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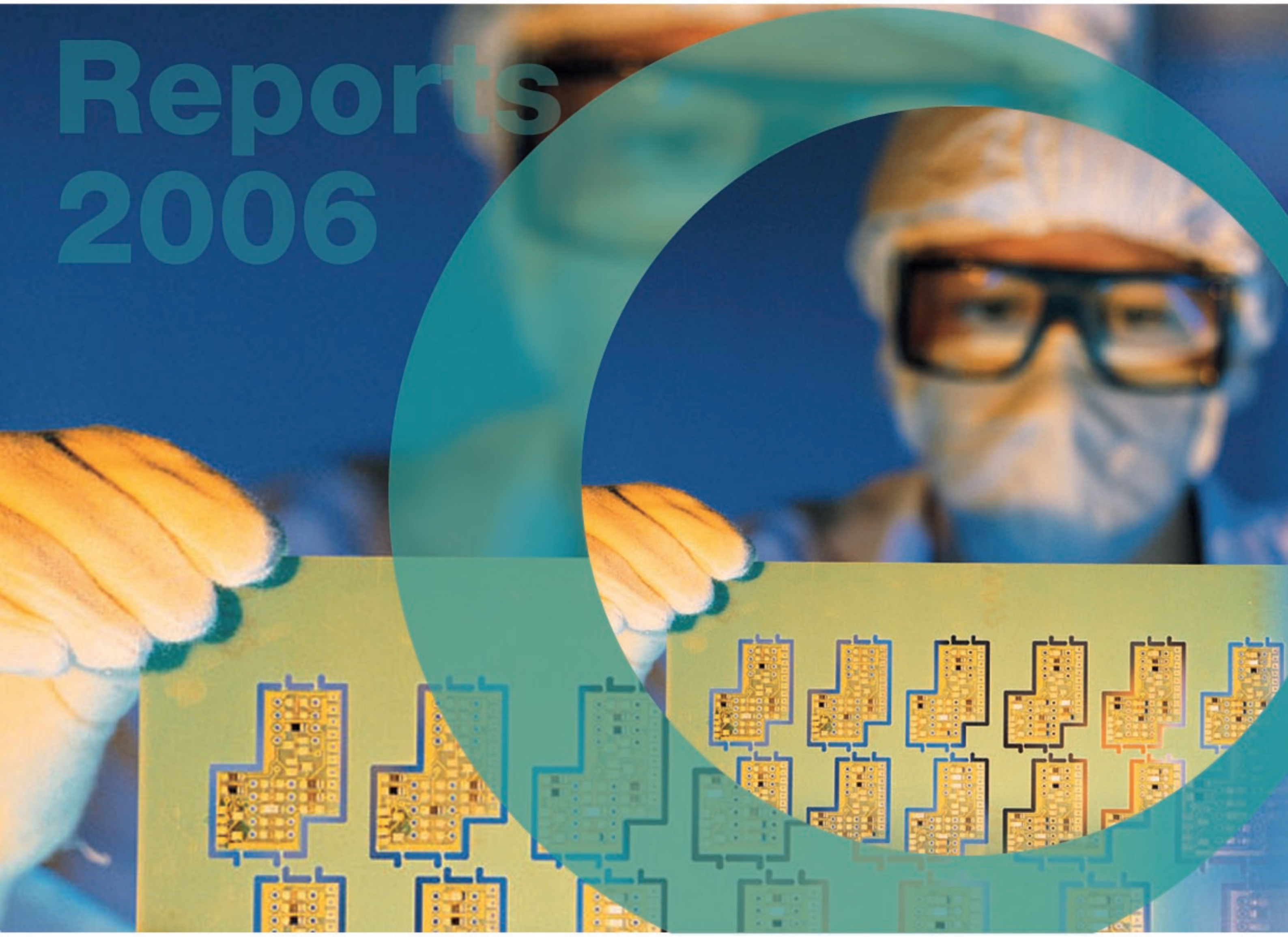
Functional Materials



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Materials Innovation and
Growth Team

Summary

Definition and Significance

"Functional materials" are defined as those materials that perform specific functions other than possessing a load bearing capacity. Examples include semiconductors, magnetic materials, piezoelectrics and ionic conductors. Unlike the more traditional materials such as metals, ceramics, cements etc, many of which have been used for millennia in buildings, tools etc, they have developed huge economic significance only over the last 50 years, in many cases through applications which did not exist prior to the discovery of the material. Hence, while the basic need for human shelter has seen a very wide range of materials applied to building (wood, stone, concrete and even bone), it was only through the discovery and applications of semiconductors and other functional materials that our modern information and communications technology (ICT) – based society has developed. The effect that ICT has had upon modern society cannot be over-estimated. It ranges from the huge economic impact – with a world market size in excess of $4 trillion, currently growing at 4.8%pa – through its effect upon human health and well-being via e.g. health care applications – to its enormous political impact through the availability of instant world-wide communications. The effects of the use of functional materials are vastly greater than the volumes, or economic values, of the materials used would imply.

This Report

One of the problems with reviewing the current position on functional materials is their diversity, both in the range of properties exhibited and exploited, and in the range of forms available.

The range of exploitable properties is very large, and includes, for example:

- semiconducting behaviour
- magnetism
- dielectric properties
- piezoelectricity
- pyroelectricity
- the ability to alter refractive indices with electric field (electro-optic effect) or stress
- the ability to conduct ions in the solid state (ionic conductivity) or
- store atoms for later use

and the range of exploitable materials forms is large and includes single crystals, ceramics, thin films, polymers and gels

The range of application sectors is correspondingly large, including:

- information and communications technology (noted above),
- energy generation and storage
- transport
- healthcare
- defence
- consumer goods

and many more through the use of the materials in, for example, information processing devices, radio-frequency (RF) transmission and reception, light generation and detection, sensing, actuation etc.

Many of the applications depend upon the use of multiple functional materials. Semiconductor devices are ubiquitous in society (there is hardly any aspect of modern society that does not, in some way, involve the use of a semiconductor device), but their use would be impossible without many peripheral devices that depend upon the use of magnetic, dielectric or conductive materials in one way or another. It will also be readily appreciated that, unlike many materials that are used in large volumes (such as, for example, building or packaging materials), the value of most functional materials lies in their enabling capabilities. Their economic impact comes from the effects of applying the devices and systems that use them, rather than the economic value of the materials themselves. This means that any strategy for investment in functional materials and the technologies based upon them must be predicated upon a clear understanding of the knock-on effects that such an investment will make, not upon the values of the materials themselves, nor even upon the devices which use them.

This report has, therefore, depended upon pulling together inputs from many different experts in the UK (see Table 1). It cannot hope to be a complete survey of all possible types of Functional Materials. However, most of the recommendations are generally applicable, and this summary is backed-up by the detailed reports from those experts listed in Table 1. The National Advisory Committee for Electronic Materials for Aerospace and Defence has also been consulted on the content of this report and its recommendations.

Table 1

Material Class/Report Section	Subject	Contributor		
Ferroelectrics	Pyroelectrics	Professor	Roger	Whatmore
	Piezoelectrics	Professor	Andrew	Bell
	Dielectrics	Professor	Neil	Alford
	Ferroelectric Memories	Professor	Jim	Scott
	Ultrasonics/NDT	Dr	Sandy	Cochran
	Electro-optic Materials	Dr	Peter	Smith
Semiconductors	Silicon/Si-Ge	Dr	John	Ellis
	THz Technologies	Dr	Douglas	Paul
	III-V's, II-VI's	Dr	Andrew	Phillips
	Quantum Structures	Professor	Maurice	Skolnick
Energy generation	Materials for Energy Generation	Professor	John	Kilner
	Materials for Fuel Cells	Professor	John	Irvine
	Hydrogen Storage	Professor	Rex	Harris
Magnetics	Magnetics/Composite Magnets	Dr	Jeff	Alcock
	Magnetic Storage Materials	Dr	Rob	Hardeman
	Magnetostrictives	Dr	Alan	Jenner
Materials Technology	Functional Materials Characterisation	Dr	Markys	Cain
	Direct Write Technologies	Professor	Brian	Derby
	Electronic Packaging Materials	Dr	Chris	Beck
Organic Materials	Adaptive Polymers	Dr	Wayne	Hayes
	LB Films & Molecular Electronics	Dr	Peter	Skabara
	Organic Electronics	Professor	Richard	Friend

Section co-ordinators are shown in red.

1 Ferroelectric Materials and Dielectrics

Ferroelectric materials offer a very wide range of useful functional properties. A reasonable working definition of ferroelectricity is "a polar dielectric in which the polarisation can be switched between two or more stable states by the application of an electric field". However, there are exceptions to this definition: some ferroelectrics are semiconducting (and thus are not dielectrics because they cannot sustain an electrical polarisation); the spontaneous polarisation in some ferroelectrics cannot be switched because they cannot sustain an electric field of sufficient magnitude to effect the switching, either because they reach electrical breakdown first, or because they are too conducting.

Since its initial discovery the ferroelectric effect has been demonstrated in a wide range of materials, from water soluble crystals through oxides to polymers, ceramics and even liquid crystals. The range of useful properties exhibited by ferroelectrics covers:

- Ferroelectric hysteresis is used in non-volatile computer information storage
- Ferroelectrics can exhibit very high relative permittivities (several thousand) which means that they are widely used in capacitors
- The direct piezoelectric effect (the generation of charge in response to an applied stress) is widely used in sensors such as accelerometers, microphones, hydrophones etc
- The converse piezoelectric effect (the generation of strain in response to an applied electric field) is widely used in actuators, ultrasonic generators, resonators, filters etc
- The pyroelectric effect (the generation of charge in response to a change in material temperature) is widely used in uncooled infra-red detectors
- The electro-optic effect (a change in birefringence in response to an applied electric field) is used in laser Q-switches, optical shutters and integrated optic (photonic) devices
- Ferroelectrics exhibit strong non-linear optic effects that can be used for laser frequency doubling and optical mixing
- Illumination of transparent ferroelectrics with light of sufficient energy causes excitation of carriers into the conduction band. Their movement under the internal bias field caused by the spontaneous polarisation causes a refractive index modulation that can be used for a variety of optical applications, including four-wave mixing and holographic information storage
- Ferroelectrics exhibit strong coupling between stress and birefringence, which can be used to couple acoustic waves to optical signals with applications in, for example, radar signal processing
- Doping certain ferroelectric ceramics with electron donors (e.g. $BaTiO3$ with $La3+$) can render them semiconducting. Heating these ceramics through their Curie temperature causes a very large, reversible increase in resistivity (by several orders of magnitude in some cases) over a narrow range of temperature (ca 10°C). This large positive temperature coefficient of resistance (PTCR) is widely exploited in electric motor overload protection devices and self-stabilising ceramic heating elements

The UK has managed to maintain a strong position is certain aspects of ferroelectric/dielectric materials and applications. The position in piezoelectric ceramic manufacture is strong, and the last 10 years has seen the birth of a number of new companies based on the use of the piezoelectric effect (in, for example, medical ultrasound devices) and the pyroelectric effect in infra-red sensing and thermal imaging. The application of high frequency dielectrics in microwave filtering applications has received considerable industrial success. The academic position is also moderately good, with a strong UK academic network and a few groups which can be classified as world-class, especially in micro-nano applications of these materials. The major directions for the future of this technology will be in the development of high performance, low-lead, high temperature performing piezoelectrics and low loss microwave dielectrics. The development of technologies for the exploitation of the materials in thin film form for micro/nano applications will also be very important and is an area where international competition is strong.

2 Semiconductors

In terms of its global economic impact, this is by far the most important class of functional materials. The whole of the multi-trillion dollar ICT industry, including software and systems as well as basic devices, is based on the successful exploitation of semiconductor materials. The class encompasses two main sets of materials: silicon and compound semiconductors, with silicon taking by far the largest share of the market. Organic semiconductors, whose useful properties have only been developed in the last 15 years, are just starting to contribute to the light emitting displays market. The range of applications for silicon based devices is huge and encompasses not only IC's (with CMOS devices taking the lions' share of the market), but also power semiconductors (growing in importance because of the need for increasingly-sophisticated power control requirements in the transport and industrial sectors) and photovoltaic devices for power generation. Recent developments have seen marked improvements in the efficiency of Si photovoltaic devices through careful attention to the details of device fabrication.

The market for silicon based IC's alone is currently $213Bn pa, projected to rise to over $1trillion by 2020. The now-famous "Moore's Law", which drives the development of high-performance silicon IC's, states that the critical dimensions of features on the highest performance silicon chips (mainly memory and microprocessors) will reduce by 40% every 18 months. 90nm line-widths are now in production, with 65nm coming along within the next 18 months. Interestingly, the drive to smaller dimensions, traditionally led by large companies such as Intel, is now being challenged by companies in the Far East, with one Chinese foundry (SMIC) developing 65nm technology. There is no reason to believe that the technology will reach a plateau within the scope of this IGT study. The ITRS "roadmap" extends to 2018, with dimensions of 6 to 10nm, without any requirement for more exotic technologies, such as self-assembling materials and structures.

Considering the global economic importance of this technology, the UK has, for the last 15 years, largely de-emphasised silicon technology. There are still a number of viable silicon device manufacturing facilities in the country, working at dimensions of 0.35 and 0.18 microns and UK academia has managed to maintain a world-competitive position in certain aspects of the technology, such as novel dielectrics (which will be essential as dimensions shrink further), but their position must come under threat from Far Eastern groups as investment there is very high.

The UK position on software and design has traditionally been strong, but is likely to come under increasing threat from India and the Far East as the materials and device technologies shift in that direction. Once companies that command the highest performance device technologies have also built-up the design expertise, those companies are likely to recognize that they will have a major strategic advantage in the market-place by keeping these technologies for their own designers.

The fact that newcomer countries like China can come from behind to leading technological positions suggests that our declining position is not unrecoverable. 10 years ago the US government perceived that the USA was falling behind the Far East in semiconductor device manufacturing and instigated an research investment programme that has redressed the balance, spawning a number of vibrant new industries. The UK still has a number of successful companies in the silicon device business, including E2V (making high performance imaging chips), XFAB and ATMEL. However, they are not well supported and there is evidence that the lack of such development support has caused inward-investors to move out of the UK. Specifically, Fujitsu moved out of their plant in Co Durham, citing the lack of availability of development support as a one reason for the move.
Compound semiconductors, such as III-V compounds based on GaAs, InP and, increasingly, GaN and II-VI compounds such as ZnO, are an important range of functional materials. (See Apprendix 1 for more detail) They provide a set of vital enabling capabilities which cannot, and probably never will, be satisfied by silicon-based devices. These include low-power RF amplifiers, optoelectronic/photonic devices, devices for high-efficiency solid-state lighting and quantum structures for novel applications such as terahertz imaging (likely to be of increasing importance for security and medical applications). It is possible, in the medium-to-long term, that the provision of compound semiconductor capabilities on-chip will enable aspects of silicon technologies which are not currently possible (such as on-chip communications using light). The ability of compound semiconductors to emit light efficiently, across a wide spectral range from the infra-red to the ultra-violet, is a key functional property that, while widely exploited, still has many potential uses and markets that remain untapped. An important potential area of growth is high-efficiency solid-state lighting. It has been calculated that the replacement of all the incandescent lamps currently used in traffic lights in the UK would save the power (and consequent carbon emissions) equivalent to that generated by a moderately-sized power station. Compound semiconductors also form the basis for

a range of new devices, such as those for terahertz imaging and devices that may form the future basis for quantum computing. Academic work on these has been well supported in the UK, giving us a lead which it is important that we do not lose in the move to widespread exploitation.

The worldwide market for compound semiconductor-related products was about $13 billion in 2004. This is expected to rise at a 17% average annual growth rate (AAGR) to nearly $30 billion by 2009. Materials account for between 5% to 7% of the market and components for more than 50% of the total revenue. This category is projected to expand at an AAGR of 18% to exceed $16 billion in 2009. The market is thus much smaller than silicon-based devices and systems, although the growth-rate is larger, and it is widely accepted that compound semiconductors, while vitally important, will not displace silicon-based devices for the vast majority of ICT applications. Hence compound semiconductor and silicon technologies should be seen as being complementary. UK industrial activity in compound semiconductors is based around a relatively small number of companies: IQE for substrates and epitaxial wafers, Bookham for InP-based optoelectronic components and Filtronic & E2V for GaAs-based microwave devices. CIP are nominally private and have the intention to sell products in the opto area, but largely survive on government funding at the moment. There are a number of academic groups doing internationally-leading materials and device work.

Organic semiconductors emerged in 1990, with the first demonstration, in Cambridge, of electro-luminescence in PPV. Since then, these materials have been demonstrated successfully in organic light emitting devices (OLEDs), "plastic logic" devices and photovoltaic devices. The materials do not exhibit the performance of conventional semiconductors, but offer the potential for novel devices and systems, such as "wearable" computers, low cost emissive displays designed to replace liquid crystals and low cost photovoltaic devices for power generation. Certain technical challenges still remain to be solved, including better environmental stability, but the materials show great promise.

It is clear that semiconductor materials remain some of the most important functional materials, both in terms of the markets that depend upon them and their strategic enabling capabilities.

3 Magnetic Materials

Like semiconductors, magnetic materials are ubiquitous in modern high technology society. In their various forms, they are used in the storage, movement and processing of energy, mass and information and as such are fundamental to all advanced economies. As an indication of the scale of use of magnetic materials, more than 15 000 patents were registered in the US between 2000 and June 2005 in which magnetic materials formed part of the claimed invention. The world market for hard magnetic materials has been estimated at $4 – 5 billion dollars and for soft, $12 billion. The uses of the materials range from prosaic applications such as the permanent magnets in electric motors, through to the very high density storage of information in the hard disk drives used in computers. There is active materials research pursuing hard magnet materials, especially for use in motors and loudspeakers/headphones, soft magnet materials for use in transformers and magnetostrictive materials for use in actuators and smart materials. The UK position has moved from a position of relative academic and industrial strength in the 1960's to a currently weak position, which is worrying given the importance of the materials and the supposed-strength of the UK in high technology.

Further details on magnetic materials is given in Appendix 2.

4 Functional Materials for Energy Generation

Functional materials do not currently play a major role in the generation of electrical or motive power, however their importance lies in their future role in novel generation and storage technologies and for clean and renewable energy. These technologies are of critical importance if the UK is to meet the dual demands of security of supply and reduction of carbon emissions. This brief report is not intended to be a comprehensive review, rather one which highlights some examples of the use of these complex materials.

The functional nature of the materials involved is diverse and, as in other areas of this report, covers material types such as metals, ceramics, semiconductors and polymeric materials. Their classification is difficult, however it is possible to make a very broad grouping based on their functionality and application areas. This is shown below in Table 1.

Functional Material	*Application*	*Examples*
Semiconductors	Photovoltaics, sensors	Silicon, TiO_2
Ionic conductors	Fuel cells, high energy density batteries, Electrolysers, sensors	Yttria stabilised zirconia, Nafion
Mixed conductors	Fuel cells, oxygen separation membranes, sensors, high energy density batteries	$La_{1-x}Sr_xCoO_3$
Superconductors	Electrical transmission	$YBa_2Cu_3O_7$
Absorbent materials	Hydrogen storage	C-nanotubes, $LaNi_5$

Table1: Functional Materials for energy applications

The potential for development of these materials is enormous. An example of a function material used in a relatively mature technology is the use of silicon in photovoltaics, however as recently as 2001 this accounted for less than 0.1% of the world total electricity generation. This gives some indication of the scope for research and development as well as the potential global market for such devices. The UK capability in the area of photovoltaics is outlined in the section on semiconductor materials.

One area where functional materials should make a very marked impact is the transition from a hydrocarbon fuelled economy to the so called hydrogen economy, although it should be noted that unlike hydrocarbons, which are a primary source of energy, hydrogen is only an energy vector and thus is reliant on nuclear or renewable primary sources. The key to this transition is to find clean and highly efficiency ways of continuing to use hydrocarbons for electrical power generation whilst anticipating the introduction of hydrogen as an energy vector. Fuel cells fulfil many aspects of this role for stationary, portable and motive power applications and in addition have other advantages including scalability which is important for applications such as distributed generation. Ionic and mixed conductors are the functional materials used in fuel cells and there is great scope for improvement in all aspects of their properties. One of the key problems in the optimisation of fuel cells is electrocatalysis at the fuel cell electrodes and in particular the reduction of oxygen at the cathode. Electrocatalysis is a problem common to both low temperature PEM cells, based on polymeric protonic conductors such as nafion, where precious metals are used as catalysts, to the high temperature solid oxide cells, where mixed electronic-oxygen ion conducting oxides are used.

Functional Materials

The UK has a very good reputation in this area known as solid state ionics which includes the study of materials for fuel cells, batteries and sensors. This ranges from the basic science underpinning atomic transport in solids, including world leading computer based materials modelling techniques, to the commercialisation of devices. The academic solid state ionics community in the UK is both one of the founders of this relatively new field as well as being one of the most active and productive in the world. It is also has a good reputation for entrepreneurship and commercialisation with several spinout companies in the field of fuel cells and batteries standing alongside established industries.

As mentioned earlier hydrogen is an energy vector, similar to electricity, and with the increasing introduction of renewables and perhaps nuclear power into the generation mix, energy storage will become an important issue. Here high energy density batteries and electrolysers to produce hydrogen for storage will play an important role. Hence one of the key enabling technologies for the hydrogen economy is the storage of hydrogen, particularly for transport applications. Here again the UK has a very good reputation in materials development and an active research consortia funded through the SUPERGEN initiatives in sustainable hydrogen and energy storage. Although much progress has been made over he last few years, significant barriers still exist to the practical use of hydrogen as a transport fuel, not forgetting the need for a distribution infrastructure.

In all the areas mentioned above the UK has a modest but high quality effort, however there is significant competition from other developed economies, in particular the US and Japan. If the UK is to retain some leadership in this field, and to meet the timescales necessary to achieve the dual targets of security of supply and emissions reduction, then there is a need for a concerted effort. A key recommendation for this area is that alongside the excellent, but necessarily broad, Supergen programmes, there is the establishment of a new strategic programme focussing solely on the development, optimisation and application of these important functional materials. This programme should integrate the whole community from the very theoretical aspects of materials modelling right through to the development of devices.

Functional Materials

Appendix 1

Compound Semiconductors and Quantum Structures

Technology

Compound semiconductor technology extends the performance of silicon semiconductor devices in a number of different directions.

- It allows devices to operate at higher frequencies, extending maximum operating frequencies from about 10 to over 100 GHz and so allowing increased exploitation of the electromagnetic spectrum for applications such as communications and sensors. The largest market for compound semiconductors is that of GaAs power amplifiers in mobile phones, where their use has helped to increase battery life by almost an order of magnitude
- Unlike silicon, most compound semiconductors interact strongly with light, and so are used to convert electrical signals to optical signals. Specific examples include light emitting diodes, giving a more efficient alternative to filament and fluorescent lights, and solid-state lasers, the key technology behind compact discs
- Wideband gap compound semiconductors, based on Gallium Nitride (GaN) allow much higher powers to be produced than does silicon, leading to amplifiers with higher dynamic range and robustness which can provide an alternative to more complex vacuum tube devices
- More generally, the variety of materials that can be used to produce the compound semiconductors has led to a whole range of new physical ideas and applications in a way not possible with silicon

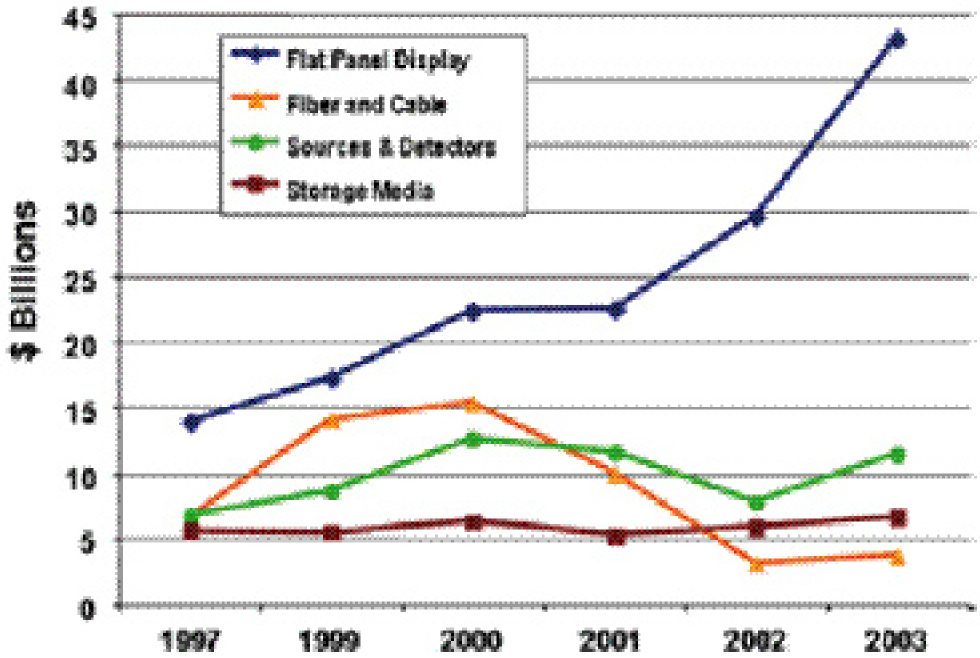
The key to the development of the technology has been the ability to control growth of the materials at the atomic level, producing well-defined layers of material only one or two monolayers thick, with very low impurity levels. Much of the early work was carried out both in the UK and elsewhere on the back of military funding, either into industry or through military research centres such as DERA, and there is some concern that future materials development will be hindered within the UK by the reduction in such funding.

Quantum structures built from III-V semiconductor materials already have very large penetration into the opto-electronics marketplace. The most common of these are light emitting diodes and lasers based on semiconductor quantum wells. These consist of alternating layers of semiconductor materials which act to confine charge carriers to 5 to 10nm regions thus giving control of light wavelength. Further enhancements to design, ubiquitous in laser structures, allows fabrication of photonic waveguides or vertical cavity structures, the essential ingredients of high efficiency light emitters. These now cover the key telecommunications wavelengths of 980, 1300 and 1550nm, the 630-670nm wavelengths of DVD readers and writers and the near uv wavelengths for displays, blue ray data storage etc. All this technology now exists and permeates everyday life. As well as covering the near infrared to ultraviolet spectral regions, IIIV quantum devices also supply highly efficient microwave emitters, in the form of devices with a single interface. Such high electron mobility transistors have major penetration of the mobile communications market. Quantum well based devices also have major promise in the mid IR and terahertz spectral regimes, in the form of the quantum cascade laser, a complex multilayer device based on up to 500 individual layers of 1-2nm thickness, in which each injected electron emits 20-30 phonons as it experiences the cascade potential through the structure.

Next generation developments in part are likely to be based on carrier confinement in all three dimensions, in so-called quantum dot structures, as opposed to the confinement in one dimension in quantum wells. Quantum dot structures have already demonstrated superior performance as 1300nm lasers to those based on quantum wells, a direct result of the full carrier confinement. Long term applications of III-V quantum dots may also be as emitters of single photons for cryptography applications, and as the basic elements of prototype quantum computers. Quantum dots in colloidal form are also attracting very considerable interest for tagging of molecules in biological systems.

Assessing the market for compound semiconductor materials themselves is almost impossible because almost all the industry is vertically integrated, with device manufacturers growing their own materials, and often packaging the resulting devices and circuits into sub-systems such as amplifiers or high intensity lights. The technology is a key element in opto-electronics, where the total world market size has been estimated as $300billion in 2003 (OITDA, Japan), increasing by 10% per year, of which the component market is $60 billion, as shown in the figure below. Of this global market, about 35% is in North America, with the remainder equally divided between Europe, Japan and the Rest of the World, although the last has the highest growth.

It is extremely difficult to analyse this global figure in order to estimate the value of the materials market, partly because of the level of business integration, but also because it is so small. Analysis of the specific case of a GaAs integrated circuit (MMIC) power amplifier demonstrates this clearly. The final cost of a MMIC is made up of substrate, material growth, semiconductor processing, and testing costs. Of the final circuit cost the substrate cost is approximately 2%, and the cost of the epitaxial material (including substrate) is about 5% even for relatively high volume production where NRE can be ignored.



OE Component Sales Worldwide
Source: OIDA Market Reports 1998-2003

Similar arguments apply to other components. Indeed a recent communications technology roadmap from MIT (Compound Semiconductor, June 2005) made the point that 80-90% of the cost of photonics components was the result of testing and packaging.

The major applications of quantum devices are based on light emission and detection and as highly efficient sources of microwave radiation. The UK has major players in both these areas.

Quantum devices are important for LED and laser application since they form the basis of highly efficient sources of radiation, with wavelength controllable by design of composition or layer widths, covering the wavelengths of a wide range of technologies. These include the key telecommunications wavelengths of 980, 1300 and 1550nm, the 630-670nm wavelengths of DVD readers and writers and the near uv wavelengths for displays, blue ray data storage etc. All this technology now exists and permeates everyday life. Bookham is a major UK based company in the field of III-V based telecommunications components.

As well as covering the near infrared to ultraviolet spectral regions, III-V quantum devices also supply highly efficient microwave emitters, in the form of devices with a single interface. Such high electron mobility transistors have major penetration of the mobile communications market. Filtronic is a major UK based company in this field. Quantum well based devices also have major promise in the mid IR and terahertz spectral regimes, in the form of the quantum cascade laser, a complex multilayer device based on up to 500 individual layers of 1-2nm thickness, in which each injected electron emits 20-30 phonons as it experiences the cascade potential through the structure.

Technology Drivers

- The expected limit on the reduction of critical dimensions in silicon devices, and hence the limit on speed (Moore's Law) has led to investigations of the use of IIIV materials as possible alternatives by some of the major silicon foundries such as Intel and Motorola. The major issue is to adapt II-V technology to make it compatible with silicon (in the way that Si/Ge is compatible) and to develop high quality oxides on III-V materials. There may be fundamental limits on the operation of III-Vs at nanometre length scales, as there are in silicon
- At present opto-electronic processing and communication involves the conversion of optical signals to electrical signals. The potential benefits in cost and speed of all-optical processing is driving
- Requirements for more reliable and cheaper high power microwave sources, to replace vacuum-tube devices is driving the development of GaN based materials and devices for microwave power amplifiers. The higher bandgap allows operation at higher voltages and powers, but the lack of bulk GaN substrates means that material quality needs to be developed further
- Replacement of incandescent and fluorescent lighting by more efficient solid-state lighting based on GaN offers the potential fro major energy savings worldwide. Major issues concern the internal quantum efficiency of quantum-well GaN based LEDs, reliability, and also the removal of heat from the active regions. The high efficiency and reliability of GaAs and InGaP based LEDs suggest that these problems are solvable

Near IR quantum well based devices have reached a high state of development. Key developments include laser structures with improved temperature performance (requiring research into new materials combinations). The drivers here are next generation telecoms systems.

The near uv and uv GaN based devices require improvements in growth technologies (UK industrial presence here through Sharp Labs of Europe), including substrate development, development of low dislocation density buffer layers, microcavity development. Drivers are display, data storage, lighting and gas detection technologies.

Quantum cascade lasers require improvements in device yield and development across a wider wavelength range to name tow areas. This is likely to be achieved by optimization of growth technology, developments into new materials systems (e.g. Sb-based from the present GaAs/InGaAs/AlGaAs/InAlAs), by growth improvements e.g. for THz lasers and processing developments e.g. single frequency lasers for gas detection. Drivers are principally gas detection technologies.

For the longer term for quantum dot based devices, improvements in dot uniformity, ability to place the dots at predetermined positions, and extension into new wavelength ranges e.g. 1500nm are all required. Drivers are next generation lasers, fundamental research and 10-20 year quantum information processing technologies.

UK Position

Industry

- The only "pure play" III-V materials company within the UK is IQE (formed by a merger between EPI, Cardiff, QED, USA and Wafertech, Milton Keynes), who supply substrates and epitaxial wafers to opto and microwave foundries
- With the closure of the GaAs foundry line at Caswell (Bookham), the only two companies involved in GaAs are Filtronic, who produce power amplifiers and switches for base stations, and E2V in Lincoln who produce Gunn diodes for automotive applications. There is no commercial foundry operating within he UK which is raising problems, for defence companies in particular, of cost-effective accessing of MMIC technology for low-volume applications
- The opto-electronic industry, based largely on InP, has one relatively large company, Bookham (although the company is now domiciled in the US), the world number two supplier of opto-electronic components with 2000 employees worldwide, and a large number of small companies that start (and stop) with a certain amount of regularity. None of these can be regarded as primarily materials companies, but almost all have materials growth and development as a primary and critical business activity. A common model is that in the initial stages materials are sourced internally, but as technology matures and volumes increase epitaxial material is sourced externally from companies such as IQE
- There are also a number of centres in the III-V area that have an ambivalent status, either because they are nominally private but survive because of government funding (QinetiQ, CST), or they are public with an intention to sell product (CIP)
- UK industry is significantly involved in supplying equipment for semiconductor material growth, processing and characterisation. They are represented by a trade body, Jemi, whose members have an annual turnover of £1billion
- There is no industrial involvement in the manufacture of high volume components such as LEDs or microwave devices, and so no obvious route to exploitation of much research and development such as widebandgap technology

The UK has strong industrial positions in the telecoms and microwave areas through Bookham and Filtronic. There are also several prominent SMEs including PRP Optoelectronics, Intense, Teraview and other developing ones including Cascade Technologies.

UK Academia

- A large number of academic groups within the UK are active in III-V research, many producing internationally leading work. The list of universities includes Bath, Bristol, Cambridge, Cardiff, Glasgow, Imperial, Leeds, Sheffield, and Strathclyde. There is an EPSRC funded centre for III-V materials based at Sheffield University
- There is no co-ordinated research base within Universities comparable to that available within, for example, the Fraunhofer Institutes in Germany, IEMN in Lille, or the MURI programme in the US. This is particularly noticeable for new topics such as GaN. An exception should be made for the strong collaboration between Scottish Universities, particularly Strathclyde and Glasgow in III-Vs
- Support for state-of-the-art growth and processing equipment within Universities lacks strategic direction. In contrast to say IMEC in Belgium or IEMN in France, there has been no attempt to rationalise facilities in order to obtain one or two general world class capabilities as opposed to a larger number of second-rate centres

UK academia has a strong position. There are clear centres of technological excellence at Sheffield, Cambridge, Nottingham, Imperial College, Glasgow, Strathclyde, Bath. There are many other institutions actively engaged in high quality research based on structures grown at these instituions. The key players in the rest of the world are too numerous to mention, but are located principally in the US, Japan, Germany, France.

Funding

- University funding of III-V materials through EPSRC has, with the exception of GaN, moved away, as it should, from materials research into opto-electronic applications research
- The MoD are funding work in GaN through a European Euclid project, with the bulk of the money going to QinetiQ for their GaN materials and processing activity. The total amount of funding available within Europe is about 40 million euros. Funding is also supporting activity at BAE Systems, Thales (UK) and AMS (UK). (both AMS UK and the relevant section of BAE Systems are now part of Selex.) Funding is also being used to support other III-V materials through the Defence Applied Research

partnership (DARP) on remote sensing

- The DTI are funding some work through their innovation fund, and through the (earlier) LINK scheme, although this funding is not generic but directed at specific applications
- There are no major government initiatives of the kind seen in Japan and the US. Historically the US in particular have been very successful in using DoD funding to develop new technologies that are then spun out into commercial markets. An excellent example is the development of GaAs based Heterojunction Bipolar Transistors (HBTs) at TRW, which then became commercialised through RFMicrodevices, who now have about 50% of the worldwide handset power amplifier market. This is now being repeated in the case of GaN for microwave power amplifiers, where DARPA have announced funding of almost $100million to commercialise the technology
- Similar scale funding is becoming available to develop GaN-based LEDs for general lighting applications. The US Dept of Energy has announced proposals worth $20million, and in Japan the Government has supported a major initiative on “Light for the 21st Century. Within the UK there appears to be no obvious body involved in energy efficiency and energy saving (in contrast to more efficient or alternative generation) which can support work at the scientific level, for example in understanding or developing materials, or simulation tools. The Energy Saving Trust, for example, appears to be more concerned with implementing existing technology, and increasing public awareness. Although here is generous funding available within the various Government initiatives, none appear to take a sufficiently broad view of energy saving. The Carbon Trust, for example, are on record as saying that their remit does not explicitly cover measures to reduce energy use

Forward Look

5-10 years

High efficiency light emitters based on III-V semiconductors covering whole range from the THz region right through to the ultraviolet all available.

20 years

To be wildly speculative, semiconductor lasers provide basis of optical interconnects in highest performance microprocessors. Arrays of quantum dots form basis of solid state quantum computer. High repitition rate single photon sources based on quantum dots. These advances require leaps in crystal growth, device processing and device architectures.

Recommendations

A number of points are given below, following various discussions with those in the field, and within the NAC.

- One point that has been emphasised by a number of contacts is the relatively long timescales involved in the exploitation of materials research. To quote a contact at IQE:"If I look back at the gestation of EPI then it is clear that the more fundamental materials work which was funded under the JOERS and (early) LINK programmes had a significant impact on our success. Much of the basic technology that we use today was developed within these projects. Much of the underlying materials research over the first 5 or so years of the company's existence was supported through DTI schemes and we are very grateful for that" However, it is probable that broadly based technology development programmes would not now be eligible for funding: both within the DTI and the EC Framework 6 initiatives the projects have to be much more focused on specific devices or applications as opposed to generic development. This means that the only projects with a realistic chance of being supported are those that include an end-user or manufacturer, and in the case of compound semiconductors these are increasingly rare in the UK
- There should be a mechanism by which SMEs can access University research, and the academic science base in general, in a cost effective way. At present most University technical assistance (RAs etc) is tied up in specific project work whatever the source of funding, EPSRC, DTI, EC, and cannot be used to provide relatively small short-term assistance to help SMEs address specific projects. To fund an RA in a university costs at least £50k per year, and this will be much greater when full cost accounting is used. To obtain quality RAs the project must last at least 2 years, leading to a very significant commitment, greater than most SMEs can afford. What is needed is some uncommitted assistance within universities that can be accessed at commercial rates, but for much shorter timescales. Schemes such as LINK (as was) or the Knowledge Transfer Partnerships are a step in the right direction, but the Innovation Fund is too project specific and prescriptive
- Government funding has focused very heavily on photonics and some elements of nanotechnology, which whilst being important still remain only part of the III-V picture. The enabling element of technologies for industry are still overlooked by government agencies - for example specifically the need to integrate the finished product into a high performance and cost-effective packaging is a real challenge for established and emerging companies. In this area both Intense and Filtronic use automated assembly equipment to mount and bond up their devices, but

the work involved in establishing the capability and developing the techniques is substantial. Furthermore, the need to update the capability is a continuing challenge. None of this element has received interest and support - yet the 'backend' (including RF and photonic test) is the most vulnerable. In general the argument of extending the coverage to manufacturing technologies is also overlooked. In the case of some start-ups, especially in photonics, they failed because of the inability to manufacture product - even though they had excellent prototypes and strong customer interest. Some level of government support would help here and the recognition of the need to help develop an infrastructure (funded) would benefit all UK III-V industry

- It is relatively easy to obtain funding for the initial stages of development, leading to the first prototypes, but much more difficult after that when the costs are in fact greater, and the work much less innovative although still pre-competitive. Government funding should move away from the "Innovation Fund" approach and put mechanisms in place to help sustain SMEs once they have an initial prototype product. As mentioned elsewhere, this could be done in a number of ways
- In general the level of support from centres such as CIP are mainly useful in the R&D stage although there is a suspicion that it is the larger companies that take advantage of this type of Centre. This is important, but I feel that it does not help the businesses sufficiently because of the technological challenges they face in transitioning a great idea into a manufacturable product. It is not trivial and is becoming increasingly challenging because of the lower cost expectations of customers (the old photonic 'hand-held' techniques just don't stack up against far eastern competition and automation is the name of the game). Again some real tangible help from government would help here by adding a new type of centre where companies can go for assistance, training and ideas. The existing centres and institutes do not offer this type of support
- Most state aid is back-end loaded for the larger schemes (such as Regional Selective Assistance and some of the special programmes - there was one on manufacturing a couple of years ago), the funding is in tranches, where the largest sums come towards the end (or at best are all equal).so that both start-ups and established companies see much of the funding several years into the support - this is exactly the opposite of what is needed. Funding needs to be up front to aid a speedy ramp up and to avoid P&Ls with huge holes in the early years. This seems to be something that RDAs and government struggle to understand. Banks and investors don't like jam tomorrow!

Appendix 2

Magnetic Materials
Jeffrey Alcock, Cranfield University

Technology

Magnetism is one of the fundamental forces of nature, and as such has wide technological application.

Technical magnetic materials can be classified into three groups: 'hard' materials, 'soft' materials and thin films. 'Hard,' refers to the 'coercivity' of the magnetic material, i.e. how strong an external magnetic field is required to demagnetise that material. Materials which are magnetically hard are also often known as 'permanent magnets.'

Composite materials, in which magnetic material is contained within a non-magnetic carrier, normally a polymer, constitute a large segment of the magnetic materials market. Their reduced magnetic properties, notably remanence, are a trade off against decreased cost and increased shape flexibility.

Thin film magnetic materials possess unique magnetic properties not seen in bulk magnetics and constitute a technological area of their own. Magnetic fluids similarly constitute a separate technological area.

Magnetic materials are used extensively in data storage, both in information technology and in consumer applications. While analog audio and video tapes are now a declining market and the floppy disc is rapidly becoming too limited in capacity to offer a useful role, hard disc storage is going from strength to strength. In the hard disc drive, the media, read-write head, motor and actuators all rely on magnetic materials for their function. It is now possible to store more than 5GB on a single 1 inch disc as a result of developments in high-coercivity media and Giant Magneto-Resistive (GMR) heads, enabling such products as the portable MP3 player. The Information Storage Guide 1 published by DTI is a valuable UK reference that should be used in conjunction with this contribution while the IMST White Book 2005 2 sets an excellent European context.

Applications & Benefits

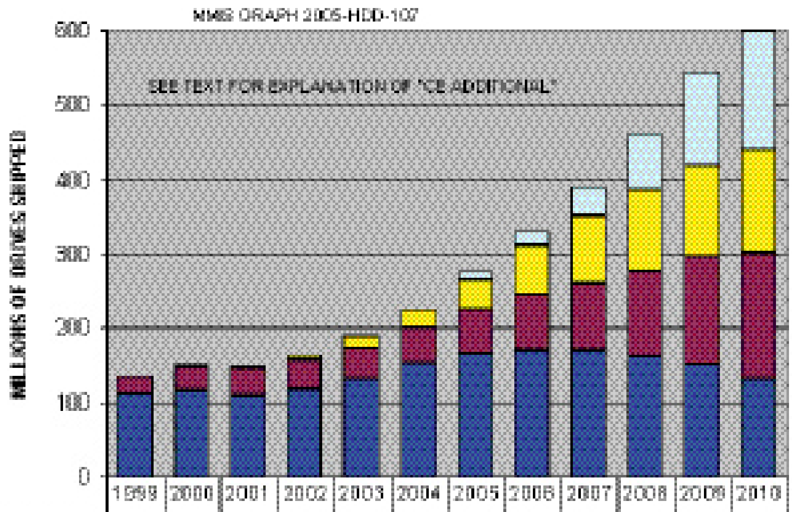
Magnetic materials are ubiquitous. In their various forms they are used in the storage, movement and processing of energy, mass and information and as such are fundamental to all advanced economies. As an indication of the scale of use of magnetic materials, more than 15 000 patents were registered in the US between 2000 and June 2005 in which magnetic materials formed part of the claimed invention. The world market for hard magnetic materials has been estimated at $4 – 5 billion dollars and for soft, $12 billion.

Industry observers foresee large increases in the demand for hard-disk drives of all kinds in the immediate years ahead. These increases will be driven primarily by the many new applications that these very-low-cost very-high-capacity units will create. Consumer-related drive revenues at the manufacturers' level will reach about $3 billion in 2005, on shipments of around 40 million units. By 2010, consumer-type drive shipments alone will certainly be larger than 200 million units, and could approach 300 million, generating revenues of $14-$15 billion (MMIS) The total market will be on the order of $100 bn.

Materials at the heart of this business include:

1. Disc media – high coercivity sputtered films of cobalt alloys with soft magnetic underlayers
2. Read-write heads – transducers with critical dimensions below 100nm. Complex multi-layer stacks to form GMR devices, soft magnetic shields based on nickel-iron alloys, laminated cobalt-iron films for poles and an increasing reliance on high-integrity dielectrics including tunneling barriers
3. Motors and actuators – high energy-product permanent magnets, ferrofluid seals and bearings.

POSSIBLE GROWTH RATES FOR HARD-DISK DRIVES
AS CONSUMER APPLICATIONS GAIN DOMINANCE



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
CE ADDITIONAL							10	20	40	75	125	160
CE BASE ESTIMATE	1	1	2	8	17	25	40	86	90	110	125	140
LAPTOP DRIVES	24	34	36	39	42	48	60	75	90	115	145	170
DESK-TOP DRIVES	110	114	109	117	130	152	165	170	170	160	150	130

Technology Drivers, Barriers and Gaps

There are several clear technological drivers for magnetic materials. The more electric future: Drivers in automotive and aerospace are towards larger numbers of electrical devices, consuming greater quantities of electricity, and in the case of automotive at higher voltage. This requires devices for the production of electrical current, and also those which will use electrical current: both of which will be dependant on magnetic materials.

Specific material drivers therefore include those towards more physically robust magnetic materials which can withstand high stress environments in rotating machines, and also those towards manufacturing methodologies which can produce complex shaped magnetic components or assemblies.

Climate change and energy efficiency: However, the above will take place in the context of climate change and perhaps the subsequent requirements of increased efficiency of energy use.

Specific materials drivers here include magnetic materials which will operate, and have a long life at, elevated temperatures and improvements in power to weight ratios of magnetic materials. Components which, via magnetics, can use energy more efficiently will also become even more important, whether in energy use or information storage. Increased energy and information density: Miniaturisation continues to be a strong driver. Specific materials drivers include higher energy products for magnetic materials and high information storage density for thin film magnetics.

Aging population and health: Magnetics in biomedical uses are becoming more important as the population ages.

Drivers here are towards miniaturisation of magnetic components, integration of such miniature components into devices and use of particulate and structured particulate materials that can be introduced into the body in medical applications.

Cost: As ever cost is a driver. Specific materials drivers include those towards cheaper raw materials, cheaper materials processing and cheaper component production processes.

An important barrier exists to the adoption of new magnetic materials. There is little in the way of a piori theories which allow the prediction of the behaviour of new classes of magnetic materials. Rather a new class is discovered and then decades are spent refining the properties of the materials within this class.

Furthermore, because of the high commercial potential of new materials such information is not disseminated until after it has been commercialised. This means that it will be unavailable in time to the UK unless produced by scientists and engineers within UK academia and industry.

In the case of magnetic storage, many of the materials share technology – for example Physical Vapour Deposition (PVD) – sputtering of films is widespread in both heads and media. Electroplating and electroless plating are also extensively used. Key alloy systems are cobalt-ironnickel. Process modeling and control for vacuum systems and in novel electrochemistry are essential underpinnings. Potentially more Chemical Vapour Deposition and Reactive Etching systems will also be explored.

UK Competitive Position

Academia

Academia benefited strongly from inward investment into the UK in magnetics in the 1960s. However, this has largely ceased and the generation of UK academics which did this work is aging.

The effect of this on the UK's research in magnetic materials is shown in Table 1, which gives the UK's scientific journal outputs, as a percentage of world output in the topic of magnetic materials, over the two most recent five year periods. On this measure, against major competitor countries, the UK's research output on magnetic materials has dropped from fourth to sixth, from a 9% to a 7% share.

Country	% Output : 2000 - June 2005	% Output : 1995 - 1999
USA	18	21
Japan	16	17
Germany	10	9
France	9	11
China	9	4
UK	7	9
Italy	6	6
Korea	3	1

Table 1 Statistics, taken form the ISI web of knowledge, for the percentage of journal papers of which at least one paper author resided within the country indicated in the table. These statistics are for articles which were written in English only, so for non-English speaking nations the figures probably represent an underestimate of the real output.

China has more than tripled its research output between the two most recent five year periods to overtake the UK to produce 9% of the world's output of magnetic materials research.

More worryingly than this, the UK's percentage increase in magnetic materials research output [Table 2] between these two time periods is the smallest of any of our major competitor countries. Germany had a similar output to the UK's between 1995 and 1999 but more than doubled its output over the following period. In contrast, the UK's output rose by 40%, half of the average world increase in output in research in magnetic materials.

Country	% Increase in research output between (1995 - 1999) and (2000 to June 2005)
China	359
Korea	315
Germany	107
World Average	*80*
Italy	77
Japan	75
USA	55
France	47
UK	40

Table 2 The percentage increase in research output in magnetic materials, based on statistics taken from the ISI web of knowledge.

Whilst the comparative picture is one of declining competitiveness, the UK still contains many niche magnetic materials groups conducting leading-edge research. Such groups include those working on processing, properties and applications of permanent magnets based on rare earth-transition metal alloys at Birmingham University, ab initio modeling of ferrites at the Open University, amorphous ribbons at QinteiQ, iron cobalt alloys and molecular magnets at Cambridge, magnetic nano-clusters at Leicester, magnetic information storage at Exeter, MEMs and magnetic alignment at Sheffield, MEMs and magnetic powder processing at Cranfield, molecular magnetic materials at Bristol and St Andrews, nano-scale magnetic storage materials and magnetic structure at Oxford, spin-valve work at Salford and Durham, structured paramagnetic materials for bio-applications at Glasgow. This list is not meant in any way to be definitive.

Country % Increase in research

There are in the UK several centres in which research activities relevant to hard disc drive technology have been established and continued over many years. Examples of these would be in Manchester and Plymouth. More specifically on materials research a wide range of institutions have groups that address these areas. Although a couple of years old now the DTI document 1 has a comprehensive searchable listing. Illustrative examples would be Glasgow and Oxford with particular strength in high resolution microscopy, Leeds with a broad range of expertise in deposition and York with an emphasis on magnetic measurements. All of these groups, together with groups in several other institutions with a broader materials remit are among the international leaders.

As noted in Table 1, research in magnetic materials is dominated by the US and Japan with some 34% of world output over the last five-year period. Somewhat in contrast to the UK, magnetic materials research groups in Japan currently have a very strong concentration on nanoscale processing and properties. Activities include: low temperature sintering of ferrites at Saitama, nanocrystalline ferrites at Okayama, nanocrystalline films at Tohoku, nanogranular cobalt based films at Sendai, nanoparticles and nanolayers at Hitachi and Osaka, nanoscale epitaxial growth at Tokyo Institute of Technology, nanoscale layered magnetic materials by ion exchange at Kyoto and Tokyo, shock compaction of bulk nanocomposites at Kumamoto, trilayer thin film structures at Osaka.

There is, however, no single location in the UK that combines the activities in the depth of the major US centres e.g. Carnegie Mellon, University of Minnesota or Japanese universities e.g. Tohoku.

UK routes to exploitation

There are serious issues with regards to the UK's current abilities to exploit new or improved magnetic materials. The UK currently lacks large companies with a high investment in magnetic materials that would act as natural technology exploiters. The exception is the disc drive industry where there is significant activity. As far as volume manufacturing is concerned Seagate is the only representative and has its main worldwide production facilities for read-write heads and disc media substrates in Northern Ireland. Technology R&D for read-write heads is a distributed activity within Seagate, the NI R&D team having significant responsibility for product and process design incorporating advanced magnetic materials.

In general terms, our major competitors, notably the USA, Japan and Germany have an industrial base much better equipped to exploit advances in magnetic materials. Hence any exploitation of technology developed in the UK will often be performed by other countries. To alter this situation would require short term investment into high-priority magnetic science that can be spun out to or is in aid of UK industry. In the longer term a strategy for magnetic materials is required [see Forward Look].

Industry

Successful UK SMEs are operating in niche environments, from magnetic powder production through to complex-shaped component manufacture. These form the basics of a supply chain. However, the UK has seen a significant reduction in its magnetics industry over the last thirty years to the point where it can be considered to be quite vulnerable to actions on magnetic materials taken by our major competitors. Exploitation of new technology within the UK would essentially be carried out by SMEs, in the absence of larger companies operating in the area. However established SMEs have limited resource for research. Hence universities and companies need to collaborate better on near-market research to help maintain the competitive edge of SMEs. Further exploitation of technology could also come from spin-out companies based on academic research.

Competitor Analysis

Because of the breadth of magnetic materials research it is difficult to give an overview of the activities of our competitors. One method available, to quantitatively analyze their technological performance, is via patent filing in the USA - the world's largest single nation economy.

On that basis, since 2000, 58 patents on magnetic materials have been granted in the US to UK assignees. In contrast 1059 patents have been granted to Japanese assignees during that time. The percentage of US patents in magnetic materials assigned to each of the UK's major competitors since 2000 is summarized in the table below. It is clear that China's greatly increased science research effort has yet to translate through to successful patents - some 7 were assigned in the period.

Country	% of US patents assigned between 2000 and June 2005
USA	40
Japan	31
Germany	6
France	2
UK	2
China	0

Table 3 The percentage of US patents assigned in magnetic materials, by country, from 2000 to June 2005.
[Data from the US Patent Office: www.uspto.gov]

Japanese assigned patents in the US since 2000 form a useful snap-shot of near-future use of magnetic technology by a major competitor. Their patent filing falls into a number of discernable disciplines, notably:

- Biomagnetic materials, e.g. capable of binding with elements within the body
- Composite magnetic materials and their production methods
- Oxide magnetic materials
- Magnets for MRI systems
- Magnetic nanoparticle coatings and their production systems
- Magnetic marker materials
- Magnetic read head materials
- Magnetic refrigerant materials
- Magnetic sensor materials, including magnetoresistive
- Motor magnetic materials - for example induction motors, rotors for induction motors; materials in alternators
- Low loss powder cores

Specifically for magnetic storage both materials and device technology in this area, leadership resides in the US and Japan with strength in academic groups, research institutes and commercial companies. The latter include end-users such as Fujitsu, HGST (Hitachi-IBM), Seagate and Toshiba as well as suppliers of critical equipment, for example the vacuum tools for thin layer deposition and etching, such as Anelva or Veeco. The level of spending on this particular area of materials technology is difficult to discern within the published R&D figures of complex vertically-integrated organisations but one salutary example is that the types of sputtering systems in common use cost over $5M per unit. This makes collaborative work with universities in this area difficult.

Forward Look

The more obvious future trends and their likely impact on magnetic materials R&D were noted earlier

With regard to the UK's industrial and academic activity, there appears to be nothing to stop the long-term trend of a relative decrease in the UK's R&D activities in magnetic materials, unless some actions are taken to reverse this trend. UK academic activity is faltering in comparison with our competitors. SMEs concentrating on short term goals will have little opportunity to take advantage of any emerging magnetic technological areas.

A two-stage approach is suggested to overcome these problems.

Near Term: In the near term the more obvious high priority magnetic materials areas should be allocated ring fenced funding from research councils, and from other funding organizations which promote industry-university collaboration: High priority areas over the next five year period - with already demonstrated industrial need - include:

- Bulk magnetic materials research for permanent magnets including oxide magnetic materials
- Magnetic refrigerant materials
- Magnetic sensor materials
- Soft powder cores with Ms >1.85 and permeability >1000
- High permeability, high resistivity solid cores.

Hard disc drives will be a ubiquitous commodity item in consumer applications, including in demanding environments such as automobiles. Advances in storage materials will provide capacities of terabytes in a desktop drive.

Longer-Term Strategy: To formulate a more robust approach to a strategy beyond the next five years, a literature search of scenario planning for magnetic materials – perhaps the most reliable technique for investigating plausible futures - was undertaken. No such scenario plan was found to be available in publicly accessible form. This does not mean that private scenario plans do not exist. - produced by interested governments or larger forward-thinking companies.

Without the use of such a robust technique, looking forward beyond the scope of the obvious technology drivers that can already be anticipated is essentially guess work. Such scenario planning is beyond the scope of this short review, but is strongly recommended. [Please see the recommendations below].

Magnetic disc drive technology will still be the mainstay of data storage. Patterned media and novel applications of nanomanufacturing for heads and drives will provide the ultimate exploitation of rotating media. Magnetic storage will move towards solid-state solutions.

Recommendations

1. That short-term activities which aim to use the UK's academic science base to support the competitiveness of the UK's magnetic-based SMEs be given high priority by UK government and other funding bodies. With continued support for activities in basic magnetic materials, deposition and patterning technologies and their interaction with broader aspects of nanotechnology.

2. That EPSRC, DTI and other funding bodies act now to ring-fence money for magnetic materials research and development in specifically targeted areas. Encourage even more materials and systems modeling activities to maximize potential of existing and new materials and structures.

3. That a scenario planning exercise be undertaken to look at future use of magnet materials, perhaps in the context of an exercise for functional materials as a whole.

4. That this exercise be used to formulate a strategy for magnetic materials in the UK. The lack of such a strategy will mean that the UK magnetics industry and academica will continue to reduce in competitiveness.

Acknowledgements

The author of this report is indebted to Dr Charles King of the Powdermatrix Faraday for discussions of the current state of powder-based magnetic materials activity in the UK. The interested reader is referred to Powdermatrix's Technology Roadmap for the Magnetics Sector. It can be found at:

http://217.118.138.78/powdermatrix/Magnetic_Roadmap_Dec04.pdf

Appendix 3

Functional Materials Characterisation

Markys Cain, National Physical Laboratory

Materials Metrology

1. Introduction

Metrology is the science of measurement and provides for the infrastructural needs of industry and academia in their pursuit of new product development or fundamental scientific advances. The ability to measure properties accurately and robustly (reliably, repeatably) and with the required degree of precision demanded by the user reduces barriers and obstacles to new product development. In this section of the Functional Materials Mat-IGT we will explore some of the issues relevant to the successful exploitation of functional materials for UK industry, through an analysis of current and future metrological needs, with a focus on piezoelectric and ferroelectric materials.

2. Metrology Description and Market Analysis

Functional Materials have been defined by a variety of bodies and organisations and, for this metrological study, it is useful to evaluate the exchange interactions that define the functionality of a material, see table 1. This understanding is also useful in exploring the metrology required to fully characterise this class of materials.

	Thermal	*Elastic*	*Magnetic*	*Electrical*	*Optical*
Thermal		SMA (NiTi) Phase Change (PLZT)		Pyroelectric (PVdF)	Thermo-refractive (Ge doped Si fibre)
Elastic			Magnetoelastic (Terfonel) Magnetorheological fluid (Lord Corp USA)	Piezoelectric (PZT) Electrorheological Fluid	
Magnetic				GMR CMR	Magneto-optical devices
Electrical					Electro-optic ($LiNbO_3$) LEDs
Optical					

Figure 1: Smart materials technology share breakdown

The expectation that most of the materials above may be produced in nanosized or thin film form whilst retaining their inherent functionality, means that we would also include these materials at various length scales.

According to a recent Frost & Sullivan Report (Nov 1999), research carried out by Etrema Products Inc, the worldwide sales of ‘Smart Materials’ exceed $1billion annually, with the following breakdown in technology share, Figure 1:

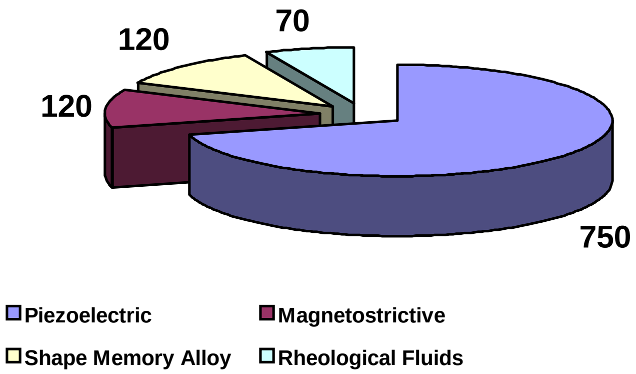
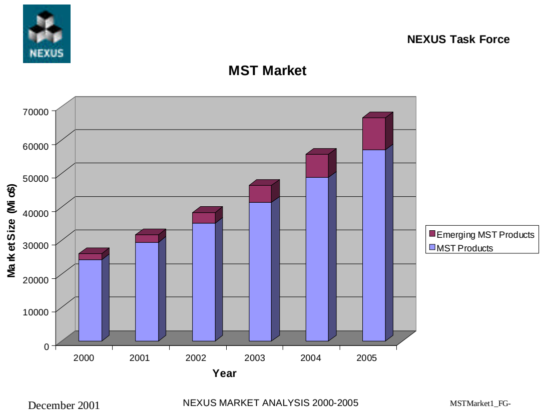


Figure 1: Smart materials technology share breakdown

These classes of materials technologies – useful as materials for sensors and actuators – represent only a part of the remit of this strategic review of functional materials. It is instructive to compare these figures with that offered by Business News Publishing Company (2002), who value the world market for piezo-ceramics at roughly $11 Billion/annum, with an expected annual growth rate of 20-25% and the majority of application being favoured within the automotive industry. This estimate clearly includes applications other than sensing and actuation such as materials for fuel cells, mobile telecommunications, filters etc.
Growth markets in piezoelectric materials have been identified (F&S 2001) and include:

- Automotive sensors and actuators (diesel injectors, pressure sensors, accelerometers etc.)
- MEMS devices to fuel the next stages witnessed in miniaturised sensors and actuators (gyrscopes, accelerometers, yaw-rate sensors, etc)
- Piezoelectric printing – better quality printing in colour, more accurate control of ink deposition and the potential for printing other materials systems such as semiconductors
- Sports equipment – smart skis, embedded piezoelectric sensing/actuation units to help absorb vibrations
- Biotechnology – ink jet printing based on piezoelectric actuation provides for faster and consistent droplet sized deposition suited to DNA Microarrays
- Nanoactuators and sensors – taking the technology based on piezo-effect and miniaturising for sensing and actuation
- Military uses – adaptive structures based on the actuation of piezoelectric or shape memory alloy type materials, rotor-blade actuation etc.
- Piezoelectric motors and engines
- Environmentally aware development of lead free piezoelectric materials and new single crystal materials offering 10 fold increase in performance leads the current strategy in Piezoelectric materials research within universities and government research labs.

The Micro Systems Technology (MST) markets are increasing year on year and many of the newer devices utilise the properties afforded by functional materials, that once integrated within the MEMS device yields better performance or a performance hitherto not achieved. The rate at which this emerging technology is influencing world-wide products is shown here, figure 2.



In other functional materials areas, we see an equally exciting increase in world markets, including that for superconductor materials applications, figure 3:

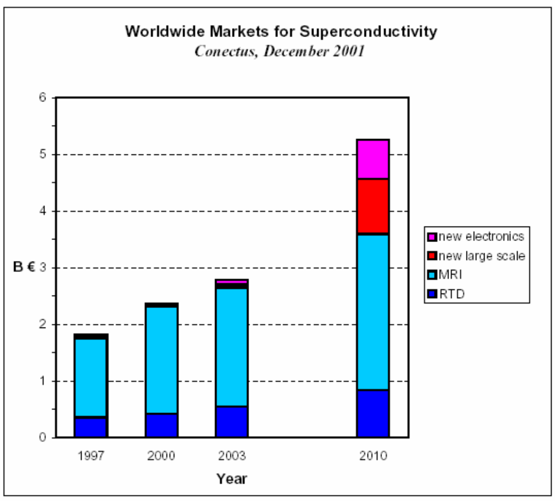


Figure3: Superconducting materials applications worldwide markets

Superconducting magnets for MRI and NMR spectroscopy, industrial processes such as magnetic separation and research infrastructure such as high energy physics accelerators constitute the main market areas for superconducting wire. At present this is mainly based on the stabilised Nb based alloys developed primarily in the UK in the 1960s but there is plenty of growth in the high temperature superconductor wire and tape markets. According to June 2002 estimates by the Conectus consortium, the worldwide market for superconductor products is projected to grow to near US $5 billion by the year 2010 and to US $38 billion by 2020. In mobile communications there will exist approximately 10^6 installed base stations by the end of 2002. At present some 1500 of these are cryocooled base stations employing high temperature superconductor filters. This number is growing rapidly in the USA with much slower implementation in Japan and Europe. A single cryo-base station costs approx. $0.5M so the market is already substantial.

Another area that is today an emerging area of scientific interest is that of Spintronic materials. The development of circuits which are sensitive to the spin of carriers instead of, or as well as, electric charge is potentially one of the most important changes to be expected in the coming years in solid state 'electronics'. Such spintronic devices depend on combinations of functional materials such as colossal magnetoresistive materials (CMR), magnetic multilayers (GMR) or magnetic tunnel junctions (layers of magnetic materials separated by ultra thin (~1nm) insulating barriers.

'Conventional electronic devices rely on the transport of electrical charge carriers – electrons – in a semiconductor such as silicon. Now, however, physicists are trying to exploit the 'spin' of the electron rather than its charge to create an remarkable new generation of 'spintronic' devices which will be smaller, more versatile and more robust than those currently making up silicon chips and circuit elements***. The potential market is worth hundreds of billions of dollars a year.***' IOP Briefing Paper.

Companies already involved include: IBM, Lucent Technologies, Hitachi. Institutes leading research in this area: Naval Research Laboratory, the Center for Spintronics, University of California - Santa Barbara. DARPA is a major driver behind Spintronics (source: IEEE Spectrum Magazine).

The current status of functional materials research in the area of RF, microwave, mm and THz frequency applications is also relevant to this study. Here, the technologies may be classified according to (1) tailored homogeneous dielectric/magnetic materials, (2) composite and structured materials including random and ordered composites, meta-materials, periodic media such as photonic (or electronic) band-gap materials, left-handed and negative refractive index dielectrics.
(3) Active, 'smart' and non-linear dielectrics: ferro- and para-electrics, ferrites, magneto-dielectrics, photonically modulated materials, etc.

A 'headline' estimate from the Business Communications Company (BCC – June 2002) is that the world market for dielectric materials, estimated at $1.2 billion in 2000 should reach $2.4 billion by 2005. The market for dielectric deposition and processing equipment is even larger, reported to rise to £6.5 billion in 2005. These figures need some qualification as (inspecting the BCC report) they clearly include some semiconductor applications. Nevertheless, they show that the market for electronic applications of electromagnetic materials is expanding rapidly. To put this into context, world semiconductor manufacturers' sales were reportedly $149.38 billion in 1999 (BCC – February 1999).

In terms of functional materials R&D for displays technologies, the world-wide markets are also impressive. Taken from BUSINESS COMMUNICATIONS COMPANY, Standard - January 2002: the growth rates for some of the selected EL display markets is give below, table 3:

Table 3: Estimated El Manufacturing By Region, Through 2006 (%)

Region	2000	2001	2006
North America	40.5	40.8	41.9
Europe	21.0	21.5	22.3
Asia/Pacific	38.5	37.7	35.8
Total	100.0	100.0	100.0

Source: BCC, Inc.

Similar figures may be found for other display technologies such as organic light emitting diodes (OLED) – see Appendix I.

Display and display material technology is experiencing an evolution as flat panel devices become more ubiquitous. On the one hand, flat panel displays make it possible for the operation of a variety of handheld communications and computing devices that would not be feasible with the traditional cathode ray tube. On the other hand, flat panel displays are driving the economic production of large screens that are used for home theatres and large venue environments. The study, Major Display Materials: Markets, Technologies, conducted by BCC states that the value of worldwide shipments of electronic display materials reached $7.7 billion in 1999. Shipments of materials are projected to grow in value by 10.9% per year and reach $12.9 billion by 2004. Flat panel displays (FPD) accounted for 43.9% of the total materials in 1999. Their value is projected to grow at an AAGR (average annual growth rate) of 16% and account for 54.9% of the total value of materials by 2004. Other technologies are also being developed including a new generation of flat panel display that combines **fluorescent materials** onto a conventional liquid crystal display (FLCD). (Fluorescent biomarkers have been one of the first commercial applications of nanotechnology (see e.g. Scientific American, Sep. 2001) http://www.sciam.com).

3. Metrology Requirements for Functional Materials

3.1 Electrical Functional Materials

External Drivers: towards low loss, tunable (dielectrics of low loss) materials; miniaturised components (smaller, smarter, cheaper) and materials with intrinsic non-linear properties (negative refractive index - media with current-dependent impedance); materials for new high power applications; materials for bio and medical applications, implantable functional materials for pressure, sensing applications; electromagnetic materials of high absorbance; new functional materials in thin film form – from 3D bulk towards lower dimension 2D films and 1D tubes (CNT) for new property performance and new functionality, as found for Carbon Nanotube.

UK Strengths: NPL has developed programmes that respond to all the above and are focused increasingly on the metrology for smaller dimensioned systems (2D films for example).

UK Recommendations: Specific metrological areas of study include:

- Metrology for application of these materials at much reduced length scale and complex environments:
    - Human body for biofunctional sensors/actuators – techniques include piezoelectric probes in thin film or sheet form for example
    - Hostile environments especially for high power applications
    - Development of measurement tools to probe and characterise important functional properties on the micro to nanoscale, for MNT/MST applications
    - Gaining an understanding of the physical processes through appropriate modelling through length scales such as ab initio, molecular modelling etc.

3.2 Magnetic Functional Materials

External Drivers: Novel sensing modes for Magnetostrictive materials may lead to new industrial applications (often driven by high power needs), ferrofluids for smart medical applications and ferromagnetic materials for high density data storage are examples of intense activity worldwide, all required substantial characterisation methods and metrology development. Superconductors will enjoy worldwide market of ~ $5B/annum by 2010, with applications for mobile base stations filters, MRI etc. Spintronics is a new field of magnetic materials research that use spin of electrons to convey information (rather than the charge), with very large market potential. Here not much is known about the properties or even how to measure them but large companies are investigating these new exotic materials.

Additionally, Magnetic RAM also an emerging field. GMR materials are now actually being used commercially in hard disk drive heads; major companies such as IBM et al., are spending huge amounts for Spintronic devices for RAM (magnetic tunnel devices and spin valves).

UK Strengths: The UK's National Measurement Institute (NMI), NPL is the only NMI to have cryogenic facilities for superconductor measurements and so can characterise their non-linear properties and these resources may be transferred to a large degree for the new class of Spintronic materials. The UK will be able to offer potential solutions to the challenges facing the development of Spintronic materials, and in the characterisation of Magnetostrictive materials. Te UK also has expertise in the measurement of magnetic fields and materials properties to extremely low values of magnetisation (suitable for the new generations of magnetic sensors and actuators), with unique equipment in measuring fields within an environment that offers zero net fields. Some expertise is also offered in the modelling of magnetic materials. NPL are beginning to work with Imperial College in the area of spintronics and also through a new proposal for a EU F6 NOE in nanoelectronics.

UK Recommendations: Presently there is no clear way of how to carry out the measurements, for example one would have to measure a spin current. The basics of this metrology requires completing. A metrological comparison between various devices will eventually be required. Quantifying the value of total spin is required in these instances. The UK will need to develop scanned probes for magnetic spin polarised currents (such as STM), or nanoscale measurements for Lorentz forces (via NEMS device fabrication). Development of the following metrology will be required to study Spintronic materials:

- Fundamental physics
- Functionalised SPM including use of CNT (or other) probes
- Study of novel magnetic materials and interfaces
- Micro or nano fabricated microelectromechanical devices with magnetic capability

3.3 Optical Functional Materials

External Drivers: Display and display materials technology is experiencing an evolution as flat panel devices become more ubiquitous. Large growth rates expected in all materials for displays technologies including panel displays, phosphors, colour filters, LED /OLED devices, fluorescent materials for LCD. Photonic band gap materials for THz radiation sources and detectors for unusual imaging and probing matter that is currently difficult to do using X-rays etc are being developed. Optical interconnects developed for low loss applications.

UK Strength: The UK's NMI, NPL, has established world-wide expertise in absolute radiometric measurement, spectral responsivity (unique pyrodetectors for primary optical radiation standards), National Laser Radiometery Facility (non-linear crystals for frequency doubling for tuneable radiation source), tailored refractive index material characterisation, metrology for 'appearance' of gonio-apparent materials and metrology for reflection/absorption of optical radiation from materials. In terms of optical characterisation in the UV to TIR spectral range NPL are world class and future NMS programmes will most likely include metrology with Photonic band gap materials.

UK Recommendations: Areas for metrological development to support the UK take-up of Photonic bandgap materials includes:

- Investment in THz
    - Microstructural evaluatiuon
    - Spectral transmission properties
    - Impurity atoms (radiators or absorbers) – determination of effect
    - Radiation over frequency range of interest – spectroscopy
    - Modelling effects of structure and radiative performance (future opportunities)

3.4 Non-Linear Thermoelastic Functional Materials

External Drivers: Medical and military aerospace markets dominate applications for shape memory alloys – SMA - (stents, pins, staples, shrouds, couplings etc.). Some new applications include eyewear and prosthetic devices, sportswear and equipment. The toxicity of the Ni content present in the most common material dominates the applications within the human body however. Nonlinear elastic electronic materials with unusual electromagnetic properties are also being investigated for error-correcting lenses, smart antennas etc.

UK Strengths: The UK has developed some experience in characterising SMA materials for medical prosthetic applications, and there is a large in-house level of expertise in modelling the properties of elastic materials properties in the form of sheets, laminates, multilayers etc with resulting properties that may be characterised as non-linear in performance. There is also some interest and expertise in non-linear materials for non-linear network analysis, and electromagnetic reverberation chambers.

UK Recommendations: The toxicity created by the Ni containing SMA materials also conveys a challenge regarding threats of substitution when more complex arrangements of linear materials may be used instead without the deleterious effects of non-biocompatibility. Nonlinear elastic electronic materials with unusual electromagnetic properties are also being investigated for error-correcting lenses, smart antennas etc.

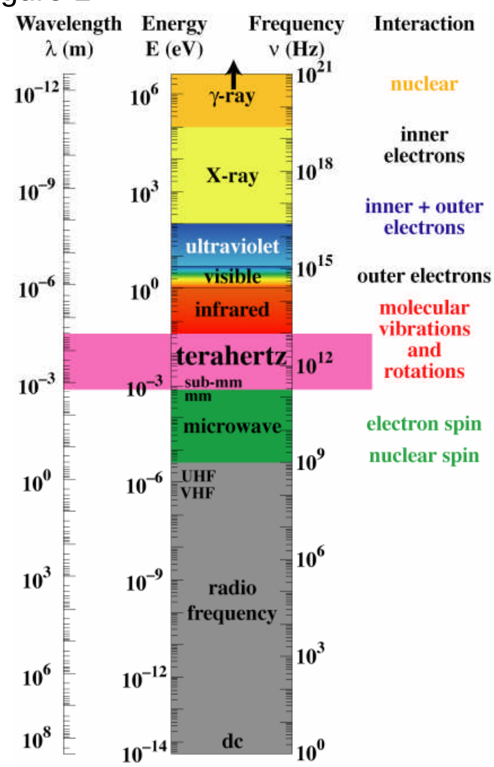
Appendix 4

Terahertz Technology
Dr Douglas Paul, Cavendish Laboratory, University of Cambridge

Area of Functional Materials

For this report, terahertz (THz) will be defined as the region of the electromagnetic spectrum between 300 GHz (1 mm wavelength or 1.25 meV) and 10 THz (30 µm wavelength or 41.7 meV) - see Fig. 1. The first papers started to appear in the 1950s on terahertz as gas lasers appeared but it is only with the realisation of time domain systems and more recently solid state sources in the last 5 to 10 years that high quality spectra and practical applications can be realised as signal to noise ratios have improved [1][2][3][4]. For many years there was a gap in available practical sources called the “terahertz gap” but as technology has progressed, this gap is being reduced especially as cheap terahertz radiation sources have become available over the last 5 years and research has started to concentrate on applications for the terahertz. As most atoms in molecules vibrate or rotate at terahertz frequencies, terahertz spectroscopy has the potential to be used to identify specific molecules. In addition the energy of terahertz photons (i.e. the energy of terahertz light) is a million times lower than X-rays and is therefore non-ionising. Therefore terahertz is significantly safer for imaging of humans and animals than X-ray imaging.

Figure 1



1.1 Technology

1.1.A Terahertz Time Domain Spectroscopy and Imaging

These systems are the most prevalent in THz research. The systems uses a Ti:sapphire femtosecond laser operating near 800 nm wavelength which coupled with photoconductive antenna [3][4][5] on a III-V substrate or an electro-optical crystal [3][4][6] results in a terahertz pulse which is mechanically rastered over the object which is being imaged. A beamsplitter is used with the original femtosecond laser beam and an optical delay line to interfere the original femtosecond pulse with that being detected to provide coherent detection. Either a non-linear crystal such as ZnTe coupled with silicon photodiodes are used for electro-optical detection [3][4][7][8] or photoconductive antennas are used as detectors [6]. As both are coherent detection schemes, the signal to noise ratio is around 60 dB even though the peak source power is less than 1 μW. The focusing optics in the system are mainly mirrors as low loss terahertz lenses are not available at present.

Three companies now sell these systems commercially: TeraView Ltd. [9] in the U.K., Picometrixs [10] in the U.S. and Nikon [11] in Japan. Most present systems in universities and research institutes are home build time-domain systems.

1.1.B Continuous Wave (CW) Systems

There are two types of terahertz CW systems, an electronic version and a photonic system. The electronic systems use a mixture of available microwave sources including Gunn diodes, high electron mobility transistors (HEMTs) and IMPATT diodes along with frequency doubling or tripling techniques and mixers [3][4]. The powers decrease significantly as the frequency is increased above 100 GHz.

Photonic systems rely on photomixing two different lasers operating at frequencies ranging from the visible to the terahertz where the difference in the frequency of the two signals will be the output frequency of the source [3][4][12]. The first examples mixed the outputs from two CO_2 lasers [4]. Low temperature III-V chips with electrodes are normally used as mixers and frequently Si lenses are used to focus the terahertz radiation out of the source [12]. More recently a Schottky diode has also been used as a mixer for two terahertz quantum cascade lasers and demonstrated 80 dB signal to noise ratio for imaging applications [13].

1.1.C Fourier Transform Infrared (FTIR) Spectrometers

FTIR spectrometers are the oldest terahertz spectroscopy systems and use a glow bar as a broadband blackbody source with a Michelson interferometer to allow detailed spectra to be built up as a single mirror is stepped [14][15]. An interferogram of amplitude against mirror step distance is Fourier transformed into energy versus amplitude. A number of detectors are used dependent on the measurement bandwidth required with liquid He cooled Si bolometers and cooled Ge photodiodes the most common for 1 to 10 THz applications. The systems also allow spectra of terahertz sources to be characterised and measured. Single to noise ratios are around 60 dB using a cooled Si bolometer with a glow bar blackbody source.

Bruker [14] and Nicolet [15] are the main supplier of research FTIR systems. Many different universities in the U.K. have such systems.

1.1.D Passive Terahertz Detection

All the astronomy based terahertz research is aimed at passive detection of terahertz from distance stars. These systems are frequently Staring arrays of heterodyne detectors using superconducting mixers and either microbolometers or superconducting hot electron detectors (dependent on the measurement frequency) with operating temperatures of 300 mK or below [16][17][18].

1.1.1 Sources

There are many different types of terahertz sources being developed and in use. It should be stated that at present there is no available accurate calibrated power measurement system or technique in the terahertz regime and therefore any powers quoted will be only accurate to within an order of magnitude. A comparison of all the sources with the powers reported in the literature is shown in Fig. 2.

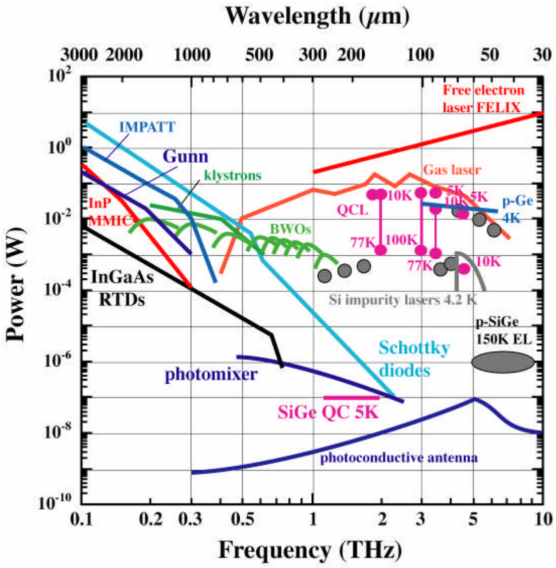


Figure 2

1.1.1.A Electro-Optical (EO) Sources

Femtosecond laser pulses from Ti:sapphire laser operating near to 800 nm can generate terahertz radiation from electro-optical crystals such as ZnTe, silicon on sapphire and GaSe via the optical rectification effect [3][4][7][8]. Since a femtosecond laser pulse contains many frequency components, any two frequency components can contribute to the difference frequency generation process. ZnTe is frequently used not because it has the highest electro-optical component but because it allows matching velocity between the femtosecond optical beam and the terahertz beam.

Typical bandwidths are from around 80 GHz to 1.5 THz with peak output powers below 1 µW. More recently GaSe crystals have demonstrated broadband emission up to 41 THz [8]. The main disadvantage of electro-optical systems is the high cost of the femtosecond laser (>£100k). As fibre based femtosecond lasers begin to appear, the cost of such source will decrease but they are unlikely to achieve the <£1k total terahertz source costs required for many mass market applications.

1.1.1.B Photoconductive Antenna

For photoconductive (PC) antenna emission of terahertz, a femtosecond laser pulses from a Ti:sapphire laser operating near to 800 nm is used to illuminate a semiconductor crystal which is biased by electric or magnetic fields, giving rise to an ultra fast current transient which emits a terahertz pulse [3][4][6]. Low temperature GaAs is frequently used as the semiconductor due to the fast generation of carriers and biased Schottky gates on the surface are used both as an antenna to absorb the radiation and to create the current transient.

The main advantage over electro-optical generation is that the peak electric field generated is significantly higher. Bandwidths are similar to electro-optical techniques and are typically 80 GHz to 2.5 THz with ultrabroadband PC emitters producing 80 to 15 THz [6]. Again the costs are high due to the cost of the femtosecond laser. As the ultrabroadband emitters have a smooth emission curve up to 7.5 THz, they are frequently used in systems for spectroscopic applications. Output powers are below 1 µW.

1.1.1.C Photomixing

The basic principle of photomixing is to mix two different lasers using a photomixer so that the output is the difference between the frequencies of the two input lasers [3][4]. The photomixers are typically interdigitated metallic antenna on top of low temperature GaAs where an applied bias collects the photogenerated carriers from the GaAs and causes radiation from the planar antenna [12]. For terahertz emission, photomixing has been demonstrated using two lasers operating at near 800 nm, 1.55 µm and from two quantum cascades lasers operating at both mid-infrared and terahertz frequencies [13].

1.1.1.D Gas Lasers

Coherent sell a terahertz gas laser tunable from 0.5 to over 5 THz with 50 to 200 mW of power which was developed as the local oscillator for astronomical heterodyne detection. The cost is $300k although it does have large consumable costs per annum to keep the system running [19]. Insight Product Co. also sells smaller terahertz gas lasers with 15 mW output at 0.964 THz, 10 mW at 1.539 THz and 4 mW at 2.521 THz [20].

1.1.1.E Optically Pumped Lasers

There are many examples of optically pumped terahertz lasers including the p-Ge laser [21], uniaxially stressed Si impurity lasers [22] and the quantum fountain laser. All only operate at cryogenic temperatures but the impurity lasers are tunable over a 5 THz range. Most of this research is undertaken by astronomy groups interested in local oscillator applications for heterodyne detection where cryogenic operation can be tolerated [22]. The cryogenic operation prevents mainstream applications from using such devices.

1.1.1.F Semiconductor Lasers

To many a cheap and compact semiconductor laser is the obvious source if terahertz is to achieve any mass market applications. For terahertz there are no practical semiconductors with appropriate bandgaps so unipolar lasers in the form of quantum cascade lasers (QCLs) are used. The first was demonstrated in 2002 by the Pisa and Cambridge groups and operated at 4.4 THz [23]. Progress has been brisk with demonstrated lasers covering frequencies from 2 THz [24] up to 4.8 THz with a maximum operating temperature of around 160 K [25]. This output temperature is significantly higher than present theory and present understanding suggest should be possible so it is unlikely that significantly higher operating temperatures may appear unless a major breakthrough can be achieved. Output powers in pulsed mode peak around 80 mW at 10 K and decrease to a few mW at 98 K [26] while continuous wave operation has also been demonstrated up to 70 K but with a few mW output increasing to 50 mW at 10 K [26]. Linewidths of devices are very narrow with measurements suggesting 20 kHz widths [27]. The major problem for many applications is the poor tunability of cascade lasers. A second issue is that it is very difficult to achieve lasing below 2 THz and the Restrahlen band prevents GaAs QCLs operating between 8.2 THz and 8.9 THz. As far as high power versus cost is concerned, GaAs QCLs represent the cheapest present source of terahertz radiation (cost ~ £1k per laser).

A consortium from Cambridge, Leeds, Imperial, Sheffield and Heriot-Watt have been investigating Si/SiGe QCLs [28]. As of yet no laser has been produced but there is enormous interest as there is no polar optical phonon scattering in Group IV materials and therefore the lifetimes are approximately constant between 4 K and room temperature, unlike all polar materials such as III-V and II-VI [29]. Surface-normal emission has also been demonstrating suggest vertical cavity surface emitting laser (VCSEL) arrays could potential be realised in the cheapest semiconductor material silicon with potentially room temperature operation [28]. The lower free carrier absorption than GaAs and no Restrahlen band are also significant advantages. Si/SiGe QCLs are therefore described as end-of-roadmap devices since they are likely to be the cheapest, terahertz compact sources operating potentially at room temperature but are still some distance from first realisation.

1.1.1.G Electronic Sources

There are a large number of electronic devices which are achieving higher operating frequencies and beginning to become major sources of terahertz radiation. These include Gunn diodes, IMPATT diodes, HEMTs, HBTs, superlattice devices and resonant tunnelling diodes [4]. The performance is predominantly limited by RC time constants which require small sizes to reduce capacitance for high frequency operation but therefore result in low output powers. Many of these sources are used with frequency doublers or triplers to achieve operation at 600 GHz and above. To date very few can generate significant power above 600 GHz but this may well change as technology progresses.

1.1.1.H Electron tubes and Backward Wave Oscillators (BWOs)

There are many different examples of electron tubes which are basically mini electron accelerators used to produce millimeter and terahertz radiation. These include klystrons [30], carcinotrons, gyrotrons and the most used in the terahertz literature are backward wave oscillators (BWOs). BWOs rely on a heated cathode to emit electrons that are focused by a strong magnetic field and drawn towards the anode through a comb like decelerating structure [31]. This results in the creation of an electromagnetic wave travelling in the opposite direction and couples into a curved waveguide that guides it into free space. The output frequency depends on the electron speed which is controlled by the applied voltage. The bandwidth varies for different devices but is typically 30 to 60 GHz centred on frequencies ranging from 36 GHz to 1.25 THz. Output powers are between 30 to 1 mW which decreases as the operating frequency increases but the major disadvantage is that the devices only have a lifetime of 500 hours before they have to be replaced. The sources also require 60 mA of current at 4 kV for operation of the anode along with water cooling [20].

1.1.2 Detectors

1.1.2.A Electro-optical Sampling

The electro-optic sampling technique is using the optical rectification effect to transfer the terahertz signal back into a near-infrared or visible signal where a standard Si photodiode can be used for detection. The typical setup for a time-domain system interferes a reference beam from the Ti:sapphire laser with the terahertz pulse from the sample. Due to the Pockels effect, the terahertz beam modifies the index ellipsoid of the electro-optical crystal transiently [3][4][8]. The linearly polarised probe beam copropagates inside the crystal with the terahertz beam and its phase it modulated by the refractive index change induced by the electric field of the terahertz pulse. This phase change is converted to an intensity change by a polarised analyser (typically a Wollaston Prism). A pair of balanced photodiodes are then used to suppress laser noise. Mechanical delay lines are used to change the delay between the probe and terahertz pulse with the electric-field waveform obtained by scanning the time delay while performing a repetitive sampling measurement [3][4]. The major advantage of electro-optic sampling is the simplicity of the technique and the ease of set-up and it is also a room temperature detection technique. The present response times are limited by the delay line and recent developments should improve the speed of scans.

1.1.2.B Photoconductive Switches

Again photoconductive sampling is almost the inverse of the photoconductive antenna sources with a biased antenna on top of a semiconducting substrate such as low temperature GaAs [3][4][5]. While the bandwidth of such systems can range from 80 GHz up to 15 THz or above, in the case of III-V materials, TO and LO optical phonon modes provide sharp features in the response curve [5]. This can complicate the analyse of measurements. The sensitivity of PC detectors is higher than electro-optical sampling and again the devices operate at room temperature. PC detection has been shown to provide eight times better signal to noise detection than electro-optic sampling.

1.1.2.C Photodiodes

Germanium photodiodes provide fast response measurements between 2.5 and 7.5 THz with good noise equivalent powers of around 10^{-12} W $Hz^{-1/2}$ [35]. The devices require liquid helium cooling and hence are sensitive but limited with mainstream applications.

1.1.2.D Bolometers

Composite silicon bolometers are frequently used with FTIR systems as they provide a cheap, broadband and very sensitive detector. The bandwidth stretches between about 150 GHz (this can be lowered by cooling below 4.2 K and changing the cryostat windows) to around 150 THz with a noise equivalent power of 2 x 10^{-12} W $Hz^{-1/2}$ [36]. Again the systems require cryogenic cooling for operation.

1.1.2.E Superconductors

Most of the work on superconductors has been on hot electron bolometers which are used as mixers in heterodyne detection arrays [16][17][18]. The advantage is the high sensitivity for very fast response times but again cryogenic temperatures will limit the practical use for many of the proposed applications.

1.1.2.F Quantum Well Infrared Photodiodes (QWIPs)

A few attempts have been made at producing QWIP detectors for terahertz, most of which are based on inverse cascade type intersubband absorption [37]. The main advantage is that a narrow absorption band can be designed thereby filtering out other frequencies. Such devices will require low temperature operation to reduce dark currents [38].

1.1.2.G Heterodyne Detection

Heterodyne detection is where a reference frequency is non-linearly mixed with the original signal to produce beat frequencies. If the reference frequency is close to the original signal then the lower beat frequency is moved to frequencies where sensitive detectors are plentiful. Heterodyne detection has been developed predominantly by the astronomy community as it provides one of the most sensitive detection techniques [16][17][18]. A local oscillator is required at the measurement frequency and this can be problematic particularly at some terahertz frequencies where few high power sources are available. More recently the techniques has been demonstrated using two quantum cascade lasers and a Schottky diode mixer [13] and also using quantum cascade lasers with superconducting mixers [39].

1.2 Applications and Benefits

1.2.1 Production line monitoring

The pulsed systems allow the thicknesses of thin multilayer materials and items to be measured provided the signal is not complete absorbed by the item under investigation. Non-destructive measurement of the thickness of drug coatings is one major application where the thickness is extremely important as it determines the position in the body where drugs will be released [9]. For some modern drug treatments where toxic drugs require to be released only at diseased sites inside a human, the thickness of the coating requires to be controlled accurately. Terahertz pulsed imaging is ideal for such measurements in pharmaceutical production lines. Other similar applications can be envisaged such as imaging ceramic turbine blades to investigate crack formation on e.g. aircraft. Drug and aircraft applications can operate with imaging systems above £200k.

Picometrixs in the U.S. has installed one terahertz system on a cigarette manufacturing plant to monitor production [10]. The system allows 4000 cigarettes to be measured every second. A similar system was also used to check the thermal tiles on the NASA space shuttle to determine if the adhesive was still functional.

1.2.2 Spectroscopy

As most molecules have their vibrational and rotational modes at terahertz frequencies, there is enormous potential for molecular spectroscopy [3] and absolute specificity has been demonstrated for a number of smaller molecules [40]. Broadband systems are ideal for spectroscopic applications and many of the applications described below either specifically use spectroscopy or the application is the result of a spectroscopic resonance in the terahertz part of the spectrum. Gases and liquids are the easiest systems to measure as many lines are available for unique identification [3][40][41]. Solids are more difficult as bulk modes between molecules are the major absorptions. This may well be a significant market in research laboratories as the terahertz spectroscopy is complementary to many other laboratory techniques for the identification of molecules and materials.

1.2.4 Onocology (cancer imaging)

The research work started with basal skin carcenoma which is the most prevalent form of skin cancer and this work is now in clinical trials [2][9][42][43]. The most important aspect of the work is that terahertz can distinguish between tumours and scar tissue unlike a number of other potentially cheap techniques such as near-infrared and visible imaging. It also produces a full 3D image of the tumour including the depth while a number of other imaging modalities only produce a 2D lateral image.

Work has now moved onto malignant melanoma, breast, prostate and oral cancers. As clinical trials take a minimum of 7 years, onocology applications are a minimum of 5 years away from fruition. Onocology especially with skin cancers will require imaging systems with low prices (<£20k) if large market penetration is to result. Present acquisition times are within the 3 minutes required for medical imaging applications.

1.2.4 Proteomics

Work has demonstrated that terahertz spectroscopy is sensitive to the structure of proteins and can be used to study such structures [9]. As proteins regulate the structures of cells and tissue such work will be important in the development of treatments for genetic diseases such as Alzheimer's cancer and diabetes.

1.2.5 Biomedical Imaging and Sensing

While onocology has been treated above there are many other biological applications of terahertz. Dental imaging was one of the first suggested applications of terahertz [2] but total internal reflection and poor penetration depth with the low powers of present time domain spectroscopy systems have prevented dental imaging being pursued by companies.

Terahertz interacts with biological material at three different levels: i) the sub-cellular (fingerprints in the spectroscopy of sugars, bases, proteins, DNA, etc...), (ii) the cellular (changes in cell shape or behaviour following irradiation) and (iii) with tissue or organisms e.g. tissue imaging of basal cell carcinoma, teeth, various tissues in disease and health) [44]. Terahertz spectra show collective modes between biological molecules while the internal vibrational modes of many of the biological produce mid-infrared modes.

There are many examples of such spectroscopy of biological materials including sugars, DNA, RNA, cell membranes, enzymes in liposomes [45][46][47][48], etc.... There are clear advantages to terahertz imaging including specificity to particular chemical species (although this is probably irrelevant for most clinical situations), safety and cost (relative to other modalities). The clear disadvantages are poor penetration depth, slow acquisition times for images, delivery methods are not advanced and the real nature of the contrast observed in images is not fully understood. This is an area that requires significantly more research before any clear applications may be demonstrated.

1.2.6 Security monitoring

Terahertz has demonstrated detection through clothing [49][50] of metals [9], ceramics [9], plastics, explosives [49][51] and illicit substances (drugs) [50]. Spectroscopy has been used to identify plastic explosives [49][51][52] and other demonstrations include the detection of materials inside sealed envelopes [50]. Explosives and drugs can be detected even with high levels of standard masking materials [51][52]. The spectroscopic aspect is extremely useful for fast (< second) identification of illicit substances and using time-domain systems, any pixel can be Fourier transformed to give the spectra.

The major issue for security imaging is image acquisition time. The single point source mechanically rastered systems presently on sale require many minutes to produce an image while at airports, images must take less than 10 seconds. Array technologies for detectors and / or sources are required before such applications can have large penetration of civil air security markets. Remote suicide bomber detection requiring a minimum stand-off distance of 10 m is an area which can withstand high imager costs as there are no safe present systems apart from hand searching. Stand-off imaging at 1 m which can identify explosives under clothing has already been demonstrated in the U.K. with a relative humidity of 70% using time-domain systems [53]. Higher power systems will be required to circumvent the high water absorption in the atmosphere.

1.2.7 Label Free Analysis of DNA Molecules

There is substantial work on genetic diagnostic applications using DNA biosensors, gene chips and lab-on-a-chip at present. Most approaches for identifying polynucleotides sequences are based on detecting a bound or hybridised unknown target DNA to a single stranded oligo- or polynucleotide with a known base sequence which is anchored to a chip as hybridisation occurs preferentially between molecules with complementary base sequences. Most present techniques use fluorescent labels to identify when hybridisation has occurred but these systems may modify the DNA strand conformation lowering the precision of the gene detection. Terahertz has been used as a label free approach for the analysis of DNA molecules using direct probing of the bind states of the DNA with electromagnetic radiation at terahertz frequencies [54][55]. At present the best resolution is about 20-mer DNA which corresponds to a thickness of 4 nm using resonators to enhance the signal to noise ratio to 90 dB. Plasmon detection techniques are more sensitive at present and work has started to investigate plasmons at terahertz frequencies [56].

1.2.8 Bioweapons detection

There is considerable work in the US sponsored by ARO and others on bioweapons detection [57][58]. There may, however, be problems with water content of biological molecules so this application needs further work.

1.2.9 Communications

As the absorption of the atmosphere is enormous at certain THz frequencies due to water absorption, there is some potential for last mile communications as the absorption in the windows between water absorption lines is lower than that at visible wavelengths for fog and rain conditions. As line of sight is required above ~ 1 THz, the cost versus performance advantages for terahertz are not clear at present.

1.2.10 Pollution monitoring

The spectroscopic and absolute specificity of terahertz spectroscopy could have uses in pollution monitoring to identify new pollutants [2]. This market is small for terahertz as present systems range from £500 for some common pollutants to £5k for high resolution systems for most of the major pollutants. Low cost and high sensitivity would need to be demonstrated before terahertz can attack this market area.

1.2.11 Clothing sizing

Commonly cited statistics suggest that 75% of all women wear inappropriate bra sizes although market data from industry sources suggest that the number is between 30 to 60% [59]. Terahertz imaging could provide a solution to this problem if cheap imaging systems can be produced.

1.2.12 Landmine detection

Estimates suggest that there are between 45 million and 110 million unexploded landmines around the world which will cost $33 Bn to safely remove [59]. Terahertz has the potential for stand-off detection of explosives and provided the water content of the soil is not too high, could also be used for this application.

1.2.13 Astronomy

Terahertz astronomy has been around for many years and has played a large role in the development of superconducting and composite bolometer detectors, mixers and local oscillators for heterodyne detection systems. As astronomy requires passive imaging and can tolerate low temperature operation to improve signal to noise ratios, the systems are extremely sensitive but impractical for most civil and security applications due to the requirement of cryogenics. A number of small companies in the U.K. and the U.S. have been set up to supply components to terahertz telescopes.

1.3 Markets

The market for terahertz systems in 2004 was over £4M with many systems being purchased to allow companies and government agencies to test and find out about terahertz systems. The U.K. companies had well over 50 % of the market share.

The DTI commissioned a market report by Freshminds Ltd. for the Foresight Exploiting the Electromagnetic Spectrum; “Picturing People: Non-intrusive Imaging” Programme in 2004 [59]. Therefore data exists for the imaging applications which will now be summarised. Aviation screening was conservatively predicted to be worth $1.7 Bn per annum (all figures is U.S. dollars) in 2010 and $4.5 Bn in 2020. Aviation screening for explosives is the fastest growing imaging market, predicted to increase at 37% CAGR to $1.9 Bn in 2008. Terahertz has already demonstrated identification of concealed explosives and is conservatively predicted to achieve at least 50 % of this market within 5 years provided acquisition times can be reduced to required levels.

Personnel medical imaging which is predominantly terahertz imaging was predicted to be worth at least $730M by 2010 and $4.5 Bn by 2020 although the report states that it is more likely that the figures will actually be $3.6 Bn in 2010 and $22 Bn in 2020. More conservative estimates suggest that within 10 years terahertz might account for 10 % of this market with a value around $200 M per annum. Imaging equipment for landmine detection could be worth $100M to $300M per year and imaging equipment for clothes sizing could be worth $100M per year, both of which may be further applications for terahertz systems.

In addition to the imaging applications, the spectroscopic market must also be added. This is more difficult to predict and no publicly available market studies have been commissioned in the U.K..

1.4 Technology Drivers, Barriers and Gaps

The major technology gap at present is a cheap room temperature source of terahertz radiation. For electro-optical and photoconductive antenna systems, the cost of femtosecond lasers will reduce as the new fibre-optic laser become available commercially but costs for the initial fibre based lasers are still > £50k. This puts a complete terahertz imaging or spectroscopy system above £100k. The major disadvantage of the time domain systems in addition to the large cost is the image acquisition time as a single spot is rastered to build up the image. Work on arrays of sources and detectors is required especially if security applications are to be achieved where image acquisition times must be below 10 seconds for a full body image.

For medical imaging applications, present acquisition times are appropriate for the market although improvements would be beneficial but costs need to be reduced by an order of magnitude (imaging systems < £20k) for mainstream use. There are also issues requiring the completion of clinical trials, issues of training of operators, acceptance by the medical profession of the technique and easy of use that must be solved before medical imaging can be a main terahertz application.

A tunable, cheap, practical, room temperature (semiconductor) laser is still lacking for many of the mass market applications where low cost is essential. While GaAs QCLs are cheaper than femtosecond lasers, THz QCLs are not presently commercially available and will always require a significant closed cycle cooler for operation at around 100 K. If a room temperature QCL could be achieved this would be significant especially for security applications. More research is required if such devices are to be realised.

There are a number of papers looking at terahertz optics, filters, waveguides and general components but so far there is very little [60][61][62]. Lens and other optical components will be required for complete systems especially if costs are to be reduced. More work in this area is essential.

2. U.K. Competitive Positions

2.1 Academia

As terahertz is extremely interdisciplinary, it is sensible to divide this section into a number of fields. There are many universities in the U.K. working on terahertz but the groups at Cambridge and Leeds cover more research areas and have more people than the other universities. Many new groups are starting in the field so it is becoming difficult to keep track of all the academic players in the U.K..

2.1.1 Time Domain Terahertz Spectroscopy

The terahertz systems are all based on femtosecond lasers with electro-optical or photoconductive antenna sources and detectors. There are a large number of universities using such systems including Bath, Cambridge, Dundee, Abertay, Durham, Leeds, Oxford, Strathclyde and St Andrews.

2.1.2 Terahertz Imaging

Imaging work has been published by the Universities of Cambridge, Leeds, Durham and Strathclyde. All these organisations use time domain pulsed imaging systems with a femtosecond laser as a source and either electro-optical or photoconductive antenna detection. In addition, work at Cambridge also includes imaging using frequency mixing and quantum cascade lasers. There is also the astronomy groups at CCLRC and the University of Cambridge making passive imaging arrays for different terahertz telescopes.

2.1.3 Sources and Source Development

While there are a number of different technologies being investigated as potential sources for terahertz imaging, the main sources can be divided into photoconductive antenna, photomixing, optically pumped lasers, electrically pumped lasers and superconductors. The superconductor work is only really being pursued by astronomers as the operation requires 4.2 K operation which is not suitable for the vast majority of the real world applications described in section 1.2.

A number of universities including Bath, Oxford and Cambridge have been investigating improved electro-optical and photoconductive antenna sources and detectors. The University of Manchester provides the low temperature GaAs and other III-V wafers used by TeraView in all their commercial machines. They are also a supplier to many of the university groups in terahertz in the U.K..

The original GaAs quantum cascade laser (QCL) was grown at Cambridge and work continues there developing cascades and now using them inside imaging systems. Two of the people have now moved to Leeds and are building a similar research group there. GaAs QCLs have demonstrated up to 80 mW pulsed emission at 10 K and have excellent potential for compact, high power sources.

A consortium from Cambridge, Leeds, Imperial, Sheffield and Heriot-Watt have been investigating Si/SiGe QCLs. As of yet no laser has been produced but there is enormous interest as the lifetimes are approximately constant up to room temperature, unlike III-Vs suggesting that room temperature lasers may be achievable. Si/SiGe QCLs are therefore described as end-of-roadmap devices since they are likely to be the cheapest high-power and compact sources but are still some distance from first realisation.

2.1.4 Detectors

There is some work at Cambridge on quantum well infrared detectors, microbolometers and photoconductive antenna arrays but overall there is relatively little research in this area as many of the detector concepts are quite mature relative to sources. There is a clear need for research in detector arrays which can be used in imaging systems.

2.1.5 Optical Components

The University of Glasgow has been involved in the design and fabrication of terahertz filters.

2.1.6 Astronomy

There are groups in Cambridge and CCLRC investigating superconductors for heterodyne detection arrays to operate up to 1.5 THz. A group at Reading is involved with integrated detectors for astronomy.

2.1.7 Physics

There are groups at Imperial College working on terahertz sideband generation from quantum cascade lasers and another on magnetic materials with terahertz response. Also Carl Pidgeon at Heriot Watt University runs the U.K. research at the free electron laser, FELIX in Utrecht, the Netherlands. This provides a tunable terahertz source with over 200 mW of power and pulse widths from 2 ps at 1 THz.

2.2 U.K. Routes to Exploitation

2.3 Industry

TeraView Ltd. is a U.K. SME solely devoted to the development and exploitation of terahertz systems and applications [9]. The company was first to market with a terahertz imaging system and has a strategic agreement with Bruker for sales, distribution and servicing of imaging and spectroscopic systems [14]. TeraView also has an agreement with Smith Industries to help gain a foot hold in the security market especially with regard to the large U.S. civil and defence markets. Most important is that TeraView has a strong patent portfolio including the original patent for terahertz medical imaging. As much of their work includes research and development work with companies interested in using terahertz, they have a strong intellectual property position as they have one of the largest databases of terahertz spectra. They also have a strong research programme to develop terahertz components required for future terahertz applications.TeraView has collaborations with a large number of U.K. universities including Cambridge, Leeds, Manchester and Bath.

QMC: Originally set up from work at Queen Mary University for astronomy, it is one of the major suppliers in the world for bolometers especially for FTIR systems operated at terahertz frequencies [36]. They also sell a terahertz spectrum analyser (up to 600 GHz) and numerous other components for terahertz systems such as Golay cells, power meters and spectrum analysers.

Oxford Instruments: a supplier of cryogenic systems and in particular closed cycle coolers which may be important to QCL based terahertz systems. They already supply dewars to both QMC and Bruker and hence almost all terahertz bolometers available commercially use Oxford Instruments components [63].

QinetiQ: developing a mm-wave imaging system and involved in collaborative research with a number of universities including Heriot-Watt [64]. To some this is not terahertz imaging as it is operated in the W-band.

ThruVision Ltd.: A startup company from the CCLRC working at mm-wave frequencies (~ 200 GHz). They have a DTI Technology Programme award to investigate passive terahertz imaging systems.

Kodak, U.K.: involved in a DTI Technology programme with TeraView Ltd. and the Universities of Cambridge, Glasgow and Leeds. They are particularly interested in terahertz medical imaging and making terahertz optical components using different inorganic and organic materials.

Home Office: The Home Office Science Development Branch is also strongly involved in a number of areas of terahertz and is actively involved both with TeraView and a number of U.K. universities investigating the use of terahertz in a number of security applications.

2.4 Competitive Analysis

The U.K. is very well placed with the first company (TeraView) to get an imaging system on the market and also a very strong intellectual property and patent position. It is also a U.K. company which has demonstrated many of the first applications in terahertz imaging and spectroscopy. Picometrixs and Nikon also have terahertz systems available commercially. A number of other start-up companies are also aiming at the terahertz market e.g. in France, U.K. and U.S..

The U.S. is the biggest funder of terahertz research with DARPA funding a £66M programme from September 2004. This is the second DARPA programme on THz imaging and a U.K. consortium was funded in the first programme from September 2000 to September 2004 to investigate Si/SiGe quantum cascade lasers (Universities of Cambridge, Leeds, Sheffield and Heriot-Watt). The U.S. is putting a lot of money into end-of-roadmap sources and detector technologies for terahertz while most of the U.K.s funding is at proof of concept and early stage research. If the U.K. is to maintain its present lead, this needs to be addressed.

3. Forward Look

3.1 Five Years

The predicted market in 2010 for terahertz imaging systems is around £600M per annum [59] (from medical and security markets). For this to be achieved, cheaper systems (~ £20k) are required for the medical applications and it is assumed that clinical trials are successful. Also if the security applications are to be achieved then arrays of sources and detectors must be realised in this time scale. Most systems will probably be time-domain with fibre based femtosecond lasers and electro-optical or photoconductive antenna. It is more likely that the market will be predominantly related to production line monitoring where high cost terahertz systems can be tolerated.

3.2 Ten Years

By 2015 the predicted market for terahertz systems is £2 Bn per annum [59] predominantly from medical and security markets. Room or near room temperature tunable terahertz (semiconductor) lasers will be required if the cheap systems costs are to be met for the markets required for £2 Bn worth of sales. Arrays of these lasers will also be required for security applications. Also large scale arrays of complmentary detectors will also be required.

3.3 Twenty Years

By 2025 the predicted market for terahertz systems is > £5 Bn per annum. Large arrays of cheap, vertically emitting, room-temperature semiconductor terahertz lasers must be easily manufacturable on large substrates. Room temperature detector arrays allowing system signal to noise ratios of 100 dB or greater are required.

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Appendix 5

Ferroelectrics and Related Materials

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Introduction

Definitions and Background

Ferroelectric materials offer a very wide range of useful functional properties. A reasonable working definition of ferroelectricity is "a polar dielectric in which the polarisation can be switched between two or more stable states by the application of an electric field". However, there are exceptions to this definition: some ferroelectrics are semiconducting (and thus are not dielectrics because they cannot sustain an electrical polarisation); the spontaneous polarisation in some ferroelectrics cannot be switched because they cannot sustain an electric field of sufficient magnitude to effect the switching, either because they reach electrical breakdown first, or because they are too conducting.

Since its initial discovery the ferroelectric effect has been demonstrated in a wide range of materials, from water soluble crystals through oxides to polymers, ceramics and even liquid crystals. The range of useful properties exhibited by ferroelectrics covers:

- Ferroelectric hysteresis is used in non-volatile computer information storage.
- Ferroelectrics can exhibit very high relative permittivities (several thousand) which means that they are widely used in capacitors.
- The direct piezoelectric effect (the generation of charge in response to an applied stress) is widely used in sensors such as accelerometers, microphones, hydrophones etc.
- The converse piezoelectric effect (the generation of strain in response to an applied electric field) is widely used in actuators, ultrasonic generators, resonators, filters etc.
- The pyroelectric effect (the generation of charge in response to a change in material temperature) is widely used in uncooled infra-red detectors.
- The electro-optic effect (a change in birefringence in response to an applied electric field) is used in laser Q-switches, optical shutters and integrated optic (photonic) devices.
- Ferroelectrics exhibit strong non-linear optic effects that can be used for laser frequency doubling and optical mixing.

- Illumination of transparent ferroelectrics with light of sufficient energy causes excitation of carriers into the conduction band. Their movement under the internal bias field caused by the spontaneous polarisation causes a refractive index modulation that can be used for a variety of optical applications, including four-wave mixing and holographic information storage.
- Ferroelectrics exhibit strong coupling between stress and birefringence, which can be used to couple acoustic waves to optical signals with applications in, for example, radar signal processing.
- Doping certain ferroelectric ceramics with electron donors (e.g. $BaTiO_3$ with La^{3+}) can render them semiconducting. Heating these ceramics through their Curie temperature causes a very large, reversible increase in resistivity (by several orders of magnitude in some cases) over a narrow range of temperature (ca 10ºC). This large positive temperature coefficient of resistance (PTCR) is widely exploited in electric motor overload protection devices and self-stabilising ceramic heating elements.

The following sections cover a range of applicable properties for ferroelectric materials.

Pyroelectrics

Technology

The pyroelectric effect is exhibited by all ferroelectric materials as a generation of an electric current when the temperature of the material is changed. It is widely used in uncooled detectors of long wavelength infra-red radiation (IR). The principle behind their operation is very simple. The radiation to be detected is allowed to fall upon a thin chip of the pyroelectric material. The energy absorbed causes a change in temperature and the generation of a pyroelectric charge, which will cause the flow of current in an external circuit. This can be amplified and used, for example, to switch an alarm. The pyroelectric signal is proportional to the rate of change of the element temperature with timeand so pyroelectric devices do not have a "DC" response. They only "see" changes in the intensity of the radiation with time. This is an important advantage in many applications, where usually there is a requirement to detect changes in the radiation coming from a scene, rather than the average or unchanging background intensity. An example of this is the requirement to detect the radiation from a person coming into the field of view of an IR detector. Pyroelectric devices have several advantages over other radiation detectors. Their response is independent of the wavelength of the incident radiation, provided there is some means to absorb the radiation. Hence, pyroelectric radiation detectors have been used across the full range of the electromagnetic spectrum, from microwaves to X-rays.

Basically a single pyroelectric detector design can be used for different wavelengths of radiation, simply by equipping the package with different windows coated with filters according to the radiation it is desired to sense. Such devices are widely used in spectroscopic sensors for, e.g. automotive exhaust gas analysis. However, by far the widest application of pyroelectric detectors is in the sensing of IR in the wavelength range 8 to 14 microns. The reasons for this are that there is an atmospheric "window" of low absorption and objects with temperatures in the range of room temperature (300K) emit most of their radiative energy in that waveband. However, all of the semiconductor detectors of 8 to 14 micron IR need to be cooled, usually to ca 77K to work efficiently. On the other hand, pyroelectric detectors work perfectly well uncooled. Cheap detectors are readily available for under $1, and have thus found their way into a host of applications, notably detectors of people in such things as intruder alarms and remote light switches. Pyroelectric arrays have been developed in which a plane of pyroelectric material is interfaced to a silicon chip bearing a 2 dimensional array of FET amplifiers and a set of switches which can be used to multiplex the pyroelectric signals onto a single output. These arrays have been used for uncooled thermal imagers with performances comparable to those that can be achieved with cooled semiconductor devices (see Whatmore and Watton (2000)[1]).

The requirements for the active materials in a pyroelectric device has been described by Whatmore and Watton (2000). Detector performance is proportional to one of three basic "figures-of-merit" (FOM), which combine the pyroelectric, dielectric and thermal properties of the pyroelectric material together. For most devices, it is important to maximize $F_V = p/c'\varepsilon$ (where p is the pyroelectric coefficient, c' the volume specific heat and ε the dielectric constant) or $F_D = p/c'\sqrt{\varepsilon \tan\delta}$ (where $\tan\delta$ is the dielectric loss tangent of the pyroelectric material). Note that it is very important to measure the dielectric constant and loss at a frequency relevant to the device use. As most pyroelectric devices are used in the frequency range from 0.1 to 100 Hz, and dielectric loss is usually much greater at <100Hz than at 1KHz, a low frequencies measurement is essential. Table 2.1 lists the pyroelectric properties of several ferroelectric materials.

The differences between the FOM for the materials where high and low frequency data are available are clear. It can be seen that that the TGS family gives the largest figures of merit. However, these materials are water soluble and have relatively low Curie temperatures and so they are only still used in the high performance devices for instruments such as in FTIR spectrometers. $LiTaO_3$ (LT) is a good pyroelectric material with relatively low permittivity. It is inert and relatively easy to handle. It is used in many single element detectors. .

[1] Whatmore R.W. and Watton R. (2000) In "Infrared Detectors and Emitters: Materials and Devices" (Chapman and Hall; ed P. Capper and C.T. Elliott) pp 99-148

Ceramic materials such as those based on modified $PbZrO_3$ (Mod PZ) or modified $PbTiO_3$ (Mod PT) are widely used in low cost detectors. Note that although their FOM are worse than LT, they are low cost and their performance is perfectly adequate for many applications. The PVDF family (represented here by a P(VDF/TrFE70/30 copolymer) have good F_V, but relatively F_D values compared with the other materials listed. They tend to be used in large area detectors because of their low permittivities, low cost and the fact that they are readily made in very thin films with low thermal mass, which is an advantage in some circumstances. They have been demonstrated in linear arrays. It is advantageous for very small area detectors (say <100 microns square), such as those used in arrays, for the pyroelectric material to have a relatively high permittivity (a few hundred) so that the detector can have a capacitance that matches the input capacitance of the FET amplifier (usually ca 1pF). The ceramic materials are well suited to this application for that reason. There has been considerable research into the use in thermal imaging arrays of ferroelectrics with T_C close to room temperature under an applied bias field, which will provide an induced pyroelectric effect well above the normal T_C. This has been called dielectric bolometer mode of operation and the best materials researched for this have been PST and $(Ba_xSr_{1-x})TiO_3$ solid solutions with $x \approx 0.35$. These materials have relative permittivities of >1000 under the operational conditions and very high pyroelectric coefficients which can give an effective F_D some three times greater than can be achieved using conventional pyroelectric ceramics.

Material	*Meas. T* °C	*p* 10^{-4} $Cm^{-2}K^{-1}$	Dielectric Properties *ε*	*tanδ*	*Freq.* Hz	*c'* 10^6 $Jm^{-3}K^{-1}$	T_C ℃	F_V m^2C^{-1}	F_D 10^{-5} $Pa^{-1/2}$
DTGS (Crystal)	40	5.5	43	0.02	1000	2.6	61	0.53	8.3
$LiTaO_3$ (Crystal)	25	2.3	47	10^{-3}	1000	3.2	665	0.17	11.1
P(VDF/TrFE) 70/30 (Polymer)	25	0.33	7.4	0.017	1000	2.3	121	0.22	1.4
Mod. PZ	25	4.0	290	0.003	1000	2.8	230	0.054	5.2
(Ceramic)			300	0.014	33			0.054	2.3
Mod. PT	25	3.5	220	0.01	1000	2.8	>250	0.063	2.9
(Ceramic)			220	0.03	33			0.063	1.6

Table 2.1 Pyroelectric properties of several ferroelectric materials (taken from Whatmore and Watton (2000))

Applications & Benefits

As noted in the previous section, by far the widest uses of pyroelectric materials are in uncooled IR sensors, although there has been some interest in using the effect of electrical energy conversion, for which there was a substantial body of work undertaken in the mid-1980's. Very recently, there has been a novel use of the pyroelectric effect in cold-fusion[2]. The market for movement sensors using point (single element) detectors based on the pyroelectric effect is about $500M pa. This is mainly in the security field, but also includes light switches, door openers etc. Other markets for pyroelectric IR detectors include gas analysis, spectroscopy, flame detection etc. Array-based devices were explored extensively during the 1980's and 1990's in the USA and UK, mainly for military thermal imaging applications. Plessey (GEC Marconi) and Raytheon both developed systems with between 50K and 100K elements which delivered thermal resolutions of about 0.1K. The UK programme stopped in ca 2003, but Raytheon manufactures a range of military and professional cameras based on their technology. This technology is experiencing stiff competition from uncooled thermal imagers based upon resistive bolometer arrays[3]. More recently, a UK company (IRISYS Ltd.) has demonstrated the use of a limited arrays size 16x16) for low cost people sensing, queue monitoring and thermal imaging applications[4].

Technology Drivers, Barriers and Gaps

What are the key areas of technology that will drive the future development of this technology?
What are the likely barriers to the technology achieving its exploitation promise? How can these be overcome? Are there any fundamental technological problems that would make it very difficult for the technology to be applied?
What are the gaps in our technological knowledge that need to be bridged in order for the functional material to be exploited?
Pyroelectric technology is now relatively mature. There is a secure, growing market for point detectors and arrays. The basic properties of pyroelectric materials and the way they control the device characteristics are well understood. Further research into pyroelectric materials could produce further improvements in the basic figures-of-merit. These are more likely to be gained by novel materials structuring than by the development of new compositions, although there is a need to develop lead-free ceramic compositions to replace those based on the PZT system. For example, recent research has shown that the structuring of pyroelectric materials through the introduction of density/porosity gradients can give significant improvements in device performance[5]. Key materials developments for the future include the development of

[2] http://www.nature.com/nature/journal/v434/n7037/abs/nature03575.html). Nature, April 28, 2005

[3] http://www.thermal-eye.com/home_flash.asp

[4] http://www.irisys.co.uk/

[5] A. Navarro, R.W. Whatmore and J.R. Alcock (2004) "Preparation of functionally gradient PZT ceramics using tape casting" Proceedings of the International Conference on Electroceramics - ICE 2003 (MIT, Cambridge MA, USA), August 2003, J. Electroceramics 13 (1-3) 413-416 (ISSN: 1385-3449) (July 2004)

structured pyroelectric materials and the integration of thin film ferroelectric technologies with MEMS structures designed to give improved array performance through the collection of incident radiation. The broad wavelength responsivity of pyroelectric devices also gives them potential for use in other bands of the electromagnetic spectrum, such as for terahertz detection and imaging. The use of pyroelectric materials for conversion of low density waste heat into electrical power also deserves further consideration. The materials requirements for this application are rather different from those for infra-red detection and are likely to require different fabrication technologies.

UK Competitive Position

Academia

There is relatively little academic work into pyroelectric materials in the UK. By far the largest activity is at Cranfield University, under Prof. Whatmore. This work is internationally recognized. There has been work into pyroelectric ceramics at Leeds University and at Napier University where there was some work into pyroelectric arrays using PVDF thin films on silicon.

UK routes to exploitation

The major route to exploitation in the UK is through IRISYS Ltd. (see above). This small company is growing rapidly and is internationally unique in the way it is exploiting low cost, small element count pyroelectric arrays in people sensing systems. Increasingly, theirs is a systems business based upon their ability to manufacture a unique supporting component (a low cost pyroelectric array). BAe Systems Infra-red have a thermal imaging array manufacturing capability, but have now ceased manufacture.

Industry

The key UK industrial player in this area is now IRISYS Ltd. Internationally, it is Raytheon for array technology. There are several international players in the point detector market (e.g. Heimann, Nippon Ceramic, Matsushita) but virtually all the point detector manufacture is in the Far East and is now of little importance to the UK.

Forward Look

5 years

Large element count arrays for uncooled thermal imaging are likely to be superseded by low cost resistive bolometer arrays. The unique IRISYS product will enter widespread international use and could well engender an upsurge in interest in competitive pyroelectric array based products, exploiting the unique characteristics of pyroelectrics of being sensitive to changes in IR flux (unlike resistive bolometer arrays).

10 years

Use of pyroelectric arrays exploiting integrated thin films for people sensing and counting applications. Use of pyroelectric materials for thermal energy conversion.

20 years

Widespread use of pyroelectric materials for recovery of energy from waste heat.

Recommendations

- Support work into lead-free pyroelectric materials and materials exploiting structure to obtain an advantage in pyroelectric figure-of-merit.
- Support work into the integration of pyroelectric thin films with MEMS for advanced people counting sensors.

Microwave Dielectrics

Technology

In the last 20 years the field of microwave communications has seen exceptional growth. Very roughly there is a new mobile phone user every second of the day. The reason for this growth is an interesting study that reflects a dramatic shift in human behavioural patterns: an ever increasing demand for access to information and communication on a continual basis both for business and social reasons. The phenomenal increase in text messaging is a reflection of this trend. This rapid growth has generated a requirement for high performance miniaturised microwave components. In this report we shall confine ourselves to ceramic microwave dielectrics but if we broaden the discussion briefly, it is very interesting to note that microwave ceramics are reaching highly sophisticated processing developments. There are, for example multilayer chip capacitors of a few microns layer thickness with dimensions 500x200x300 microns made by ceramic processing techniques. Worldwide, there are more than 20,000 ceramic chip capacitors made *and individually tested* every second of the day and night or around 40 billion each month.

This IGT will focus on two main areas – Microwave dielectrics for resonator filters in both mobile handsets and for base stations and dielectric resonator antennas. These materials are oxides, generally manufactured by ceramic processing techniques and the key properties are that the materials should possess are sufficiently high relative dielectric constant for the purposes of miniaturization, a low dielectric loss for reduced power consumption and better selectivity and a low temperature coefficient of frequency to prevent frequency drift in changing temperature conditions.

These key properties are explained in more detail below.

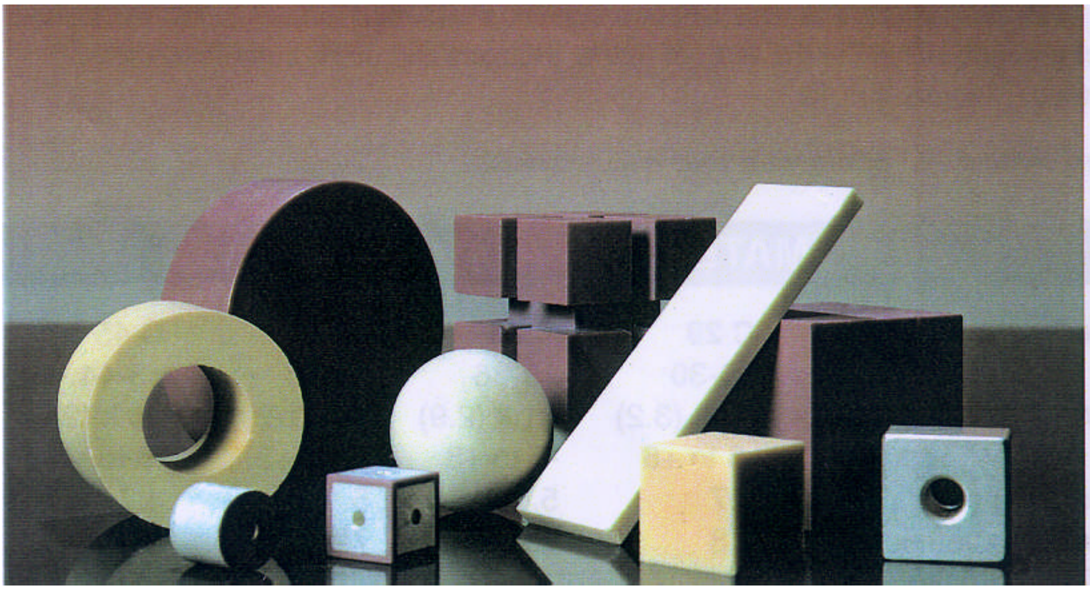


Fig 1 A range of ceramic dielectric resonators (courtesy Filtronic Comtek).

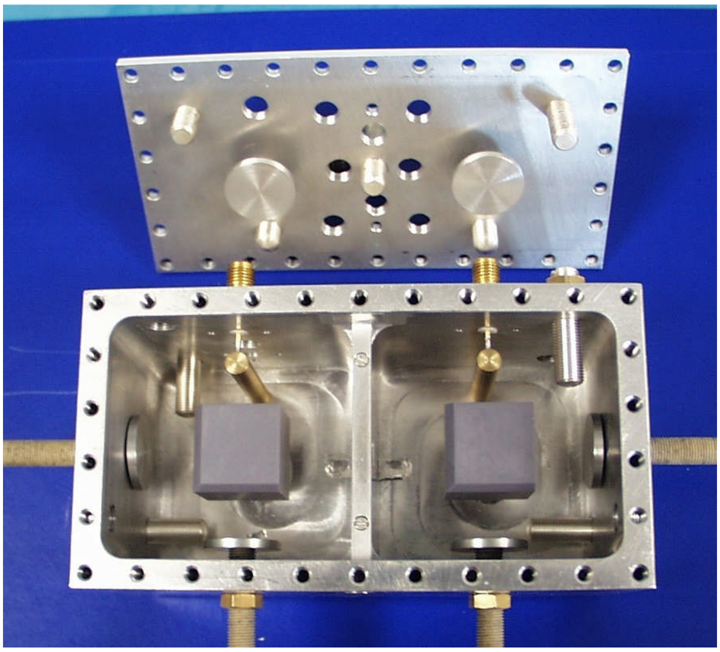


Fig 2 Two triple mode resonators providing a six pole filter (courtesy Filtronic Comtek).

Relative Dielectric constant (ε_r)

high ε_r is required for a small size and thus low mass as the size of a dielectric resonator is proportional to $\sqrt{\varepsilon_r}$. This is especially important for mobile handsets and satellite systems.

Dielectric loss (tan δ ~1/Q)

A low tan δ is essential for high performance devices since the lower it is the higher the efficiency and lower the noise. For example, in filters a lower tan δ leads to a lower insertion loss (higher efficiency) and sharper filter characteristics (better selectivity). The *Q* of a resonator in the absence of other losses is 1/tan δ. Unfortunately, materials with a higher ε_r also tend to have higher losses. Of the three properties tan δ is the most sensitive to material preparation and processing conditions. Because the *Q* is frequency dependent it is important to note the frequency at which measurements are made. Results are often quoted in terms of $Q \times f$ as to a rough approximation, in the microwave region, $Q \times f$ is a constant

Temperature Coefficient of Resonant Frequency (TCF).

For a resonator to be practical its resonant frequency (f_0) must be stable to changes in the temperature of its operating environment. The temperature coefficient of frequency is defined as

$$TCF = \frac{1}{f_0}\frac{\partial f_0}{\partial T} \qquad (1)$$

and should be very close to zero for most applications. The shift in f_0 with temperature is due to thermal expansion dimensions and changes in the materials ε_r. Thus the TCF can be related to the material's linear thermal expansion coefficient (α_l) and temperature coefficient of ε_r ($TC\varepsilon_r$) by

$$TCF = \frac{-TC\varepsilon_r}{2} - \alpha_l \qquad (2)$$

Applications & Benefits

In the area of microwave dielectric ceramics thee is a strong requirement for materials that do not contain Pb (lead). In time (10-15 years) there will probably also be a requirement for Bi and Ni free. We anticipate higher operating temperatures (particularly automotive, under bonnet applications). We observe that capacitors are moving to X8R, X9R performance.
A general theme is continual cost reduction. Low cost electrode structures will be required and this may mean a move to copper electrode Cu technology. It is conceivable that nano-sized materials will allow the use of lower processing temperatures but nanocrystalline materials may also offer performance advantage. .

In Telecoms applications we see a trend to higher frequencies. Voice to 5 GHz (4G and 5G technology). Wi-Max and Wi-Fi applications will require a range of dielectrics for antenna applications and we anticipate active antenna arrays.

There will be a requirement for predictive radar technology in automotive applications (80 GHz) and we foresee applications in Imaging (medical, security). The area of sensors will expand particularly embedded in chip devices. Many of these sensors will be thin film devices and the issue of thin film reliability and homogeneity will be key particularly with the drive towards miniaturization as structure size decreases. We will see an increased use of polymer structures and environmental concerns will place a greater importance on sustainability and re-cyclability.

Dielectric technology for the antenna industry

Context - a description of the technology, applications and benefits.

Dielectric materials can be used to improve the performance of electrically small antennas such as those used on cellular radio handsets, PDAs, laptop computers, PCMCIA cards, etc. The improvements are generally to the efficiency of the antenna and to extent to which it detunes when used in different environments, e.g. a mobile phone when held in the hand and next to the head. Dielectrically based antennas are particularly useful when some degree of isolation is required between several closely spaced antennas. Dielectrics may be used in antennas in a number of different ways:

- *Dielectric Loaded Antennas:* Here a conventional conductive element radiates and the dielectric modifies the medium surrounding it.
- *Dielectric Resonator Antennas (DRAs):* In the 1980's a new type of dielectric antenna evolved in which the radiation arises from the dielectric material itself though a mechanism known as a displacement current.
- *Broadband Dielectric Antennas:* DRAs have a well-resolved resonance because of the groundplane beneath them. It has been found that if the groundplane area is reduced, the bandwidth of the antenna increases significantly. To distinguish this new type of antenna from DRAs we have called them Broadband Dielectric Antennas. The radiating mechanism is thought to be a combination of radiation from the feed structure, the edge of the groundplane and a displacement current in the dielectric.
- *Dielectrically Excited Antennas:* The last category of dielectric antennas involves conductive parasitic antennas with no feeds of their own but which are instead excited by DRAs or other types of dielectric antenna.

All four types of dielectric antenna are used in the UK antenna industry.

Technology Drivers, Barriers and Gaps

Technology gaps & barriers:

In the UK there is a lack of Lack of LTCC (Low Temperature Co-fired Ceramics) experience, design and production facilities (embedded features, multifunctionality of on-chip packages). Similarly with Microelectromechanical devices (MEMS) there is a lack of true production outlets.
There is a lack of integration between materials industries and electronics
Product / process reliability is not seen as 'useful' and therefore is not normally well funded.

Dielectric Antennas: Issues - technology drivers, barriers and technology gaps.

The technology is driven by the materials available and how well they can be characterized. The most important property of a radio frequency electro-ceramic material is the relative dielectric constant, which needs to be higher than most conventional materials that surround us. Other important properties are the quality factor (Q), which is inversely proportional to the loss and the temperature coefficient of the dielectric constant. Most available high dielectric materials are ceramics and these need to have good physical integrity, as ceramic materials possess low fracture toughness with K_{1c} between 1 and 3 $\mathrm{MPam}^{1\backslash 2}$ and can be prone to brittle fracture.
Good quality high relative dielectric constant ceramics are available up to a relative permittivity of about 100. They are mainly sourced from Japan (Murata, Maruwa, Taiyo Yuden, TDK, Kyocera). Materials with higher relative permittivities would be useful, but both the Q and the temperature coefficient tend not to be good enough for antenna purposes. For relative permittivities below 10, some good quality polymer materials are available. It is not easy to characterize the electrical properties of any of these materials and we have relied on London South Bank University to help us validate the manufacturers claims.
Gaps in the available technology are perceived to be:

- Good quality dielectric ceramics with permittivities significantly greater than 100.
- Lower cost materials.
- Ceramic loaded plastics.
- High dielectric polymers.
- Better characterization/measurement systems.
- Electronically tunable materials (e.g. voltage controlled permittivity).
- Possibly, functionally graded materials.

UK Competitive Position

Academia

Key academic players: UK-London South Bank University, Sheffield, Manchester, Queen Mary; good academic ability, poor exploitation (little UK industry left). In the rest of the world, the key players are found in the USA and Korea.

Dielectric Antennas UK position - academia, industry, competitor analysis

There are two UK companies making dielectric antennas, Antenova and Sarantel. Sarantel make high quality helical antennas and Antenova manufacture dielectric multiband handset antennas. There are many Japanese companies selling ceramic chip antennas that are low-cost, low-performance, for such applications as Bluetooth, WLAN, etc.

UK routes to exploitation

Industry

Competitor Analysis (country/organization/spend)

The main commercial suppliers of microwave dielectric ceramics are :
Kyocera (http://www.kyocera.com/kicc/industrial/products/dielectric.htm)
TransTech Inc. (http://www.trans-techinc.com)
Murata (http://www.murata.com)
Trak Ceramics Inc.
NTK
Tekelec Temex

Company	Dielectric sales	Total turnover
TransTech	$12.6M	$43M
Trak		
NTK	¥11.5Bn	¥1700B
Tekelec Temex		$226M ('99)
Siemens		
EPCOS		100M€
Morgan		£4-5M
Murata	(see below)	(see below)

End Users

Major telecom equipment manufacturers. Goods manufactured include practically all aspects of high end telecomms equipment.

Company	Income 2000 $BN	Income 1999 $BN	Position previous year
Ericsson	31.3	25.7	2
Nortel	30.3	21.3	3
Nokia	27.2	20.1	4
Lucent	25.8	33.8	1
Cisco	23.9	15	8
Siemens	22.8	20	5
Motorola	22.8	19.7	6
Alcatel	21.6	17.1	7

Forward Look

Future:

Industry perceives a decreasing academic standard of graduates. There is no pull for students to go into industry (let alone materials / electronics) – the topic is too difficult, there is little security of employment and salaries in this sector cannot compete with those in the Financial Sector.

The Industry view is to fund modelling and basic science (do we understand today's materials / applications). Industry sees far too much emphasis on tomorrow's new dawn and not enough R&D spend on real problems that face industry now.

Forward look over 5,10,15 years – Dielectric Antennas

Worldwide there is a great deal of interest in dielectric antennas. The total market for antennas on handsets and mobile data terminals is expected to be around 770 m in the year 2006 rising to 2120 m in the year 2010 (this assumes multiple antennas on some terminals).   Not all these antennas will be ceramic; a reasonable prediction is 15 m in the year 2006 rising to 300 m in the year 2010 will be ceramic based.
If we assume an average selling price of US$ 50 cents/antenna, this means the market for ceramic antennas is potentially a US$ 150 m industry.

Forward Look – Dielectrics for resonator applications

It is always rather dangerous to make predictions about the future developments in a field capable of such astonishingly rapid change but it is also necessary to attempt these predictions. We can be fairly certain that the ingenuity of Materials Scientists will mean that higher Q materials will be found at relative permittivities of interest (ie ~30, ~50, ~80 and above). We can also be reasonably sure of frequency agile or tuneable components and these are worth examining.

Tuneable Devices

Recently there has been interest in low loss ferroelectric/paraelectrics based on $Ba_xSr_{1-x}TiO_3$. Ferroelecrically tuned dielectric resonators are shown to possess reasonable tuning with Q factors acceptable for devices. In a piezomechanical tuning arrangement, the tuning is effected by applying an electric field to a piezoelectric which results in a movement. This method of tuning can give large tuning ranges of around 20-25%.

New Structures

Paradoxically, the ideal resonator structure would contain no dielectric – the drive towards miniaturization combined with manufacturability demands planar structures or at the least, flip chip structures. The problem is that current state of the art and current thinking says that high *Q* structures require big volume. There *are* structures such as very thin dielectric plates which possess relatively high *Q*. This is more amenable to integration but as soon as metallisation is integrated then loss increases. So as ever there is a compromise. But there are new and exciting ideas emerging that may impact strongly on our thinking. Currently, device design involves using modelling the electromagnetic response of a structure to predict device performance using well known bulk properties. This approach is only valid when the wavelength of physical processes, i.e. phonons, is very much smaller than the dimensions of the structure. When the physical dimensions of structures are of the order of quanta wavelengths, the intrinsic behaviour of the material is altered. This effect has been observed for thin films with thickness of the order of a few nanometres. The measured material properties of thin films differ greatly from those of bulk or thick film materials. Indeed, there is still much debate as to the causes of these differences. This is principally a size effect where phonon complex frequencies are dependent on film thickness. Quantum confinement allows one to engineer the properties of a material by carefully prescribing the dimensions of the structure. For example, by patterning a thin film dielectric it should be possible to alter the phonon decay channels which are intrinsic to bulk materials. In this way, dielectric loss mechanisms such as defects, impurities and surfaces, which are usually regarded as unwanted extrinsic factors in bulk materials, themselves having no effect on the intrinsic properties, become extremely important because they can alter the behaviour of the intrinsic properties. In the same way that patterning of dielectrics can produce widely different electromagnetic responses (photonic band-gap crystals – see metamaterials below), patterning of thin films on a nanometre scale will produce a similar effect on phonon dispersion. For instance, the transverse optical phonon mode of a film usually decays into acoustic phonons. If the pattern produces Bragg reflection at the acoustic phonon frequency then the optical phonon decay channel will be narrowed. The effect of this will be a narrower observed linewidth for the optical mode and hence a lower loss.

Multiferroics

Materials capable of responding to a range of external stimuli offer interesting new potential device applications. Integration of dissimilar materials is now less of a barrier to progress and it is this feature that has renewed interest in magnetoelectric materials (or Multiferroics). For example the combination of transition metal oxides onto silicon is now common. "Multiferroic" is a term given to materials that exhibit coupled electric, magnetic and structural order parameters that result in simultaneous ferroelectricity, ferromagnetism and ferroelasticity. What this means in practice is simple: more functionality and more functionality means a combination of electromagnetic and ferroelectric effects, giving real potential to new device possibilities.

Metamaterials

Metamaterials have received a great deal of attention recently. Some of this attention is a direct result of interesting work by John Pendry at Imperial College whose theories indicate that so-called negative refractive index materials might be constructed with novel properties. The electromagnetic properties of certain class of metamaterials in which both permittivity and permeability attain negative real parts in a given band of frequencies have attracted a great deal of interest in recent years.

An interesting class of metamaterial structures in which the period arrangement of elements can provide interesting features is the electromagnetic bandgap (EBG) surfaces with high surface impedance. In such surfaces, by properly selecting the geometry, composition, arrangement and alignment of planar elements one can achieve high impedance surfaces, which can effectively behave as "artificial magnetic conductors (AMC)" These can lead to useful applications in various problems involving low-profile, conformal antennas, miniaturized cavities, and thin absorbing low-observable surfaces.

The challenge here is in both modeling the structures to provide interesting effects and in particular, constructing the structures. Such structures are periodic arrangements that possess electromagnetc interactions that are sensitive to such arrangements.

5 years – Drive towards cost reduction and miniaturization but essentially similar. Metamaterials and multiferroic research highly active.
10 years – miniaturization and multiferroic and Metamaterials begin to be embedded via thin film techniques.
20 years – full integration of semiconductor active devices, passive devices, metamaterials and multiferroics. Very high development of use interfaces, seamless combination of multifunctional devices.

Recommendations

The UK government supports the area via EPSRC research programmes and to a limited extent through the DTI. There is also indirect support through the UK's contributions to the EU Framework programme. However, it is clear to the authors and contributors of this report that the activity into new research areas that will have a significant effect on future technologies is far more aggressive in competitor institutions abroad and in particular in the USA and Japan. The Global market demands access to information on a constant basis and this means wireless.
The future will see miniaturization and multi-functionality. It will be achieved by the introduction of new materials science i.e. metamaterials, multiferroics, and functional electronic materials and it will rely on thin film deposition processes with sophisticated patterning techniques. Failure to engage in these activities will prejudice the UK's ability to compete in this expanding Global market.

Piezoelectric Materials

Technology

Piezoelectric materials develop an electric charge in response to an applied load or stress, and conversely deform or exhibit an elastic strain in response to an applied electric field. The use of these effects, individually, sequentially or resonantly coupled, provides many different modes of application in sensing, actuation and signal processing. Hence, piezoelectric materials are truly multifunctional. They can be found at the functional heart of devices throughout modern technology, from musical greetings cards to life-saving medical imaging equipment, from mobile phones to astronomical telescopes.

Piezoelectric materials can be produced in a number of forms, including single crystals, monolithic ceramics, multilayer ceramics, thick films, thin films, polymers and ceramic-polymer composites of various geometries and connectivities. The vast majority of commercial devices are based on lead zirconate titanate ceramic (PZT); polymers typified by polyvinylidene difluoride (PVDF) and quartz crystals also have established, if relatively limited, markets. The majority of this review is therefore devoted to PZT, its competitors and possible developments thereof.

Applications & Benefits

The multifunctional nature of piezoelectric materials has engendered an exceptionally wide variety of applications. Table 1 provides a summary of a number of well-known applications, however it is far from exhaustive and new means of exploiting the piezoelectric effect are constantly appearing on the market. It is a characteristic of this market that no one piezoelectric material serves all applications. PZT meets the requirements of a large majority; however PZT itself is not a single material, but encompasses a range of materials that have been tailored to meet the demands of individual devices, or groups of similar applications.

The world market for piezoelectric materials is currently estimated to be approximately $1 billion p.a., with a growth rate approaching 10% p.a. This figure includes the materials themseleves as well as simple devices and components such as buzzers and filters, but does not include more complex subsystems for which the piezoelectric is the main functional component and which accounts for a market worth many times the above figure.

The diversity and rate of development of new applications guarantees that the market is particularly vibrant. For example, one of the simplest applications of piezoelectric materials, actuation, has for many years been underrepresented in the market place. The small magnitude of the piezoelectric effect has suited it to micro- or nano-positioning applications, however, improvements in the fabrication technology for piezoelectric devices now offer a number of opportunities for engineering accumulation or amplification into the device at an intrinsic level, promising all the advantages of piezoelectric actuation but at a greater magnitude of displacement. A critical development in this context has been that of multilayer actuators for automotive fuel injection, recently introduced by a number of European car manufacturers to help meet the increasingly emissions targets. Although multilayer actuators have been available for some years, they have only recently been developed to meet the price and reliability requirements of automotive systems. Although in its infancy at present, the potential market for piezo-injection actuators is probably worth in excess of €80M p.a. in the UK alone. Lower cost is still sought, the major issue being the use of base metal, rather than precious electrodes within the actuator structure. Due to the fabrication conditions necessitated by the use of base metals, there are issues with the reliability of such actuators. However, the availability of robust high strain actuators at both the price and quantity required by such a mass market will render viable a new set of previously unexploited applications. Hence the ~10% growth rates in the piezoelectric market are likely to continue for some time, if not increase further.

Direct Effect	Charge creation	Spark ignitors
		Impact fuses
	Pressure sensors	Load cells
		Weighing machines
		Intruder alarms
	Acoustic sensors	Microphones
		Gramophone pick-ups
		Passive sonar
	Vibration sensors	Strain gauges (smart structures)
		Seismophones
Converse Effect	Axial transducers	Servo valves
		Automotive fuel injection
		Micro- and nanopositioners
	Bimorphs & helimorphs	Large displacement, low load positioners
	Combined modes	Ink-jet devices
	Accumulation devices	Pumps
		Rotary motors
		Linear motors
	Acoustic transducers	Buzzers
		Tweeters
	Ultrasound (high power)	Cleaning baths
		Dispersing horns
Combined	Sonar	Ship-borne
		Buoys
	Ultrasound (high power)	Medical imaging
		Intravascular instruments
		NDT
		Range finders
	Smart structures	Vibration & noise control
Resonant Devices	Bulk wave devices	IF filters (TV & radio)
	SAW devices	Filters
		Delay lines
		Signal conditioning
	Transformers	Step-up
		Step-down

Table 1. Applications of Piezoelectric Materials

Technology Drivers, Barriers and Gaps

For materials with so many different fields of application it is perhaps inadvisable to attempt to definitively identify which market sectors will drive future developments. The above example identified how low cost, robust multilayer actuators have been developed to fulfill a demand in the automotive industry. It is a reasonable certainty that the use of multilayer actuators on engines will lead to a greater use of these components in other areas of the vehicle.

However, the next significant development in piezoelectrics may equally well come as a result of meeting a problem in completely different industry. For example, and purely as an illustration, the computer industry already employs piezo-actuators in the read-write heads of hard disk-drives to correct for tracking errors due to extraneous impacts and vibration. As the demand for high density, non-volatile data storage increases, new developments in the field of integrated piezo-devices may become imperative as parallel scanning probe approaches take over from rotating magnetic discs. This is one of a perhaps a hundred potential large scale market needs that if solved would significantly impact on the market size of for piezoelectric technology.
So, rather than examine specific market needs, a number of generic issues which identify the likely gaps and barriers to exploitation are discussed below.

New materials

A number of market sectors are likely to demand higher performance than is currently available from PZT, particularly in terms of the basic piezoelectric coefficients,. The solution to this may be found in completely new materials, or as has been shown recently, from employing different forms of familiar materials. Eight years ago, single crystals of materials related to PZT were shown to exhibit piezoelectric effects 5 to 10x that of PZT. In the last 12 months, new medical imaging transducers have appeared on the market based on these crystals, which while more expensive than PZT, provide twice the bandwidth and hence greater clarity and detail in the image. The extra cost of the aw material is rather insignificant compared to the cost of the full imaging system. It is interesting to note that these materials in ceramic form showed little promise as replacements for PZT, it was only when grown as single crystals as a surrogate for PZT, (which is notoriously difficult to grow in single crystal form) was it apparent that there was great potential in these materials. This example highlights the necessity of curiosity driven research.

Although single crystals are able to exhibit 5 to 10x the maximum strain of PZT, by far the most significant factor limiting the growth of piezoelectric applications is the rather limited strain available (1 to 2 % from the crystals). This limit, in current materials, is linked to the differential lattice strain across phase boundaries within the material system. Hence any progress in producing “giant” strain materials (strain = 2 to 10%) is likely to come from investigations of field enforced phase transitions both in crystal and ceramic form. This could open up completely new applications in smart aerodynamics, high power motors, braking systems and smart structures.

The new single crystals suffer from a shortcoming that is shared with PZT and which indicates a clear need for new materials development. The range of applications for which PZT may be used is currently limited by its upper operating temperature.

PZT loses its ferroelectric properties above its Curie temperature (T_c), which is approximately 300°C in the most commonly used compositions. However, an effective limit on the temperature of use is approximately 200°C, as beyond this temperature the material gradually depolarises. Indeed, in the recently developed piezo-diesel injectors, PZT just meets the operating temperature requirement.
Hence, there is a clear need for piezoelectric materials with similar performance to PZT, but which can operate at the higher temperatures. Applications include control actuation in aero-engines for greater fuel efficiency, sensors employed at drilling depths for more effective oil exploration, in-service non-destructive testing for safety assurance in chemical and nuclear plant, and direct-write of high melting point solids for the next generation of electronic and photonic circuits. Although there are a number of well known ferroelectric materials with higher transition temperatures than PZT, none of these come close, by a significant margin, to the room temperature performance of PZT.
A second driver for the search for PZT alternatives is the potential restrictions which may be placed on the use of PZT by the RoHS and WEE legislation introduced by the EU. At present, electroceramics containing lead are exempt from these directives, however the potential removal of the waiver at a later date acts as a spur to develop new lead-free materials. Recent innovations at Toyota Laboratories have demonstrated that novel ceramic processing techniques can generate “grain-oriented” lead-free materials on a par with PZT. Such approaches are now likely to be followed elsewhere to maximise the performance of PZT replacements

Inevitably the search for new single crystal, lead-free or high temperature materials currently focuses on materials which exhibit the structural motif that has been identified as being at the heart of PZT’s outstanding performance. Whilst progress is currently being made within the box defined by this motif, the insight required that may lead to a major step forward by searching outside the box is probably lacking. Our understanding of the fundamentals of the piezoelectric effect, even in familiar materials, is still rather poor, so progress on the basic science of piezoelectric materials, particularly in the field of structure-property relationships, is also required

Innovation in Design and Manufacture

Recent years have seen rapid growth in the design and development of piezoelectric strain accumulation devices, including both linear and rotary motors. Such devices make innovative use of the high frequency repetition of the small micro-strains provided by the piezoelectric effect, to build up macroscopic movement. Such devices enjoy the advantages of small size, high torque, high efficiency and low electrical noise when compared to conventional electromagnetic motors.

However a major barrier to their widespread use is the precision, and associated cost, of their manufacture. This applies both to conventionally sized devices, where the precision engineering of ceramic devices is in its relative infancy and to micro-engineered devices, which might rely on thick or thin-films of piezoelectric material. If such issues can be successfully addressed, then the availability of giant strain materials is likely to stimulate a revolution in motor design which could see the replacement of electromagnetic motors in many sectors.

Again, motors serve as only one example of innovative design with piezoelectrics, where progress is required in manufacturing to allow new products to be introduced. Other high value, potentially high volume devices, such as micro-pumps for drug delivery, intravascular imaging/therapy instruments & scanning probe memory devices, all would come to market more quickly through investment in precision and micro-manufacturing methods.

In the latter case, piezoelectricity is one of the candidate phenomena that could be used as the motive force in micro-electromechanical systems (MEMS). At present one of the obstacles in the path of greater use of piezoelectricity in this field is integrating layers of material of sufficient thickness to meet the force criteria of many applications. Current technologies for thin film, thick film and discrete approaches all suffer significant drawbacks in their applications. Hence further work is required on the methods of integration of piezoelectrics into microsystems.

Reliability

Innovation in new materials, design and manufacturing will be of no consequence if devices cannot meet the reliability requirements of modern markets. Ageing, degradation and fatigue are well recognized, but not well understood aspects of piezoelectric materials. At present they are not a major barrier to existing applications, but better understanding of the problems may aid the penetration into new product areas. Again this is an area in which improved basic understanding needs to improve if progress is going to be made.

Summary

The key gaps and barriers are summarized below:

- New materials
  - High operating temperature materials
  - “Giant” strain materials
  - Lead-free materials
- Processing and manufacturing
  - Low cost co-fired electrode systems
  - Grain-oriented ceramics
  - Precision engineering with ceramics
  - Thin films and microsystems integration

- Basic science
    - Structure-property relationships
    - Ageing and fatigue

UK Competitive Position

Academia

Table 2 lists some of the key UK academics currently research active in the field of piezoelectric materials. Those who should be regarded as internationally leading in their specialism are marked with an asterisk. Table 3 shows a list of academic research leaders from the rest of the world. Each of these has a reputation at least equal to those found on the UK list and in many cases far greater.

Academic	Institution	Area of Expertise
Bell, Andrew	Leeds	New materials (high temp.); Structure-property relationships
Bowen, Christopher	Bath	Composites
Button, Timothy	Birmingham	Ceramic processing
Cain, Markys	NPL	Metrology
Cochran, Sandy	Strathclyde	Ultrasound transducers
*Glazer, Michael	Oxford	Crystallography
Hall, David	Manchester	Domain studies
*Hayward, Gordon	Strathclyde	Ultrasound transducers
Milne, Stephen	Leeds	Thin films
*Reaney, Ian	Sheffield	Structure-property relationships (electron microscopy)
Reece, Michael	Queen Mary	Mechanical properties
Thomas, Pamela	Warwick	New materials (lead free)
*Whatmore, Roger	Cranfield	Precision and microengineering; thin films; nanotechnology

Table 2. Key UK academics in the field of piezoelectrics; international leaders marked with an asterisk (*).

Country	Academic	Institution	Area of Expertise
Canada	Ye, Zuo-Guang	Simon Fraser Univ.	Structure property relationships
France		Ecole Centrale Paris	Structure-property relationships
France	Mercurio, Jean-Pierre	Université de Limoges	Structure-property relationships
Germany	Hofman, Michael	Karlsruhe	Structure-property relationships
Germany	Rodel, Jurgen	TU Darmstadt	Fatigue
Germany	Schönecker, Andreas	Fraunhofer Institute	Structure-property relationships
Germany	Waser, Rainer	RWTH Aachen	Structure-property relationships
Israel	Rosenman, Gil	Tel Aviv University	Domain engineering
Japan	Adachi, M.	Toyama Prefectural Univ.	Thin films; single crystal fibres
Japan	Ichinose, N.	Waseda University	New materials (single crystals)
Japan	Ishibashi, Y.	Aichi Shukuto University	Theory
Japan	Nakamura, K.	Tohoku University	Single crystal devices
Japan	Shiosaki, T.	Nara Institute	Thin films
Japan	Takenaka, T.	Science University, Tokyo	New materials (lead-free)
Japan	Tsurumi, T.	TIT	Fundamental studies
Japan	Wada, S.	TIT	Single crystals and thin films
Poland	Hilczer, Bozena	Polish Acad. of Science	Polymers
Portugal	Kholkin, Andrei	Universidade de Aveiro	Scanning microscopy
Portugal	Vilarinho, Paula	Universidade de Aveiro	Composition-property relationships
Slovenia	Kosec, Marija	Jozef Stefan Institute	Ceramic and thin film processing
Spain	Pardo, Lorena	CSIC - ICM Madrid	Ceramic processing
Switzerland	Dragan Damjanovic	EPFL	Structure-property relationships
Switzerland	Muralt, Paul	EPFL	Thin films, microengineering
USA	Cross, Eric	Penn State	All aspects of piezoelectric science
USA	Randall, Clive	Penn State	Structure-property relationships
USA	Shrout, Thomas	Penn State	Composition-property relationships
USA	Trolier-McKinstry, Susan	Penn State	Thin-films
USA	Viehland, Dwight	Virginia Polytechnic	Structure-property relationships
USA	Uchino, Kenji	Penn State	Device physics
USA	Zhang, Qiming	Penn State	Polymers

Table 3. Key academics outside the UK.

UK routes to exploitation

Whilst there are some large UK-based companies involved in the manufacture of piezoelectric materials (see below), the exploitation of new innovations is often in the hands of SMEs and start-ups. Recent examples include TCC Ltd (Glasgow) who are developing growth methods for piezoelectric single crystals (discovered in the US) and Polatis (Cambridge) who are developing switches for fibre-optic communications based on piezoelectric actuators. 1Limited have pioneered the use of novel actuator designs and excellent materials processing methods to provide real innovation in the actuator market. However the large-scale manufacture and incorporation of these actuators into professional and consumer products is being carried out in the Far East rather than in the UK.

The real barriers to exploitation are not specific to the area of piezoelectrics, rather they are the more generic ones of the reluctance of individuals or the stock market to invest in manufacturing and high technology.

Industry

The piezoelectric industry is structured such that a handful of manufacturers in the world provide PZT materials in both standard and bespoke shapes and sizes to OEMs. A number of these companies will also take on further engineering of simple devices. However, it is normally the OEMs who design and build the higher value-added devices employing materials provided by the materials manufacturers. A potential exception to this supply chain arrangement is in multilayer actuators for automotive applications which is seeing the growth of newer device manufacturers, providing their materials in-house.

One of the largest of the materials manufacturers, Morgan Crucible, is UK-based and supplies PZT and related piezoelectric materials through its Technical Ceramics (previously Electroceramics) Division. It has manufacturing sites in the UK, the Netherlands and the US. Hence the UK competes quite strongly in the materials supply market. Whilst Morgan cannot be said to be ignoring new technology, - for example, investing in facilities in the US for the growth of new single crystals for supply into the medical ultrasound imaging market, - there is concern that investment is low in the UK, which is not untypical of materials industries. In contrast to other parts of the Morgan business, piezoelectrics is a fast developing area and is atypical in its need for development funds; it is also a minor part of the Morgan global business, differences which perhaps make it vulnerable to divestment.

As alluded to above, the exploitation of piezoelectric materials in devices in the UK (other than those parts of Delphi involved in the automotive piezo-injection programme) is mainly in the hands of SMEs.

Competitor Analysis (country/organization/spend)

Figure 1 provides an indication of the level of activity in the major research active countries, by comparing the number of entries in the ISI publications database appearing between January 2000 and July 2005 containing keywords based on the “piezo-” stem. It is not surprising that the US has the highest entry, with over 10% of US papers emanating from the Pennsylvania State University. The level of activity in China is notable, although that of Japan is perhaps less than might have been anticipated. The UK activity appears to be similar to that of Korea and France, but is some way behind that of Germany.

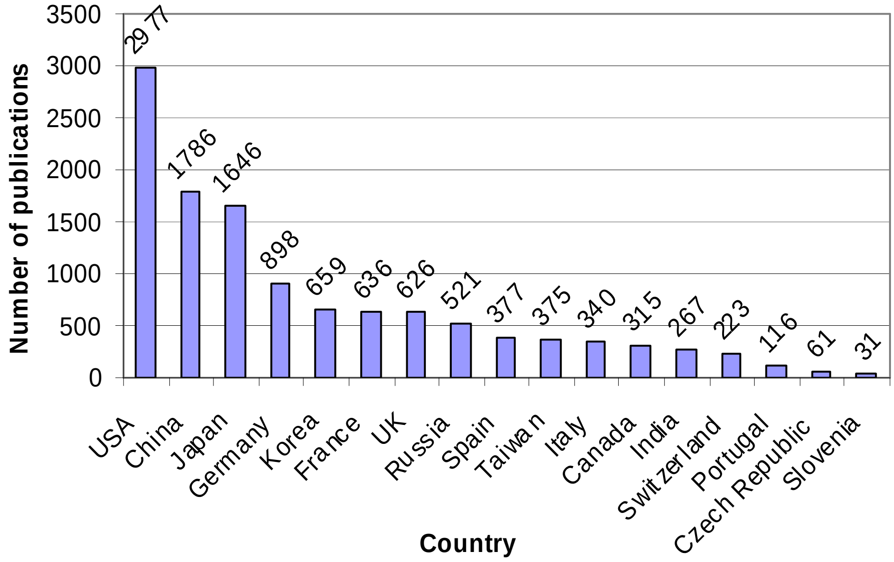


Figure 1. Number of publications by country from 2000 to 2005 containing the keyword stem “piezo-”.

Forward Look

5 years

Within 5 years it is likely that good progress will have been made towards filling a number of the gaps indicated above. The piezoelectric materials market will have grown to nearly €2 billion. Both high temperature and practical lead-free materials will be entering the market place. New knowledge will have been generated on aging and reliability and will have been adopted by materials manufacturers in formulating their products. The automotive industry will have adopted piezo-injection for both diesel and petrol engines, helping to reduce emissions and improve fuel economy. Progress in precision manufacturing and microsystems integration will have been made. Hence a large percentage of electronic products, from professional instruments to consumer goods, will include microengineered piezoelectric motors and actuators. Research into giant strain materials will be gaining momentum.

10 years

The first giant strain materials will become available, inspiring a revolution in active structures and motor design. Programmes will be in place by major manufacturers to replace a large percentage of conventional electromagnetic motors by piezoelectric devices. Unprecedented growth in the piezoelectric materials market would follow.

20 years

Piezoelectric devices will be rather more common as the source of motive power in electronic products than electromagnetic devices are today. The range of products based on piezoelectrics will be many times greater than at present.

Recommendations

- There are a significant number of companies in the UK involved in both the manufacture and exploitation of piezoelectric materials. Piezoelectric technology based on the current generation of materials has the potential to continue to grow at a rate above the general trend in electronics due to its multifunctional nature and continuing innovation in new applications. To ensure that this growth potential is fulfilled in the UK, investment is required in :
    - the basic science associated with ageing, fatigue and reliability,
    - low-cost electrode systems for multilayer ceramics
    - precision engineering of systems based on piezoelectric materials
    - thin films and microsystem integration.
- There is a threat that the current generation of materials will be subject to restrictions under EU environmental legislation. It is therefore necessary to invest in the search for new lead-free alternatives to PZT and other lead-based piezoelectrics.
- The growth in piezoelectric applications will be greatly increased by the availability of new materials with extended performance.
    - Investment in the development of piezoelectric materials with higher operating temperatures will help improve fuel efficiency and reduce emissions in the automotive and aerospace sectors.
    - Completely new areas of application would be opened up by the availability of “giant” strain materials requiring investment in basic new materials research.

- Britain is well equipped academically to innovate in the fields of piezoelectric materials and devices referred to above. The types of applications that could grow as a consequence are fully consistent with the current vision of a knowledge-based economy. However, the transfer of knowledge into products is hampered by the long-held myth that Britain is somehow ill-equipped, in both attitude and infrastructure, for manufacturing. This myth, which ultimately will be self-fulfilling, stifles investment and must be countered vigorously. An economy cannot be sustained on knowledge alone.

Ultrasonics

Technology

Ultrasound is sound at frequencies higher than the human audible range, from 20kHz up to more than 200MHz. Sound and ultrasound are fundamentally mechanical vibrations and, as such, depend on the medium in which they travel. Ultrasound travels well through liquids and many solids and much less well through air. Crucially, the medium can be optically opaque and ultrasound can therefore be used to “see” into media such as turbid seawater, human tissue, and many engineering materials.

Ultrasound occurs widely in nature, the best known examples being use for navigation by bats and dolphins. The vast majority of human applications of ultrasound rely on piezoelectric materials for generation and detection. These functional materials are the crucial components in the ultrasonic transducers that form the interface between the real world and electronic systems. Piezoelectric materials for ultrasonic transducers come in various forms including polymers such as polyvinylidene fluoride (PVDF), ceramics such as lead zirconate titanate (PZT), and single crystals such as lithium niobate (LNO). Piezoelectric material suppliers typically specialise in only one form of the material as the manufacturing processes for polymer, ceramic and single crystal are distinctly different.

Applications and Benefits

The main application areas for ultrasonic transducers are biomedical imaging and therapy, underwater sonar, nondestructive testing (NDT), industrial processing, and remote sensing. The focus here is on the first three as these motivate the vast majority of innovation in the field. All these applications exist because ultrasound is safe and works in real time. In addition, ultrasonic systems are generally inexpensive, convenient to handle, and often portable. As an example, ultrasound is used in more than 20% of clinical imaging, where the piezoelectric materials form the elements within the imaging arrays. Another example is in the automotive industry, where ultrasound is used for tyre pressure sensing, burglar alarms, airbag sensors and car parking collision avoidance.

Across all applications, the total market for ultrasound systems worldwide is put at around $4.5bn per annum. Within this total, biomedical systems comprise $3.5bn – 4bn, with the other applications having smaller markets. The benefits of ultrasound are widely recognised and, with the increasing capability of electronic and computing systems, growth in the total market is forecast to be of the order of 10% per annum. The ultrasonic transducers and arrays used within the systems are estimated to account for 10% of the cost of the system, therefore comprising a market of around $450m per annum.

Technology Drivers, Barriers and Gaps

Although ultrasound is already very widely used, major developments are continuing.

Across all three major applications, the integration of electronics with the transducers will increase. This may increase development costs but will cut system costs. An example of this is the replacement of cables by wireless links which will make ultrasound systems more convenient to use and simplify their engineering into NDT and underwater sonar platforms. Electronics integration will also allow ultrasound to reduce accessibility limitations, for example internally within the human body and in difficult structures in NDT.

There will also be advances in specific applications.

- In biomedical ultrasound the major advances will be in 3D imaging, in high frequency imaging, and in therapeutic applications. For 3D imaging, fine-grained ceramics or new single crystal materials with very high electrical permittivity in small scale multilayer structures will be necessary to enhance the sensitivity of the very small array elements. For high frequency imaging for ophthalmology, dentistry, dermatology and other clinical specialisms, still smaller structures, with dimensions of the order of 10μm, will be needed. In biomedical therapy, ultrasound is utilised as a source of energy, for example to heat a tumour beyond its thermal limit. In the present developmental stage of this field, the design flexibility of the material is crucial, requiring better computer modelling.
- In ultrasonic transducers for underwater sonar, the major driver is to increase operating bandwidth. In common with biomedical imaging and NDT, this is because ultrasonic transducer development has not matched the recent advances in electronic systems and there is therefore “spare capacity” within the potential capabilities of electronic systems.
- In NDT, the major development will be the increasing adoption of ultrasonic arrays; as for biomedical arrays, the sensitivity of the piezoelectric material will be crucial. Another area of interest is in transducers for use at temperatures of 600°C and more, to allow testing of industrial plant in operation. This also relates to condition monitoring and the topic of smart structures, in which ultrasonic sensing has a major role.

In summary, the gaps in the capabilities of piezoelectric materials for ultrasound applications are in the ease of integration of electronics; in small and ultrasmall scale structures; in the temperature range of operation; in bandwidth; and in the capability to incorporate these materials within computer aided design procedures for design flexibility.

A further area that must also be mentioned is lead free materials. Such materials already exist but their performance does not satisfy the needs of cutting edge applications. Nevertheless, there are many routine applications of piezoelectric materials in ultrasonic systems where lead free materials could be used, for example by adopting modern composite material designs or by accepting some transducer performance degradation and compensating with better electronics. A key issue in this area is the balance between acceptable economic and environmental costs.

UK Competitive Position

Academia

There are two academic groups in the UK with specialist capabilities in ultrasonic transducer and array design, the longest established being at Strathclyde University and a newer group at Paisley University beginning to make an impact. There is an estimated total of 10 - 15 others that have some capability, usually related to a specific application such as NDT at Imperial College and small scale devices at Cranfield University.
Internationally, France is quite strong in this area, with at least two notable groups, Germany not so strong though maintaining relevant institutions, and there is at least one excellent academic group in each of Italy and Spain. The US has traditionally been strong in ultrasonic transducer design, with particularly notable groups at Penn State University, Stanford, the University of Southern California, Duke University and the University of Virginia. Canada is surprisingly strong, probably matching the capability of the UK in strength if not depth. In contrast, Japan is surprisingly weak in academic terms and little has come out of China.
In terms of the overall structure of academic research, it is characterised by groups with just one key academic (Strathclyde – Hayward, Stanford – Khuri-Yakub, Duke – Smith). Possible explanations of this are that ultrasonic transducers and arrays are a niche area and it is impossible to achieve the level of income needed to maintain a larger group; that the cost of the equipment required for state of the art research is around $1.5m or less, viable for relatively small groups; and that the multiple, highly distinct markets addressed by ultrasound confer little advantage in terms of critical mass.

Industry

The UK was in the vanguard of biomedical ultrasound imaging in its early days in the 1950s and 1960s, along with Japan and the US, because of its strong industrial position and technology transfer from NDT. This position has now been lost and the key industrial players are in the US. Indeed, both Philips and Siemens relatively recently relocated their operations there from Europe, at the same time acquiring second-tier US companies. Some viable operations also remain in Japan (Hitachi, Toshiba, Aloka) and Korea (Medison). The UK has only one biomedical imaging systems company, Dynamic Imaging, a niche player. In NDT, historic UK strength has been lost along with the UK's industrial base. Worldwide, there has been a recent consolidation, with many small companies now grouped into several larger ones, notable examples being in the US (GE Inspection) and Canada (R/D Tech). The UK company Sonatest is the largest European supplier, operating on a global scale. There are also several UK SMEs relatively secure in niche areas, such as Diagnostic Sonar (Livingston), operating internationally and dealing directly with companies such as Boeing. From technology roots in WWII, the UK was historically strong in underwater sonar, principally for defence. Nowadays, the ultimate players remain typically defence majors including BAESystems, Thales and Lockheed Martin. As with NDT, these companies sometimes deal directly with SMEs which may also participate in the industry through consortia.

UK routes to exploitation

UK routes to exploitation are best considered by application. In biomedical imaging, the routes to viable exploitation presently mainly lie outside the UK, notably in the US, Korea and Japan. Biomedical therapy is a similar picture. In NDT, companies are typically smaller and therefore easier to approach but also typically more conservative in their acceptance of new technology. The UK has or hosts several underwater sonar companies, with complete supply chains from boutique transducer suppliers such as Alba Ultrasound (Glasgow) and PCT (Aberdeen) through to the defence majors.

A key difficulty in the UK is that piezoelectric material and transducer suppliers are near the bottom of the value chain, typically at least three steps away from the ultimate customers. For example, in underwater sonar, systems customers such as Subsea 7 act as contractors to oil and gas suppliers. Subsea 7 talks to sonar systems suppliers, who talk to systems manufacturers, who talk to transducer manufacturers, who deal with materials suppliers. As an example, this has meant that, despite private and public investment in new single crystal materials in the UK, with no effective European competition, it has so far been impossible to build a secure UK effort. In contrast, there are now several suppliers of such materials in the US and Korea, apparently because of stronger government support for what is seen as an underpinning technology, more cohesion between basic academic research and knowledge transfer, and stronger levers to support technology-based science and engineering SMEs prior to profitability.

Forward Look

Over the next five years – There will be increasing use of ultrasound as its benefits continue to weigh against the costs and safety implications of other techniques such as MRI and radiography. The capabilities of electronic systems and computing will continue to improve and, although advancing, transducer and arrays are likely still to lag behind, with "spare capacity" within the electronic systems and the front end devics operating to their maximum extent. One major step forward is likely to be the widespread rather than the present experimental adoption of imaging arrays for NDT.
In 10 years time – 3D medical imaging systems will be in routine use, probably very significantly increasing the proportion of clinical imaging performed with ultrasound above its present level of 20%. Ultrasonic therapy will also be in widespread use, the necessary highly reliable transducers and treatment planning capabilities having been developed. Underwater sonar systems will be less expensive, operating almost exclusively with electronic arrays rather than mechanical scanning, and they will be making a significant contribution to the use of autonomous underwater vehicles (AUVs), for example for harbour surveillance and mine hunting. In NDT, embedded sensors for condition monitoring will finally be in widespread use, contributing to increasing "smartness" of structures. Fewer lead-based materials will be in use.
In 20 years time – High frequency medical imaging systems will allow easier intralumenal examinations. Better electronics, combined with more sophisticated signal processing and better arrays, will have substantially increased the clarity of realtime 3D imaging to the extent that ultrasound will be a genuine competitor for MRI but at much lower cost. AUVs powered by fuel cells will have very significantly taken on the role of underwater exploration and monitoring, with better piezoelectric materials in high performance arrays integrated with smart electronics and computing. The present manual approach to NDT will have been completely superseded by traceable digital data recording utilising wireless devices in which the piezoelectric transducers are integrated with electronics. This will be essential for technological challenges such as the next generation of nuclear power plant.

Recommendations

Recommendation 1 – The ultrasonics industry is characterised by many small organisations, whether companies or research groups. The establishment of a directory of relevant UK organisations, cutting across the present market stratification is recommended as entrepreneurial gains are likely to follow from coherent effort.
Recommendation 2 – The crucial nature of ultrasonic transducers in ultrasound systems may make it possible to capture unusual profits from systems supply if control of the transducer design and manufacturing processes can be retained in the UK. This should be recognised in governmental thinking on an area which is presently controlled by upstream, mainly non-UK organisations.

Recommendation 3 – That careful attention is paid to the possibilities of lead free materials, which may be neglected through lack of sophistication in industry rather than through a genuine impossibility to develop and use such materials, with consequent avoidable environmental damage.
Recommendation 4 – That recognition is given to the fact that a knowledge-based economy cannot be based just on obvious winners and that, for such an economy to be more than words, it must have the sophistication to be able to support genuinely complex areas such as ultrasound systems, necessitating on-going short term financial losses for underlying long term prosperity.

Electro-Optic Materials

Technology

Functional periodically poled optical materials cover a range of important technologies. Common to these is an underlying technology based on domain inversion in ferroelectrics. In essence this means working with a class of materials that show permanent electrical effects within the crystal, and in particular ones where it is possible to rearrange the crystal structure by applying a high voltage electrical pulse. The result is a crystal in which domains have been selectively inverted to add new functionality to the material. The resulting domain inverted material shows a much richer set of optical properties than the virgin crystals. The prime example is PPLN (periodically poled lithium niobate), which can be used to convert light from lasers to new wavelengths. Figure 1 shows a spectrum of light generated in an Optical parametric oscillator configuration at Southampton University.

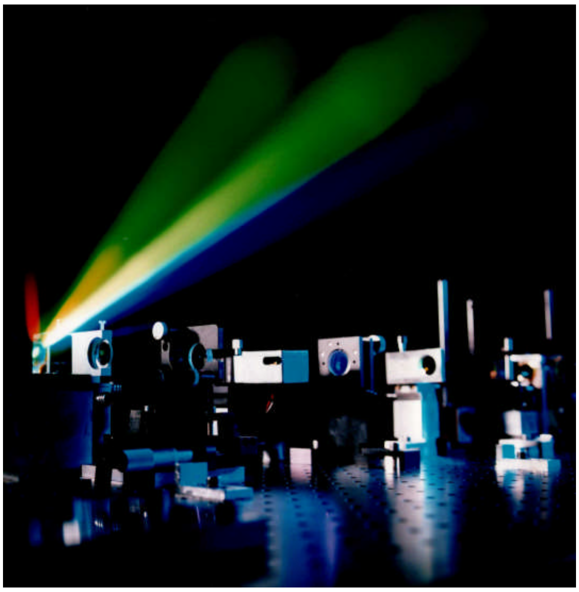


Figure 1

Although the primary application of domain inversion technology is in optics they also show potential in areas such as high density disk storage and lithographic processes. Recent scientific uses of the underlying material even extend to the recent demonstration of particle acceleration resulting in nuclear fusion using lithium tantalate (B. Naranjo, J.K. Gimzewski and S. Putterman "Observation of nuclear fusion driven by a pyroelectric crystal" (http://www.nature.com/nature/journal/v434/n7037/abs/nature03575.html). Nature, April 28, 2005)

The principal material for periodic domain inversion is PPLN, which is produced by application of a high voltage electric field to a patterned electrode. Careful control of the poling process, lithography, surface condition, electrode design, etc., allows crystals with sophisticated designs to be fabricated.

Applications & Benefits

Functional periodically domain inverted ferroelectric materials are important in a wide range of fields of optical technology. Within optics they are driven by the desire of technologists and scientists to have laser light at wavelengths not available from conventional laser sources. Nature gives us certain wavelengths where transitions in atoms can be used to yield laser action. The most familiar such examples being the red He:Ne laser, 1.064 micron Nd lasers, etc. However, most wavelengths do not have suitable laser sources, which is where PPLN and related materials such as PPKTP (periodically poled potassium titanyl phosphate) come in. By using an approach known as quasi-phase matching (or more commonly as QPM) it is possible to tailor the response to give high conversion efficiency for virtually any wavelength by re-phasing the converted light.

The markets for wavelength converted sources are very substantial. The largest is probably in aerospace, which includes LIDAR and directed infra-red countermeasures. This application is concerned with the provision of laser sources on aircraft to defeat heat seeking missile technology. In this time of global terrorism, the risk to aircraft is no longer confined to military aircraft, and so the provision of such sources on aircraft, the test & calibration equipment for such sources, etc, provides a huge potential market. An estimate of this market is the planned $10bn figure quoted in the Sunday Times May 30th 2005. This is based on the need to equip 6800 commercial aircraft in the US with each system likely to cost around $1m per plane.

Less politically sensitive applications of wavelength conversion are to be found in remote sensing, atmospheric spectroscopy, scientific research, etc. The ability of QPM materials to provide sources at IR wavelengths provides a major scientific opportunity. Particularly crucial are the areas of the spectrum where the atmosphere transmits.

Market estimates here are more difficult, but a surrogate is the market for diode pumped solid state laser, which share some characteristics with wavelength converted sources (in terms of power handling, uses, etc), for which, data from Laser Focus World in 2003, showed a market of about $200m. If 10% of this opportunity were to involve wavelength conversion the market here could well be $20m. This is reinforced by the views of companies in which the author has direct interest which predict a market of $5m for PPLN based sources by 2008.

The next significant market area is in blue sources to replace air-cooled argon ion lasers. These are widely used in fluorescence microscopy, and to measure fluorescence lifetime on tagged biological molecules. The existing lasers are very inefficient and bulky, and so an alternative based on frequency doubling of diode lasers (976nm to 488nm) provides a viable alternative. The market for such sources is estimated to be $50m per annum (based on discussions with the CTO of a large US based diode manufacturer).

Thus, in summary, significant opportunities exist for lasers and light sources utilizing poled functional materials.

Technology Drivers, Barriers and Gaps

The future development of this area will be driven by technological developments in three areas – firstly the underlying materials, secondly in processing the materials and making devices, and thirdly in applications of the materials in photonics.

The first area will be driven by the limitations of existing materials, these may either affect the ability to periodically pole the crystals or may provide limitations to their end application. The primary problems lie in optical induced damage (the photorefractive effect that is seen in existing LiNbO3 at visible wavelengths, limited transmission (oxide materials are not really useable above 5 microns, and generally do not transmit below 280nm for standard ferroelectrics). Some materials have very high coercive fields and the difficulties in controlling the domain dynamics limits the ability to periodically pole large aperture crystals for high power laser applications.

The routes to overcome these limitations are either to improve crystal growth (and composition) or to investigate new materials. For example, it is attractive to improve LiNbO3 materials by adding dopants and stoichiometry – work in Japan at Oxide Corporation has led to a ten fold improvement in visible light production, and work at MIT in BaMgF2 has allowed the use of functional poled materials down to below 200nm (a wavelength range critical for deep UV lithography).

The second area in need of technological improvement lies in the poling processes. Limitations exist in lithography, poling uniformity, poling control, and underlying understanding of material properties – especially in surface and polishing related issues. Improvements in these areas coupled with improved materials leads to tantalizing prospects for very low cost visible sources for projection TV and other high power visible applications.

The third area where technological innovation is desirable is in laser sources, where the high cost of existing lasers limits the ability to create truly low cost tunable sources. This is particularly an issue in the mid-IR where the sources can be intrinsically laser eye safe, and widespread adoption for pollution monitoring, civil defence, ranging, weather forecasting, etc would be possible if the unit costs became low enough.

The existing area of PPLN commercialization is fairly low risk, because it has used cheaply available LiNbO3 that is produced for the world-wide SAW filter market. As applications start to demand novel crystals with improved or modified compositions we will see the emergence of barriers. The underlying material costs will be much higher, and there will be a funding gap in crystal growth – especially in the UK which risking losing competitive advantage. Crystal growth is inherently slow, expensive and also requires reasonably high volumes to yield high quality (one-off crystals tend to show large variability), and while the UK has strengths, it is not resourced at a level that is competitive with Japan and the US where crystal growth of ferroelectrics is seen as a significant national resource enabling other industries.

There are some fundamental barriers that limit applications in the deep-UV and long infra-red. In particular materials such as BaMgF2 will likely form the next generation of functional ferroelectric devices and the UK has no activity in the their growth or processing.

The final barrier come from gaps in knowledge – particularly in how to get finer periods, thicker materials, overcome PR damage, better control of growth, interactions between surfaces / surface treatment & poling. These process development topics are not "exciting" in terms of EPSRC funding but in many ways are critical if the UK is to keep its advantage.

UK Competitive Position

Academia

There are a number of workers in the UK with significant track record and expertise in functional poled materials. In particular, the largest effort has been led by Hanna, Eason and Smith at Southampton in fabrication, and nonlinear optics. Thomas at Warwick has significant expertise in underlying ferroelectrics, particularly KTP family. Other UK optics groups have strong track record in using functional poled materials in nonlinear optics, especially Heriot Watt, St Andrews, and Strathclyde. Related is work on the development of laser sources (particularly fibre laser sources – at Southampton (Richardson, Payne, Nielson, and at Imperial (French))

Worldwide there are a number of strong groups, most notably Fejer's group at Stanford, Baldi and De-Micheli in Nice, INO in Canada, Sohler and Suche at Paderborn, Laurell at KTH, Ito at Sendai in Japan. Kitamura at NIMS in Japan is leading the activity in growth of advanced LiNbO3 family materials. Trying to assess achievement is always difficult, but it is reasonable to hope that the Southampton activity is viewed as 2nd or 3rd ranked to Stanford worldwide. However, this only part of the story as the new directions in functional poled materials are increasingly coming from novel crystal growth and the UK is weak in this area compared to the US, Japan.

UK routes to exploitation

The technology of nonlinear optical function al materials is being taken up by a number of companies. Established defence companies (such as BAE and Qinetiq) have activities. There are also spin-outs – particularly, Stratophase Ltd in Southampton, Crystal Consortium In Glasgow, and Oxford Medical Diagnostics Ltd.

The opportunities in nonlinear optical functional materials are considerable, but will require more activity to bring together UK laser activity (for example in solid state lasers and fibre lasers, together with the newly developed functional nonlinear optical materials. While this activity is developing, the process is slow and could certainly be enhanced by increased government support, both for product development and also for University level research. Leading industrial competitor nations to the UK have considerably more activity, particularly through SBIR support in the US, and larger scale DoD funding. In Japan there is a considerable amount of coordinated development, especially between NIRIM and Oxide Corporation on new crystals, and at larger companies (especially Fuji, NGK Insulators, JVC, etc.)

Optoelectronics is a global industry and so companies benefit considerably from collaboration with overseas companies, so for example Stratophase Ltd has a strong partnering relationship with Thorlabs (headquartered in Newton, NJ). This covers sales and marketing. It also purchases all of its underlying raw materials from overseas – either the US or Japan where the major suppliers of LiNbO3 are located.

Another example of this globalization is the work Oxford Medical Diagnostics Ltd with PPLN produced by HC Photonics in Taiwan.

UK research in functional materials has been largely fundamental in nature, and there has been a considerable gap between the type of research carried out by EPSRC funding in Universities (typically leading to single – proof of concept – devices, and the needs of industry. UK research funding is very strongly driven by the need for research novelty – making it virtually impossible for scientists to secure follow on funding.

Industry

Functional poled optical materials have a wide range of potential end-applications, and so identifying industrial players depends critically on market segment. For aerospace it is BAe Systems, Selex, Smiths, Thales. Looking wider, in terms of volume applications large players are Bookham and Marconi. Laser companies such as Thorlabs, Point Source, Southampton Photonics, Coherent Scotland, GSI Lumonics, and Elforlight will be important for developing systems based around functional poled optical materials.

In terms of production of functional poled optical materials, Stratophase Ltd is the leading company in Europe producing periodically poled lithium niobate.
The UK is probably in a broadly comparable position with regard to Germany and France in developing functional poled materials, although somewhat ahead in terms of SME activity. Germany, in particular has seen wider government support through activities at Paderborn and the Fraunhofer Institute Physikalische Messtechnik.

Competitor Analysis (country/organization/spend)

Japan is seeing considerable commercial activity in growth of novel materials for poling (NIRIM, Oxide, Yamaju), in poling research (RIKEN, NIMS) and in commercialization (Fuji, JVC, NTT). Total expenditure must exceed $10m per annum.
The US is concentrating on aerospace and countermeasures, and heavily funds groups at Stanford, USAF, Crystal Technology, etc. Again basic research funding must exceed $10m and commercial development by Aerospace companies (such as Lockheed Martin) must be greater.
Germany and France are probably spending a few $m per annum in total.
The UK is probably spending less than half of what is spent in France and Germany, mostly through EPSRC grants and venture investors.

Forward Look

5 years

In the next five years basic poled functional optical materials will start to mature and see wider spread applications. The availability of “standard” products from Stratophase, HC Photonics, and Crystal Tech, will start to make manufacturers feel that the technology has moved from lab demonstrator to commercial product. This in turn will fuel growth in applications.

10 years

In the next 10 years new materials with better power handling, better transmission will start to find widespread application in optics. Larger volumes will lead to lower production costs, which in turn will fuel growth. Functional poled optical materials will start to find application in consumer products – eg displays, high density storage, etc. Medical uses will start to become more common.

20 years

It seems likely that poled functional optical materials will become a mainstay of laser technology, with widespread deployment. Scientists will continue to strive for better materials.

If significant breakthroughs do occur, particularly in achieving much finer poling periods, then the materials may start to see widespread deployment in telecomm systems. Hugh growth in internet data is creating interest in next generation optical processing, and also in secure quantum communications, in which case the materials will be critical there too.

Recommendations

1) Ensure that funding is available to Universities for follow-on and development type work. Such funding is essential – it is akin to moving from a single transistor to a working CMOS technology without any route to fund the research – such work can look derivative and lack novelty (and thus not get funded by EPSRC) but is essential if we are to maintain our leading UK position.
2) Undertake a review of crystal growth facilities, with particular emphasis on production of commercial grade materials in LiNbO3, LiTaO3, doped LiNbO3, doped LiTaO3 and BaMgF2. Consider funding such activities as core to the UK's position in poled functional materials.
3) Continue to fund high quality science in the UK in lasers and optics.
4) Consider reviving the old ROPA awards to allow better support of groups involved in significant commercial activity. (Perhaps like the old ROPAs but only related to money from SMEs).

Ferroelectrics in Microsystems and Nanotechnology

Technology

The broad range of properties exhibited by ferroelectric materials are eminently exploitable in microsystems (MEMS) devices and in certain aspects of nanotechnology. The piezoelectric effect can be used in microsensors, such as accelerometers and resonant gyroscopes, and actuators such as micro-motors and bimorphs, as well as high frequency devices, such as acoustic resonators and ultrasound transducers. The pyroelectric effect can be used in thermal IR sensors. The strong electro-optic effects can be used in photonic devices and the polarization hysteresis can be used in non-volatile memory devices. There are also novel processes which exploit the polarization of ferroelectric films, which can allow the ordering of polar species such as virus particles and nanoscale metallic particles.

Applications & Benefits

The area of exploitation of these materials in this field is relatively young. However, some new devices with commercial potential have been demonstrated, including accelerometers (Fig. 1) and IR sensor arrays.

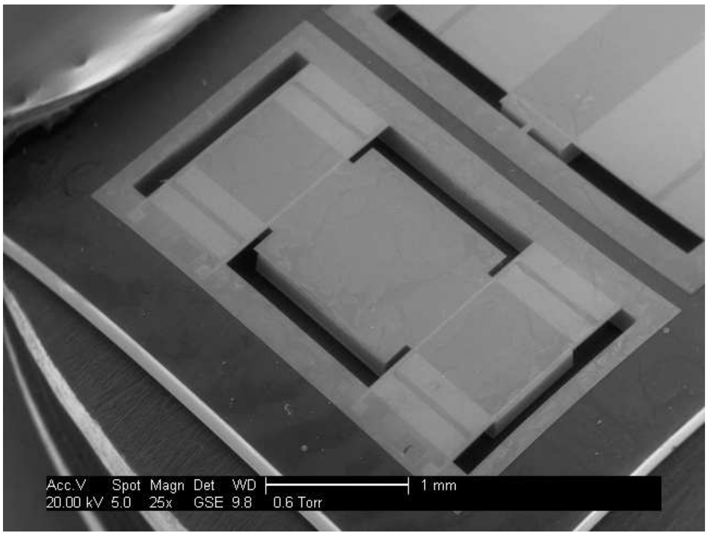


Figure 1: Part of a 3-axis piezoelectric accelerometer developed at Cranfield University

Resonant devices such as FBAR filters for mobile phones based on thin film AlN technology are now available. The potential for this technology is very great over the next 20 years, especially as most of the technological basis has a great deal in common, being based on techniques for depositing ferroelectric thin films. An example of a novel structure based on the technology is ferroelectric nanotubes. Unlike carbon nanotubes (which are usually metallic), ferroelectric nanotubes are highly insulating. However, they are all piezoelectric. Thus, when you apply a voltage to them, they expand or contract, which can be used to deliver very small amounts of liquid (ink, medicine) --picolitres -- in a very fast highly controllable manner. These nanotubes can also provide self-trenched three-dimensional capacitors for DRAMs (dynamic random access memories). They are prepared by coating the insides of pores in silicon. The porous Si is used as a sacrificial template and then 90% etched away, leaving the free-standing array of piezoelectric nano-tubes (Fig.2).

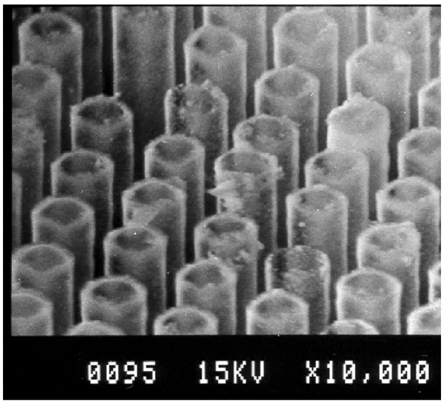


Figure 2: Ferroelectric nanotubes fabricated at Cambridge University

Technology Drivers, Barriers and Gaps

The exploitation of ferroelectric materials in Microsystems and nanotechnology depends fundamentally on the development of technologies for the growth of ferroelectric thin and thick films on silicon and other substrates, at temperatures which are compatible with the underlying substrates. It also depends on the development of technologies, such as patterning and dry etching, and electrode materials for the fabrication of these materials into useful devices. Many of these techniques are now in a state of advanced development, which has allowed the fabrication of successful demonstrator devices. A range of techniques have been used for the film deposition, the most successful being based on chemical solution deposition (CSD) and sputtering. MOCVD has also been successfully used, especially for memory devices. The major issues that remain to be addressed are mainly to do with device fabrication processes and chemical compatibility. Exploitation of the materials at the nanoscale is relatively new and will require further research.

UK Competitive Position

Academia

The UK has a fairly strong academic position in this area. Key academic players in the UK, all of whom have internationally acknowledged reputations, include Cranfield University (under Prof. Whatmore), who have made major advances in the exploitation of thin and thick film materials in practical devices, Leeds University (under Dr.Milne) who have done very good work original on the fabrication of ferroelectric thin films by CSD, Cam bridge University (under Prof. Scott) who are doing very good basic work in ferroelectric thin films for memory applications and on ferroelectric nanotubes, Queens University Belfast (under Dr. Gregg) who have done excellent basic work on the physics of ferroelectric thin films deposited by pulsed laser deposition. There is a good level of collaboration between the groups, fostered through the EPSRC Ferroelectrics Network. Internationally, there is a strong level of activity in this technological area. Leading groups include EPFL (Switzerland), Tokyo Institute of Technology, Penn State University (USA).

Industry

This technology is ripe for exploitation. Potential exploiting companies include Xaar (ink-jet printing), IRISYS (thermal IR sensing), PTB (accelerometers).

Competitor Analysis (country/organization/spend)

If possible, provide a quantitative view of our main competitors abroad in terms of what they are doing. How much are they spending on this technology? Any informed or expert opinions on this area will be particularly valuable.

Forward Look

5 years

First commercial devices and systems available using ferroelectric thin and thick films.

10 years

Value of UK exploitable technology exceeds £50M pa.

20 years

Widespread use of ferroelectric thin films in nanotechnology.

Recommendations

- Support high quality university research into ferroelectric thin and thick film technology.
- Ensure UK research is coordinated and well networked.
- Encourage knowledge transfer from universities into exploiting industries.

Appendix 6

Magnetic Storage

Technology

Magnetic materials are used extensively in data storage, both in information technology and in consumer applications. While analog audio and video tapes are now a declining market and the floppy disc is rapidly becoming too limited in capacity to offer a useful role, hard disc storage is going from strength to strength. In the hard disc drive, the media, read-write head, motor and actuators all rely on magnetic materials for their function. It is now possible to store more than 5GB on a single 1 inch disc as a result of developments in high-coercivity media and Giant Magneto-Resistive (GMR) heads, enabling such products as the portable MP3 player. The Information Storage Guide 1 published by DTI is a valuable UK reference that should be used in conjunction with this contribution while the IMST White Book 2005 2 sets an excellent European context.

1.1.1 Applications & Benefits

Industry observers foresee large increases in the demand for hard-disk drives of all kinds in the immediate years ahead. These increases will be driven primarily by the many new applications that these very-low-cost very-high-capacity units will create. Consumer-related drive revenues at the manufacturers' level will reach about $3 billion in 2005, on shipments of around 40 million units. By 2010, consumer-type drive shipments alone will certainly be larger than 200 million units, and could approach 300 million, generating revenues of $14-$15 billion (MMIS) The total market will be on the order of $100 bn.

Materials at the heart of this business include:

1. Disc media – high coercivity sputtered films of cobalt alloys with soft magnetic underlayers.
2. Read-write heads – transducers with critical dimensions below 100nm. Complex multi-layer stacks to form GMR devices, soft magnetic shields based on nickel-iron alloys, laminated cobalt-iron films for poles and an increasing reliance on high-integrity dielectrics including tunneling barriers.
3. Motors and actuators – high energy-product permanent magnets, ferrofluid seals and bearings.

1.1.2 Technology Drivers, Barriers and Gaps

Many of the materials share technology – for example Physical Vapour Deposition (PVD) – sputtering of films is widespread in both heads and media. Electroplating and electroless plating are also extensively used. Key alloy systems are cobalt-ironnickel. Process modeling and control for vacuum systems and in novel electrochemistry are essential underpinnings. Potentially more Chemical Vapour Deposition and Reactive Etching systems will also be explored .

Management of the structure and interfaces, to control magnetic properties such as coercivity, permeability and magnetostriction underpins the ability to manufacture the heads and media to support high areal densities (greater than 200 Gb per sq.in. is the current state of the art). As the manipulation of electron spins becomes an even more significant part of the function of transducers, the incorporation of high spin-polarization materials and control of their electronic interface properties is a probable area for fruitful work. The formation and control of extremely thin dielectric barriers in association with ferromagnetic films is an essential to exploit Tunneling Magneto Resistance (TMR).

As working environments expected for drives become more extreme, maintenance of properties to higher temperatures and with resistance to corrosion also become more significant.

One persistent problem is the limit on writing fields available created by the physical barrier of material saturation magnetization (maximum around 2.4T for any known material – obtained in a CoFe alloy). A material with saturation magnetization consistently above this value persisting to temperatures of above 50 C would be a radical addition to the capability – there are indications that nanocluster materials may offer some promise in this area.

1.2 UK Competitive Position 1.2.1 Academia

There are in the UK several centres in which research activities relevant to hard disc drive technology have been established and continued over many years. Examples of these would be in Manchester and Plymouth. More specifically on materials research a wide range of institutions have groups that address these areas. Although a couple of years old now the DTI document 1 has a comprehensive searchable listing. Illustrative examples would be Glasgow and Oxford with particular strength in high resolution microscopy, Leeds with a broad range of expertise in deposition and York with an emphasis on magnetic measurements. All of these groups, together with groups in several other institutions with a broader materials remit are among the international leaders. There is, however, no single location that combines the activities in the depth of the major US centres e.g. Carnegie Mellon, University of Minnesota or Japanese universities e.g. Tohoku.

1.2.2 UK routes to exploitation

In the UK there was a significant disc drive industry through the 1980's, but in line with the worldwide pattern of supplier consolidation that continues to this day, this has largely disappeared. There remain specialist companies, some of them sizeable in related industries (test equipment and Xyratex is a leading example) and in parallel activities e.g. Plasmon in optical storage.

As far as volume manufacturing is concerned Seagate is the only representative and has its main worldwide production facilities for read-write heads and disc media substrates in Northern Ireland. Technology R&D for read-write heads is a distributed activity within Seagate, the NI R&D team having significant responsibility for product and process design incorporating advanced magnetic materiuals.

There is a substantial entry barrier to the industry because of start-up and overhead costs in clean-room operations for example.

1.2.3 Industry

See above for key players

1.2.4 Competitor Analysis (country/organization/spend)

For both materials and device technology in this area, leadership resides in the US and Japan with strength in academic groups, research institutes and commercial companies. The latter include end-users such as Fujitsu, HGST (Hitachi-IBM), Seagate and Toshiba as well as suppliers of critical equipment, for example the vacuum tools for thin layer deposition and etching, such as Anelva or Veeco. The level of spending on this particular area of materials technology is difficult to discern within the published R&D figures of complex vertically-integrated organisations but one salutary example is that the types of sputtering systems in common use cost over $5M per unit. This makes collaborative work with universities in this area difficult.

1.3 *Forward Look*

1.3.1 5 years

Hard disc drives will be a ubiquitous commodity item in consumer applications, including in demanding environments such as automobiles. Advances in storage materials will provide capacities of terabytes in a desktop drive.

1.3.2 10 years

Magnetic disc drive technology will still be the mainstay of data storage. Patterned media and novel applications of nanomanufacturing for heads and drives will provide the ultimate exploitation of rotating media. Magnetic storage will move towards solid-state solutions.

1.3.3 20 years

Materials and technologies developed for rotating media storage will dominate in other sectors e.g. a solid-state magnetic memory, sensors and actuators as well as in their traditional applications, which will remain a volume market.

1.4 *Recommendations*

What should UK government be doing about this particular technological area?

Continue to support activities in basic magnetic materials, deposition and patterning technologies and their interaction with broader aspects of nanotechnology.

Encourage even more materials and systems modeling activities to maximize potential of existing and new materials and structures.

References

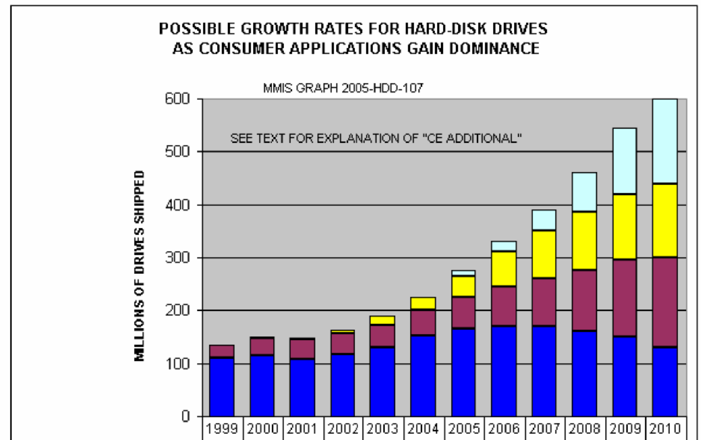
1. www.linkisd.org.uk /storageguide
2. www.projects.ex.ac.uk/dsnet/**white_book**.htm
3. Several items of text and charts denoted MMIS are included with kind permission of Magnetic Media Information Services (MMIS) www.mmislueck.com/

Illustrations:

Hard drive consumer applications

Market Growth projection for hard disc drives (MMIS July 2005)

“Rather than change the 2004 estimates for non-consumer applications, the graph shows these as "basic estimates", and adds a set of additional estimates that reflect the more optimistic opinions voiced by industry experts for consumer-type drive demand growth from 2005 to 2010. As in all such projections, the figures are little more than guesswork, but those in the know do not consider them impossible of attainment.”



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
CE ADDITIONAL							10	20	40	75	125	160
CE BASE ESTIMATE	1	1	2	8	17	25	40	65	90	110	125	140
LAPTOP DRIVES	24	34	36	39	42	48	60	75	90	115	145	170
DESK-TOP DRIVES	110	114	109	117	130	152	165	170	170	160	150	130

Appendix 7

Silicon Technology

1. Introduction

1.1 Technology, background and definitions

mm: millimeters, or 0.00 1 of a meter
µm: micrometers, or microns, equal to one millionth of a meter nm: nanometers, one thousand-millionth of a meter
billion: one thousand million (U.S. definition now predominant)

Silicon technology is an essential industrial and commercial driver in today's economy. The term "silicon technology" describes the manufacturing processes by which circuits are turned from a concept into functional silicon chips; but is often taken to mean the whole of the design and process cycles. Silicon chip design turns the concept of an idea into a practical specification, and then to a functional electronic circuit using transistors at the basic level; logic gates at an intermediate level and with the emergence of system-on-chip (SOC), circuit blocks already built and tested some of which may be known as intellectual property (I.P.: in which companies have developed a particular circuit function such as a microprocessor (µP) or digital signal processor (DSP) and sell or license their use) in more complex levels. Increasingly, computer software can be used to compile circuits – that is, to determine the logic blocks needed; lay them out into mask patterns and connect the blocks together from a specification automatically. As a result, design processes continue to become more automated, and designers are able to concentrate on the specification and operation rather than the details of the individual transistors and wiring. This has facilitated the design of mobile phones and digital television systems, for example.

Despite the increased drive towards higher automation, at the leading edge, transistor characteristics are still critical for the design process. High frequency (the term radio frequency, or RF, sometimes means the highest frequencies which people are currently designing with; or, more generally, all frequencies "above audio") design is a complex procedure and requires skilled engineers to obtain the best results. Also, analogue circuits which deal with real world signals need to be developed with increasingly skilled engineers as issues of matching, gain linearity and accuracy in operational amplifiers are optimised.

The “silicon technology” label as meaning design, therefore, covers many possibilities for engineering jobs: these need skills in computing usage (software and digital logic); or for specific radio communication design, knowledge and skills in analogue, RF and the transistor level. Silicon technology offers wide ranging opportunities.

The manufacturing process turns the designs into silicon chips. Wafers of silicon, disks of typically 200 or 300 mm in diameter, and just under 1 mm thick, are put through a number of processing stages. These grow the layers transistors need, such as the insulating oxides, gate electrodes and sources and drains, and then the metal layers which connect transistors together. Photographic processes are used to convert the mask layer data, which has been previously defined as a chrome pattern on a glass plate from the design data, into the transistor structures. One of the key parameters the technology uses to refer to the state-of-the-art is the dimension of the transistor gate electrode. Most integrated circuits are now built using complementary metal-oxide¬semiconductor (CMOS) technology where p-channel and n-channel transistors form logic functions which are efficient in terms of power consumption because power is used only when the transistors switch through a transition, either “on” to “off” or vice versa. The control electrode or gate defines how far apart the main terminals are, and hence how far electrons or holes have to move in order to respond to a signal. The transistor responds more quickly if the gates, or channels which the gate defines, is shorter, and therefore the gate dimension is a measure of the performance of the technology.

It is in this area where the world has seen tremendous progress with the transistor dimensions reducing approximately 40% every 18 months for the last 30 years in accordance with Moore’s “law” (1). The progress can be illustrated by comparing 1975 technology with today’s standards. A microprocessor chip such as might have been used in early 8-bit home computers would have measured about 5x5 mm. That would have contained about 5000 transistors with gates around 3.5 microns long. Today, the same chip could be made in a technology at least 10 times smaller (0.35 µm) and require only 0.5x0.5 mm of silicon; but the leading edge technology at 90 nm would mean a chip only 0.13 x 0.13 mm: this is as small as a full stop.

Fig. 1: 5,000 transistors in a 1975 processor chip would now fit into a full stop.

The drive to miniaturise the silicon chip continues to shape the industry globally. In practice, some chips become smaller while others stay larger, and increase in complexity, supporting maybe 10 million transistors. The UK is regarded as lagging against leading edge players; but this has serious implications for the future of the UK's technological capability, strategic capability and potential economy. Last year the silicon industry was valued at $213 billion (2). Its importance cannot be overstated. Projecting this current figure over the next 15 years at just 10 % growth (CAGR) implies a potential $1 trillion by 2020.

1.2. Applications & Benefits

1.2.1. Ubiquitous chips

Silicon chips are used in not just many but virtually all electronic applications. The term ubiquitous would not do silicon justice. Most people will have probably heard of the chip through owning one or more products which exploit them. The most common are mobile phones, personal computers and digital cameras. They bring the power of the chip into everyday experience through terms like "SIM cards" which are used in mobile phones to store numbers and provide a unique number; or "Flash cards" which store photographs taken with digital cameras. Fig. 3 shows an optical imaging chip made in the UK for a European company (now taken over by a US company).

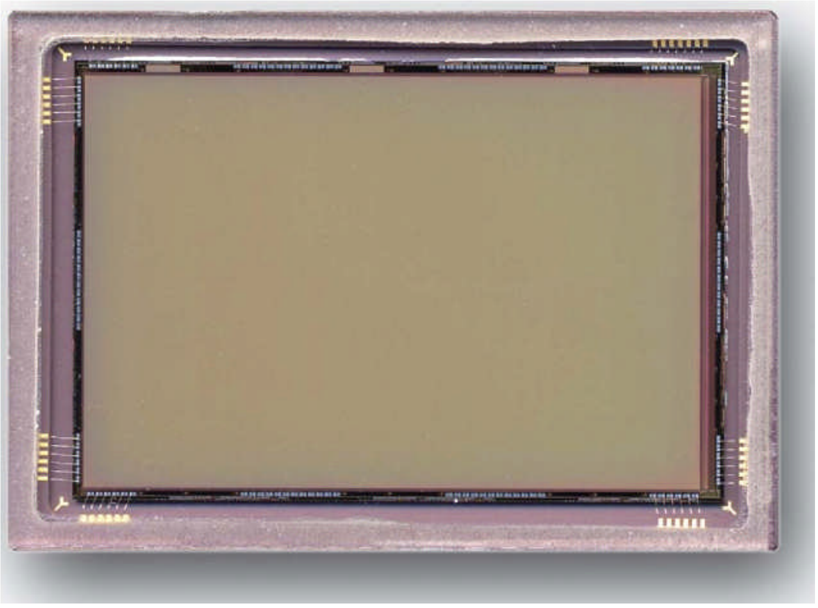


Fig. 3: CMOS Imaging (camera) chip, made in the UK for a US company†
This particular chip has 1028 x 1288 pixels and is covered with colour filter layers
†by courtesy of Cypress Semiconductor (formerly FillFactory)

Another widespread application is the use of a silicon chip in smart cards which are now being widely used in banking cards, referred to in the banking industry as “chip and pin”. In addition to the examples already mentioned, silicon chips enable digital television broadcasts to be received economically through the “set-top box”, discussed in the industry 10 years ago but now becoming widely available. Chips are used to control engines in automobiles in “engine management systems”; they are enabling digital audio broadcasts to be made viable; and to provide security for home, both domestic and for the UK in industrial, travel and retail applications through scanners; various detectors, imagers and sensors.

A trend which is less widely reported but still undergoing significant growth is in the medical field. Increasingly small transistors mean that computer chips can be fitted to or within the body. Pacemakers continue to be needed by some: these run on very low power, but monitor and kick-start the heart when needed. Imaging “pills” can be swallowed and transmit images of the digestive tract to a radio receiver worn on a belt: this conveys the condition of the gut to doctors without intrusive or uncomfortable equipment being used. There is considerable scope for steady progress to provide chips to monitor, analyse and respond to conditions which will assist the quality of life for many. Digital hearing aids, though not life-critical, have revolutionised the industry through the use of custom-trimmed, digital circuits which fit, with a battery, in a device which is inserted into the ear so as to be unobtrusive.

Increasing use of the chip is seen in the aircraft industry. Modern aircraft rely on “fly by wire” control: automatic landing systems can land a plane using radar, satellite navigation and computer controlled flight surfaces with little or no pilot intervention. It is possible of course to pilot a plane now without human pilots on board: something being explored by the military for weapon systems.

The silicon market continues to diversify. During the 1980’s perhaps most of the market was split between memory, processor and general logic. But now memory accounts for about 22% (2); and of the others digital signal processing; analogue and optical imaging systems have grown. Overall, the processor market may have lost a little ground but the overall expansion of the market means that the diversified applications are extending rather than replacing the market for processors and memory.

1.2.2. Silicon photovoltaic cells

It is worth a special mention the ability of silicon to generate electricity. In the optical imaging chip, photodiodes are used to convert images to electrical signals which are then processed digitally. In solar cells, similar photodiodes are used to convert sunlight to electricity directly. In the debate over the future of power generation, silicon offers an attractive alternative to nuclear power, and complements wind power.

Silicon cells are theoretically 28 % efficient. Long wavelength light is transmitted directly through the silicon without interacting; medium and short wavelength light is stopped and converted; ultraviolet light in silicon stops so quickly that conversion is inefficient or ineffective.

Silicon solar cells can be made with pure silicon, which is the type used to make chips; or polysilicon, which is multi-grained; and more like a “cast iron” version of silicon compared with steel. Some transistors are made with polysilicon in LCD displays because these are cheaper and cover larger areas needed for display screens than single-crystal wafers. Polysilicon solar cells are less efficient. Commercially, one US company (3) offers 20 % conversion efficiency in single crystal cells which represents the current state-of-the-art; polysilicon cells are typically half this and although cheaper, a solar panel installation would have to be twice the area of a single crystal system of the same power rating.

The potential of silicon solar photovoltaics has been largely ignored until recently. One cause might have been that in the U.K, the relatively common cloud cover limits their effectiveness, but in today’s environmental consciousness, the true cost of burning fossil fuels or nuclear energy is being realised. Nuclear waste lasts for so long that it is untested, in reality, and over long periods it is not clear that we would be able to ensure the safety of the planet – or at least in some areas where waste is stored. Further, recent cost estimates of existing nuclear waste clean-up at £58 billion shows that the true costs of nuclear power are much higher than the build cost of nuclear power stations. In the debate of future energy needs, silicon is

- clean (no radioactivity)
- unobtrusive (most panels are fitted onto roofs)
- silent (no wind noise, nothing)
- non-hazardous (silicon is non-toxic)
- recyclable (can be reformed if necessary)
- long life (P.V. panels are sold with 20 or 30 year lifetimes)
- distributed (by nature, roof panels generate electricity close to point of use)

The costs are often cited as too expensive. Single-crystal cells are usually made in wafer form, trimmed to enable more efficient packing than a circular wafer would allow; but cost estimates are about £5 to £10/watt currently. Prices around $3/W are quoted on some US web sites. Realistically, less than £5/watt should be possible with volume production in the near term for single crystal cells; polysilicon cells will be cheaper. Estimated costs of nuclear are £1 .5/watt; but this, it appears, assumes that several nuclear power stations of one type are to be built – it has been reported that 8 similar power stations are assumed to be constructed to give economies of scale. And it is virtually certain that this includes no provision for waste storage and management. Policing and storing nuclear waste for generations will be a very expensive exercise. Accidents could be absolutely catastrophic. The costs of such provision would make the true costs of nuclear more expensive than silicon is today. Processes exist today which can be used to make solar cells. It is not essential for new research into new cells and techniques: while welcome and important for the future; this is a diversionary tactic to avoid large scale silicon installation programs with today's technology.

The company manufacturing 20% efficient cells predicted recently that costs will fall to below the price of nuclear (to $1.5/W) over the next 10 years. Silicon PV can not only reduce carbon emissions right now, without further research, but may even be cheaper than nuclear ***within the time frame that any new nuclear power station might be built.***

Utilisation of solar energy is a concern. It is estimated from the DTI's own field reports (4) that perhaps a utilisation factor of around 12 % is possible across the UK. This means that of the capacity of a solar panel, such as 10 kW, only 1 kW is generated on average over a year. To some extent this is because of using a fixed installation, which is cheap. Nevertheless, a 10 kW panel generating electricity at 10% utilization represents an energy level of 9 MW.h over a year; and this is greater than typical household usage. It is possible of course to install solar panels in larger areas than roofs: in unused land, or on the tops of large buildings, and here the possibility of tracking panels can be used. These track the sun across the sky, and may improve the utilisation factor up to double the fixed-panel value, but tracking panels will be slightly noiser, more expensive and more obtrusive, which would probably prevent their use in domestic applications.

Undoubtedly, research will continue, seeking greater efficiencies in silicon and exploring different materials. Multiple layered cells, wide band-gap materials and novel designs can improve efficiencies to 40% or more. Costs of any alternatives to silicon need to be demonstrably lower: this is actually where the challenge lies.

To equip the majority if not all houses with solar panels represents a major challenge that cannot realistically be addressed by individuals without government support, leadership and investment. Such a challenge would be stimulating; could bring together disparate manufacturers; could combine the UK into a national strength in renewables, lead to sought-for cost reductions, and reinvigorate UK manufacturing. This could establish a strong credibility in the UK for directed investment; and if successful could lead to substantial growth and business in exporting to virtually all countries in the drive to eliminate greenhouse gases while avoiding nuclear power and the issues associated with that. The solar market needs serious attention to kick-start; but the market could reach $10 billion within 5 years and $100 billion alone over the next 20 years. In fact, the same company (3) report that more silicon has already been used in solar panels than in the whole of the chip industry.

Market value is calculated on the following basis:
2kW panel at £1 .5/W (estimated) =£3000 per installation
10,000 houses =£30 million
1,000 towns =£30
billion Export volumes to at least three
countries = £90 billion

These costs are comparable with nuclear, but cheaper if waste management and policing costs are included. However, it will require leadership if other governments are to be persuaded to follow this route to clean energy to achieve potential export volumes.

The logistics of solar PV favour a measured approach, suiting a soft start but needs management for the longer term. The periodic nature of the electricity generation, peaking in the middle of the day, would not be an issue while overall levels of solar PV electricity remain modest. While householders tend not to use electricity during the day, industrial users probably would. As installed capacity increases, the problem of electricity generation in the daytime and in summer can be addressed in the medium term by combining excess electricity with existing hydroelectric schemes: and in the longer term by new or extended hydroelectric schemes or even by hydrolysis of water to make hydrogen. Hydrogen can be stored for winter and off-peak use, by burning it in existing power stations (which may need minor modifications). This could kick-start the switchover from oil and coal to hydrogen. Such a move is going to be required as oil prices rise, oil becomes scarce, and the true costs of nuclear become apparent.

A demonstration of solar PV is recommended and one or two towns might be selected for piloting solar PV at potentially less than £100 million each. While it is tempting to use the lowest cost cells, for the UK we need to consider the more efficient single crystal cells. At the very least, a 2 kW panel should be fitted to at least 10,000 houses per town (many moderate towns would qualify). The costs of the large volumes of cells this represents should be used for obtaining a good value and customers who wish to contribute might be encouraged to augment government spending if offered some percentage of electricity sales from their own panels in return. For optimum self-sufficient power, it may be that a 5 or 10 kW panels are needed; and in due course if prices reduce these can become standard installation capacities. With a directed effort between all the UK manufacturers, this is something that could be nationally innovative, leading to new recognition, and which does not require state of the art printing. The future market for solar PV could exceed $100 billion alone if companies are encouraged to innovate and export their knowledge: but there is a potentially large opportunity to be gained against moderate investment requirements.

2. Technology Drivers, Barriers and Gaps

2.1: Electronics and politics

The technology drivers for silicon will continue in the foreseeable future in computing, communication and consumer applications. For example, rather than stagnating, printer technology diversifies with the appearance of small, high quality colour printers to print digital pictures, complementing digital cameras. Each requires a relatively modest processor to convert the image data to colour prints. Automobiles are predicted to continue to rely on electronics. The electronic component content of a car is predicted to rise to be 30% by 2007, of which some 60% of the electronics is silicon and has chips valued at $25 billion (5). Uses include engine management as already mentioned; increasingly, the use of LEDs for indicator lights and headlights will require electronic control systems; safety features will increase (ABS and airbags being current examples: future uses include collision-avoidance radar and possibly head-up displays for night time and fog vision systems) and these in turn require developments in all types of silicon device. This would raise the electronics content even further. Some opportunities are suitable for the UK as they have not been exploited currently: but with increasing industrial demand; suppliers outside the UK will rush to fill any gaps with increasing competition in volume and price. This is the familiar dilemma for the UK in finding niche markets; but also where leading technology concepts are developed, there needs to be vastly improved mechanisms to rapidly turn functional demonstrators into products which volume markets may need. It should be noted that IBM have recently launched a 130 nm, SiGe technology which they believe will address 77 GHz collision-avoidance radar applications. **Such opportunities will be lost on the UK without leading edge capabilities.**

In the power supply market, companies are exploiting new areas and striving for greater efficiencies. Modern switch mode power supplies can reach efficiencies of 95%; and as environmental pressure requires less waste, this trend will probably continue and we might expect to see 99% by 2010. To achieve such high efficiencies, devices such as magnetic transformer materials (ferrites) are needed with higher operating frequencies; transistors with higher switching speeds and lower on-state resistances are needed. This has generated new devices in both MOSFET and bipolar transistors which are often designed specifically for particular power supply or switching converter applications, causing more of the older, standard and general–purpose devices to continue to decline.

Mobile phones are nearing a first level of market saturation in the UK, but consumers are being enticed with video phones which will combine phones and digital cameras with increasing levels of resolution to keep development and market turnover progressing. However, the UK is not a major player in phone chip manufacture although Nokia and Siemens are two companies which actively design in the UK.

Silicon presents the UK with a set of challenges against the world scene where technological developments are increasingly being pursued with vigour. There are no indigenous companies in the UK which are currently able to produce 90 nm technology, although some foreign-owned companies operating in the UK may have access to the technology or declared an intention. 90 nm is, however, the current state of the art; and many fabs around the world are developing 65 nm technology including the relatively new Chinese foundry SMIC. This probably represents the biggest dilemma for UK policy and once again, **it has to be emphasised that if the UK wants to retain a credible technology base, silicon has to be given greater priority than it currently enjoys.** There is a substantial political influence globally in that governments in many countries, such as Korea, China and Israel, support their manufacturing organizations. Silicon is technology which now commands political support, not just markets alone. The House of Commons criticised the government’s response to the House of Lord’s report “Chips for Everything” (6) as “too little, too late” (7). Over the last 5 years, companies in China have powered forward: they were behind but are overtaking rapidly. India has declared an intention to actively consider semiconductor manufacturing. Up to now, India has excelled in and promoted software and design skills: it is now catching up with the technology and is considering whether it too can make money building chips. It is never too late. But it is increasingly important to support silicon technology as more of the industries around the world rely on silicon. With a predicted market of $1 trillion by 2020 it is hard to imagine how even the UK could lose: except that doing nothing will ensure that this is so.

2.2: The Technology Issues

The key problems which need to be addressed to continue silicon technology development world-wide have been well covered in the International Technology Roadmap for Semiconductors (ITRS) (8). It is worth noting that in the 2002 report, and its 2001 predecessor, from where some of the information was obtained for the Lords' report (op.cit.) indicated that "the end of CMOS" was foreseen to be taking place around 2015. Transistors would have been shrunk to 20 nm, and at this level several physical problems would have arisen which means that transistors perform increasingly less well than they might have given an ideal development path. However, in December 2002, IBM published details of a 6 nm transistor and in 2003, they published details of an 8 nm device with better electrical characteristics (9,10). In the latest Roadmap, 2004, the "end of CMOS" has now been deferred for at least another three years to 2018. Realistically, there is, in 2005, little prospect of any material replacing silicon within the timeframe to at least 2020. No other technology can provide the computing power, memory density, processing speed at the cost of silicon; and while there are emerging technologies and competing technologies, silicon remains the lowest cost option in many cases. The UK needs to face this challenge and accept that if it is to retain any hope of silicon as a strategic "computing" driver, for most industries which are increasingly taking up digital technology, we need to provide adequate support.

The ITRS Roadmap for 2004 has added some "technology nodes" to the map which supports the view that at geometries shrink, the rate of shrinking may slow a little. Over the next 15 years there are technologies predicted at 90 nm (about now); plus 80 and 70 nm leading to 65 nm in 2007; then through 60, 50 and 45 nm in 2010. We then see effectively a shrink to 40, 35 and 32 nm in 2013; and progress as shown in an annually-based table shown below to 2018.

Year	2005	2007	2010	2013	2016	201
Technology (nm)	90	65	45	32	22	18
Processor Gate Length	32	25	18	13	9	7

Table 1: Feature size, adapted from ITRS 2004 (4)

The UK has a dilemma in how to research the issues identified in silicon; yet achieve return on investment novel ideas might command. This is more than technology: it is part of the concerns expressed by the EIGT and requires a collective new approach to funding and supporting businesses.

Problems faced by the silicon chip are concerned with the transistor, as well as so-called back-end issues of metallisation. A typical cross-section of a CMOS technology is shown in fig. 4. It is defined by the major parts comprising a gate; an insulating dielectric; a source and drain for the transistors, a further insulating layer (often a junction or "well") to enable N and P channel transistors to be built in the same silicon chip. Contacts are made to the electrodes indicated by grey regions, to which metal layers connect the transistor to other devices.

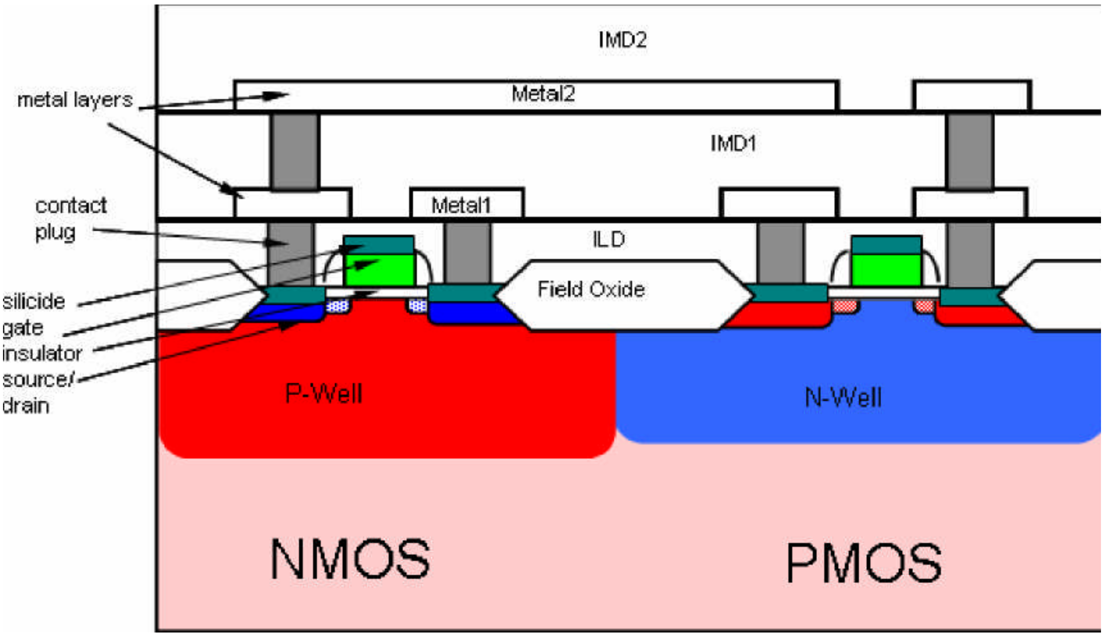


Fig. 4: Section through CMOS transistors: the NMOS and PMOS devices are essentially the same but doping regions are opposite

Technological problems concerning the transistor leave almost no part of its design untouched. Future devices will require:

- new gate materials – typically, polysilicon is used. At small geometries, the electric field across the gate insulator is very high, and polysilicon does not behave ideally: being a semiconductor, it depletes, even very slightly when doped heavily, which reduces the gain. Instead, metal gates are predicted to be needed to avoid depletion effects. The metal will probably not be aluminium (as it was, once many years ago) but more likely a refractory metal which can withstand higher processing temperatures. Even silicided poly tracks, used in most advanced processes, still leave an interfacial layer of polysilicon and are not suitable

- new contact materials – currently, the state of the art is to use tungsten as a contact plug. Once, aluminium metal was used in chips as a combined trackand-contact technology, but this had step coverage concerns below 0.6 microns which the tungsten plug has eliminated. However, the resistivity of even tungsten seems to be too high when contacts become about 25 nm diameter: and carbon nanotubes may provide a solution as they have higher conductivity in the conducting direction than metals.

- new metal interconnect layers and dielectrics – as tracks reduce in width, the resistance increases. As tracks become closer together, the inter-track capacitance increases. These combine to form a classical RC delay which is increasing. It was first shown at 0.25 microns where the metal interconnect speed matched the transistor speed, and becomes dominant below 0.25 microns unless new materials are used. This caused the changeover from aluminium to copper; and for lower permittivity dielectrics to be used compared with silicon dioxide. In future, even copper seems to have limitations at 20 nm, and once again, novel alternatives to the metal layers will be needed (power metal layers with wider tracks could still use copper or aluminium). Novel alternatives to inter-metal dielectrics will continue to be required.

- new transistor structures – the classical planar transistor, as illustrated above, will increasingly suffer from several effects. Many are just old, known effects re-emerging in these smaller devices such as punch-through. But now that the geometries are so small, the doping levels in the channel cannot any longer be regarded as “average”: instead, the position of individual atoms will be important and dominate the transistor behaviour. Punch-through problems will have to be addressed with some form of surround-gate concept: of which silicon fins are being explored as a leading candidate. High electric fields in the channel cause the channel mobility to reduce, degrading the performance of the transistor. To maintain a near-scaled performance, new channels are needed. Strained silicon has been determined to improve the mobilities of the carriers, and channels built using silicon-germanium have been used to generate the strain.

- Packaging – not related to the transistor directly, but equally important for new technologies, packaging covers chip sawing and bonding to provide the final product. Lead counts of over 1000 are anticipated in leading edge products, as computers become faster, not just in terms of transistor speed, but in terms of architecture (addressing capability; memory transfer speed; communication with other processors for example). New packaging methods will include cooling systems for chips dissipating 100W; flip-chip bonding such as solder ball; ball-grid arrays; maybe 2000 leads; and at the lower end, small packages with finely-spaced leads, but lead counts may be as few as 4 upwards.

It is common for each generation of technology to add one or two major innovative process steps: this would mean that by 20 nm, almost the whole process could change from today’s standards. The scope for R&D is broad: virtually all aspects of the transistor can be investigated. It is an exciting prospect with so much potential in the silicon nanoscale era.

Photolithographic advantages are not limited to leading-edge resolving power and wide field of view. There is still scope for developing tools which might allow processing to be made without masks. Leading edge technology mask costs are stratospheric, having been reasonable (typically £10,000) up to the 0.35 micron node. Mask costs in fact have contributed to the economy of scale issue which favours only large scale industries. Below 0.35 microns, there was a paradigm shift where photolithography moved from wavelength-limited to sub-wavelength. It had been assumed that printing features below the wavelength of the light used to illuminate the photoresist would not be possible. Classical physics shows that diffraction limits the definition of a feature to the wavelength of light used; and typical printing systems using 5:1 image reduction were able to define 0.35 micron features using 365 nm light from a mercury lamp. For the next generation, 180 nm features were printed with a 257 nm light using a krypton fluoride laser source, but to overcome the diffraction limit the masks were formed with quarter-wave features etched each side of the pattern being defined. This has the effect of suppressing second-order diffraction patterns by changing the phase of the light, allowing half the wavelength feature size to be printed accurately. As a result, the masks now need to be processed using etching, as well as being printed; but this has caused prices to increase by a factor of about 4 times for 180 nm rather than simply reflecting the increased number of transistors on a typical mask set. The cost of a typical mask set for 90 nm technologies is in the region of $1 million. Therefore, only large volume products justify the investment and only large scale production returns the revenue to cover the costs. Consequently there is a substantial drive for “right first time”, through better design tools, improved use of statistical design and proper tolerancing to ensure that circuits simulate as intended; and that simulation accurately represents the silicon.

A typical silicon process requires between 10 and 20 masking layers to produce the chips. Leading edge processes may have 10 layers of metal on top of the silicon; and each metal layer requires two masks: one for via holes to the layer below, and the

other for the metal layer itself. This may easily bring the total mask count up to 30 or more. However, the mask costs of 0.35 micron technology are still too high for smaller customers – some of whom may have potentially valuable ideas. In the past, electron beam technology (direct write) has been used to expose the silicon wafers in the printing process, but it has proven too costly to use electron beams for production quantities. One company in France, ES2, pioneered rapid prototyping on a commercial scale for several years but eventually gave this up and was sold. Electron beam tools are still used however, to make the masks; and for defining very small linewidths (typically 45 nm is a current possibility) in universities, but they remain, as ever, a purely research tool and are not realistically even pilot-production capable because of very slow throughput. This can be seen in context where a 90 nm chip containing perhaps 100 million features needs to be drawn – on each of perhaps 100 chips on a single layer on a wafer. If each transistor has only one contact to each electrode (and often they have several) this makes at least 300 million features to be defined. The data base and processing needed is excessive. Exposing the features in a single photographic flash (usually, one exposure per chip) is much faster. One novel approach discussed widely some years ago was to use multiple beams to improve throughput. This remains a goal and so far still seems to be out of favour compared to advanced optical systems.

New ideas to eliminate the glass mask are emerging. Modern high intensity, U.V. LEDs might possibly be used to form an image in much the same way as large scale LED television displays, but on a much finer grid to be able to program the required patterns for each layer. Such a concept is being pursued industrially, but is likely to appear in the next generation of printing tools. The UK could pursue similar concepts to form a replacement “mask” which could be retrofitted into existing tools. This would mean that mask costs would be eliminated, finally, and as this represents typically half the cost of a batch of wafers for prototyping, and could open the door to many smaller companies.

There are some approaches which reduce costs to small and medium size companies such as multi-project wafers, where several chip designs are processed on a wafer at once and the mask costs can be shared between the users. However, while this favours prototyping, any volume product will need its own mask set eventually because only a part of the wafer has any particular customer’s chips available to them.

Photolithography is perhaps the most critical process stage which needs new ideas and research; and where there could be substantial markets to be opened up with major breakthroughs in developing a mask-less capability.

Regarding the potential problems of the classical planar CMOS transistor, the UK is well placed to explore novel structures, and while there are many possibilities, there is no clear industrial preference emerging yet to take over. There are many contenders: these are all aimed at providing the gate on at least two sides of the channel, and "finFET" transistors can have gates on three sides. Other structures, such as gate all-around (G-A-A) provide for gates on four sides, or perhaps circularly in a tubular device. Note, however, that these apparently advanced concepts, they are, in all likelihood, going to continue to be built in CMOS style: that is, there will still be NMOS and PMOS complements for building circuits. Hence, silicon in the nanotechnology era offers possibilities and rather than "after CMOS" we should really think of "after planar CMOS" and not confuse this with "after silicon".

The UK is well placed for exploring novel oxides which might be used as replacements for silicon dioxide. But once again, the UK is hampered from exploiting any promising compounds without a leading edge capability. And without leading edge capability we may not be able to demonstrate industrial relevance. This is for the simple reason that any replacement which is commercially useful has to be able to answer the question whether it yields better than silicon dioxide; and whether it is more reliable. Yield is a measure of how many chips on a silicon wafer are functional. The state-of-the-art technology may provide millions of transistors on a chip; and a 12 inch (300mm) wafer may contain 1000 chips, of which 90% have to be functional. Deposited oxides are traditionally inferior to thermally grown oxides: the bonds tend to form in clusters of molecules with weak bonds between clusters; while thermally grown oxides tend to be stochiometrically pure: most bonds are well formed. To be competitive, dielectric deposition systems will have to operate in extremely clean environments where the surface of silicon must not be rough at the atomic scale; nor be contaminated (perhaps even by oxygen). This places demands on even experimental systems to be leading-edge in terms of cleanliness and wafer engineering which may not always be possible. Growth or deposition of dielectrics can always be demonstrated with some types of equipment but need to demonstrate real capability to be industrially useful; which means to show that there will be commercial returns on the investment.

Doping placement affects not only digital performance by changing the threshold voltage or punch-through characteristics of transistors between one and another, but particularly affects analogue circuits which rely on transistors being matched. One of the niche differentiators in the UK is to specialise in analogue. Analogue circuits, and in many respects, RF design is similar in that individual transistor performance is still considered in the design phase rather than relying on software descriptions of pre-defined digital functions, and transistors are required with accurate control of threshold voltage to give good performance in comparators, operational amplifiers, A - D converters and so on. As mentioned, the operation of transistors up to now is based a physical model description where average doping levels in the silicon are accounted for using these averages; and relies on electrons following largely averaged processes of drift and diffusion, two methods by which semiconductors can convey current. At the atomic, or nanoscale, level the method of producing transistors by making N and P type junctions becomes more difficult. As the transistors become smaller, the number of dopant atoms becomes small and no longer are average descriptions adequate. Ideally, each transistor will have dopants in exactly the same place relative to the terminals (gate, source and drain). But doping is still formed with ion implantation, and even new techniques proposed for doping using plasma immersion (actually not a completely new process; but relatively new in silicon processing) only permit doping levels to be known "on average". At the nanoscale, the exact location of individual atoms is never known but the position of the individual dopant atoms affects the transistors. One consequence is that the matching of the threshold voltages (the turn-on voltages of a transistor) between two transistors, as often used in RF and analogue circuits, becomes increasingly difficult.

Device modellers are addressing the effects of atomic statistical variation using "atomistic" simulation approaches where individual atoms are taken into account. The UK is able to participate in atomistic modeling, Glasgow is a world-class, well-respected centre for atomistic simulation, and for small device characterisation.

The use of silicon for non-electronic applications such as pressure sensors (although they rely on electronics to measure the signals and provide an electrical response) will increase. The market for chemical sensors will increase as security becomes a problem; and many applications use variants of the MOS transistor as part of the sensor. Changes in the chemical environment alter the charge on the gate of a transistor, or act directly on the gate which causes the transistor to respond. This in turn is usually connected to an amplifier and from there to a digital processor to provide calibration and responses. Thus, many chemical and increasingly biological sensors will use a form of silicon chip, probably in addition to underlying CMOS circuitry so that functional devices can be used alone (with a simple processor functionality) or as inputs to larger systems.

Biological uses include virus screening, DNA replication and drug dosimetry; in future it is conceivable that an in-body chip could administer controlled drug release possibly in response to a physiological or biochemical situation.

MEMS (micro electro-mechanical system) technology was only recently given press coverage as the “next manufacturing revolution” in silicon. Unfortunately, MEMS is not just a silicon manufacturing challenge: each MEMS device usually requires specific assembly and packaging techniques suitable for the application. This has prevented the widely envisaged universal MEMS manufacturing plants being established: products need clear marketing definition; from concept to packaged device. The best known application of automotive air bag sensors still remains the major MEMS market; but it is highly likely that more MEMS devices will emerge as products drive the requirement. Lower growth is therefore expected in the MEMS market than originally envisaged: but it is also possible that some particular developments will periodically emerge which command large markets.

The biggest gap the UK faces is not in ideas; nor in problems needing to be addressed, but the lack of a large industrial base to support the research and exploit the results.

3. Opportunities in the UK for silicon R&D

3.1. UK versus global research

From the previous paragraphs, it is clear that there is a lot of work still to be done to understand how to best model, simulate, design and build very small transistors in the nanoscale era, and that opportunities exist in silicon in the nano age, despite predictions of its demise. However, since the UK has no large company capable of providing clear paths to exploitation, research is driven by perceived needs of foreign-owned companies and world-status such as identified in the ITRS Roadmap. Some argue that the sheer global drive behind the Roadmap supported by most of the world players means that any UK R&D would be irrelevant or redundant. This would be a totally inappropriate response to perhaps the most important technology since the first
industrial revolution. Many issues in silicon are being and can be researched in the UK. Some of the contributions to the list of issues mentioned include:

- Atomic level placement – it will be preferable in the long term to define precisely where atoms are implanted; but in the meantime, to determine the effects of transistors made up from statistically varying placement of atoms and "atomistic" simulations will continue to be relevant to nanoscale design.

- New dielectrics are needed for the insulator to be able to use physically thick layers which are still responsive in terms of transistor gain. UK universities can still explore novel layers particularly with reference to surface cleaning and preparation, and the nature of initial and subsequent reactions for oxide growth or deposition.

- Photolithography – the main processing step defining the technology is increasingly expensive. Perhaps new, U.V. LED technology can be used to eliminate masks, at least at current 0.35 micron levels, and thus open up new markets for many smaller customers. There are always possibilities for new printing technologies and the UK may be innovative to define such tools. However, some routes may prove to be dead ends as IBM recently declared with X-ray printing. New tools therefore may carry high risk but could be high reward if successful. Extreme U.V. with phase-shift masks is currently favoured; but niche areas reducing costs for non-minimum geometries may be beneficial.

- Strained channels – a consequence of thinner dielectrics is to increase electric fields in the gate. Increased fields leads to reduced performance by reducing the mobility, and straining the silicon has been shown to partially restore the mobility. Commercially, strained transistors are being produced and will continue to form a useful area of research using primarily germanium to form silicon-germanium compound semiconductors which generate the strain.

- Metallisation – for nanoscale transistors interconnect will require high conductivity. As copper is now being reported as having too high a resistance for 20 nm technologies, the search for alternatives is on. Carbon nanotubes may provide a timely alternative. It has been demonstrated that carbon nanotube resistances are lower than metals under some conditions, and clearly there is a need to explore these options further at the basic research level.

- Contacts – there is a lot of interest currently in carbon nanotubes also used for metal contact replacement, as the resistivity along the tube is lower than metal such as tungsten which is commonly used to fill contact and via holes in silicon oxide insulating films in the metallization layers. This is a similar problem to the metallization issues above.

- Low capacitance dielectric layers – traditionally, I.C.'s use silicon dioxide for interlayer (poly to metal) and intermetal (metal n to metal n+1) isolation. The relative permittivity of oxide is 3.9, and this is rather high for small geometry interconnects. Structures using, in effect, bubbles or organic-like materials which have lower intrinsic permittivity, or encapsulate air, have been proposed

  and are referred to as lo-k dielectrics. There will always be a potential application for dielectrics having permittivities close to 1. Possible nanostructures might provide solutions where new materials combine physical strength, to support metallisation layers, with near air-like performance for high speed interconnect.

- Passives – with increasing use of CMOS for RF, passive components such as resistors, capacitors and inductors are being sought to be included on the chip. Inductors take a lot of silicon area - for example, a 2 nH coil requires an area of silicon approximately 160 microns in diameter, which could otherwise be used to contain thousands of transistors. Possibly, magnetic layers can be developed along with metallization to be silicon-compatible, and used to increase the inductance of nano-Henry valued inductors. High Q-factors are needed for high selectivity in some circuits; and silicon as a substrate is generally inferior to semi-insulating gallium arsenide, but silicon on insulator, bonded wafers and silicon–on–sapphire technologies offer competitive approaches. Capacitors with high Q-factors are possible using existing metallisation layers; but high permittivity dielectrics will permit higher performance or smaller areas and should be explored. Resistors are often formed from silicon but junction isolated devices suffer voltage effects, being similar in some respects to a JFET. Isolated resistors in polysilion suffer higher noise and worse matching, so there is a continual requirement for improved resistors while using primarily silicon-based technology – that is, customers will often put up with worse resistor performance if the costs are essentially "nil". But, some niche markets may support a specific resistor layer.

3.2. Signal propagation: the lightspeed solution

The problems facing standard metallization tracks and interconnects have been mentioned. However, in the longer term, such as 20 nm technology or smaller, it is possible that a disruptive approach will be needed. One of these is optical communication and rather than transmit electrical signals across a chip, the speeds will be so slow due to RC time delays that optical means could be preferred. However, this represents a major revolution in the approach to silicon chip design. To communicate optically, there will need to be on-board means of light generation; and on-board light reception. Light paths will need to be defined as a replacement for wires; but the beginnings of this are being seen in university departments where optical waveguides are being made. However, the ends of the optical interconnect paths need to be terminated on a transmitter device, or receiver. Silicon is notoriously bad at generating light: it has left the LED market largely to 3-5 compound devices with a direct band gap. It is conceivable that gallium arsenide devices could be built onto silicon through crystal growth and matching; but this is likely to be an expensive process. Silicon photodiodes on the other hand are well able to receive IR signals from such light sources.

One concept with today’s forward look is to consider that chips will need optical guides to replace wires; at least for “long distance” routing; such as from one side of the chip to the other. Computer buses, with 64 or 128 bit words will need 64 or 128 bit optical interconnects without cross-interference but could be transmitted across the whole chip at lightspeed; assuming that the optical guides are air-based with total internal reflection. As might be possible with fine glass tubes, such as might be etched into silicon dioxide, but this presents its own problems to be evaluated.

Such a concept would require first a silicon leading edge process to prepare a processor chip, for example, at 45 nm or below: then to grow (expensive) gallium arsenide on the silicon and LED devices defined; finally the optical interconnects defined (which may take several layers alone; but could replace some metal layers to offset the additional complexity). Efficiencies regarding optical light generation and detection could limit the chip performance in terms of power consumption: but research into new materials might prove successful in finding suitable emitter materials with lower cost or easier integration.

So it seems a possible, but difficult challenge to utilize optical communication across a chip, within the same chip, but a potential solution to the problem of higher resistance and capacitance limiting the speed in ordinary wiring.

3.3. Metrology

As geometries shrink, there is an increasing need to be able to measure devices at the smaller dimensions; to analyse doping levels in very small junctions, and generally assess the construction of devices to establish and troubleshoot new processes. The UK has traditionally been leading in metrology but is in danger of being left behind as key equipment manufacturers provide advanced tools for the challenge.

Optical microscopes are limited in their ability to image sub-micron features. However, the lens material used in photoprinting tools have been developed to withstand extreme U.V. in order to print the patterns. It may be possible to develop optical systems based on similar lenses and extreme U.V. light sources with imaging chips sensitive to the U.V. light used or at least using fluorescent screens to convert E.U.V. to visible light (after magnification). This could open up opportunities in the optical market with novel approaches. Attention to focussing will be equally important as the depth of focus becomes small: liquid immersion techniques may be needed (as are being used in phototools also).

Scanning electron microscopes – once leading, the UK competitive position is lagging behind Hitachi and JEOL, two Japanese companies leading the field in silicon in-line inspection microscopes. The need for large diameter wafer handling chucks, low energy sources, minimizing charging effects and so on continue to be required; but the market is small as it is largely limited to semiconductor manufacturing plants. However, this surely fits in with the UK view of niche markets: limited volume, but required high technology and capability that it seems to be potential opportunity to

recover lost ground. The market for such machines would be typically a few per manufacturer; the number of manufacturers is limited but nevertheless this is a technically demanding application.

Transmission electron microscopes – as devices become smaller, the need to image devices with high resolution becomes more important. TEM images usually require sample preparation using focussed ion beam (FIB) milling, and polishing, so that the electron beam can be transmitted through the silicon device, and the UK hosts an established U.S. company operating in this area. The transmission electron microscope market, however, is typically led once again by Hitachi and JEOL. One difficulty with modern TEM microscopes is that many are designed for high magnification, often for the specific purpose of lattice (atomic-scale) imaging, where it is possible to observe the locations of atomic lattice sites if not quite individual atoms. This has the effect of making the lowest magnification rather high as a consequence; and there may be a market for machines which can cover high and low magnifications maintaining a field of view with precision. Once again, this is a high technical specification demanding new solutions and ideas which the UK could be good at.

Doping profiling – as the need for small geometry devices increases, the need to measure atomic level doping distributions in shallow junctions and small transistors increases. Measurement techniques currently in use include SIMS where ablated material is analysed using magnetic lenses; but sensitivities need to increase both for shallow junctions and lighter doping junctions such as a may be needed in PIN (P-intrinsic-N type) diodes which are used in high speed optical communication links.

Electrical – as geometries shrink, the need to measure devices at lower voltages and higher frequencies increase. Currently a lot of the test equipment market is dominated by Agilent (HP) and Keithley Instruments; but formerly, companies like Marconi produced RF test gear which was world-class. As in most cases for silicon, the need for new test equipment is clearly needed (the frequency response is increasing and currently world records are around 400 GHz: to be fair, these records are usually held by heteroj unction technologies, of which SiGe is the silicon-based contender) but a lot of test equipment also requires dedicated supporting software to simplify measurements.

Silicon technology thus provides many opportunities for specialized test equipment in metrology both for physical and electrical evaluation of devices; in many respects this is as great as ever and increasing the need to find high technology solutions. The markets for microscopes is covered in commercial reviews such as MarketResearch.com's Microscope report (no further reference available: details are on the Web). The total market for JEOL alone was about £250 million alone (covering microscopes and other analytical measurement equipment) in 2002.

3.4. Memory

Memory has not been discussed up to now because many UK companies operating in silicon manufacturing offer limited standard silicon solutions, and few if any operate in the leading edge, high density area such as DRAM and NAND-flash. However, there will be a continual drive to increase the capacity of memories and the field is wide open for any new concepts to prove more capable than silicon. Few alternatives have, though, made any substantial impact on the silicon market.

Permanent storage is dominated by hard-drive technology. Dynamic storage is dominated by the DRAM, but contenders for new memory architectures are being considered such as MRAM, magnetic tunneling junction devices pioneered by IBM; and some commercial examples exist. There is a UK project to explore MRAM but developments may not be applied to leading edge technologies in the UK.

The Hitachi laboratory in Cambridge has pioneered single electron device research for many years. The problems facing these potential new devices are essentially those of defining small enough control structures: though “single electron”, electrodes of the transistor are certainly much larger and are built with more or less conventional silicon processing technology. In future, 3D integration might lead to solutions to the control electronics issue, and maximise the potential benefit of devices which ought to be only the size of an atom or so per storage bit.

Non-volatile memory used in camera Flash cards and so on is dominated by the Flash EEPROM, often as a NAND variant pioneered by Toshiba. This is one of the smallest packing cells available, and as an estimate, 90 nm technology can store 1 bit in an area of silicon of under 0.05 square microns. Cells are being evaluated for multi-level data storage: four levels permits 2 bit data storage per cell.

While the UK is not a heavy player in this area; there are possibilities emerging all the time. Self-assembling nanoscale molecular memories might be a potential high capacity technology in future, and no doubt there will be many contenders over the next decade or two. However, to be industrially relevant, solutions may have to be able to be demonstrated with silicon or silicon-support such as standard logic decoders, multiplexers and so on, that the challenge may not be so much in fundamental memory technology – though this is a wide field – but in how to integrate solutions into silicon.

3.5. Design

The UK is noted for operating in niche markets; and with noted skills in design. Many small and medium size companies throughout the UK provide designs, and chips based on their designs, but many use external foundries such as TSMC. Profits from UK design houses will be reduced a little as those external silicon vendors take their percentage, rather than reaping the benefits of a UK supplier.

While the UK enjoys a competitive position in design, there is a looming problem for the future. To design competitive products in the RF market, which represents a significant growth area, designers need access to the latest silicon technology. At the 1 80nm technology node, now 4 years old, it became possible for CMOS to provide chips which operated at 2.4 GHz, widely used in mobile phones. This has spurred the growth in markets for Bluetooth, and other RF communication systems. Bluetooth was developed as a solution for local area communication exploiting CMOS at 180 nm and operating at 2.4 GHz; Zigbee is another concept used at other frequencies for various communication systems. UK designers have demonstrated that they can offer competitive Bluetooth and Zigbee-standard chips. If such a lead is to be maintained, it will be important in future to be able to design circuits at leading edge technologies. This means designing with devices at 65 and 45 nm for example over the next 5-10 years.

65 and 45 nm technologies offer transition frequencies in the range of 200 GHz and this opens up new possibilities. If designers are going to be able to exploit these technologies to maximum profitability, they will need to be able to access the technologies earlier rather than later. Since most design processes now require the use of computer models, the first requirement for design will be for a model, known as "compact" to distinguish between using a set of analytical equations, which can be solved quickly, rather than the numeric models solving physics-based equations for the transistor which run slowly and require large memory storage capacities. Models, however, need to represent a realistic, manufacturing process. It will not be sufficient for a university department, for example, to build a device model for a 45 nm transistor, even if possible, (although this would be admirable to demonstrate the relevance to modern technologies) if the process uses processing stages which are slow and expensive. A possible scenario is that some processing stages will be state-of-the-art while others may be less so. In this case, only a partial solution will be possible, and this will not necessarily represent any particular manufacturing process. Designs need to be designed for the process on which they will be used in production.

The importance of models needs to be considered further: when designing for manufacturing, (DFM), an important concept for modern design, designs have to be checked not against standard "worst case/best case" models as they once were, but statistically against realistic manufacturing performance variations. Only a real production process can provide such statistically based models: and therein is the big problem for UK design houses who wish to maintain state-of-the-art design expertise. The problem is that **leading edge companies who develop the processes will have first access to the data to provide statistical models;** and this has secondary knock-on effects as will be explained shortly.

Over the last decade in particular, a significant change has occurred in the silicon chip industry. The trend is a move away from integrated device manufacturers, such as IBM and ST for example (and as GEC-Plessey once were); to the foundry-fabless model. UK design houses, relatively numerous and often small and dynamic, represent the growth in the "fabless" part while global foundries are used to source the silicon such as TSMC, UMC and others, of which X-FAB in the UK represents a smaller example. IBM, however, are apparently aiming to exploit the best of both worlds as they have opened their fabrication plants to the foundry business; yet still continue to develop their own chips for internal products.

Leading foundries like TSMC can now invest in small geometry processes, addressing the issued raised in the ITRS Roadmap. Having developed a process, they will be able to provide models which represent normal or mean processing values of transistor parameters; plus the statistically based variational models needed to ensure that designs yield well to the specification. Therefore there is a hidden danger of not only visible mainstream manufacturing migrating to the Far East, for example, but also the support for new technologies which is following increasingly closely.

Just a few years ago, maybe as recently as 1995, TSMC were trailing behind in the state of the art for RF CMOS applications. They now lead; and are generating models for new transistors which exploit the RF capabilities. The lead coincided with the abandonment by UK companies of pursuing the "microns" as the race was known, and along with some other smaller companies in Europe ceased mainstream CMOS development at 0.35 microns. Several of the companies who took such a decision are no longer the companies they were: Mietec, in Belgium, for example are now owned by AMIS; and GEC-Plessey in the UK are now owned by X-FAB.

The major lesson the UK needs to address is that firstly, silicon is a leading technology which is not only evolving in a growing market, but is predicted to continue to expand by dollar value for at least the next 15 years and probably longer (2). Mainstream manufacturing has eroded UK competitiveness: often put down to cheaper manufacturing costs, a major factor is rather the lack of appropriate investment early enough by companies who could have benefitted: large scale production would bring costs down, inherently. And, while the UK manages to hold onto some capability, the supporting industries of printed circuit manufacture, assembly of chips into packages; and equipment build has followed: the majority of electronic equipment such as DVD players; computers and digital camera circuit boards are now made in Taiwan or mainland China since manufacturers of such equipment find it easier to build the application boards where the chips are made, at least to save shipping costs.

While Far Eastern companies associated with the semiconductor industry benefit from the infrastructure of silicon chip manufacturers through circuit board fabrication and assembly manufacturing near the foundries, leading foundries are now taking charge of the characterisation of the new processes they are developing. The importance of this is easy to overlook but absolutely critical to understand the implications. To properly characterise a new transistor for designing, engineers need to know a fair amount about device models, and the behaviour of devices at RF. The models need to be verified; and circuits built with them checked again to ensure that the results as seen on the silicon chip really were predicted by the models. Consequently, the whole supporting technical capability of RF-knowlegable engineers follows.

From characterization, models are generated which lead to designs. Therefore, design jobs will spring up around the “knowledge” labs of the advanced foundries which will, if not addressed, erode the technological capability of the UK in design in the same way that manufacturing has been decimated over the last few decades. Consider a parallel in the UK. Tesco is widely known for its business practice of selling anything to anyone. TSMC is similiarly demonstrating a capability of providing not just silicon, but design blocks, I.P. and design support, and appears to be following a path of providing more of the design support services to its customers. This is the starkest warning that needs to be heeded: **failure to access advanced technologies will erode the UK’s competitive position in design in due course through continued erosion of technical knowledge.**

At the very time the world is undergoing the combined forces of global markets with upheavals in trading blocks, it seems incredible that the UK should not see any need to support silicon technology capability. Just three years since the 2002 report from the House of Lords seeking to succeed in “technologies beyond CMOS”, silicon seems as robust, and more important, than ever. And has potential to respond of its own in the nanoscale world. Predictions of “end of CMOS scaling” seem to be used to avoid investment: in contrast, the rest of the world is pursuing silicon with even more vigour than ever. Aerospace, automobiles, medical, consumer applications are only possible today using computing technology. Mistakes of the past (largely through insufficient funding and the will to succeed) seem to have clouded the decision making in government; to the detriment of UK capability. We need to learn the lessons of the reasons for the failures and not use these as an excuse to avoid the most empowering technology ever. We may have lost the “micron” battle, but this can be addressed any time the decision is made to redress the balance. Examples of companies catching up and overtaking are illustrated by SMIC, whose growth is outstanding, powering from behind to working on 65 nm technology. Korea’s Samsung is number 2 in the league tables. Design, it is noted here, will suffer similar fates to manufacturing if state-of-the-art technology is not maintained and researched within the UK.

4. UK Competitive Position

4.1 Academia

In the UK, several universities are demonstrating that they can contribute to silicon technology development. Warwick has researched the growth and development of strained silicon technology, which allows transistors to increase the channel mobility and therefore operate more rapidly than they would have. This is important because, as noted above, smaller transistors operate with higher electric fields which cause a reduction in performance. Strain is created in silicon by growing a layer which has a different atomic spacing to silicon, usually by adding germanium which has a slightly larger spacing.

One approach is known as pseudomorphic in which germanium is introduced into the silicon crystal in such a manner that the germanium takes up the horizontal spacing of silicon but stretches vertically; the thickness of such layers is limited before significant defects occur. The other approach, known as virtual substrate, is to gradually grade silicon-germanium by changing the proportion of germanium in an epitaxial layer which can be grown without strain, but then a further layer of silicon can be grown on this which becomes strained. Each is more suited to a particular type of transistor (NMOS or PMOS) and forming both in one wafer is a potential future application to be solved.

Glasgow is internationally respected for its expertise in hafnium oxide measurement and characterisation, which is seen as an effective high dielectric constant replacement for oxide; and in simulating devices at the atomic level where nanoscale effects become important. This emerged in the materials department rather than electronics, but also in electronics, Glasgow is a leading player in atomic-scale simulation.

Southampton are able to provide silicon wafers for a range of experimental and research oriented device structures, and provide a service to the rest of UK universities. Closely associated, Surrey University provides ion implantation services with a modern implanter capability; and often performs novel implants for devices built at Southampton. Southampton are able to process small geometries using electron-beam lithography for research devices

Cambridge is well-known for research into single-electron devices, and has laboratories sponsored by industrial heavyweight companies like Hitachi. New areas include research into silicon and other semiconductor materials for so-called “terahertz” (THz) applications for medical imaging and high frequency applications bordering electronic and optical systems. Other universities capable of developing nanoscale silicon concepts include Newcastle (SiGe devices); Warwick (SiGe growth systems); Liverpool (nanoscale device concepts in collaboration with Southampton); Edinburgh (power and test structures in particular); DeMontfort (power devices); Swansea (power devices) and Imperial College (low power design).

This snapshot of some universities indicates that while the UK may be lacking a large mainstream silicon manufacturer with leading edge technology, the universities are able to generate world-class research in nanoscale devices in silicon and other materials. The problem this presents for UK government is that the benefits of the research are unlikely to be taken up by UK companies, at least in the near term, or unless some substantial breakthrough occurs which would support start-up spin-off companies. The consideration needs to be made regarding the benefit to UK public whose taxes have enabled university research to be possible. Of course, some companies support research directly; but without a UK heavyweight, they are largely offshore.

IBM supports some of the work at Glasgow; Hitachi at Cambridge, and as might be expected, leading companies will show interest wherever there may be some relevant research work. It is not sufficient to say that external companies might invest: profits ultimately appear in the budget sheet of the country in which the company has their head office.

Southampton University has renowned work in optical and photonic systems. Their pioneering work may prove useful in defining a long-term objective of finding ways to implement optical signal routing on chip to replace metal wiring- at least on some critical paths. This has been noted as a major potential application: but is probably more than 10 years away from industrial use. Industry is likely to take up optical interconnection technology once techniques have been demonstrated; and coincide with a technology node whose performance is no better than the previous one without such a paradigm shift.

5. UK routes to exploitation

By implication, the previous section noted that much of the research work in the UK may not be taken up by UK-owned companies, particularly if the devices, processes or methods apply to deep-sub-micron technologies.
Considering niche areas in which UK manufacturers are finding opportunities, silicon technology is still potentially developable for high voltage; high voltage integrated devices; RF applications; imaging and optical devices (PIN diodes for high speed IR detection; photodiodes for imaging chips) and efficient discrete transistors. All of these areas are being exploited; Swansea and DeMontfort universities as well as Cambridge Semiconductor, operating in Germany, are developing new types of power transistor. Zetex is developing low on-resistance, high gain transistors for efficient converter and inverter applications: along with the PC, their niche exapnded to provide efficient converter transistors for cold-cathode fluorescent back lights in LCD displays.

Routes for exploitation are limited in terms of volume; but need not be in terms of innovative ideas in medical, security, aerospace and domestic markets including I.D. cards, biometric passports, roadside car identification, automotive and so on but often, such new ideas stumble if investment is required for large volume. If the UK is to benefit from the extensive research into silicon which is still, fortunately, continuing, then greater emphasis needs to be given to venture capitalist investment; and finding new ways to encourage the critical development period between the demonstration of a concept and any manufacturing which may ensue. Often this is the period which the UK fails at, with the result that return on investment is late or never: this has contributed to the situation we are currently in. In future, we need to find a way to support potential new companies from university spin-outs, and exploit UK research for UK companies. This is a difficult challenge and ideas on how to address this should be sought, because it is more likely that without any leadership, any opportunities where start-ups perform well will be snapped up by larger foreign companies with the benefits going outside the UK.

6. Industry

Some of the silicon companies operating in the UK are:

National Semiconductor (CMOS, bipolar)
ON Semiconductor (formerly Motorola)
(CMOS) Philips (CMOS power)
Zetex (bipolar discrete, analogue I.C.'s; power MOS)
International Rectifier (formerly ESM) (CMOS power and power controller chips) Zarlink (bipolar I.C.'s)
Intel (Ireland, CMOS)
Analog Devices (Ireland, CMOS)
X-FAB (CMOS, BiCMOS I.C.'s; photodiodes)
Atmel (CMOS to 130 nm (90 nm), former Siemens plant) Semefab: (discrete bipolar, opto devices, I.C.'s, modules) Dynex (IGBT's, power devices, military rad-hard processors)

X-FAB in the UK is able to provide 0.35 micron technologies with high voltage and low-voltage optimised variants; and extensions for RF-CMOS and general communication and mixed signal areas. IR, widely credited with introducing the power MOSFET in the late 1970's, recently purchased ESM, the former foundry which was sold off from ST who took over from the Government's INMOS establishment which was intended to address the very topic this report is about, some 20 years ago!. Atmel took over the Newcastle operations after Siemens decided to pull out of the UK: Atmel is currently able to offer 0.18 micron, and is preparing 0.13 micron technologies. Zetex continues to innovate in discrete devices, one of its original technologies it was noted for when it was Ferranti, prior to being taken over and later sold by GEC-Plessey. Other manufacturers such as Motorola (now ON semi or Freescale divisions) and National Semiconductor still operate in the UK.

Semefab, who emerged from General Instrument in Scotland, are managing to find niche markets in optical devices, power transistors suitable for audio amplifiers; and transistors for military and aerospace applications. Dynex, formerly owned by GEC, are still manufacturing power devices such as IGBT's for the transport industry; where geometries are less important than power handling of devices. Some devices in fact require the whole silicon wafer to be assembled as a single device.

There are, therefore, manufacturers in the UK who could exploit research emerging from UK universities, but the technology will be limited to nodes around 0.35 microns rather than leading edge 90 or 65 nm. This creates a mismatch in high performance computing and digital applications; but a better match for optical, power, and general computing where geometries are less important than power handling or dark currents in the case of imaging chips, for example.

Clearly, the UK cannot currently compete head-on with leading-edge players. This however, is a problem and not a statement of intent for the UK to remain in this position. Through leadership from government, and collaboration between UK manufacturers, this situation may in the long term be addressed. It is only in the medium term where the drive to explore possible niche areas needs to be filled to ensure that the UK does not fall further behind. The niche areas where the UK can compete, such as optical devices in silicon, where low dark currents require very high quality surfaces, are generally areas where more attention to the manufacturing process is needed than geometrical features. High voltage devices are potentially competitive, and power control will be growing in significance. Is sues of reducing on-state resistance in high voltage devices can be worthwhile, but the costs of the silicon will be important, and some companies such as IR may do better than others which are smaller. Zetex is managing to stay competitive in the discrete business while IR sees the need to provide “up-integration” whereby they are increasingly developing complete converter units and controllers rather than just the transistors as this tends to command greater revenues than just the silicon.

6. Competitor Analysis

Worldwide, there is strong competition in manufacturing. However, unless action is taken, design will inexorably follow. Commercially, manufacturing offshore is argued on the basis of low cost in lower economy regions; yet closer examination reveals that governments in many countries are contributing substantial aid to their indigenous companies. India seems to be jumping onto the manufacturing bandwagon with a declaration earlier this year suggesting that they too would like to enter silicon manufacturing and augment their services in software and design. While the UK ponders, other countries are making strategic investments to ensure that their technological capability remains world class.

It has not been possible to determine a detailed breakdown of competitor investment but the Lords’ report (op.cit) gave some interesting figures showing that the largest European investor in R&D in the IT sector was Germany, followed by France, the UK at about $2 billion, and then Italy. Intel, however, invested $3 billion, even during the last downturn (2001), which is more than the UK total. If we are to remain competitive, R&D spending needs to be increased as a percentage of GDP and one way to ensure that this is effective in stimulating new silicon technology would be to focus in a single Central Research Establishment. As predicted after the government rejected the Lords’ recommendation, what funding has been made available has been diluted among regional development agencies; none have had significant funding for realistic advanced technology and we are further behind than in 2002 in terms of world-class technology; though in terms of niche areas, companies continue to make progress if this is still somewhat limited.

Key players worldwide are ST, the former SGS (Italy) and Thomson (France) semiconductor operations merged into one company; Philips in Holland, and Infineon in Germany, the former Siemens semiconductor group. In the US, Intel is the largest player by far at around $30 billion; once just a few years ago, Intel and Motorola were similar at around $8 billion. According to IC Insights (11) the European players are ranked 5 (Infineon), 6 (ST) and 10 (Philips). TSMC is at 8; while the fastest growing company was Samsung with over 50% growth to achieve $15 billion sales and stands at number 2 after Intel.

Competitors to UK companies – other than large players such as Freescale (formerly Motorola) and National Semiconductor – tend to operate at much lower revenues in the range of £10 to £100 million. Direct competitors may be AMIS in Belgium (formerly Mietec), AMS in Austria, and various smaller players around the world such as Jazz, (US); Tower (Israel). The market for such companies represents something like $10 billion of the total $213 and the top 20 companies take about $155 billion. This illustrates quite dramatically that there are very high revenues to be made provided the investment and motivation is directed to achieving such sales.

One important consideration is the growth in China's mainland. SMIC has only recently been formed; yet is already installing 90 nm and also plans to develop 65 nm technologies. This covers the period in which the Lords conducted their review; and at a time when the UK government response suggested it was “too late” to respond in silicon. Meanwhile, Samsung in Korea continue to make progress and are also valued around the $15 billion level; double the sales of ST, having been supported at least initially by government grants which are reportedly around the $500 million mark. The UK needs to restore technological capability not only in manufacturing but also to provide models for advanced design; and to ensure that the UK is able to sustain a competitive position in associated industries such as circuit board manufacturing, design tools; design expertise in new and advancing technologies, significant investment is needed. Throwing small amounts at the problem is a woefully shortsighted approach, as is expecting regional agencies to address a national problem; and returns on investment are even less as a result since the level of funding is barely able to sustain current activities let alone restore state-of-the art. Yet, given sufficient investment and a determination, Samsung, SMIC and in future, possibly India, have demonstrated that success can be achieved even from a position of behind. It is not a matter of being late: 15 to 20 years of silicon in a growing market is a massive opportunity but has to be taken wholeheartedly. Samsung were small or non-existent at the time the UK had strong silicon players. Samsung has grown over the last decade while UK has declined. Governments have supported their industries: the UK seems content to let them, but this will have severe consequences, worse in future than we have seen up to now as potentially the design companies are impacted by increasingly knowledgable competitors.

7. Silicon Forward Look

The leading edge of silicon is largely covered in the ITRS Roadmap. This now maps out generations of technology up to 2018, and it is evident that accounts of silicon reaching the “end of the road” by 2015 were short of the mark. Even if scaling stops, it should be evident from the wide number of applications reported above that silicon, a key driver in virtually all industrial applications, will continue to provide computing power for a decade after “end of scaling”; but in the nanotechnology era, quantum computing devices for high performance computing could be based on silicon technology. We can consider some relevant areas for the UK as follows.

7.1. 5 years ahead

Optical imaging chips

Because imaging chips actually suffer as the pixel size reduces (because each pixel receives light in proportion to its area, smaller pixels suffer increasing noise) there is an optimum around 0.35 microns which enables efficient and large chips to be built with good optical response. However, even 0.35 micron metallisation patterns tend to take up a lot of area in relation to the pixel; and some high volume applications benefit from 0.18 micron not for smaller pixels, but reduced interconnect area which enables more light to be absorbed. Even the use of microlenses has been demonstrated already by competitor countries, but integrating lenses to direct light around 0.35 micron metal tracks might extend competition in 0.35 micron node. Continued growth in security applications may drive infra-red imaging systems using silicon to be developed and although the UK may not provide a significant proportion of the total world demand, the overall demand will continue to increase because of combined mobile phone and camera technology, video communication, and even entertainment (downloadable films onto mobile phones). The UK can expect and should strive to increase its market share in niche areas in security and industrial applications.

General silicon applications

These will continue unabated. The market is expected to continue to grow some 10% per annum, taking the total sales value to $350 billion by 2010, on average. If the advantages of solar PV are supported by the public, government support could lead to a potentially huge market in power generation. Solar cell markets could increase the total silicon market by $100 million to $1 billion or more given the right conditions. This will need government and business coordination to manage and present the case, but as the need for alternatives becomes greater, silicon is able to fill the gap.

Applications for silicon will continue to drive chip designs to support high voltage, RF, analogue and low power applications with technologies optimised for each. Continued decline will be seen in standard chips; with discrete and older I.C.'s being replaced by specifically designed and optimised devices. This will require skilled engineers to continue the trends in the UK if we are to capitalise on the continued growth of silicon.
Design companies will continue to survive against increasing technological competition, but unless the issues identified in this report are addressed, design of I.P blocks in RF communications, TV's, DVD's and computers will increasingly be seen from Far Eastern companies, and growing technology companies in China's mainland; and possibly India.

7.2. 10 Years ahead

By 2015 we will be closer to the 2002 vision, tarnished before the ink was dry, of the "end of CMOS". However, silicon, and CMOS at that, is likely to be providing the mainstream electronic support for computing power; transistors in power converters and logic for virtually all electronic equipment. Other semiconductors will have taken their competitive position from silicon: for example, gallium arsenide and indium phosphide may still hold records for speed (potentially reaching beyond 1 THz): it seemed for a while in the first half or the '00 decade that 3-5's had lost ground. But now scaling is being applied to them (following silicon) with improving results, now also uncovering similar limitations to those seen in smaller silicon devices. Silicon may well be able to reach 1 THz also. All of the developments in other semiconductors for displays (OLEDS); lighting systems (LED traffic lamps, and possibly LEDs in the home) will demand greater use of silicon for controlling them rather than less. Silicon may have reached 20 nm technology node in accordance with the ITRS proposals. Automotive systems may well demand greater use of power transistors and switches as cars move from petroleum to LPG and hydrogen power, with increasingly likely some form of electric hybrid. This will again add to the demands for silicon devices to control the systems rather than replace silicon. However, other semiconductors may offer competition in specific areas. For example, silicon carbide devices may then be able to be processed on 6 or even 8 inch wafers; and could displace today's IGBT's for high voltage high power use.

If silicon is adopted for solar power generation, the solar PV industry could be worth $100 billion alone, from modest beginnings. Continuing with 10% growth (CAGR) the present $213 billion may reach $1 trillion. It is possible that silicon chips will have such a market; but an alternative scenario is that silicon is used in power generation and together, market saturation in many areas means that while the overall market is over 1 trillion, its makeup is from solar PV and conventional chips rather than "conventional" chips alone. Global factors affecting the continued growth in silicon are primarily matters of supply: energy and chemicals for manufacturing. Should energy costs rise, this could cause further flat cycles in the "silicon market" curve. But, this would only be a consequence of continued reliance on oil as a prime mover. Silicon PV could ameliorate such problems by not only replacing oil as the driving force, but thereby increasing its market at the same time.

Coupled with smarter software, computer imaging and pattern recognition could drive this industry forward. A combination of smart software with imaging chips could lead to automatic recognition of peoples' faces; industrial objects, and generally continue the development of robotic devices to assist manufacturing and assembly processes. The government recently launched the "Identity Card" program which emerged as needing fingerprint data, facial and iris scan data to be stored. However, the software for handling such data efficiently is probably still several years away; but when it eventually emerges will provide powerful identification systems. But this could need advanced technology for readers to identify the card holder, for example, and match the information to the card data.

Computing, digital cameras, mobile phones, DVD players, recorders, portable music systems and so on will continue to expand and adapt to market changes. Over the next 5 years, computers may hit 5 GHz, but are now approaching the point where processor chips are getting hotter despite reducing power supply voltages. Parallel processing will increase, improving throughput. In 10 years, probably film-based cameras will be virtually extinct: progress in digital will continue and will be adopted in mainstream professional applications. Computers in 10 years will become limited by silicon power dissipation. Throughput in supercomputers will be achieved by cooling; even PC's may need special cooling arrangements; but surround-gate device chips on insulating substrates (oxide) may enable a performance step up and limit power dissipation for laptops.

Improvements will be needed throughout the manufacturing process in photolith., film deposition, etching and control. Assembly techniques will be needed to handle chips with thousands of connections at the high end of computing while at the lower end cheaper solutions to manufacturing silicon will be needed for technologies in the range of 35-350 nm, which have specialized additions for high voltage and RF.

Software importance will continue to grow with improved processing capability in silicon. Software storage on chip will become as important as the chip in some applications: already the mobile phone needs software support, but future systems will be more dependent and may need reprogrammability in virtually all applications.

Chips will be developed for direct off-line mains power applications to simplify controls in lighting (fluorescent or LED) systems and switch mode supplies for computers and other appliances.

7.3. 15 Years ahead

By 2020, silicon will have reached the end of present-day planar scalability. However, it is strongly suggested that silicon will still be the driving force behind most industrial, commercial and consumer applications. CMOS will still be the dominant technology, though leading edge devices will almost certainly be some form of surround-gate channel (non-planar). There will need to have been developments in contacts, metallization, insulating layers, packaging and assembly for virtually every application including power, computing and so on.

The recent ITRS Roadmap extends ultimate silicon to 6-10 nm in 2018: silicon will continue to provide supporting computing in automobiles (radar for collision avoidance; automatic navigation; route planning, superior engine management, dual fuel engines (electric being one possible choice of the two further ahead).

Silicon will be so prevalent that almost all imaginable uses will use chips in some form. By 2020, silicon technology such as 0.35 micron might still be useful for simple applications, probably in chips as small as 1 square mm or less, where the processing power is required for very basic functions: perhaps intelligent light switches which detect whether people are in a room: and if not, turn unused lights off to improve efficiency in the home. It is expected that automobiles will be hydrogen or hydrogen-electric dual power with petroleum and diesel in sharp decline. This will maintain the need for silicon power devices, which will not shrink at the rate of leading edge technologies, to handle the voltages. The need for low on-resistance will be as important as ever to handle high power systems. Evidently the requirement for continued research into power applications could be a niche relevant to the UK.

Optical chips may be widespread and worth $several billion, probably more than reported in the EIGT report (5). Once again the UK may find that without supporting nanoscale technology, it will lose out in such markets.
Silicon clearly has some possibilities for new nanoscale concepts and it is quite probable that some form of silicon device based on quantum technology will be starting to displace conventional transistors, but only at a modest level. It is expected that quantum, or electron-level, devices will have yield problems, communication delays across chips needing optical solutions and so on will limit early replacement of silicon for mainstream computing. Regarding the optical replacement of wiring for communicating signals across a chip, the potential is there for novel ideas to find low cost methods of implementing efficient light sources (LED's) in silicon–based technology without having to use expensive 3-5 layers; though it would in principle be possible to use 3-5's. Building transistors to handle electrical-to-light conversion may need novel solutions (direct light output: optical transistors?) and the usual challenge to demonstrate its relevance against industrial 20 nm processes. By this time, replacement technologies for conventional CMOS using optical interconnect, novel structures and so on may be apparent, but silicon will still be the backbone of a major industry.

8. Summary

It is worth repeating that no other technology can match silicon for cost-effective processing power that silicon offers. Transistor performance has reached almost 400 GHz in MOSFET and bipolar devices; and may reach 1 THz by 2010. Applications for silicon (silicon-germanium, actually) are foreseen in 77 GHz radar which was once considered well beyond the capability of silicon and was the preserve of 3-5 devices. Carbon nanotube devices are only just beginning to be evaluated and may appear as part of the silicon manufacturing process rather than displacing silicon. Silicon seems well positioned to generate over $1 trillion by 2020 and still no replacement technology seems likely within that time period.

Possibly, new techniques which may lead to much faster and intelligent machines will be based on quantum effects (such as spintronics). There is however much work to be done to get such laboratory ideas ready to market in the form that silicon is currently, and even today, if there were a possible route defined, it would take 15 years to build up to the levels of investment which silicon has. Therefore, it is concluded that despite the exciting developments in the lab today regarding quantum effect technologies, silicon will have at least 20 years life in which it continues to dominate electronics.

9. Recommendations

The UK government has largely ignored silicon. Even the Lords' report which called for a national centre which was focussed on design was rejected. However, the issues surrounding design are becoming more apparent as competitor countries and businesses develop. As indicated in this report, concerns are increasing that as the Far East continues to build its expertise in silicon processing and knowledge extensions into RF and analogue applications, the differentials between the UK and competitors will diminish. Circuit board manufacture and layout is migrating closely to the chip fabrication plants; RF characterisation and modelling skills are being learned quickly not only in Taiwan where TSMC has a leadership facility, but also in mainland China. A decade or so ago Korea launched its Samsung microelectronics initiative, and although Hyundai and LG failed to match the challenge, LG is large in equipment while Samsung has effectively taken the lead. Samsung is a prime example where dedication to succeed, and targeted and appropriate investment have made substantial returns on the investment. Meanwhile, India has declared an interest, and Japan continues to invest although even Japan has succumbed to some extent to growing Chinese capability.

There are few recommendations, but it is to be stated that while those in government might choose to avoid investing in silicon because of “limitations ahead” silicon is more important than even in 2002 when the Lords made their report. Far from declining silicon continues to grow.

The EIGT report (5) is to be congratulated in its in-depth analysis of the UK electronics manufacturing situation. It performed detailed interviews with many companies and concluded that the UK's problems were worse than at first feared, with the diversity of companies in small and medium areas maintaining an uncoordinated existence, thereby denying themselves the position of influence in the government. However, despite this excellent study the one conclusion they rejected; namely to form a Central Research Centre; was probably the very decision which needed to be made. By not supporting this proposal, they have allowed the present situation to continue to drift; leave unfocussed the government strategy to support semiconductor manufacturing and failed to address the very concerns that are causing the present dilemma.

The UK government should invest in a single Semiconductor Research Centre. Its objectives are

- to maintain state of the art technological capability
- to provide the ability to develop new equipment for new processes
- to facilitate investment in new products
- to provide limited production capability
- to enable state of the art devices to be manufactured ahead of the competition in order to service advanced design needs
- to provide training for engineers whose knowledge in state-of-the-art equals or exceeds that of anywhere else in the world, and, by implication, where graduates are more able to develop ideas for companies they may work for than existing companies might offer
- to consolidate R&D investment instead of divisive diversification and thereby ensure that all processing steps required in nanoscale technologies are under one roof
- to support advanced design knowledge in globally important and strategically significant technologies and state of the art characterisation

Such a centre was costed recently at around £150 million, which probably caused the Treasury to decline any idea of supporting the proposal. Instead, a figure of £100 million had been suggested as support for nanotechnology. However, the returns on investment could be worth £1 billion each in the following market areas:

medical electronics	disease diagnostics, scanning and maintenance
security	optical imaging chips and software
communications	in fact, the total product of design companies could be worth more than £1 billion as communication systems grow (digital audio broadcasting; television and satellite transmissions; local networks (wireless computer connections) but stand to continue to decline if design skills are not maintained.

lighting systems	commercial companies working in non-silicon devices are driving forward light emitting diodes which require support in silicon because of their power needs (typically 3.5V at 350 mA, current limited, for a state of the art LED) and as prices fall, increasing popularity of colour displays needs silicon to drive them
computers	there will be a need for support chips for LCD displays (LED and fluorescent); sound processing and power supplies etc which are equally important to but less glamorous than processor and memory chips
memory technologies	while the memory field has diversified with MRAM as a recent contender, memory will continue to be an important and necessary complement to processor chips. Continued research into new memory technologies may lead to opportunities which a research centre could pilot and would be worth a substantial fraction of the computer market (memory value was about $22 billion) itself.
solar PV	given the public concern over nuclear, and (sometimes biased and spurious) objections to wind power, silicon solar PV is able to offer unobtrusive, non-toxic, non-polluting and silent alternative to power generation. If supported in the UK, existing manufacturers could be persuaded to work together to provide suitable cells in a program which could be worth $100 billion over 10 years in exports if the UK leads suitably environmentally preserving technologies for power generation as fossil fuels vanish, and nuclear waste costs mount.

There is no shortage of potential markets for silicon; but there will be serious consequences for UK profitablility and relevance to world technology without such support. In particular, one design area which could be regarded as a niche area would be to design and build for high reliability applications. Currently, while silicon chips are still designed for 10 year life, the practical life of equipment (computers and mobile phones, for example) is only 3 years. This may cause commercial lifetimes to be gradually reduced in accordance with equipment life expectancy. In which case, there is a niche area for more conservative design rules and technologies for reliable service over many years when safety is paramount. Designs for chips to survive high level atmospheric events; radiation of other sorts and in general offer reliable operation almost certainly requires a larger chip than commercially considered possible. "COTS" is a popular military method of acquisition these days; but reliability is not necessarily 10 years as a result, and particularly with modern trends to replace designs every 3 years.

For security systems for home defence and personnel identification, reliability ought to be stipulated for longer operating service life than commercial devices, which is to go against the flow. But, with increased collaboration between manufacturers and government, our expertise in processor design as demonstrated by ARM could be linked with high reliability processing for such applications, which would have increased levels of reliability for national security important markets. These could best be addressed in the proposed Central Research facility.

Industries which ought to be concerned about the reducing equipment life and the implications on silicon include:

- home office areas of security and personal identification
- military for defence and security systems
- aerospace for high reliability control systems, and increasing security measures
- automotive, for improved road safety, electronic engine systems, electric power etc.

In fact, the aerospace and automotive industries already have strict reliability requirements. This must be maintained, and companies supplying these markets will undoubtedly strive to maintain their relevant approvals. But this may not apply to small geometries which are geared at the consumer product areas with only 3 years average usage before replacement, even if the equipment is not worn out).

Another separate but equally catalysing recommendation is

- to invest in a solar PV programme for UK renewable electricity generation

One proposal is the establishment of a UK Semiconductor Manufacturers Association for Solar PV (UKSMAS-PV) which would be intended to pool all of the UK resources and focus effort into defining low cost, single crystal silicon cells which all manufacturers could make and supply to the government as part of a consortium. This would be needed to address the volume of silicon required; it would focus attention on a renewable energy plan; it needs little initial capital other than to define a working program, manufactures of cells, panels and equipment and could lead the world into a renewable energy source. Investment in solar cell panels could start softly and ramp up as manufacturers optimised the process. Although the UK weather is responsible for limiting the utilisation factor to about 10-12%, the UK market would be dwarfed by potential export markets to sunnier areas such as Africa, the Sahara, and current Middle Eastern blocs currently supplying oil but who could generate solar power to replace oil trade in future. The world energy requirement is a global problem, but the UK could find its niche in the supply of silicon PV.

As such, the UK market would be worth £10 billion at least; exports could be worth £100 billion over 20 years and generate silicon trade at least equal to the current total world wide use of silicon. This would more than cover the costs of starting late, but would need investment of new research facilities to avoid any technological developments which may occur in the period where nanotechnology MAY find more efficient, lower cost solutions. However, this is unproven. If we wait for others to lead, we are doomed to follow – typically late and unprofitably. However, the point about silicon PV is that any investment from right now is not wasted: all solar cells will generate electricity for maybe 30 years or more and will reduce carbon emissions effectively from the moment they are installed.

In terms of maintaining a leading edge capability for military, aerospace, defence, and industrial applications, the government should aim at better dialog between suppliers and manufacturers and require, for security reasons,

- purchases of silicon devices should be from approved UK sources

This is in fact in line with the EIGT recommendations for increased government purchases, but may go further. It should not be qualified "if possible" but to insist that all domestic security arrangements are handled within the UK. For example, the government could require that all smart cards intended to contain personal information on UK citizens should be designed and sourced in the UK. This would increase direct government expenditure in the industry and allow businesses to invest in technology which would otherwise not be; or at least to improve investment opportunities through better defined market requirements. Competitor governments have supported their industries directly (in the case of China and Korea; and possibly India if they should also install semiconductor foundries) or indirectly (as reportedly in the US where government spending on defence has allowed companies to establish radiation–hard process lines, small geometry facilities under contract; or in France (where, it is reported, CNET have recently given LETI a contract to develop small geometry CMOS devices – 90 nm as it happens in this case- the equivalent of which would be for BNFL to give a UK semiconductor company a contract for 90 nm technology development: unheard of, and unlikely).

The statement encouraging government purchase and leadership in technology – as it once did- is wide reaching and intentionally so. Processor design is highly commercialised with Intel leading, but at the expense of monochrome diversity. The UK has skills to develop world-class cores: and technology to build these devices would enable UK companies, whether foreign owned or not, to regain momentum. Defence, in particular, may be opening itself to problems unless reliability issues involved in COTS are given proper consideration in light of reducing equipment life expectancy: not necessarily the fault of technology, but through marketing and commercial equipment design seeking to "upgrade" more often and earlier than was the situation maybe 20 years ago when equipment was built to last.

One message is to recognise that silicon is a strategic technology. Not just that it happens to be a $200 billion industry today and is growing and is on track for a $1 trillion by 2015; but silicon underpins computing power in pattern recognition, smart card technology, automotive controls; industrial controls, digital communications, cameras, from high power (locomotive controllers operating at 6 kV) to low (kitchen timer and quartz watches) and rather, almost nothing is not affected in some way by silicon. Solar PV, given government direction, could be the catalyst needed to bring diverse manufacturers together and lead the world in solar PV installations, which could increase silicon market value by more than £100 billion over 10 years alone.

It can be summarised in one sentence: silicon is still here, it is growing in importance, and nanoscale silicon is extending the expected life to beyond 2020. To regard this as a commodity only is to ignore the dependencies of many other businesses on silicon, and overlooks the more serious consequences of not maintaining relevance to the world of the UK's technological capability particularly for engineering knowledge base.

Silicon is undoubtedly a major technology. The UK cannot afford to be left behind in this area in the 21st century which has begun with even greater importance on silicon than the end of the 20th.

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