currently funded polymer materials research contributes significantly to the **Healthcare Technologies** theme particularly under the Medicines and Regenerative Medicine areas, in targeted drug delivery, biomaterials and stem cell technologies. Healthcare Technologies relevant research is a large part of the current investment in this research area and researchers should continue to take into account the priorities of the Healthcare Technologies theme when applying to EPSRC.

Within the **Manufacturing the Future** theme Frontier Manufacturing is a new opportunity for polymer materials researchers to engage with emerging priorities and highlight physical sciences contribution to the manufacturing agenda, particularly in the areas of sustainability through polymers from renewable feedstock and large scale manufacturing of soft nanotechnology. Investment in the polymer materials research area will be maintained, relative to that in other areas. EPSRC will continue to fund high quality polymer materials proposals through standard routes as well as encouraging researchers to respond to opportunities in the Healthcare Technologies and Manufacturing the Future Themes.

Alongside the input detailed in the **Physical Sciences: Our Approach** page the **Medical Engineering Centre for Excellence**, **Association of the British Pharmaceutical Industry**, SoftComp brochure **Soft-Matter Research for Society** and a number of individuals identified by the Royal Society of Chemistry and the Institute of Physics provided additional information on this research area.

ANNEXE 2: EPSRC RESEARCH AREAS WITH RELEVANCE TO MATERIALS SCIENCE

A number of themes support work directly or indirectly related to Materials Science. These are covered by the following Research Areas:

Biomaterials and tissue engineering

Biophysics and soft matter physics

Energy storage

Fuel cell technology

Hydrogen and alternative energy vectors

Manufacturing technologies

Materials engineering - ceramics

Materials engineering - composites

Materials engineering - metals and alloys

Microsystems

Optical devices and subsystems

Resource efficiency

Superconductivity

Solar technology

Full descriptions of these can be found on the EPSRC website:
http://www.epsrc.ac.uk/ourportfolio/researchareas/Pages/default.aspx

ANNEXE 3: PANEL TERMS OF REFERENCE AND MEMBERSHIP

1. TERMS OF REFERENCE

Within the context of EPSRC's existing programme structure and policies and against the background of initiatives in other countries (for example, USA, EU, China, Japan) the Panel's Terms of Reference are to:

- produce a roadmap for materials science research in the UK that, in each of the relevant Research Areas identifies:
  - research opportunities
  - importance to the UK
  - strengths and weaknesses in the UK
  - the need for underpinning techniques (for example modelling)
  - the links to other Research Areas and EPSRC Challenge Themes
  - opportunities for international collaboration.
- suggest research priorities for the UK materials science community.
- oversee a consultation with community on the roadmap and priorities.
- report to the Physical Sciences Strategic Advisory Team.

2. DEFINITION

For the purposes of this review Materials Science is defined as those research areas for which the Physical Sciences Theme as the prime responsibility namely:

- Condensed matter: magnetism and magnetic materials
- Functional ceramics and inorganics
- Graphene and carbon nanotechnology
- Materials for Energy Applications
- Photonic materials and meta-materials
- Polymer materials

3. MEMBERSHIP

Professor Cameron Alexander, School of Pharmacy, University of Nottingham

Professor Neil Alford, Department of Materials, Imperial College

Nigel Birch, Senior Portfolio Manager, Physical Sciences, EPSRC

Professor Claire Carmalt, Department of Chemistry, UCL

Professor Peter Edwards, Department of Chemistry, University of Oxford

Professor Saiful Islam, Department of Chemistry, University of Bath

Dr John Morlidge, TSB

Dr Mike Murray, The Morgan Crucible Company

Professor Michael Preuss, School of Materials, University of Manchester

Professor Matt Rosseinsky, Department of Chemistry, University of Liverpool

Dr Renald Schaub, Department of Chemistry, University of St Andrews

Professor Henning Sirringhaus, Cavendish Laboratory, University of Cambridge

Professor Pamela Thomas, Department of Physics, University of Warwick